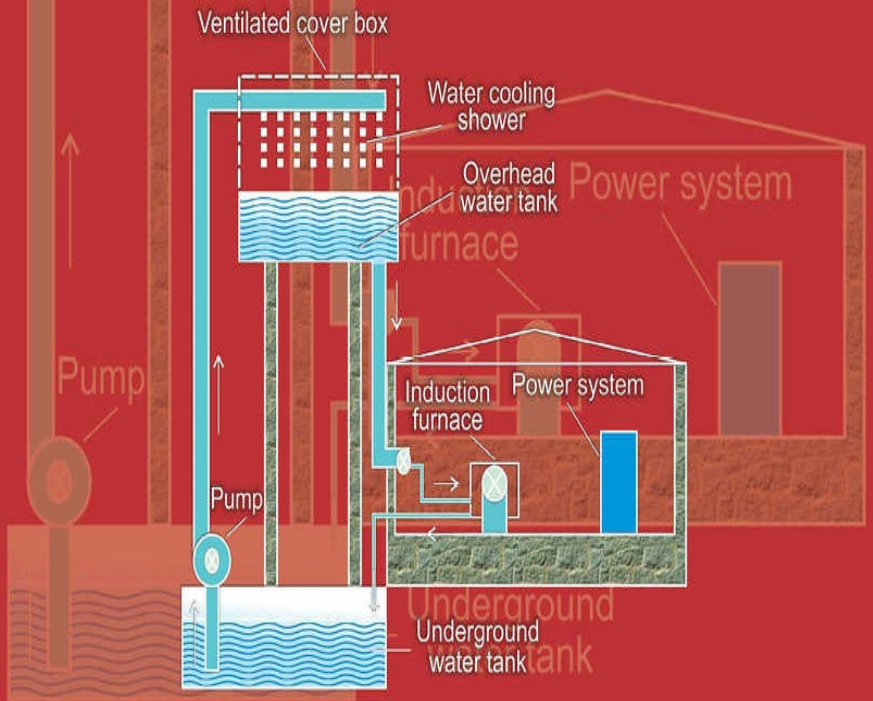
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Fuels, Furnaces and Refractories



PHI

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FUELS, FURNACES AND REFRACTORIES

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FUELS, FURNACES AND REFRACTORIES

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To



Bharat Ratna Awardee Pandit Mahamana Madan Mohan Malaviyaji

The Freedom Fighter, Great National Leader, Visionary,
Founder of Banaras Hindu University having
first Mining and Metallurgical Engineering Department
in India
and
Mentor and Patron of my Father

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Preface

‘Fuels, Furnaces and Refractories’ are important subjects for metallurgical engineering students. The knowledge of these subjects is necessary for understanding various phenomena of extractive metallurgy (ferrous and non-ferrous). The fuels are used as energy source in various metallurgical operations (e.g. raw materials preparation, smelting, refining, shaping and treating). The furnaces serve as a unit to perform various metallurgical operations, where the refractory lining renders furnaces to operate at elevated temperatures. Thus, fuels, furnaces and refractories play important role in many metallurgical activities.

The importance of these subjects could be realised by the fact that many important metallurgical operations have undergone radical changes due to the availability of fuel at given time. The most classical example is iron making. In early 19th century, the iron was produced in blast furnaces using wood char. Later, the non-availability of wood char led to the use of coke in the blast furnaces, which is being used even today. In the mid of 20th century, it was realised that coke may not be available in future due to limited global reserve of coking coals. This led to the development of DRI technology using coal and natural gas in the mid of 20th century. At the end of 20th century, it was felt that solid DRI produced may not get sufficient electrical power in future to melt it, and this led to the development of smelting reduction (SR) technology of making hot iron which is still under development. In the early 21st century, excessive use of fossil fuels (coal, coke, natural gas) causing global warming germinated the thought of making iron using eco-friendly fuels like wood char and hydrogen. The development of eco-friendly fuel for iron making may take time, but the

importance of fuel for the development of metallurgical processes remains unquestionable in light of the given example.

In many metallurgical engineering courses, these three subjects are covered in a single course titled “Fuels, Furnaces and Refractories”. This book, divided into ten chapters, is presented to cover the entire syllabus of the subject. The 1st chapter on ‘Fuels, Furnaces and Refractories–Need and their Significance’ highlights the importance of the subjects.

Chapter 2, on ‘Solid Fuels–Coal and Coke’ gives the origin, classification, preparation, properties, testing, and selection of coal and coke for use. The 3rd chapter on ‘Liquid Fuels’ deals with the sources, preparation, properties, testing and applications of oil in plants. The 4th chapter on ‘Gaseous Fuels’ describes the sources (natural, prepared and by-product), properties, testing and applications of gaseous fuels. Chapter 5, on ‘Combustion of Fuels’ introduces the combustion system, combustion mechanism (solid, liquid and gas), and burners. Chapter 6, on ‘Furnaces and its Accessories’ describes furnaces using solid, liquid and gas, design factors and instrumentation. Chapter 7 concerns with ‘Refractories’ giving their properties, preparation (shaped and monolith), testing and selection for furnaces. Chapter 8, on ‘Heat Transfer and Energy Management’ emphasises on heat transfer modes, furnace heat losses, waste heat use and energy audit. Chapter 9, on ‘Furnace Atmosphere Control and Environmental Issues’ describes the types of furnace atmosphere, its selection, monitoring, environmental issues and safety. The last chapter on ‘Fuels, Furnaces and Refractories–Indian Scenario’ discusses the India’s energy (coal, oil, gas, electricity) resources, production and demand along with a picture of refractory and furnace industry in India. The useful data, bibliography and subject index are provided at the end of the book.

Thus, this book aims to provide information to the undergraduate students of IITs/NITs and other engineering colleges as prescribed in their course. This book would also be useful to plant managers and research scientists in knowing the fundamentals and test procedures. It would serve as a reference to students preparing for AMIIM, AMIE and other competitive examinations requiring knowledge of the subject.

The author would welcome suggestions from the enlightened readers to further improve the text in its next edition. The author would welcome views by email (rcgupta.bhu@gmail.com).

R.C. Gupta

Preface

Acknowledgements

I am indebted to Bharat Ratna awardee Pandit Madan Mohan Malaviyaji for founding India's first Department of Metallurgical Engineering in 1923, where I had the privilege to study as a student and serve as a faculty member for four decades. I am personally thankful to Pandit Malaviyaji for transforming my business-oriented family into a group of teachers through personal public invitation picked up by my father in 1940s to study at BHU.

I am thankful to Late Professor S.K. Dixit (Fuel Technologist) for teaching me and laying fundamentals during my undergraduate study at BHU (1961–1966). I am also thankful to Late Professor T.R. Anatharaman for assigning the subject 'Fuel and Refractory' to teach UG students at BHU. I had the privilege to teach this course for many years. I am further thankful to my students, fellow colleagues and laboratory staffs, who co-operated with me in discharging my responsibility as teacher and laboratory in-charge over this long period.

I am grateful to Late Professor Bhanu Prakash for inspiring me and providing help and encouragement during my academic career in learning various practical aspects of fuel technology and extractive metallurgy.

Writing this book was a time consuming process, and it was possible to complete it in two years due to sustained care taken by my loving wife Smt. Asha Gupta. She had to bear with my odd working schedule forgoing many of her programs. I shall remain thankful to her forever.

R.C. Gupta

1

Fuels, Furnaces and Refractories

Need and Their Significance

Introduction

The metallurgical industries need fuels, furnaces and refractories as essential requirement. The fuels are needed as a source of heat energy to meet various thermal requirements of the metallurgical operations, carried out in a furnace which is lined by suitable refractory to sustain the temperature of metallurgical operation.

1.1 FUELS

The fuels are used in metallurgical furnace to meet its chemical and thermal energy needs. The substances having carbon, hydrogen, hydrocarbons, etc., which can react with oxygen to give energy in the form of heat and light, are generally used as fuel. However, all substances having hydrocarbons cannot be called as fuel.

1.1.1 Definition

The substances which give energy in the form of heat and light on their combustion with air in a manner which could be utilised efficiently and economically are known as fuel.

In this definition of fuel, there are three conditions which are needed to qualify a combustible substance to be designated as fuel, viz. *utilisation, efficiency* and *economics.*

The first condition refers to its utility. The energy released by combustion must be sufficient enough to be utilised. Thus, materials having very low quantity of combustible material rendering low calorific values cannot be called

as fuel. The green water hyacinth does not qualify to be called as fuel, since it contains more than 90 per cent water. The second condition is the efficiency of combustion of the material and recovery of its thermal energy for some application. Some material may be combustible in nature but combustion process may be such (too slow or too fast) which may have difficulty in its utilisation. Thirdly, the amount of energy obtained must be economical to use. In some cases, the cost of combustible material may be more than the value of heat energy obtained which would disqualify it to be termed as fuel. As an example, the paper is combustible material, but it is an expensive material for using as fuel.

1.1.2 Classification of Fuels

The fuels can be commonly classified on the basis of physical state of their occurrence, source, process of production and renewable/non-renewable quality as follows: (a) Physical state of fuel, i.e., solid (coal, coke, charcoal, etc.), liquid (petrol, diesel, etc.) and gas (methane, hydrogen, etc.).

(b) Source of fuel, i.e., primary sources like coal, crude oil, and natural gas which occur in nature or secondary sources like coke, diesel, hydrogen, etc. which are prepared by some industrial processes.

(c) Process of production, i.e., purposefully manufactured fuel like metallurgical coke or by-product fuel like blast furnace gas.

(d) Nature of fuel—Non-renewable (fossil) fuels like coal, crude oil, natural gas or renewable fuels like hydrogen, biomass, etc.

The primary and secondary sources for solid, liquid and gaseous fuels, classified as renewable and non-renewable (fossil) fuel, are given in Table 1.1.

Table 1.1 Classification of Solid, Liquid and Gaseous Fuels

Physical State of Fuels	*Renewable and Non-renewable (Fossil) Fuels*	*Primary Sources or Naturally Occurring Fuels*	*Secondary Sources (Industrial Processes)*	
			Manufactured Fuels	*Fuels Obtained as By-product*
Solid	Renewable fuel	Wood	Wood charcoal	Wood refuse (saw dust, shavings, trimming, etc.), charcoal, sugarcane refuse, waste grains
	Non-renewable (fossil) fuel	Peat, lignite, bituminous coal and anthracite	Semi-coke (LTC), coke, briquettes of lignite char, coal, etc. and pulverised coal	Coke breeze, DRI kiln char and carbonaceous sludge
	Renewable	Oil seeds and	Vegetable oils and alcohol	Paper mill sludge

	fuel	sugarcane		
Liquid	Non-renewable (fossil) fuel	Petroleum crude oil	Petrol, solvent spirit, kerosene, diesel, furnace oil, naphtha, coal tar fuels (from oil shale), synthetic oils, etc.	Coal carbonisation by-products during coke making (e.g. tar, pitch, benzol, naphtha, etc.) petroleum refinery residue
Gas	Renewable fuel	Hydrogen in water	Hydrogen	Sewage gas
	Non-renewable (fossil) fuel	Natural fossil gas	Producer gas, water gas, coal gas, oil gas, reformed natural gas, butane, propane, acetylene, hydrogen	Blast furnace gas, coke oven gas, LD steel gas, COREX gas, oil refinery gas

1.1.3 Use of Fuels by Metallurgical Industries

The metallurgical industries mainly deal with making, shaping and treating of metals. The fuels are required at every step in the metallurgical process. However, every type of metallurgical operation needs specific type of fuel which will be discussed in this text. It may be noted that each fuel given in Table 1.1 does not find application in metal industry.

The metal making process uses different routes to extract metal from its ores. The pyro-metallurgical route depends mainly on some solid/gaseous fuels which are used as reductants and heat sources. The hydrometallurgical/elecro-metallurgical methods also need liquid/gaseous fuel to melt and refine the electro deposited metal from the leached liquor. Thus, fuels are required for metal extraction from their ores.

The extracted metals are given shape by processes like casting, rolling, forging, extrusion, etc. These processes are conducted at elevated temperature and fuels (liquid/gaseous) are required to raise the temperature of the metal to the required level. In case of electrical heating, the electricity is generated by thermal power plants mainly using coal as a fuel, though liquid and gaseous fuels are used by some plants.

The suitably-shaped metals are given heat-treatment to generate required micro-structural features in the metal rendering suitable mechanical properties for use. This heat-treatment process requires some fuels (liquid/gaseous) to provide suitable temperature and atmosphere.

Thus, we find that fuel is needed at every step in the metallurgical process, and it becomes an essential raw material for any metal industry.

1.1.4 Merits and Limitations of Fuels

The metallurgical industries use all the available forms of fuels in view of their merits and limitations. The merits and limitations of solid, liquid and gaseous fuels are discussed as follows: Solid fuels

Merits

(a) Abundance in nature
(b) Ease of availability due to global distribution
(c) Ease of transportation by road, rail and ship
(d) Ease of storage on ground with safety
(e) Ease of use
(f) Low cost

Limitations

(a) Presence of mineral matter yielding ash posing disposal problem
(b) Contamination of product by mineral matter constituents
(c) Environmental issues related with trace elements in mineral matter
(d) Environmental issues related with dust during handling
(e) Handling needs heavy equipment
(f) Needs large floor space for storage which is costly in industrial area Liquid fuels

Merits

(a) Rich energy source
(b) Ease of combustion with flame and atmosphere control in the furnace
(c) Ease of storage in tank suitable to space, shape and size (over or underground) (d) Ease of handling through pipes and pumps
(e) Ease of long distant pipe transportation
(f) Free from ash and any major impurity except sulphur content

Limitations

(a) Not evenly distributed on globe
(b) More expensive fuel
(c) Needs extra safety during handling and storage to avoid fire hazard
(d) Needs pre-heating in cold regions to maintain its fluidity
(e) Needs flame temperature control to minimise NO_x emission

Gaseous fuels

Merits

(a) Ease of combustion with flame and atmosphere control in the furnace
(b) Free from any impurities
(c) High flame temperature with pre-heating air and/or gas
(d) Ease of handling and use
(e) Ease of transportation by gas pipeline
(f) Surface transportation feasible by road, rail or ship in liquid state, in specially designed cryogenic tanks (g) Can be generated by using solid and liquid fuels also

Limitations

(a) Not evenly distributed on globe as natural gas
(b) Needs big storage tanks as the large welded tanks are unsafe under pressure (c) Needs extra safety during handling and storage to avoid fire hazard

1.1.5 Fuel Requirements by Some Major Metallurgical Units

As indicated earlier, all metallurgical units require fuels as a source of energy to meet the chemical, thermal and process needs. The fuel acts, as a reluctant in some processes to facilitate the chemical reaction in addition to meeting the thermal needs by combustion process. In some processes, fuel provides only thermal energy. The thermal energy obtained mostly by fossil coal in power plants gets converted into electrical energy to be used by processing systems of the metallurgical plants. This electrical energy is also needed during elctro-metallurgical methods of metal production.

The use of different types of fuels by some major metallurgical plants is given in
Table 1.2 in addition to electrical energy which is needed to operate electrical systems. In most of the plants, this electricity is generated by thermal power plants using coal or waste heat/gas available within the metallurgical plants.

Table 1.2 Fuels Used by Some Common Metallurgical Units

Metallurgical Plants	*Solid Fuel*		*Liquid Fuel*	*Gaseous Fuel*	
	Primary	*Secondary*	*Secondary*	*Primary*	*Secondary*
BF-BOF integrated steel plant	Coking coal, non-coking coal	Met. coke	Diesel, furnace oil	–	Blast F/c gas, coke oven gas,

					producer gas
DRI (Coal)-EAF integrated steel plant	Non-coking coal	Dolochar	Diesel, furnace oil	–	Producer gas
DRI (Gas)-EAF integrated steel plant	–	–	Diesel, furnace oil	Natural gas	–
COREX-BOF integrated steel plant	Non-coking coal	Coke	Diesel, furnace oil	–	COREX gas, Producer gas
EAF steel plant, EAF steel foundry and non-ferrous foundry	–	–	Diesel, furnace oil	–	Producer gas
Cast iron cupola foundry	–	Coke	Diesel, furnace oil	–	–
Aluminum industry	Non-coking coal for power	–	Diesel, furnace oil	–	Producer gas
Copper extraction	–	–	Diesel, furnace oil	–	–
Heat treatment plants	–	–	Diesel, furnace oil	–	Producer gas
Re-rolling units	–	–	Diesel, furnace oil	–	Producer gas

It can be, thus, noted that all metallurgical units use fuel in the form of solid, liquid and gas. The solid fuels like non-coking coal is mostly used in coal-based DRI units and COREX plant. The coking coal is used to make metallurgical coke for blast furnace iron making and melting cast iron in cupola. The dolochar generated in coal DRI plants is used to generate power. The liquid fuels like diesels and furnace oil are practically used by every metallurgical unit. The diesel is used for emergency power generation, and furnace oil is used in furnace for heating applications. The natural gas is useful only for gas-based DRI plants, to be used as reductant after its reformation to a mixture of hydrogen and carbon-monoxide. The waste gases like blast furnace gas and coke oven gas are used for heating purposes within the plants. The producer gas plant serves to provide heating gas in emergent conditions.

1.2 FURNACES: NEED AND TYPE

The furnaces are required for various manufacturing processes dealing with materials like metals, chemicals, glass, cement, etc. The furnaces dealing with different materials and processes work at different temperatures which may range from 100 °C to 2000 °C. The thermal energy required for the working may

be obtained from various sources of energy. In view of wide range of work conditions, the furnace type may look different from one another. The technique of heat transfer and thermal efficiencies of such furnaces may also be quite different.

1.2.1 Definition

The furnace or oven could be defined as a chamber or working enclosure where higher temperature is maintained for the conduction of some operations related to industry, research or domestic life. The word furnace is derived from Latin word *fornax* .

1.2.2 Basic Features

The basic purpose of a furnace is to have a chamber or enclosure where required working temperature with suitable atmosphere could be maintained with acceptable thermal efficiency, which would be economical in operation and use. In view of this, a furnace will have following features: (a) ***Furnace name:*** The furnace has a name to identify its features necessary for performing some processes.

(b) ***Furnace purpose:*** The process performed in the furnace has a purpose which could be physical (heating, melting, etc.), chemical (calcination, roasting, smelting, etc.) or physicochemical (e.g. sintering) in nature.

(c) ***Furnace temperature:*** The furnace should have thermal zone which could be low (< 1000 °C), high (> 1400 °C) or very high (~ 2000 °C).

(d) ***Energy source:*** The furnace uses some energy sources like coal, coke, oil, fuel gas or electricity.

(e) ***Furnace shape:*** The furnace has a typical shape like rectangular chamber, circular tower (shaft), long chamber (tunnel), rotating drum (rotary kiln), etc.

(f) ***Furnace material:*** The furnace has a structure made of a refractory material or combination of refractory materials which would sustain high temperature working conditions.

(g) ***Furnace charging and discharging:*** The furnace structure is designed in such a manner that it facilitates charging and discharging of the processed material.

(h) ***Energy conversion method:*** The furnace has some means to convert the inherent energy in the fuel into thermal energy like grate combustion,

pulverised coal burner, oil or gas burner, electrical current flow through resistance or arc gap.

(i) ***Heat transfer mode:*** The furnace uses some means of heat transfer from source to object like thermal conduction, convection or radiation.

(j) ***Air supply mode:*** The furnace gas flow could be due to natural draft or forced draft.

(k) ***Batches or continuous operation:*** The furnace operation could be in batches or made to function continuously.

(l) ***Furnace atmosphere:*** The furnace atmosphere could be made oxidising, reducing or inert in nature.

(m) ***Furnace control:*** The furnace could be controlled manually or made automated.

(n) ***Furnace flue gas treatment:*** The method of discharging flue or waste gases could be after cleaning or without cleaning.

In practice, there are many furnaces which have their own characteristic features which make them different from one another. The list of such furnaces could be very long, however, Table 1.3 illustrates some common furnaces used in industry with their features.

Table 1.3 Some Common Furnaces Used in Industry with Their Features

Name	*Purpose*	*Temperature* (°C)	*Energy Source*	*Furnace Shape*
Coke oven	Coke making	1100–1200	Coal V.M. evolved and used	Rectangular—long, narrow and tall
Blast furnace	Pig iron making	300–2000	Coke	Tall shaft
Soaking pit	Ingot heating	1200	BF + CO gas	Rectangular
Lime kilns	Calcination of limestone	~1200	F/C oil or coal gas	Rotary kiln or shaft
Alumina kilns	Production of anhydrous alumina for electrolysis	~1300	Oil	Rotary kiln
DRI kiln	Production of sponge iron	~1200	Pulverised coal	Rotary kiln
Multiple hearth roaster	Roasting sulphide ore	~900	Sulphur in ore	Multiple hearth shaft
Fluidised bed roaster	Roasting sulphide ore	~900	Sulphur in ore	Fluidised bed reactor
Billet reheating	Reheating billet for hot working	~1200	Oil or gas	Hearth type
Heat treatment	Phase/Structural change in metal	400–1000	Gas	Hearth and box type

Sintering furnace	Metal powder sintering	Depending on metal powder	Gas and electric	Box type
LD converter	Refining pig iron to steel	~1500 – 1600	C, Si, Mn in melt	Pear shape
EAF	Steel melting and making	~1500 – 1600	Electrical energy	Hearth type
Induction furnace	Steel melting	~1500 – 1600	Electrical energy	Crucible type
Flash smelter	Copper matte making from sulphide concentrate	~1200	Sulphur in concentrate	Flash smelter

1.2.3 Methods of Furnace Classification

All the furnaces which are used could be grouped or classified on the basis of some parameters to assess and select when required. This classification could be based on parameters listed in Section 1.2.2. The furnaces grouped on the basis of some of these parameters are given as follows.

Energy source

Energy is an important basis to group the furnaces. The use of energy is based on its availability and need. The merits and limitations of every energy source are given in Section 1.1.4. The furnaces using the energy will be affected by the merits and limitations of their sources.

The furnaces using various energy sources could be listed as follows:

(a) *Coal-based furnaces* : Boiler house furnace, cement kilns, sponge iron kilns, etc.

(b) *Oil-based furnaces* : Reheating furnaces, heat treatment furnaces, metal melting furnaces, calcination kilns, etc.

(c) *Gas-based furnaces* : Coke ovens, soaking pits, reheating furnaces, calcination plants, etc.

(d) *Electricity-based furnaces* : Resistance heat treatment furnaces, induction heating, induction melting furnace, electric arc furnace, plasma arc furnace, etc.

(e) *Chemical energy-based furnaces* : The elements like carbon, silicon, manganese, etc. present in hot pig iron generate thermal energy while reacting with oxygen blown in the melt to sustain process in pneumatic furnaces (Bessemer converter, LD converter, etc.). Similarly, the sulphur present in copper sulphide concentrate provides heat of oxidation to sustain hearth roaster and flash smelting furnaces.

Furnace temperature and operation

The furnaces could be grouped on the basis of temperature used to conduct a unit operation like drying, calcinations, roasting, sintering, coking, heating, melting smelting, etc. Such grouping helps in the selection of furnace construction materials is given as follows: (a) *Drying ovens* (10 0 –250 °C): Moisture ovens of different types

(b) *Calcination kilns* (80 0 –1200 °C): Lime kilns, alumina kilns, cement kilns, etc.

(c) *Roasting furnaces* (80 0 –1000 °C): Multi-hearth roaster, flash roaster, etc.

(d) *Metal powder sintering furnaces* (500–1200 °C): The temperature would depend on metal but the sintering of aluminum, copper and nickel-based composites are common.

(e) *Coke ovens* (110 0 –1300 °C): By-product coke oven, non-recovery coke oven and beehive coke ovens.

(f) *Reheating furnaces for steel* (110 0 –1200 °C): Different types of steel reheating furnaces could be grouped under this class.

(g) *Non-ferrous melting furnaces* (50 0 –1200 °C): Various crucible melting furnaces can be grouped under this category.

(h) *Ferrous melting furnaces* (130 0 –1500 °C): The cast iron and steel melting furnaces would fall in this group like cupola, induction melting, arc melting, etc.

(i) *Plasma arc furnaces* (1500–2000 °C): These furnaces offer very high temperature and have special design and refractory to meet high temperature working conditions.

Furnace shape

The furnaces are sometimes classified according to their shape which offers advantages with respect to heat and mass transport. This kind of grouping is discussed as follows: (a) *Shaft furnaces* : The furnaces like blast furnace, cupola, midrex sponge iron, lime ovens, producer gas, etc. could be classified in this category. The shaft furnaces have advantage that they need less floor area, being tall with circular or rectangular cross-section. The furnaces being vertical, the material fed from top moves down under gravity requires less effort. The heat source being located at lower end, the hot gases move up. These furnaces offer good heat transfer by counter current flow of upward moving gas and downward

moving charged burden. These furnaces offer production on continuous basis.

(b) *Rotating kilns* : The rotary sponge iron kiln, lime kiln, cement kilns are typical example of such furnaces. This is horizontally laid rotary shaft furnace which is kept inclined down at discharge end. This furnace design needs more floor space and requires a mechanical system to rotate the kiln. However, this is useful in dealing with materials which cannot be fed in vertical shaft due to their poor strength at high temperature with low bed permeability. These furnaces offer production on continuous basis.

(c) *Retorts* : These are shaft type furnaces with closed ends and thus work in batches. This type of furnaces offer means to regulate the process in better manner as charge is stationary. The typical examples of such furnaces are water gas production unit, sponge iron retorts (HyL, Hoganas, etc.), titanium sponge retort reactor, etc.

(d) *Fluidised bed furnaces* : In such furnaces, the material is treated in fluidised state. The examples are coal combustion in fluidised bed for steam generation, gas-based fluidised sponge iron reduction for iron powder production, fluidised bed drying operation, etc. These furnaces have merit to treat fine size material.

(e) *Rotary hearth furnaces* : In this type, the circular hearth rotates in an enclosed furnace with required temperature profile. The counter current movement of gases and material help in better heat transfer. These furnaces are becoming popular to make DRI using composite pellets of iron ore and coal fines.

(f) *Hearth furnaces* : The typical examples of hearth furnaces are open hearth furnaces for steel making, electric arc furnaces, reverberatory furnace for copper smelting, hearth reheating furnaces, etc. These furnaces have the advantage that they can have large working capacity. Such furnaces yield product in batches with quality, hence they can be used when quality of the product is more important than the thermal efficiency. The open hearth furnaces have been currently phased out due to their poor thermal efficiency and slower production rate by more productive pneumatic steel making processes (like LD steel). However, such furnaces are still in operation though in small number due their special merits. The large steel foundries making heavy castings like pressure reactors weighing 100–400 tons need liquid steel with strict chemical composition at right temperature which can only be supplied by open hearth furnaces. Such furnaces fired by oil and/or gas can be maintained easily

for limited working period by heavy steel foundries. The electric arc furnaces are useful at lower capacities (5–50 ton) with regular production. Maintaining a large (> 100 ton) EAF for periodical working would be uneconomical.

Mode of heat transfer in the furnace

The furnaces act as a means to utilise the heat generated by an energy source that can be transferred by conduction, convection, radiation or a combination of the two or all together. The following variety would cite some furnaces as examples:
(a) *Thermal conduction* : In such furnaces, heat is transferred by thermal conduction from heat source to the interior of the material. The induction melting furnace
and salt bath heat treatment furnace are good examples for such furnaces. In induction furnace, heat is generated on the surface of metal by resistance due flow
of eddy current and this heat is transferred by conduction to the interior of the material. In case of salt bath, heat treatment furnace, a bath of molten salt is maintained at required temperature to heat the metal object to be heat treated which remains immersed in the bath. The heat in the metal is transferred by conduction.

(b) *Thermal convection* : In such furnaces, the heat is transferred by hot flowing gases to heat the object. The drying oven is the best example where hot gases are circulated to remove moisture in the material.

(c) *Thermal radiation* : In such furnaces, the heat is radiated on the object to be heated. The muffle furnace is the best example where heat is radiated on the object to be heated by hot furnace walls, which are heated by some means to the working temperature.

(d) *Convection and radiation* : The transfer of heat from an oil/gas burner to the object is a good example of this kind of thermal transfer. Here, the object is heated both by hot flowing gases of the burner and radiant heat.

(e) *Conduction, convection and radiation all together* : The heating in case an electric arc is done through all means put together. The electric arc between metal and electrode gives a passage to the flow of current in the charge which is heated by metal resistance to the flowing current. The heat generated by arc gives a pool of liquid metal at the hearth bottom which heats metal and hearth by conduction. The hot gases generated in the arc space move up and heat the surroundings by convective mode of heat

transfer. The furnace roof redirects thermal energy on to the top of metal charge by radiation process. Thus, all three modes of heat transfer operate in such type of furnace.

Location of heating system

The location of heating system gives a flow pattern of hot gases which would affect heat transfer. The furnaces identified by such method of gas flow are direct fired furnaces, top fired furnaces, bottom fired furnaces and indirect fired furnaces. A direct fired furnace is illustrated in Figure 1.1.

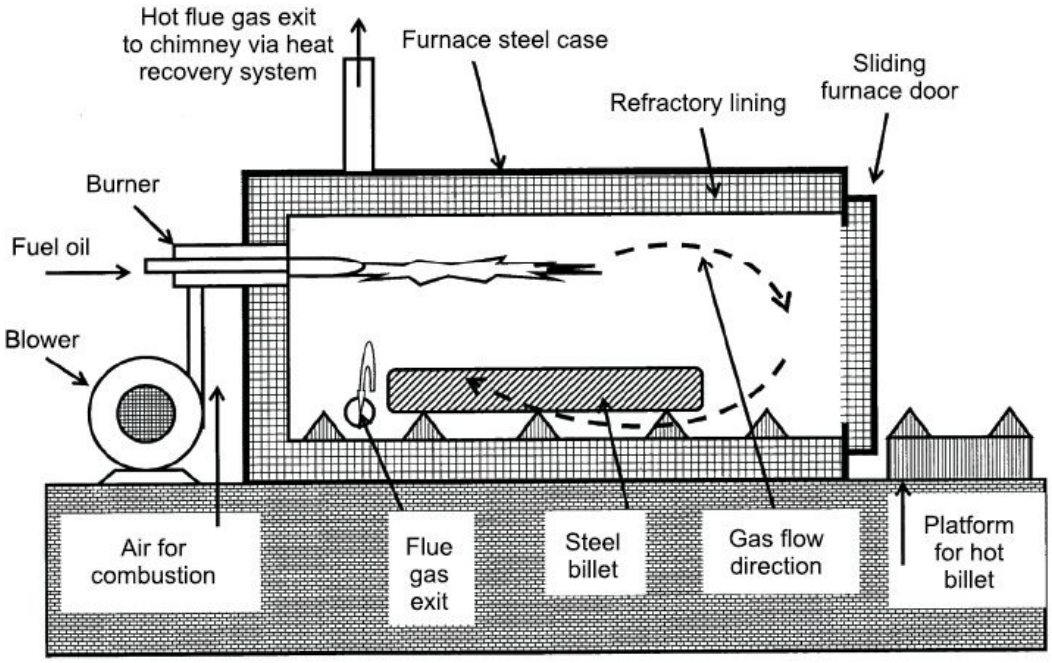


Figure 1.1 A direct fired heating furnace.

Working pressure in the furnace

There are only two types of furnaces under this category: Furnaces working at atmospheric pressure and vacuum furnaces.

The pressure in the furnaces is generally kept a little more than the atmospheric pressure to avoid air infiltration within the furnace and lower the temperature. The infiltrated air would not only lower the working temperature but it would affect the working atmosphere also. The slight positive pressure in the furnace helps in avoiding air infiltration. The hot gases escaping out from furnace through all passages do not allow air infiltration.

Certain furnaces maintain vacuum in the furnace due to process requirements. Generally, the vacuum furnace uses electrical heating like electric vacuum drying oven, electric vacuum induction melting furnace, etc.

Working atmosphere in the furnace

The working atmosphere in the furnace could be oxidizing, reducing or inert in nature as desired by the process.

(a) *Furnaces with oxidising atmosphere* : Most of the furnaces operate with excess air which provides oxidising atmosphere. The steel making units (LD process, open hearth, etc.) and cupola melting unit use oxidising atmosphere.

(b) *Furnaces with reducing atmosphere* : In such furnaces the oxygen in the furnace is made absent by excess use of fuel that gives CO and hydrogen rich gases. The blast furnace and smelting furnace are typical examples for such furnaces. The heat treatment furnaces also use reducing atmosphere to avoid oxidation of the metal.

(c) *Furnaces with inert atmosphere* : The use of inert gases like nitrogen and argon is made in some furnaces to avoid oxidation by oxygen or carburisation by CO or hydrocarbons while heating and performing heat treatment.

1.2.4 Basic Components of Furnace

A furnace should have a few common components as described below:

Furnace enclosure or chamber

Every furnace needs an enclosure or chamber lined with suitable refractory to sustain working temperature and atmosphere. This refractory chamber structure could be encased in thick steel plate structure for handling (e.g. LD converter, electric arc furnace, induction furnace, etc.) or could remain without any steel plate encasing (e.g. Coke ovens, heating furnaces, etc.). The design of furnace chamber depends much on the process to be conducted. The refractory types and their nature are discussed in detail in Chapter 7. The furnace design is a very big subject but some glimpses are given in Section 6.2.1.

Heat generating device

The thermal energy required for the furnace to sustain the process is generated through some kinds of device to burn the fuel (coal/oil/gas), convert electrical energy into heat by resistance/induction/arc or convert the chemical energy present in molten steel as carbon, silicon, manganese, etc. into heat by oxidising through oxygen lance. These aspects have been discussed in various sections of this book as given below: (a) Fixed bed (Grate)/Fluidised bed (Fluidised reactor)

for solid fuels (see Sections 5.3.1 and 5.3.3).

(b) Burner for pulverised coal/oil/gas (see Sections 5.3.2, 5.4 and 5.5).

(c) Electrode/induction coil for electrical based furnaces (see Section 6.1.4).

(d) Oxygen lance for steel making units (see Section 6.1.5).

Gas movement system

The gases in the furnace move under pressure generated by chimney draft or forced draft due to use of blower. These have been discussed in Section 6.2 while giving basic principles of furnace design.

Waste heat recovery

The waste heat in the flue gases needs recovery to improve thermal efficiency of the furnace by using recuperator or regenerator system. These are discussed in Chapter 8.

1.2.5 Factors Responsible for Selection of Furnace

There are a variety of furnaces available for any specific purpose like heating, melting, heat treatment, etc. The selection of the furnace is based on some major factors like: (a) Environmental laws

(b) Energy availability and cost

(c) Furnace cost and maintenance cost

(d) Thermal efficiency

(e) Product quality and contamination

(f) Floor space requirement

(g) Cooling water requirement

(h) Furnace instrumentation and accessories

These are discussed briefly in following sections.

Environmental laws

The use of every type of fossil fuel (coal/oil/gas) is associated with some environmental issues related to disposal of solid waste, liquid and gaseous discharges from combustion systems. These laws are mandatory and violation is punishable by act. These laws are specific for many locations and hence the furnace selection has to be based on the prescribed norms by local authorities.

The Agra may be cited as an example where cupola melting practice by foundries is not allowed due to emission problems that damage the world

heritage monument—The Taj Mahal. The foundries in Agra have to install gas fired melting furnaces or electricity based melting units. This aspect has been discussed in more detail in Section 9.4.

Energy source availability and its cost

The energy source availability and its cost is another important factor before making a choice of the furnace. Consider a small foundry industry in hilly district of Himachal Pradesh or Arunachal Pradesh where the energy sources have to be transported from long distances. The use of cheaper solid fuel may prove more difficult and costly due to its high transportation cost. Considering the cost of thermal energy (Rs/GJ), the solid fuels may become costly compared to oil which is rich energy source and it can be transported at low cost. The gas transport by pipeline may not be feasible due to rough terrain. The electrical energy use may be possible and cheap due to its high thermal efficiency provided it is available. Thus, one has to assess the net cost of energy required to perform a job related to heating or melting and the first preference has to be given to the cheapest energy source at the point of use subject to its availability.

Furnace cost and maintenance cost

Once the energy source is ascertained for its availability, the choice could be made for the furnace type. Assume, the electrical energy is available in Maharashtra region for steel melting industry then selection has to be made between induction furnace and arc furnace. While considering furnace cost and maintenance cost, one has to consider all furnace accessories and maintenance requirements. In such situation, the working condition has to be taken into consideration. The smaller units may prefer induction melting (1–5 ton) compared to bigger units may go for arc furnaces (5–20 ton). The induction furnace may be more suited for small scale, non-continuous melting operation of varied type of steel melts. The arc furnaces serve better on continuous operation of bigger steel melt batches of more common and regular variety. The capital cost and maintenance cost would be comparable after fixing the scale of working and type of melt practice.

Thermal efficiency

Thermal efficiency is dependent on the mode of heat transfer and operating practice. The high thermal efficiency gives saving on operating energy cost. Various furnace types may be available for a given job.

Product quality and contamination

The fossil fuels are associated with impurities, mainly sulphur, which may contaminate the product. The contamination could be minimised or avoided by suitable furnace selection. The example may be given for lime calcinations. This can be done in shaft furnace using coal or in rotary kiln using oil. In shaft furnace the ash of the coal contaminates lime and makes it unsuitable for many purposes while in rotary kiln calcinations with oil produces good quality lime free from ash.

Another case may be cited of sponge iron production. In case of rotary kiln, the coal used as energy source and reductant contaminates the sponge iron by ash and sulphur but when it is reduced in shaft or retort using gas as reductant and heat source, the sponge produce is free from such contamination and is rated as high quality sponge iron.

Floor space requirement

The floor area required by a furnace and its accessories is very important in areas where the rental value is very high like Mumbai. The industry would like to accommodate all its facility in minimum area if it is possible. In such case, the furnaces working on electrical energy may suit better than oil or coal fired units. The decision for furnace type is taken based on total cost of manufacturing rather than just on the cost of energy or furnace alone.

Cooling water requirement

The water is needed by many furnace systems to cool their electrical and mechanical components. This water sometime needs demineralisation which adds to the cost. The availability of right quality water in required amount needs attention and affects selection process.

Furnace instrumentation and accessories

The furnace instrumentation and automation are the means for better furnace control and thermal efficiency. The feasibility of adopting these instrumentation and accessories are examined before furnace selection. The list of such instruments could be long but important items could be: (a) Temperature measurement and indication

(b) Pressure measurement and indication

(c) Gas analysis and control

(d) Gas cleaning system

(e) Thermal shields

(f) Acoustic chambers

All these equipment and accessories are discussed in Sections 6.3 and 6.4.

1.3 REFRACTORIES

1.3.1 Definition and Function of Refractory

Refractories are materials that can withstand very high temperatures (up to 3000 °C or more) without degrading or softening. The refractories are used in furnaces to sustain high temperature and maintain the furnace structure. Refractory materials include certain ceramics and super-alloys and are used as heat insulator in furnaces. The metallurgical operations like smelting, melting, heating, etc. are possible due to use of refractories.

1.3.2 Classification of Refractory based on Chemical Nature

The furnaces use several types of refractory bricks made from refractory materials. The refractory materials are generally classified on the basis of their chemical behaviour, i.e., their reaction to the type of slag. Accordingly, refractories can be classified as: acid, basic and neutral.

Acid refractories

Acid refractories are those which are attacked by basic slag. These are not affected by acid slag, and hence it can be used in furnaces having acidic work environment. The following types of refractories fall in this group: (a) Silica (most acidic)

(b) Semi silica

(c) Alumino-silicate refractories (e.g. high alumina (as exception since it reacts with slag), Fireclay group refractory (e.g. LHD-Low Heat Duty, HHD-High Heat Duty, SD-Super Duty and Grog), Kyanite, Sillimanite and Andalusite.

Basic refractories

Basic refractories are those which are attacked by acid slag. These refractories are of considerable importance for furnace linings where the environment is basic, for example, basic steel making and furnaces for non-ferrous metallurgical operations. The following refractories fall in this category: (a) Magnesite

(b) Magnesite-Chrome

(c) Chrome-Magnesite
(d) Dolomite
(e) Forsterite

Neutral refractories

These refractories are attacked neither by acid nor by basic slag. The following refractories are known for their inertness: (a) Graphite (most inert)

(b) Chromites
(c) Synthetic refractories (e.g. zirconium carbide and silicon carbide)

1.3.3 Classification of Refractory based on Other Considerations

The refractory materials find high temperature applications in many forms and shape. These refractory materials could be classified as: Special refractories, Insulating refractories and Cermets.

Special refractories

These refractory materials are specially manufactured using synthetic (fused/sintered) grains free from impurities under highly controlled production parameters for special applications. They are used for purposes like fabrication of crucible, some parts of furnaces and research and developments. These applications of the refractory do not consider cost as a factor for selection. The refractories included in this group are: (a) Alumina, (b) Pure sialons (Si-Al-O-N), (c) Thoria (ThO_2), (d) Beryllia (BeO),

(e) Zirconia, (f) Boron nitride, (g) Spinel, etc.

Insulating refractories

These are high porosity refractories having low thermal conductivity used for reducing the rate of heat flow (heat losses) to maximize heat conservation within the furnace. The development and application of a wide variety of insulating refractory materials are gaining importance with increasing energy costs in present days. The production of brick shape refractories utilises China clay, asbestos (kieselguhr), glass wool, mica (vermiculite), bubble alumina, carbon, paper wool, ceramic fibers, saw dust, etc. as raw materials.

Cermets

The refractories produced from the mixtures of high purity refractory oxides,

carbides, borides, and metals or alloys fall under this category. Depending on the composition and quality, they are used as abrasives (cutting, grinding, boring tools), in parts of spacecrafts, missiles, atomic power plants, etc.

1.3.4 Forms of Refractories: Shaped and Monolithic

The refractory materials are available in basically three forms—shaped, unshaped (monolithic) and fibrous.

Shaped refractories

The shaped refractory has a specific brick shape for a given purpose. The various common shapes include straight (rectangular), side arch, end arch, wedge, key, flat circle, combined arch and wedge, circle, splits, dome brick, skew (end/side), bullnose or jamb brick and
soap or closer. These shapes are illustrated in Figure 1.2. The refractories bricks that have different shapes are used to line furnaces, kilns, cupola, blast furnaces, etc. The insulating firebrick having desired shape posses low thermal conductivity and are used to minimise heat transfer.

Unshaped refractories (monolithic)

The unshaped refractories (monolithic) are used as mortar, castables, plastics, gunning mixes, ramming mixes, slinger mixes, patching materials and coating materials. These are produced in powder or granular form for various applications.

(a) ***Mortar*** **:** These are materials for bonding bricks in a lining. Three types of mortars are used—heat-setting, air-setting and hydraulic-setting. These three mortars have different setting mechanisms.

(b) ***Castables*** **:** These are refractories for giving a shape in the furnace. Here, the refractory materials and hydraulic-setting cement are mixed. They are formed by casting and used to line furnaces, kilns, etc.

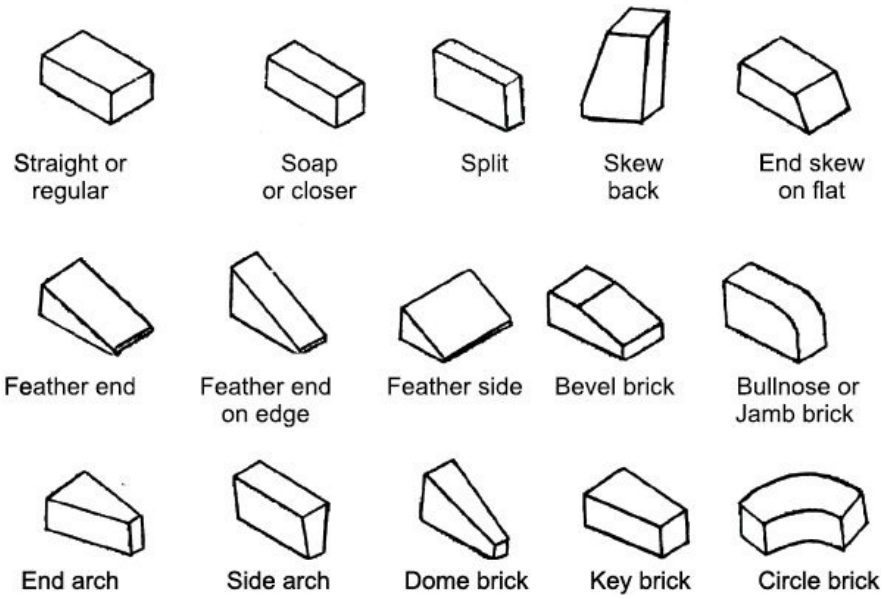


Figure 1.2 Commonly used shapes of refractory bricks.

(c) ***Plastics*** **:** These are refractories in which raw materials and plastic materials are mixed with water for use. The plastic refractories are formed with chemical additives.

(d) ***Gunning mixes*** **:** These are powder refractories that are sprayed on the surface by a gun.

(e) ***Ramming mixes*** **:** These are granular refractories that are strengthened by gunning formulation of a ceramic bond after heating. The ramming mixes have less plasticity and are installed by an air rammer.

(f) ***Slinger mixes*** **:** These are refractories installed by a slinger machine.

(g) ***Patching materials and coating materials*** **:** These are refractories with properties similar to refractory mortar. However, patching materials have controlled grain size for easy patching or coating.

(h) ***Lightweight castables*** **:** These are refractories in which porous lightweight materials and hydraulic cement are mixed. They are mixed with water and formed by casting. Lightweight castables are used to line furnaces, kilns, etc.

Fibrous refractories or ceramic fibers

These are man-made fibrous refractory materials. There are several different types of ceramic fibers including blanket, felt, module, vacuum form, rope, loose fiber, etc. These are mostly used as heat insulator.

1.3.5 Applications

The refractories are essential part of any given type of furnace. The refractory linings face the high temperature front and require several properties depending on the working condition. The brick shape is common to line a furnace. Table 1.4 gives the general property and use of various refractory bricks.

1.3.6 Performance of Refractory

The performance of refractory depends on the following three factors:

Selection of refractory

The refractory selection for any given application must be done keeping in view of following considerations: (a) Working temperature

(b) Working load under high temperature

(c) Chemical nature of the environment (acidic, basic or neutral)

(d) Physical nature of the environment (dust level and abrasive particle nature) (e) Thermal condition (constant or fluctuating)

(f) Heat transfer rate requirements to define acceptable thermal conductivity of the refractory (g) Furnace job economics to accept refractory quality cost

Installation of refractory

The method of laying refractory bricks, their dimensions, selection of mortars, expansion joints and many other factors affect the refractory performance. The equipment used for application, e.g. mixer machine for castable, vibrator for installation, forma also affect the performance. The brick laying needs proper expansion gaps, correct bricks dimension and anchor fixing to have better life of refractories.

Table 1.4 The General Property and Use of Bricks Made from Various Refractory Materials

Chemical Nature	*Refractory*	*General Characteristics*	*Typical Applications*
Acidic	Silica	Resistant to acidic slag, Resistance to thermal shocks, Higher strength at elevated temperatures, low specific gravity	Electric arc furnace roof, Furnace hearth for steel melting with acidic slag, Copper refining furnace
	Silica (Fused)	Lower thermal expansion coefficient, Highly thermal shock resistance, low specific gravity, low thermal conductivity, less specific heat	Coke oven wall, Soaking pit upper section, Furnace doors
	Fireclay (Chamotte)	Spalling resistant, low thermal expansion coefficient, low thermal conductivity, low	Coke oven regenerator checker bricks, Hot stove checker bricks, Blast furnace, Ladle, Cupola,

		specific gravity, low specific heat, low slag penetration	Runner, Sleeve, Annealing furnace, Reheating furnace
Basic	Magnesia	High basic slag resistance, High refractoriness, Low thermal shock resistance, Good electrical conductivity at high temperature	Hearth for basic steel making furnaces, Hot-metal mixer, Secondary refining vessel, Electric arc furnace
	Magnesia chrome	High refractoriness, High refractoriness under load, high basic slag resistance, Relatively good thermal shock resistance (low MgO bricks)	Non-ferrous smelter (Copper, Nickel, Platinum), Hot-metal mixer, Electric arc furnace, Vacuum Steel degassing, lime and dolomite kiln
	Dolomite	High basic slag resistance, High refractoriness, high refractoriness under load, low durability in high humidity	Sub layer of basic furnaces (e.g. LD, EAF), Cheaper substitute for MgO, Ladle, Tap hole for basic steel
Neutral	Carbon	High refractoriness, high slag resistance,	Blast furnace hearth, Crucibles, Moulds
	Silicon carbide	High refractoriness, high strength at high temperature, high thermal conductivity, high thermal shock resistance, high slag resistance	Kiln furniture
	Silicon nitride	High strength, high thermal shock resistance, relatively high oxidation resistance	Kiln furniture
	Alumina	High refractoriness, high mechanical strength, high slag resistance, high specific gravity, relatively high thermal conductivity	High-temperature kiln, Hot stove cap, Stopper head, Sleeve, Soaking pit cover, Reheating furnace
	Chrome	High refractoriness, low strength at high temperature, low thermal resistance	Soaking pit bottom, Buffer brick between acid and basic brick
	Zirconia	High melting point, low wet-ability against molten metal, low thermal conductivity, high corrosion resistance, high specific gravity	Crucible, Nozzle for continuous casting, High-temperature furnace, Peep Hole, Burner Area,
	Magnesia-carbon	High slag resistance, high thermal shock resistance, basic oxygen furnace, electric arc	LD Converter, Electric Arc Furnace, ladle
	Alumina-carbon	High refractoriness, high thermal shock resistance, high corrosion resistance	Submerged entry nozzle, slide gate

Operational practice

The optimum life of the refractory lining requires less down time with maximum availability of the furnace to derive the benefit of lower refractory cost per ton of finished product.

Review Questions

1. Define the following terms:

(a) (i) Fuel (ii) Primary fuel (iii) Manufactured fuel (iv) By-product fuel (v) Renewable fuel (b) (i) Furnace (ii) Oxidising furnace atmosphere (iii) Inert furnace atmosphere

(c) (i) Refractory (ii) Monolithic (iii) Castables (iv) Mortar

2. Differentiate between the following terms:

(a) Coal and Coke
(b) Crude oil and Furnace oil
(c) Natural Gas and Producer gas
(d) Manufactured fuel and By-product fuel
(e) Acid and Basic refractory
(f) Shaped refractory and Monolithic refractory
(g) Rotary kiln and Rotary hearth furnace
(h) Calcination and Roasting furnace
(i) Thermal conduction and Thermal radiation
(j) Shaft furnace and Retort furnace
(k) Soaking pit and Reheating furnace

3. Name suitable energy source for the following furnace applications:

(a) Blast furnace
(b) Cupola
(c) DRI rotary kilns
(d) Lime kilns
(e) Alumina kilns
(f) Induction furnace

4. What are the merits and limitations of the following fuels:

(a) Solid fuel
(b) Liquid fuel
(c) Gaseous fuel

5. On what factors can the furnace classification be done?

6. What considerations are made while selecting furnace for a location?

7 . What are the basic components of any furnace?

8. What is the basis of refractory classification?

9. What are the parameters used to assess the performance of any refractory?

10. Give at least two suitable applications for the following refractories:

(a) Silica brick
(b) Fireclay brick
(c) High alumina brick
(d) Magnesia brick
(e) Dolomite brick

(f) Carbon brick

2

Solid Fuels

Coal and Coke

Introduction

Chapter 1 has introduced a variety of solid fuels out of which only few are suitable for metallurgical applications like coal and coke. This chapter will deal with coal and coke used mainly for metallurgical industries.

Coal is a naturally occurring carbonaceous rock. The coal is formed from vegetal matter over a long period on the geological time scale. There are many varieties of coal occurring in nature. The coal suitable for making of coke is designated as *coking coal* . Every coking coal does not yield coke suitable for metallurgical applications and thus, coals yielding coke for metallurgical applications are termed as *metallurgical coal* .

This chapter deals with the origin of coal, types of coal, coal constituents, coal classification, properties of coal and testing, coal washing, coal storage and transportation, coal carbonisation, coke properties, coke testing and applications of coal and coke.

2.1 ORIGIN OF COAL

Coal occurs in nature as sedimentary rock where the carbonaceous matter is present with many other minerals. The structural examination of the coal shows confirmed evidence of its formation from vegetal matter. The fossil imprint of leaf, bark and other tree components on the coal provide evidence of its vegetal origin. The micro-structural examination of the thin section of coal reveals the presence of spores, pollens, resins and other essential components of vegetal matter which help in confirming and identifying the type of tree from which such coal is originated in the nature. It is believed that the large forest vegetation growing long ago got buried in the ground and was fossilised to become coal.

There are two theories for origin of coal: '*In-situ*' theory and 'Drift' theory. The '*in-situ*' theory describes it as natural growth of trees in swamps, their death and accumulation as peat over long period of time followed by its coalification to coal due to some geological action in nature, sustained for long duration of time. The 'drift' theory differs in first part of the process of coal formation to deposit peat at other location than its growth, while the second stage process is identical to the '*in-situ*' theory. The 'drift' theory describes the growth of trees in high regions, and these are transported by river water after they die and get uprooted down to estuary where they get deposited as peat due to lower velocity of water. This deposited peat gets converted to coal by long geological action of the earth. Such peat formation can be noticed even now in Sunderban area of West Bengal which is the delta region of Ganges river. Thus, the process of coal formation could be divided in two periods: (a) Peat formation and
(b) Conversion of peat into coal.

2.1.1 Peat Formation (Biochemical Period)

The forests grow in tropical climate. The swamps provide ideal place for the thick growth of the vegetation. The trees germinate from the fallen seeds on the soil. The tender tree grows fast in tropical climate and dies on maturity. When the tree dies, it falls on the ground and starts decomposing or decaying. This decomposition (or rotting) process is the disintegration of plant molecular structure aided by bacteria, moisture and air. When the process of decay of the dead tree is in progress and if another dead tree falls over it then the partially decayed tree gets buried in the soft swamp soil and the decay process is slowed down or arrested depending on the supply of oxygen necessary for the bacterial growth. This partially decayed vegetal matter is termed as *peat* .

During the process of peat formation, the various constituents decay at different rate. The protoplasm and oils in the plant matter decay rapidly. The carbohydrates like cellulose, lignin, etc. decay slowly, whereas the spores, pollens, resins and waxes resist decay action. Thus, the nature of vegetation, its constituent and extent of decay will decide the peat composition and properties.

This process of tree germination, growth, maturity death and partial decay process continues to form peat and its accumulation as layers buried under soft swamp soil (Figure 2.1). The peat layer thickness depends on the period of peat formation which may be hundreds of years. This peat layer awaits some geological action to cause its conversion into coal.

2.1.2 Conversion of Peat into Coal (Dynamochemical Period)

The earth crust is dynamic in nature, and it undergoes depression or elevation at any given point due to movement of plates in the earth crust. It may be possible that at sometime the area having peat deposit underwent depression causing peat layer buried at considerable depth with a formation of large depression of surface on its top. This depressed land filled with rain water would destroy all growing vegetation and would look like a huge water lake. In every rainy season, the flowing water to the lake would bring soil and get deposited at the bottom of lake. This soil silting process may continue for long time to eventually fill the lake and make it a plain ground over which the vegetation may start growing again with peat formation and accumulation to give another layer of peat deposit. It may also happen that another earth movement may push the buried layer of peat upward creating an mountain like elevated topology. In this process of geological action, the peat layer buried in the soil may be subjected to considerable pressure and temperature, rendering chemical and physical changes in peat properties.

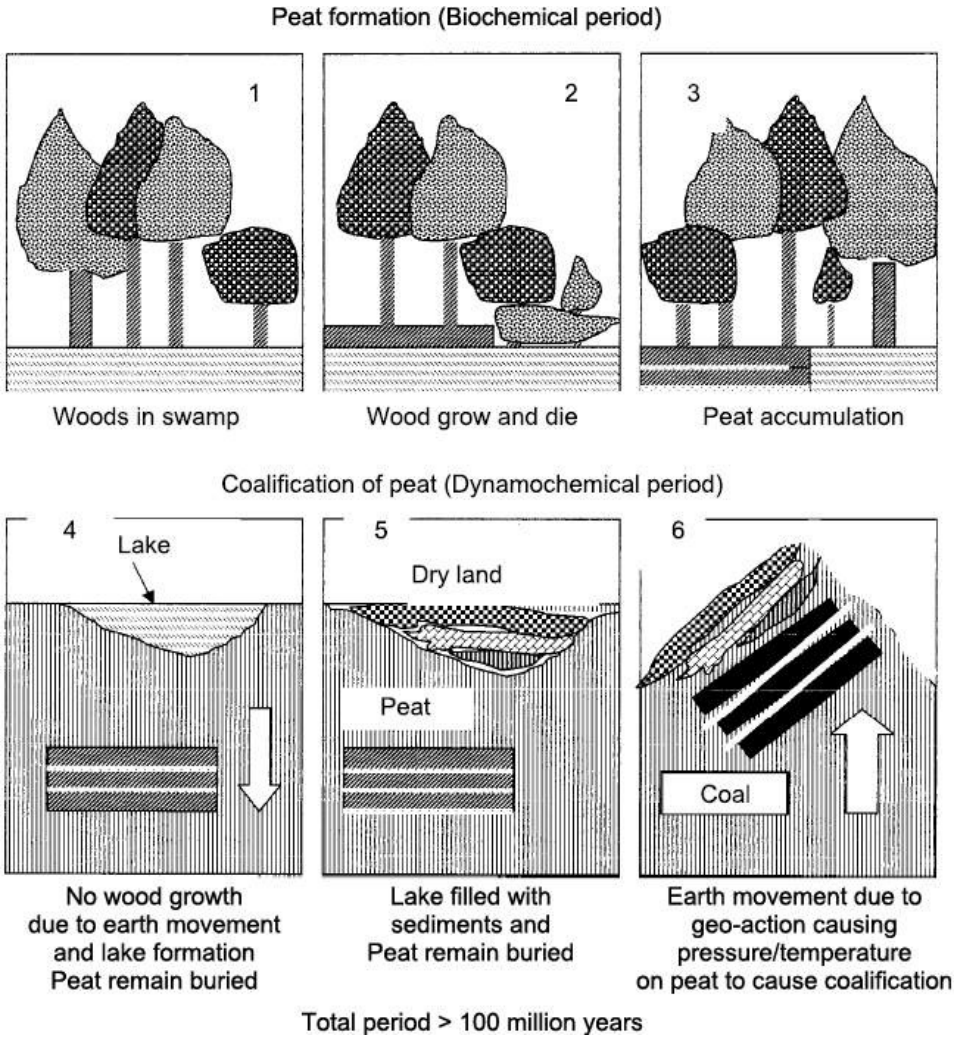


Figure 2.1 Origin of coal from vegetal matter over geological period.
(Adopted from R.C. Gupta, *Theory and Laboratory Experiments in Ferrous Metallurgy* , PHI Learning, Delhi, 2010.)

The chemical changes due to application of temperature and pressure would be the loss of moisture and evolution of carbon dioxide and methane. The oxygen content of the carbonaceous matter would be decreased with increase in temperature and time. This change in chemical composition is illustrated in Table 2.1. These conversion changes get reflected in physical nature of the deposit. The colour, hardness and density keep changing with the advancement of the conversion from peat to anthracite. The peat has more than 90 per cent of water and can be squeezed by hand. This water content is reduced in lignite which can be felt as wet. The bituminous and anthracite coal have very little moisture to be felt by hand. The brown colour of the peat becomes dark brown in lignite which further turns black when it becomes bituminous and anthracite. The coal hardness also increases with conversion from lignite to anthracite stage.

The lignite is friable in nature, while bituminous is hard, but soils the hand with black carbon. Anthracite is quite hard and does not soil hand on rubbing on its surface.

Table 2.1 Changes in Composition of Wood, Peat and Coal during its Formation

State	*Colour*	*Material (Typical Cases)*	*Moisture in Raw State wt.%*	*Analysis (wt.%) on Dry Ash Free (daf) Basis*					*App. sp. gr.*	*CV*** MJ/kg
				C	*H*	*N*	*O*	*Volatile matter at* 900 °C		
Fibrous Hard	Wood	Wood	22	~ 50	6	–	44	~ 75	0.6	20
Fibrous Friable	Brown	Peat	> 90	50–60	~ 5.5	1–3	30–40	~ 65	–	–
Friable	Brown to black	Lignite	40–20	65–75	~ 5	1	20–30	40–60	–	25.5–31.4
Hard and soils hand*	Black	Bituminous coal	~ 10	75–90	4.5–5.5	~ 2	5–17	18–32	1.14–1.4	33.5–36
Hard and does not soil hand*	Black	Anthracite coal	< 5	92–94	3–4	1	~ 2	< 15	1–1.8	34.7–36.4

*On rubbing finger at coal surface
**Calorific value

(Adopted from R.C. Gupta, *Theory and Laboratory Experiments in Ferrous Metallurgy* , PHI Learning, Delhi, 2010.)

The peat is not coal, but it is the initial stage of coal formation. The peat is converted to lignite, bituminous or anthracite, depending on the extent of application of temperature and pressure caused during geological time period which is termed as *dynamochemical period* or *coalification period* . The process of conversion of peat to coal is also termed as *metamorphism* . The total time period for coal formation may span several hundred million years, hence, it is referred as geological period. This large period of coal formation renders it as a non-renewable energy source, since it is not possible to recycle the coal formation process in a given civilisation period.

The property of coal from every mine is different from the other, as they might have undergone a different history of peat formation and extent of coalification.

2.2 TYPE, RANK, CLASS AND GRADE OF COAL

The words like type, rank, class and grade of coal are commonly used to

differentiate its nature which has specific meaning.

Type of coal

The word *type* of coal indicates whether it is anthracite, bituminous or lignite coal. All these three types of coal have distinct properties which render their identification.

(i) *Lignite:* It is brown/black in colour with considerable amount of moisture to soil the hand. It is fibrous in nature and crumbles easily on pressing. It has high porosity. It contains high volatile constituents with low fixed carbon.

(ii) *Bituminous coal:* It has characteristic layers of bright and dull banded matter. It has typical cubic fracture. It is relatively hard (3–4 Mohs scale) in nature. It burns easily with smoky yellow flame. It has many commercial applications. The coking coals falling under this type are used for coke making.

(iii) *Anthracite:* It is a hard and compact variety of coal with pitch like appearance. It breaks with irregular fracture and does not soil the finger on rubbing. Anthracite ignites with difficulty, but once ignited, it burns and gives intense local heat with very short and non-luminous flames. Anthracite does not have caking property and is unsuitable for coke making. It has limited industrial use as fuel, but often used to make artefacts.

Rank of coal

The word *rank* denotes the degree of coalification the peat has undergone to yield coal. The carbon content and calorific value of coal increase with rank, while the volatile matter is found to decrease. The different coals with increasing rank can be shown as: lignite → bituminous → anthracite.

Class of coal

The term *class* is retained for its actual use such as coking coal, steam raising coal, gas making coal, etc.

Grade of coal

The *grade* refers to the degree of purity of the coal. The coals with higher ash and moisture content are referred as lower grade coals, while high grade coal, means coal with low ash and moisture content.

2.3 COAL CONSTITUENTS

The coal contains various constituents to render specific properties which cause its selection for various applications. These constituents could be grouped in three categories viz. (a) Petrological constituents, (b) Elemental constituents and (c) Constituents important for its use. These are discussed in the following sections.

2.3.1 Petrological Constituents in Coal

The coal contains various constituents which can be identified under geological microscope. These petrological constituents are known as macerals. These macerals differ significantly in their properties present in various coals. These macerals are grouped as vitrinite, exinite and inertinite.

(a) ***Vitrinite*** is a primary constituent of coal. It usually occurs in bands. It is bright, black and brittle having conchoidal fracture. It is derived from woody tissues of the plant from which it was formed. Chemically, it is rich in polymers, cellulose $(C_6\ H_{10}\ O_5\ )_n$ and lignin $(C_{30}\ H_{33}\ O_{11}\ )$. It burns easily during combustion.

(b) ***Exinite*** group of macerals are minor component of coal. These are rich in volatiles and hydrogen content that render it most reactive.

(c) ***Inertinite*** is oxidised organic material or fossilised charcoal. It is found as tiny flakes, generally forming 1–3 per cent in coal seam. It is least reactive group of macerals. The most common inertinite maceral is *fusinite* .

The natural minerals of different types are also found to be present in coal. These minerals get incorporated in early stage of peat formation. The *intrinsic mineral matter* originates from minerals present in the wood, since trees need various minerals as nutrient. These mineral constituents are finely sized and remain distributed in the whole coal body as fine particles. Such fine size mineral matter cannot be separated from coal by washing methods. The *extrinsic mineral matters* are those which get incorporated with peat during its formation and collection process. The extrinsic mineral matters are present in bulk and could be separated by coal cleaning methods. These mineral matters are uncombustible constituents and remain as ash after coal combustion. These mineral matters are not desired in coal.

2.3.2 Elemental Constituents in Coal

The major elements present in coal are carbon, hydrogen and oxygen. The minor elements include nitrogen, sulphur and phosphorus. In addition, any known element could be present in trace quantity. This elemental analysis is done using different instrumental techniques. The results of the analysis is reported as weight per cent of each element present in coal including major (in bulk per cent), minor (in per cent) and trace constituents (in ppm, i.e., parts per million and ppb i.e. parts per billion) depending upon its need. Such elemental analysis of coal is reported as *ultimate analysis* . The ultimate analysis of coal is useful in estimating air requirements for its combustion, flue gas analysis along with estimation of its calorific value. The presence of minor constituent like sulphur (wt.%) helps in deciding pollution abatement methods caused by its emission. The trace elements in coal would be discharged along with ash and flue gases. The presence and quantity of trace elements in coal help in providing adequate management systems to avoid hazards caused by toxic elements like Hg, As, Cd, Pb, Cr and radioactive elements.

2.3.3 Constituents Important for Coal Use

The coal contains moisture, incombustible inorganic matter and volatile constituents in addition to carbon. These constituents affect the use of coal. The *proximate analysis* of coal deals with the determination of following constituents by weight per cent:

(a) Moisture
(b) Volatile matter
(c) Ash, and
(d) Fixed carbon

The knowledge of these constituents is useful in the selection of coal for a given purpose.

Moisture

The moisture (H_2 O) is present in every type of coal in varying amount (0.5 wt.% to 20 wt.%). In peat, the moisture content could be 90 per cent. It is an undesired constituent in solid fuels. The moisture present in the solid fuel is removed during use at the expense of its heating value. The moisture could be present in free (surface), adsorbed (inherent) or combined (chemical compound)

state.

(i) Free or surface moisture

As the name suggests, this kind of moisture is loosely present on the surface or in the pores of coal. This moisture is derived from rain during storage, transportation and washing of coal. When water saturated coal is left in air for sometime, the excess free water evaporates and the moisture content in the coal attains equilibrium with the atmospheric humidity. The per cent weight loss of free water by air drying at room temperature is termed as *free* or *surface moisture* .

(ii) Inherent moisture

The water molecules adsorbed on the external surface and internal open pore surface is termed as *inherent moisture* . Its value would depend on porosity and atmospheric humidity. As the lower rank coals possess high porosity, therefore, the inherent moisture content would also be more in lower rank coals compared to higher rank coals.

The coal sample when heated to 110 ± 5 °C temperature for sometime, then the adsorbed (inherent) moisture molecules are detached and get removed. However, if the coal sample is left again in open atmosphere for longer time, then it may regain its inherent moisture content. This regaining tendency for inherent moisture will be more for high rank coals, while this readsorption will be less in lower rank coals, since their cell walls may breakdown during drying stage due to weak structure. This reduces the number of pores available for readsorption of moisture, causing lower inherent moisture in coal sample which has been heated and cooled.

This inherent moisture content in coal cannot be avoided. However, a lower value would be appreciated.

(iii) Combined moisture

Coal contains mineral matter which, sometimes, contains water molecules that are chemically attached. Such chemically bonded water molecules do not evolve when the coal is heated at 100°C. This kind of moisture can be removed only when the coal is heated at higher temperature. Such combined moisture forms the part of volatile matter, and it is not determined separately. However, the presence of combined water in coal is not appreciated as it consumes some heat for its own dissociation, rendering lower net calorific value of coal for use.

Volatile matter

It is the part of coal which is evolved as volatile (gaseous) product when the coal is heated in the absence of air. As the quantity of volatile product is dependent on temperature, time, surface area, etc., therefore, a specified procedure is adopted to make the result reproducible and comparable.

The quantity of volatile matter in coal may range from 2 wt.% to 40 wt.%, while it is below 2 wt.% in coke and wood char. The volatile matter content plays an important role during its selection for a given application. Its higher content could be useful in gas making coals, but may not be appreciated in coking coal. The knowledge of volatile matter content helps in designing combustion system to provide appropriate primary and secondary air. Table 2.2 gives use of coal with different volatile matter content.

Table 2.2 Application of Coal with Varying Volatile Matter in Coal

VM in Coal, wt.%	*Type of Coal*	*Application of Coal*
< 10	Anthracite	Intense heat in coal bed for hand forging of steel
15–18	Non-caking bituminous	Combustion
22–30	Caking bituminous	Coke making
27–40	Non-caking bituminous	Steam boiler/Gasification
45–55	Lignite	Gasification/Distillation/Lignite briquette

Mineral matter and ash

Coal contains various minerals which are uncombustible part of coal, called *ash.* It is common to state that coal contains ash, but technically coal contains mineral matter and yields ash on combustion. Chemically, mineral matter is different from ash. The coal may have following minerals in varying quantities in addition to oxides of sodium and potassium: (i) Shale or silt (Hydrated silicates of aluminium)

(ii) Pyrite (FeS_2)

(iii) Gypsum ($CaSO_4 \cdot 2H_2O$)

(iv) Lime stone ($CaCO_3$)

(v) Siderite ($FeCO_3$)

(vi) Magnesite ($MgCO_3$)

(vii) Apatite ($Ca_5(PO_4)_3(F, Cl, OH)$)

Some of these minerals originate from the vegetal mass from which the coal was formed. These minerals are required by the tree for its growth. Such mineral

matter is known as *intrinsic mineral matter* and is present in very fine form in the matrix of coal which cannot be liberated or separated by coal cleaning methods. The bulk of the mineral matter present in coal is incorporated during peat formation stage and termed as *extrinsic mineral matter* . These could be present in coarser form which could be removed by coal cleaning methods.

Table 2.3 Constituents Present as Mineral Matter in Coal to Yield Ash on Combustion

Mineral Matter Constituents Present in Coal	*Constituent in Ash Yielded on Coal Combustion*	*Volatile Constituent Removed during Coal Combustion*
$Al_2O_3 \times x\ SiO_2 \times yH_2O$	$Al_2O_3 \times xSiO_2$	yH_2O
$CaCO_3$	CaO	CO_2
$MgCO_3$	MgO	CO_2
$FeCO_3$	Fe_2O_3	CO_2
FeS_2	Fe_2O_3	SO_2

When the coal is heated or burned, the minerals undergo changes depending upon temperature to yield ash as given in Table 2.3. Table 2.4 gives ash composition range yielded by coal on combustion. The ash content in a given coal is determined by observing the weight of uncombusted matter left after exposing the coal sample to oxidising condition at 800 °C. In Indian coals, which contain low ‘sulphur’ and ‘carbonate’ minerals, the mineral matter (*M* % wt.) is given by:

$$M = 1.1\,A$$

where, *A* is the ash (wt.%) determined by proximate analysis of coal sample assuming the sulphur and carbonate are very low.

Table 2.4 Chemical Composition Range of Ash Yielded by Coal Combustion

Ash Constituents	*Wt. %*
Silica (SiO_2)	20–60
Alumina (Al_2O_3)	10–35
Ferric oxide (Fe_2O_3)	5–35
Calcium oxide (CaO)	1–20
Magnesium oxide (MgO)	0–5
Alkalies ($Na_2O + K_2O$)	0–4

Sulphur trioxide (SO_3)	0.1–10

Fixed carbon

Fixed carbon content in the coal is considered to be useful for a given application, e.g. combustion, reduction, etc. There is no direct method for its determination. It is estimated as: Fixed carbon = 100 – [$M + VM + A$]
where, M , VM and A are moisture, volatile matter and ash content in coal determined experimentally. This fixed carbon value is not the total carbon in coal. A higher fixed carbon content in coal increases its commercial value.

2.4 COAL CLASSIFICATION

The coal occurring in nature differs in their properties due to various factors affecting its formation. All such coals are classified to help the users in their selection. The proximate analysis (volatile matter and fixed carbon) and heating value or the ultimate analysis (carbon, hydrogen and oxygen) of coal are used for its classification. There are different systems of coal classification followed in various parts of the world, developed in the past. These are as follows.

Regnault–Gruner system

The first attempt to classify coal was made in UK in 1837 by Regnault, which was modified by Gruner in 1874. This classification system was based on carbon, hydrogen and oxygen content (%) in coal which were correlated with volatile matter obtained during carbonisation.

Parr's system

The American coals were classified by S W Parr in 1928. This classification of coal was based on volatile matter percentage and calorific value based on unit coal basis (coal free from moisture and mineral matter [see section 2.5.2(v)].

Seyler's system

A comprehensive classification system was developed by C.A. Seyler in 1900. This system was based on calorific value, volatile matter, maximum inherent moisture and swelling number correlated with carbon and hydrogen content derived from coal analysis based on dry ash free basis [see section 2.5.2(iv)]. In this graphical presentation of coal classification, the different coals were found to occupy position within fairly defined curved band of data points.

British National Coal Board system

The British National Coal Board attempted to classify Bristish coals in 1950s. Their classification was based on volatile matter content and appearance of solid residue of coal heated to 600°C (Gray King Assay).

ASTM (American Society for Testing Materials) system

The ASTM system was developed for American and Canadian coals by E Sherlock in 1949. This system was based on proximate analysis and calorific value of coal containing its natural bed moisture excluding any visible surface moisture. The ‘weathering’ behaviour of coal was also used as parameter to classify coal based on its nature to breakdown in pieces when exposed to atmosphere for longer period. The ASTM system of classification is shown in Figure 2.2.

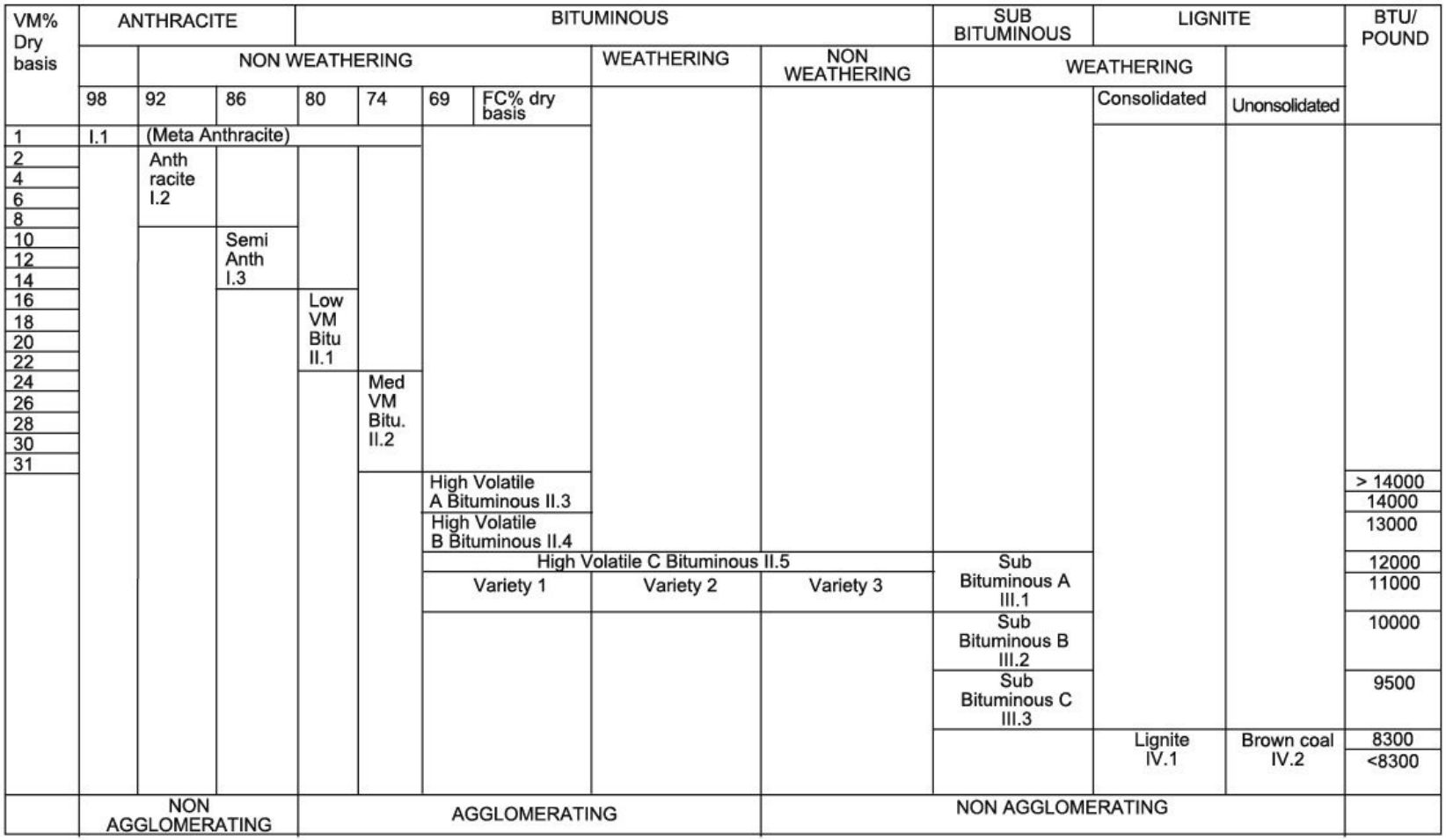


Figure 2.2 ASTM Coal classification system.

(Adopted from R.C. Gupta, *Theory and Laboratory Experiments in Ferrous Metallurgy*, PHI Learning, Delhi, 2010.)

Indian Standards Institution system

The Indian coal and lignites were first tentatively classified by Indian Standards Institution (IS-770-1955) in 1955, which was published in 1964 (IS-770-1964) followed by IS-5018-1968. This was further revised in 1977 (IS-770-1977). The Indian classification is based on gross calorific value and volatile matter content on dry mineral matter free basis together with GK Assay. The Indian coal classification is given in Table 2.5.

Table 2.5 Classification of Indian Coal

Type	*Symbol*	*Nature #*	*Calorific Value* kcal/kg *(dmf)**	*Volatile Matter% (dmf)**	*GK Type*	*Moisture at 60%* RH	*Carbon (dmf)**	*Hydrogen (dmf)**	*Uses*
Lignite	L	NC	6150–7300	> 50	A	> 20	67–73	4.5–5.5	Combustion, Gasification, Hydrogenation and Briquetting
Sub-bituminous	SB	NC	6950–7500	33–50	A	10–20	76–79.5	4.5–5.5	Combustion, Gasification
Bituminous (High VM)	B_1	NSC	7500–8500	> 45	A–C_1	2–9	75-82.5	5.3–6.3	Combustion, Blending and Hydrogenation
Bituminous (Med-high VM)	B_2	NC	7500–8200	27–43	A–B	7–11	79.5–83	4.7–5.3	Combustion, Gasification, Hydrogenation
Bituminous (High VM)	B_3	WC	8250–8400	33–43	C–D	5–7	82.5–83.5	5.0–5.4	Hydrogenation, Blending, LTC
Bituminous (High VM)	B_4	MSC	8250–8500	33–43	E–C_3	2–5	83.5–87.5	5.0–5.8	Hydrogenation, Blending
Bituminous (Medium VM)	B_5	WMC	8500–8700	22–33	C–F	< 2	86.5–88.0	4.7–5.0	Blending
Bituminous (Medium VM)	B_6	SC	8500–8900	22–33	G–G_2	< 2	88.0–90.5	4.8–5.2	Coking (Metallurgical coal)
Bituminous (Low VM)	B_7	WMC	8500–8900	18–22	C-G	< 2	90.5–91.5	4.5–4.9	Combustion and Blending
Bituminous (Low VM)	B_8	NWC	8250–8700	15–18	A-D	< 2	91.5–92.0	4.2–4.5	Combustion
Semi-anthracite	SA	NC	8250–8700	10–15	A	< 2	92–93	3.7–4.2	Combustion and Carbon artifacts
Anthracite	A	NC	8500–8700	< 10	A	–	> 93	< 3.7	Combustion and Carbon artifacts

Non-Caking–NC; Non-caking to Strong Caking–NSC; Weakly Caking–WC; Medium to Strong Caking–MSC; Weakly to Medium Caking–WMC; Strong Caking–SC; Non-Caking to Weak Caking–NWC

* dmf–dry mineral matter free basis

2.5 PROPERTIES OF COAL AND ITS TESTING

The various properties of coal are tested to assess its nature which could be helpful in selecting it for a given application. The following properties and test methods are described in the forthcoming sections: (i) Ultimate analysis of coal

(ii) Proximate analysis of coal
(iii) Coking property of coal and text method
(iv) Fusion behaviour of coal (Coal rheology or plasticity)
(v) Coal ash fusion behaviour coal
(vi) Coal calorific value
(vii) Coal grindability test (HGI)

2.5.1 Ultimate Analysis of Coal

In ultimate analysis of coal, the percentage value of all elements are reported including major, minor and trace constituents, depending upon its need. The major elements present in coal are carbon, hydrogen and oxygen, while the minor elements include nitrogen, sulphur and phosphorus. In addition, any known element could be present in trace quantity.

(i) The *carbon* and *hydrogen* are determined by burning the coal with oxygen under controlled condition and measuring the product CO_2 and H_2O by suitable absorption tubes.

(ii) *Nitrogen* in coal could be determined by Kjeldahl method. A small sample of the coal is completely oxidised by boiling with a mixture of concentrated sulphuric acid, potassium sulphate and a little mercury. After precipitating mercury, sodium hydroxide is added in excess and the ammonia formed during the oxidation is distilled off and determined by standard analytical method. The nitrogen in coal varies from 1–2 (wt.%).

(iii) *Sulphur* in coal is determined by oxidising it to sulphur dioxide and sulphur trioxide. These are absorved by an alkali to form corresponding sulphite or sulphate, which is finally converted to barium sulphate. The weight of clean and dried barium sulphate weight could be used to calculate sulphur in coal sample.

(iv) *Phosphorus* is present as phosphate and organic phosphorus compound. The burning of coal yields all phosphorus in ash and can be analysed easily.

(v) *Oxygen* in coal is obtained by adding all the contents including ash and

then subtracting the total from 100, i.e., Oxygen (wt.%) = 100 – (Ash + C + H + N + S + P) wt.%. This method has a major drawback as all the error in analysis is pushed to oxygen (wt.%).

The impurities like sulphur affect the utility of the coal. Assam coking coal in India is a typical example which cannot be used for coke making due to its high (up to 3%) sulphur content. The sulphur dioxide rich gas emission from cupola furnaces in Agra resulted a total ban on the local foundry units due to its bad impacts on TAJ (a world heritage).

The value of ultimate analysis is useful in estimating the calorific value of coal using *Dulong's formula* :

$$\text{Calorific Value (kJ/kg)} = 337C + 1442\,[H - (O/8)] + 93\,S;$$

where, C, H, O and S are carbon, hydrogen, oxygen and sulphur (in wt.%).

The ultimate analysis is also used to estimate the air needed for fuel combustion and flue gas analysis. In view of the need of ultimate analysis on routine basis by many industries, the instruments are available for speedy and reliable analysis.

2.5.2 Proximate Analysis of Coal

The proximate analysis of coal concerns with the determination of moisture, volatile matter, ash and fixed carbon contents. These values are needed for selecting coal for given applications. The proximate analysis does not give approximate values. It gives the specific values determined under standard test procedures. The various test specifications are given in following sections:
Sample preparation
Coal and coke are bulk materials. The analysis of a given batch of shipment or production has to be monitored on regular basis. The size of a batch could range from a few tons to hundreds of tons. Collecting a representative sample for proximate analysis becomes very important to increase the validity of the test. There are standard sampling procedures which are strictly followed during sample preparation amounting 1 kg (–72 mesh, i.e., –200 μm). This sample is stored in a glass bottle with proper labelling.

Specifications for the test

The proximate analysis would need only a few grams of coal. Basically, sample amounting 100 g is taken and stored in a glass bottle after air drying for 24 hours. This sample is utilised for the following tests: (i) Moisture test

A glass dish (50 mm diameter and 10 mm deep) with lid is used to determine moisture
content. One gram air-dried coal sample is taken in the glass dish with lid and weighed in a chemical balance. After weighing, the coal is made to spread by gentle tap in the dish to nearly 0.3 g/cm^2 for uniform evolution of moisture. The sample is exposed to 110 ± 5 °C temperature for one hour in a moisture oven without lid on the dish. The sample is cooled after heating by keeping it in desiccator with lid in position to avoid atmospheric moisture adsorption. After cooling, the sample is weighed, keeping the lid in position. The loss in weight is accounted for inherent moisture content.

(ii) Volatile matter test

The specially designed silica crucible (Figure 2.3) with lid is used to determine volatile matter content in coal/coke. The deep crucible with lid allows heating the sample in the absence of air. The volatile matter can exit through loose lid but air is unable to infiltrate in. One gram sample is taken in the crucible and weighed with lid accurately in a chemical balance. This crucible is then placed over a nichrome (80% Ni – 20% Cr alloy) wire tripod to keep its bottom 5 mm above the floor of the oven. This is done to have uniform heating of sample in the crucible as oven floor temperature may be different from the oven space. The crucible kept on tripod is heated in oven at 925 ± 5 °C for seven minutes. After that the crucible is taken out, cooled in air with lid in position and then weighed to notice the loss in weight due to the removal of volatile matter and inherent moisture. As the inherent moisture content can be known, the volatile matter content can be estimated.

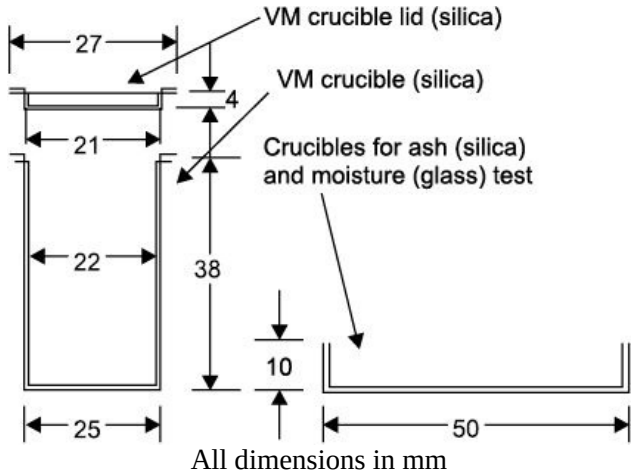


Figure 2.3 Crucible shape and size for proximate analysis of coal and coke.
(Adopted from R.C. Gupta, *Theory and Laboratory Experiments in Ferrous Metallurgy* ,

PHI Learning, Delhi, 2010.)

(iii) Ash determination

Silica dish (50-mm diameter and 10-mm deep) without lid is used for this purpose. One gram sample is taken and weighed accurately in a chemical balance. The coal is spread uniformly in the crucible by gentle tapping. This is then heated at 450 °C for 30 minutes in oven to oxidise all the sulphur and part of carbon in coal. Then the crucible is transferred to another oven at 800 ± 5 °C to oxidise the sample for 60 minutes. Samples having low reactivity (e.g. graphite, petroleum coke, coke) may take time to complete the combustion. This two stage heating is done to remove all the sulphur and carbon without the formation of $CaSO_4$. If the coal is heated directly to high temperature, the sulphur may get fixed in ash as $CaSO_4$ rendering higher ash value. After ensuring the complete oxidation of carbon, the dish is cooled to weigh the residue ash.

Basis for reporting the results

The results of the test are reported based on the level of moisture in the sample like:

(i) As received basis
(ii) Air-dried basis
(iii) Dry basis
(iv) Dry ash free (daf) basis and
(v) Dry mineral matter free basis or unit coal basis

These different ways of reporting the test result are explained as follows:

(i) As received basis

The coal sample may have free moisture in as-received condition. This sample is weighed and left in room spread in a tray for 48 hours, to be weighed again. The weight percent lost is taken as free moisture in as-received sample.

(ii) Air-dried basis

The air-dried sample is tested for moisture (*M*), volatile matter (*VM*), ash (*A*) and fixed carbon (*FC*) and the results are reported as *M* %, *VM* %, *A* % and *FC* % without any subscript letter. The *M* % is indicative of inherent moisture.

(iii) Dry basis

Utilising the results reported under air-dried basis, the volatile matter, ash and

fixed carbon is calculated by excluding the moisture content and reported by adding “dry” in subscript as:

$$VM_{dry}\% = \frac{VM\%}{(100 - M\%)} \times 100$$

$$A_{dry}\% = \frac{A\%}{(100 - M\%)} \times 100$$

$$FC_{dry}\% = \frac{FC\%}{(100 - M\%)} \times 100$$

(iv) Dry ash free (daf) basis

Sometimes coal analysis free from ash and moisture is needed. This is indicated by adding “daf” in the subscript and calculated as:

$$VM_{daf}\% = \frac{VM\%}{[100 - (M\% + A\%)]} \times 100$$

$$FC_{daf}\% = \frac{FC\%}{[100 - (M\% + A\%)]} \times 100$$

(v) Dry mineral matter free basis or unit coal basis

The *unit coal* is the organic substance present in coal which does not consider moisture (*M* %) and mineral matter (*MM* %) content. This requires expressing the proximate analysis giving mineral matter *MM* % content in coal against ash (*A* %) content and calculating the values of moisture (*M* ′%), volatile matter (*VM* ′%) and fixed carbon (*FC* ′%) as given below:

The mineral matter content is estimated assuming the sample has low sulphur content.

$$\text{Mineral matter content} = 1.1 \times A\ \%$$

This gives total constituent present in the sample

= Moisture + Mineral Matter + Volatile Matter + Fixed Carbon

= (M + 1.1 A + VM + FC) %

Thus, the coal analysis is estimated having mineral matter as:

$$\text{Moisture } (M') \% = \frac{M}{(M + 1.1A + VM + FC)} \times 100$$

$$\text{Mineral Matter } (MM') \% = \frac{1.1 \times A}{(M + 1.1A + VM + FC)} \times 100$$

$$\text{Volatile Matter } (VM') \% = \frac{VM}{(M + 1.1A + VM + FC)} \times 100$$

$$\text{Fixed Carbon } (FC') \% = \frac{FC}{(M+1.1A+VM+FC)} \times 100$$

The apostrophe mark (′) is used with values (*M* ′%, *MM* ′%, *VM* ′% and *FC* ′%) based on mineral matter free basis to differentiate it from normal proximate analysis using ash value.

Knowing the coal analysis having mineral matter content, the values of volatile matter and fixed carbon values are estimated without considering moisture and mineral matter and "dmmf" is added as subscript (VM_{dmmf} and FC_{dmmf}) to differentiate it from other values as given below:

$$VM_{dmmf} = \frac{VM'}{[100 - (M' + MM')]} \times 100$$

$$FC_{dmmf} = \frac{FC}{[100 - (M' + MM')]} \times 100$$

2.5.3 Caking Property of Coal and Test Methods

The coals when heated in the absence of air behave differently. Certain coals undergo physical change on heating while some coals do not exhibit this behaviour. Thus, the coals are grouped as 'caking coal' and 'non-caking coals'.

(i) *Caking coals:* The coals which soften on heating (~ 400 °C) to become plastic in nature and on further heating (~ 600 °C) render them to resolidify as a hard coherent mass are termed as 'caking' coals. These caking coals are used for coke making, but it is not necessary that every caking coal is suitable for coke making. Coke making needs many other properties alongwith caking property. The caking coals are not suitable for combustion as they fuse on heating and cause difficulty in combustion process.

(ii) *Non-caking coals:* The coals which do not display any change in physical state and give a non-coherent mass of char on heating are called 'non-caking' coals.

The cause for this caking behaviour is not well understood. However, the degree of caking behaviour can be tested by the following four methods which are very commonly used: (a) Volatile Matter Test under Proximate Analysis

(b) Gray King Caking Index

(c) Swelling Index (CSN) and

(d) Reflectance of Vitrinite in Coal as Coking Property

These four methods are described in detail as follows:

Volatile matter test under proximate analysis

The proximate analysis could be used to observe the caking behaviour of coal on heating in the absence of air. The residue left by coal is examined after performing the volatile matter test by gently inverting the crucible on a glazed sheet of paper. The charred coal residue in the form of coherent button is an indicator of its caking behaviour, while the powder form will result from non-caking coals. The extent of caking property could be measured by gently keeping a 500 g weight on the cake and then taking the weight of coherent cake expressed as per cent of total residue coal char weight. A high caking behaviour does not mean it will give good coke but it does indicate that the coal deserves further test for assessing its coke making ability.

Gray King caking index

This is a test to measure the caking property of the coal. The test consists of taking 20 g sample in a silica tube kept in a furnace which is heated with the prescribed rate to 600 °C. The boat with coal is withdrawn and cooled. The appearance of the coal residue is noted and compared with standard samples (Figure 2.4) and are given index (A to G). Table 2.6 gives the GK index, residue appearance and equivalent CSN value (Figure 2.5). The non-caking coal is given GK index A while B and C index indicate weakly caking property. The caking coal is given index D, E, F and G. The coals which are highly caking in nature are tested with some inert (sand/carbon) material mixed with coal sample and the resulting cake nature is observed. These coals are given index G_1 to G_{10} indicating increasing tendency for caking property.

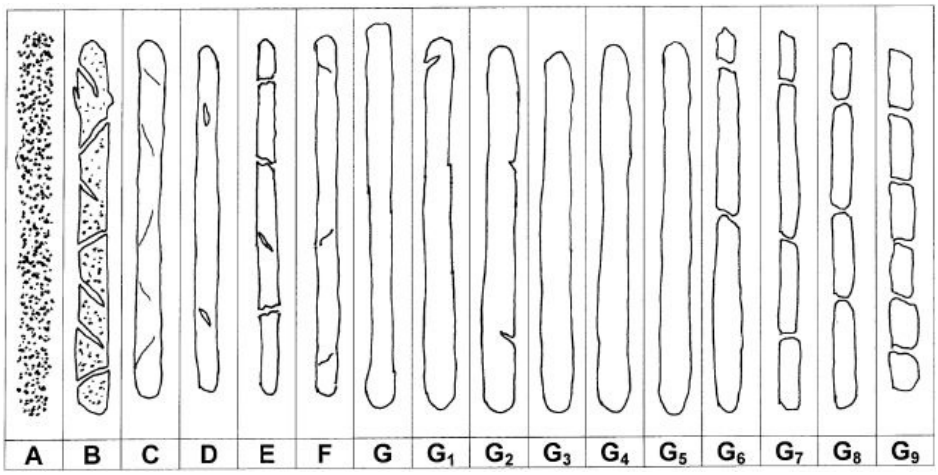


Figure 2.4 GK index of coal (A-G) residue appearance (schematic).

(Adopted from R.C. Gupta, *Theory and Laboratory Experiments in Ferrous Metallurgy* , PHI Learning, Delhi, 2010.)

Table 2.6 GK Index and Coal Residue Appearance

GK Index	*Coal Residue Appearance*	*Caking Nature*	*Equivalent CSN*
A	Non-coherent or pulverised	Non-caking	0
B	Coherent but fragile breaking on handling	Weakly caking	1
C	Coherent but friable on rubbing	Weakly caking	1.5
D	Shrunken and moderately hard	Caking	2
E	Shrunken, fissured and hard	Caking	2.5
F	Slightly shrunken and hard	Caking	3
G	No change in shape and hard	Caking	4
G_1	19 part coal sample + 1 part inert (sand/carbon)	Highly caking	4.5
G_2	18 part coal sample + 2 part inert (sand/carbon)	Highly caking	4.5
G_3	17 part coal sample + 3 part inert (sand/carbon)	Highly caking	5
G_4	16 part coal sample + 4 part inert (sand/carbon)	Highly caking	5.5
G_5	15 part coal sample + 5 part inert (sand/carbon)	Strongly caking	6
G_6	14 part coal sample + 6 part inert (sand/carbon)	Strongly caking	7
G_7	13 part coal sample + 7 part inert (sand/carbon)	Strongly caking	8
G_8	12 part coal sample + 8 part inert (sand/carbon)	Strongly caking	8.5
G_9	11 part coal sample + 9 part inert (sand/carbon)	Strongly caking	9

Swelling Index (CSN)

The coal undergoes volume change during heating process. The swelling behaviour has been found useful to assess coking coal quality. This test requires 1 g coal sample (–0.212 mm, i.e., –72 mesh size) held in a silica crucible covered with a lid and heated in oven under standard condition. The carbonised coal button in the crucible is observed and compared with standard samples to assign a *crucible swelling number (CSN)* from 0 to 9 (Figure 2.5). The coals with CSN 4 and above are considered good for coke making.

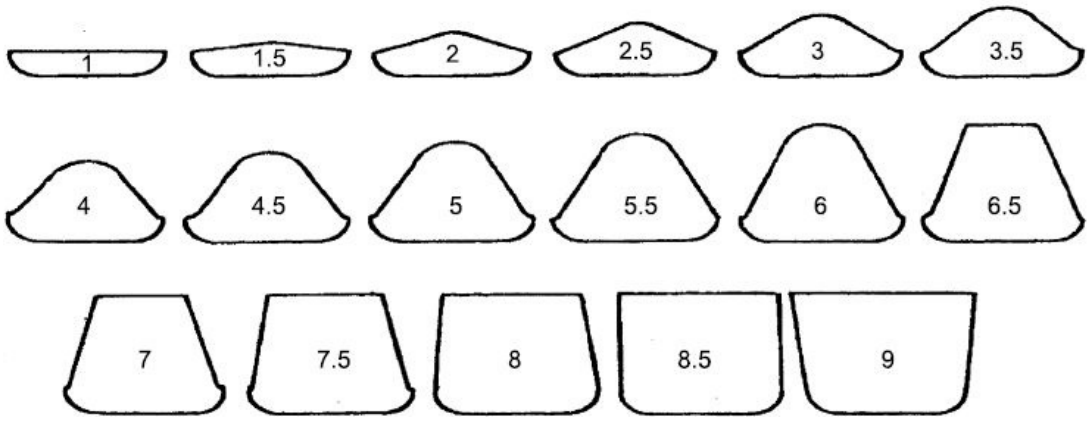


Figure 2.5 Crucible swelling number (CSN) chart.
(Adopted from R.C. Gupta, *Theory and Laboratory Experiments in Ferrous Metallurgy* , PHI Learning, Delhi, 2010.)

Reflectance of vitrinite in coal as caking property

Reflectance of vitrinite is obtained by microscopic examination of fine coal sample which is fixed by adhesive, polished and covered with oil layer (refractive index 1.585). During observation the objective lens is allowed to touch the oil layer. When a monochromatic (wavelength 546 ± 5 nm) light without polarisation impinges on polished coal surface, the extent (%) of incident light reflected by the coal sample is the measure of rank of coal. An average of 100 reflectance readings is reported as the *average reflectance of coal in oil* (R_O , the subscript O denotes oil). The amount of light reflected by vitrinite is measured by a photo-multiplier. The number of readings made is 250 for a blend of coal.

In another method, the measurement is carried out using monochromatic (546 ± 5 nm wave length) polarised light keeping the polariser at 45 degree position. The sample stage is rotated through 360 degrees and two maxima of reflectance are observed as vitrinite is bi-reflective. This is repeated for 100 particles (to yield 200 maxima readings) and the mean of all these reflectance reading gives *mean maximum reflectance* (*MMR*). Empirically, it has been found that MMR = 1.066 × R_O . The values of R_O % and MMR % are found to indicate caking behaviour of coal.

2.5.4 Fusion Behaviour of Coal (Coal Rheology or Plasticity)

The caking coals exhibit change in their physical state during heating from 400

°C to 500 °C. The solid coal starts softening, becomes fluid and then re-solidifies into solid mass called coke. This behaviour of coal influences coke quality.

The *Gieseler Plastometer* , used for testing fluidity of coal, consists of a rotor fitted with a paddle which remains inserted in coal sample held in a cup located in a furnace. The speed of rotation is measured in *dial division per minute (ddpm).* There are 100 divisions for one revolution of the paddle, thus, 100 ddpm corresponds to 1 rpm. The maximum speed of 280 rpm can be recorded by the instrument rendering a maximum fluidity range up to
28000 ddpm. A sample weighing 5 g coal (–0.5 mm, i.e., –35 mesh) is taken in the cup and loosely compacted. Then the furnace is heated (2–3°C/min) slowly. The value of fluidity (ddpm) is noted with rise in temperature as shown in Figure 2.6 which will give the values of *maximum fluidity* (*MF*) and *fluid temperature range* (*FTR*).

Some studies have indicated a relationship between MF and MMR% (Figure 2.7) and R_o % (Figure 2.8). This is due to the fact that fluidity in coal is controlled by plastic (vitrinite and liptinites) and inert (inertinite and mineral grains) components. The plasticity at higher temperature ceases due to loss of hydrogen by plastic bitumen.

2.5.5 Coal Ash Fusion Behaviour

The ash left after combustion behaves differently depending on its composition and combustion zone temperature. The refractory ash is desired for its removal in solid form. This ash fuses in some cases and forms clinker, and in extreme cases it may melt to give slag. This fusion behaviour of ash affects the combustion process and ash removal method.

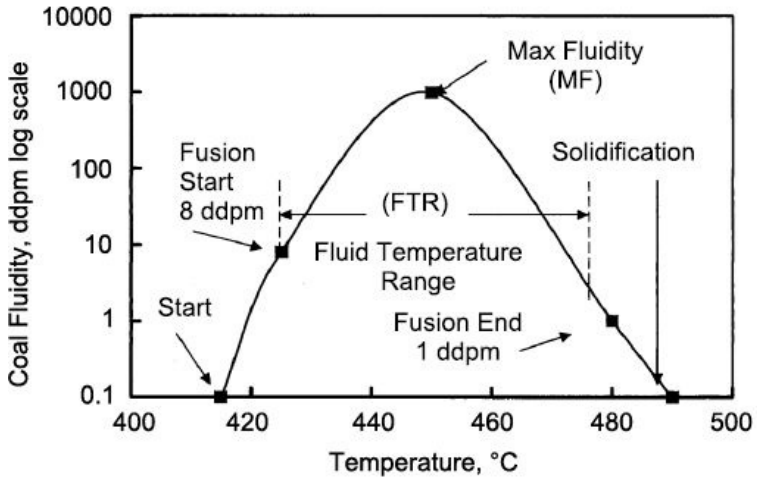


Figure 2.6 Changes in coal fluidity with temperature (Gieseler Plastometer).
(Adopted from R.C. Gupta, *Theory and Laboratory Experiments in Ferrous Metallurgy* , PHI Learning, Delhi, 2010.)

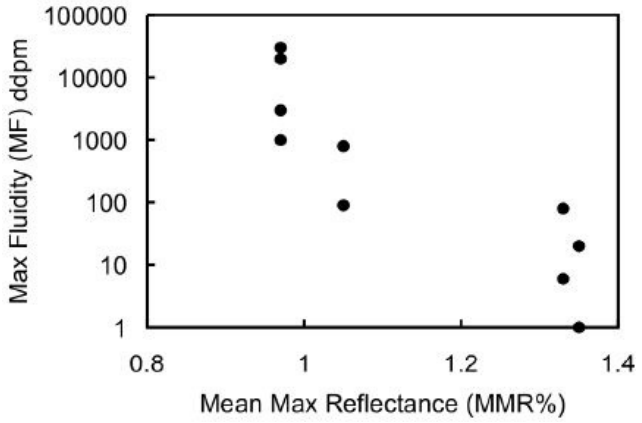


Figure 2.7 Relation between coal maximum fluidity and mean maximum reflectance values.
(Adopted from R.C. Gupta, *Theory and Laboratory Experiments in Ferrous Metallurgy* , PHI Learning, Delhi, 2010.)

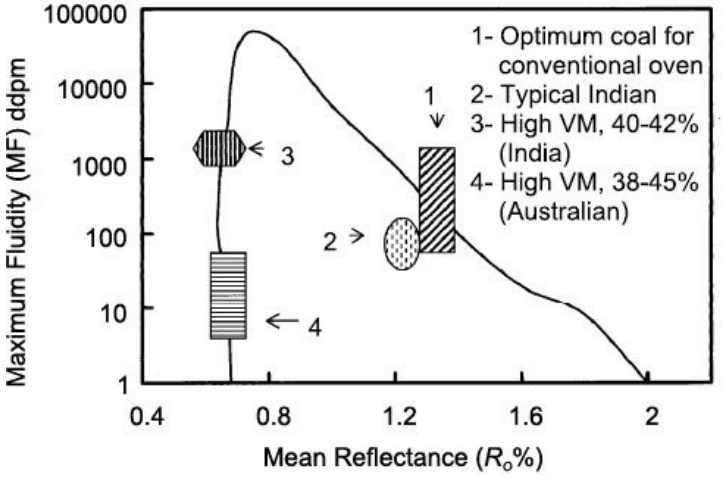


Figure 2.8 Maximum fluidity and mean reflectance values of some coals.
(Adopted from R.C. Gupta, *Theory and Laboratory Experiments in Ferrous Metallurgy* , PHI Learning, Delhi, 2010.)

The coal ash (Table 2.4) contains various oxides like silica (SiO_2), alumina ($Al_2 O_3$), lime (CaO), ferric oxide ($Fe_2 O_3$), ferrous oxide (FeO), alkali oxides (K_2 O, Na_2 O), etc. The total ash content and its composition differ from one coal to another due to different conditions prevailing during their formation. The quality of coal is assessed by the total ash content present and its composition. The higher percentage of silica (SiO_2) and alumina ($Al_2 O_3$) content in the ash increases its fusion temperature being refractory constituents. The basic oxides like CaO and MgO may be appreciated in ash for certain applications. The presence of iron oxide (FeO) lowers the fusion temperature of ash and promotes

clinker formation.

The ash fusion temperature is determined by grinding ash to make a cone for PCE test (Section 7.1.1). Ash behaviour during its use alongwith ash fusion temperature and Ortan scale is given in Table 2.7.

Table 2.7 Ash Behaviour with Ash Fusion Temperature and Ortan Scale

Ash Behaviour during Use	*Ash Fusion Temperature* ° C	*Ortan Scale PCE no.*
Refractory ash with no clinker formation tendency	> 1500	> 17
Less refractory ash with scope of clinker formation	1300–1500	12–17
Fusing ash forming clinker	< 1300	< 12

2.5.6 Coal Calorific Value

The heating value of coal is important while using as heat source. The coal calorific value is a measure of heat which can be obtained from its combustion. *The calorific value is defined as total heat available as a result of complete combustion of unit weight of material and the products of combustion are cooled down to 15 °C temperature* . Theoretically, all the heat liberated by combustion must be available for use, but in practice some heat is lost with gases and other sources. As coal contains hydrogen, it forms steam (H_2 O) on combustion and some heat is lost as steam latent heat and sensible heat of hot steam. Thus, the following two calorific values are quoted for any fuel:

(i) The *gross or higher calorific value* —obtained by calorific value test, by cooling the products of combustion to 15°C.

(ii) The *net calorific value* or *lower calorific value*— obtained by deducting the heat given by cooling the combustion product gas to 15°C.

In practice, the *net calorific value* is more realistic figure as useful heat value. With increasing hydrogen content in the fuel, the *net calorific value* gets lower.

The calorific value of coal is expressed as joules/kg or calories/kg.

$$1 \text{ calorie} = 4.186 \text{ joules} = 1.163 \times 10^{-6} \text{ kWh}$$

$$1 \text{ joule} = 0.2389 \text{ calorie} = 2.778 \times 10^{-7} \text{ kWh}$$

The *Bomb calorimeter* is used to determine the gross calorific value of solid and liquid fuels. Figure 2.9 shows the sketch of a bomb calorimeter. It has the following four main components:

(i) Stainless steel combustion chamber-“Bomb”

(ii) Calorimeter vessel

(iii) Beckmann thermometer
(iv) 9 V DC power source

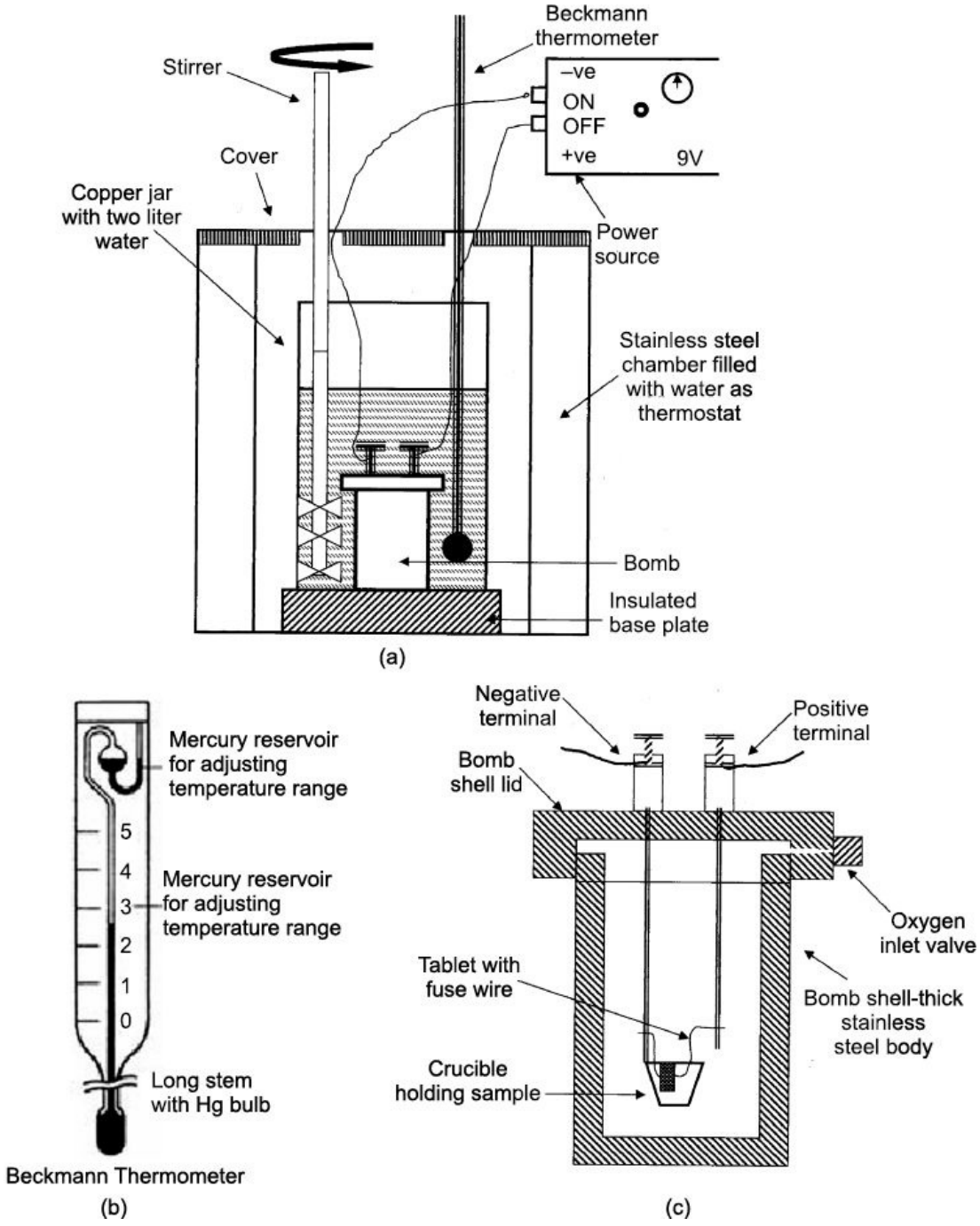


Figure 2.9 (a) Bomb calorimeter (b) Beckmann Thermometer and (c) Bomb.
(Adopted from R.C. Gupta, *Theory and Laboratory Experiments in Ferrous Metallurgy* , PHI Learning, Delhi, 2010.)

The ‘bomb’ is made of stainless steel to give thick wall combustion chamber, having 250–300 ml volume, which can sustain 30 atmospheric pressures. It has a

provision to keep the sample (solid or liquid) in a crucible which has a fuse wire connected to power source (9 volts DC). The chamber has provision to fill oxygen under pressure (20 atmosphere) to burn the fuel completely. The calorimeter vessel is made of copper which is filled with water (2 litres) to receive the heat released by the combustion of fuel in the bomb immersed in water. The water is stirred with a stirrer. The increase in water temperature up to 5 °C is noted by a Beckmann thermometer with an accuracy of 0.001 °C. The 9 volt DC power source is used to ignite the fuse wire, causing the fuel to burn in oxygen atmosphere.

The calorimeter works on the principle of heat given by the combustion of fuel is taken by the calorimeter itself.

Thus, $M \times CV = W_{eq} \times \Delta T$

w here, M is the mass of fuel in g

CV is the calorific value of the fuel in calories/gram

W_{eq} is the water equivalent of the calorimeter (with 2 litres of water) in gram and

ΔT is the increase in temperature due to heat given by fuel in °C.

To determine the water equivalent (W_{eq}) of the calorimeter, a known material is selected (say Benzoic acid – 6319 cal/g) and the value of ΔT is noted to calculate W_{eq}. Once, the calorimeter is calibrated (with known water equivalent), the calorific value of any solid or liquid fuel can be easily determined.

During the experiment, a tablet of coal sample (1 g) is kept in the crucible of the bomb. This coal tablet has an embedded length of iron fuse wire which is connected with terminals. The bomb is then filled with oxygen (20 atmospheres). The calorimeter vessel is filled with known quantity of water (2 litres) in which the bomb is immersed with electrical wire connected to 9 V DC source. The stirrer and Beckmann thermometer are placed in position and the system is allowed to maintain constant temperature. The initial temperature is recorded and ignition is made by passing current at 9 volts. The increase in water temperature is noted when it reaches the maximum value. Now, the fuel mass (M), water equivalent (W_{eq}) of calorimeter and the rise in temperature (ΔT) is known. Therefore, the gross calorific value (CV) of fuel is calculated as

$$CV \text{ (Gross)} = \frac{W_{eq} \times \Delta T}{M} \text{ calories/gram}$$

2.5.7 Coal Grindability Test (HGI)

The Hardgrove Grindability Index (HGI) is a measure of ease for coal pulverisation. The coal in pulverised form is used for firing boilers and furnaces. A 50 g sample of coal, which has been prepared (1.18 mm), is kept in a grinding mill having eight steel balls running in circular path as grinding media. These balls move under 284 N load provided through a cover ring. The mill is rotated for 60 revolutions and the coal sample is screened though 75 micron sieve.

Hardgrove Grindability Index (HGI) = $6.93\,M + 13$

where, M is the weight of the coal powder passing through 75 micron sieve in grams.

The coals having HGI value close to 100 are considered soft and easy to grind like lignite. The HGI values less than 40 are considered hard and are difficult to grind (higher rank coal like anthracite). The bituminous coals have HGI value close to 50.

2.6 COAL PREPARATION AND CLEANING

The coal occurring in nature is extracted out by open pit or underground mining techniques. The open pit mining is practiced when the coal seams are present on elevated surface or very close to ground level. In either case, the over burden consisting of clay, rocks, shale, etc. are removed and the coal seams are taken out using heavy machines. In case of underground mining, first a shaft is made deep up to coal seam level and then mining of coal is carried out in horizontal direction creating tunnels with advancing mining front. The underground mining is done by machines if the coal seam is thick, otherwise it is done manually when the space is limited. The mined coal is brought on the surface through the lift operating in the mine shaft. The run-of-mine coal contains various sizes of coal particles alongwith unwanted pieces of rocks, shale, broken machine parts, etc.

In the mining process, every effort is made to cut and remove only coal bed, but it is difficult to avoid cutting rock or shale bed when the mining is done on such a large scale using machines. In case of manual mining, the workers make effort to avoid siliceous rocks, but it becomes very difficult under very odd mining conditions. This requires run-of-mine coal to be cleaned from unwanted accompanying materials. The coal mined from a particular place may have composition which sometime may need washing to upgrade its quality by

discarding some materials inherent in the body of the coal. Further, the coal required for many applications has to meet the size specifications. This would require breaking, crushing and sizing operations. These sized coals often need to be blended with coal from two or more sources to meet the specifications desired by the user industry.

In view of all the above factors, the run-of-coal requires preparation (breaking, crushing and sizing) with cleaning operations.

2.6.1 Impurities in Coal

The coal contains many minerals which are undesired and are termed as 'impurities' in coal. These impurities are present in two forms:

(i) *Extrinsic mineral matter:* These are coarse and segregated mineral particles embedded in the coal body which can be removed by adopting different coal cleaning methods. These include shale, clay, pyrites, slate, gypsum, and other minerals. These impurities get incorporated in the coal body during peat formation. The soil minerals in the area of vegetation sometimes get sandwiched between peat layers and appear in coal body as extrinsic mineral matter.

(ii) *Intrinsic mineral matter:* These are very finely divided particles distributed in the matrix of the coal structure. Such mineral matter cannot be removed by coal cleaning techniques. These mineral matters are derived from vegetal mass which formed the coal. Some coals have sulphur minerals admixed with coal body and are not possible to be removed.

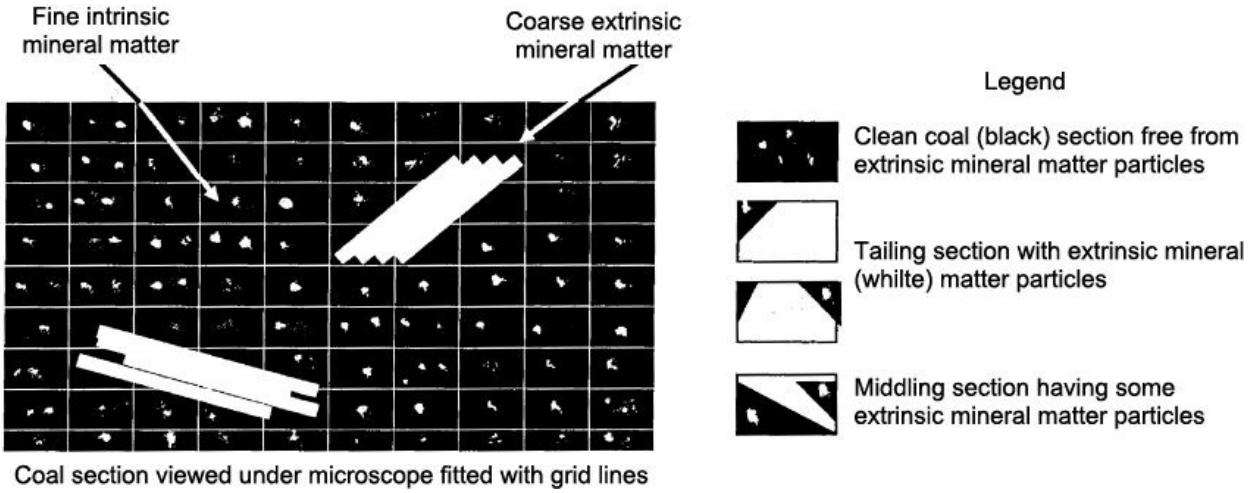


Figure 2.10 Schematic view of different particles present in the coal body.
(Adopted from R.C. Gupta, *Theory and Laboratory Experiments in Ferrous Metallurgy* , PHI Learning, Delhi, 2010.)

2.6.2 Liberation of Impurities

The liberation is a process of freeing two or more minerals or rocks by fracturing into smaller particles. The impurity mineral particle embedded in a larger coal body gets broken and many smaller coal pieces are found without any impurity minerals and are called ‘clean coals’. There may be few coal particles having very little embedded minerals; which are treated as ‘midlings’. The pieces having larger or whole part consisting of minerals only, are termed as ‘tailings’ or ‘waste’. This mixture of particles (Figure 2.10) consisting of ‘clean coal’, ‘midlings’ and ‘tailings’ is now available for separation from each other using some of their physical or physico-chemical characteristics, known as ‘coal cleaning methods’.

The extent of size reduction to set free the minerals is decided after study of coal petrology using suitable techniques. Effort is made to have lesser size reduction to keep the product in usable form with least preparation cost.

2.6.3 Principles for Separation of Coal from Impurities

The various constituents of coal have their characteristics like colour, lusture, hardness, fracture, specific gravity and surface properties which could be used to separate them from each other employing some techniques.

Colour of coal and minerals

The coal is black in colour with lusture, depending on its rank. The minerals like silica, gypsum, pyrite, shale have their own distinct colour which renders them identifiable under light when present as bigger particles. The use of specific type of lights in some cases help in easy identification.

Fracture behaviour

The clean coal on fracturing yields cubic shaped particles while shale breaks as plates. Some minerals break with irregular fracture and give irregular shape to particles. The particles having different shapes such as cubic, flat, plate or irregular offer a method to separate them. A mixture of such particles when placed on inclined surface with flowing water, they get moved downward by the force of flowing water. The rate of their movement will depend on the forward force for movement, affected by surface area available on the particle, by the flowing water and opposing frictional force by area of contact between mineral

particle and floor. The particles will travel at faster rate when forward force by water is more than the retarding frictional force. The cubic particles of clean coal travel at fastest rate and the flat shaped shale pieces travel at least rate; while the irregular particles having the middle path. The cubic shaped particles offer more surface area to flowing water with least floor contact to experience more forward force for movement. The flat shaped particles offer high floor frictional force due to larger floor contact and allow the least distance movement. This different rate of movement in particles are utilised to separate them by some mechanical methods.

Specific gravity of coal and minerals

The clean coal particles, midlings and tailings consisting of various minerals have certain specific gravity which offers a means to separate them. This specific gravity could be exploited to cause separation of particles while settling in a fluid. The specific gravity of fluid becomes important in such case.

(i) In case the fluid density is less than that of coal and tailing, then both particles would settle down when dropped in a fluid tank. However, their settling rate would be affected by particle specific gravity for equal size particles. The heavier particle will settle faster than lighter ones.

(ii) In case the fluid density is higher than clean coal but lower than tailings, then the tailing being heavier will sink to the bottom while coal will float being lighter. This float and sink method is exploited to cause separation between clean coal and tailings.

The values of specific gravity for clean coal and tailing constituents are given in Table 2.8 along with fluids which are used in the laboratory for testing and during industrial practice.

The selection of fluids for this process needs following care:

(i) The fluid selected is easily available and cheap

(ii) The fluid does not react with the coal and other constituents

(iii) The fluid is easily recovered with minimum loss

(iv) The fluid causes no effect on the coal quality

(v) The fluid does not pose any kind of hazard during use, storage and disposal

These factors pose serious problem in selection of fluid for industrial practice since most of the aqueous salt solutions or organic fluids used in laboratory cannot be used in industrial practice due to their high cost and hazards. As an

alternative for industrial use, the pseudo-fluids are prepared by suspending solids (sand, magnetite, barite, clay, etc.) in water or air to give the desired fluid density. The suspension of solids in water or air needs selection of solid particles in a very close size range (40–80 mesh) with mechanism to keep the fluids agitated. The sand or magnetite particle is selected for the purpose which is easily recovered for reuse.

Table 2.8 Specific Gravity Values for Solids and Fluids Used Float and Sink Method

Specific Gravity of Solid Particles		*Specific Gravity of Fluid Mediums*			
		Laboratory use		*Industrial practice*	
Bituminous coal	1.28–1.37	$CaCl_2$ Aqua sol.	1.40	Sand + Water	1.35–1.65
Bone coal (Coal + Shale)	1.40–1.60	$ZnCl_2$ Aqua sol.	1.90	Sand + Air	1.20–1.50
Shale, clay and sand stone	2.00–2.64	Chloroform	1.50	Magnetite + Water	1.25–2.50
Pyrites	2.40–2.95	Carbon Tetrachloride	1.60	Barite and clay (1 : 2) + Water	1.30–1.55
Calcites	2.70	Bromoform	2.90		
Gypsum	2.30				

With these few basic theoretical knowledge, the industrial practice of coal preparation and cleaning is given in the following sections.

2.6.4 Coal Breaking Equipment

The conventional breaking and crushing equipment like jaw crusher or roll crusher cannot be used for coal breaking due to its fragile nature. The coal crushed in conventional units will generate large fraction as fines which may be undesired for its applications.

The Bradford breaker is used for primary stage size reduction of run-of-mine coal. The specially designed roll crusher and hammer mills are used for generating smaller-sized coal.

Bradford breaker

These are used to break the run-of-mine (ROM) coal to about 25–50 mm size. The Bradford breaker (Figure 2.11) consists of a large rotating (12–18 rpm) cylindrical drum made of thick steel plate having perforations. The drum is fitted with lifters to carry coal up for certain height and then drop it when it is at its maximum height. The falling coal on piece resting at bottom imparts force to

cause breakage of both the pieces. The working principle of Bradford breaker is the application of impact force by the dropping coal piece on to another coal piece. This impact force causes fracture in the fragile coal body to break it down into smaller sizes while the tough and strong shale/stone pieces remain unaffected. The smaller coal pieces fall in the bottom trough passing through perforated drum and unbroken larger shale pieces are discharged out from the down sloping drum into waste bucket. Thus, this breaker not only causes the size reduction of coal pieces but it also removes impurities like shale, quartzite, stone, etc. as bigger unbroken pieces. These are very rugged equipment designed to work under very hard conditions to handle coal up to 500 ton/hr. They are available with different working capacities.

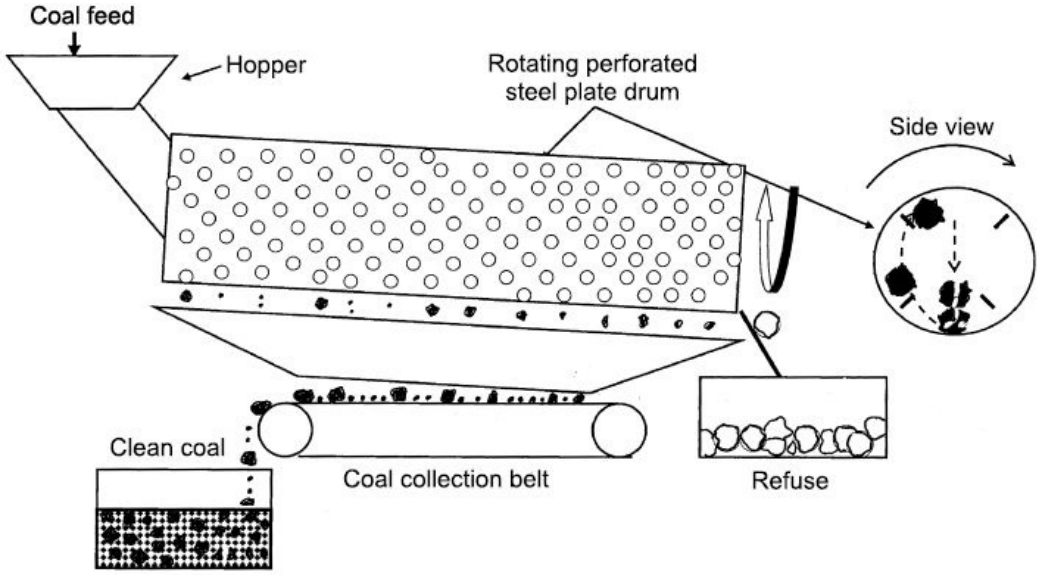


Figure 2.11 The Bradford breaker (schematic).

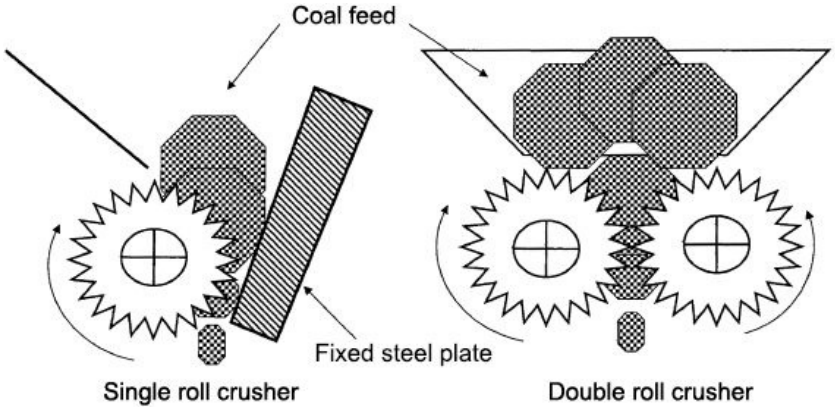


Figure 2.12 The roll breaker (schematic).

Roll crusher

These (Figure 2.12) are also used as primary breaker for larger coal pieces (80–100 mm) to generate
25–35 mm particles. These crushers use toothed rolls to break the coal pieces caught between roll gap and heavy crushing steel plate. The toothed sleeves are mounted on the roll spindle and are replaced after getting broken or damaged. The rolls are attached with two types of teeth. The bigger size teeth (40–100 mm long) act to grip the incoming coal pieces while the smaller teeth (20 mm) subject point pressure to shear the coal pieces. The broken coal particles are discharged out through adjustable gap between roll and plate. The roll crushers are available upto 500 ton/hr capacity.

These breakers need precaution to prevent the entry of any metallic object between the roll and plate gap which would make teeth to break. The harder shale and stone particles entering with feed will be broken down and cannot be removed at this breaking stage like Bradford breaker.

Hammer mill

These (Figure 2.13) are used as secondary coal crushing unit. The coal obtained from primary breaking is further crushed to obtain 3–12 mm particle size. This type of crusher consists of a high speed (600–1800 rpm) rotating hammers fitted in the spindle arms attached to a shaft. The hammers are enclosed in a heavy steel plate enclosure with curved perforated bottom steel plates. The coal feed falling from the top is hit by rotating hammers and moves in the direction of hammers to hit the heavy steel plate and gets shattered and falls down. The particles smaller than the perforation size in the plate fall down while bigger particles are retained on the screen top. These bigger particles are sheared into smaller pieces when caught between moving hammer and bottom plate. The smaller pieces fall down and retained bigger particles are further sheared to lower size. The various petrological constituents have different breaking behaviour. The vitrain is more friable and breaks easily than clairain. The clairain is easy to crush but resists breakage. Fusain breaks down easily. The durain is the toughest and resists breakage.

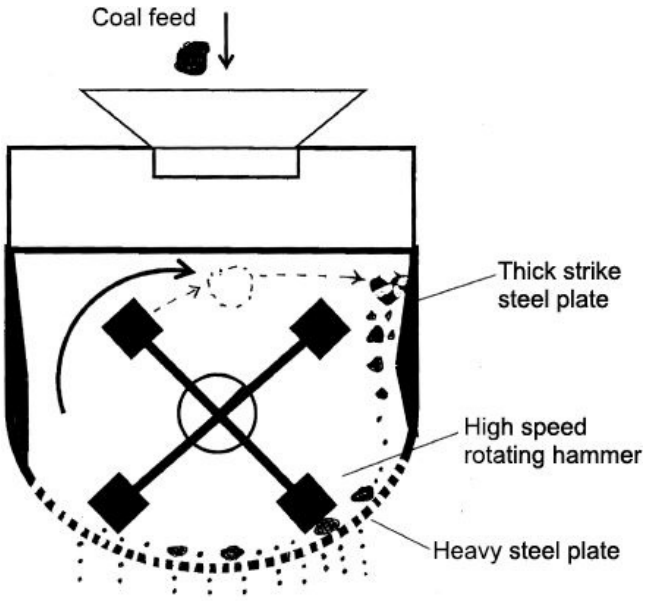


Figure 2.13 The hammer mill (schematic).

2.6.5 Coal Sizing Equipment

The coal particles need sizing for their efficient handling, storage, cleaning and use. There are variety of equipment available (Figure 2.14) which can be used depending on need. These are briefly described in the following sections.

Fixed bar grizzlies

The fixed bar grizzlies consist of assembly of long bars at desired gap. The bars can be held together by cross bars to act as a screening surface measuring 1–2 metre wide and 2.5–3.5 metre long. This bar screen can be kept on the ground in inclined manner supported by a structure. The screen inclination angle must be more than angle of repose of coal particles. The mixed coal particles fed on the screen will allow the undersize to fall below and oversize to roll down at screen bottom causing separation of larger particles from smaller ones.

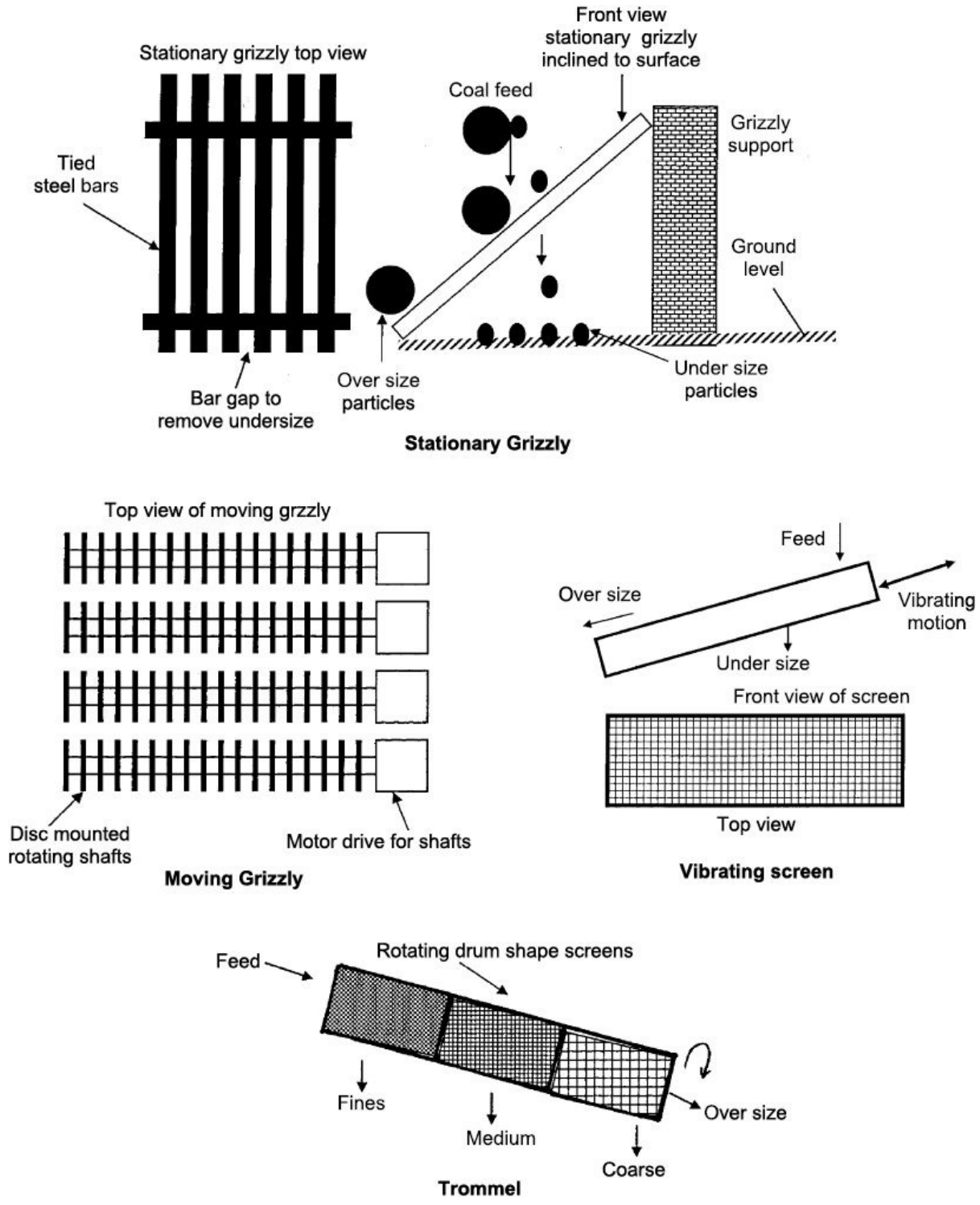


Figure 2.14 The coal sizing equipment.

The steel bars are generally used to make such grizzlies. The use of round (l) or square (n) section bars may cause clogging of the particles stuck in the bar gap particularly in rainy period. The use of triangular (t) shape bars with flat surface on the feed end side will avoid coal clogging.

The merits of stationary grizzly are as follows:

(i) It is the simplest type of screening equipment which is cheap and rugged
(ii) It can handle large tonnage.
(iii) This does not need power
(iv) This is highly suited for intermittent requirements for short duration at remote places in yards with no power

Revolving grizzlies

These consist of thick steel disc attached to main rotating shaft placed horizontal to the ground. There are number of such disc mounted rotating shaft placed at certain distance from the neighbour shaft. The gap between two discs and two shafts will provide an aperture of definite desired size. The shaft length would give grizzlies width as decided by the driving mechanism. The number of shafts put parallel to each other would give grizzlies length. This length and width of the grizzlies can be designed for the required capacity.

The advantage of such revolving grizzlies is their operational freedom on large scale in all weathers. The high cost is the main limitation for places with intermittent need on smaller tonnage.

Trommel

The trommel is a cylindrical drum made of perforated steel fitted with rotating mechanism which is kept inclined at an angle keeping the elevated end for feeding the charge. The size separation of the particles occurs as the charged coal spirals downward in the rotating cylindrical drum. In the process of movement, the coal particles smaller than the trommel apertures drop out from the trommel and the larger particles are retained and discharged out from the drum end.

The merits of the trommel are as follows:

(i) It is simple to install and operate
(ii) The trommel screens are able to screen smaller particles (> 1 mm) than grizzly screens (> 50 mm).
(iii) It takes up less head room compared with stationary grizzly screens which need an angle of 40° to 60° for the feed to slide down.
(iv) It gives lower operation cost than vibrating screens.
(v) It causes less noise than vibrating screens due to less vibrations.
(vi) It is mechanically robust than vibrating screens and last longer.

Shaking screens

These consist of flat horizontally placed screens made of perforated steel sheet or strong wire mesh which has mechanical arrangement for shaking in forward and backward motion at lower frequency. The feed end is kept raised to allow the forward movement to the feed. The undersized particles in the mixed size feed pass through the openings and fall down while the oversized gets discharged at exit end of the screen. These shaking screen can be used to separate the material in different size fractions by arranging a set of screens one over the other, keeping larger aperture screen on the top and the smallest in the bottom with intermediate size in the middle. These are commonly used to size coal above 6 mm.

Vibrating screens

Such screens are used for coal particles in the range of 8–10 mm. These are flat screens made of steel wire mesh mounted in a frame placed at an angle with horizontal. The screen is vibrated at high speed by electrical and mechanical arrangements. The undersized coal particle passes through the openings and oversize is discharged out at lower end of the screen. These screens are made in different sizes ranging 1–2 m wide and 1–7 m long.

2.6.6 Coal Cleaning Methods

The coal cleaning process starts at mining stage itself by demarcating the seams of coal from the seams containing shale, rocks and other undesired minerals. In the manual mining, the workers are trained to be selective but such practice becomes difficult during machine mining. Once the ROM coal is brought on the surface, it is subjected to cleaning process either at mine site or at the point of use. The washing plant at the user end has the advantage that it can receive coal from any source to clean and use it.

The ROM coal once transported to the coal washing (cleaning) plant, it is first prepared to meet the size requirement of the cleaning process. There are a variety of cleaning methods which are adopted depending on factors like form of the impurity present in coal, its distribution in the coal body, coal friability and relative specific gravity of clean coal and impurity minerals. The various industrial practices adopted to clean coal based on its colour, fracture, specific gravity and surface properties are given in Table 2.9.

Table 2.9 Various Techniques of Coal Cleaning

Physical Property of the	*Techniques Used in Industry*	

Coal	*Wet method (water as medium)*	*Dry method (air as medium)*
Colour	*Hand Picking*	*Hand Picking*
Specific gravity	Launder washer, Jigs, Rising current classifier, Tables	Jigs, Tables, Launders
	Float and sink using fine solids suspended in water	Float and sink using fine solids suspended in air
Physico-chemical property	Froth floatation	

Table 2.9 indicates that the coal cleaning process may be operated in ‘dry’ or ‘wet’ condition depending on the use of cleaning media as air or water. The use of media like water or air is necessary to cause segregation of the material in a mixed bulk which is separated by using some cleaning equipment. Currently water is more commonly used in coal cleaning plants due to its ease of operation and deployment of water based equipment which are less expensive compared to air based equipment. It is very likely that in coming time air based equipment may become more in demand due to stringent water pollution laws and envisaged water scarcity in future.

2.6.7 Hand Picking of Coal Impurities

This technique is based on the colour difference between the clean coal and waste mineral particles. It is a labour intensive and less reliable method of coal cleaning. In this method, the workers are trained to identify waste pieces which contain shale, slate, silica, etc. and remove them manually. The workers standing by the side of a conveyer belt knock out the rejected piece in a bin located below. The conveyer belt is illuminated to make the identification easy with dust free pieces using water showers.

The hand picking method is very old method and is now rarely practiced. The modern coal cleaning plants use mechanical means largely based on gravity separation techniques.

2.6.8 Wet Gravity Separation

This technique uses different settling rates of particles having equal size with different specific gravity when suspended in water. The heavier shale particles will settle faster than lighter coal pieces. This stratification of shale and coal particle in a bath of water offers a means to separate these two different particles using various equipment like launder, jigs, classifiers and tables. Such techniques require the feed to be closely sized for being more effective. These techniques are described in the following sections: Launder washer

Launder is a trough which has been used for cleaning coal for a long period. It is simple in design and very effective in coal cleaning. It consists of long trough which is placed inclined to keep the feed point at the raised end. This trough is fed with water to flow down alongwith clean coal particles retaining the shale particles at the bottom. When the mixed feed is fed in the water current the particles follow different trajectory. The heavy particles of shale, etc. sink fast and reach at the bottom and move forward slowly due to floor friction while the clean coal being lighter settle slowly and roll faster due to cubic shape close to water surface and is discharged out with flowing water.

Two different designs for launder washer are explained as follows:

(i) Elliot washer

The Elliot washer is shown in Figure 2.15 which consists of inclined trough which is narrow (450–975 mm) at the feed end and wide (500–750 mm) at the discharge end. The trough is nearly 300 mm deep, 18 meter long and its inclination is 1 in 12. The trough is fitted with mechanical scrapper travelling with speed of 4–6 meter/min for removing the refuse lying at the trough bottom. The refuse is discharged at the top end of the trough. The coal feed and water are fed at the higher end and the clean coal flowing with water is discharged out from the trough at lower end. The settled refuse is removed by moving mechanical scrapper. In absence of mechanical scraper, it is taken out manually. Such equipment can clean 8–12 ton coal per hour consuming nearly 1600 litre/hour water which can be recycled. It can clean coal having particles 2–50 mm, but the feed must have close size range particles for effective cleaning.

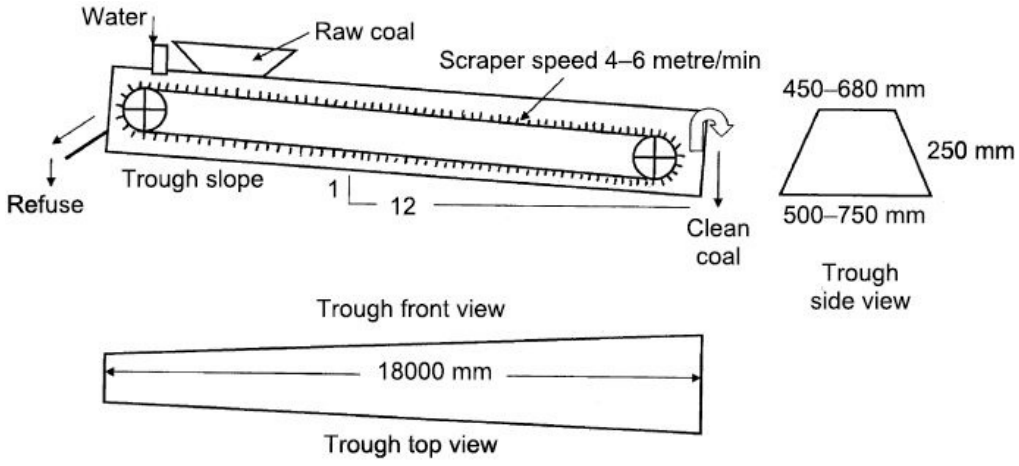


Figure 2.15 Elliot washer.

(ii) Rheolaveur launder

The Rheolaveur launder is shown in Figure 2.16(a) for coal cleaning. This type of launder has better control on the stratification of coal, middling and impurities with different specific gravities for their more efficient separation. In this launder, the Rheo boxes are attached at the bottom of the launder to trap and remove the heavier fraction as reject or middling. The Rheo boxes are divided in two chambers by a parting plate. The controlled flow of water is admitted in one chamber of the box which is allowed to move upwards through another chamber opening to the launder bottom. The lower section of the box has a collection hatch which is fitted with double gate for periodical discharge of the collected refuse. The long trough fitted with two or more Rheo boxes is kept mildly inclined to let the feed flow with water towards the exit. The primary water to the launder is fed before coal feeding point. The functioning of the launder is similar to that of previous case, except having a different method of catching the refuse with ability to get middling in addition to clean coal and refuse. Figure 2.16(b) illustrates the functioning of Rheo boxes. The coal charge containing clean coal, middling and tailing is fed at top end in the flowing water. The flowing water force is exerted on the particles settling at different rate. After some distance from feed point, the clean coal remains closer to upper section of the water current being the lightest fraction. The shale and other heavier objects with plate like shape occupy the bottom section of the water current, leaving the middling in the intermediate zone of the flowing water. When these stratified particles come over the Rheo box, they encounter secondary regulated water flow at launder floor moving upward from the open chamber. This secondary water flow speed is kept adjusted in such a manner that the buoyancy force for clean coal and middling is higher than their gravitational force for settling and they are allowed to move forward. The shale and other heavier objects moving close to the bottom of the water current fall in the box open chamber as they experience more gravitational force than buoyancy force of water in the chamber. The trapped shale and other refuse get collected at the bottom of the Rheo box and are discharged periodically by double gate system. The middling and clean coal moving onward with water current meet another Rheo box which has water flow regulated in such a manner that the middling gets trapped in this box and only clean coal is allowed to move further to be discharged at the end as main product. These launder are capable of cleaning coal having size 100–5 mm provided they are closely sized while feeding. The coal having wide size range is divided into close size fractions to be treated separately.

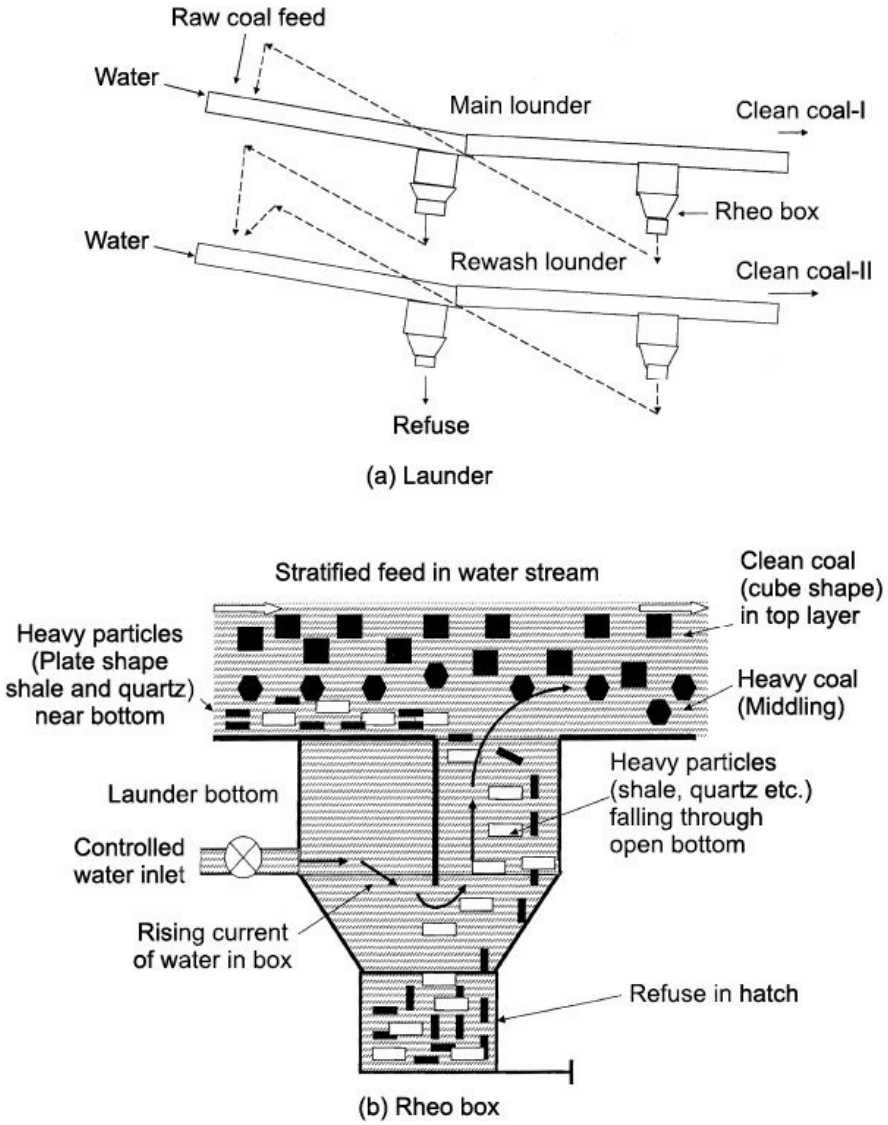


Figure 2.16 Rheolaveur launder.

Jigs

The baum jig is a very popular coal cleaning equipment used in the industry. Its working is based on hydraulic principle. It consists of a U-shaped chamber filled with water which is partitioned in two non-equal sections as shown in Figure 2.17. The smaller section is sealed on the top and fitted with mechanical valves, pipe and air pump to subject air pressure and its release with certain frequency (30–50 strokes/min) to give a pulsating up and down action to the water held in adjoining wider chamber. This wider chamber has a perforated steel plate fitted at certain depth to hold the coal feed and serve as settling chamber. This wider section has device to feed raw coal and water with attached weir to discharge clean coal with excess water. The bottom of U-shaped chamber serves as tailing

hatch. The tailings can be discharged periodically by a mechanical gate system.

The working method involves starting of air pump to give pulsating action to the water level in the wider section chamber of the jig followed by feeding water and raw coal. The fed raw coal gets stratify during settling under pulsating water action. The heavier fraction consisting of rejects and middling will occupy lower position in the settling chamber. The clean coal being lighter, occupy upper portion in the chamber. When more water and raw coal is fed at one end, this top floating clean coal overflows with water on the weir and gets discharged. In the settling chamber, the heaviest particles smaller than perforations in the steel plate will fall down in the U-shaped chamber to discharged as tailings mostly consisting of shale, pyrites and quartz. The middling with some shale held in the settling chamber is periodically taken out and treated further in another jig for separation of middling
and rejects.

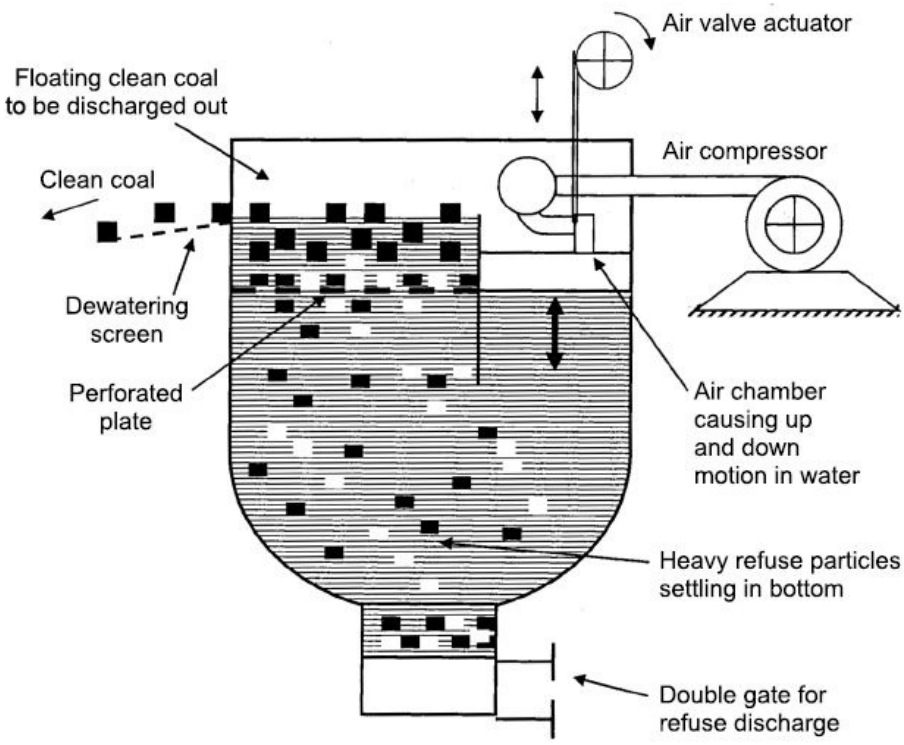


Figure 2.17 The baum jig.

These jigs are manufactured with certain capacity and they are multiplied for capacity enhancement. The jigs are suitable to clean coal having 100–10 mm size, provided they are fed in close size range for effective cleaning.

Rising current classifier

The rising current classifiers utilises the buoyancy force on the settling particles in a tank where the water is kept agitated by a rising flow of water. The particles experiencing high gravitational pull than buoyancy would tend to sink. This applies to particles which are larger in mass or have high specific gravity. The smaller and lighter particles would remain afloat and could be separated out from the tank. This necessitates feeding particles in close size range such that only specific gravity plays role for treating closed size particles and helps in their separation using such classifiers.

The popular Menzies cone classifier is shown in Figure 2.18. It consists of an inverted cone shape tank having short cylindrical shaped section on its top. The conical section of the tank is filled with water and is provided with water inlets at various levels with regulating valves. The water enters at an angle downwards in the direction of rotating stirrer. The water in the pipe is supplied by a pump which draws water from a tank. The water entering from these water inlets rises upward to create rising water current. An agitator is provided in the centre of the tank to keep the charged coal in suspension. The rising water comes out and gets discharged over a perforated inclined weir to allow the water to be separated from the clean coal discharged out from the classifier. The water is collected in tank for reuse. The conical classifier tank has a small cylindrical hatch section at the bottom to collect the settling shale particles. This hatch has a mechanical scrapper to discharge the shale particles out from it continuously.

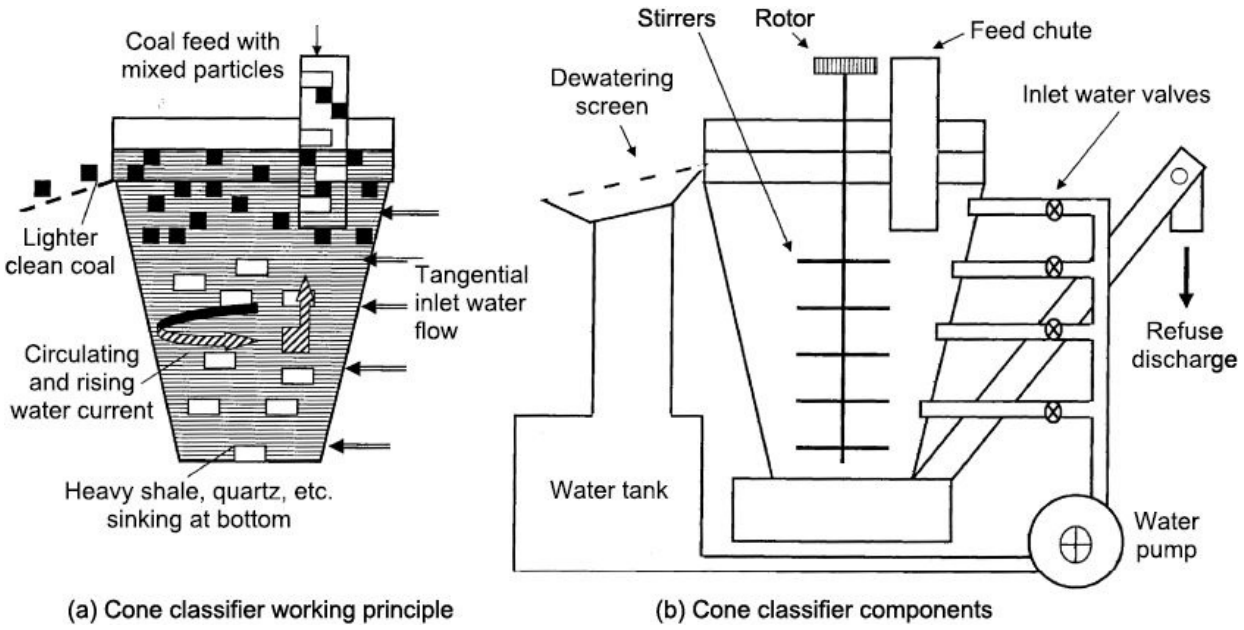


Figure 2.18 Menzies cone classifier.

The coal is fed in the centre at a depth of about 300 mm below the level of

water in the tank. The charged particles start stratifying and settle in the tank which encounters the rising water flow. The clean coal being lighter tends to keep afloat, while the shale particles tend to sink at the bottom of the cone which is discharged continuously by a mechanical scrapping device. The clean coal remaining afloat in the upper section of the classifier gets removed out by the rising water current on to the perforated inclined weir. The water passes back to the tank for reuse while cleaned coal is collected as product.

Tables

The tabling is a common method for cleaning heavy metallic minerals, but it is also used for cleaning coal. The table is a rhomboidal deck fitted with ribs on its surface. The ribs play vital role in stratifying the particles having different density. The ribs height and spacing between ribs depend on the table design for a given mineral of specific size to be treated. However, the ribs height and inter ribs gap must provide space for a few layers of the particles to be treated. The ribs height tapers down towards discharge end of the table. The length of ribs also keeps increasing from top section of the deck to the lower section as shown in Figure 2.19. The deck is slightly kept raised at the top feed end. The arrangement is made to feed water before the point of coal feed. The deck is given longitudinal reciprocating action by a mechanical arrangement. The forward movement is slow with rapid reverse movement. The frequency of this motion could be 250–300 per minute.

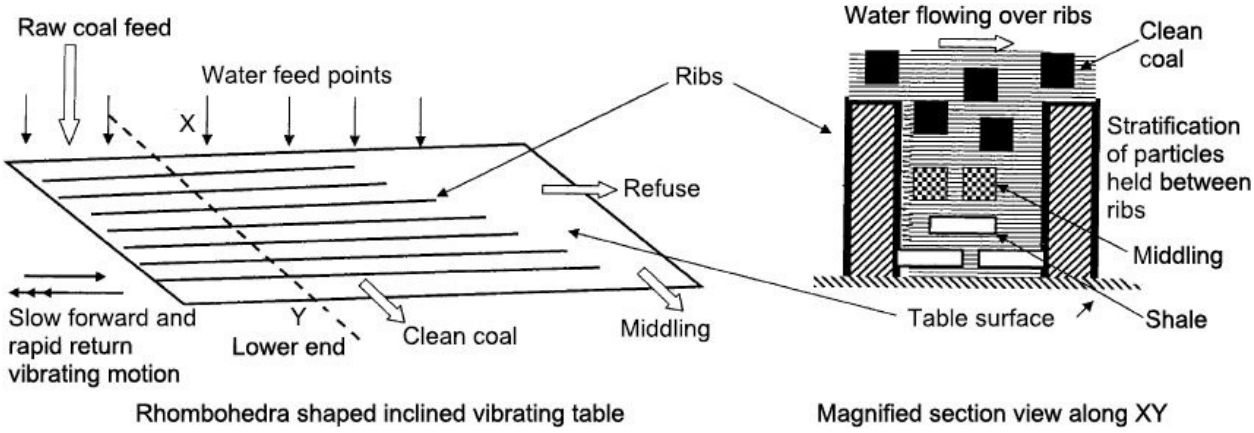


Figure 2.19 The vibrating table.

The coal and water fed on to the table get filled and distributed in the ribs gap. When the deck starts vibrating, the coal particles start stratifying held in between ribs which acts like a narrow and long trough. The shale particles which are heavy, occupy bottom position and lighter coal particles remain close to ribs

top. The flowing current of water washes down the coal in the upper section of the ribs which roll down to the bottom section of the deck and collected as clean coal product. The shale particles held between ribs close to deck surface move forward due to jerking deck motion. The heavy particles resting on deck move alongwith deck during slow forward motion and retained there while the deck returns back with rapid jerk. This process allows the heavy particles to keep moving onwards till the longitudinal end side of the deck and get discharged as refuse. The clean coal particles rolling down over ribs with water are removed at the lower end of the deck as product. The middling is discharged at the corner section of the table. The water flow rate helps in separating clean coal at the bottom of the deck.

The tabling is practiced for finer size coal fractions with maximum 25 mm particles. It can clean 6–7 ton coal per hour for 8 mm coal particles.

Dewatering coal and water treatment

The cleaned coal and middling dewatered over screens contain sufficient quantity of water. This wet coal is stored in bins having water drainage system. The coal stored for several hours looses water by draining. Some plants use centrifugal driers to remove the retained water.

The water recovered after coal cleaning contains coal fine particles and requires treatment before its reuse. The recovered water is treated in thickener to allow particles to settle down and reuse the decanted water. The coal slurry from the thickener is dewatered using drum vacuum filters.

2.6.9 Dry Gravity Separation

The dry coal cleaning techniques have merits and limitations both. The merits include (a) delivery of dry clean coal, (b) avoiding water as media which is getting scarced in nature and (c) its suitability for treating finer size (<12 mm) coal particles. The major limitation of the process is dust emission during dry cleaning of coal which needs elaborate dust catching devices rendering it capital intensive. Another limitation is its less effectiveness for cleaning very fine (–0.7 mm, i.e. –20 #) size coal. The various equipment used for dry coal cleaning are:

(a) Air Launders

(b) Air Jigs and

(c) Air Tables

These are described briefly as follows:

Air launders

This consists of a stationary inclined perforated trough fitted with an air chest at the bottom. The width of the trough gets narrower at the lower discharge end of the trough. The upper wider end is the feeding point for coal to be cleaned. The air is blown through air chest which emerges out from trough perforations causing stratification of coal particles lying on it. The lighter clean coal particles are pushed to the upper layer while the heavy shale pieces remain close to the bottom layer. The trough vibration causes the coal bed to slide downwards in the trough. The clean coal moving in the upper layer gets skimmed by narrowing shape of the trough at lower end to get discharged out. The heavy shale pieces moving close to bottom fall below from a slot located at the end of the trough bottom. The entire system is enclosed in a chamber to arrest dust.

This dry launders can clean coal particles in the range of 50–1 mm provided the feed is closely sized.

Air jigs

It consists of an inclined perforated deck (Figure 2.20) having a bed of marble pieces to serve as a air distributor. The air chest is located below the deck. The deck is divided in segments and has gaps to discharge out the particles moving close to the bottom of the deck. The deck has arrangement to provide short and rapid strokes to cause motion to the coal bed.

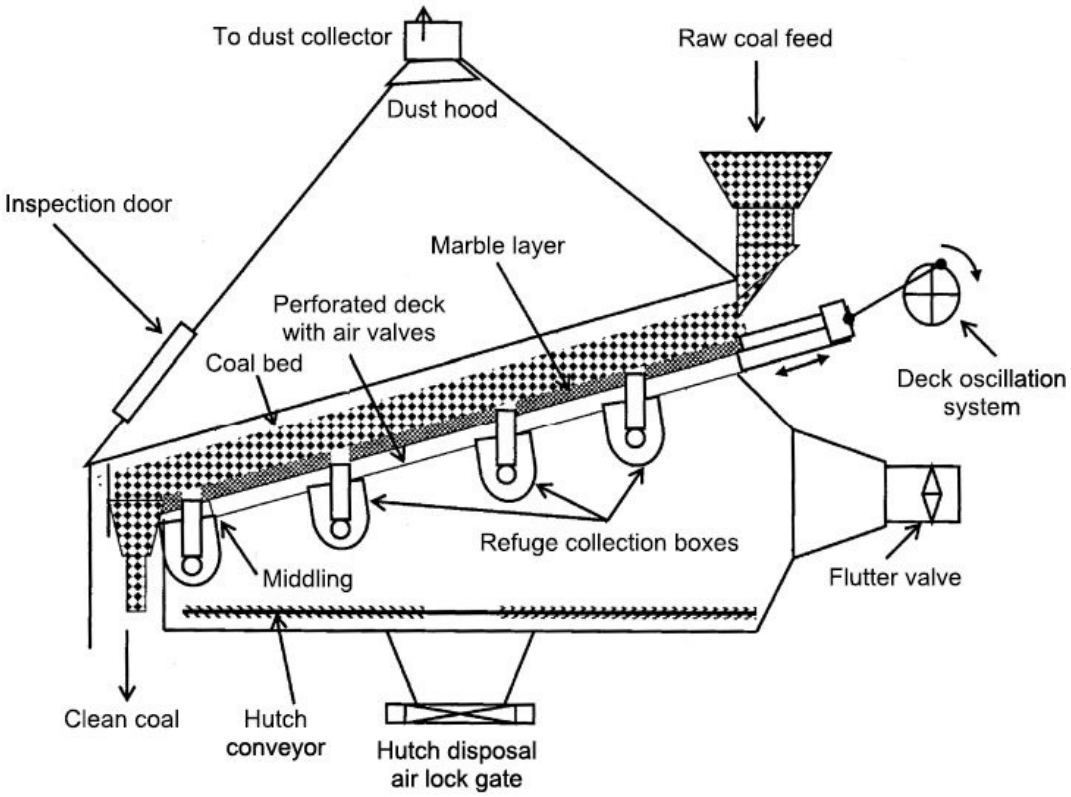


Figure 2.20 Air jig for coal cleaning.

The deck vibration is initiated with the coal feed which is charged at the upper end of the deck. The air is blown from the chest which emerges out through the marble particles causing stratification of the charged coal particles. The lighter coal particles gradually move to upper layer as the coal bed slides down while the heaviest particle (shale, quartz, etc.) remain at the bottom layer. When the heavier particles reach over the gap between deck segments, they fall below by gravity and are discharged out as reject. The advancing coal bed would have now middling coal particles occupying bottom layer position due to their higher density than clean coal particles. These middling coal particles would get discharged at next gap in the deck. This advancing coal bed when reaches at the end of the deck, the clean coal particles are skimmed over while second middling coal particles fall down in the gap. Thus, this air jig is able to separate charged coal as clean coal, middling and refuse.

The entire system is enclosed in a chamber to keep check on dust emission.

Air tables

The air table design resembles the table used in wet method. This differs by having the perforations in the table to blow air from the air chest attached below. The rhombohedra shaped inclined deck has ribs to stratify the coal particles and

it tapers down same as in wet table. It has a mechanical system to give vibrations identical to wet table. The entire system is enclosed in chamber to arrest dust.

The coal feed spread on the upper end of the deck is subjected to combined action of air flow and table vibrations to cause stratification of coal pieces lying between ribs of the table. As the coal feed advances on the table, it gets stratified. The lighter clean coal particles occupy the top layer while the heavy shale particles remain close to table surface. The deck vibrations, gravity force due to inclined deck and air flow let the clean coal particles lying on the upper region of the ribs gap to roll over the ribs and move down to the lower end of the table as clean coal product. The shale particles being heavy remain close to the table surface and keep moving forward to get discharged as rejects from the upper end of the table. The intermediate specific gravity coal particles (middling) are discharged from the lower corner end of the table.

2.6.10 Float and Sink Method

This method uses a fluid having density intermediate to that of coal and impurity minerals. When the coal charge is fed into a tank of such fluid, the coal being lighter floats on the surface and the impurity minerals sink as they have higher densities. This stratification of coal and impurity minerals gives a very good means to separate the two different particles.

The greatest advantage of such method is the possibility of using mixed size of coal without any size limitations. However, this method needs cheap, non-toxic, non-hazardous and easily separable fluid in large volume. The aqueous salt solutions and several organic fluids may be suitable for laboratory testing but are unsuited for the industry. The pseudo liquid prepared by suspending solids in water and air has been found to be useful and practiced.

Methods having fine solids suspended in water

The fines sand, magnetite, barites and clays have been found suitable to be suspended in water to give pseudo liquid of desired density Table 2.8. The solid particles are selected on the basis of their low cost, ease of recovery and their non-contaminating effect on coal. The processes using these solid particles are briefly given in the following sections: (i) Chance process using sand

Figure 2.21 shows a schematic diagram of the Chance process for coal cleaning. The main cleaning tank is conical in shape (60^o angle) which has water pipe inlets located at various levels in the tank. The water flow rate in these pipes is controlled by valves in a desired manner to regulate the ratio of water and sand

in the main tank. The lower end of the conical tank has a hatch tank to collect refuse. The refuse from this tank can be discharged periodically by double gate system. The entrance of the refuse tank has water pipe connection to dislodge any choked particles. The conical tank is fitted with agitating device to keep the sand in suspension. The upper part of the conical tank has a short cylindrical section with discharge door opening to a inclined weir which is perforated to dewater the product clean coal. The water is collected by a trough located below the weir. In order to remove sand on the coal surface the water showers are provided over the weir. The water and removed sand particles are collected by the trough to be reused. The water and sand collected in this trough is transported by pipe to the sand sump. In the sand sump, the sand particles settle down and decanted water overflows to a collection chamber to be pumped back to the main tank in controlled manner. The sand settling at bottom is pumped as sand and water slurry to the main tank to keep the sand and water ratio in the desired range to give pseudo media specific gravity as 1.35–1.65. The coal to be cleaned is fed in the centre of the tank at a level below the water.

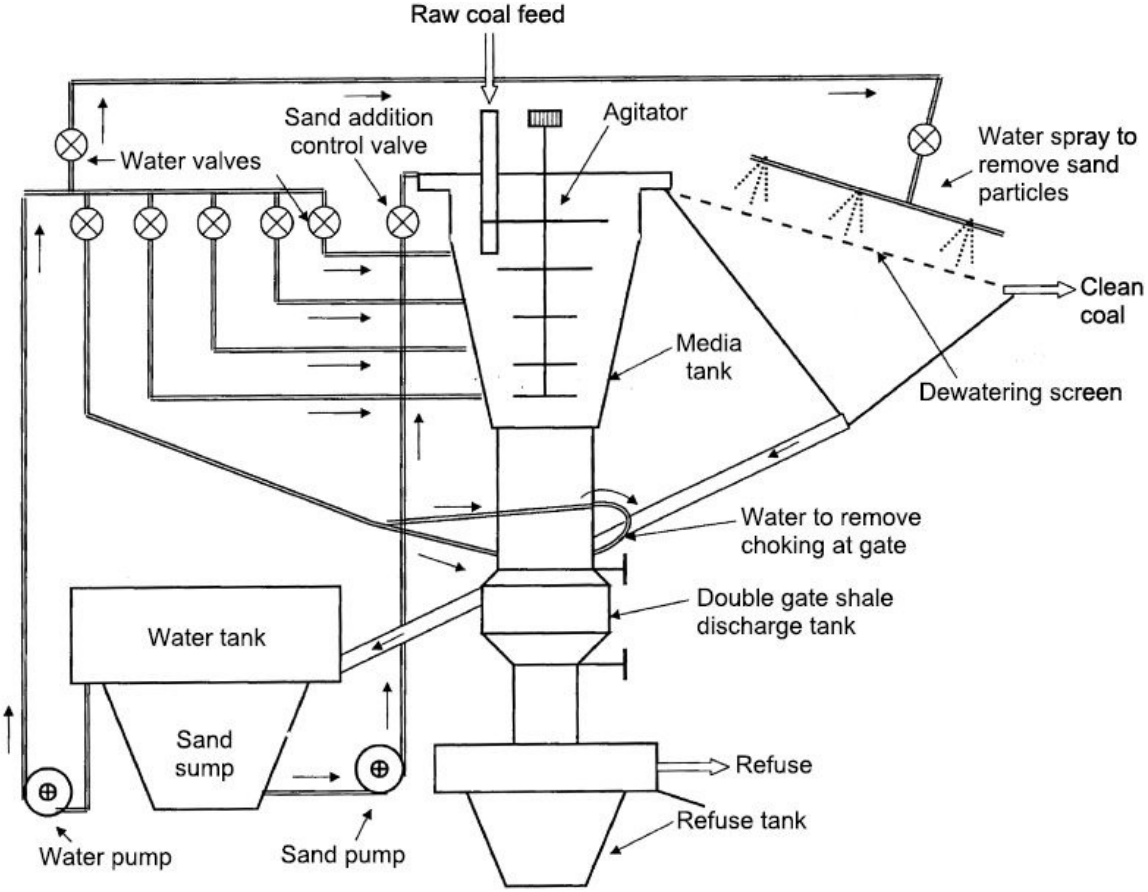


Figure 2.21 Chance process for coal cleaning using sand.

The major advantage of this process is its ability to clean coal having mixed particles in the range of 200–2 mm. However, very fine particles must be avoided as they tend to alter the specific gravity of the fluid, since they remain in suspension and cannot be separated out. The sand particles in the range of 0.35–0.20 mm (40–80 N) are used with water to get pseudo liquid. The sand particles finer than 0.20 mm would not easily settle in water and bigger than 0.35 mm would be difficult to keep them suspended in water. The sand loss due to adherence with coal pieces is made up by feeding 0.6 kg sand per ton coal cleaned. A unit having 3 metre top diameter Chance process system can clean up to 550 ton coal per hour.

Processes using other particles

In other processes, magnetite, barites, clays have been used to make pseudo media to have desired specific gravity as given in Table 2.8. The magnetite particles have the advantage that they could be recovered using magnetic property of the mineral.

Air-sand float and sink method—A dry coal cleaning technique

This technique uses a tall chamber to keep sand in fluidised state using air flow which gives a pseudo fluid media with specific gravity in the range of 1.2 to 1.5. The coal charged in this media is stratified according to particle density. The clean coal having lesser specific gravity keeps floating on the top section in the chamber, while the heavier particles have a settling tendency to the lower section of the chamber. The coal particles separated on the basis of their specific gravity are collected separately by specially designed chutes in the chamber to be taken out.

In this method, the sand particles of –14# are used. This technique needs 40–70 m^3 /min air to clean 100 ton coal/hour.

2.6.11 Froth Floatation Method

This technique is suitable for finer size coal particles (< 0.35 mm or < 48 #), but it can clean particles up to 3 mm size also. Such fine particles may be obtained as a result of washing lump coal or sometimes a coal needs to be ground to liberate ash bearing minerals.

The froth floatation technique exploits the physico-chemical properties of the mineral surfaces. The addition of chemical agents can bring changes in their surface properties which render them wetable or non-wetable by water. When

bath is aerated in the presence of a frothing agent, froth is formed to which non-wetable particles are attached and the wetable particles remain in the slurry.

The common frothing agents used are cresylic acid, pine oil and alcohol. The collecting agents used for coal include higher boiling petroleum fractions, fatty acids, xanthates and soaps.

The coal prepared by sizing and cleaning are despatched to the various users. The regular supply of prepared coal requires coal storage in specific quantity at pit head, coal cleaning plant and at user end.

2.7 COAL STORAGE

The storage of coal is common in plants producing steel, sponge iron, aluminium, power, etc. The various aspects of coal storage are discussed as follows:

2.7.1 Aim of Coal Storage

The coal storage is a *necessity* due to following reasons:

(i) To maintain a minimum inventory for uninterrupted production,

(ii) To have surplus stock of coal to meet the unforeseen factors like closure in mining process, breakdown in the means of transportation, weather problem, etc., (iii) To blend coal from different source for meeting required specifications and

(iv) Difficulties associated with import process from other nations with short notice.

2.7.2 Problems with Coal Storage

Coals cannot be stored in larger quantities due to the following problems associated with it:

(i) Storage of coal requires capital,

(ii) Storage of coal requires extra handling and land which add to cost,

(iii) Prolonged coal storage causes it to deteriorate in quality due to slow oxidation and

(iv) In some cases, the open stored coal may catch fire by itself.

2.7.3 Factors Promoting Natural Oxidation of Coal

Coal oxidises when it is exposed to air. This process of oxidation is associated with release of heat due to exothermic reaction. This causes gradual rise in temperature of the coal bed. The rate of oxidation being slow in normal conditions, the heat generated gets dissipated in the atmosphere without raising the coal body temperature significantly. As the coal bed temperature keeps increasing, the oxidation rate is enhanced and it may reach to a point of self ignition causing the fire in the coal pile.

The rate of coal oxidation and rate of dissipation of generated heat would depend on several factors (Figure 2.22) prevailing during storage. The factors affecting the oxidation of coal and heat dissipation depend on the given factors:
(i) Type of coal and its constituents
All the coals do not oxidise with same rate. Some coals oxidise faster than others. The rate of oxidation is high for coal having more oxygen, volatile matter, fine particles of pyrite and bed moisture. Coals with high sulphur content are highly oxidising in nature. Generally, the higher rank coals oxidise less.

(ii) Surface area available for oxidation

The coal is stored in the form of piles. These piles are formed by discharging coal from a given height. The freely falling particles occupy different position in the pile. The bigger particles having low angle of repose roll down to farther area and are present at edges, while the finer particles possessing higher angle of repose remain in the central and top section of the pile. Such pile prepared from the mixed size coal particles offers worst situation. The bigger particles at the edges allow air to enter in the pile to oxidise fine size coal at the centre and generate heat which cannot be dissipated easily. This results in gradual rise in the coal pile temperature. The situation is not so bad for coal pile prepared of fine size coal which has more surface area but does not oxidise fast due to less air flow in more packed bed. The less oxidation and lesser rise in heat in fine size coal pile result from non-circulation of air in a densely packed bed. The surface layer of such pile may get oxidised due to large surface area of fine size coal, but the generated heat is radiated out and the entire pile does not get heated. In case of pile made of only bigger coal particles, the free circulation of air in the pile though voids would cause oxidation and dissipation of heat together causing less harm to the pile. Thus, it is only the mixed particle size coal pile which poses problem of increasing pile temperature with storage time.

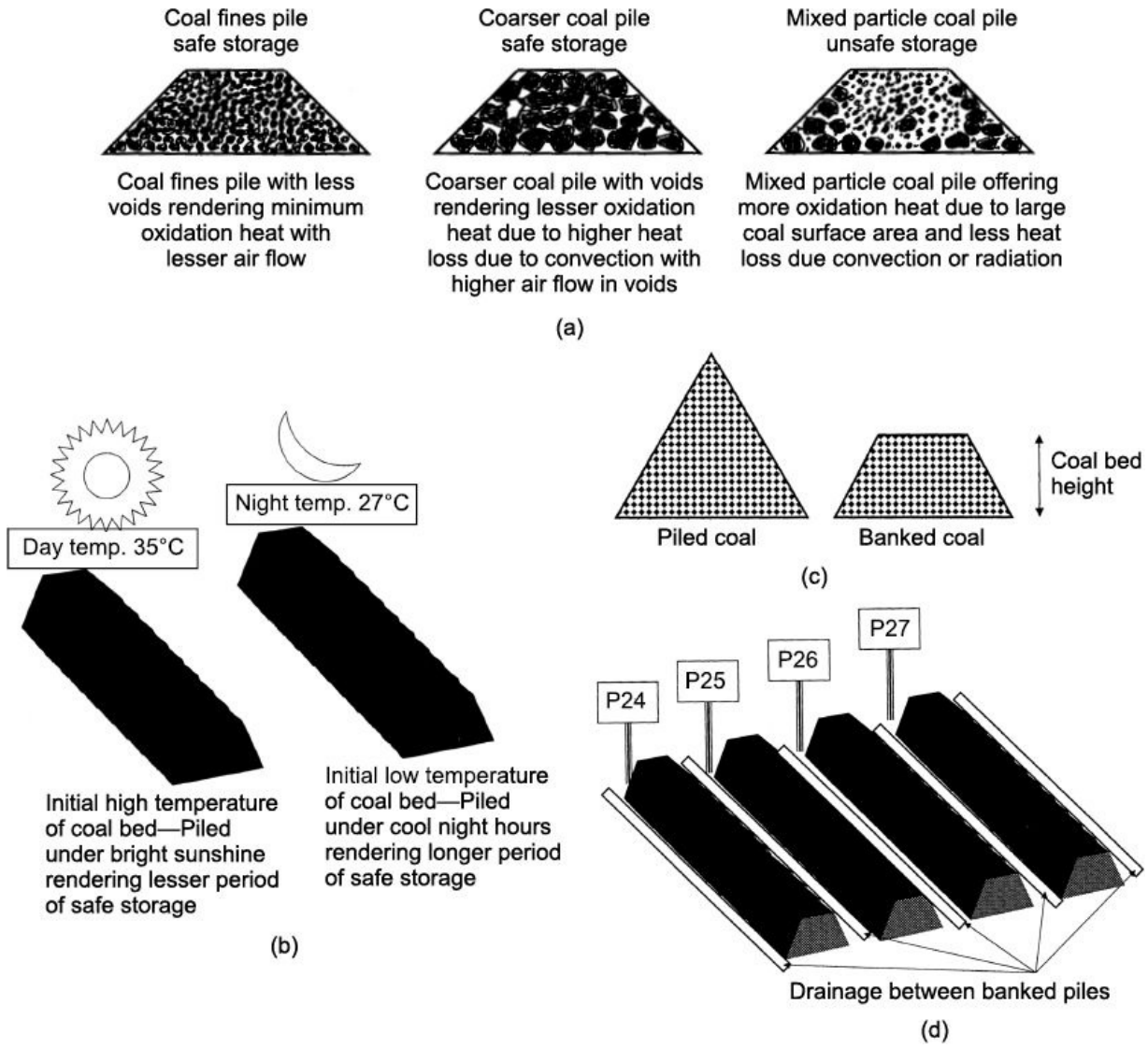


Figure 2.22 Storage of coal.

(iii) Initial temperature of coal bed

The weather condition of day provides the initial temperature to the coal which is being stored. Therefore, it is better to make coal pile on cool hours in the day. The bright sun and hot hours may be avoided. The coal piling at lower temperature during cloudy day or in night would be safe for longer duration storage before the pile reaches the critical self ignition temperature.

(iv) Moisture in the coal bed

The alternate wetting and drying is found to enhance the oxidising tendency in the coal. The coal must be stored in an area which is free from water logging and frequent watering the pile to suppress dust must be avoided.

(v) External heat sources

A heat source like steam pipe line, hot air duct or furnace in the vicinity would be radiating thermal energy on the coal pile and would tend to raise its temperature.

2.7.4 Precautions Required during Storage

In view of the oxidising nature of the coal, certain precautions are taken during storage. These are as follows:

(i) *Separate coal bed for each source:* The coal obtained from different sources must be stored separately with all details including piling date and pile number.

(ii) *Utilise coal piled earlier* **:** The coal obtained earlier must be given priority in use. The date of piling is an important data to be maintained.

(iii) *Coal bed size:* The coal bed height is kept low (< 6 metres) to minimise air circulation in the bed. The bed pile must be banked by running a roller on its top.

(iv) *Coal particle size in bed:* The mixed size coal must be avoided in the pile. The different size coal must be piles separately.

(v) *Coal handling:* More handling causes coal breakage and generation of fines. Minimum handling is better.

(vi) *Temperature during coal storage:* Coal piling may be preferably done in cool hours.

(vii) *Storage ground with drainage:* Coal storage ground should have water drainage to avoid water logging. High ground with floored surface is ideal.

(viii) *Avoid water sprinkling:* The periodical water spraying must be avoided.

(ix) *External sources of heat:* The coal storage area must be kept away from external heat sources like steam pipe line, furnaces, etc.

(x) *Monitoring coal bed temperature* : The coal bed temperature must be monitored manually at given interval. This is done by piercing a pointed steel rod deep in the pile and withdrawing it after holding for sometime. The rod temperature could be felt by touching it. The feel by hand would give the idea of temperature of the pile. The modern auto-temperature recording method could be installed permanently by locating thermocouples at various points in the coal bed which are connected to the control room. The pile getting hot must be utilised on priority.

2.8 COKE MAKING

The caking coal when heated in the absence of air, at coking temperature, yields a strong and porous carbonaceous mass termed as *coke* . All caking coals do not yield coke and every type of coke is not termed ‘metallurgical coke’. The term *metallurgical coke* is designated to a specific variety of coke useful for iron blast furnace applications, which possesses required low porosity, high strength and low reactivity.

The coke making requires selection of caking coal based on its properties like:

(i) *Caking behaviour:* The coal must be strongly caking in nature.

(ii) *Swelling Behaviour:* The coal must not have swelling behaviour during heating. High swelling nature would cause pressure in coke chamber and may damage it in some cases.

(iii) *Plastic Behaviour:* The coal must not exhibit excess plasticity during heating which may give spongy type of coke with low strength.

(iv) *Ash content:* Ash content in the coal must be in minimum quantity as it adds the demand for fluxing agents during blast furnace iron making and cupola melting with enhanced slag volume.

(v) *Sulphur content:* The sulphur content in coal must be less as it mostly passes to blast furnace hot metal (pig iron) which has to be removed before steel making by desulphurising treatment which adds cost to hot metal.

2.8.1 Coke Making Methods

The coke is being made by following three methods:

(i) Beehive Coke Making Method

(ii) Non-Recovery Coke Oven Method and

(iii) By-product Coke Oven Method

Table 2.10 gives the comparative picture of all the three methods of coke making.

Table 2.10 A Comparative View of Coke Making Processes

Factors	*Beehive Method*	*Non-recovery Ovens*	*By-product Ovens*
Production cycle	Batch Method	Batch Method	Batch method
Oven shape	Beehive	Beehive	Rectangular
Coal charge/Oven	5–10 ton	10–15 ton	16–20 ton

Coking time	48-72 hours	24-30 hours	14-18 hours
Longest coke piece length	600 mm max	600 max	150–200 mm
Coke quality variation in one coke piece	Non-uniform	Non-uniform	Uniform
Heating energy source	Coal VM	Coal VM	BF + Coke oven gas
Scale of operation	Small ~ 0.03–0.05 mt/yr	Medium 0.1 < 1 mt /yr	Large > 1 mt/yr
Coal chemicals	Lost	Lost	Recovered
Pollution level	Maximum	Moderate	Minimum
Working conditions	Very odd	Moderate	Better
Capital investment	Minimum	Moderate	Very High
Coke quality produced	Poor	Moderate	Best
Indian production share	Very less	Moderate	Maximum

2.8.2 Beehive Coke Making Method

This is an old method of coke making on small scale (~ 0.03–0.05 million ton per year). The coke oven appears like a beehive (Figure 2.23) which is constructed by using fireclay bricks. Such ovens can make a batch of 4–6 ton of coke. A number of beehive ovens constitute a beehive battery to produce desired quantity of coke.

The coal is charged in a hot oven which has just discharged its previous batch of coke. The coal is charged from the top hole and the bed is levelled from front manually using steel bars to give a thick bed of coal. The front door is closed using bricks and mud, leaving a gap on the top to allow air for combustion of the volatile matter. The stored thermal energy in the beehive oven from previous operation provides heat to cause evolution of volatile matter from coal adjoining oven surface. This volatile matter catches fire in the presence of air leaking from door openings. The burning of volatile matter on top of the coal generates heat to heat the top coal layer and further volatile matter joins combustion process. The liberated heat is radiated upwards to be reflected back on the coal bed to cause further heating and the coking process is initiated. This process of coking proceeds downwards in view of top unidirectional heating. It takes nearly 48–72 hours for the entire coking process. The mudded stone door is dismantled and coke is raked out manually to be quenched with water on the spot before loading coke in cars for dispatch. The hot oven door is closed and another coal charge is made to continue coke making.

Due to unidirectional heating, the top layer of the bed is heated for longer duration and gets over coked while the bottom layer is heated for the least time period and sometimes, it may not be fully coked. This unidirectional heating renders long coke columns in beehive ovens. These are easily distinguishable due to their longer coke pieces with one end coked differently than other end.

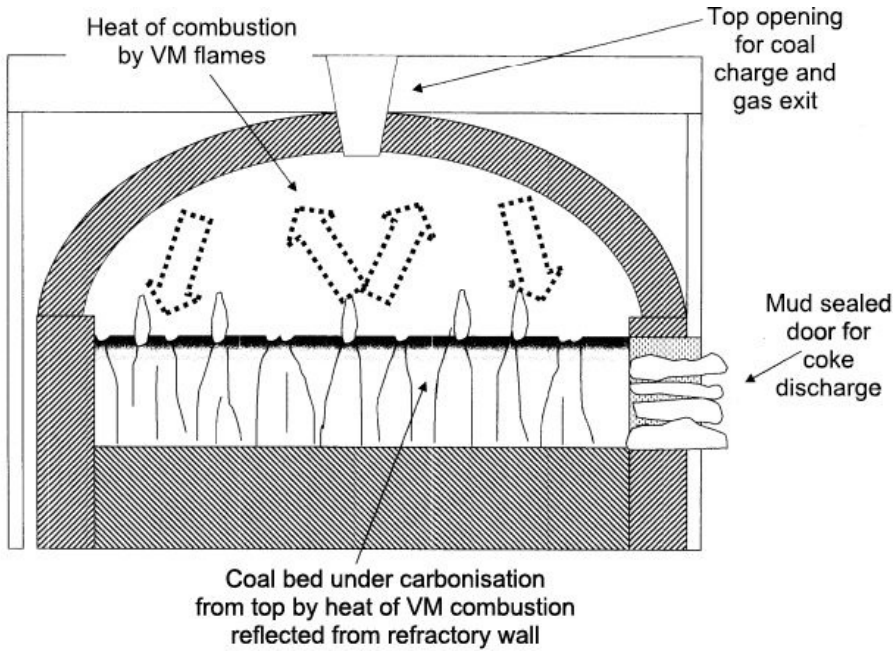


Figure 2.23 Beehive coke oven.
(Adopted from R.C. Gupta, *Theory and Laboratory Experiments in Ferrous Metallurgy* , PHI Learning, Delhi, 2010.)

This beehive coke making is an old technique which does not yield any coal chemicals, but it is still in practice due to commercial reasons.

The merits and limitations of this method are as follows:

Merits

The process is simple and oven can be easily built and operated without skilled workers

Less capital investment—good for small scale operation

Can use variety of coking coals for coke making

Limitations

There is no recovery of coal chemicals in this method

The process is polluting in nature due to gaseous emissions

The methods is labour intensive and health hazardous

2.8.3 Non-recovery Coke Oven Method

The non-recovery coke oven is a modified form of beehive coke oven. These ovens look similar to beehive ovens (Figure 2.24), but have difference in design and operational facilities as they work on medium scale of coke production (0.05–1 million ton per year). The main difference with old beehive oven being more modern and energy efficient due to using waste heat for power generation.

The non-recovery coke oven battery consists of several coke chambers arranged together. Each coke chamber has a cross-section like a beehive, but it is a long chamber. Unlike small beehive oven, which is heated unidirectional manner, the coke chamber in non-recovery oven is heated from top and bottom as illustrated in Figure 2.25. The coke chamber is heated from top and bottom by the gas consisting of volatile matter evolved during coking. The partial combustion of volatile matters occurs at oven crown above the bed. The products of combustion having sensible and potential heat is further utilised for power generation. The burning of exit oven gases occurs in power plant combustion chamber where more air is introduced resulting in eliminating all the toxic volatile constituents such as tar, benzol, napthalene, thereby avoiding air pollution. The sulphur in coal is evolved with gases and is removed from flue gases using lime scrubbers.

The production facilities for such coking plant consists of coal tower, coal stamping station, coke oven batteries, stamped coal charging machine, coke pushing machine, gas collection main flue tunnel, stacks, coke quench tower, settling ponds, quenching pump house, etc.

The blended coking coal from coal handling plant is delivered to coal tower wherefrom the coal is received by the coal box for charging through wiggling feeders to ensure that coal is evenly spread in the coal box. The coal stamping is mechanically driven and there are several stamping heads on each side of stamping station. The stamping of coal takes 6–8 minutes to finish, giving a coal cake having dry bulk density of ~1.05 ton m^{-3} .

The coke pushing car is first located in front of the designated coke oven to discharge out the hot coke. The doors of the oven are removed mechanically on both sides and the hot coke is pushed out through a guide car into a coke car. Now, the coal charging car with stamped coal cake is located in the front of the oven and coal cake is pushed in the hot oven and doors of the oven are closed.

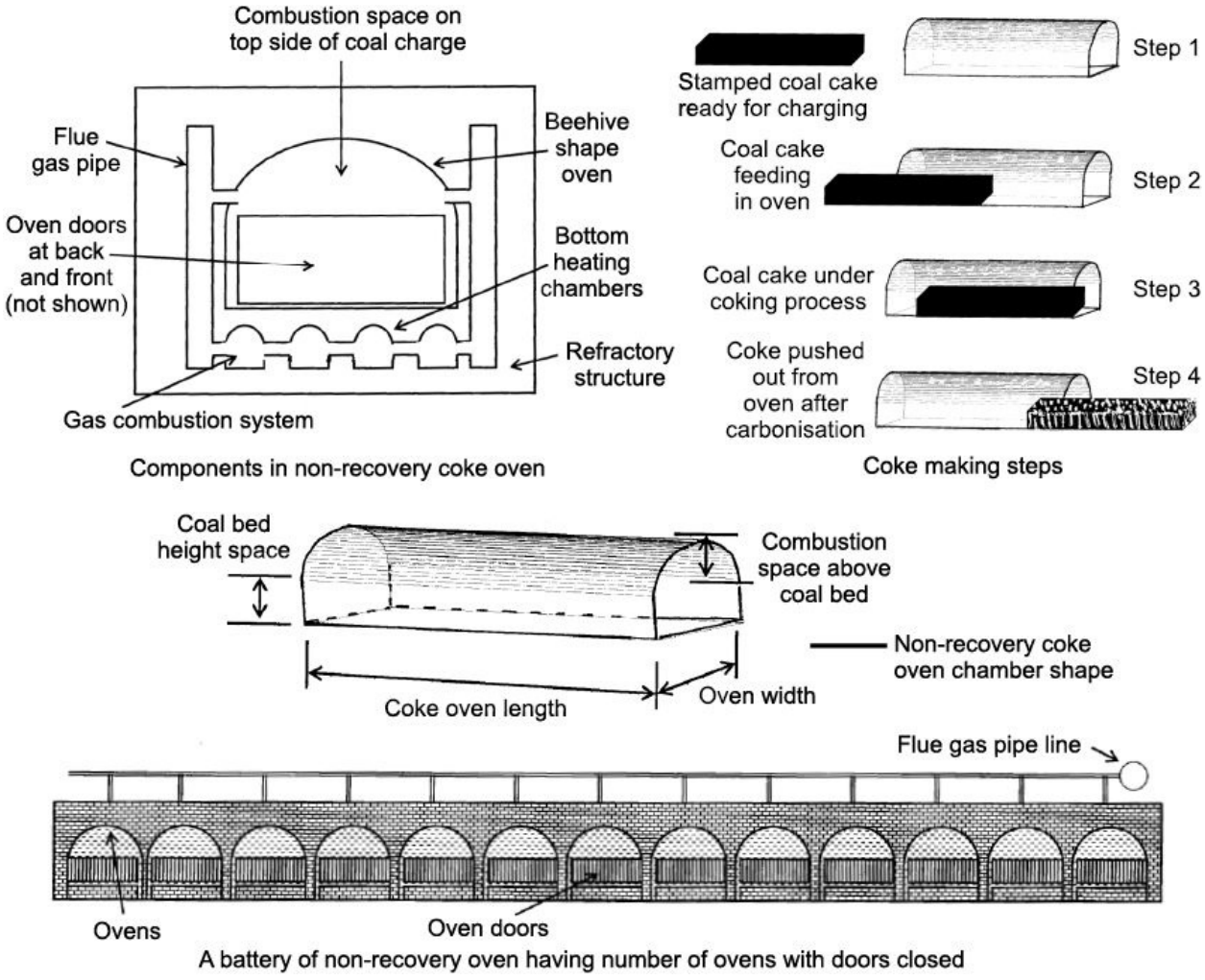


Figure 2.24 Non-recovery coke oven.

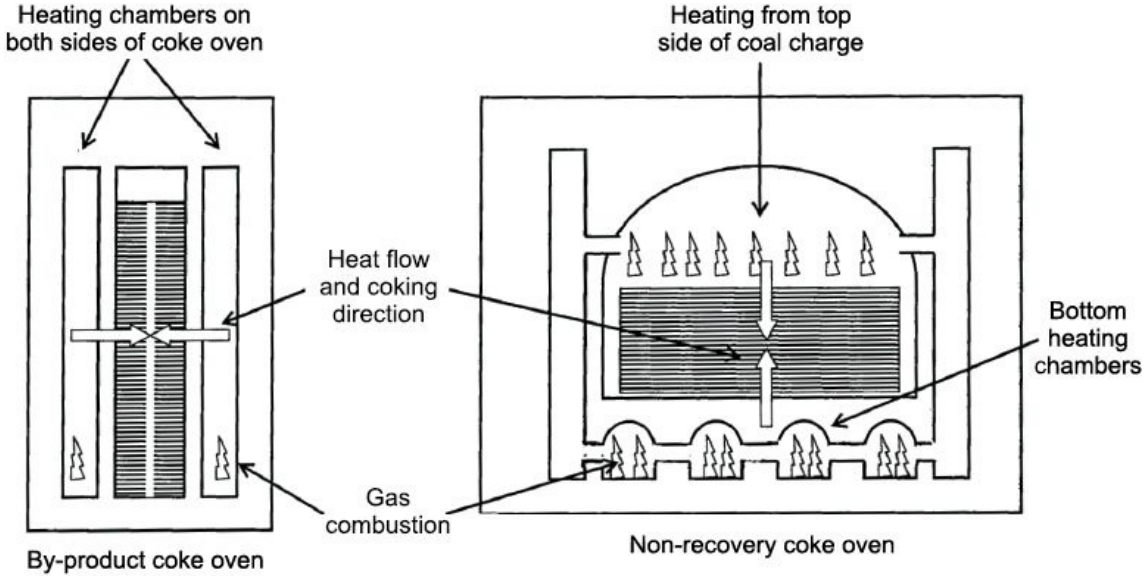


Figure 2.25 Heating method in non-recovery coke oven compared with by-product oven.

The coke car receiving red hot coke moves to the quench tower which showers water over coke car located below to quench hot coke. During quenching, huge quantity of pollutants are emitted with steam evolved by hot coke. After quenching, the coke car discharges the coke on a wharf to be sent for sizing operation before despatching coke for use.

This type of coke oven operates under suction, and therefore, during coal charging, no flame or smoke comes out of the ovens as the burning gas is sucked into the oven automatically, ensuring pollution free environment.

Soon after coal charging, the coal absorbs heat from refractory material in the vicinity to cause evolution of volatile matter. This volatile matter evolving from coal bed starts burning to give heat. This heat is transferred back to oven refractory and the coking proceeds.

The merits and limitations of this method are as follows:

Merits

This method requires less capital

Method is capable of producing coke for metallurgical applications

This method uses exit gases for heat recovery and waste gases are discharged through chimney

This method works under negative pressure and does not release polluting gases in the atmosphere near oven chambers.

Limitations

No recovery of valuable coal chemicals

The coke quality is lower compared to by-product coke

Limited coke production capacity

2.8.4 By-product Coke Oven Method

The by-product coke oven method involves heating a relatively thin section of coking coal in absence of air held in a narrow, long and tall coke chambers from either side by two heating (combustion) chambers. The charged coal bed gets converted into coke after being heated for
14–18 hours at ~1200°C temperature. The hot coke is pushed out, cooled (wet/dry), sized and used.

The by-product coke ovens (16–20 ton coal charge/oven) are used mainly for producing metallurgical grade coke, but smaller ovens (4–6 ton coal charge/oven) are used for generating coke oven gas for use in chemical plants. The coke produced in such ovens is taken as a by-product and used according to

its grade.

The by-product coke oven consists of set of coke chambers and heating chambers placed in alternate manner such that a coke chamber lies in between two heating chambers. This set of coke ovens and heating chambers is called a coke battery (Figure 2.26). In a coke oven plant, there could be more than one coke battery each having 40–60 coke ovens to give required coke production.

The merits and limitations of this method are as follows:

Merits

Capable of yielding metallurgical grade coke

Generates valuable coke oven gas—a rich gaseous fuel for use in integrated steel plants

Valuable coal chemicals are recovered as by-product giving the name to the process

Capable of adopting automation and modern pollution abatement devices

Limitations

Considered most polluting devices in the plant and needs good operating and maintenance practice

Capital intensive

Coke oven once heated has to be operated till its full life as intermediate cooling will damage the refractory structure.

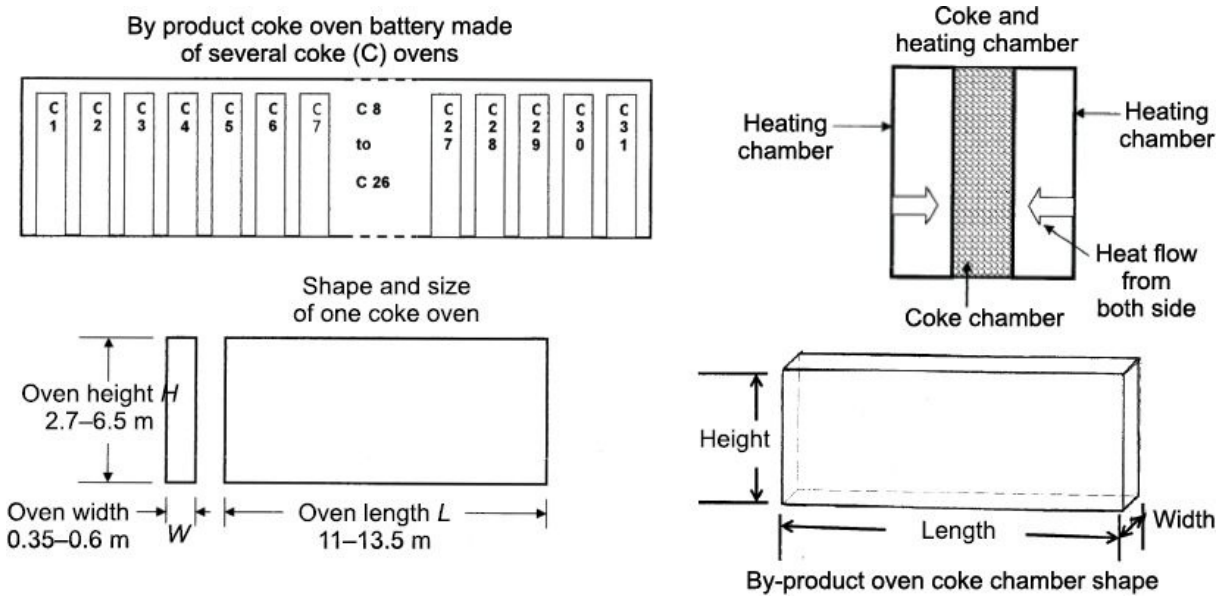


Figure 2.26 A by-product coke oven battery.

The major components of by-product coke ovens (coking chamber, heating chamber, regenerators, charging cars, pusher car, coke guide, oven doors, gas

collection and its treatment plant), coke oven operation, oven temperature control, coking process and coke quality are described in subsequent sections.

(a) The major components of by-product coke ovens

The entire coke oven consisting of number of coke chambers is a refractory structure without any steel casing to accommodate the volume changes occurring in the refractory with temperature. A battery of coke oven have the following major components: (i) Coking chamber

(ii) Heating chamber
(iii) Regenerators
(iv) Self sealing oven doors
(v) Coal charging (Top charge/Stamp charging)
(vi) Pusher car
(vii) Coke guide
(viii) Oven doors
(ix) Gas collection and treatment unit

(i) Coking chamber (shape, design and refractory): The by-product oven coke chamber is rectangular in *shape.* It is narrow in width (0.35 to 0.6 m), longer in length (11 to 13.5 m) and tall (2.7 to 4.5 m) in size (Figure 2.26).

The *design* of the coke chamber is made to fix the width, length and height of the coke chamber. The narrow width of the oven helps in fast coking rate and uniformity in temperature across the oven width. The poor thermal conductivity of coal charge limits its width. However, the minimum width is needed to lay the brick structure by man. The length of the coke chamber is decided by the length of the pusher car arm. The oven design is done after ensuring the availability of the pusher car of desired size. The height of the chamber is decided by the design of heating chamber selected. The heating chamber must be able to provide uniform coking temperature over entire cross-section of the chamber.

The *refractory* selection for the coke chamber is made in view of the working conditions which involve high temperature operation with corrosive gases, refractoriness under load, thermal shock during charging coal and discharging coke with wear and tear during coke pushing operation. The fully fired silica brick (96% SiO_2) is found to serve better under the conditions prevailing in coke chamber. These silica bricks provide good thermal conductivity for better heating and resist alkali attack. These silica bricks are not joined by any mortar to avoid differential thermal expansion and give gas leakage. Instead a tongue and groove shape is used to interlock the bricks and stop gas leaking. The

bending path of the gas does not allow it to leak out due to drop in gas pressure.

(ii) Heating chamber: The heating chambers provide heat for coking the coal held in coke chamber. The heat is conducted through silica wall. The heat energy is obtained by combusting gaseous fuel in flues with pre-heated air. The flues are narrow ducts for burning fuel gas to heat the entire oven chamber. The heating chambers are designed with following objectives: (i) Production of coke in good and uniform quality

(ii) Minimum consumption of fuel gas

(iii) Minimum leakage of gas

(iv) Stable and strong oven with all parts easily accessible for repair.

(v) Simple in design and flexible (with regards to fuel choice) in operation

The coke oven heating generally uses a mixture of coke oven (5100 kcal/m^3) and blast furnace (818 kcal/m^3) gas. The producer gas (1450 kcal/m^3) is used when the coke oven and blast furnace gas are not available for some reason.

The flues could be arranged vertically or horizontally. The four different designs are illustrated in Figure 2.27 using these different arrangements. In all these four different systems, the combustion of fuel gas and hot air occurs in some section of the heating chamber in flues and hot gases escape through flues in another section of heating chamber. This hot flue gas passes through the regenerators located below the heating chambers. The sensible heat in the exit flue gases is absorbed by the bricks of the regenerator to become hot. Another set of hot regenerator provides stored thermal energy to pre-heat the incoming air for combustion in flues and get cooled gradually. The cycle of heating and cooling of regenerators are reversed after certain period.

The Koppers oven type system uses vertical flues in the combustion zone which is partitioned in two segments. The combustion is allowed in one segment while the other is heated by hot gases passing through it, which ultimately escape through ports leading to regenerators. The combustion and escape route is reversed after certain period to have even temperature along the entire length of the oven.

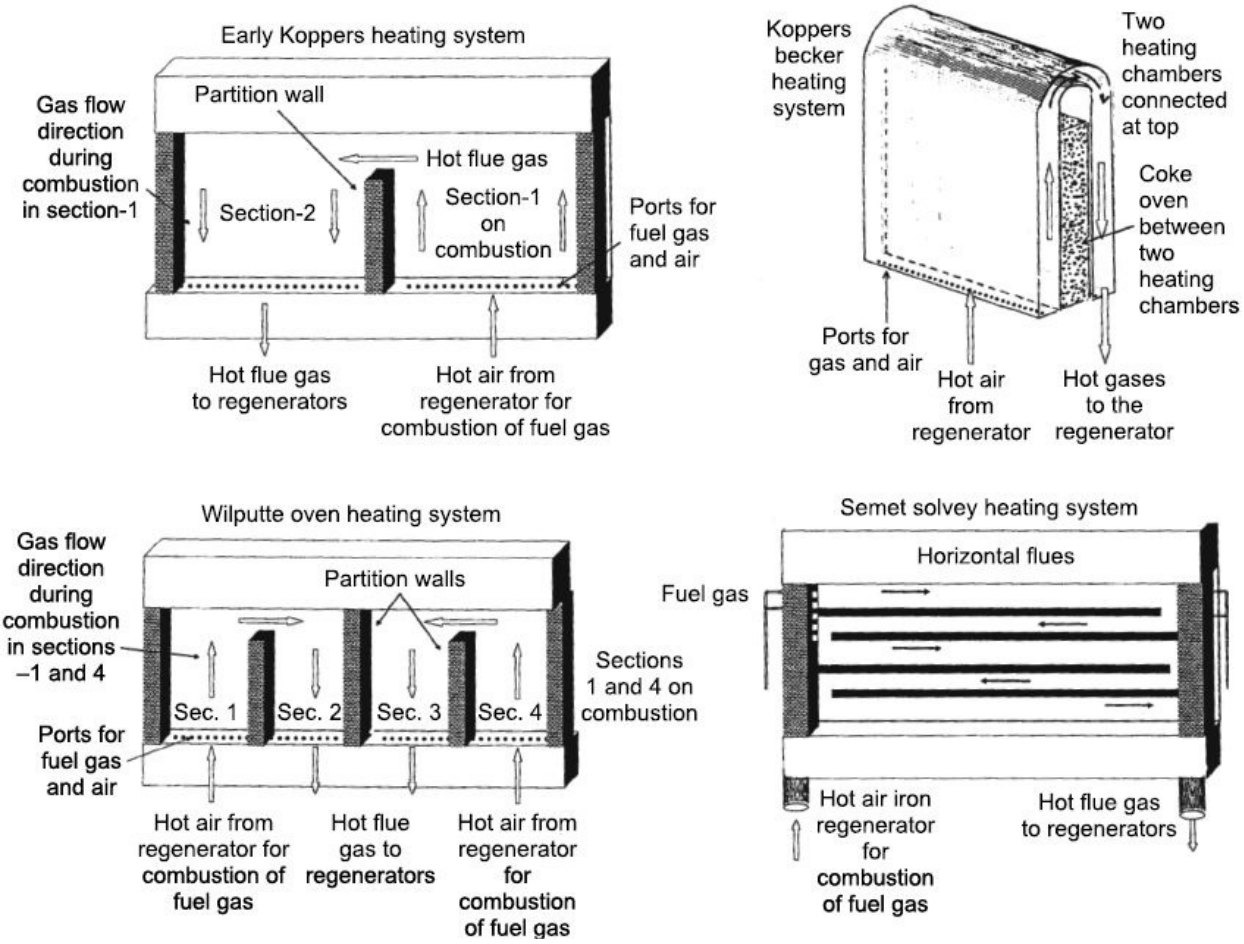


Figure 2.27 Various types of flues in heating chamber of by-product coke oven.

In the Wilputte oven system, the combustion chamber is divided in four segments. The combustion occurs in vertical flues located in outer segments and hot gases move though central segment. This movement of gases is reversed after certain period to cause combustion in central segment and move out from outer segments.

In Copper Becker oven system, the combustion chamber is not divided in segments, but the two nearby heating chambers are inter-connected from top end. In one part of the combustion cycle, the gas and hot air is combusted in vertical flues in one of the heating chamber and the hot gases escape through adjoining heating chamber. This cycle is reversed after certain period to keep uniform temperature in both heating chambers.

In Semet Solvey oven system, the flues are horizontal and the gas and air combusting in top part travel along the chamber in zigzag fashion to get discharged at lower end of the chamber. This direction of gases is reversed after certain period.

The production of good quality coke requires high temperature ~ 1200 °C. which is provided by burning gaseous fuel in the heating chambers. The temperature fluctuation in the range ± 50 °C (Figure 2.28) is practical in view of size and reversal sequence of the fuel burning operation.

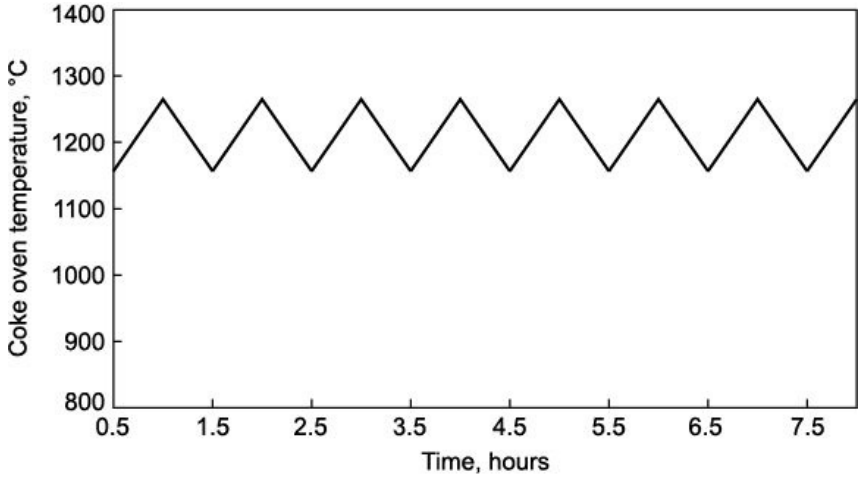


Figure 2.28 A typical coke oven temperature profile with time.

(iii) Regenerators: The regenerators are heat exchanging device to recover heat from outgoing hot gases and use it for pre-heating the incoming cool air to get high temperature in the combustion chamber. There are set of twin firebrick chambers located below the heating chambers which are called regenerators (Figure 2.29). When one chamber is getting heated by the outgoing gases the other keeps supplying stored thermal energy to the incoming cool air. It is common to have regenerators for pre-heating air. The coke oven gas is not pre-heated as it may cause cracking of larger hydrocarbon-molecules into lower ones rendering loss of heating value with carbon deposition in the bricks. The fuel gas like blast furnace gas or producer gas may be pre-heated as these do not contain hydrocarbon molecules.

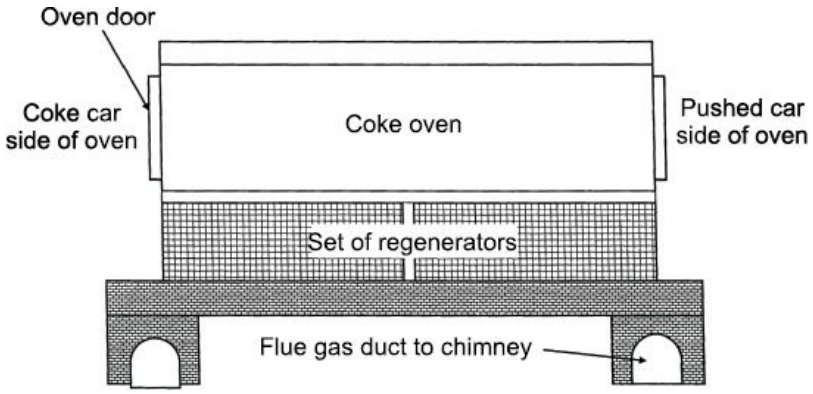


Figure 2.29 Location of regenerators in by-product coke oven.

The service conditions in the regenerator need refractoriness, resistance to alkali attack and good thermal conductivity. The fireclay brick with slotted shape is used to have larger surface area for heat absorption and delivery.

(iv) Coal charging system (top charge/stamp charging): The *top coal charging* is common in earlier designed coke ovens. It is done from top using a charging car. These charging cars have number of hoppers matching to number of top charging holes. The hoppers have arrangement to discharge a weighed amount of coal in the oven. The charging car moves on rails built at the top of the coke oven and it can locate itself over any coke chamber when needed. These charging cars receive coal stored in a tall coal bin located at the end of the oven battery.

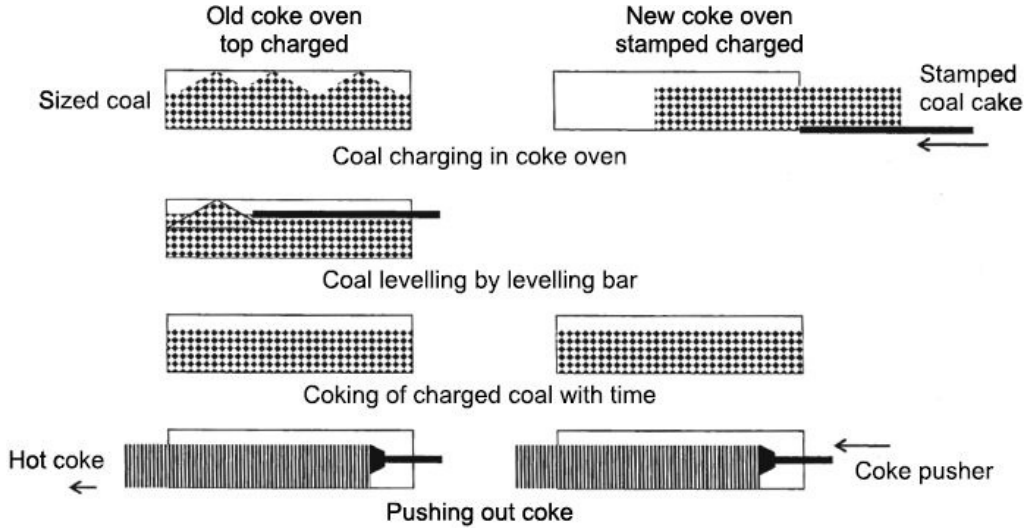


Figure 2.30 Coal charging methods and coke pushing in the by-product coke oven.

The modern coke ovens use *stamp charging* technique. In this method, the coal is fed on to a stamp charging car which has a box matching the dimensions of the coke chamber. The coal charge fed in the box is subjected to stamping by several hammers which are raised and dropped over coal to compact it into a green cake. The coal particles get interlocked due to compaction and have sufficient strength to be pushed into the empty coke chamber mechanically from the pusher end of the oven.

(v) Pusher car: The pusher car is a giant machine moving on the pushing end of the coke oven battery. Normally, one pusher car can serve a battery, but for a battery having large number of ovens two pusher cars may be needed. This machine performs several functions like opening/closing coke chamber door, levelling coal charge in top charged ovens and pushing hot coke out from coke

chamber.

(vi) Coke guide: The coke guide is a steel box with two open ends to guide the hot coke to fall in the coke quench car parked in its front. This coke guide moves on a car along the coke oven battery on the coke side.

(vii) Self sealing oven doors: The coke chambers are closed at both ends by self sealing doors. These doors fit in the grove in such a manner that leakage of gas is avoided. These doors are opened and placed by pusher machine at pusher end and by coke guide at the coke discharge end. The good door maintenance renders leak free service. The badly damaged doors are replaced by a new door. A lower percentage leaking doors (PLD Index) indicate good plant working.

(viii) Gas collection pipes: The volatile matter evolved from coal during heating process is collected by network of valves and pipes. These volatile matter is treated for recovery of several coal chemicals, tar and coke oven gas.

(ix) Coke quenching unit: The hot coke discharged from the coke chamber is received in a coke quench car for cooling. There are two methods of cooling the hot coke: (a) Wet method and (b) Dry method. These two methods are discussed as follows: *Wet Quenching.* This method uses water shower to cool the hot coke. The system consists of a quenching station where the coke quench car is located and heavy water shower fitted in the station cools the hot coke. The heat energy (~1 GJ/ton coke) is lost in the form of steam which is equivalent to nearly 240 kWh power for every ton of coke. This method is very commonly used in old units due to its merits though the present laws discourage and prohibit for new installations. Its merits and limitations are as follows: **Merits**

(i) Easy in operation and

(ii) Requires low capital investment

Limitations

(i) Consumes large quantity of water which is undesirable

(ii) Creates air pollution

(iii) Loses all the thermal energy

(iv) The coke gets wet and needs time to dry

Coke Dry Quenching (CDQ) Method: This method uses air or nitrogen to cool the hot coke and the thermal energy of hot coke is recovered to generate power. The method of cooling consists of transferring coke car to the CDQ station which is a tall chamber. The hot coke (1000–1050 °C) is fed in the tall chamber and the air tight doors of the chamber are closed and air or nitrogen is circulated through hot coke to cool it. In case of using air,

which is cheaper than nitrogen gas, its oxygen is converted into carbon monoxide, carbon dioxide and nitrogen mixed gas consuming insignificant amount of carbon in coke. The hot gas resulting from cooling is circulated through heat exchanger (boiler tubes) to generate steam for power production. The coke cooled to 200–250 °C is discharged out from the chamber. The CDQ method is shown schematically in Figure 2.31.

The CDQ method has merits and limitations as follows:

Merits

(i) Recovers coke thermal energy for power generation

(ii) Delivers dry coke

(iii) Avoids air pollution

(vi) Avoids use of water which is expected to be in scarce supply in coming time

Limitations

(i) Requires high capital investment

(ii) Installation possible with new plants due to design constrains

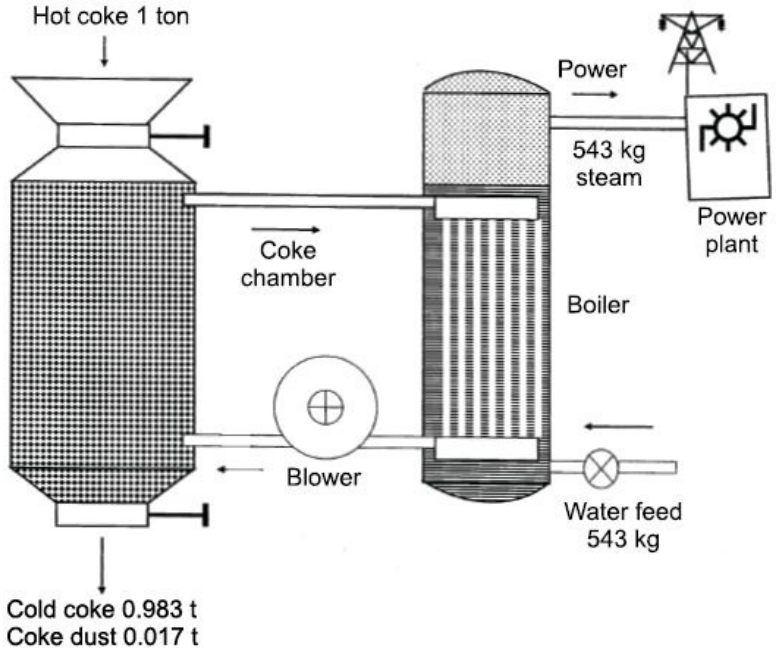


Figure 2.31 Coke Dry Quenching (CDQ) method.

(b) Coke oven operations

The production operation of a top charged by-product coke oven involves four steps: (i) Coal charging in oven, (ii) Coal bed levelling, (iii) Coal carbonisation

in oven, and (iv) Pushing out coke (Figure 2.30). In case of stamp charged coke oven, the stamped green coal cake is pushed in the oven through pusher side door and the number of operational steps are reduced to only three: (i) Coal Charging, (ii) Coal Coking and (iii) Coke pushing out.

(c) Coking process

The coking process in a by-product oven is shown schematically for a single oven in
Figure 2.32. The Stage I in Figure 2.32 depicts the condition of coal after it is charged in the oven and few minutes have lapsed. It can be seen that a thin layer of coke (C) is formed close to the wall surface, since the temperature is high (> 1000 °C). Next to the coke layer lie a semi-coke (S) layer as the temperature at this point is lower (> 600 °C) than the coke layer. Adjoining the semi-coke layer the zone is plastic (P) in nature (~ 400–500 °C) and in the
core of the oven, the coal charge (G) remains unchanged (< 400 °C) as this zone of the oven is still not heated. The heat flowing through the walls by conduction takes time to reach the interior zones.

As the time progresses, the interior zones are heated (Stage II) and more coal gets converted to coke. The middle zone is the last to get heated and coked. As a result of coking (Stage III) there is shrinkage in volume which is needed to push out coke easily from the oven. This shrinkage is evident as median crack (M) in the hot coke emerging out from coke oven. This median crack (M) location in the middle of the oven is indicative of its uniform heating from either sides. Thus, we find that coal undergoes changes during the coking process. These are summarised as follows: 0 –300 °C Evolution of moisture and volatile matter (G)

400 –500 °C Conversion of coal into a plastic mass (P)
500 –600 °C Conversion of plastic mass into semi-coke (S)
600 –1200 °C Conversion of semi-coke to coke (C)

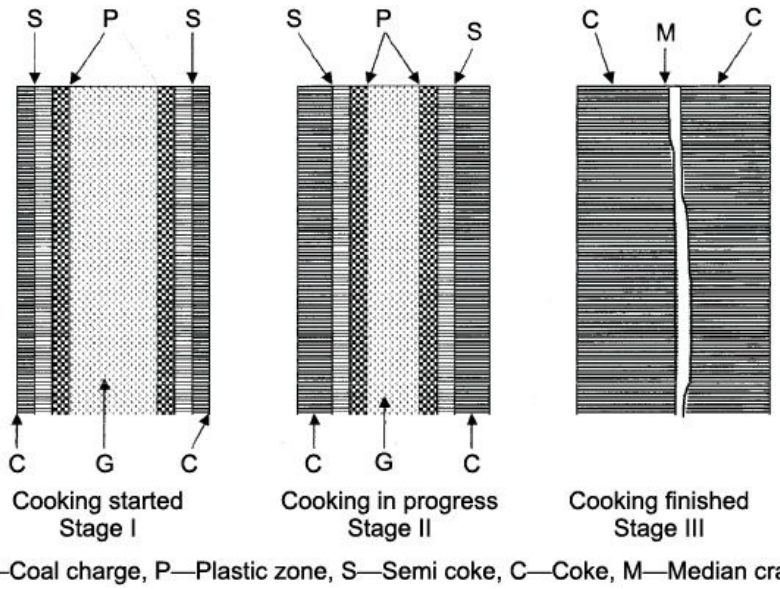


Figure 2.32 Coking process in a by-product coke oven heated from either side.
(Adopted from R.C. Gupta, *Theory and Laboratory Experiments in Ferrous Metallurgy* , PHI Learning, Delhi, 2010.)

During these changes, the plastic stage is very important. When the coal is solid, the gases can move easily, but when it turns plastic, the movement of gas gets restricted. This restricted gas movement due to highly plastic layer may cause pressure on the oven walls which is undesirable. Further, if the plastic mass is too fluid, it may come out alongwith gases on the top of coal bed as froth and get solidified in the upper zone of the oven which is exposed to high temperature. The solidification of coal froth will yield *sponge coke* with low strength. This is a undesirable condition. Thus, the optimum plastic behaviour of coal is required for good coking practice.

(d) Pre-carbonisation coal treatments as modern coking practice

The bulk density of the coal charge is an important parameter to decide the coke quality and oven productivity. The high bulk density of the coal charge enhances the throughput of the ovens with better quality coke. This bulk density is affected by the following techniques: (i) Selective coal crushing

(ii) Coal pre-heating
(iii) Coal briquette blending
(iv) Coal stamping

These aspects are described briefly as follows:

(i) Selective coal crushing: In this method, the coal is crushed in two stages to finer size in a manner such that particles below 0.2 mm are generated in minimum quantity while crushing the bulk coal to –3.2 mm size. This two stage

crushing avoids over crushing of vitrinites in the coal and thus, the coke properties are improved.

In the crushing process, vitrinites and exinites are softer constituents and get easily crushed while the harder inertinites and mineral matter need intensive crushing. This selective crushing is thus done in two stages. The coal crushed after first stage to coarser size is screened to remove –3.2 mm fraction containing mostly easily crushable vitrinites bearing particles. The second stage involves crushing the remaining coal particles containing harder constituents in coal to –3.2 mm size. This method has been found to give better quality coke.

(ii) Coal pre-heating: In this technique, the coal is pre-heated to 300^{o} C with an aim to remove free moisture to improve the bulk density of the charge. The coal is heated to a temperature just below the threshold of thermal decomposition temperature. This method can offer a coal bulk density of 800–850 kg/m^3 against the conventional value of about 700 kg/m^3 .

The coke produced with pre-heated charge has been found to yield coke with lower fines having M10 index lowered from 12–15% to 9–11%. This method also helps in using poorly caking coals for blending.

(iii) Coal briquette blending: In this method, the coal fines are compacted to briquette form and then blended partially with fine coal to enhance the density of the charge. The tar and pitch is added to coal as binder to make briquettes using briquette roll press to have enough strength for handling. The blending of 50% briquettes has been found to give bulk density in the range of 740–800 kg/m^3 .

(iv) Coal stamping: In this technique, the coal fine below 3.2 mm size is compacted using

10 ± 1% moisture to prepare a compact mass coherent enough to handle as green cake and introduce in the oven from pusher side door. The stamping operation is done by a special machine known as SCP (Stamp Charging cum Pusher) machine. The coal blend from coal bunker is obtained in the box fitted in SCP machine where a number of hammers are actuated to compact the coal mass into a coherent mass called ‘coal green cake’. The coal particles are held together by interlocking without any binder. The stamped green coal cake may have bulk density

1050–1150 kg/m^3 . The resulting coke by such technique has improved quality in terms of CRI (25.4–24.5%), CSR (57–59.5%) and Micum Index M_{10} (7–8%).

Table 2.11 gives a comparative view of all four techniques.

Table 2.11 Comparative View of Modern Pre-carbonisation Treatments to Coal

Parameter	*Conventional*	*Selective Crushing*	*Pre-heating*	*Briquette Blending*	*Stamping*
Feed coal size (–3.2 mm wt.%)	78–80	98–100	78–80	78–80	89–91
Additives	0.2% LDO	0.2% LDO	–	8–10%% Pitch/tar	–
Moisture	6–8%	6–8%	–	–	8–11%
Coal charge bulk density	700–750 kg/m ^{3}	650–700 kg/m ^{3}	800–850 kg/m ^{3}	750–800 kg/m ^{3}	1050–1150 kg/m ^{3}
Coke M $_{10}$ index	10–11	9–10	8–9	8.5–9.5	7–9
Coke M $_{40}$ index	77–80	78–79	79–81	79–81	80–81
Coking time*	100	100	80–85	105–110	110–115
Coke throughput*	100	96–98	110–115	105–110	112–115
Oven maintenance*	100	105–110	150–175	105	110–115

* Relative to conventional practice.

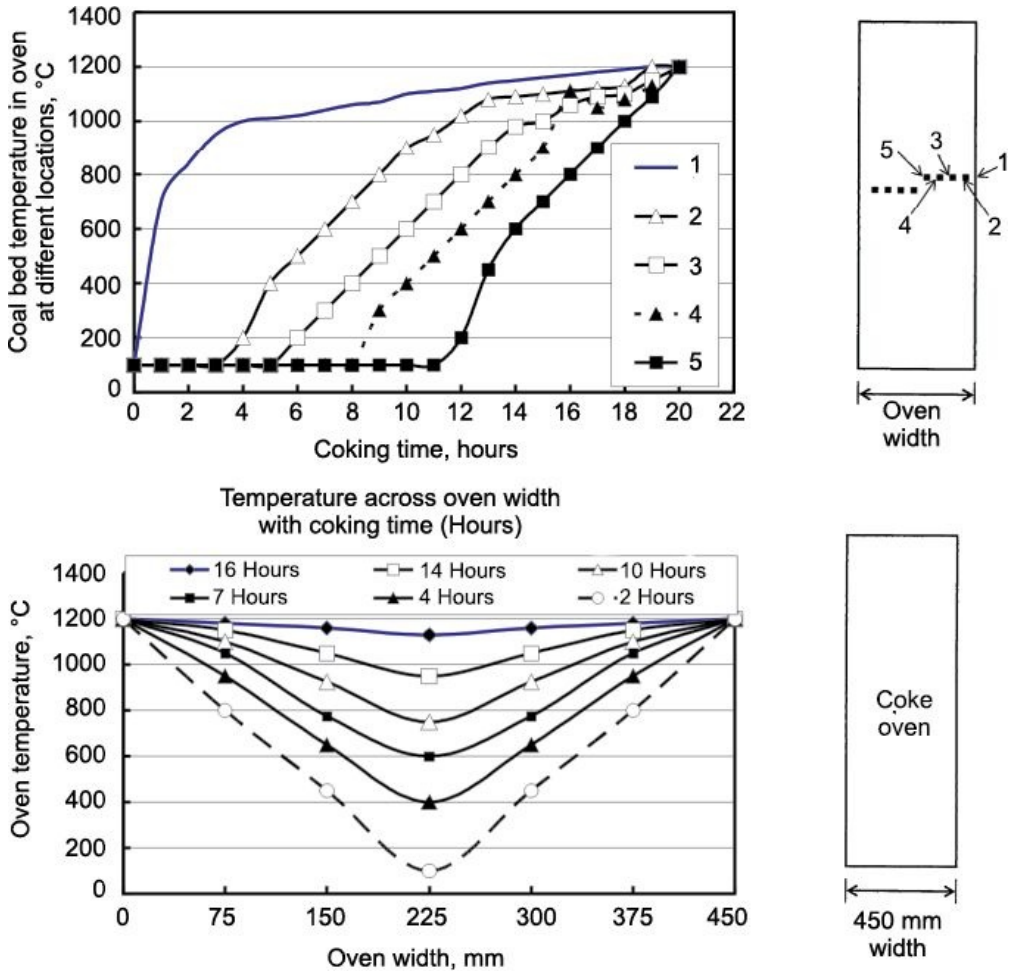


Figure 2.33 The thermal profile of coal charged in coke chamber with time.

(e) *Heating of coal in the oven*

The coke oven is maintained at high temperature 1200 ± 50°C. The coal charged in the hot coke oven chamber starts getting heated by conduction process in the outer layers coming in refractory contact. This heat travels to the interior layers of coal by conduction and convection through escaping hot volatile matter. The coal being a poor conductor of heat, the interior layers of coal are heated slowly. Figure 2.33 shows the temperature rise in a coal bed along the width of the oven with coking time. It may be observed that the central part of the coal bed is fully heated after several hours of time. The coking usually is completed in 12–18 hours depending on the width of the oven. The wider oven takes longer to coke than narrower. A thumb rule of one hour for 25 mm thick layer coal is considered normal.

(f) Coal charging and coke discharging sequence

The coke oven chambers are numbered in a given battery. The two adjoining chambers are never charged or discharged in sequence as this will cause heavy thermal demand from adjoining heating chambers causing fall in oven temperature and damage to refractory. All the charging and discharging is done keeping a good gap in the running and fresh charged oven. A common method of '3+' sequence is adopted.

Consider a battery having 40 coke chambers, then the sequence of charging would be charging oven number 1 followed by oven number 11, 21 and 31 giving a gap of 10 ovens to avoid heavy thermal demand in nearby ovens. After charging 31st oven, next oven to
be charged would be 4th(1 + 3) oven followed by 14th(11 + 3), 24th(21 + 3) and 34th(31 + 3) oven. The next oven to be charged would be 7th(4 + 3), 17th(14 + 3), 27th(24 + 3) and 37th (34 + 3) oven followed by 10th, 20th, 30th and 40th. Further sequence would be 3rd, 13th, 23rd and 33rd and likewise continued till all 40 ovens are charged. The discharging of remaining ovens would follow the same sequence. The complete coke discharging sequence for a typical 40 oven battery is shown below.

1	11	21	31
4	14	24	34
7	17	27	37
10	20	30	40
3	13	23	33

6	16	26	36
9	19	29	39
2	12	22	32
5	15	25	35
8	18	28	38

(g) Coke quality with oven temperature

The coking temperature is found to have significant affect on the coke properties. We have discussed in Section 2.8.4c that coking coal undergoes changes when heated in absence of air. The low temperature carbonisation (~600°C) yields semi-coke. Further, carbonisation at higher temperature (1200°C) coke is obtained. The carbonisation temperature causes chemical and physical changes in coke. These changes are highlighted here.

(i) Effect of carbonisation temperature on composition (chemical change): The increasing carbonisation temperature causes removal of volatile matter in coke. This is associated with removal of nitrogen, hydrogen and oxygen content in coke. Such removal of gaseous constituents renders enrichment of carbon content as illustrated in Figure 2.34. The good metallurgical coke needs high carbon with low volatile matter which is obtained by carbonising coal at higher temperature (>1200°C).

(ii) Effect of carbonisation temperature on graphitisation (structural change): The higher carbonisation temperature is found to affect the carbon structure causing lowering of interlayer spacing of <002> plane (*d* -value) and enhancement of crystallite diameter. These structural changes cause change in chemical reactivity of carbon. The carbon reactivity towards CO_2 , vital for gasification in blast furnace, is lowered with increasing carbonisation temperature. This aspects is further explained in Section 2.10.2.

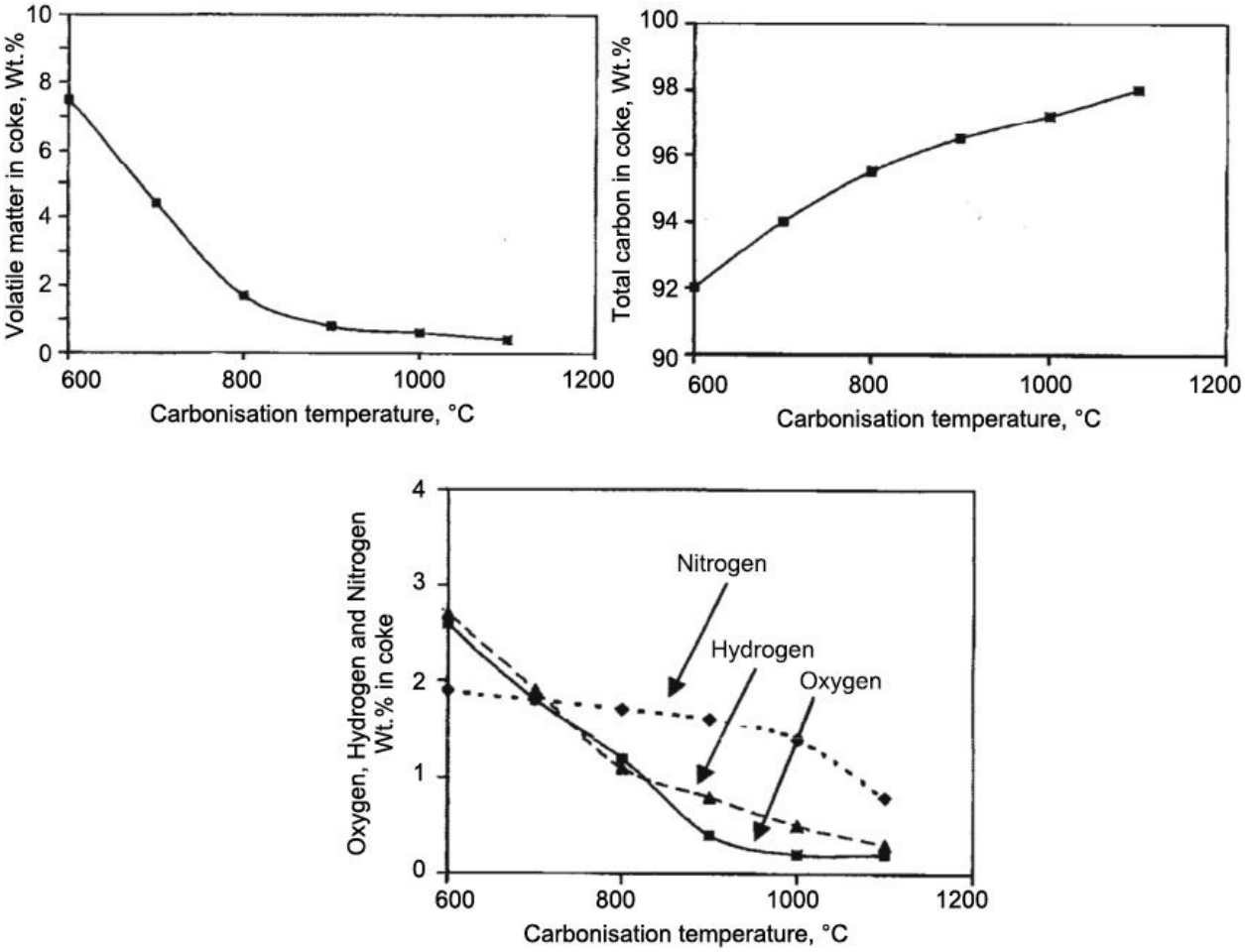


Figure 2.34 Effect of coke carbonisation temperature on the coke chemical analysis.
(Adopted from R.C. Gupta, *Theory and Laboratory Experiments in Ferrous Metallurgy* , PHI Learning, Delhi, 2010.)

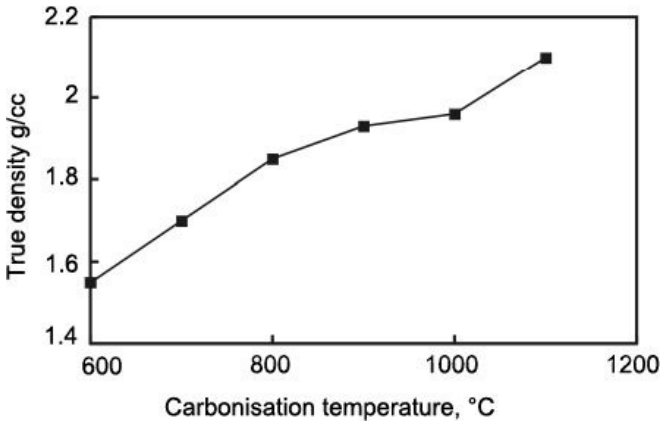


Figure 2.35 Effect of coke carbonisation temperature on the coke true density.
(Adopted from R.C. Gupta, *Theory and Laboratory Experiments in Ferrous Metallurgy* , PHI Learning, Delhi, 2010.)

(iii) Effect of carbonisation temperature on density (physical change): The increasing carbonisation temperature causes densification of the carbon layers in

the structure rendering lowering of interlayer spacing (d-value). This enhances the true density of the carbon in coke as shown in Figure 2.35.

(iv) Effect of carbonisation temperature on porosity (physical change): The carbonisation temperature causes removal of volatile constituents when the coal is in plastic state. This removal of gaseous constituents causes porosity in coke on solidification from plastic state. The total porosity or true porosity is found to increase with coking temperature as shown in Figure 2.36.

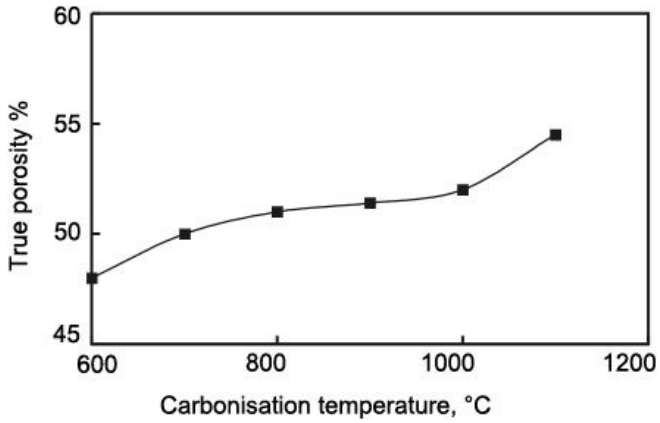


Figure 2.36 Effect of coke carbonisation temperature on the coke true porosity.
(Adopted from R.C. Gupta, *Theory and Laboratory Experiments in Ferrous Metallurgy* , PHI Learning, Delhi, 2010.)

2.9 COKE PROPERTIES AND TESTING

The coal carbonisation at high temperature yields coke. The coke is a hard carbonaceous porous mass having cellular structure. The freshly produced coke piece looks silvery in appearance with irregular shape and size. Some coke pieces give metallic sound on being struck. The coke pieces obtained from beehive oven appear as irregular columns having nearly 600 mm length. The by-product oven coke pieces are always smaller than half the oven width and maximum coke size ranges between 200–250 mm. The non-recovery coke ovens also yield coke with size ranging 200–300 mm. The coke produced is routinely tested for various properties to regulate its quality. These tests conducted routinely on the coke produced in the plant are described as follows.

2.9.1 Coke Appearance

The coke oven operator keeps a visual watch on the colour, shape and size of the coke obtained from each oven and maintains a record by comparing some standard pieces kept in his office. The detailed investigation may proceed on

observing any deviation in the pattern.

2.9.2 Cell Size

The coke is porous carbonaceous mass. The pores are partitioned by solid carbon wall termed as ‘cell wall’. The largest dimension of the pore is called ‘pore size’. These are shown schematically in Figure 2.37. This pore size and cell wall thickness could be observed in a coke piece by cutting it using steel blade or disc cutter. The plain coke surface is cleaned to remove dust particles in the pores and crevices using brush and air blow. This plain coke surface is given a coat of ‘Plaster of Paris’ slurry and allowed sometime to harden it. The surface is then cleaned with sand paper to remove the excess ‘Plaster of Paris’ and reveal black and white structure. The pores and cell wall could be easily viewed with a magnifying glass to compare with the standard sample.

The cell wall thickness plays role in offering strength to the coke. This wall thickness becomes more important during carbon reacting with carbon dioxide during its gasification process inside blast furnace and the remaining wall gets thinner and thinner. The coke strength after the reaction is reduced and it is measured as ‘coke strength after reaction’ (CSR test).

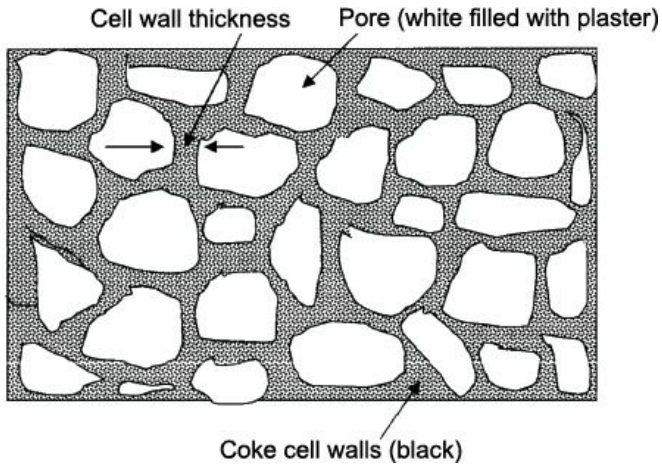


Figure 2.37 Coke section cut and pores filled with white plaster to reveal the pore shape and size (schematic).
(Adopted from R.C. Gupta, *Theory and Laboratory Experiments in Ferrous Metallurgy* , PHI Learning, Delhi, 2010.)

2.9.3 Coke Size

The separation of coke pieces produced from the ovens for various sizes is done by using stationary grizzly. The bigger coke pieces (40–50 mm size) are useful for blast furnace applications depending on their size. The smaller coke pieces (–

40 mm) are useful for mini-blast furnaces and many other applications. The coke size fractions yielded by coke oven are expressed in percentage.

In industry, it is common to use terms like ‘egg’ (50–75 mm), ‘stove’ (30–50 mm), ‘nut’
(18–30 mm), ‘pea’ (9–18 mm) and ‘breeze’ (< 9 mm) for various size fractions, though there is no standard for such terminology.

2.9.4 Coke Porosity

The coke possesses pores of different sizes and nature. The porosity affects the coke quality by providing surface area for reaction between carbon and carbon dioxide gas. The pore volume and size affect the strength of the coke.

The *pores and cavities* in coke could be differentiated on their length to diameter ratio. The pores have longer length and their length to diameter ratio is more than the cavity. The coke particles possess pores of different nature as open pores, interconnected pores and sealed pores. These pores and their nature is different as given below: (i) *Open pores* have one of their ends on the outer surface of the coke particle. This open end allows the movement of gas to the interior location of the coke, permitting chemical reaction. The coke with less porosity is ideal for use in blast furnaces as it will keep gasification reaction slow to retain after reaction strength of the coke for longer duration till the coke reaches near raceways in the blast furnace.

(ii) *Interconnected pores* have both of their ends opening to the outer surface of the coke particle. This allows a free movement of gas and offers site for chemical reactions. Such pores offer higher coke gasification rate and hence are not very much desired in coke pieces.

(iii) *Sealed pores* are deep seated and do not open up to the surface of the coke particle. These sealed pores do not offer any site for chemical reaction.

The coke porosity is easily measurable by boiling water method. The *porosity test* procedure is as follows:

A piece of solid dry sample is weighed in air (W_1). This solid material is then dipped in boiling water for 30 minutes. The boiling action will cause expansion of air bubbles trapped in the pores and cause its expulsion. Once the heating is stopped, the water cools and enters into the pores to fill it completely. The weight (W_2) of the water saturated sample is taken while dipped fully under

water (Figure 2.38). The sample is now taken out and surface water is removed by soaking with cotton cloth. The weight of water saturated sample is taken in air (W_3).

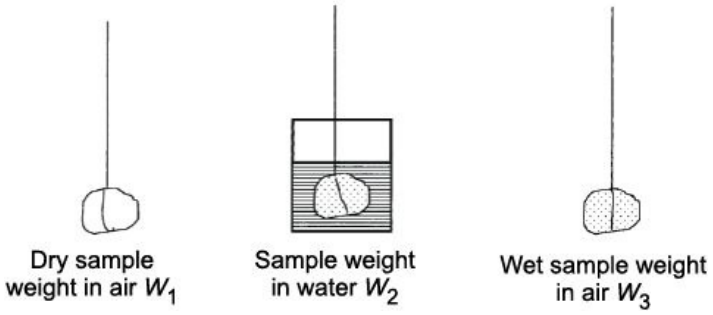


Figure 2.38 Determination of apparent density and porosity.
(Adopted from R.C. Gupta, *Theory and Laboratory Experiments in Ferrous Metallurgy* , PHI Learning, Delhi, 2010.)

Now, the weight of water absorbed in open pores = $W_3 - W_1$ g
or volume of water absorbed in open pores = $(W_3 - W_1) \times \rho$ cc
where, ρ is the density of water.

The loss in weight of the sample due to buoyancy while being dipped in water
$= (W_3 - W_2)$ g
or the volume of sample $= (W_3 - W_2) \times \rho$ cc

Hence, the Apparent porosity (%) $= \dfrac{W_3 - W_1}{W_3 - W_2} \times 100$

As it is known that the true porosity (%) $= 100\left(1 - \dfrac{\text{App. density}}{\text{True density}}\right)$

The sealed porosity (%) = (True porosity – Apparent porosity)%.

This is a simple, direct and accurate method to determine apparent porosity. The procedure for knowing apparent density and true density is given elsewhere (Gupta, R.C., *Theory and Laboratory Experiment in Ferrous Metallurgy* , PHI Learning, p. 45, Delhi, 2010).

2.9.5 Coke Analysis

The coke obtained is tested for its constituents to assess its quality by the following two methods:

(i) Ultimate analysis and
(ii) Proximate analysis.

The procedure for testing is same as that for coal given in sections 2.5.1 and

2.5.2.

2.9.6 Coke Strength

The coke strength is very important for its use in metallurgical furnaces. The coke is handled, transported, stored and charged in furnace mechanically. In all these operations, the coke particles breakdown to smaller particles which is undesirable. The coke particles breakdown by impact forces caused by dropping during handling coke and by shearing force (wearing) during movement. The coke is tested for its ability to sustain impact and wear actions by (i) Shatter test (Impact strength) and

(ii) Tumbler test (Wear strength)

These two tests are described below:

Shatter test (impact strength)

(i) Equipment

It consists of a steel box with open top and drop bottom. The base plate is in two half hinged at one end with a locking latch in the middle to be held as ‘closed’ or ‘drop open’ position. This box is fitted at a height of 2 meters above the base plate made of thick steel supported on steel frame (Figure 2.39).

(ii) Test procedure

The coke pieces weighing 34 kg bigger than 50 mm is collected as sample to represent the batch. None of the coke piece should pass through a 50 mm screen in any position. Out of this sample, 22.7 kg is selected for the test. The test sample (22.7 kg) is dropped 4 times on steel plate from a height of 2 meters and the surviving material is sized by using 50 mm,
37 mm, 25 mm and 12 mm screens and weighed.

$$\text{Shatter Index \%} = \frac{\text{Weight of coke surviving bigger than 50 mm}}{\text{22.7 kg coke of + 50 mm size}} \times 100$$

However, the better practice would be to report material weight (%) on all screens (50, 37, 25 and 12 mm) to give a better picture of the coke strength.

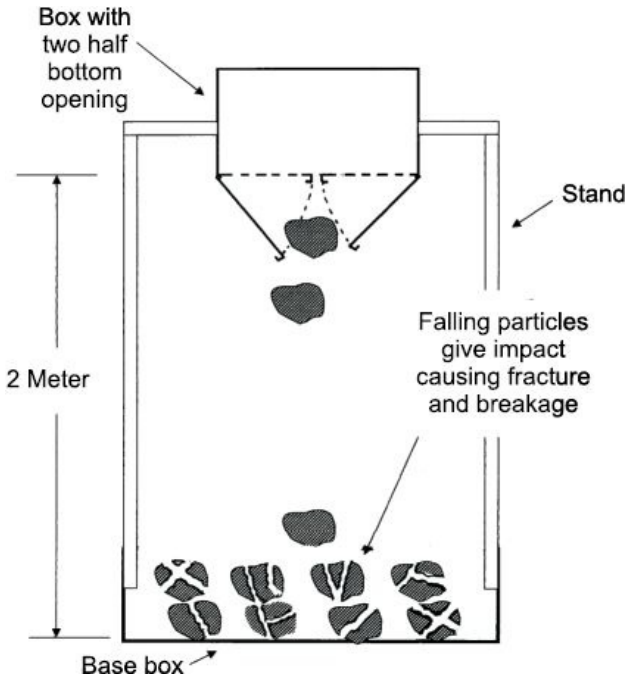


Figure 2.39 Shatter test (schematic).
(Adopted from R.C. Gupta, *Theory and Laboratory Experiments in Ferrous Metallurgy* , PHI Learning, Delhi, 2010.)

Tumbler test (wear strength)

The tumbler strength which is indicative of generation of fines due to abrasion is also taken as strength due to impact in substitute to shatter strength. The material to be tested is held in a drum fitted with two or four lifters (Figure 2.40).

(i) Equipment

The equipment is a rotating drum fitted with lifter made of steel plate. The diameter and width of the drum depend on the test specifications. When the drum is rotated, the coke moves up due to frictional force and tends to slide down by gravity. This coke movement causes wear due to abrasion. The lifter (projecting plate) pushes coke piece and carries it to a height till it slides and falls over coke pieces at drum bottom. During free fall, it causes impact and renders breaking of particle into smaller fragments (Figure 2.41). The process continues during drum rotation period. After given time, the size fraction of surviving particles is weighed to know its behaviour.

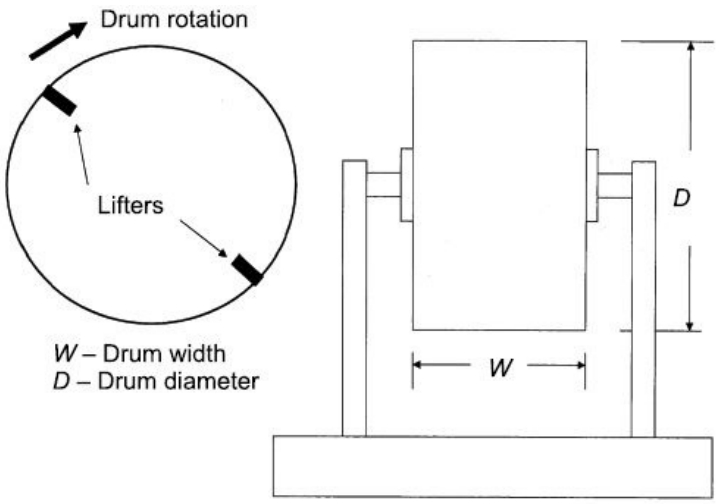


Figure 2.40 Rotating drum for testing tumbler index.
(Adopted from R.C. Gupta, *Theory and Laboratory Experiments in Ferrous Metallurgy* , PHI Learning, Delhi, 2010.)

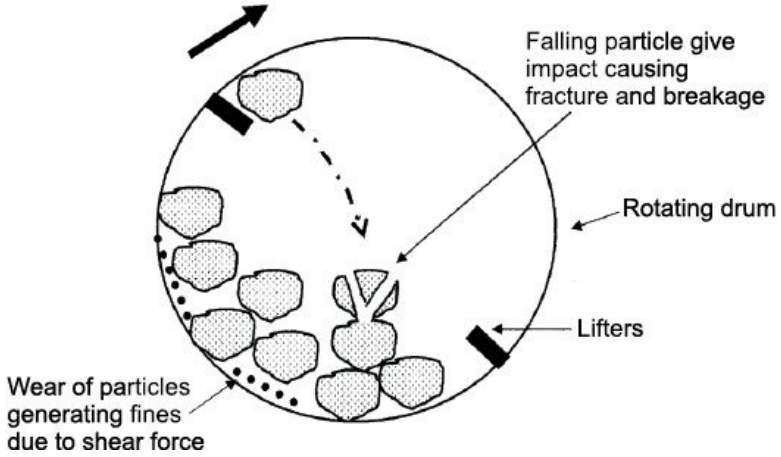


Figure 2.41 Application of impact and shearing force during drum testing.
(Adopted from R.C. Gupta, *Theory and Laboratory Experiments in Ferrous Metallurgy* , PHI Learning, Delhi, 2010.)

(ii) Test methods

There are various methods which are in practice to test tumbler index for coke. These are described as follows:

ASTM method: The test consists of selecting 11.3 kg coke sample (–75 to +50 mm size) and testing 10 kg sample in a drum (900 mm dia. and 450 mm wide) fitted with 2 lifters
(50 mm size). The drum is rotated at 24 rpm for 1400 revolutions. The coke is then sized by 50, 37, 25, 13 and 6.3 mm screens. The strength is reported as:

$$\text{Stability factor} = \frac{\text{Weight (kg) coke retained on 25 mm screen}}{\text{10 kg (Initial wt.)}} \times 100$$

$$\text{Hardness factor} = \frac{\text{Weight (kg) coke retained on 6.3 mm screen}}{\text{10 kg (Initial wt.)}} \times 100$$

Micum test **:** In this method, 50 kg coke sample (–75 to +50 mm size) is tested in a drum (1000 mm diameter and 1000 mm wide) fitted with 4 lifters (100 mm size). The drum is rotated at 25 rpm for 100 revolutions and the product is sized by 60, 40, 20 and 10 mm screens and weighed. The strength values are represented as:

$$\text{Micum 40 } (M_{40}) \text{ Index} = \frac{\text{Weight (kg) of coke retained on 40 mm screen}}{\text{50 kg (Initial wt.)}} \times 100$$

$$\text{Micum 10 } (M_{10}) \text{ Index} = \frac{\text{Weight (kg) of coke passing 10 mm screen}}{\text{50 kg (Initial wt.)}} \times 100$$

The higher value of M_{40} is indicative of good resistance to impact while higher value of M_{10} is indicative of poor resistance to abrasion. A coke with high M_{40} and low M_{10} value would be appreciated for use in blast furnace. The Micum 40 (M_{40}) index represents the tumbler index while the Micum 10 (M_{10}) index indicates abrasion index. These two indices (M_{40} and M_{10}) are found to change linearly with shatter index as shown in Figure 2.42.

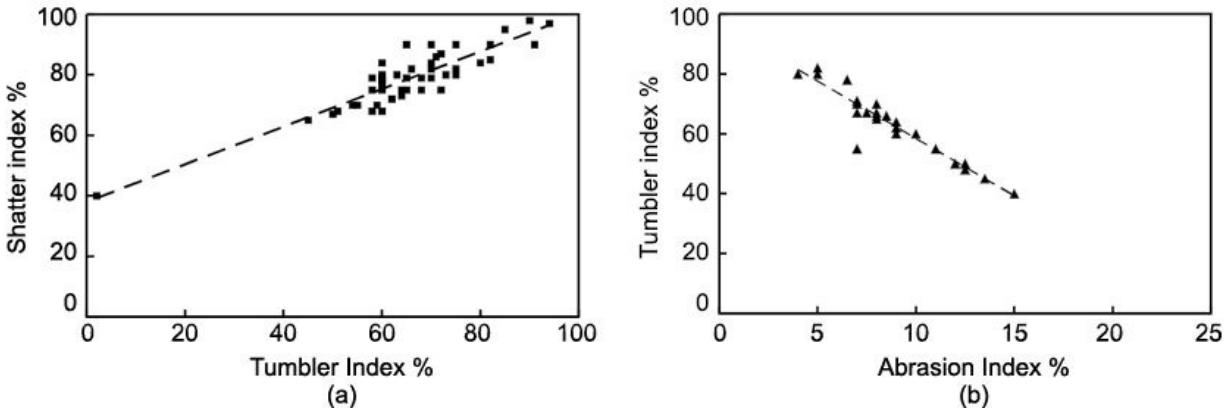


Figure 2.42 (a) Linear relationship between Shatter index vs. Tumbler index and (b) Tumbler index vs Abrasion index.
(Adopted from R.C. Gupta, *Theory and Laboratory Experiments in Ferrous Metallurgy* , PHI Learning, Delhi, 2010.)

IRSID method **:** This method, suggested by Institut de Recherches de la Siderurgie (IRSID), France, has been accepted as ISO method to test coke strength. This method is identical to Micum except it selects smaller size (20 mm) coke. The strength is represented as IRSID Index.

$$\text{IRSID 20 } (I_{20}) \text{ Index} = \frac{\text{Weight of coke retained on 20 mm screen}}{\text{50 kg (Initial sample wt.)}} \times 100$$

$$\text{IRSID 10 } (I_{10}) \text{ Index} = \frac{\text{Weight of coke passing 10 mm screen}}{\text{50 kg (Initial sample wt.)}} \times 100$$

2.9.7 Coke Strength after Reaction (CSR)

The strength of coke is minimised due to reaction of cell wall carbon with CO_2 gas to generate CO gas. If this happens rapidly, then the cell wall thinning may cause breaking of coke under load at high temperature. In order to assess this behaviour of coke, Nippon Steel Corporation of Japan has developed a method to test the reactivity of coke (CRI) alongwith coke strength after reaction (CSR).

For this purpose, 240 kg sample is collected from the coke oven wharf which is reduced to 10 kg sample weight by following standard sampling method. This 10 kg sample is crushed to 20 mm size and 200 gm coke sample is taken and placed in a reaction tube having CO_2 gas (5 litres per minute) flow at 1100°C for 2 hours. The remaining coke after cooling is weighed to get Coke Reactivity Index (CRI) value. The coke sample remaining after reaction is then fed into an I-shaped drum (130 mm dia. and 700 mm long) hinged at middle of its length. The drum is revolved for 30 minutes at 20 rpm speed. The product material is sieved using 9.52 mm screen. The values of CRI and CSR is calculated as follows:

$$\text{IRSID 20 } (I_{20}) \text{ Index} = \frac{\text{Weight of coke retained on 20 mm screen}}{\text{50 kg (Initial sample wt.)}} \times 100$$

$$\text{IRSID 10 } (I_{10}) \text{ Index} = \frac{\text{Weight of coke passing 10 mm screen}}{\text{50 kg (Initial sample wt.)}} \times 100$$

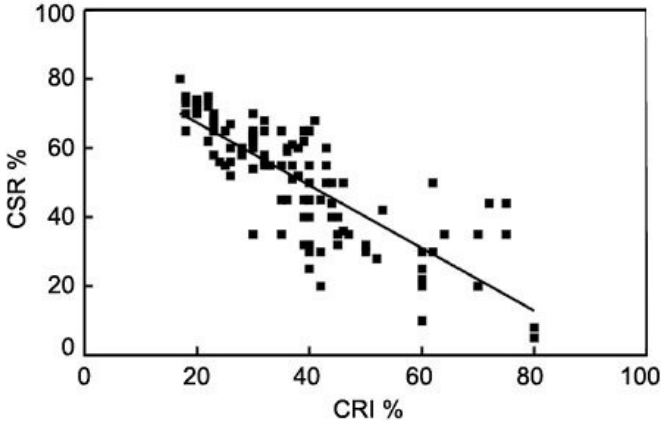


Figure 2.43 Correlation between CSR% and CRI% of coke.
(Adopted from R.C. Gupta, *Theory and Laboratory Experiments in Ferrous Metallurgy* ,

PHI Learning, Delhi, 2010.)

A correlation of CRI(%) and CSR(%) is shown in Figure 2.43 to indicate that highly reactive coke (high CRI%) possesses poor coke strength (low CSR%) after reaction.

2.9.8 Coke Reactivity

Carbon reacts with oxidising gases like carbon dioxide and steam to yield gases like CO and H_2 .

$$C + CO_2 \times 2CO$$

$$C + H_2O \times CO + H_2$$

The *coke reactivity* is a measure of the rate at which coke carbon is able to react to get converted into carbon monoxide gas. The coke reactivity is important for its gasification to carbon monoxide to be used as gaseous reducing agent in metallurgical furnaces. The coke reactivity differs from coke combustibility.

The *coke combustibility* refers reaction of carbon with oxygen to yield CO_2 gas with heat.

$$C + O_2 \rightarrow CO_2$$

The coke combustibility aims to produce maximum heat due to carbon burning with generation of carbon dioxide gas as a waste product.

The carbon present in different forms like graphite, coal, coke, charcoal, etc. react differently because of carbon structure which is not same in all the forms of carbon. Like any chemical reaction, the rate of carbon reaction will be influenced by temperature, surface area and rate of gas flow and it is necessary to keep all the reaction parameters identical to be able to see the effect of carbon structure on its ability to react with carbon dioxide. It is, therefore, necessary to understand the carbon structure before discussing the test procedures

2.10 CARBON STRUCTURE AND ITS REACTIVITY

In this section first the carbon structure will be explained before describing the reactivity test procedures in order to understand fundamentals involved.

2.10.1 Carbon and its Structure

The element carbon (atomic weight 12 and valence bond 4) occurs in nature as mineral (graphite and diamond), fossil fuel (anthracite, bituminous and lignite), biomass (wood) and living organisms (hydrocarbons). Various types of carbon forms are prepared for use like wood char, coke, pitch, etc. The crystal structure of carbon, carbon graphitisation and effect of temperature on its structure are discussed below.

Crystal structure of carbon

The crystal structure of two commonly known forms of carbon as diamond (cubic) and graphite mineral (hexagonal layered) is shown in Figure 2.44. The diamond is inactive form of carbon and graphite is the least reactive form of carbon. The structure of coal, coke, wood char, etc. is not perfect graphitic. The layer of carbon atoms are not plane as in graphite, instead it is broken and imperfect as shown in Figure 2.45. This imperfect structure is known as 'turbostratic'. The carbon dioxide reacts with carbon of coal/coke/wood char with different intensity according to their degree of imperfection in the structure.

Carbon graphitisation

Carbon occurring as hydrocarbons in nature is set free with four valence bonds when heated to nearly 500°C. The carbon at this stage is present in amorphous form (e.g. lamp black) which could be taken as micro-crystallites of carbon. These carbon micro-crystallites are basic structural unit (BSU) of carbon which arrange themselves into various structures with increasing temperature as shown in Figure 2.45.

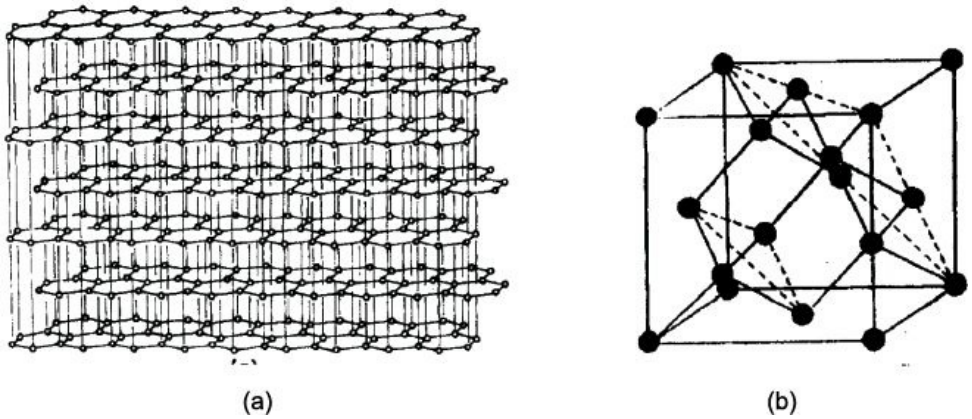


Figure 2.44 Crystalline forms of carbon (a) Graphite (hexagonal layered), (b) Diamond (cubic). (Adopted from R.C. Gupta, *Theory and Laboratory Experiments in Ferrous Metallurgy* , PHI Learning, Delhi, 2010.)

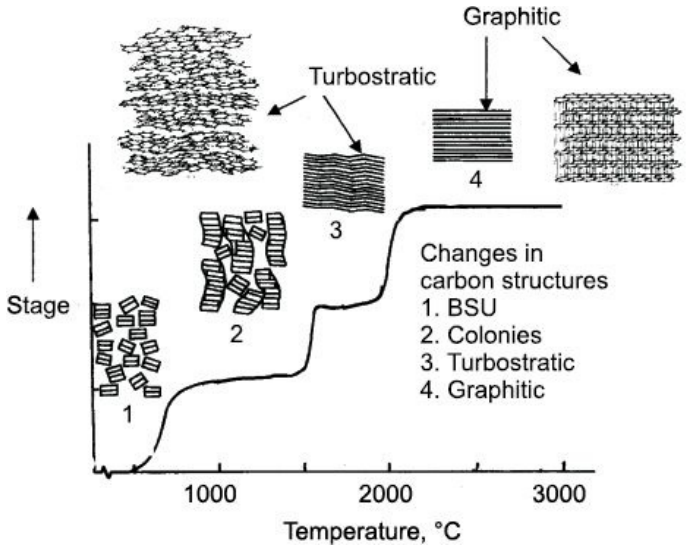


Figure 2.45 Structural changes in carbon due to heating temperature.
(Adopted from R.C. Gupta, *Theory and Laboratory Experiments in Ferrous Metallurgy* , PHI Learning, Delhi, 2010.)

As the temperature exceeds 500 °C these BSU's form colonies by agglomeration process. These colonies of BSU's get more organised when temperature exceeds 1200 °C, as turbostratic structure. This turbostratic structure resembles graphitic structure with broken hexagonal planes. On further rise in temperature, beyond 2000 °C, the graphitic structure will be obtained. The simultaneous application of pressure would result these transformation at lower temperature. The graphitic carbon when exposed to very high pressure and temperature gets transformed to diamond (cubic form).

In nature, every coal has undergone different exposure of temperature, pressure and time resulting into different stage of graphitisation (i.e., coalification). The reactivity of these different types of coal would depend on their structural (atomic) features.

A unit cell of graphite is shown in Figure 2.46 which has certain layers of graphite to give crystallite height (L_c). The graphite layer spread gives its size as crystallite diameter (L_a). The gap between two graphite layers (d_{002}) is termed as inter-layer spacing and is indicative of packing density of carbon layers. The value of d_{002} for graphite is 0.335 nm which represents most dense packing.

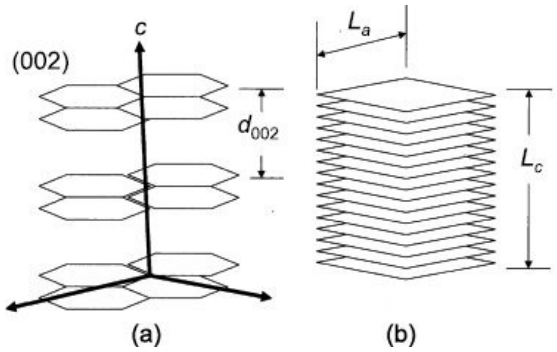


Figure 2.46 A unit cell of graphite.
L_c – Crystallite height, L_a – Crystallite diameter and d_{002} – Interlayer spacing.
(Adopted from R.C. Gupta, *Theory and Laboratory Experiments in Ferrous Metallurgy* , PHI Learning, Delhi, 2010.)

Effect of temperature on carbon structure

The carbon undergoes structural changes due to increasing temperature. The carbon layer packing becomes denser with decrease in interlayer spacing (d_{002}), while crystallite height (L_c) and crystallite diameter (L_a) increases as the temperature of carbonisation is raised. These changes are shown in Figure 2.47.

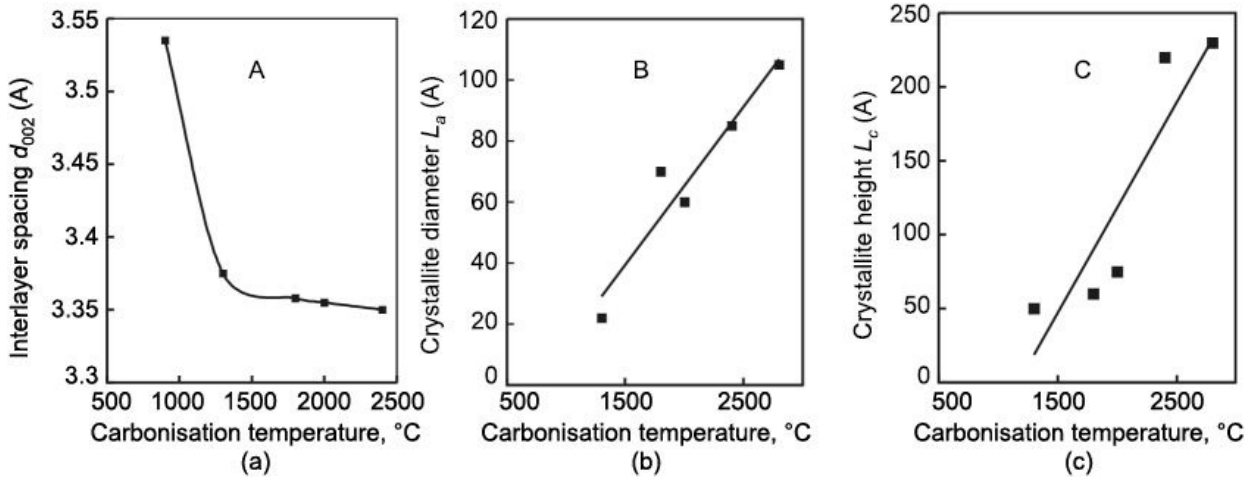


Figure 2.47 Effect of carbonization temperature on graphite lattice parameters for a typical Indian coking coal: (a) Interlayer spacing ($\boldsymbol{d}_{002}$), (b) Crystallite diameter ($\boldsymbol{L}_a$) and (c) Crystallite height ($\boldsymbol{L}_c$).
(Adopted from R.C. Gupta, *Theory and Laboratory Experiments in Ferrous Metallurgy* , PHI Learning, Delhi, 2010.)

2.10.2 Carbon Structure and its Gasification Rate

When a carbonaceous material is exposed to oxidising gas (CO_2 or O_2), the carbon tends to react and form gaseous product (CO or CO_2) provided it is available for reaction. The carbon atomic arrangement in a plane is shown in Figure 2.48. The carbon atoms in the interior are bonded by four atoms (three in

same plane and one in lower plane) and hence, it is not able to react with CO_2 or O_2 molecules. However, the carbon atom at the edge (active site) is bonded by only three atoms (two in same plane and one in lower plane) leaving one valence bond free to react with CO_2 or O_2 gas. This implies that a structure with more number of active sites (edges) will be reacting faster than structure having less number of active sites. The number of active site will be more in graphite crystallite with smaller crystallite diameter (L_a) and larger inter layer spacing (d_{002}) values. Such reactive structure is offered by carbon heated to lower temperate rendering higher reactivity as shown in
Figure 2.49.

Thus, we find that carbon gasification is affected by its graphitic structure which in turn is affected by its formation process parameters.

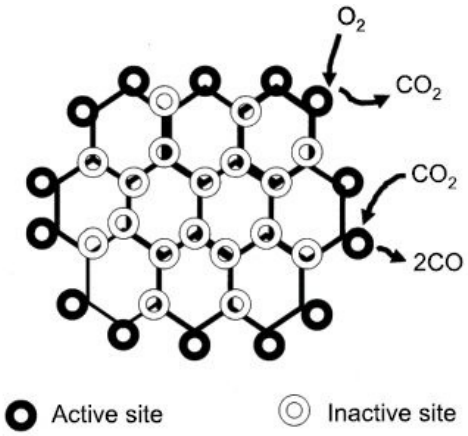


Figure 2.48 Active sites for reaction with oxidising gases in graphite layer.
(Adopted from R.C. Gupta, *Theory and Laboratory Experiments in Ferrous Metallurgy* , PHI Learning, Delhi, 2010.)

2.10.3 Carbon Reactivity Determination Techniques

It has been explained that the reactivity is a measure of rate at which carbon can be reacted by carbon dioxide or water. The reactivity of carbon in various forms can be determined by using four different techniques. The procedure followed in steel plant has more practical approach to assess the coke and testing method is designed to virtually simulate working conditions in the furnace. The methods followed by research workers are basic and fundamental in principle. The testing methods followed under these two approaches are: Practical Method Used by Steel Plants

(i) Coke Reactivity Index (CRI) Test

Basic Methods Used by Research Workers

(i) Thermo-gravimetric Technique (TG)

(ii) XRD Technique

(iii) True Specific Gravity Test

These four techniques are described in following sections.

(i) Coke Reactivity Index (CRI) Test

This test method, developed by Nippon Steel, Japan, has become very common amongst blast furnace operators to assess the coke quality.

The test is conducted on larger size (20 ± 1 mm) coke pieces. The coke sample (200 g) is kept in a reactor tube having flow of carbon dioxide gas (5 litres per minute flow) for two hours at 1100 ± 5 °C. The weight of residual coke is taken after cooling and reactivity is calculated as

$$\text{CRI}(\%)=\frac{\text{Loss in coke weight}}{\text{Initial coke sample weight}}\times 100$$

The higher percent of CRI is indicative of its high reactivity which is not good for blast furnace applications as coke after reaction strength value (CSR%) is lowered and it would break during use causing operational difficulty. The correlation between coke reactivity index (CRI%) and coke strength after reaction (CSR%) has been shown in Figure 2.44 while discussing after reaction coke strength (CSR).

(ii) Thermo-gravimetric Technique (TG)

In this method, the carbon sample (powder/lump) is taken in a thermo-gravimetric (TG) set-up [Figure 2.49(a)] and then heated under inert atmospheric condition (argon flowing gas). The dry carbon dioxide gas (800 ml/min) is admitted in the system to react with the carbon at the reaction temperature (say 900 °C). The change in weight is noted with reaction time till 95% weight loss occurs or 120 min reaction time lapses.

A typical fractional weight loss plot with time is shown in [Figure 2.49(b)]. The reactivity at any given gasification temperature is calculated as:

$$R=\frac{1}{W}\frac{dW}{dt}$$

where,

R is the reactivity of carbon (mg min^{-1} mg^{-1} or min^{-1})

W is the initial sample weight on dry ash free basis (mg) and

dW/dt is the change in sample weight with time (mg min^{-1})

during 20–80% weight loss period.

In literature, the reactivity is sometimes expressed as per second (s^{-1}). A typical TG study on the carbonisation of wood chars (gasification temperatures 900 °C and 960 °C) is shown in Figure 2.49(b). The reactivity of wood char was found to decrease with increasing carbonisation temperature (Figure 2.50) when studied in the range of 400 °C to 1200 °C. This decrease in reactivity is due to more graphitisation at higher carbonisation temperature. Table 2.12 gives the reactivity values of some typical carbon/coal/coke used for various applications.

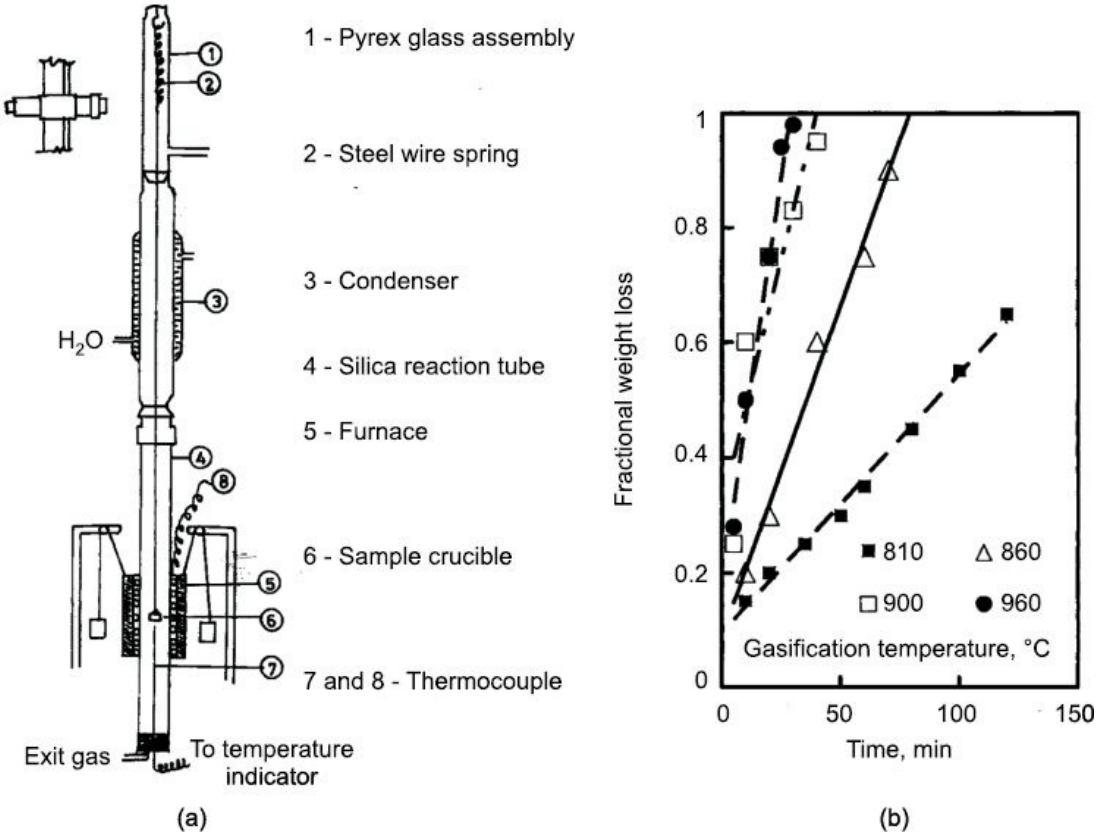


Figure 2.49 TG setup for measuring weight changes with time (a), fractional weight loss during carbon gasification at different temperatures (b).
(Adopted from R.C. Gupta, *Theory and Laboratory Experiments in Ferrous Metallurgy* , PHI Learning, Delhi, 2010.)

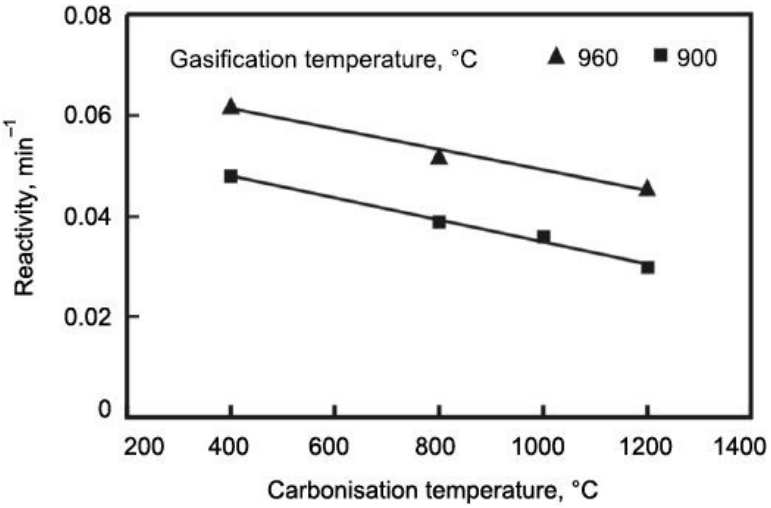


Figure 2.50 Effect of carbonisation temperature on the reactivity of some typical wood chars. (Adopted from R.C. Gupta, *Theory and Laboratory Experiments in Ferrous Metallurgy* , PHI Learning, Delhi, 2010.)

Table 2.12 Reactivity of Some Forms of Carbon

Forms of Carbon	*Carbon Reactivity*		*Qualitative Reactivity*
	$\times 10^{-4}$ s^{-1}	$\times 10^{-3}$ min^{-1}	
Lignite Char	3–33	18–198	Most reactive
Wood chars	1.6–10	10–80	Highly reactive
Activated char	1.5	9	
Coconut char	0.3–2	1.8–12	
Bituminous coal High Volatile	1–2	6–12	Reactive
Bituminous coal High carbon (C ~ 80%)	0.2–1.8	1.2–10.8	
Anthracite (C ~ 92%)	0.3–1.2	1.8–7.2	Less reactive
Coke	0.1–0.5	0.6–3.0	
Graphite	0.03	0.18	Least reactive

(iii) XRD Technique

In this method, a powdered (–90 μm, i.e., –170 mesh) sample is taken for XRD studies in the angular (2θ) range of 6–90° at a scanning speed of 3° min^{-1} in 2θ . Nickel-filtered Cu k_{α} radiation (λ = 0.1541841 nm) with tube operating at 30 kV and filament current of 20 mA. The diffraction profile could be obtained on the chart. The chart speed, count per second and time constant could be 30 mm min^{-1} , 200 s^{-1} , and 10 s respectively. In modern units, most of the functions are automated.

The changes in (002) diffraction profile with carbonisation temperature of

some chars are shown in Figure 2.51 which indicates the formation of more graphitised carbon (sharper peak) with increased temperature. The interlayer spacing (d_{002}) indicating the packing of carbon layers could be estimated by using equation:

$$n\lambda = 2d_{002}\sin\theta$$

where,
λ is the X-ray wavelength
and θ is the Bragg's angle.

The micro-crystallite diameter L_a could be calculated using Warren's equation

i.e., $$L_a = \frac{1.84\lambda}{B\cos\theta}$$

where, B is breadth at half-maximum intensity in radians.

Due to the breath of the peak its precise position determination becomes difficult and may cause error in d_{002} values. Similar difficulties are encountered in estimating L_a values.

The effect of increasing carbonisation temperature on increasing L_a value for some chars is shown in Figure 2.52. Figure 2.53 shows the lower reactivity of the char with increasing L_a values. This implies that measurement of L_a values could be useful in estimating reactivity from the literature values.

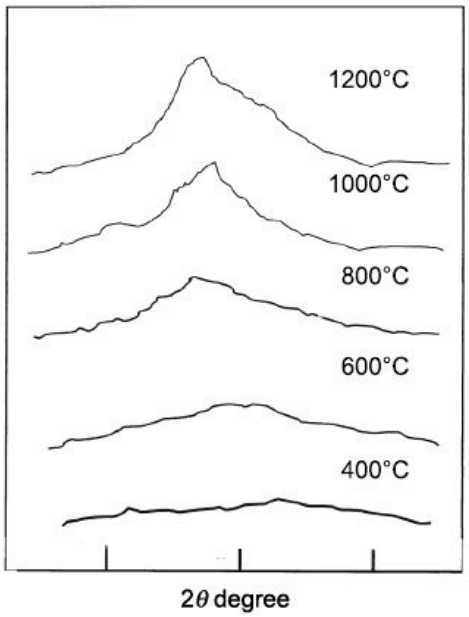


Figure 2.51 Effect of carbonisation temperature on the changes in (002) diffraction profile (schematic) for some chars.

(Adopted from R.C. Gupta, *Theory and Laboratory Experiments in Ferrous Metallurgy* , PHI Learning, Delhi, 2010.)

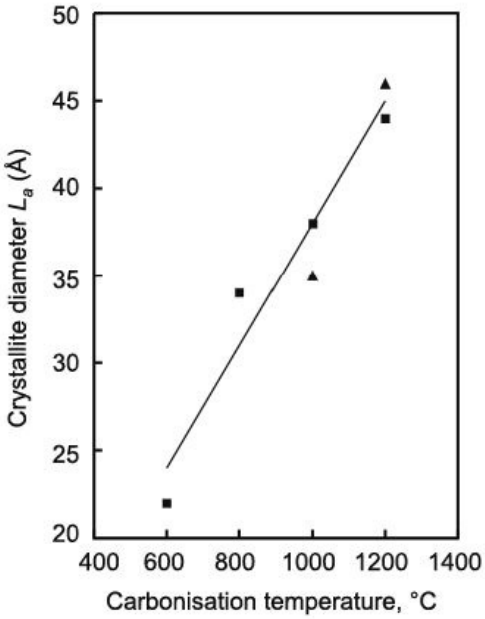


Figure 2.52 Effect of carbonisation temperature on the micro-crystallite diameter (L_a) of some wood chars.

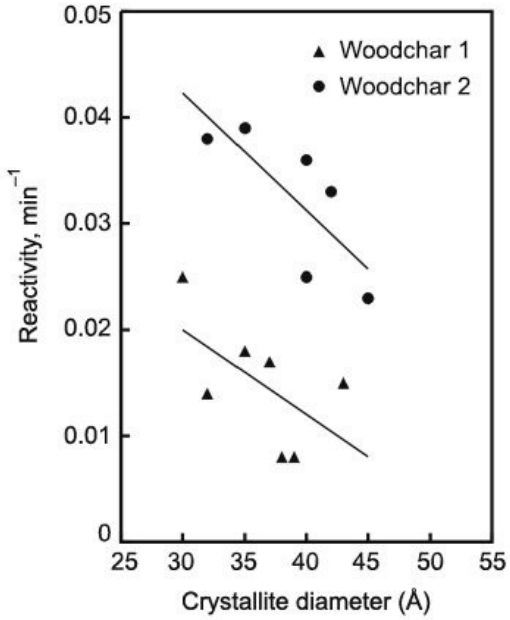


Figure 2.53 Correlation between micro-crystallite diameter (L_a) and reactivity of carbon for some wood chars.

(Adopted from R.C. Gupta, *Theory and Laboratory Experiments in Ferrous Metallurgy*, PHI Learning, Delhi, 2010.)

(iv) True specific gravity test

It has been shown in Figure 2.35 that the true density of coke increased with carbonisation temperature. This is due to decrease in interlayer spacing (d_{002}) of the carbon with increased carbonisation temperature. The high density carbon structure would exhibit lower reactivity. It may be cautioned here that the presence of ash in coke would affect its density measurement and comparing data could be difficult.

2.11 COKE OVEN EMISSIONS

The atmospheric pollution due to industrial emissions has become an important issue socially and legally. The industries are now required to take care for any kind of environmental emissions to avoid social protest by locals and legal action by the law enforcing agencies.

The metallurgical industries, in general, are classified as highly polluting and highly hazardous industries and remain under the notice of various agencies. The

iron and steel plants discharge various types (solid, liquid and gaseous) of pollutants and in steel plants the coke oven unit is considered as the highest polluting point in view of the nature of its activity.

The emissions occur during coal handling, coal charging, coking operation, coke discharging, coke cooling and treating coal chemicals. These aspects are summarised in Table 2.13 for three different coke making methods.

Table 2.13 Emission Sources during Coke Making by Different Coking Techniques

Point of Emission (Particulates, Gases and Liquids)	*Beehive Coke Oven Small Scale Units* ~ 0.03–0.05 mt/yr	*Non-recovery Coke Oven (Modified Beehive Oven) Medium Scale Units* 0.05 < 1 mt/yr	*By-product Coke Oven Large Scale Units* > 1 mt/yr
During handling coal	High dust discharge due to manual/semi mechanical operations	Controlled dust discharge due to mechanical coal handling systems	Less dust discharge due to mechanical handling with dust controllers
During feeding coal in oven	Dust and volatiles are fully discharged in air causing Serious air pollution	High dust and VM discharge in *top car charged* ovens Very less emission in *stamped cake charged* ovens from front	High dust and VM discharge in *old type* top car charge system Very less emission in *new type* stamp charging
During coking in coke oven	Heavy emission of gases from open top and leaking doors	Less emission expected from doors as the system works under negative pressure.	Minor emission from doors and top due to leaking joints (it works under positive pressure)
During coke discharging	Manual coke pulling out Heavy emission of heat and gases	Mechanical coke pushing: Heavy emission of heat and gases	Mechanical coke pushing Heavy emission of heat and gases
During coke cooling	Wet quenching: Water is sprayed manually on the site giving huge steam emission laden with dust, VOC, SO_2, etc.	Wet quenching: Spray of water on hot coke held in coke car. All the steam with VOC and sulphur fumes escape to air High emission of toxic gases.	*(Old) wet quenching:* spray of water on hot coke held in coke car. All the steam with VOC and sulphur fumes escape to air. *(New) dry quenching:* close circuit gas cooling with heat recovery boilers. No emissions of toxic gases
Waste gas discharge	All VOC, NO_x, sulphur, ammonia etc get discharged in air Highly polluting	Exit hot gases are burned in boiler to get power causing burning of VOC. The exit gases contain NO_x, CO_2 and SO_2. This SO_2 is removable by lime scrubbing. Treatment dependent	Exit gases are treated and limited discharge Emission controlled
While producing coal chemicals in	Not adopted	Not adopted	Adopted and lead to gas and liquid effluents which are treated

the plant			
Overall thermal pollution	Very high	Moderate	Moderate
Suggestion in light of environmental assessment	Should not be adopted	May be adopted with dry quenching of coke and effluent treatment devices	May be adopted with dry quenching of coke and effluent treatment devices

2.12 APPLICATIONS OF COAL IN METALLURGICAL PLANTS

The various applications need coal of required quality. The following sections give the properties of coal needed by different industries.

2.12.1 Coke Making

In view of very stringent chemical and physical properties needed by blast furnace coke, the coal selected for the purpose must have following properties:

(i) Good caking properties

(a) CSN : > 6
(b) MMR (%) : 1.3–1.4
(c) Reflectance R_O Av : 1.23 to 1.35%
(d) Vitrinite (%) : > 60
(e) Fluidity : 300 to 1000 ddpm

(ii) Good grade

(a) Low ash : 8–10 wt.%
(b) Low VM : 21–26 wt.%
(c) Low S : < 0.5 wt.%
(d) Low alkalies : < 0.2 wt.%

The properties of typical important prime coal, medium blendable and Indian non-coking coal is given in Table 2.14 which is used for coke making in an Indian plant.

Table 2.14 Properties of Coal Used by a Steel Plant in India for Making Coke

Coal Properties	*Imported Premium Coal*	*Imported Medium Rank Coal*	*Imported Low Rank Coal*	*Indian Non-caking Coal*
Proximate analysis	9.1	9.2	9.3	20.26

(dry basis) Ash VM	20.1	21.8	24.0	27.89
Crucible Swelling Number (CSN)	8.5	8.5	8.0	0
Maximum uidity ddpm	340	275	480	0
Vitrinite %	67.8	69.6	66.7	4.7
Reflectance R_O %	1.34	1.23	1.16	0.97

2.12.2 Sponge Iron Making in Rotary Kilns

The coal used in rotary kiln sponge iron units is assessed based on following properties:

(i) Proximate analysis

(a) Ash –
- Minimum possible
- Common 20–24%
- Maximum 35% with many problems

(b) VM –
- 20–24 wt.%
- High % – the excess may be unutilised
- Low % – it may not meet energy demand

(ii) Reactivity

Use of less reactive reductant (coke breeze, anthracite coal) helps to operate kiln at higher (~ 1100 °C) temperatures (Figure 2.54), but the highly reactive carbon (lignite char and high volatile coal) provides high productivity (Figure 2.55) due to more working days as ring formation is minimised. In practice, extreme conditions are avoided.

(iii) Ash softening temperature

Minimum – 1050 °C. (Ash softening temperature more than 80–100°C than operating temperature would avoid ring formation)

(iv) Sulphur content

Low sulphur is desirable (Higher than 1% S. should be avoided)

(v) Caking and swelling

Non-caking coals with low swelling nature needed

Caking Index < 5

CSN < 3

(vi) Grain size

for co-current feeding –15 + 6 mm
for counter current feeding –10 + 6 mm
(with minimum % of –1 mm size fraction)

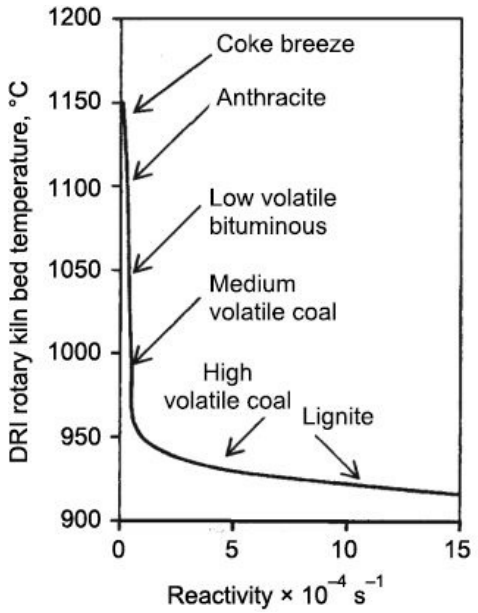


Figure 2.54 Effect of coal reactivity on the DRI rotary kiln operating temperature.

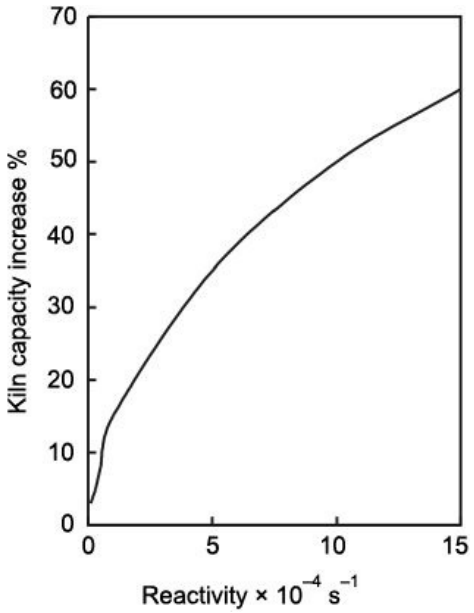


Figure 2.55 Effect of coal reactivity on DRI rotary kiln capacity.

(Adopted from R.C. Gupta, *Theory and Laboratory Experiments in Ferrous Metallurgy* , PHI Learning, Delhi, 2010.)

2.12.3 Smelting Reduction (SR) Process (COREX)

COREX technology for hot iron production requires non-coking coal and oxygen to generate heat and reducing gas. The process can use wide variety of coal as shown in Figure 2.56. In case the high ash and high volatile coal is used, then coal consumption is increased by 3.5% for every 1% VM content and 10–15 kg extra coal for 1% added ash content. The desired and tolerable coal analysis for use in COREX process is given in Table 2.15.

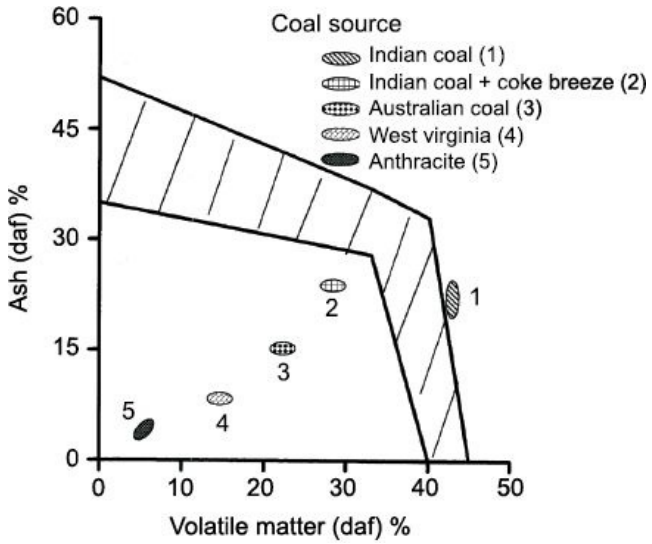


Figure 2.56 Volatile matter and ash content in coals suitable for COREX iron making technology. (Adopted from R.C. Gupta, *Theory and Laboratory Experiments in Ferrous Metallurgy* , PHI Learning, Delhi, 2010.)

Table 2.15 Analysis of Coal Used by COREX Iron Making Unit

Proximate Analysis (wt. % Dry Basis)	*Desirable*	*Tolerable*
Moisture	5–10	10–15
VM	20–30	15–36
Ash	5–12	10–25
Sulphur	0.4–0.6	0.5–1.5
Size mm	5–40	50% + 10 mm

2.13 USE OF COKE FOR VARIOUS APPLICATIONS

The blast furnaces are the major user of best quality coke. The coke used by other units can be of lower grade. The properties of coke needed by different users are discussed as follows.

2.13.1 Blast Furnace

Coke is a very important feed material for the blast furnace. It serves as fuel, refractory and reducing agent. The larger mean size 50–40 mm fraction is fed to the blast furnace. During feeding, it is subjected to number of drops causing impact. It is subjected to compressive force during storage in bin and within the furnace. This compressive force increases as the coke descends down in the blast

furnace stack with increase in working temperature. The coke has to sustain stress at high temperature retaining its shape and size till it reaches the tuyere line where it reacts with air to generate heat and reducing gas. Such strength in coke is derived from the cellular structure of coke. The more cell wall thickness and higher degree of graphitisation would render better coke strength. The cell wall thickness (Figure 2.37) and its graphitisation degree depend on coking process parameters. The coke strength at room temperature is assessed by testing shatter and tumbler strength. The behaviour of coke at higher temperature is assessed by testing coke reactivity index (CRI) and coke strength after reaction (CSR) with CO_2 . It is found that coke with low CRI (~ 20%) possesses high CSR (~ 80%) value. A value of 28% CRI is considered good for blast furnace use offering ~ 60% CSR. The coke with high CRI per cent is not desirable because the coke may loose strength due to its rapid reaction with carbon dioxide and thinning of cell wall to an extent that it may fail much before reaching to tuyere zone where it is needed. Typical blast furnace grade coke properties are given in
Table 2.16.

Table 2.16 A Typical Blast Furnace Coke Properties		
Chemical Analysis	Volatile Material	0.75–2% wt.
	Sulphur	0.65–1% wt.
Physical	Size	50–100 mm
	Porosity	45–49%
Strength	Shatter test (+50mm)	70–78%
Reactivity	CRI%	23–24
After reaction strength	CSR%	64–66

2.13.2 Cupola

The coke used in cupola for melting pig iron is also required to possess good strength and low reactivity. However, due to less furnace height, the after reaction strength is not so important. The properties of a typical cupola coke are given in Table 2.17.

Table 2.17 Properties of a Typical Foundry Coke			
Proximate Analysis (wt. %)		*Physical Properties*	
Volatile material	1.2	True sp. gravity	1.8
Fixed carbon	79	Porosity	45%

Ash	19	Shatter index	83%
Sulphur	0.5	Tumbler index	62%
		Ash softening temperature	1410°C

2.13.3 Water Gas

High temperature coke is needed for preparing water gas ($CO + H_2$) by passing steam through a hot bed of coke. The important property desired by coke is its high reactivity. The low coke strength (CSR%) for high CRI(%) coke (more than 30) is not harmful as the coke bed
remains static and bed height is also less. The high ash in coke is also not harmful as it is discarded at the end. The volatile matter in coke must be less than 7 per cent as it will need gas cleaning to use the product gas.

2.14 NUMERICAL PROBLEMS

2.14.1 Surface Moisture

PROBLEM 1 The coal costing ` 5000/ton on air dry basis was supplied to a industry which got wet during transit by rain. The wet coal weighed 253 ton at the time of delivery. The industry made a deduction of ` 165000 against surface moisture in coal while making the payment. What was the surface moisture percentage in the coal at the time of delivery?

Solution Given,

Coal cost (air dry) = ` 5000/ton
Total coal weight at delivery = 253 ton
The total deduction made for surface moisture = ` 165000
The weight of added moisture (considering charged at coal cost)
= ` 165000 / ` 5000 per ton
= 33 ton (surface moisture in coal due to rain)
Weight of the wet coal = 253 ton
Thus, weight of air dry coal = 253 – 33 = 220 ton
Hence, surface moisture in wet coal = (moisture weight/air dry coal) × 100
= [33/220] × 100 = 15%

The surface moisture in wet coal was 15% wt.

2.14.2 Proximate Analysis

PROBLEM 2 A coal sample weighing 548 g in 'as received' condition was left spread in a tray to air dry for two days. The air dried sample weighing 503 g was ground for proximate analysis test which reported 2.67% inherent moisture, 29.21% volatile matter, 36.64% ash and 31.48% fixed carbon.

Calculate the coal analysis based on:

(i) as received basis

(ii) dry basis and

(iii) dry ash free basis

Solution

Weight of coal sample in as received basis = 548 g

Weight of coal sample in air dry condition = 503 g

Weight of surface moisture removed = 45 g (= 548 – 503)

Surface moisture (%) in coal sample = (surface moisture wt/dry coal wt.) × 100

$$= (45/503) \times 100 = 8.9\%$$

The air dry coal sample analysed as:

Inherent moisture – 2.67%

Volatile matter – 29.21%

Ash – 36.64%

Fixed Carbon – 31.48%

Now, considering 100 g air dry coal sample, the weight of various constituent could be calculated and tabulated as follows:

Table 2.18 Weight of Coal Constituents Calculated as per Coal Condition

Coal Condition	*Weight of Coal Constituents* (g)					
	Surface moisture	*Inherent moisture*	*Volatile matter*	*Ash*	*Fixed carbon*	*Total coal weight*
As received basis	8.9	2.67	29.21	36.64	31.48	108.9
Dry basis	Nil	Nil	29.21	36.64	31.48	97.33
Dry ash free basis	Nil	Nil	29.21	Nil	31.48	60.69

Knowing the weight of various coal constituents and total weight, the percentage constituent could be calculated and tabulated as given in Table 2.19 for various coal conditions.

Table 2.19 Coal Analysis Calculated on Different Reporting Basis

Coal	*Wt. of Coal Constituents* (g)				*Total Coal wt.*	*Coal Analysis wt.%*			
	Total	*Volatile*	*Ash*	*Fixed*		*Total*	*Volatile*	*Ash %*	*Fixed*

Condition	*Moisture (Surface +Inherent)*	*Matter*		*Carbon*		*Moisture (%)*	*Matter (%)*		*Carbon (%)*
As received basis	8.9 + 2.67 = 11.57	29.21	36.64	31.48	108.9	(11.57/108.9) × 100 = 10.62	(29.21/108.9) × 100 = 26.82	(36.64/108.9) × 100 = 33.64	(31.48/108.9) × 100 = 28.98
Dry basis	NIL	29.21	36.64	31.48	97.33	NIL	(29.21/97.33) × 100 = 30.01	(36.64/97.33) × 100 = 37.64	(31.48/97.33) × 100 = 32.34
Dry ash free basis	NIL	29.21	NIL	31.48	60.69	NIL	(29.21/60.69) × 100 = 48.13	Nil	(31.48/60.69) × 100 = 51.87

Hence, coal analysis based on:

(i) As received basis: Total Moisture–10.62%. Volatile Matter–26.82%, Ash–33.64%, Fix Carbon–28.98%

(ii) Dry basis: Volatile Matter–30.01%, Ash–37.64%, Fix Carbon–32.34%

(iii) Dry ash free basis: Volatile Matter–48.13%, and Fix Carbon–51.87%

2.14.3 Coal Blending and Coke Making

PROBLEM 3 A coal blend, containing 60% primary, 30% blendable and 10% imported coal, was charged in a by-product coke oven. Assuming 95% volatile matter and moisture content being removed during coking process. Calculate the coke yield and coke analysis.

The coal used for charging analysed as follows:

Constituents in Coal	*Primary Coal, wt.%*	*Blendable Coal, wt.%*	*Imported Coal, wt.%*
Fixed carbon	55	45.5	69
Ash	20	26	10
Volatile matter and moisture	25	28.5	21

Solution Assuming the total weight of coal blend charge as 1000 kg, the weight of each type coal and its constituents could be calculated and given in Table 2.20 as follows:

Table 2.20 Weight of Constituents in Blended Coal

Constituents in Coal	*Weight of Constituents in Blended Coal – Total* 1000 kg		
	From primary coal	*From blendable coal*	*From imported coal*
Fixed carbon	330 kg	136.5 kg	69 kg
Ash	120 kg	78 kg	10 kg
VM and moisture	150 kg	85.5 kg	21 kg

	Total–600 kg (60% in blend)	Total–300 kg (30% in blend)	Total–100 kg (10% in blend)

The constituents in coke will include 100% fixed carbon, 100% ash and only 5% VM + M as 95% is removed during coking operation. Using these values, calculation of coke analysis is shown in the following table:

Table 2.21 Calculation of Coke Analysis

Constituents in Coke	*Wt. of Coke Constituents in* kg	*Analysis wt.%*
Fixed carbon	100% of [330 + 136.5 + 69] = 535.50	(535.5/756.32) × 100 = 70.80
Ash	100% of [120 + 78 +10] = 208.00	(208/756.32) × 100 = 27.50
VM and Moisture	5% of [150 + 85.5 + 21 = 256.5] = 12.82	(12.82/756.32) × 100 = 1.69
	Total coke wt. after coking in kg = 756.32	100.00

Thus, coke yield = [Wt. of coke/wt. of coal charged] × 100 = [756.32/1000] × 100 = 75.6%

∴ Coke Yield = 75.6 %

Analysis of dry coke: Fixed carbon – 70.80 wt.%,

Ash – 27.50 wt.% and

VM + Moisture – 01.69 wt.%

2.14.4 Coke Oven Design

PROBLEM 4 A by-product coke oven plant having annual production capacity of 3 million ton coke uses good quality coking coal to give 71% yield. The plant uses stamped coal charging technology to make green coal cake having 1 ton/ m^3 bulk density (dry) for feeding in coke ovens. The coke oven chamber is 16.19 m long, 6.3 m high and 540 mm wide. The coking time provided in a oven is 24 hours/batch. The number of coke ovens in one battery is 60. Assuming 340 working days/yr in the plant leaving 25 days for repair and considering 95% of the volatiles including moisture being removed during coking, then, calculate (i) The percentage of volatile matter + moisture in the coal charge

(ii) The amount (ton) of coal used by the plant annually

(iii) The number of coke oven batteries in the plant

Solution

(i) Consider 100 ton raw coal charge

The coke yield = (wt. of fixed carbon + ash left after coking/wt. of raw coal) × 100 = 71% (given)

Or the wt. of fixed carbon + ash = 71 × (100/100) = 71 ton

The wt. of volatile matter and Moisture removed during coking = 100 – 71 = 29 ton

Given that the volatile matter and moisture removed in coking constitute 95% in coal

Then, volatile matter and moisture present in raw coal = 29/0.95 = 30.52 ton

Percentage of Volatile matter + moisture in raw coal = (30.52/100) × 100 = 30.52%

∴ Volatile matter + moisture in raw coal = 30.52%

(ii) Given, the coke yield = 71% = (wt. of coke made/wt. of coal used) × 100

As the wt. of coke made = 3000000 ton/year (given)

Therefore, wt. of coal used = (3000000/71) × 100 = 4225352 ton/year

∴ Coal used per year for coking = 4225352 ton

(iii) Given, coke oven chamber length (L) = 16.19 m

Coke oven chamber height (H) = 6.3 m

Coke oven chamber width (W) = 0.54 m (= 540 mm)

Coke oven chamber volume (V) = $L \times H \times W$

Hence, coke oven chamber volume (V) = 16.19 m × 6.3 m × 0.54 m = 55.078 m^3

Wt. of one green stamped coal cake = Bulk volume (V) × Bulk density

= 55.078 m^3 × 1 ton/m^3 = 55.078 ton

Coking time in one oven is 24 hrs.

Thus, one coke oven uses 55.078 ton coal/day

Hence, coal used per year = 55.078 × 340 days/yr = 18726.52 ton/yr

Or number of coke ovens needed to use 4225352 ton coal/year

= (4225352 ton/18726.52 ton) = 225.6

Number of coke ovens theoretically required = 226 (By rounding the oven nos.)

Since each battery has 60 coke ovens.

Hence, no of batteries required = 226/60 = 3.76 batteries, i.e., ~ 4 batteries (i.e., 240 ovens)

Few extra batteries over theoretical number would help in meeting the coke production in case some ovens are not available for repair/maintenance.

∴ No. of coke oven battery (each with 60 ovens) in the plant = 4

Review Questions

1. How coal was formed in nature? What is meant by biochemical and dynamochemical period of coal formation?

2. What changes in physical and chemical property occur when peat is converted to coal?

3. What do you understand by the terms – type, rank, class and grade of coal?

4. What are petrological constituents in coal? How do they affect its property?

5. What is the difference between ultimate analysis and proximate analysis of coal?

6. Why does coal need classification system? List the various coal classification systems and describe the Indian coal classification system.

7. What are the two different methods of coal analysis? What different constituents are analysed under these two types of coal analysis? Give their utility.

8. What is Dulong's formula?

9. Describe proximate analysis in detail, giving the need of using different crucible type for different constituents. Why a metallic wire tripod is used for keeping volatile matter crucible in the test?

10. How can you test the coal for its suitability for coke making?

11. Describe the changes in coal fluidity with temperature noted by Gieseler plastometer test. How is this test useful in coke making process?

12. How are the coal maximum fluidity and mean reflectance values related? How is this relationship useful in coke making process?

13. How does coal ash fusion behaviour affect its utility?

14. What is the difference between 'gross' and 'net' calorific value of coal? How can you determine these two values experimentally? Describe with the help of neat sketches.

15. What is the difference between 'intrinsic' and 'extrinsic' mineral matter in coal? How do these get incorporated in coal during their formation period? Is it possible to remove them by coal cleaning process?

16. How are the physical properties like colour, fracture and specific gravity of coal constituents useful in coal cleaning process?

17. How does Bradford breaker serve as equipment for coal cleaning and sizing?

18. Why roll crushers are used for coal size reduction? What is the difference in working of roll crusher and hammer mill? Discuss with the help of neat

sketches.

19. What is the utility of Baum Jig? Describe its functioning with the help of neat sketch.

20. Describe the working principle of a vibrating table for coal cleaning. What is the difference between ‘dry tabling’ and ‘wet tabling’?

21. What are the merits and limitations of float and sink method of coal cleaning? Describe ‘Chance process’ of coal cleaning with the help of neat sketches.

22. Why coal storage is necessary in plants? What are the problems associated with coal storage? Give precautions taken for coal storage.

23. Can you make metallurgical coke with every caking coal? Give coal properties required for producing good quality coke.

24. What are the different methods available to make coke? Give a comparative view with their merits and limitations.

25. Describe by-product process of coke making with the help of neat sketches.

26. Describe the coke making process in ‘non-recovery ovens’ and discuss the difference in coal bed heating process in comparison to by-product oven. How can you identify the coke making process by observing the freshly made coke piece?

27. What is the shape of coke oven in by-product process? What factors are considered while designing such ovens?

28. How are the coke ovens heated? What are the various heating systems available for by-product coke ovens? Give brief description with sketches.

29. What are the different methods available for cooling hot coke? Give their merits and limitations.

30. What are the various modern features adopted by by-product coke oven? Give their merits.

31. What physical changes occur in coal bed with rise in coking temperature in a by-product process of coke making? What is median crack? Give its significance.

32. How does the chemical composition of coke change with temperature in by-product coke making?

33. What is the difference between graphite and diamond? How does the carbon basic structural unit (BSU) form and undergo change with application of temperature and pressure?

34. What do you understand by ‘graphite crystallite diameter’, ‘graphite crystallite height’ and ‘graphite inter layer spacing’?

35. How is the coke reactivity affected by its carbonisation temperature? Give a technique to measure the coke reactivity.

36. What is the difference between coke quality used in blast furnace and cupola?

37. How would you select coal for rotary kiln DRI process?

38. What are the environmental issues related with coke making? Give a comparative view for different coke making technologies.

39. Differentiate between the following:

(i) In-situ and Drift theory of coal formation
(ii) Peat and Coal
(iii) Intrinsic mineral matter and Extrinsic mineral matter
(iv) Surface and Inherent moisture
(v) Ash and Mineral matter
(vi) Air dry basis and Dry mineral matter free basis of coal analysis
(vii) Fixed carbon and Total carbon in coal
(viii) Caking and Non-caking coal
(ix) Metallurgical coal and Coking coal
(x) Gray king caking index and Swelling index
(xi) Clinical thermometer and Beckman thermometer
(xii) Liberation and Separation of mineral matter in coal
(xiii) Coke ‘cell size’ and ‘porosity’
(xiv) Shatter and Tumbler strength of coke
(xv) Micum 40 index and Micum 10 index
(xvi) Coke strength and Coke strength after reaction (CSR)
(xvii) CRI and CSR
(xviii) Coke combustibility and Coke reactivity

40. Write short notes on the following:

(i) Proximate analysis
(ii) Bomb calorimeter
(iii) Coal grindability test
(iv) Bradford breaker
(v) Grizzlies

(vi) Trommel
(vii) Elliot coal washer
(viii) Rheolaveur launder
(ix) Menzies cone classifier
(x) Chance process
(xi) Coal storage
(xii) Beehive coke making
(xiii) Stamp coal charging
(xiv) 3 + system of coke pushing
(xv) Coke Dry Quenching (CDQ)

3

Liquid Fuels

Introduction

Liquid fuels are combustible materials which find applications in generating heat, light, electrical or mechanical energy. The liquid fuels are obtained from earth as fossil fuel (crude oil) and from some vegetal plants (e.g. ethanol, bio-diesel, coconut oil, etc.). The liquid fuels are important for any nation due to their application in energy and transport sector which affect the economy.

The liquid fuels find large number of applications in iron and steel industries as they offer many advantages compared to solid (coal, coke, etc.) and gaseous fuels in view of their properties.

The ***advantages of liquid fuel*** are as follows:

a. *High calorific value* : Liquid fuels are considered as rich and compact energy source in view of high calorific value on weight or volume basis.
b. *Ease of storage and handling:* The oils, being fluid form of energy, can be stored in tanks depending on space available on the site either over the ground or under the ground. Further, oil can be handled easily through pipes from the storage tank located at any site to the furnace.
c. *Ease of combustion:* The oils have low ignition temperature and can be ignited easily by remotely operated devices.
d. *Ease of flame regulation:* The liquid flow in the pipe could be regulated easily by automatic devices and thus, flame regulation becomes easy.
e. *Ease of furnace atmosphere control:* The furnace atmosphere can be easily controlled by regulating the air/fuel ratio by manual or remotely controlled systems.

f. *Ease of long distance transportation through pipes:* The technology of long distance pipeline liquid fuel transportation on ground and in the sea has made the transportation easier, safer, and cheaper. This has led the exploitation of oil fields in remote areas.
g. *Rail and road transportation:* The oil tankers on wheels (rail/road) render mass transportation of energy in far off areas for industrial and domestic use.
h. *Less impurity:* The oils are practically free from uncombustible substances (e.g. ash) and have very low levels of sulphur as impurity.

The biggest *limitation* , however, in using liquid fuel is its limited global resources and availability. The applications of liquid fuel must justify its use on the basis of energy gained for the cost paid (e.g. GJ/` or GJ/$).

3.1 ORIGIN OF LIQUID FUELS

Crude oil and natural gas are fossil fuels which derive their origin from marine life which lived millions of years ago, similar to coal deposits which were formed from vegetal matter. Figure 3.1 illustrates in a simplified manner the process of oil and gas formation. The marine life living in the sea millions of years ago were perhaps died due to natural incident and these got buried at sea bottom. The long period of application of pressure and temperature might have caused the conversion of marine life into oil. The geological changes in the earth moved some of these deposits on soil, while some remain in sea even now. Unlike solid fuel (coal), liquid fuel could flow within soil through rock faults, and their composition is much more uniform throughout the globe.

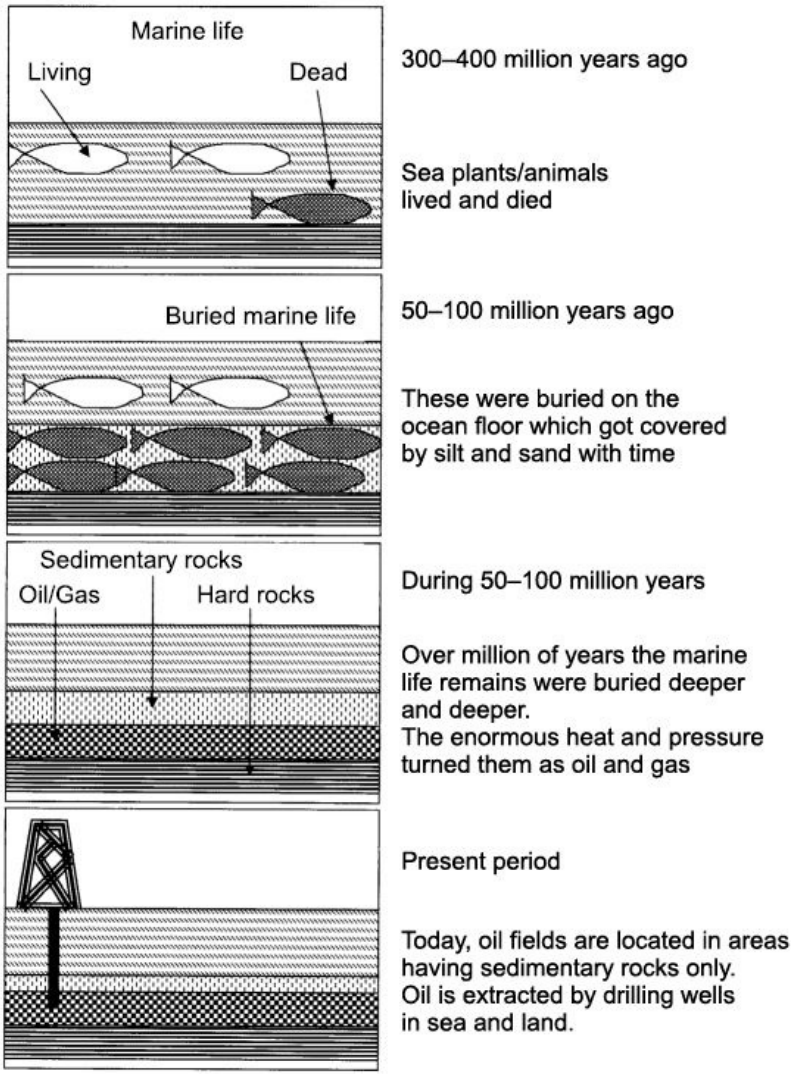


Figure 3.1 Formation of crude oil and natural gas in nature.
(Adopted from R.C. Gupta, *Theory and Laboratory Experiments in Ferrous Metallurgy* , PHI Learning, Delhi, 2010.)

3.2 SOURCES OF LIQUID FUEL

The oil is derived from the following four different sources including crude petroleum:

a. Crude oil
b. Oil shale
c. Coal tar fuels and
d. Synthetic oil or hydrogenation of coal

These four oil sources are being utilised in different proportion in the world dominated by crude petroleum.

3.2.1 Crude Petroleum

History

The modern history of petroleum began in the mid of 19th century when oil was found in hand dug well in Poland, although some evidences are available for its use in earlier period by civilisations in Babylon, China, Egypt, etc. The first large petroleum refinery was built in Romania in 1856 using the abundant oil deposits. The first oil well was drilled in 1858 in Ontario, Canada. The petroleum industry in USA began in 1859.

Crude oil composition

The crude petroleum is available in different parts of the world, but unlike coal, they do not differ in composition widely. The chemical compositions of crude petroleum vary within narrow limits as given in Table 3.1. The crude oil is a mixture of hydrocarbons, paraffin, olefin, naphthalene, aromatic and asphaltic compounds ranging from simplest gaseous member methane to complex waxes and bitumen. Some of these members are listed in Table 3.2.

Table 3.1 Average Chemical Composition of Crude Oil

Elements	C	H	N	O	S	Metals
Wt. %	83– 87	10–14	0.1–2	0.1–-1.5	0.5–-6	< 1000 ppm

Table 3.2 Organic Compounds Present in Crude Oil

Hydrocarbons	*Compounds*	*Range, wt.%*	*Average, wt.%*
Paraffin ($C_n H_{2n+2}$)	Methane (CH_4) Butane ($C_4 H_{10}$) Octane ($C_8 H_{18}$)	15 to 60	30
Naphthalene ($C_n H_{2n}$) (ring structure)	Cyclobutane ($C_4 H_8$)	30 to 60	49
Aromatic ($C_6 H_{2n-6}$) ($n \geq 6$)	Benzene ($C_6 H_6$) Toluene ($C_7 H_8$) Xylene ($C_8 H_{10}$)	3 to 30	15
Asphaltic	Compounds with more than 35 carbon atoms	Rest	6

Distillation of crude oil

Crude oil is separated into fractions by fractional distillation. Fractional distillation is a process where separation of constituents in a mixture occurs into its components or fractions based on its boiling point. The crude oil held in column is heated gradually to cause evaporation and collection of fractions as distillation product at the given temperature. Generally, some of the constituent parts start boiling at less than 25 °C under a pressure of one atmosphere. With increasing temperature, the fractions having more boiling temperature are evolved from crude oil and get collected. In this process, a sharp temperature boundary between two fractions cannot be made. Each collected fraction represents a range of temperature. The fractions with boiling point more than 300 °C are recovered by lowering the partial pressure during heating. After removing the volatile fraction the semi-solid tar and solid petroleum coke are obtained as product. All the fractions obtained during distillation are further processed and refined before use.

The various fractions present in crude petroleum are obtained by fractional distillation of crude oil according to their boiling temperature range as given in Table 3.3. The present distillation technique uses catalyst which offers better control over reaction than old thermal cracking technique. The product fraction is controlled by temperature, pressure, catalyst and time of contact. The granules of aluminosilicates are employed, and fluidised bed technique is used to put the process on a continuous production basis.

Table 3.3 Crude Oil Distillation Fractions and Their Use

S. No.	*Fraction Distilled*	*Distillation Pressure*	*Boiling Range* (°C)	*Use*
1	Natural Gas	Under reduced pressure	Below 30	Fuel, reductant in DRI
2	Gasoline (Petrol) Aviation petrol Motor petrol Vaporising oil	Atmospheric	30–200 30–150 40–180 110–200	Engine fuel Aviation Automobile Heavy engine
3	Solvent Spirit	Atmospheric	120–250	Organic solvent for cleaning and paint industry
4	Kerosene Domestic grade signal oil	Atmospheric	140–290 140–250 140–290	Heating/lighting Domestic fuel Railways signal post
5	Diesel	Atmospheric	Above 180 and leaving residue at 350	Heavy vehicles fuel
6	Light fuel oil	Vacuum distillation	Above 200	Fuel for ships and industrial furnaces
7	Heavy fuel oil	Vacuum distillation	Above 250	Fuel for industrial furnaces

8	Paraffin Waxes Jelly (Vaseline) Lubricating oils Greases Tar Pitch (Petro coke)		Residual fractions	Chemical industry Chemical/domestic Medicine (ointment base) Lubricating oil Lubrication Road making Electrical items, e.g. electrode

3.2.2 Oil Shale

These are sedimentary rocks impregnated with oil. These are recovered by rock mining. The cost of recovering oil is higher than conventional crude oil, and therefore, these are least exploited.

Resources

The oil shale has been found in many parts of the world, but bigger deposits are found in America. The global deposits of oil present as oil shale are estimated around 3 trillion barrels. These deposits may gain importance with increase in oil price.

Exploitation technique

In conventional method, the oil shale is mined out and then its oil fraction is recovered in plants located outside mining area. In the in-situ technique, the oil fractions are recovered at the mining site.

In conventional process, the rocks are heated (450–500 °C) in absence of oxygen to evolve oil vapours which are condensed identical to distillation process for crude oil.

Applications

The oil shale as such can be used for burning (like coal) to generate steam. The oil produced from oil shale can be used for combustion.

Environmental issues

The exploitation of oil shale has initiated several environmental issues like ground water contamination by acids, presence of mercury and ground water contamination during mining, sulphur emissions during burning, etc. The large scale use would require attention to such environmental problems.

3.2.3 Coal Tar Fuel (CTF)

Generation as a by-product

Coal tar is obtained during coke making process as a by-product volatile fraction. The coal carbonisation done at low temperature (700 °C) yields semi-coke and tar, called low temperature tar, as by-product in addition to coke oven gas as main product for the production of chemical fertiliser. The high temperature (1200 °C) by-product coke making process gives metallurgical coke as main product alongwith coke oven gas and tar (high temperature tar) as by-product.

The tar, thus obtained, is used for various applications including fuel. The tar obtained during low (700 °C) and high (1200 °C) temperature carbonisation of coal differs in properties due to variation in its constituents as given in Table 3.4.

Table 3.4 Properties of Tar Obtained during Coal Carbonisation

Tar Properties	*Coal Carbonisation Temperature*	
	700 °C	1200 °C
Specific gravity	1.03	1.17
Chemical analysis, wt% Carbon Hydrogen Nitrogen Sulphur	 84.0 8.3 1.1 0.7	 90.3 5.5 0.9 0.8
Ash, wt.%	0.1	0.24
Toluene insoluble (TI), wt.%	1.2	6.6
Water content, wt.%	2.2	4.9

Distillation of tar

The coal tar generated during coal carbonisation process contains a number of valuable organic compounds. This tar is distilled to recover some of these compounds based on economics and produce better quality of fuel oils. The fractions which are derived from fractional distillation are given in Table 3.5.

Table 3.5 Distilled Fractions Derived from Coal Tar

Oil Fraction	*Boiling Range,* ^{o} C	*Yield (%)*	*Chemical Constituents*
Light oil	Up to 170	2–4	Benzol, naphtha, phenol
Carbolic oil	170–230	5–7	Phenol, naphthalene, pyridine
Creosote oil	230–270	15–25	Naphthalene, creosote oil
Anthracene oil	230–350	14–17	Anthracene oil
Pitch	Residue	60–70	Carbon

These fractions are used as coal tar fuels in suitable blend for commercial use.

There are following six grades of CTFs: (i) CTF50

(ii) CTF100

(iii) CTF200

(iv) CTF250

(v) CTF300

(vi) CTF400

The numbers following CTF indicate in degree Fahrenheit (°F) at which the blend is fluid enough for atomisation having maximum viscosity of 0.25 stokes. This would mean that CTF50 is fluid enough for atomisation at 50 °F (10 °C) temperature whereas the CTF400 would be fluid at 400 °F (200 °C) and would require pre-heating before its atomisation in burner.

Properties of coal tar fuels

The properties of various grades of CTF are given in Table 3.6. The CTFs distinguish themselves from petroleum fuels in following properties:

a. CTFs have lower calorific value compared to corresponding petroleum oils.
b. CTFs have low sulphur content (< 1%) compared with corresponding petroleum oils which may have sulphur up to 4%.
c. CTFs have higher flame emission than petroleum oils and hence give better heat transfer.
d. CTFs have low hydrogen (up to 6%) compared to petroleum oils (12%). This lower hydrogen content results in narrow gap (~325 kcal/kg) between gross and net calorific value in case of CTFs as compared with ~625 kcal/kg for petroleum oils.

Table 3.6 Properties of Coal Tar Fuels

Properties of Oils	*Coal Tar Fuels*					
	CTF50	*CTF100*	*CTF200*	*CTF250*	*CTF300*	*CTF400*
Viscosity, Redwood-1, s	60	100	1000–1500	–	–	–
Flash point, ^{o} C	> 65	> 65	> 65	> 65	> 65	> 65
Sulphur content, %	< 1	< 1	< 1	< 1	< 1	< 1
Ash content, %	Nil	Nil	0.1	0.1	0.2	0.2
Calorific value (net),	9150–	9150–	9000–	9000–	8900–	8750–

kcal/kg	9750	9750	9450	9300	9200	9050

Application of coal tar fuel

Coal tar fuel is used in metallurgical furnaces due to its low sulphur content and high flame emissivity. It is also used in power plants, calcinations rotary kilns, cement kilns and glass melting furnaces.

3.2.4 Coal Liquefaction

Coal liquefaction is a general term referring to a family of processes for producing liquid fuels from coal. There are two methods for coal liquefaction: DCL (direct coal liquefaction) and ICL (indirect coal liquefaction).

DCL method

In this process, the coal is converted into liquid directly by using autoclaving coal with catalyst at high pressure and temperature.

ICL method

In this technique, the coal is gassified to get a mixture of hydrogen and carbon monoxide gas which is then liquefied using Fischer–Tropsch process.

The coal liquefaction involves higher temperature with high-pressure technology requiring significant amount of energy and with huge capital investment for an industrial plant. Thus, the process has remained unattractive for commercial uses. Further, this process yields lighter oil fractions only which are not used by metallurgical furnaces.

3.3 COMMONLY USED PETROLEUM PRODUCTS

3.3.1 Petrol (Gasoline)

Petrol (gasoline) is the most common liquid fuel for automobiles. The main constituents of petrol include aliphatic hydrocarbons.

Petrol has boiling point below room temperature which causes its evaporation and vapour formation. This petrol vapour is highly flammable and must be guarded for any exposure to fire source.

The petrol marketed in many countries bears an ‘octane number’. This octane number is an empirical figure to express resistance to premature combustion termed as knocking. The higher octane value fuel is resistant to auto ignition

under high pressure permitting higher compression ratio. The high compression engines are used to give more power needed in racing cars. The petrol sold in past used to mix lead tetra ethyl as ‘anti-knocking compound’ but nowadays these additives are avoided as they lead to pollution problem. These days, petrol is refined to remove compounds which cause knocking.

3.3.2 White Spirit

The white spirit is obtained during distillation of crude oil. It appears as clear and transparent fluid. This is a common organic solvent used in paint and decorating industry.

The white spirit consists of aliphatic and alicyclic (C_7 to C_{12}) hydrocarbons. The typical composition of white sprit has nearly 65% C_{10} or higher hydrocarbons, aliphatic solvent hexane with maximum 0.1% benzene.

The main uses of white spirit are solvent for paint industry, degreasing agent, lacquers, varnishes and preservatives for wood.

3.3.3 Naphtha

Naphtha is a product of crude oil distillation process. Naphtha boiling point ranges from
60–200 °C. Naphtha contains C_5 to C_{13} hydrocarbons consisting of 55–65% paraffin, 20–30% naphthalene and 10–15% aromatic compounds depending on type of crude oil.

Naphtha is classified on the basis of boiling point as:

a. Light naphtha (bp below 100 °C)
b. Intermediate naphtha (bp 100–150 °C)
c. Heavy naphtha (bp above 150 °C).

Naphtha is also classified on the basis of process of distillation as:

a. Straight run naphtha—produced by atmospheric distillation of crude oil
b. Cracked naphtha—produced by conversion process like fluidized bed catalytic cracking, hydro-cracking and coking.

Naphtha is used to enrich blast furnace gas in metallurgical plants when coke

oven gas is in short supply. The naphtha is vaporised and mixed with blast furnace gas for use as fuel.

3.3.4 Kerosene

Kerosene, produced by crude oil distillation, contains $C_{1\ 0}$ –C_{14} hydrocarbons (boiling point
150–250 °C). A good quality of kerosene should have high proportion of paraffin hydrocarbons and less of aromatic. It burns with smoky flame.

It finds use as a cleaning agent for machines in industrial unit including metallurgical plant. It is also used as fuel in hand held burners for local heating in repair shop.

Kerosene is mainly produced for domestic applications like lighting lamp and fuel for cooking. The kerosene signal lamps were common in Indian railways which have now been mostly replaced by electrical or solar lamps. Kerosene is sometimes used for running engines for small power generators.

3.3.5 Diesel

It is a product of crude petroleum oil distillation obtained in between kerosene and lubricating oil. The distillate oil boiling point in the range 150–400 °C is found suitable as diesel fuel.

Diesel consists of aliphatic hydrocarbons. It also contains sulphur as an impurity which causes corrosion of burner parts and emits gas containing sulphur during its use which cause environmental problem. Currently, sulphur level is kept below 10 ppm. Diesel is mainly used in internal combustion engine for automobiles, heavy vehicles, power generators and small heating furnaces.

The specification of diesel oil is given in Table 3.7. The high speed diesel (HSD) is used in automotive vehicles (trucks, buses, locomotives, etc.). The light diesel oil (LDO) is used for marine ship engine, power generators and small furnaces.

Table 3.7 Specifications for Diesel Oil (IS-15770-2008)

Properties	*Type of Diesel Oil*	
	Gr. A–HSD	*Gr. B–LDO*
Kinematic viscosity, centistokes at 37.5 ^{o} C	2–7.5	2. 5 –15.7
Pour point, ^{o} C	6	1 2 –18
	38	66

Flash point, ^{o} C		
Carbon residue, wt.%	0.2	1.5
Water content, vol.%	0.05	0.25
Sediment content, wt.%	0.05	0.10
Ash content, wt.%	0.01	0.02
Sulphur content wt.%	1.0	1.8

3.3.6 Furnace Oil

Furnace oil or fuel oil is obtained from petroleum distillation. The term fuel oil is used to refer only the heaviest commercial fuel that can be obtained from crude oil, i.e., heavier than gasoline and naphtha. Broadly speaking, furnace or fuel oil is liquid petroleum product that is burned in a furnace or boiler for the generation of heat or used in an engine for the generation of power.

The light furnace oil is produced from gas oil cracking units and heavy furnace oil is produced from residue of crude distillation units and thermal catalytic cracking unit. Furnace oil contains long chains of hydrocarbon consisting of cycloalkanes, alkanes and aromatic compounds.

The furnace oil produced in India has maximum viscosity of 1500 s (Redwood no. 1) at 50 °C. The low sulphur heavy stock (LSHS) furnace oil containing less than 1 wt.% sulphur appears semi solid at room temperature. This LSHS oil has to be heated at 60 °C for pumping and 100 °C (yielding 25 centistokes viscosity) for atomisation by nozzle in a burner. The specification of furnace oil in India (IS 1593-1960) is given in Table 3.8.

Table 3.8 Indian Specifications of Furnace/Fuel Oil

Properties	*Furnace/Fuel Oil*		
	Low viscosity	*Medium viscosity*	*High viscosity*
Kinematics viscosity, centistokes at 50°C max.	50	125	370
Flash point, °C (Pensky Marten)	66	66	66
Water content, vol.%	1	1	1
Sediment content, wt.%	0.25	0.25	0.25
Sulphur, wt.%	3.5	4.0	4.5
Ash, wt.%	0.1	0.1	0.1

Table 3.9 Summary of Liquid Fuels Properties

Properties	*Gasoline (Petrol)*	*White Spirit*	*Kerosene*	*Diesel*	*Light Furnace Oil*	*Heavy Furnace Oil*	*CTF 200*
Specific gravity at 15 °C	0.73	0.76	0.79	0.87	0.89	0.95	1.1
Kinematics viscosity at 20 °C cs at 100 °C cs	0.75 –	0.74 to 1.6 –	1.6 0.6	5.0 1.2	50 3.5	1200 20	1500 18
Flash Point °C	–40	30 to 31	39	75	80	110	65
Residue at 350 °C wt.%	–	–	–	15	50	60	60
Gross calorific value cal/g GJ/t	10450 43.7	10450 43.7	10400 43.5	10300 43.1	10000 41.8	9900 41.4	9000 37.6

3.4 PROPERTIES AND TESTING TECHNIQUES FOR LIQUID FUELS

The various applications of liquid fuels are based on its properties (Table 3.9), e.g. viscosity, flash point, calorific value, etc. These properties are briefly described as follows:

3.4.1 Viscosity

The ability of oil to flow is determined by its viscosity. This property is important for oil transportation through pipe or using in a burner.

Definition and units

It can be defined in two ways as absolute viscosity and kinematic viscosity.

(i) Absolute viscosity (or dynamic viscosity)

It is the force required to move a plane surface at rate of 1 cm/s having 1 cm^2 area over another plane at a distance of 1 cm, while both are immersed in the fluid. In cgs unit, the force required is 1 poise (P).

It is expressed by Greek letters η (Eta) or μ (Mu).

In cgs unit, the viscosity is generally expressed in centipoises.

1 P (poise) = 100 cP (centipoise)

In SI unit, the viscosity is expressed as pascal-second (Pa.s).

1 Pa.s (pascal second) = 10 P (poise) = 1 $kg.m^{-1}.s^{-1}$

1 m Pa.s (milli pascal second) = 0.001 Pa.s = 1 cP

(ii) Kinematic viscosity

It is the ratio of absolute viscosity to the density of oil when both are measured at the same temperature.

$$\text{Thus, Kinematic viscosity } (\nu) = \frac{\text{Absolute viscosity in poise}}{\text{Density (g/cc)}} = \frac{\eta}{\rho} \text{ or } \frac{\mu}{\rho}$$

where, η or μ are absolute viscosity in poise,
ρ is oil density in g/cc and
ν is oil kinematic viscosity.

The cgs unit for kinematic viscosity (ν) is stokes (St)

$$\text{In SI system, unit for kinematic viscosity } (\nu) \text{ is } m^2\ s^{-1} \left[= \frac{\text{Pa.s}}{kg/m^3} = \frac{kg\ m^{-1}.s^{-1}}{kg/m^3} = m^2 s^{-1} \right]$$

1 stokes (St) = 100 centistokes (cSt) = 10^{-4} m^2 s^{-1}

1 centistokes (cSt) = 10^{-6} m^2 s^{-1}

Effect of temperature and pressure

The viscosity is independent of pressure (except at very high pressures), however, the viscosity tends to decrease as the temperature increases. The viscosity of water at 25 °C (0.894 cP) may be used as reference. The absolute viscosity of some liquids is given in Table 3.10.

Viscometers

The viscosity of oil is measured by observing the time taken by 50 ml of the oil to flow through a standard orifice in a viscometer of standard design at a specified temperature. The kinematic viscosity in centistokes is given as: $\nu = c \times t$

where, c is the viscometer constant in centistokes/second and

t is the time in seconds for 50 ml oil discharge.

The value of c (viscometer constant) is determined by using a reference fluid (e.g. 40% sucrose water solution having kinematic viscosity 4.39 centistokes at 25 °C).

There are two types of viscometers which are used to measure the kinematic viscosity of oils.

Table 3.10 Absolute Viscosity of Some Liquids

Liquids at 25 °C	*Absolute Viscosity*	
	Pa.s	cP
Acetone	3.06×10^{-4}	0.306

Methanol	5.44×10^{-4}	0.544
Benzene	6.04×10^{-4}	0.604
Water	8.94×10^{-4}	0.894
Mercury	1.526×10^{-3}	1.526
Sulphuric acid	2.42×10^{-2}	24.2
Glycerol	0.934	934
Pitch	2.3×10^{8}	2.3×10^{11}

(i) Redwood viscometer

It consists of a metal cup placed in a water bath whose temperature could be regulated

(Figure 3.2). The cup has an orifice at bottom fitted with ball plug. The orifice size of Redwood no. 1 is smaller than Redwood no. 2. The commonly used Redwood no. 1 viscometer is suitable for viscosity from 30 seconds to 2000 seconds. Number 2 is used for viscous oil which gives nearly 1/10th flow time than No. 1 viscometer.

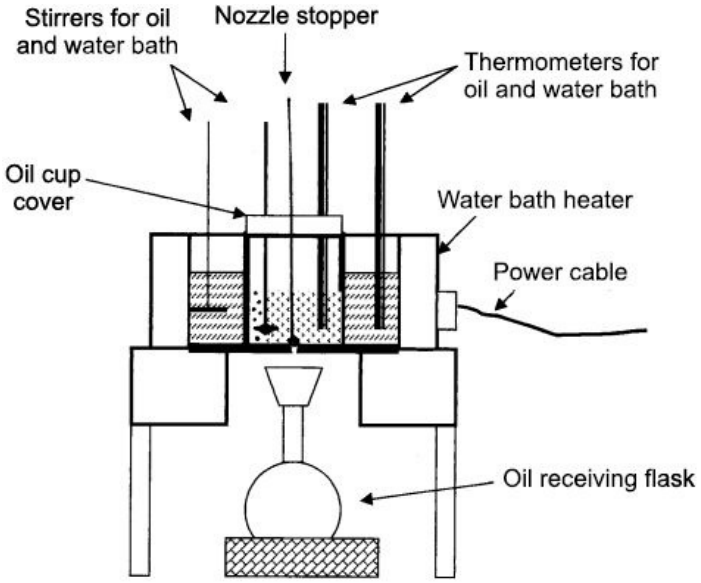


Figure 3.2 Redwood viscometer.

(Adopted from R.C. Gupta, *Theory and Experiments in Ferrous Metallurgy* , PHI Learning, Delhi, 2010.)

The test procedure consists of filling the cup with oil to be tested. A level mark is provided for this purpose. The water bath temperature and oil temperature are adjusted to the required degree and time of 50 ml oil efflux in a receiving flask is noted with stop watch in seconds.

(ii) U-Tube viscometer

It consists of a glass tube in U-shape with specific design (Figure 3.3). It has the following advantages in comparison to Redwood viscometer: The apparatus is cheaper and easy to clean.

Temperature control is better.

The quantity of oil sample needed is much less.

It is useful to measure viscosity for variety of fluids.

The test procedure involves filling oil in the viscometer through its wider end up to the mark E (Figure 3.3), taking care that no air bubble is trapped inside. This U-tube is placed in a thermostat and maintained at the desired temperature. The U-tube is mounted such that it is vertical in the bath. Now, the oil is sucked in the thinner tube to bring oil level 1 cm above the mark B. The oil is then allowed to flow freely down through capillary tube. The time taken by the oil from mark B to C is noted by stopwatch reading in second up to one decimal place.

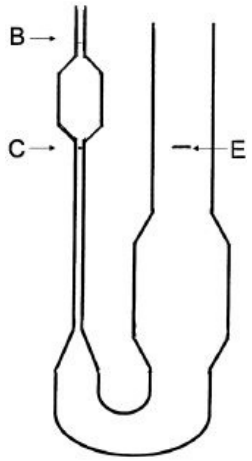


Figure 3.3 U-tube viscometer.
(Adopted from R.C. Gupta, *Theory and Experiments in Ferrous Metallurgy* , PHI Learning, Delhi, 2010.)

3.4.2 Flash Point and Fire Point

Definition

Flash point

It is the lowest temperature at which oil gives sufficient vapour which offers a momentary flash on exposure to a standard flame in air.

At the flash point, oil may ignite briefly but vapour might not be produced at a rate to sustain the fire. It is, thus, a measure of fire risk of oil stored or transported in oil tanks.

Fire point

It is the temperature at which oil will continue to burn for at least 5 seconds after ignition by an open flame.

The fire point temperature is little higher than flash point temperature. Most tables of oil properties will only list flash points, but in general the fire points can be assumed to be about 10°C higher than the flash points. However, for critical applications the fire point must be tested.

Auto-ignition temperature or Spontaneous Ignition Temperature (SIT)

It is the minimum temperature required for igniting gas or vapours in air without a spark or flame.

Applications

The flash point of oil is useful while storage and transportation. The oil having flash point below 0 °C are regarded as *dangerous–highly inflammable oil* and need care and precautions. The oils having flash point above 65.5 °C (150 °F) are considered as *safe oil.*

Most of the petroleum oils have SIT value in between 260 °C (500 °F) and 370 °C (700 °F), while their flash point temperature is much lower (–40 to 80 °C). The flash point, fire point and SIT value for some oils are given in Table 3.11.

The external fire sources like static charge, sparks, welding spark, grinding sparks, etc. should be avoided in oil storage area to prevent the fire hazard. The oil tanks must be kept full to avoid vapour accumulation.

Table 3.11 Flash Point and Autoignition Point for Some Fuels

Liquid Fuels	*Flash Point,* °C	*Fire Point,* °C	*Autoignition Point (SIT),* °C
Gasoline (Petrol)	–40	–30	280
Kerosene	39	49	295
Diesel	75	85	210

Test apparatus

The following two equipment are commonly used:

a. Abel apparatus (Figure 3.4) for flash point below 50 °C
b. Pensky Marten apparatus for flash point above 50 °C.

Both these apparatus work on same principle, but differ in design and method of

heating the oil held in the cup. The cup is fitted with spring loaded window which can be opened by pressing a latch for a second. The cup is also fitted with a stirrer for homogenisation of oil bath temperature and a thermometer to indicate its temperature. A tiny flame is kept burning close to the window to ignite the oil vapour emitted through it on opening.

The test procedure involves filling the cup with test oil up to the given mark and then heating at a prescribed rate (5 °C per min). The oil is kept stirred continuously and slowly (1 rpm). The window is opened after every 5 °C rise in temperature. The lowest temperature at which a momentary flash is observed is taken as an approximate flash point. The test is terminated and used oil is discarded. The test is repeated with fresh oil sample. Now, since approximate flash point is known, the window is opened 5 °C before the approximate value. In case no flash is noted, it is closed and opened after every 1 °C rise in temperature to reach the exact flash point temperature. The used oil is never tested again as some volatiles are lost and its value will change.

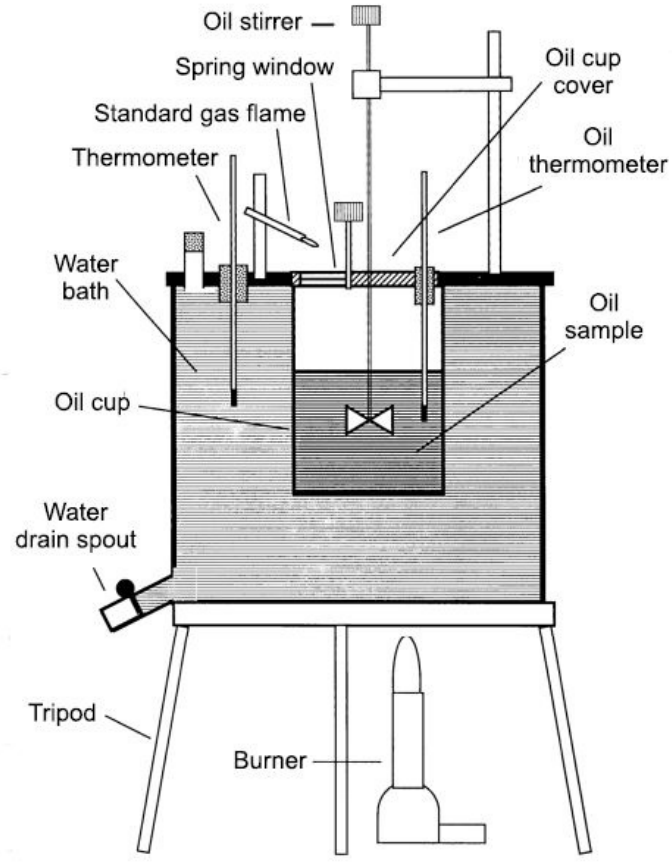


Figure 3.4 Flash point test equipment (Abel Apparatus).

3.4.3 Specific Gravity

The specific gravity is an important property of an oil. It gives an indication for mass per unit volume. This is important for designing oil storage tanks and oil carriers. It also gives calculated gross calorific values of petroleum products (by using US Bureau of Mines Formula) as: Calorific value (Gross) = 12400 – 2100 ρ^2 kilo-calorie/kg
where ρ is the specific gravity of oil at 15.5 °C.

The specific gravity of oil (ρ) can be determined by various methods as given below:

a. **Hydrometer:** The hydrometers are common for measuring specific gravity of oils which are available in different ranges giving upto 10^{-3} value.
b. **Specific gravity bottles:** Standard specific gravity bottles are available for different volumes (10–50 ml). These bottles could be used for oils which are fluid at room temperature.
c. **Specific gravity for viscous oils:** The viscous oil like tar is made fluid by mixing with equal volume of kerosene to yield a mixture which is fluid enough to be tested by specific gravity bottle. The specific gravity of tar is then calculated as: $(\text{Specific gravity})_{\text{Tar}}\ (\rho_T) = (\rho_M) - (\rho_K)$

where,

ρ_M is specific gravity of tar and kerosene mix and

ρ_K is specific gravity of kerosene.

d. **API gravity:** It is the ratio of the density of a substance to that of water at 15 °C. It can be determined with specific gravity bottle or hydrometers. The American Petroleum Institute (API) gravity is expressed as:

$$\text{API} = \frac{141.5}{\text{Specific gravity of oil at } 15^{\circ}\text{C}} - 131.5$$

The specific gravity of some oils are given in Table 3.12.

Table 3.12 Specific Gravity of Some Oils

Petroleum Oils	*Specific Gravity*	*Bio-Oils*	*Specific Gravity*

Propane at 25 ^{o} C	0.495	Olive oil	0.703
Butane at 25 ^{o} C	0.601	Alcohol, ethyl (ethanol)	0.787
Naphtha	0.66–0.72	Alcohol, methyl (methanol)	0.791
Gasoline at 15.5 ^{o} C	0.70–0.76	Sunflower oil	0.92
Kerosene at 15.5 ^{o} C	0.82	Linseed oil at 25 ^{o} C	0.932
Diesel at 15.5 ^{o} C	0.82–0.86	Castor oil	0.959
Fuel oil at 15.5 ^{o} C	0.893		
High temp. tar	1.18		
Low temp. tar	1.06		
Crude oil at 15.5 ^{o} C	0.87–0.97		

[Specific gravity of water at 4 ° C (39.2 ° F) is 1.000]

3.4.4 Calorific Value

The definition of calorific value, difference between ‘gross’ and ‘net’ caloric values, its units and description of ‘bomb calorimeter’ for its testing are already discussed in section 2.5.6. In this section, only testing procedure will be described which is slightly different from the solid fuel.

The oil sample is collected (50 cc) and 1 g is placed in the crucible of the bomb calorimeter. The known length of iron wire fuse is connected with terminals to touch oil in crucible. The bomb is filled with oxygen (~20 atmospheres) and the calorimeter vessel is filled with known quantity of water (2 litres). The bomb is immersed in water with electrical wire connected to 9 V DC source. The stirrer and Beckmann thermometer is placed in position and the system is allowed to come at constant temperature. The initial temperature is recorded and ignition is made by passing current at 9 volts. The increase in water temperature is noted when it reaches the maximum value.

The fuel mass (M), water equivalent (W_{eq}) of calorimeter and the rise in temperature (ΔT) is known in the test and, therefore, the gross calorific value (CV) of fuel is calculated as:

$$\text{Gross CV} = \frac{W_{eq} \cdot \Delta T}{M} \text{ calories/gram}$$

Sometimes oil ignition by fuse wire is not easily done. In such case, a solid base (e.g. benzoic acid) is taken as a tablet made from a known weight of powder (say

1g). While making the tablet, a fuse wire of known length is embedded in it. This tablet is weighed accurately and then a few drops of oil is soaked in the tablet and weighed again. The difference in weight will give oil weight absorbed by the tablet. Now, this oil soaked benzoic acid tablet is placed in the bomb and heating value of this oil soaked tablet is determined. Since, the heat liberated from benzoic acid and fuse wire is known, the additional heat is taken from the oil and its calorific value is calculated.

3.4.5 Sulphur in Oils

Sulphur originates from crude oil and various fractions contain sulphur as given in Table 3.13. The sulphur present in the oil is undesirable as it causes several problems:

a. The sulphur in oil contaminates the products directly, e.g. steel billet during heating or heat treatment.
b. Produces corrosive SO_2 gases
c. Raises dew point of flue gases
d. Accelerates the formation of gum and sediments during its storage

Table 3.13 Sulphur Content in Some Fuel Oils

Fuel Oil	*Sulphur wt.%*
Kerosene	0.05–0.2
Vaporising oil	0.1–0.4
Diesel oil	0.3–1.5
Furnace oil	2.0–4.0
Coal Tar fuel	0.5–1.0

The sulphur content in oil can be determined by the following two methods: (a) Qualitative test by copper strip and
(b) Quantitative test by bomb calorimeter

Copper strip test

A piece of mechanically cleaned pure copper sheet (75 × 12 mm) is kept in a wide test tube with 40 ml oil sample such that the copper strip is immersed. The test tube is closed with a vented cork and placed in a water bath for three hours. The corroded copper strip is compared visually with a unexposed fresh copper

sheet to notice the extent of black scale visually and the following inferences are derived: **Free or negligible sulphur level:** Copper sheet colour with no change in colour or slight discolouration.

Tolerable sulphur level: Copper sheet colour with brown shade or steel grey.

Unacceptable sulphur level: Copper sheet colour with black not scaled or black scaled.

Bomb calorimeter method

While determining the calorific value of oil, 2 ml water is placed in the bomb to absorb all SO_2 generated during oil combustion. When the calorific value test is over, the bomb cover is opened after releasing oxygen pressure. The bomb vessel is washed with water and barium chloride is added to precipitate as barium sulphate which is filtered, washed, ignited and weighed. The per cent sulphur is calculated from weight of barium sulphate and oil weight taken initially.

3.4.6 Carbon Residue

Many oils have tendency to leave carbon deposit during heating. Such deposit can affect the functioning of oil burners. This is determined by taking a weighed quantity of oil in a crucible which is heated slowly to red hot temperature in absence of air, till all volatile matter is removed. The crucible is cooled and weighed to know the quantity of deposited carbon.

The oils giving carbon residue beyond a value are unsafe for use in burners of specific size.

3.4.7 Ash Content

The liquid fuels, as such, do not contain any uncombustible constituent to yield ash. However, iron oxides as rust, dust, etc. get associated during storage and handling of liquid fuels. Their quantity rarely exceeds 0.25 wt.%. The presence of such constituent could damage the nozzle of the burner due to wear.

The ash content in oil is determined by taking 20 gram of oil in a clean, dry weighed silica dish. This is placed inside a cold muffle furnace which is heated slowly till oil burns, when a flame is applied to the surface. When all the oil is burnt, the furnace temperature is raised to 800 °C and heated for one hour more. The crucible is withdrawn, cooled and
weighed to get the residue ash weight. The ash content is expressed as per cent of oil sample weight.

3.4.8 Cloud Point

When oil is cooled at specified rate, it becomes hazy or cloudy at some temperature to be termed as ‘cloud point’. This haziness is due to separation of wax crystals rendering increase in its viscosity at low temperature. This property is tested for those petroleum products which are transparent to 40 mm thick layer and have cloud point less than 50 °C. This is important for oils since it may clog filters.

The cloud point is tested by taking oil in a flat bottom glass test tube (30 mm diameter and 120 mm long). This test tube is encased in a air jacket which is placed in the ice box containing freezing mixture (ice and common salt). The flat bottom glass test tube is filled half by oil to be tested and a thermometer is placed inside to indicate its temperature. Once the oil filled glass test tube is placed in air jacket surrounded by freezing mixture, the oil temperature starts dropping. This tube is withdrawn for 2–3 seconds after every 1 °C drop in temperature to note the oil transparency till a haze is noted in the oil which is taken as ‘cloud temperature’.

3.4.9 Pour Point

The pour point of a liquid is the lowest temperature at which it becomes semi solid and loses its flow characteristics. The oils flow is retarded due to increase in viscosity at low temperature due to the formation of wax crystals. The pour point is a temperature 3 °C higher than temperature at which oil ceases to flow when poured in a prescribed manner. This can be tested by manual or using standard automatic device.

Manual method

The oil sample held in a wide test tube is cooled inside a cooling bath to allow the formation of paraffin wax crystals. At about 9 °C above the expected pour point and for every subsequent 3 °C, the test tube is taken out and tilted to check for its surface movement. When the oil does not flow, the test tube is held horizontally for 5 sec. If it does not flow, then the pour point is taken as 3 °C higher than the oil temperature.

Automatic device

The standard test method for pour point of petroleum products (automatic pressure pulsing method) is based on ASTM standard. Under This automatic equipment, for testing oil sample, has arrangement to heat and then cool oil by a

Peltier device at a rate of 1.5 ± 0.1 °C/min. The pressurised pulse of compressed gas is imparted onto the surface of the sample at an intervals of 3 °C. The detectors (multiple optical devices) continuously monitor the sample for its surface movement.. The lowest temperature, at which movement is detected on the sample surface is determined to be the pour point.

3.4.10 Sludge and Sediments in Oil

The sludge and sediment content in oil become important during oil storage. The unsatisfactory blending of oils or presence of unstable components oxidises and causes the formation of sludge and sediments. These sludge and sediments clog the filters or nozzles and affect corrosion of the tank and pipeline. The oils are mixed with oxidation and corrosion inhibitors to minimise this sludge formation.

The sludge and sediment content in the oil is tested by dissolving oil in benzene and separating the sludge as insoluble content. The test procedure is described below: The oil sample (10 g) is taken in a clean dry alumina extraction thimble (25 mm diameter and 70 mm high) which is porous enough to allow the oil dissolved in benzene to pass out retaining the insoluble content. This thimble (Figure 3.5) is suspended below a cold finger condenser and placed in a one litre Erlenmeyer flask containing ~100 ml benzene. The cold finger is connected to a cold water source for cooling the vapours condensing on its surface. The flask is now heated gently to cause benzene evaporation. This evaporated benzene would condense on cold finger condenser and then drop in the alumina crucible containing oil sample. The oil dissolving in benzene would filter out from the porous alumina crucible. This process of oil dissolution in benzene and filtering out is allowed till all the oil in the crucible is removed. When all the oil is washed out, the alumina crucible is dried and weighed to give the weight of residue as sludge and sediments.

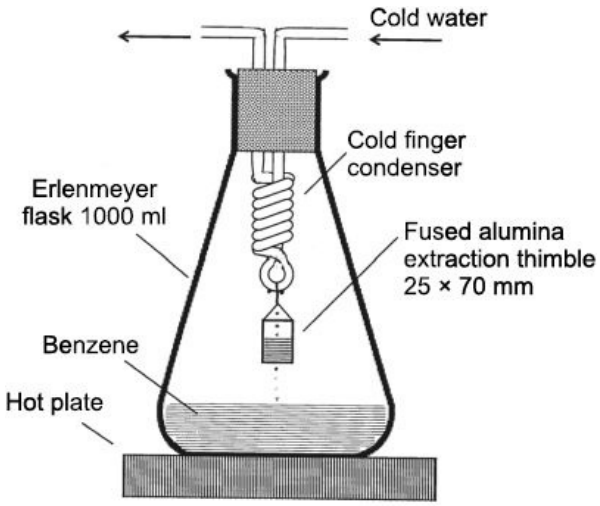


Figure 3.5 Apparatus for determination of sludge and sediments in oil.

3.4.11 Water in Oil

The oil, in general, does not have water content. The water in oil may originate during atmospheric exposure, leakage of water or some other external sources. This water content is not desired in oil, specially, when it is used for electrical applications in transformers.

The water content in oil is determined by Dean and Stark apparatus developed by E.W. Dean and D. D. Stark in 1920. The apparatus consists of glass assembly as shown in Figure 3.6. The apparatus is cleaned and dried before fitting together for the test. The round bottom flask (500 ml capacity) is filled with 100 ml oil sample and 25 ml toluene. The cooling water system for the condenser is initiated before heating the oil in the flask by a small burner. The toluene starts evaporating and the vapour gets condensed in condenser and is collected in the graduated burette at the bottom. The water content in the oil also get vaporised and is condensed to be collected in the burette. The water being heavier than toluene gets at the bottom layer in the burette. The toluene in the upper layer of the burette flows back to the flask to be evaporated again. The toluene vapours drive out the water vapours till it is present in the flask. The process of heating oil is continued till the water level collected in the burette remains constant with time.

The volume of water content collected in the burette can be noted with accuracy of 0.1 ml to give the water content in 100 ml oil sample.

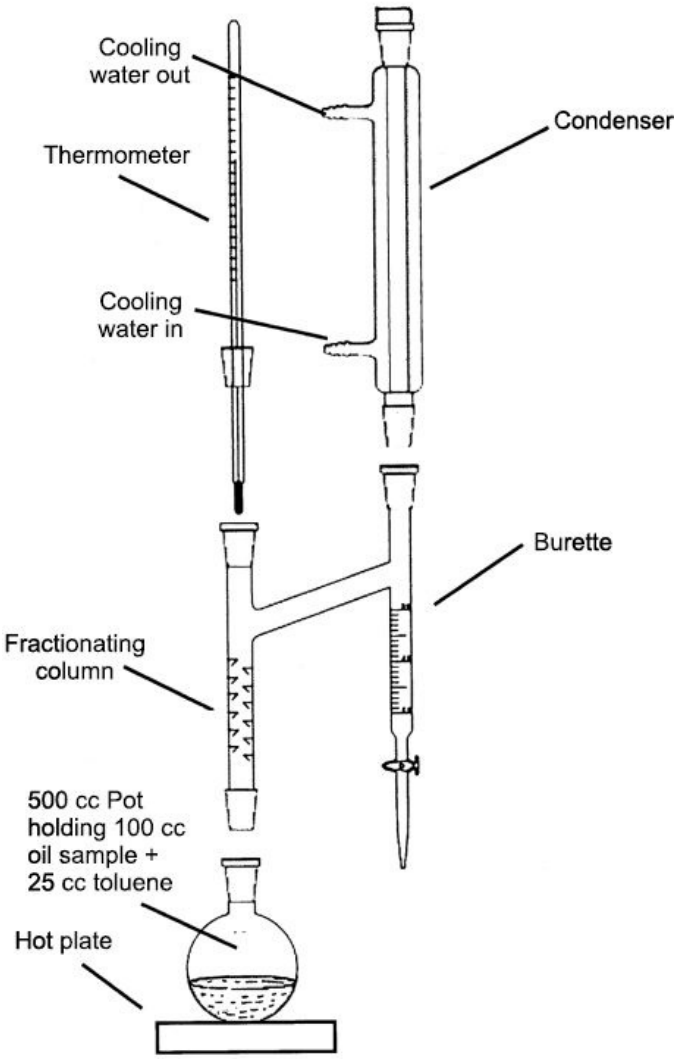


Figure 3.6 Dean–Stark apparatus set up for water test
(the separated parts fitted in place before use).

Review Questions

1. What are the merits and limitations of liquid fuels?
2. How is crude oil formed in nature? Give its chemical composition. Why does the chemical composition of crude oil not change much with geographical location like coal deposits?
3. What are the other sources of liquid oil in addition to natural crude oil? Describe in brief about such oil sources.
4. What is distillation process for treating crude oil? What are the various products obtained by oil distillation process?

5. What do you mean by CTF 50? How is it produced? Give its application.
6. Give suitable applications for the following oils:
   (i) White spirit
   (ii) Diesel
   (iii) Furnace Oil
   (iv) Tar
   (v) Naphtha (vi)
   CTF 200
7. Write short notes on the followings:
   (i) Oil shale
   (ii) Coal liquefaction
   (iii) Gasoline (Petrol)
   (iv) White spirit
   (v) Diesel
   (vi) Naphtha
   (vii) Furnace oil
   (viii) Redwood viscometer
8. Define the following terms:
   (i) Viscosity
   (ii) Absolute viscosity
   (iii) Kinematic viscosity
   (iv) Flash point
   (v) Fire point
   (vi) Spontaneous ignition point
   (vii) Oil specific gravity
   (viii) Gross calorific value
   (ix) Cloud point
   (x) Pour point
9. Give test procedure for determining the following oil properties: (i) Absolute viscosity
   (ii) Specific gravity
   (iii) Flash point
   (iv) Pour point
   (v) Cloud point

(vi) Sulphur content
(vii) Gross calorific value
(viii) Carbon residue
(ix) Ash content

10. Differentiate between the following terms:
(i) Dynamic viscosity and Kinematic viscosity
(ii) Poise and Stokes
(iii) Redwood 1 and Redwood 2 viscometer
(iv) Abel’s and Pensky Marten flash point apparatus
(v) Redwood and U tube viscometer
(vi) Flash point and Spontaneous ignition point
(vii) Gross and Net calorific value
(viii) Cloud and Pour point
(ix) Sludge and Sediment in oil
(x) Flask and Erlenmeyer flask

4

Gaseous Fuels

Introduction

The various applications in the metallurgical plant require gaseous fuels due to their merits, as discussed in Chapter 1. Following are some of the applications:

a. Coke oven heating
b. Heating blast furnace stove
c. Reductant in MIDREX DRI plant
d. Gas turbines for power generation
e. Soaking pits for ingot heating
f. Reheating furnaces
g. Heat treatment furnaces
h. Core baking in steel foundry
i. Ladle drying and preheating
j. Drying of newly lined furnaces
k. Drying of metal runners and spouts

The gaseous fuels may be derived from the following three sources:

a. **Natural source:** Natural gas
b. **Manufactured or commercially produced gases:** Producer gas, water gas, carburetted water gas, reformed natural gas, coal gas, oil gas, butane, propane, etc.
c. **By-product gases from metallurgical and petroleum units:** Coke oven gas, blast furnace gas, LD gas, gases from iron making units like COREX, oil refining gas, etc.

The generation, properties and use of these gaseous fuels are discussed in this

chapter.

4.1 NATURAL GAS

Natural gas is found in nature, buried under the rocks. The origin of natural gas is related with fossil fuel formation. The hydrocarbons released by the decaying vegetal and marine matter buried under the earth remains entrapped between rocks. The pressure and temperature of the overlying earth exerted on the vegetal and marine matter help in release of gaseous constituents. This natural gas is explored and taken out by drilling bore up to the deep pockets of gas in earth. Petroleum is also another resource found in proximity to and with natural gas.

Natural gas is a hydrocarbon gas-mixture consisting primarily of methane, but commonly includes varying amounts of other higher alkanes or paraffins (saturated hydrocarbons) and even a lesser percentage of carbon dioxide, nitrogen and hydrogen sulphide. Natural gas is an energy source often used for heating, domestic cooking and electricity generation. It is also used as a reductant for producing DRI (sponge iron) in processes like MIDREX.

The natural gas recovered from wells is treated to remove solid particulates. The natural gas containing less recoverable condensate (< 15 g/m^3) is termed as ‘dry natural gas’. When the recoverable condensate is more than 15 g/m^3 , it is called ‘wet natural gas’. The hydrogen sulphide (H_2 S) present in the gas is removed as elemental sulphur and the sulphur free natural gas is known as ‘sweet natural gas’. Thus, the processing of raw natural gas yields products like LNG (liquefied natural gas), CNG (compressed natural gas), ethane, propane, butane, pentane and elemental sulphur. Figure 4.1 shows a typical natural gas processing plant. In such plant, various unit processes are used to convert raw natural gas into saleable gas for the end user and various other products.

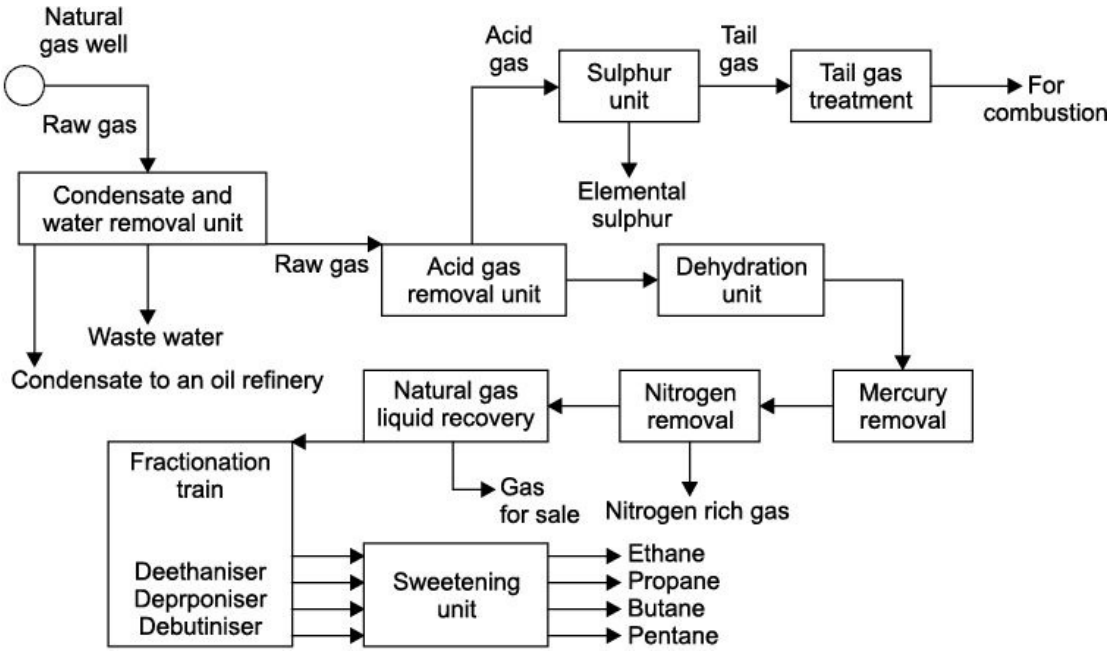


Figure 4.1 Natural gas processing plant flow-sheet.

The natural gas is distributed locally by pipeline (0.5–0.6 m dia) having gas pressure
15–30 kg/cm^2 . The long distance transportation is facilitated in liquid state as LNG and CNG.

The LNG (liquefied natural gas) is obtained as liquid by cooling natural gas at –160 °C. The CNG (compressed natural gas) for use in vehicles is produced by compressing the natural gas into liquid form at 200 atmospheric pressure. The properties of natural gas are given in Table 4.1.

Table 4.1 Properties of Natural Gas

Properties Composition, % Vol.	*Natural Gas*	
	Dry and sweet	*Wet and sweet*
CH_4	96.9	77.2
C_2H_6	1.3	11.2
C_3H_8	0.2	5.8
C_4H_{10}	0.05	2.3
C_5H_{12}	0.02	1.2
CO_2	0.8	0.8
N_2	0.7	1.4

Calorific value: MJ/m^3 kcal/m^3	37.68 9000	46.89 11200
Specific gravity	0.57	0.74
(Air specific gravity = 1)		

4.2 REFORMED NATURAL GAS

The reformed natural gas is prepared by synthesis of steam/flue gases (CO_2 + H_2 O) and natural gas to generate hydrogen rich gas for use as reductant in gas based DRI plants. The natural gas, LNG or naphtha is converted into synthesis gas (CO + H_2) after passing through catalytic tube reactors.

4.2.1 Technique Used by HyL III

The sulphur free hydrocarbon feed is mixed with superheated steam in accordance with the steam/carbon ratio necessary for the reforming process (Figure 4.2). This gas mixture is heated up and then distributed on the catalyst-filled reformer tubes. The gas mixture flows from top to bottom through tubes arranged in vertical rows. While flowing through the reactor tubes heated from the outside, the hydrocarbon/steam mixture reacts, forming hydrogen and carbon monoxide in accordance with the following reactions:

a. $C_n H_m + n H_2 O \rightarrow n CO + [n + (m/2)]H_2$

b. $CH_4 + H_2 O \rightarrow CO + 3H_2$

The removal of sulphur as H_2 S or COS from the feed gas is essential as it can poison the nickel used as a catalyst by forming NiS. The steam based reformation system is used by HyL III and HYTEMP process for DRI production. Table 4.2 gives the composition of reformed natural gas used in HYTEMP process. The units with production capacities of 1000 to over 120000 Nm^3/h are available for the plants.

Table 4.2 Analysis of Reformed Natural Gas

Reforming Agent	*Reformed Natural Gas (% Vol.)*								*User Industry*
	H_2	CO	CO_2	CH_4	H_2O	N_2	C_2H_6	C_3H_8	
Steam	73.0	16.8	6.2	2.6	1.0	1.1	–	–	DRI (HyL)

DRI off gas	53.0	35.0	2.0	2.5	5.0	2.5	–	–	DRI (MIDREX)

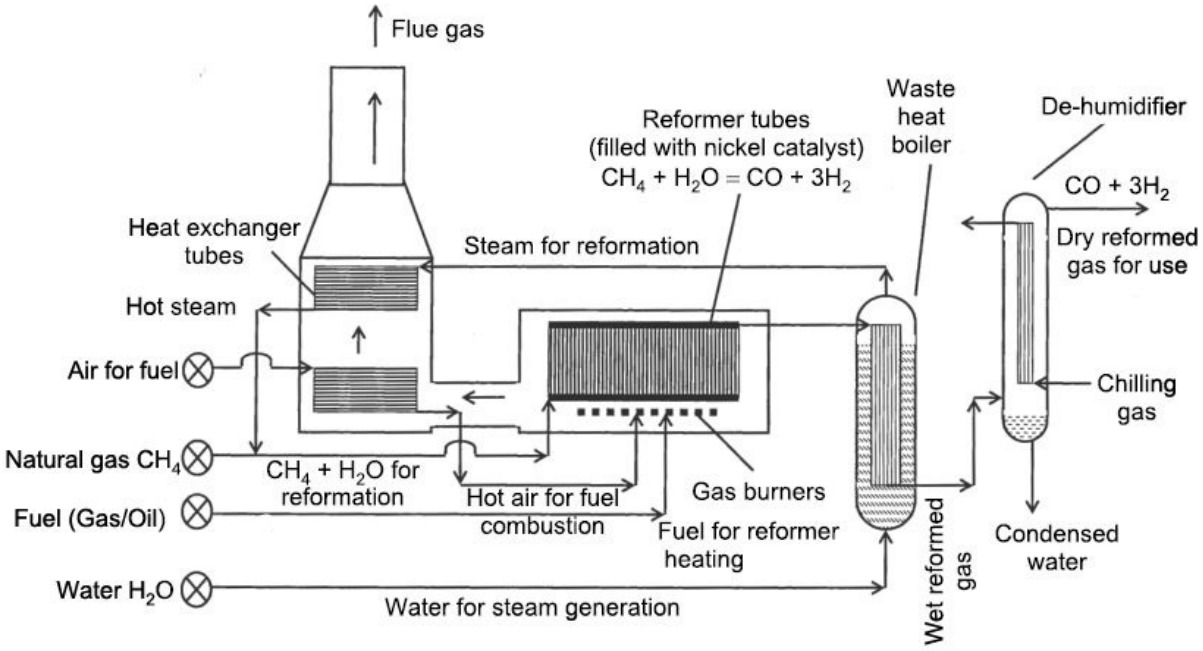


Figure 4.2 Flow sheet of natural gas reformation unit using steam.

4.2.2 Technique Used by MIDREX Process

The exhaust gas containing H_2 O and CO_2 is used by MIDREX process to generate rich reducing gas having CO and H_2 in the desired ratio.

The exhaust gas (top gas) emitted (Figure 4.3) from the top of the MIDREX shaft furnace is cleaned and cooled by a wet scrubber and recirculated for reuse. The top gas containing CO_2 and H_2 O is pressurised by a compressor, mixed with natural gas, preheated and fed into a reformer furnace. The reformer furnace is provided with several hundreds of reformer tubes filled with nickel catalyst. Passing through these tubes, the mixture of top gas and natural gas is reformed to produce reductant gas consisting of carbon monoxide and hydrogen. The reactions that occur in the reformer tubes are as follows: (i) $CH_4 + CO_2 \rightarrow 2CO + 2H_2$

(ii) $CH_4 + H_2O \rightarrow CO + 3H_2$

4.3 LPG (LIQUEFIED PETROLEUM GAS) OR BOTTLED GAS

LPG (liquefied petroleum gas) or bottled gas is prepared from natural gas and

refinery gas. LPG is often marketed in steel cylinders and hence also called ‘bottled gas’.

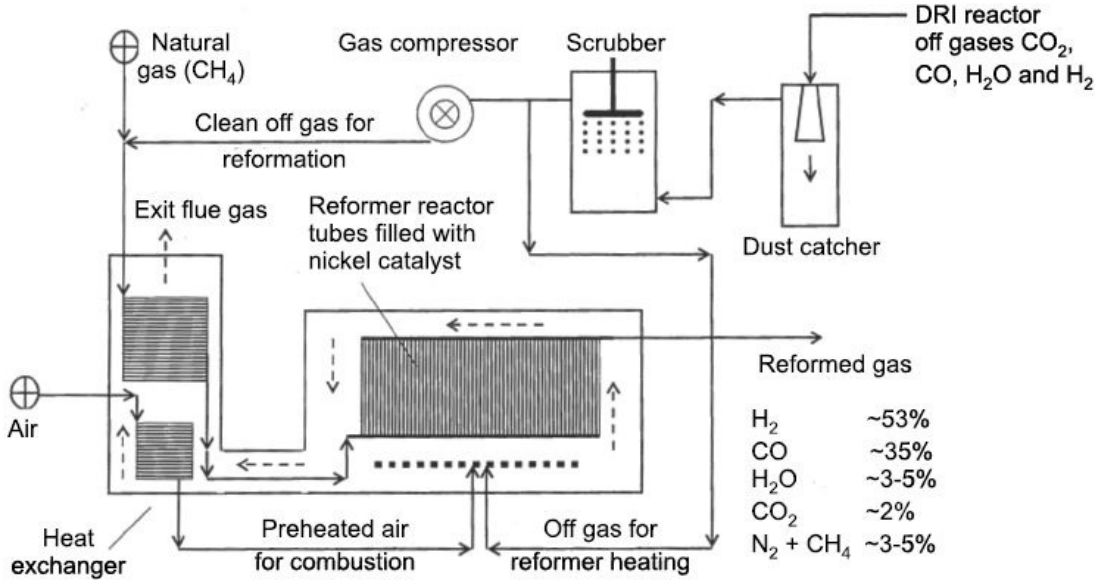


Figure 4.3 Reformation of natural gas using DRI off gases (MIDREX).

LPG is a mixture of 80% propane and 20% butane. The propane and butane are easily liquefied at room temperature with application of very low pressure. The LPG cylinders, therefore, do not require very strong extruded steel cylinders like other gas cylinders. The welded steel cylinders are used for LPG.

The properties of butane and propane are given in Table 4.3.

Table 4.3 Properties of Butane and Propane

Properties	*Butane*	*Propane*
Composition	C_4H_{10} –100%	C_3H_8 100%
Calorific value, kcal/m^3 MJ/m^3	30680 128.45	23670 99.10
Specific gravity As gas (specific gravity with respect to air) As liquid (specific gravity with respect to water)	2 0.584	1.52 0.508
Sulphur, wt.%	0.02	0.02
Liquid flash point, °C	–60	–105
Maximum flame temperature, °C	1925	2000

LPG has high calorific value, high specific gravity and possesses no odour. As LPG is highly inflammable, pungent smelling liquids like mercaptans (50 ppm) or sulphides are added to help in detecting leaking LPG. The LPG is very heavy gas than air, and therefore, the leaked gas does not diffuse easily in air.

The leaked LPG may flow like water in the direction of floor slope and can catch fire even if fire source is located far away in the direction of gas flow. Such leaking LPG cylinder gave back fire in an incident and caused the explosion of entire LPG depot.

The common use of LPG includes domestic use and heating industrial furnaces like annealing furnace, ceramic firing unit, etc.

4.4 BLAST FURNACE GAS

It is a by-product gas generated by conventional blast furnace iron making process. The exit gas laden with dust (10–25 g/m^3 with size 5 mm to 0.1 μm) emerges out at 200–380°C temperature and 1.03–1.14 atmospheric pressure. The exit gas contains considerable amount of carbon monoxide gas which is needed to maintain reducing atmosphere inside the blast furnace. This CO is generated by the gasification of coke fed from top and coal fines injected through tuyeres. The blast furnace yields nearly 2.5–3 tons off gas for every ton hot metal (thm) produced when coke rate is 550–700 kg/thm. This amounts to 1800–2000 m^3 gas per thm or 3000–3200 m^3 gas per ton coke charged in the blast furnace.

In view of this large quantity of CO rich gas generated during iron making, it is utllised as fuel gas. The off gases are passed through dust catcher which removes nearly 60–70% dust to bring down dust level from 10–25 g/m^3 to 4–6 g/m^3 . This dust is further removed in a wet scrubber to a level of 5 mg/m^3 . However, this old wet method of dust cleaning causes moisture saturation in the gas, which is passed through chilled chamber to remove moisture to a level of 5 g/m^3 . This cooled and cleaned blast furnace gas is stored in gas holders for use in the plant.

In the modern plants, this wet gas cleaning is replaced by bag filters and electrostatic precipitators to get the dust level below 5 mg/m^3 for use. This dry method of gas cleaning has several advantages like producing hot blast furnace clean gas which is good for use in blast furnace stoves. This dry method generates dry dust for reuse in the plant. The avoidance of water lowers the water need/thm and does not pose any waste water disposal issue.

The blast furnace gas is colourless, odourless and tasteless. It is highly **poisonous** due to its high CO content. The presence of the blast furnace gas in the working area is detected by various devices for safety of working people. The devices include old technique of keeping bird in a cage, pocket pen size indicator filled with chemical (palladium sulphide) and electronic devices (hand

held indicator or wall mounted alarm system). The exposure of CO gas beyond acceptable limits causes bird to faint, change of colour of chemical from green to blue or beep from electronic systems as a warning sign to move out and take remedial measures.

The blast furnace gas and air form a explosive mixture when gas is present between 37–71% in gas–air mix. The gas pipe is, therefore, always kept with positive pressure to avoid air infiltrating into gas pipe line and form explosive mix.

The blast furnace gas possesses low calorific value (800–850 kcal/m^3), high specific gravity (1.02) and low theoretical flame temperature (1450 °C) giving non-luminous flame. The properties of blast furnace gases are given in Table 4.4.

The blast furnace gas is used for various applications in the steel plant including:

a. Blast furnace stove heating,
b. Coke oven heating,
c. O perating gas engines for blowing air or power generation,
d. Heating applications in plant, e.g. soaking pits, reheating furnaces, etc.
e. Heat treatment furnaces and
f. Foundry and melt shop for ladle drying, mould drying, etc.

The blast furnace gas can be easily pre-heated (due to absence of any hydrocarbons) to get high flame temperature.

Table 4.4 Properties of Blast Furnace Gas

Properties	*Blast Furnace Gas*
Composition	CO 21–23% CO_2 18–20% H_2 4–5% N_2 53–55% O_2 0.2–0.5%
Calorific value, kcal/m^3 MJ/m^3	800–850 3.3–3.5
Specific gravity (air as 1.0) Density kg/m^3 (air as 1.28 kg/m^3)	1.01–1.09 1.3–1.4
Maximum flame temperature, °C	1450

4.5 COKE OVEN GAS

The coal carbonisation in by-product coke oven yields metallurgical coke as main product and coke oven gas as by-product. When the coking coal is heated in the coke ovens the volatile matter present in it is evolved as gas which is collected for the preparation of various liquid fuels (coal tar fuels–CTFs) and gaseous fuel termed as ‘coke oven gas’. Nearly 280–350 m^3 gas is generated for every ton coke production, however, the amount of gas and its composition depend on operating parameters like coke oven temperature and volatile matter present in coal.

The quantity and composition of coke oven gas are affected as follows:

Factors affecting the quantity of coke oven gas

a. The gas yield increases with higher carbonisation temperature due to cracking of hydrocarbons, e.g. tar.
b. The gas yield increases with higher volatile matter content in the coal which is carbonised.

Factors affecting the composition of coke oven gas

a. The hydrogen content of the gas increases with higher carbonisation temperature due to cracking of hydrocarbons.
b. Methane and other hydrocarbon constituents decrease with higher carbonisation temperature due to their cracking into hydrogen.
c. The higher volatile matter in coal gives a gas rich in hydrocarbons.
d. The calorific value of gas decreases with higher carbonisation temperature due to reduction in hydrocarbons which is not compensated by increase in hydrogen content.

Table 4.5 Composition and Properties of Coke Oven Gas

(a) Gas Analysis

Methane CH_4	H_2	CO	CO_2	N_2	H_2S	*Ethane* C_2H_6	*Ethylene* C_2H_4	*Propane* C_3H_8	*Butane* C_4H_{10}	*Acetylene* C_2H_2
24–29	58–60	7– 8	1– 4	1–3	0.5–1	0.5–1.5	1–2.5	0.05–1	0.01–0.05	0.01–0.05

(b) Properties

Density, kg/m^3	0.43–0.45
Specific gravity	0.33–0.36
Calorific value, $kcal/m^3$ MJ/m^3	4200 17.58
Explosion limit, percentage of gas in gas–air mix	5–32
Theoretical flame temperature, °C	>2000

The composition and properties of coke oven gas are given in Table 4.5. The coke coven gas is used as fuel in various sections of the steel plant which include the following:

a. Coke oven heating
b. Blast furnace stoves
c. Blast furnace cast area for drying runners
d. Power plant
e. Furnaces like soaking pits, reheating furnaces, heat-treatment furnaces, etc.
f. Foundry shop for baking and drying
g. Forge shop for reheating billets
h. SMS for ladle drying

4.6 LD STEEL GAS

The hot metal from blast furnace is converted to steel by blowing oxygen in most commonly used LD converter (Basic Oxygen Furnace–BOF). The carbon in hot metal is oxidised to CO and CO_2 during blow period. The exit LD gases during blow period contain more than 60% CO alongwith other gases like CO_2 and N_2 . The CO formed during steel making burns partially at the converter mouth to give some amount of CO_2 . The nitrogen and oxygen are derived from air getting mixed with exit LD gases at the mouth of the converter which are collected, cleaned and stored for use as a fuel due to their high CO content. This

gas has net heating value equivalent to 3 kWh/Nm^3 .

The merit of this gas includes waste gas utilisation, avoidance of air pollution caused by its emission to the atmosphere and cost effective energy/power alternate source in the plant. The source has limitation of its availability on continuous basis, since LD steel is a batch process and the LD gas is generated for a short duration (15 min/blow) during oxygen blow. This needs gas storage and use as a fuel within the plant.

4.7 COREX GAS

The COREX iron making technology is based on using non-coking coal as fuel to produce liquid iron by a newly developed smelting reduction technology. In India, this is being practiced at Bellary JSW Plant. The COREX process produces hot metal and COREX gas as two major products. Figure 4.4 shows the salient features of COREX plant.

The COREX iron making system consists of two reactors—melter gasifier and pre-reduction shaft.

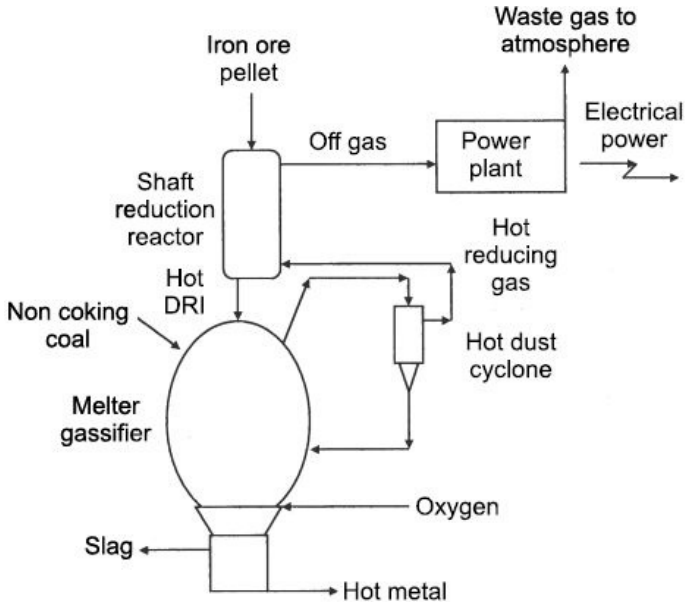


Figure 4.4 Flow sheet of a COREX iron and COREX gas making unit.
(Adopted from R.C. Gupta, *Energy and Environmental Management in Metallurgical Industries* , PHI Learning, Delhi, 2012.)

Melter gasifier

This is the main reactor of the COREX plant. The hot pre-reduced iron ore from the shaft reactor is delivered by screw conveyors into the melter gasifier where it

is melted and slag separation occurs from molten iron. The required heat energy is met by the combustion of non-coking coal. The non-coking coal (–50 mm, +6 mm) is fed separately into the reactor alongwith pure oxygen for combustion. When the coal fed at upper level comes in, contact with the hot gases, it is dehydrated and degasified forming coal char. This coal char is gasified to reducing gas after reacting with pure oxygen injected in the lower part of reactor. As a result of an exothermic reaction, high temperature > 2400 °C is generated. The hot gases mainly consisting of carbon monoxide flowing from the fluidised bed to the top of the reactor. The slag and hot metal layers are maintained in the bottom section of the reactor. The upper part of the reactor is designed as freeboard.

The raw gas from the reactor has a temperature > 1200 °C in the freeboard. These hot gases are cleaned from dust in hot cyclone. The major part of the entrained coal char dust, and ore particles are recycled to be reduced as iron. The hot gases are fed into the shaft reactor to cause reduction of the ore charge.

Pre-reduction shaft

This reduction shaft pre-reduces the ore burden fed in the form of lump or pellet. This feed is pre-reduced to more than 85% metallisation by a hot gas containing CO and H_2 supplied from the melter gasifier.

The exit gas from iron ore pre-reduction shaft is still rich in CO content and it is used as a fuel in the power plant. The gas is generated at the rate of 1650 m^3 /thm. This COREX gas is available in the plant as a by-product fuel. The properties of COREX gas are given in Table 4.6. The COREX is utilised by a dedicated power generation plant. The process economies provide opportunity to produce iron and power together in a plant.

Table 4.6 Properties of COREX Gas

Properties	*COREX Gas*
Composition	CO ~ 44% CO_2 ~ 34% H_2 ~ 15% N_2 ~ 3% O_2 0.2 – 0.5%
Calorific value, kcal/m^3 MJ/m^3	1790 7.49

4.8 PRODUCER GAS

Producer gas, rich in CO and H_2 is manufactured by using solid fuel like coal or coke. The manufacture of this gas combines the merits of easily available solid fuel as primary source and clean rich gaseous fuel as final product for use.

The producer gas is manufactured by blowing air with or without steam through a thick bed of hot solid fuel (coal/coke). The air blown causes carbon in coal/coke to get converted into CO and CO_2 gas. The introduction of steam gives hydrogen as a result of reaction with carbon. The volatile matter present in the upper layer of coal/coke bed evolves due to heat and joins the out going gases.

4.8.1 Properties of Producer Gas

The typical producer gas analysis, generated by using coal as fuel and air as blowing media, is given in Table 4.7. The producer gas rich in hydrocarbons is obtained while using coal as fuel due to high volatile matter content present in coal. The introduction of steam increases hydrogen content of the gas.

The calorific value of producer gas ranges from 1200 to 1500 kcal/m^3 depending on the fuel and blow media. The flame propagation rate is slow due to the presence of large (60–65%) volume of inert constituents like N_2 and CO_2 . The producer gas burns with luminous flame when produced from coal due to the presence of hydrocarbons. The flame is non-luminous when made from coke or anthracite due to absence of hydrocarbons in the gas. The specific gravity of producer gas is high (0.85–0.9) which is helpful in directing the flame in the desired direction. The producer gas can be preheated to get high flame temperature as it is free or contains very low in hydrocarbon.

Table 4.7 Properties of Producer Gas

Gas Analysis, % Vol.	CO	H_2	CH_4	CO_2	N_2
	20–30	1–15	0–3	1–6	45–75
Calorific value, kcal/m^3 MJ/m^3	1000–1400 4.0–6.0				
Specific gravity	0.85–0.90				

4.8.2 Manufacturing Process of Producer Gas

The producer gas manufactured by using a reactor is shown in Figure 4.5

schematically. It is a shaft type cylindrical reactor having three major sections, the charging system located at the

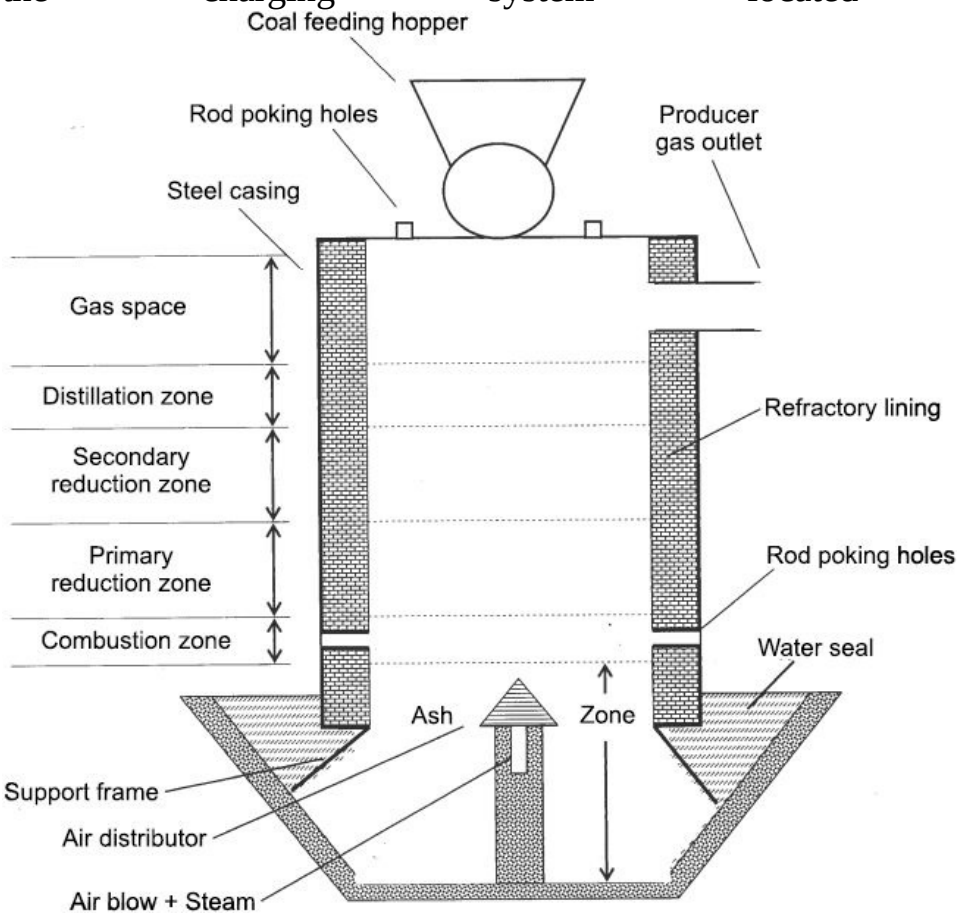


Figure 4.5 Producer gas unit (schematic).

top, shaft reactor forming the middle section and air blowing with ash disposal system located at the bottom. The diameter of the reactor depends on the desired rate of gas generation. The reactor shell is made of steel which is lined with fireclay bricks. The gas off take is located at the top. The holes are provided on the top and side wall to poke the coal bed in case it gets fused. The shaft reactor rests on the bowl shape trough on the ground level. This trough is filled with water which acts as bottom gas seal. The air distributor hood is located above the water level. The air hood is designed in a way to allow air to move up, but the ash descending down does not block the air hood.

The top feeding system is a rotating chamber attached to hopper which prevents the gases leaking out while the charging is made continuously. The cylindrical reactor is tall enough to accommodate coal charge to give specified gas rate. This reactor may be assumed to have the following five zones: (i) Free space zone

The first top zone is a free space for the gas and it extends from top to a level below the gas off take point.

(ii) Distillation zone

The second zone, extending below free space to about 300–350 mm, serves as a distillation zone. This zone has temperature 400–600 °C to cause the removal of moisture and volatile matter.

(iii) Secondary reduction zone

The third zone (~ 900–1100 °C) extending 450–500 mm below the distillation zone is called secondary reduction zone. In this zone, the hydrogen gas is formed due to following reaction: $CO + H_2O \rightarrow CO_2 + H_2$ (Shift reaction—Exothermic

(iv) Primary reduction zone

This is a high temperature (1200–1300 °C) gasification zone extending to a depth of about 300–350 mm between secondary reduction zone and combustion zone. The generation of H_2 and CO occurs as a result of the following reactions:

$$C + H_2O \rightarrow CO + H_2 \text{ (Carbon gasification—Endothermic)}$$

$$C + CO_2 \rightarrow 2\,CO \text{ (Baudouard reaction—Endothermic)}$$

(v) Combustion zone

This combustion zone, extending about 150 mm above the ash zone, is the highest temperature zone (1300–1500 °C) where the carbon in the feed is burned to give heat and CO_2 gas.

$$C + O_2 \rightarrow CO_2 \text{ (Combustion reaction—exothermic)}$$

The steam is injected in regulated quantity to give granulated ash for easy disposal.

The ash zone below the combustion zone is located in the bottom trough filled with water to act as gas seal. The ash is periodically removed out from the trough for disposal.

The good operating conditions are indicated by cherry red top surface with off gases leaving at 600 °C. This hot gas is useful if it is used without cooling. When cool gas is needed the off gas temperature is kept low (~ 400 °C) rendering top surface looking black. The very high temperature of exit gas is indicative of thin fuel bed and very low off gas is indicative of too thick coal bed or moist coal feed.

4.8.3 Flexibility of Use of Fuel for Generating

Producer Gas

The producer gas can be generated from a variety of solid fuels (Table 4.8) like anthracite coal, bituminous non-coking coal and low grades of coke. The coal used for producer gas should not be caking in nature and must not swell on heating. The low ash in coal is preferable, but not a necessity. The coal size ranging 20–30 mm are common. The bigger size coal (30–50 mm) is preferred by large plants. The refractory ash (fusion temperature ~ 1400 °C) is preferred as it helps in smooth operation of the plant.

4.8.4 Applications

The raw hot producer gas was used as fuel in the past for open hearth steel making process in non-integrated steel plants. Even now, at some places the open hearth furnaces are useful for generating liquid melt for big steel castings. Such open hearth furnaces have choice to adopt producer gas over liquid fuel.

Table 4.8 Producer Gas Composition with Different Fuel and Blow Media

Blow Media	*Fuel*	*Producer Gas Analysis*					*Calorific Value*	
		CO	H_2	CH_4	CO_2	N_2	$kcal/m^3$	MJ/m^3
Air	Bituminous coal	31	5	2	1	61	1190	4.98
Air	Coke	32	1	–	1.5	65	940	3.93
Air + Steam	Bituminous coal	26	15	3	6	50	1390	5.82
Air + Steam	Coke	27	13	–	6	54	1170	4.90
Air + Steam	Anthracite	26	17	1	6	50	1420	5.94

($1\ kcal/m^3 = 0.0042\ MJ/m^3$)

At present, the producer gas is commonly used in non-integrated steel plants for soaking pits and reheating furnaces due to its flexibility of adopting different types of solid fuel. Further, the heavy gas with long luminous flame is highly desired for reheating long billets.

The conventional integrated steel plants use producer gas plant as stand-by system if there is a problem in coke oven or blast furnace to meet the gas supply for other units under special circumstances. This is very useful during blast furnace relining period to meet the plant gas supply.

The producer gas plants are easy to install with wide range capacity in short time which make it highly flexible for use.

4.9 WATER GAS (OR BLUE GAS)

The water gas or blue gas is manufactured to obtain rich fuel gas containing H_2 and CO. This gas burns with non-luminous intense flame. This gas is produced when steam is passed though hot bed of carbon (coke) giving H_2 and CO according to the following endothermic reaction:

$$C + H_2O \rightarrow CO + H_2$$

The endothermic reaction between carbon and steam lowers the coke bed temperature after certain period and this reaction cannot be sustained further. Therefore, gas generation has to be carried out for short period, called ‘run period’ followed by flow of air to burn carbon (coke) to regain the coke bed temperature which is called ‘blow period’. Thus, the water gas plant follows ‘blow’ and ‘run’ period in cyclic manner to generate the gas. The gas generated during ‘run’ period is collected while gas generated in ‘blow period’ is bled out as it contains waste gases like carbon dioxide, nitrogen and oxygen.

4.9.1 Water Gas Generation Unit

The water gas generation unit consists of a shaft type reactor shown schematically in Figure 4.6. It has a tall refractory lined chamber to hold a thick (2.1–2.2 m) bed of coke. This coke can be fed from the top end. The un-consumed coke and ash is discharged out after the end of batch operation through a man hole. The air is supplied to the unit during ‘blow period’ from air distributor located at the bottom end. The arrangement is made to collect water gas both from top and bottom end. The steam can be supplied from top and bottom end during ‘up run’ or ‘down run’ period. The gases during blow period are bled through a valve at the top. The entire system is controlled by regulating the following six valves (Figure 4.6):

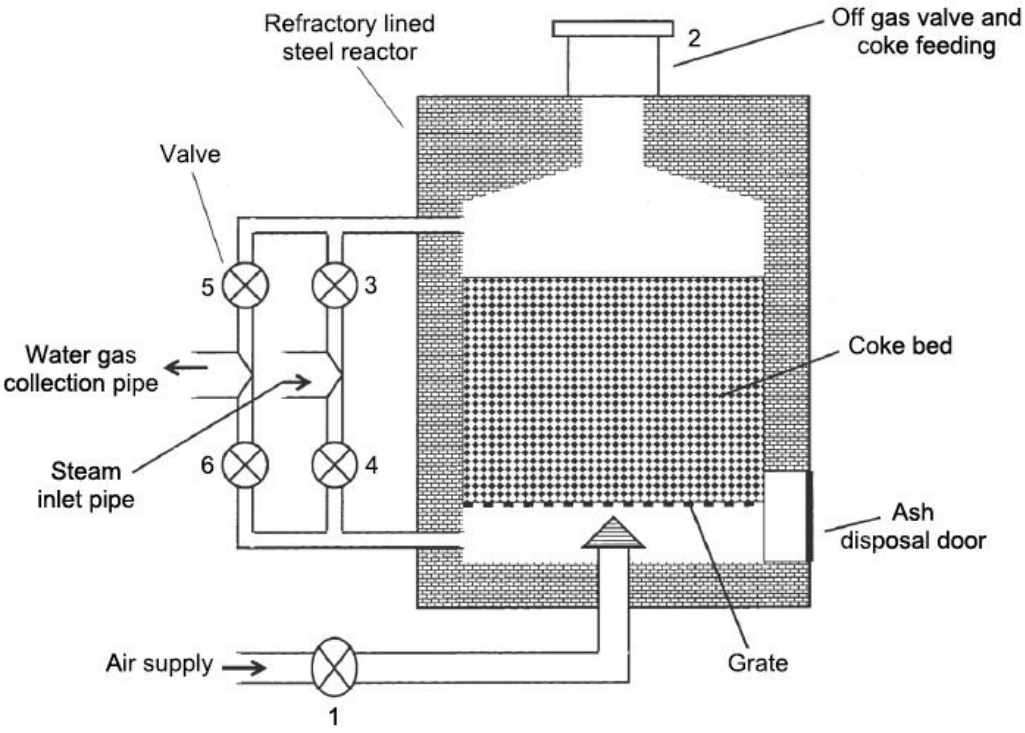


Figure 4.6 Water gas unit (schematic).

Valve 1 – Air valve
Valve 2 – Stack valve
Valve 3 – Steam valve
Valve 4 – Steam valve
Valve 5 – Gas valve
Valve 6 – Gas valve

The running water gas plant operation has following eight steps which are conducted in cyclic manner actuating the six valves in prescribed manner: **Step I (*Blow Period*):** Open Valve 1 and Valve 2 to burn coke (heating of coke bed) an bleed out waste gas.

Step II (*Blow Purge*): Open Valve 3 and Valve 2 (for 20 seconds) to purge out waste gases present in the chamber by steam flow.

Step III (*Up Run*): Open Valve 3 and Valve 5 to blow steam and collect water gas for 2–3 minutes.

Step IV (*Run Purge*): Keep open Valve 5 for few seconds to collect water gas present in the system.

Step V (*Blow Period*): Open Valve 1 and Valve 2 to burn coke (heating of coke bed) and bleed out waste gas.

Step VI (*Blow Purge*): Open Valve 3 and Valve 2 (for 20 seconds) to purge out

waste gases in the chamber by steam flow.

Step VII (*Down Run*): Open Valve 4 and Valve 6 to flow steam in downward direction and collect water gas for 2–3 minutes.

Step VIII (*Run Purge*): Keep open Valve 6 for few seconds to collect water gas present in the system.

These eight operational steps are repeated in cyclic manner to keep the plant running.

This cycle of blow, up-run, down-run and again blow is repeated in cyclic manner with purge intervals. The steam flow from two directions, i.e., upwards during up-run and downwards during down-run keeps the coke bed temperature uniform across the section. The composition and property of the gas is given in Table 4.9.

Table 4.9 Properties of Water Gas

Gas Analysis, % Vol.	CO	H_2	CH_4	CO_2	N_2
	4 0– 42	4 8– 51	0.1 – 0.5	3–5	3 – 6
Calorific value, kcal/m^3 MJ/m^3	250 0 – 2800 10. 5 –11.7				
Specific gravity	0. 5 – 055				

4.9.2 Fuel Quality for Water Gas Generation

The fuel used for water gas plant must have high carbon content and free from volatile matter. The volatile matter evolved during gasification will add hydrocarbons in the product gas which is undesired. This is the reason of using only coke as a fuel for the preparation of water gas. The coke used must be highly reacting in nature for faster gasification. The porous and low strength coke which are unsuitable for metallurgical use are suitable for water gas production. The low ash content is desirable, but not essential requirement for use. The ash fusion temperature must be high to avoid its fusion and inhibit gasification process. The coke size 25–75 mm is suitable for use which must be freed from fines as it may affect the permeability of the bed.

4.9.3 Applications of Water Gas

It is used for burning at places which require non-luminous (blue) flame or need

reducing atmosphere containing CO and H_2 . The water gas also forms a source of hydrogen for chemical plants. The applications include:

a. Heating furnace
b. Chemical plants
c. Synthesis of liquid fuel (Methanol) [$CO + 2H_2 \rightarrow CH_3 OH_{liquid}$ (Methanol)]

4.10 CARBURETTED WATER GAS

The carburetted water gas is a mixture of water gas and oil gas. The oil is heated to give various hydrocarbons which when mixed with water gas renders it higher calorific value and flame luminosity which is needed for some applications. The property of carburetted water gas is given in Table 4.10.

Table 4.10 Carburetted Water Gas Properties

Gas Analysis, % Vol.	CO	H_2	CH_4	C_mH_m	CO_2	N_2
	30.5	37	14	7	5	5.5
Calorific value, kcal/m^3 MJ/m^3	4700 19.67					
Specific gravity	0.63					

4.11 OIL GAS

It is a combination of cracked petroleum oil and water gas made by passing oil vapours with steam through hot refractory checker work. The oil gas is commercially important in regions where cheap oil is available compared to coal or coke. The typical oil gas property is given in Table 4.11.

Table 4.11 Oil Gas Properties

Gas Analysis, % Vol.	CO	H_2	CH_4	C_2H_4	C_6H_6	CO_2	N_2
	12.7	48.6	26.3	2.7	1.1	4.7	3
Calorific value, kcal/m^3 MJ/m^3	4903 20.5						
Specific gravity	0.47						

4.12 TESTING OF GASEOUS FUELS

The gas in industrial units is tested very often mainly for its following two properties to regulate the process:

a. Composition of gas and
b. Calorific value

These are discussed in the forthcoming sections.

4.12.1 Gas Analysis Methods

The instruments developed for determining the qualitative and quantitative composition of gas mixtures are widely used in the industry to monitor the gas composition changes in the process on-line or off-line. These gas analysers are of two types—manual and automatic as given below: **Manual Operated Gas Analysis Instruments:** These gas analysers are based on the absorption principle. The desired component of a gas mixture is absorbed one after another by different chemical reagents. The *Orsat Apparatus* is a typical example.

Automatic Gas Analysis Instruments: These are based on measuring chemical or physical property of gas. These instruments analyse gas continuously with time. Such instruments are called by different names based on measuring technique.

Instruments using chemical property of gases

Chemical gas analyser: These instruments measure change in volume or pressure resulting from chemical reactions of its components.

Thermo-chemical gas analyser: These are based on the heating effect of the reaction of gas combustion (oxidation). These are useful in detecting high concentrations inflammable gases (e.g. CO in air).

Electrochemical gas analyser: These are based on electro-conductivity of a solution absorbing the gas in question.

Photo-colourimetric gas analyser: These are based on the colour change of certain chemicals when they react with a component of a gas mixture. Such instruments are useful in detecting toxic impurities in gas mixtures in small concentrations (e.g. hydrogen sulphide and nitrogen oxides).

Chromatographic processes: These are most widely used to analyse mixtures of

hydrocarbon gases.

Instruments using physical property of gases

Thermo-conductometric gas analyser: These are based on thermo-conductivity changes in gases. These may be used to analyse two-component mixtures or multi-component mixtures.

Densimetric gas analyser: These are based on the change in the density of a gas mixture. These are used chiefly to determine the quantity of carbon dioxide in a mixture.

Magnetic gas analyser: These are used mainly to measure the concentration of oxygen in a mixture. The oxygen gas is known to have great magnetic susceptibility.

Optical gas analyser: These are based on the light absorption. The light absorption or the emission by a gas mixture is used to analyse the gas.

Ultraviolet gas analyser: These are based on using ultraviolet light to detect the small quantity of halogens, mercury vapours and certain organic compounds in a gas mixtures.

The gas analysis is a subject itself, and various advanced instruments are available to determine chemical analysis on-line with accuracy. The equipment are maintained by experts in the field. Any detailed discussion on such methods is beyond the scope of this book.

4.12 .2 Gas Analysis by Orsat Apparatus

The plants which are not equipped with modern instruments, the old chemical absorption method of gas analysis by Orsat apparatus is still in practice due to the following merits:

a. The method is based on absorption of gas by a fluid and hence provides direct gas analysis without any calibration
b. The apparatus is portable and can be taken to site for on spot analysis.
c. It is cheap and easy to maintain.
d. It can determine gases like CO, CO_2 , H_2 , O_2 , N_2 and total hydrocarbon gases which are common in fuel and flue gases.

The working principle, apparatus details, analysis preparatory procedure, analysis procedure for gas with and without hydrogen and saturated hydrocarbon

analysis of gas by Orsat apparatus are described in the next sections.

Working principle

The Orsat apparatus works on the principle of gas absorption by a chemical solution. The change in gas volume due to absorption is measured at constant atmospheric pressure and room temperature. The solutions used to analyse the gases are as follows:

a. KOH solution for carbon dioxide
b. Bromine water for unsaturated hydrocarbon gases
c. Alkaline pyrogallol solution for oxygen
d. Amonical cuprous chloride solution for carbon monoxide.

The unabsorbed gas is taken as nitrogen. In case the gases contain hydrogen or methane, then these can also be determined by providing additional arrangement for their conversion to H_2 O and CO_2 to be absorbed by water and KOH solution.

Apparatus details

The Orsat apparatus consists of following components:

a. U-shaped absorption bulbs
b. 100 ml capacity gas tube with graduations.
c. 250 ml bottle filled with mild acidic water, coloured with methyl orange to regulate the gas movement and measure gas volume.
d. A glass many-fold fitted with two way stop cock for each bulb and one three way stop cock to connect gas source and atmosphere to the Orsat apparatus.

All these components are shown in Figure 4.7 which is mounted in a wooden case with sliding front and back covers for safety. The total weight of the apparatus is about 7–8 kg which makes it portable.

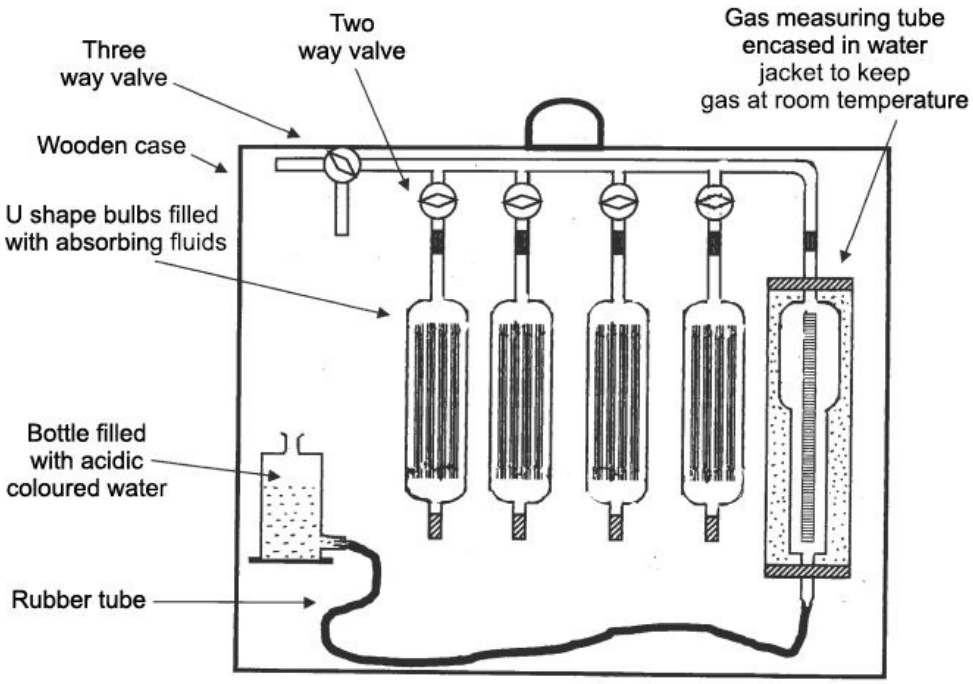


Figure 4.7 Orsat's apparatus for gas analysis.
(Adopted from R.C. Gupta, *Theory and Laboratory Experiments in Ferrous Metallurgy* , PHI Learning, Delhi, 2010.)

The U-shaped bulb shown in Figure 4.8 is open at one end while the other end is connected to the apparatus. The bulb connected to the apparatus is filled with glass tubes to offer increased surface area for gas absorption. The tube connecting the bulb and apparatus is narrow in diameter and bears a mark up to which solution level is maintained.

The volume of gas depends on two parameters, viz. pressure and temperature. The volume of gas is measured at room temperature and this is possible by keeping the measuring tube in a water jacket which acts as a thermostat. The pressure while measuring volume is always kept as one atmosphere. This is possible by adjusting the water in the bottle and the measuring tube at same level. The open bottle is exposed to the atmospheric pressure which is equal to pressure of gas in measuring tube as both are connected by a rubber tube filled with water, thus, forming two limbs of a U-tube. The bottle when lowered gives a negative pressure in the measuring tube, and when raised it puts positive pressure. Hence, by moving the bottle up or down the gas in measuring tube can be provided positive or negative pressure, causing the gas in and out from the measuring tube provided stop cock (2 or 3 way) is open for gas movement.

The three-way stop cock has three openings (Figure 4.9) which are connected to the source of gas to be analysed (G), Orsat apparatus gas intake (O) and atmosphere (A) for expelling gas from the source or apparatus. These three

openings are indicated by two ends of the knob and a mark or projection on one side of the knob. The knob position will indicate which two points are connected as shown in Figure 4.9. An inclined position disconnects all points and the system gets closed.

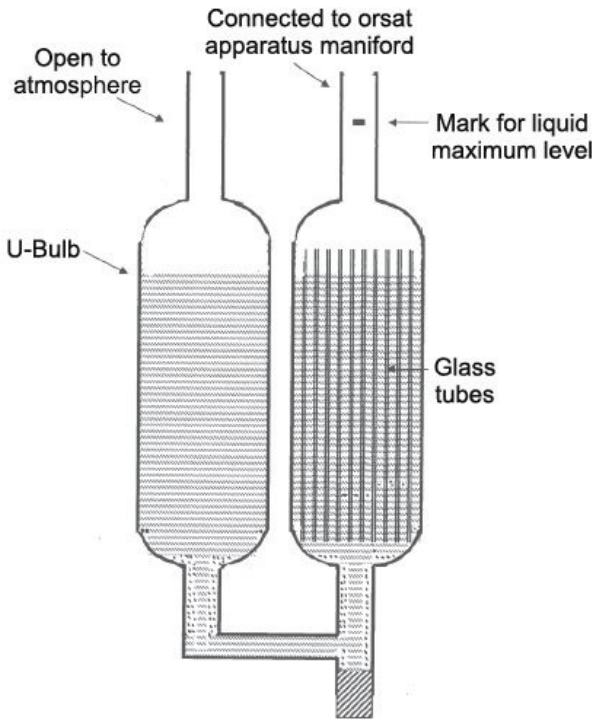


Figure 4.8 U-shaped absorption bulb in Orsat apparatus (side view).

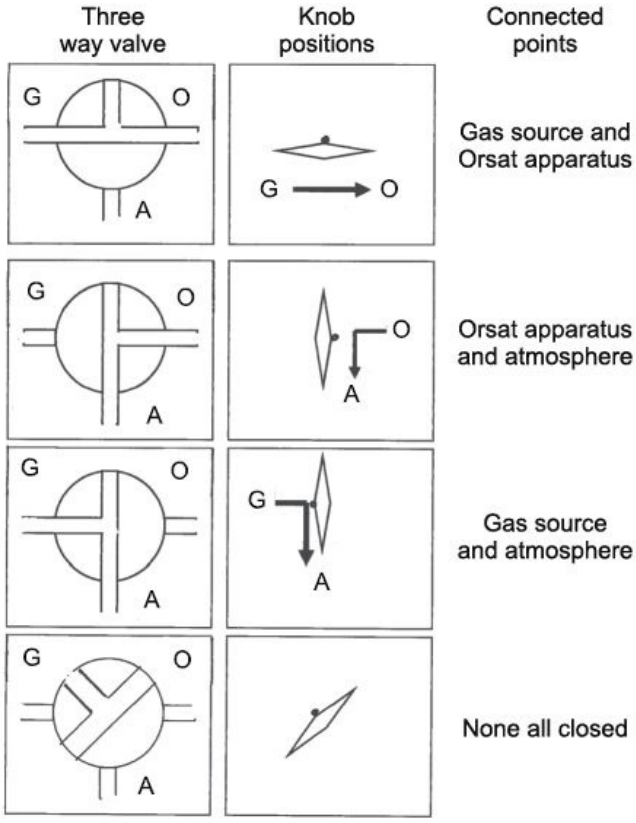


Figure 4.9 Various positions of three way valve to give suitable connection.

(Adopted from R.C. Gupta, *Theory and Laboratory Experiments in Ferrous Metallurgy*, PHI Learning, Delhi, 2010.)

The combustion attachment shown in Figure 4.10 is optional. It is used when the analysis of hydrogen and methane is needed. It consists of an additional U-shaped bulb filled with distilled water. This bulb is fitted with a bent tube filled with a catalyst (palladium asbestos), and wound with heating element wire to provide heat when a 9 V DC current is passed. This heated catalyst causes conversion of H_2 or CH_4 into CO_2 and H_2O in the presence of oxygen. The H_2O formed gets condensed in water bulb and the CO_2 generated by the reaction is measured by KOH bulb. The O_2 remaining unused is determined by pyrogallol solution. All these measurement would give H_2 and CH_4 content by calculation which is illustrated in following section.

Analysis preparatory procedure

The analysis of gas requires few preparatory procedures:

Gas Sampling: The gas to be analysed is collected in a gas bottle as shown in Figure 4.11. It is a 5 litre jar having water filled funnel at its top. The water flowing in from the funnel will displace the gas held in it which will come out from gas exit. The drain tap at bottom allows water to drain causing negative pressure in the bottle to suck gas from the source. The bottle filled with water is connected to source and drain tap is opened to collect the gas in the bottle. The source is disconnected and all the collected gas is expelled to the atmosphere as the pipe line may have some other gases. The gas collected in second or third attempt is used for analysis by Orsat apparatus.

Removal of waste gas from Orsat apparatus: The Orsat apparatus is a system with glass bulbs and connecting tubes which may have waste gases, and it needs to be expelled before analysing the sample gas. This is done in following manner:

a. Keep the 3-way valve open to the atmosphere.
b. Raise the water bottle to expel all the gases in the measuring tube and bring the water level at zero ml reading.
c. Close the 3-way valve.
d. Open the 2-way valve of KOH bulb and lower the water bottle to raise KOH solution level to the maximum level mark on the capillary tube of U-shaped bulb and close the 2-way valve.
e. Repeat Step 4 for all the remaining bulbs such that liquid in all bulbs is brought to the maximum level mark on the capillary tube.
f. Expel all gases to the atmosphere thus collected in measuring tube.
g. Connect the 3-way valve to gas sample bottle and suck gas into measuring tube up to 80 ml mark.
h. Expel this collected gas to the atmosphere.
i. Repeat it again to ensure that capillary system is free from other gases.
j. Now, the apparatus is ready for gas analysis.

Analysis procedure for gas without hydrogen and saturated hydrocarbon

a. Connect the apparatus with gas source and collect 80 ml in the measuring tube (at atmospheric pressure and room temperature).

b. Open the 2-way valve of KOH bulb and raise the water bottle to pass nearly 60 ml gas into KOH bulb and then lower again to take it out. This sending gas in the bottle and taking out gives one cycle of absorption. Repeat this to get three cycles and bring the KOH solution to its original mark. Notice the change in volume of gas. This is due to absorption of CO_2 by KOH solution. Give one more cycle of gas absorption and notice the change. If no further change in volume is found, then final reading is taken.
c. Now, pass the remaining gas in 2nd bulb having bromine water for 3–4 cycles to remove unsaturated hydrocarbons. Before noting the change in volume, the gas is passed two times in KOH bulb. This will help in removing bromine vapour which might have been added to the gas as it is volatile. Now, note the volume of the remaining gas. The difference from previous reading will give the volume of hydrocarbon gases.
d. The remaining gas is now passed into 3rd bulb, containing alkaline pyrogallol. This is a slow absorbent and hence, would need minimum 6–7 gas cycles to notice the change due to removal of oxygen.
e. The remaining gas is now passed into 4th bulb having ammonical cuprous chloride solution for 3–4 cycles to note the change due to removal of CO.
f. The remaining gas in measuring tube is taken as inert gas and accounted for nitrogen.

The per cent gas analysis is calculated after knowing the volume of CO_2 , hydrocarbons, O_2 , CO and N_2 in 80 ml gas sample.

Analysis procedure for gas having hydrogen and methane

a. Follow the procedure given in section 4.12 .2.
b. Assuming the remaining volume of gas is *x* ml which contains H_2 , CH_4 and N_2 .
c. Attach a sample bottle filled with pure oxygen to the 3-way valve at point open to gas (G) and take (80 – *x*) ml of oxygen to make total volume as 80 ml in measuring tube. The oxygen is taken in excess to burn H_2 and CH_4 .

d. Supply 9 V current in the heating coil on the catalyst tube, and then pass the gas having H_2 , CH_4 , N_2 and O_2 through it. The following reactions will occur:

$$H_2 + \frac{1}{2}O_2 \quad H_2O \qquad CH_4 + 2O_2 \quad CO_2 + 2H_2O$$

The steam formed by above reactions will get condensed in water bulb. The volume measurement will give volume of CO_2 and unused O_2 with N_2 .

e. Pass this gas mixture to KOH bulb to know the volume of CO_2 gas.

f. The remaining gas is passed to pyrogallol bulb to know the unused O_2 volume.

g. The unabsorbed gas is accounted for nitrogen present in the gas.

The volumes of H_2 and CH_4 gases are calculated as follows:

Volume of $H_2 + CH_4 + N_2 = x$ ml

Volume of O_2 added = $(80 - x)$ ml

Volume of CO_2 generated by combustion = y ml

Volume of unused oxygen = z ml

Since, 1 mol. of CH_4 gas reacts with 2 mol. of oxygen and gives 1 mol. CO_2 and 2 mol. H_2O as per combustion reaction given above,

Therefore, volume of CO_2 generated by combustion = y ml = Volume of CH_4 and oxygen needed for CH_4 combustion = $2y$ ml

Now, the oxygen consumed by hydrogen combustion = $(80 - x - z) - 2y$

Therefore, the hydrogen in gas = $2 \times [(80 - x - z) - 2y]$ ml

Once the H_2 and CH_4 content is known, the remaining gas volume is accounted for nitrogen and the composition of gas is expressed as per cent of gas sample volume.

4.12.3 Gas Calorimeter

The gas calorimeter is used to determine the gross and net calorific value of any gaseous fuel. It requires gas source to supply the gaseous fuel, flow meter to measure the volume of gas, gas calorimeter, 2-litre measuring jar, stop watch, small bottle and weighing device.

The working principle of the gas calorimeter, its construction, test procedure

and calculation method for knowing the calorific value is given in the following sections.

Working principle

The gas calorimeter works on the principle of heat given by a system is equal to heat taken by another system. The calorimeters, in general, is so insulated that there is no heat loss, but the gas calorimeter works under steady state heat flow and there is no insulation provided in the calorimeter.

In steady state gas flow type calorimeter, the fuel gas is burnt through a burner and the heat evolved is absorbed by water flowing in a chamber which gets heated to ΔT °C. Under steady state condition when rate of fuel gas combustion (heat delivery) and rate of water flow (heat recovery) both are constant, then heat given by V m^3 of gas burnt having calorific value Q (cal/m^3) is taken by W g of water to get heated by ΔT °C, thus:

Heat delivered = Volume of gas burnt × Gas calorific value = $V \times Q$

Heat received = Mass of water × water specific heat × rise in water temperature = $W \times 1 \times \Delta T$

Since, Heat delivered = Heat received

$\therefore V \times Q = W \times 1 \times \Delta T$

or Calorific value of gas, $Q = W / V \times \Delta T$ calories/m^3

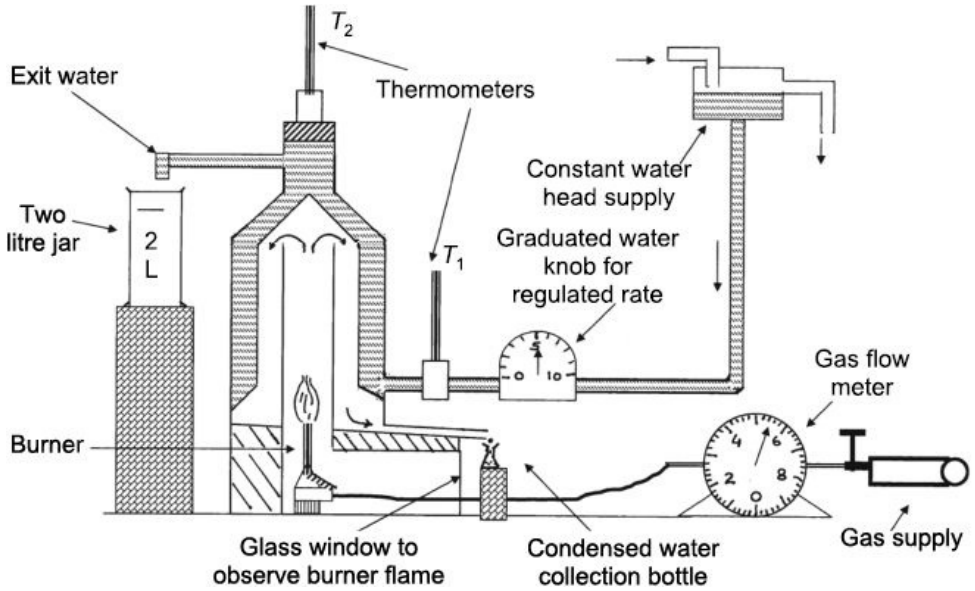


Figure 4.12 Gas calorimeter.
(Adopted from R.C. Gupta, *Theory and Laboratory Experiments in Ferrous Metallurgy* , PHI Learning, Delhi, 2010.)

Construction

The main components of gas calorimeter are shown in Figure 4.12. It has a combustion chamber made of copper for good heat conduction to water flowing in water chamber surrounding the combustion chamber. This water chamber is made of stainless steel and is not insulated. A burner connected to gas flow meter is placed in the combustion chamber. The water in the chamber is provided continuously from a constant water head supply fitted with the graduated valve to regulate the flow. Two thermometers are placed to measure the water temperature at inlet and outlet point of water. The water outlet point has a rotating tap for discharging water either to measuring jar or sink. The steam formed during gas combustion gets condensed on the inner wall of stainless steel water chamber and trickle down for being collected in a glass bottle for measurement.

Test procedure

The tap of constant head water supply is first opened and the water flowing through the calorimeter is allowed to be discharged in the sink. The water flow rate is kept 50 per cent of its flow capacity. The gas tap is now opened when burner is located outside the calorimeter and is ignited. The *burner is never ignited in the calorimeter* as it may explode. The ignited burner flame is adjusted to become non-luminous ensuring complete combustion. This can be done by adjusting air/fuel ratio. This ignited burner is now placed inside the calorimeter with care such that it is not extinguished in the process. *In case it is extinguished* , then it should be taken out and ignited on the table. It *should never be placed inside the calorimeter* unless all fuel gas discharged by extinguished burner is purged out by a hand blower/fan. Once ensured that there is no fuel gas in the chamber, the burner is placed inside and the glass window is closed to observe that the flame is burning.

The burner heat will raise the water temperature and outlet water temperature will start increasing as shown in Figure 4.13. After sometime, the exit water temperature attains a steady state, since the rate of heat supply by the burner is equated with rate of heat taken by water and rate of heat radiation by the surface of calorimeter. The outlet water temperature will not change for a given rate of water supply. A lower or higher water flow rate will increase or decrease the exit water temperature.

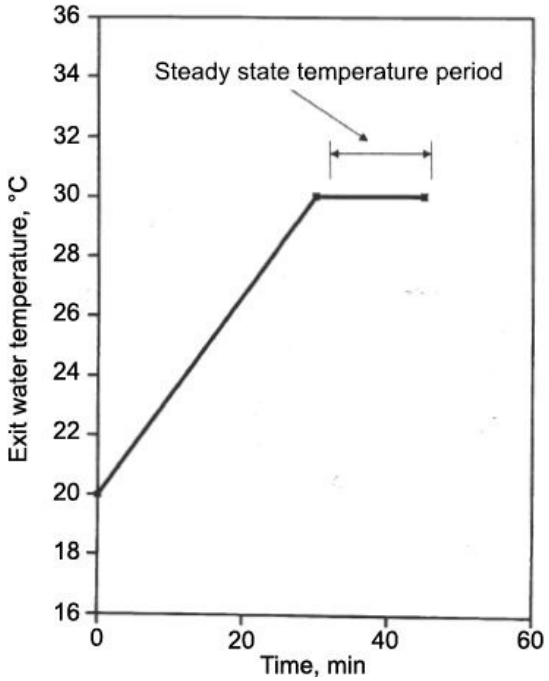


Figure 4.13 Exit water temperature with time during the gas calorific value determination. (Adopted from R.C. Gupta, *Theory and Laboratory Experiments in Ferrous Metallurgy* , PHI Learning, Delhi, 2010.)

In principle, the measurements can be done once the steady state condition has been reached, but the water rate is so regulated that the exit water temperature is only 10 °C more than inlet water temperature to minimise radiation heat losses and keep the radiation loss value constant in all measurements. Once the outlet water is 10 °C more than inlet water temperature and does not change with time (minimum 15 minutes), then a 2 litre jar is positioned near water outlet and water is directed to get collected in the jar. The initial reading (V_1) of gas flow meter is taken while directing the water to 2 litre jar, and final reading (V_2) is taken when 2 litre water is collected in the jar.

Calculation for calorific value

Now, the volume of gas burnt during the collection of 2 litre water in jar = ($V_2 - V_1$) m^3

Weight of water in the jar (density of water 1 g/ml) = 2000 g

Rise in water temperature (Exit temperature – Inlet temperature) = 10 °C

Thus, the total heat given by the burner = [($V_2 - V_1$) × Q] calories

where, Q is the calorific value of gas in calorie/m^3 .

The heat taken by water = Water mass × Water specific heat × Rise in temperature

$$= 2000 \text{ g} \times 1 \text{ cal/g/°C} \times 10 \text{ °C} = 20000 \text{ calories}$$

Since, heat given = heat taken

or $(V_2 - V_1) \times Q = 20{,}000$ calories

or $Q = \frac{20{,}000}{(V_2 - V_1)}$ calorie/m ^{3}

The value of calorific value, thus, obtained is *gross* value since the products of combustion leave at room temperature.

When the fuel gas contains hydrogen or hydrocarbon, then the steam is formed which is collected in the glass bottle kept at the gas exit. The weight of water can be used to calculate the latent heat and sensible heat lost with steam if the exit gas temperature is known. The lost heat is deducted from *gross* calorific value to get the *net* calorific value of gas.

4.13 STORAGE AND SAFETY OF GASEOUS FUELS

The gas is stored in large size holders before distribution to point of use through a network of pipe lines. The gases stored in these gas holders are flammable and toxic in nature which requires precautions as safety measure.

4.13.1 Gas Holder

A gas holder is a large container in which the gas is stored at ambient temperature and positive pressure very close to the atmospheric level. The gas holder capacity depends on the volume of gas storage, while the stored gas pressure is due to the weight of movable cap.

The gasholder serves two purposes: (i) stores the clean and metered gas and (ii) acts as a regulator between production rates and more erratic consumption rates.

The gas holder with 50000 – 80000 cubic meter capacity are common, though large gas holders with 165,000 cubic meter capacity are being designed (Table 4.12). Currently, these gas holders tend to be used for balancing purposes (making sure gas pipes can be operated within a safe range of pressures) rather than for actually storing gas for later use.

The gas holder operates on a basic principal of a gas filled floating vessel, rising and falling in a seal of water (Figure 4.14). The water acts as an elastic

gas-tight seal in which the vessel may rise or fall. Their simplicity and reliability has lead to their longevity of over 200 years.

The gas holders contain a single vessel (lift) floating within the tank in early days, but now multiple lift (telescopic) gas holders are being used. The telescopic gas holders allow a larger volume of gas to be stored in roughly the same area of land. The use of water as a sealing material was difficult in cold regions due to water freezing and this led to the development of various other systems and materials.

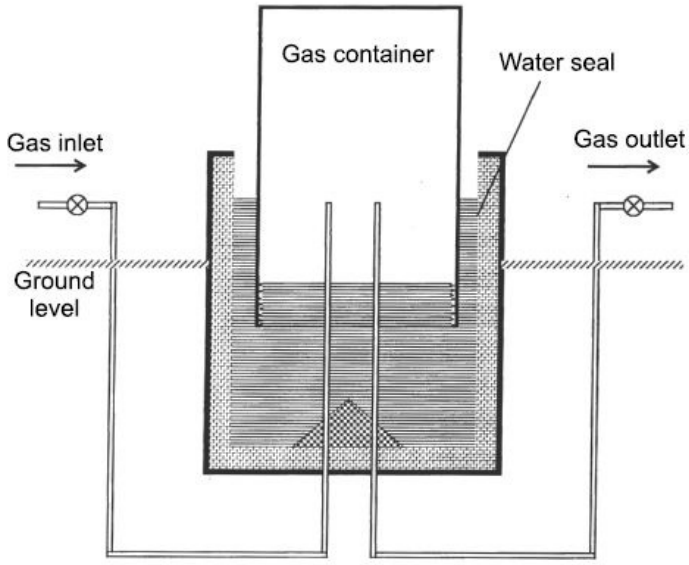


Figure 4.14 Gas holder (schematic).

Types of gas holders

There are several key factors to be considered in the selection of a gas holder for the recovery and storage of gases. Some of these considerations are as follows:

a. Seal compatibility with contained gases
b. Suitability for use with wet/saturated gases and condensates
c. Suitability for use with gases carrying particulates/dust
d. Seal operating temperature range
e. Maximum gas flow rates (which convert to maximum piston operating speed)
f. Pressure profile
g. Simplicity of operation
h. Capital and long-term cost
i. Maintenance

Table 4.12 Gas Holder Capacity and Size							
Gas Stored	*Company, Place*	*Gas Holder Type*	*Capacity* m^3	*Gas Pressure* kPa	*Gas Holder Dimensions*		*Remark*
					Dia. m	*Height* m	
Blast furnace gas	JSW & Bhushan Steel & Power	Single dry seal type	50,000–100,000	NA	NA	NA	
	Tata Steel	Dry seal	150,000	NA	NA	NA	One of the world's largest
	Shuicheng Steel	NA	165,000	10	51.2	106.5	One of the world's largest
LD gas	Rourkela Steel	Single dry seal type	50,000	NA	NA	NA	
	Bhilai, Bokaro & Vizag Steel	Single dry seal type	80,000	NA	NA	NA	
	Tata Steel	Single dry seal type	80,000–100,000	NA	NA	NA	
	Vizag Steel	Double dry seal type	80,000	NA	NA	NA	
COREX gas	JSW	Single dry seal type	100,000	NA	NA	NA	
Coke oven gas	Bhushan Steel	NA	50,000	NA	NA	NA	
	Rourkela Steel	MAN oil seal type	100,000	NA	NA	NA	

There are four types of gas holders which are commonly used:

Column and Spiral Guided Water-Sealed: These water-sealed gas holders are designed to store town gas, natural gas and industrial gases, and range from a few cubic meter in capacity right up to 350,000 m^3. These are used all over the world for being simple, low-maintenance cost for storage of gas, and they are known for their reliability. These type of gas holders are in service for over 100 years.

Wiggins Type Dry Seal: These type of gas holders are characterised with low foundation cost, ease of erection and minimal maintenance requirements. These

gas holders work with constant working pressures, and are available with a range of rubber and synthetic seals to suit a variety of applications. These gas holders are used for the dry storage of gas down to –40 °C working temperature prevailing in cold countries, thus eliminating freezing problems caused by water.

M.A.N. Waterless: This type uses oil and tar seal systems. In this gas holder, the floating piston-type gas holder operates within a fixed tank construction for the dry storage of gases in towns and steel works around the world due to their low foundation costs, small plant area need and constant working pressure.

Klonne Grease Seal: These piston-type gas holders, with lubricated packaging ring seals, are used extensively on blast furnace gas plants for the dry storage of gas, as their constant working pressures offer savings in foundations costs, particularly on bad ground.

Safety of gas holders

Concern for the safety

This is needed to avoid release of stored gases in the atmosphere due to accidental leakage, fire or sabotage. The toxic gases released in the atmosphere in large volume would pose threat to safety of life and property.

Gas holder explosion cases

There have been several cases of gas explosion due to accidental reasons in steel plant. The two incidences are given here briefly as illustration to the extent of damage that can be caused.

Coke oven gas holder explosion: An explosion and fire of a gas holder at an iron factory in Japan was reported in 2003 which occurred at a dry-type coke oven gas (COG) holder. In addition, nine days after the first explosion, rubber at the lid ignited during cutting work at the wall of a different COG holder, which was damaged by the preceding explosion. In addition, grease at the seal ignited, and there was a fire. It was indicated that the first explosion and fire occurred due to a reaction of carbon monoxide with oxygen in the holder. The second fire was caused probably by ignition of a rubber seal of the tank on cutting the side plate, and the fire spread when grease ignited. At the factory, the roof of a coke oven gas (COG) holder was damaged completely and 1/3 of the roof of a blast furnace gas (BFG) holder was also damaged. The explosion also caused breaking of building windows within the plant and outside the factory. Window damage and door deformation at 38 housing units (within 3 km) occurred. This incidence led to ~15 million USD investment for reconstruction of three gas holders.

LD gas holder explosion: The explosion in LD gas holder occurred in India which was reported in newspapers (15th November 2013) causing injury to 11 persons.

Precautions required

The gas holders containing large quantities of toxic gases are considered as high risk unit and need full care against any type of hazardous incidents. The following precautions are required:

a. Use of best material and technology while construction
b. Regular maintenance
c. Following standard operating procedures and restricting any fire source in vicinity
d. Restricted entry zone
e. Secured boundary for preventing any forceful entry by uncontrolled vehicle
f. Adequate security and patrolling to guard the installation

Preparedness for accidents

The plants must have sufficient fire fighting and first aid arrangements alongwith local administration coordination planning to meet any challenge.

Review Questions

What are the merits and limitations of gaseous fuel? Give some major applications of gaseous fuel.

What are the various sources available for obtaining gaseous fuel? Describe briefly.

How do you get natural gas? Give a flow sheet showing the natural gas processing plant.

What is the difference in techniques adopted for reforming natural gas by HyLIII and Midrex plant? What is the use of such reformed natural gas?

Why is the removal of sulphur from natural gas necessary before its reformation?

What are the major chemical constituents in LPG? Why is small quantity of chemicals like mercaptan added in LPG before its marketing?

Why the leaking LPG cylinder may catch fire even if the fire source is located

far away?

Why is blast furnace gas is treated as highly toxic gas? What are the devices used to detect leakage?

What are the factors which affect the composition and yield of coke oven gas?

The blast furnace gas can be preheated before combustion, but the coke oven gas cannot be preheated. Why?

Why water gas generator cannot produce gas continuously? The water gas unit requires coke as a fuel and not coal. Give reasons.

Differentiate between the following terms:

(i) LNG and CNG
(ii) Dry and Wet natural gas
(iii) Sweet natural gas and Reformed natural gas
(iv) LD Gas and COREX gas
(v) Shift reaction and Boudouard reaction
(vi) Water gas and Carburetted water gas
(vii) Producer gas and Oil gas
(viii) Thermo-chemical and Electro-chemical gas analysis instruments
(ix) Thermo-conductometric and densimetric instruments for gas analysis
(x) Wet seal and Dry seal gas holder
(xi) Single vessel and Multiple lift gas holder

Write short notes on the followings:

(i) Producer gas
(ii) Water gas
(iii) Blast furnace gas
(iv) Orsat apparatus
(v) Determination of hydrogen and methane by Orsat apparatus
(vi) Gas sampling for analysis
(vii) Gas calorimeter
(viii) Gas holder safety

5

Combustion of Fuels

Introduction

In simple term, combustion is an act or process of burning. The combustion process generally needs an oxidising agent resulting in rapid oxidation of hydrocarbons present in fuel with emission of heat and light. Combustion need not always involve oxygen, for example hydrogen can react exothermally with chlorine forming hydrogen chloride with generation of heat and light, which is characteristic of combustion. However, generally the combustion of fuels like coal, oil or gases need air (oxygen) to produce heat for industrial use.

In this chapter, the various terms related to combustion are discussed followed by the combustion mechanism of solid, liquid and gaseous fuels. This chapter also gives the method to estimate the air required for combustion of these fuels as it is needed while designing combustion systems (burners).

5.1 DEFINITIONS AND TERMINOLOGY

Oxidation

Oxidation generally refers to reaction with oxygen to form oxide of an element. In case of solid fuel, the coal oxidises to form carbon dioxide even at ambient temperature with release of heat. The rate of coal oxidation at ambient temperature, however, is very slow to be noticed till the temperature of coal bed reaches about 300 °C to cause evolution of volatile matter as smoke rendering the process visible. This slow oxidation of coal requires care during its storage [see Section 2.7.3].

Smouldering

If the combustible material burns slowly without giving flame, then it is termed as ‘smouldering’. In smouldering, smoke is liberated due to limited supply of oxygen without any visible flames. Such slow combustion sustains with

minimum oxygen supply at lowest possible reaction temperature. All combustible materials like coal, wood, saw dust, etc. can oxidise slowly in the presence of oxygen and heat generated would further keep increasing the rate of combustion while smouldering.

Combustion

It is the high temperature reaction between oxygen (air) and combustible substances like carbon (coal) and hydrocarbons (oil and natural gas) giving flame with release of intense heat and light. The products of combustion (flue gases) essentially consist of oxides of the constituents present in fuel as CO, CO_2 , SO_2 , NO_x and unburnt solid substances like unburnt carbon and ash. This combustion process could be complete or incomplete, depending on the various conditions of the combustion process.

(i) Complete combustion

The complete combustion refers to complete conversion of reacting (carbon and hydrocarbons) substances to carbon dioxide and water vapour with full release of its thermal energy (gross calorific value of the fuel). This would require sufficient quantity of air which is often supplied with excess air during combustion. In real practice, the complete combustion is not achieved due to various technical reasons. The complete combustion is characterised by non-luminous flame and absence of carbon monoxide or unburnt carbon in the products of combustion.

(ii) Incomplete combustion

It refers to a combustion process where the products of combustion contain some amount of carbon monoxide or unburnt carbon. In this process, the thermal energy (gross calorific value) inherent in fuel is not released to its full extent.

Explosion

The word explosion is used to cover all processes characterised by a sudden flow of material (usually hot gases) outward from the point of combustion. When the highly combustible substances like coal dust suddenly reacts with oxygen and the resultant heat energy causes an outflow of hot gases at high velocity, it results into shock wave and thundering noise.

When the burning velocity is about 1 m/s, it is referred as ‘deflagration’, and when this velocity is in the rage of 2000–3000 m/s, it is termed as ‘detonation’. The controlled explosion is used in mining process to break large stone pieces,

while the accidental or uncontrolled explosion could cause damage to property and life due to shock and heat wave.

Gasification

It is the process of converting solid or liquid into a gas. In case of fuel, the solid fuels (e.g. coal, wood, biomass, etc.) and liquid fuels (oils) are converted into synthetic gas for use to derive the merits of original fuel (solid or liquid) for its availability, and gaseous fuels for its combustion qualities.

Wobbe index (I_w) or Wobbe number

It is a measure to know the flexibility of changing fuel gas in a system.

The Wobbe Index (I_w) is expressed as:

$$I_w = V_c / \sqrt{G_s}$$

where, V_c is the gross calorific value of the fuel gas and G_s is the fuel gas specific gravity.

This index is helpful in comparing energy generation from different fuel gases while using a burner. When the Wobbe index for two fuel gases is identical or very close (less than 5%), then for a specified gas pressure and burner valves settings the energy generation would be nearly identical.

Turndown ratio

It is the ratio between burner maximum firing (heating) capability and burner minimum firing capability. Process control is enhanced with a high turndown ratio. Maintenance costs are reduced with a high turndown burner because there is much less thermal cycling taking place in the combustion system.

5.2 COMBUSTION SYSTEMS

The various combustion systems are used to utilise available fuel type for specific purpose. All such systems have some common features like (i) Process requirements and (ii) Combustion system design factors.

5.2.1 Combustion Process Requirements

The combustion process needs four basic requirements. These are as follows:

(a) *Fuel preparation* : The fuels are prepared before combustion. This preparation method is different for solid and liquid fuels. The gaseous fuels

need no preparation. The solid coal is crushed or ground according to the combustion system adopted, while the liquid fuel is atomised using different techniques.

(b) *Supply of air* : The air in required quantity is supplied by suitable system to sustain the combustion.

(c) *Use of appropriate combustion system* : The system used for combustion would depend on the purpose of combustion and type of fuel used.

(d) *Raising the fuel temperature to kindling point* : The fuel would sustain combustion after reaching kindling temperature of the fuel. The solid, liquid and gaseous fuels have different kindling temperature, and suitable methods are needed to achieve it.

5.2.2 Air for Combustion

The supply of air is essential for combustion. This air is supplied in suitable quantity and at appropriate place to perform combustion of fuel. The various terms associated with air supply are explained in the following sections.

Theoretical or stoichiometric air

The air supply is necessary to react with the fuel and generates energy contained in it to the greatest extent. This is illustrated by combustion of methane gas (CH_4) which needs two molecules of oxygen for complete combustion according to the equation given below. This means 1 m^3 methane at STP would need 2 m^3 oxygen for complete combustion to give 1 m^3 carbon dioxide and 2 m^3 steam as product of combustion (flue gas). This required oxygen is derived from air containing 21% oxygen and 79% nitrogen. Thus, with each cubic metre of oxygen 3.76 m^3 nitrogen will also be present. In other word, 1 m^3 oxygen is present in 4.76 m^3 air and in order to burn 1 m^3 methane, the air required would be 9.52 m^3 which is termed as theoretical or stoichiometric air.

$$CH_4 + 2(O_2 + 3.76\ N_2) \rightarrow CO_2 + 2\ H_2O + 7.52\ N_2 - 889\ kJ$$

Thus, theoretical or stoichiometric air could be defined as minimum amount of air required for complete combustion of the fuel.

Excess air

The excess air is the extra amount of air (in per cent) supplied over theoretical air to complete the combustion of the fuel. This excess air is needed as the theoretical supplied air is not able to mix and react with fuel due to design

constrains. However, this excess air is limited to minimum value to achieve complete combustion, since the excess air supplied will be reflected in the product gas (flue gases) which would be a means for heat loss or lower furnace thermal efficiency (Figure 5.1). The thermal efficiency would be at maximum with excess air depending on the type of fuel and combustion system. The typical excess air to achieve the highest efficiency for different fuels could be 5%–10% for natural gas, 5%–20% for fuel oil and 5%–60% for coal. The flue gases must have carbon dioxide with no CO or free oxygen when the combustion is complete. In practice, small amount of CO is noticed when the air has its theoretical value due to combustion process limitations. With some excess gas, this CO in flue gas is minimised. However, increasing excess air gets reflected in flue gas as free oxygen.

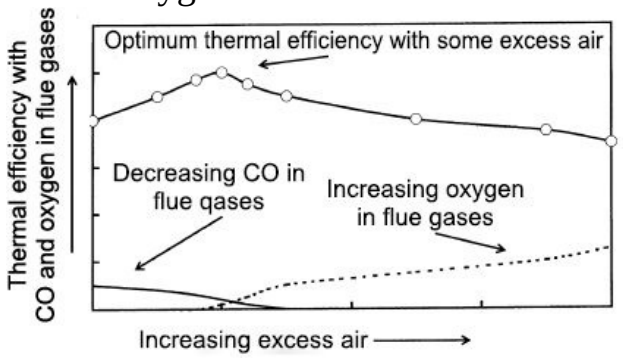


Figure 5.1 Effect of excess air on thermal efficiency (typical case).

Total or actual air

The total or actual air supplied for combustion is the sum of theoretical air and excess air requirement. Considering the example cited earlier the combustion of 1 m^3 methane requires 9.52 m^3 theoretical air. If the burner is supplied with 10% excess air, then actual air provided will be 10.47 m^3 (= 9.52 + 0.95).

Air to fuel ratio (λ)

The ratio of air to fuel gas is represented by the greek letter lambda **(λ)** .

Thus, lambda λ = (air/fuel gas)

λ = 1 for Theoretical or stoichiometric air to fuel ratio

λ > 1 When air is in excess or gas is lean

λ < 1 When air is short supply and gas is rich or in excess

Primary, secondary and tertiary air

The total or actual air used for combustion is generally divided into two or three parts to ensure its full utilisation for complete combustion of fuel.

a. *Primary air:* It is the amount of air which is supplied with the fuel. In case of solid fuel this is supplied through grate. In case of liquid fuel, this is supplied in the burner which helps in atomisation of liquid fuel and provides oxygen for combustion.
In case of gas burners, it helps in generating flame flow pattern (laminar or
turbulent).

b. *Secondary air:* It is the amount of air supplied at suitable location in the system to help in combustion of volatile matter liberated in case of solid fuel. In case of liquid and gaseous fuel, this helps in burning any remaining unburnt constituent.

c. *Tertiary air:* It is the third portion of air supplied near the furnace exit to burn any remaining combustible constituents. This is needed particularly in the case of solid fuel.

The percentage of primary, secondary and tertiary air supply would depend mainly on system design, whose main objective would be complete combustion of fuel with maximum thermal efficiency.

5.2.3 Combustion System Design Factors

While designing combustion system, certain basic factors have to be kept in view such as:

(i) Operational factors

Reliable ignition: The combustion process needs ignition to begin the process. This is more important in case of liquid and gaseous fuel where the burner may need ignition at short intervals several times for operational requirements.

Good combustion stability: The oil and gas burners needs good flame stability to deliver the heat.

(ii) Environmental regulations

High combustion efficiency: The high combustion efficiency is not only required to use the fuel but it is necessary to follow local rules which prohibit emission of harmful gases due to inefficient combustion process.

Low smoke: The combustion system must work to offer complete combustion with no smoke in exit gas which attracts the law enforcing agency without any special check.

Satisfactory emissions levels: The percentage of SO_x and NO_x must be within prescribed level by proper selection of fuel and system design.

(iii) Performance

Minimum thermal loss: The system must give minimum thermal loss due to its combustion system.
Temperature distribution: The combustion system must give the desired temperature distribution.
Minimum maintenance: The design must offer longer working hours with minimum maintenance.

(iv) Durability

System life: The combustion system must last longer.

In view of the above factors, burners with different design are available for selection and used as per requirements.

The combustion system designs chosen for solid, liquid and gaseous fuels differ due to different fuel requirements which give different mechanism for fuel combustion. These combustion mechanisms are described in the following sections.

5.3 COMBUSTION MECHANISM FOR SOLID FUELS

Once the suitable conditions are available, the combustion of fuel occurs. This combustion mechanism would be different for different combustion systems. In this text, three types of combustion system for solid fuel are discussed:

(i) Solid fuel bed combustion on hearth or grate,
(ii) Pulverised fuel combustion through burner and
(iii) Solid fuel combustion in fluidised bed

5.3.1 Solid Fuel Bed Combustion on Hearth or Grate

Applications

The solid fuel (coal or coke) is commonly burnt over a grate for heating metal for forging or melting on a small scale. This method is also used for raising steam in a fixed bed or travelling grate boilers. These applications are illustrated in Figure 5.2.

In such method of fuel bed combustion, the air required is supplied through

the grate which is supporting the fuel bed. The ashes (ash and unburnt carbon) fall through grate on the bottom and get discharged out. The fresh fuel is fed continuously on the top to keep the process of combustion continued.

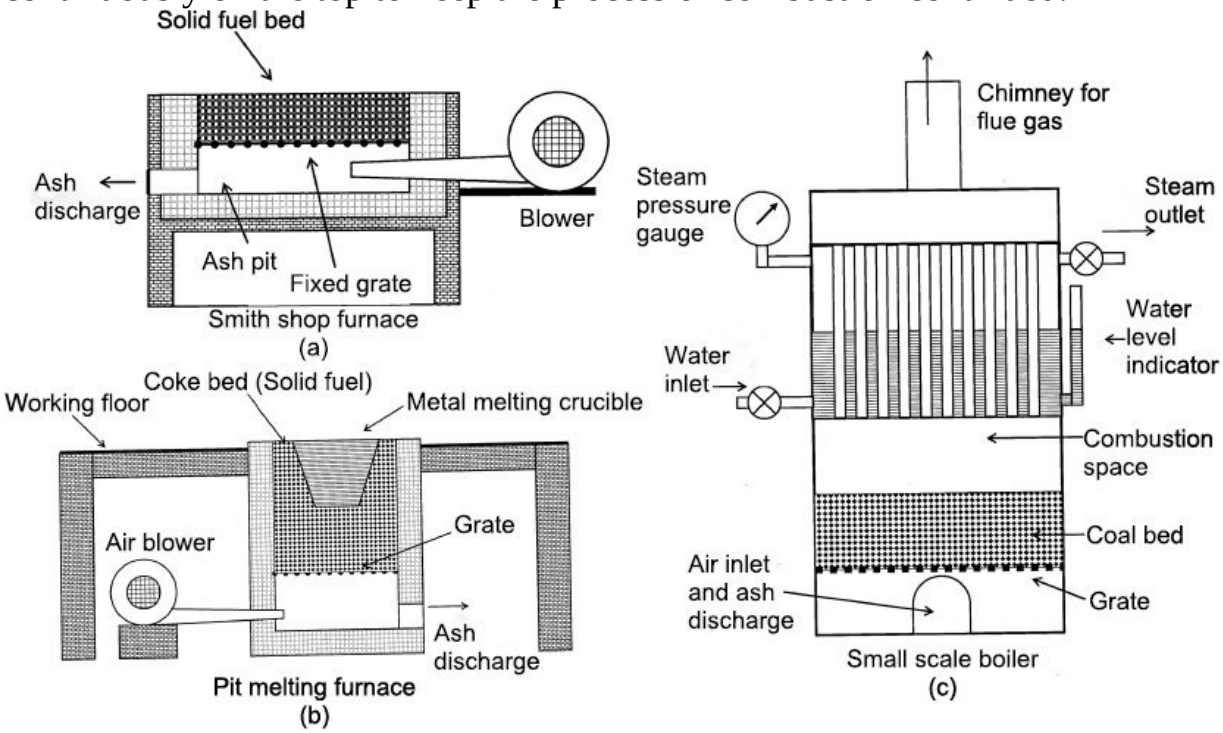


Figure 5.2 (a) Smith shop furnace, (b) pit melting furnace and (c) small scale boiler.

Combustion mechanism

In such method, the combustion occurs in the bed of fuel resting on the grate. The required air for combustion is provided by some system (blower or chimney draft). The bed of fuel generally consists of few layers of coal/coke particles. The combustion is initiated by a kindling process and once the combustion starts it proceeds till the fuel is available on the grate.

Figure 5.3 illustrates the on-going solid fuel combustion process on a fixed grate.

The upper layer of fuel particles is freshly charged and they are pre-heated by hot gases emerging from the bed alongwith radiated heat from lower hot layers of the fuel bed. The pre-heating of coal particles removes moisture and volatile constituents present therein. The volatile matter would burn and deliver some heat to the upper layer, if secondary air is available for combustion. The removal of volatile matter from fuel renders additional porosity which is helpful in its combustion process.

This pre-heated fuel layer reaches to the combustion zone after some period. The process of combustion starts at the surface of fuel particles and would proceed towards central part. The carbon on the surface reacts with oxygen and

it would form carbon dioxide (CO_2) or carbon monoxide (CO) with the liberation of heat (Chemical equations 5.1 and 5.2) depending on the supply of oxygen. The carbon dioxide formed may also react with carbon in thick bed to form carbon monoxide (Chemical equation 5.3). The carbon monoxide thus formed would burn to give heat at the fuel top provided secondary/tertiary air is supplied for combustion (Chemical equation 5.4).

(i)	Complete combustion	$C + O_2 = CO_2 - 393.5$ kJ/mol	(5.1)
(ii)	Incomplete combustion	$C + 0.5\ O_2 = CO - 110.5$ kJ/mol	(5.2)
(iii)	Carbon gasification in thick bed	$C + CO_2 = 2\ CO + 172.5$ kJ/mol	(5.3)
(iv)	CO combustion by secondary or tertiary air provided at fuel top	$2\ CO + O_2 = 2\ CO_2 - 283.0$ kJ/mol	(5.4)

The process of combustion continues till most of the carbon present in fuel is burnt. The size of the fuel particle goes diminishing with the consumption of carbon at the surface. When the size of fuel particles becomes smaller than grate spacing, it falls below the grate. This combustion process is illustrated schematically in Figure 5.3.

The small particles of solid fuel containing carbon alongwith uncombustible constituents (ash) are termed as ashes. These ashes falling below the grate are discharged out.

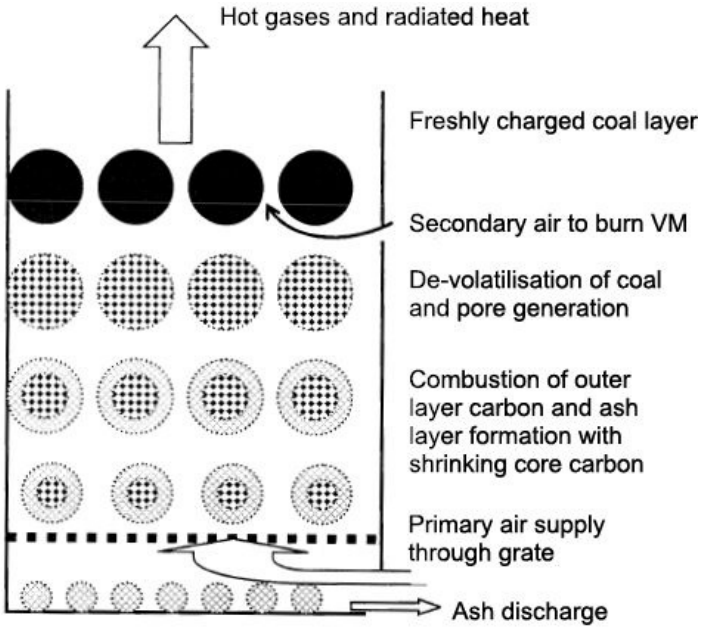


Figure 5.3 Combustion mechanism of solid fuel on fixed grate (schematic).

Factors affecting combustion

The combustion process is affected by several factors which are used to regulate the process in the desired manner. These are briefly discussed in the following sections.

(i) Moisture content

The fuel contains moisture due to its nature and weather conditions. However, this is undesirable as it gets removed at the cost of heat present in the fuel. It is preferred to use air dried fuel having minimum inherent moisture.

(ii) Volatile matter content

The volatile matter content is removed in the upper layer of the fuel bed and would need secondary air for its utilisation. The fuels with higher volatile content can be ignited easily compared to fuel with low volatile matter.

(iii) Fixed carbon

The high fixed carbon is preferred for deriving high heat value in concentrated manner.

(iv) Ash content

This represents the uncombustible part of the fuel and is discharged out carrying sensible heat. Higher ash content means lower heat generation (due to less fixed carbon) and higher heat loss through its sensible heat alongwith its disposal problems.

(v) Ash fusion temperature

The fusion temperature of ash affects its dislodging tendency from fuel surface after combustion process. The refractory nature of the ash is helpful in its dislodging from the surface of the fuel. This ash removal exposes fresh fuel surface to air for its further combustion. The refractory nature in ash is derived from the presence of high melting constituents like alumina, silica and lime. The higher content of iron oxide lowers the fusion temperature of ash which tends to fuse and dislodges with difficulty.

(vi) Reactivity of carbon

The reactivity of carbon is very important in promoting combustion reaction (see Table 2.12). The reactivity of anthracite and coke is very low ($0.1 – 0.5 \times 10^{-4}$ s^{-1}) compared to wood char ($1.6 – 10 \times 10^{-4}$ s^{-1}). This would mean wood char may burn at high rate compared to anthracite and coke under a given condition. The reactivity of bituminous coal is moderate ($0.2–1.8 \times 10^{-4}$ s^{-1}).

(vii) Fuel bed thickness

The higher fuel bed thickness would cause gasification reaction between CO_2 and C to form CO and this may remain unutilised if secondary/tertiary air is not

available for its combustion. Hence, higher fuel bed on grate is generally not preferred. Very thin
layer of fuel bed is also not good as it may not be able to sustain combustion for shortage
of fuel, and therefore an optimum fuel bed thickness is preferred for sustained combustion process.

(viii) Fuel particle size

A suitable particle size is preferred depending on the combustion system design. A smaller size will give more loss as unburnt carbon by falling through grate. The very large particles will take time to get pre-heated and ignited.

Selection of solid fuel for different applications

The selection of solid fuel would depend much on the nature of use. In this text, the following combustion applications of solid fuel are given.

(i) Smithy shop furnace

The smithy shop furnace is used to pre-heat steel for forging purpose. This requires intense heat in the bed of fuel at the hearth. This can be obtained by using solid fuel with high fixed carbon and low reactivity as exhibited by anthracite coal or coke. The high fixed carbon would give intense heat at fuel bed with suitable air supply. The low reactivity of such fuel will keep it burning at slower rate without blower air during non-forge period.

(ii) Pit furnace for melting non-ferrous metals

The pit furnace is commonly used for melting aluminium alloys (470–680 °C), copper (1085 °C), brass (940–1000 °C), etc. in small foundries. Such temperatures are easily obtained by using solid fuel with high fixed carbon and low reactivity. The use of coke as fuel in pit furnace is common. This coke need not be of metallurgical grade. The size of coke pieces would depend on the size of the furnace and grate spacing. The use of 12–18 mm size coke is common in foundries.

The coals cannot be used for melting purpose, because they have lower fixed carbon value and high volatile matter content. The evolution of volatile matter causes problem during working in small foundries and available heat content of fuel is minimised. Further, many coal undergo volume change during heating and this would cause bed disturbance making melting operation difficult.

(iii) Pit furnace for melting cast iron and steel

Small foundries use pit furnace for melting cast iron (1120–1200 °C) and steel (1450–1550 °C). Such high melt temperature is possible by selecting good quality of coke having high fixed carbon and refractory nature ash. The reactivity of carbon must be low. The higher coke bed height would further help in achieving higher temperature. The refractory ash is essential to keep the fuel bed permeable to air flow for combustion. The lower temperature fusing ash in the coke bed will inhibit combustion process, and melting temperature may not be achieved.

(iv) Small boiler for raising steam

The steam is required for various industrial applications including chemical, textile, pharmaceutical industries where small boilers are used depending on the requirement. These small boilers use grate combustion method which is different from power plant boilers using pulverised fuel burners or fluidised bed combustion. These boilers burn coal to heat water for raising steam. Such application requires non-caking type coal. The caking coals are not suitable as they will get fused in the fuel bed during heating process and air flow would get retarded. This less air flow due to fused bed may even inhibit combustion process. The coals with varying volatile matter content can be used and it would need suitable changes in supply of secondary air for burning the emitted volatile constituents. The sub-bituminous coals having 30–50% volatile matter, bituminous coals containing 20–45% volatile matter can be used for such application. The lower ash content in coal is desirable, but not essential. The ash fusion temperature is also not important, since the coal bed temperature is not likely to fuse ash, unless it is highly fusing in nature.

5.3.2 Pulverised Fuel Combustion through Burner

In this system, the pulverised (powdered) coal is burnt through a burner giving a flame similar to that of liquid fuel burning. The various aspects of the system is described below:

Merits and limitations

Merits

(i) The pulverisation process offers a method to eliminate the siliceous matter present in fuel while grinding. This pulverisation step, thus, acts as a method of size reduction with fuel enrichment. The softer constituents in fuel, rich in carbon, get pulverised and the harder fractions mostly as shale

remain as lump and discarded during coal preparation step.

(ii) This method offers a means to use cheaply and widely available solid fuel for combustion in a manner giving advantages similar to liquid fuel, where the flame characteristic can be manipulated as per the requirement.

(iii) The method offers a better way of handling solid fuel through pipe as in case of liquid fuel.

(iv) The furnace atmosphere can be controlled as oxidising or reducing by regulating air fuel ratio.

(v) The method gives long flame for heating longer furnaces like rotary kilns used for sponge iron production and cement making.

(vi) The method offers a way to utilise a variety of solid fuels including waste like dolo-char generated in coal based sponge iron plants.

(vii) The combustion of solid fuel is done more efficiently with very less excess air giving little unburned carbon (~ 0.5%) left in ash.

(viii) The system generates 80–90% ash in very fine form (fly ash) which is utilised by cement plants as a raw material.

(ix) The burners can be designed as per the requirement.

(x) The burner is simple in design.

Limitations

(i) The coal needs drying and grinding to nearly 75 micron in size, which is a costly step.

(ii) The coal storage and handling as powder require more care and precautions, since powdered coal and air forms an explosive mixture.

(iii) The ash generated after combustion joins the product as in the case of DRI production which could affect its quality.

(iv) The sulphur in coal could pose problem during use.

(v) High erosion of boiler parts occurs due to abrasion by fly ash.

Coal preparation

The solid fuels must be free from moisture before combustion which needs coal drying. The modern mills perform drying and grinding operation simultaneously. The grindability of coal (see HGI value, section 2.5.7) is very important which affects grinding process and energy consumption. The coal preparation system differs according to firing system: indirect firing and direct firing.

The *direct firing* uses a grinding mill put in line with primary air, where the generated coal powder is swept by flowing primary air and immediately

conveyed into the combustion system without any intermediate storage of the finely ground fuel. Thus, with a small delay, the fuel feed to combustion system is controlled by the feed-rate of raw fuel to the grinding unit.

The *indirect firing* uses a grinding mill that is not connected to the blowing air for firing. The pulverised coal is first stored, and then used as required.

These two systems have their own advantages and limitations. The size of coal particles in the pulverised form may vary depending on the grinding and coal nature, however, the average particle size remains ~ 75 μm.

Burner design

The pulverised coal (bituminous) is injected in the burner alongwith ~ 20% primary air. The burner is provided secondary air (~ 65%) separately to regulate the combustion flame. The remaining 15% air is provided as tertiary air in the system to burn out all combustible constituents. The proportion of primary, secondary and tertiary air may differ for different grades of coal. The air velocity for primary air is kept low to deliver coal in the combustion zone, while secondary air velocity is kept high to provide a longer flame. This secondary air velocity is further high for coal having more volatile matter, and larger deliveries by bigger burners.

The point of delivery of secondary and tertiary air depends on burner design for different applications. The burner nozzle shape could be circular or rectangular.

In circular nozzles, the secondary air is delivered around the central pipe supplying coal with primary air as shown in Figure 5.4. Such nozzles are commonly used in rotary kiln furnaces.

In rectangular nozzles, the secondary air nozzles are stacked on either sides of primary nozzle carrying coal as shown in Figure 5.5. These are used in power plant boilers.

Table 5.1 illustrates the air velocities used by Figure 5.5 typical burners using different coals.

Table 5.1 Air Velocities Used in Pulverised Coal (PC) Burners

Burner Capacity MW	*Air Velocity with Type of Coal Used*			
	Coal type-Anthracite		*Coal type-Bituminous*	
	Primary air velocity, ms^{-1}	*Secondary air velocity,* ms^{-1}	*Primary air velocity,* ms^{-1}	*Secondary air velocity,* ms^{-1}
24	18–20	28–30	24–26	36–42
35	18–20	30–32	26–28	42–48
50	20–22	34–37	28–30	48–50

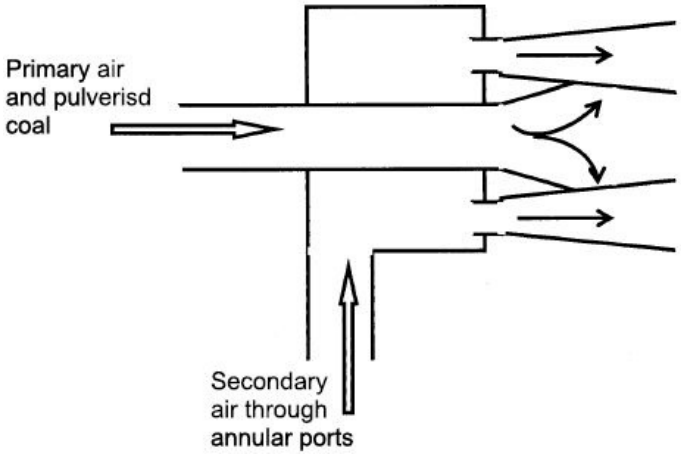


Figure 5.4 Secondary air supply around central circular nozzle carrying coal with primary air.

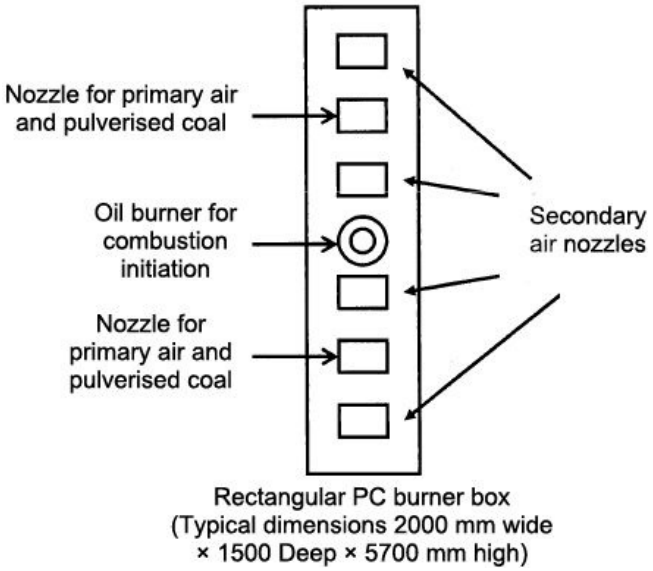


Figure 5.5 Rectangular burner nozzles where secondary air nozzle is located on either side of primary air nozzle carrying coal.

The pulverised fuel burners could be mounted in boiler furnace in three different positions:

(i) Front firing
(ii) Opposed wall firing and
(iii) Tangential firing

These three burner firing location is illustrated in Figure 5.6. All these different firing positions have their own merits and limitations which are not discussed presently.

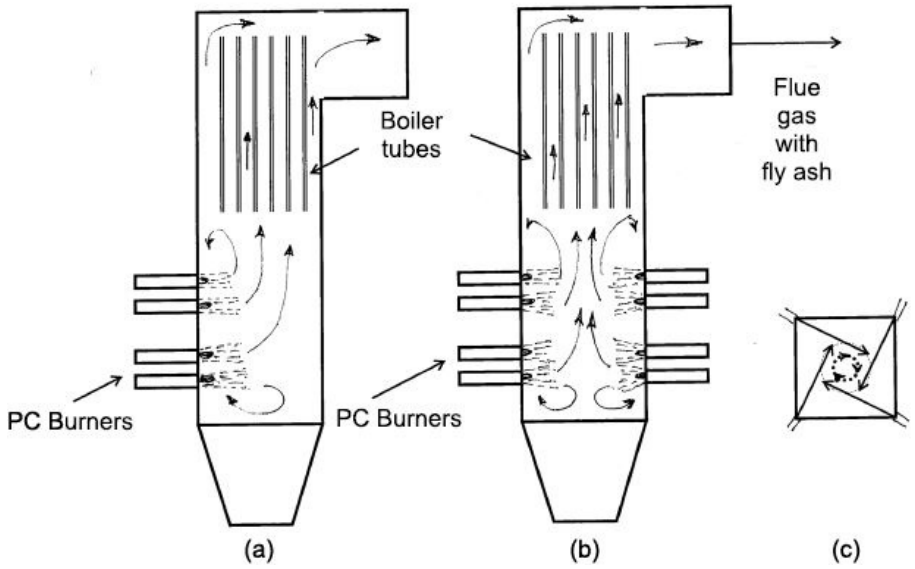


Figure 5.6 Pulverised fuel firing locations in power plant boiler furnace: (a) Front firing, (b) opposed wall firing and (c) tangential firing.

Combustion mechanism

The combustion mechanism of fine coal particles in a pulverised coal (PC) burner is illustrated schematically in Figure 5.7 for an operating burner**.** The initiation of the combustion requires preheating the system with alternate fuel. A diesel burner is common to pre-heat the system to the coal ignition temperature before initiating PC firing.

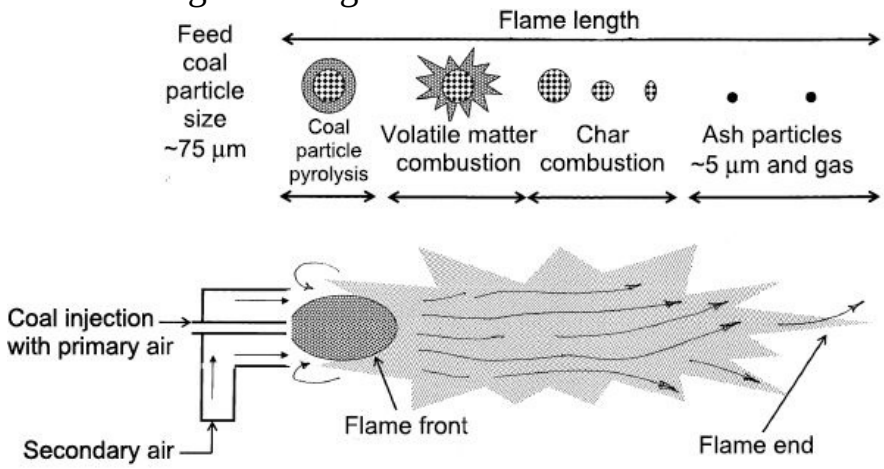


Figure 5.7 Mechanism of coal particle combustion in a pulverised coal burner (schematic).

The fine coal particles carried by primary air at lower velocity enter combustion zone through burner nozzle. The coal particles when heated emit their volatile content as gas which surrounds the coal char particles. This pyrolysis of coal particles occurs in the flame front section. The gaseous volatile matter liberated

in the flame front section is swept forward and gets ignited in the presence of secondary air forming the first part of the luminous flame. The devolatilised coal (char) becomes more porous offering larger surface area for carbon to react with oxygen supplied by secondary air. The carbon particles burn and diminish in size as they advance to the end part of the flame. The tertiary air supplied in this region helps to completely burn all the carbon particles. The ash particles generated are very fine in size (~ 5 μm) and are swept away with hot flue gases. This fly ash (80–90%) is recovered with flue gas cleaning system as wet slurry which are dewatered and used as raw material for various applications including cement making and brick manufacture. Nearly, 10% fly ash drops below the burners as bottom ash whose size is larger than 10 μm due to fusion at high temperature.

Coal selection

A variety of coal (Table 5.2) could be used as fuel for PC burners depending on need. These can be selected for obtaining desired flame properties.

Short and intense high temperature flame : The anthracite with high fixed carbon and low VM can give very intense high temperature flame. The flame length would short due to lower VM content. This would also need high kindling temperature.

Long and luminous flame: The steam coal and bituminous coal would be suited for the purpose. The higher VM content would offer longer luminous flame with high flame temperature needed by cement kilns and sponge iron kilns. The power plants also use such type of fuels.

Short and luminous flames: The lignite would offer luminous flame due to higher VM content, but the flame would be shorter due lower fixed carbon and high reactivity. This may be used in power plants.

Table 5.2 Coal Compositions for PC Burners

Coal Type → *Coal Constituents* ↓	*Anthracite*	*Steam Coal*	*Bituminous Coal*	*Sub-bituminous Coal*	*Lignite*
Volatile matter	2.8–8.0	11–24	26–41	34–39	20–55
Fixed carbon	84–92	71–82	45–64	42–49	31–46
Gross CV, MJ/kg	31–34	32–36	26–35	24–28	16–27
Net CV, MJ/kg	30–33	31–35	25–34	22–27	15–25
S (organic)	0.2–0.6	0.2–0.7	0.3–1.3	0.5–1.4	0–2
S (in sulphates)	0.01–0.03	0.01–0.03	0–1.1	0–0.3	0–0.3

S (in pyrite)	0.01–0.47	0.01–0.54	0–3.5	0.1–1.1	0–0.2

Applications

(i) Rotary kiln furnaces

The rotary kiln furnaces consist of long revolving kilns supported on rollers and driven by a gear and pinion arrangement. The kilns are inclined and the raised end, serves as charge end while the lower end provides the discharge of the products. The pulverised coal burner is generally located on the discharge end (Figure 5.8) to provide counter current movement of the charge and hot gases which offers very good heat transfer.

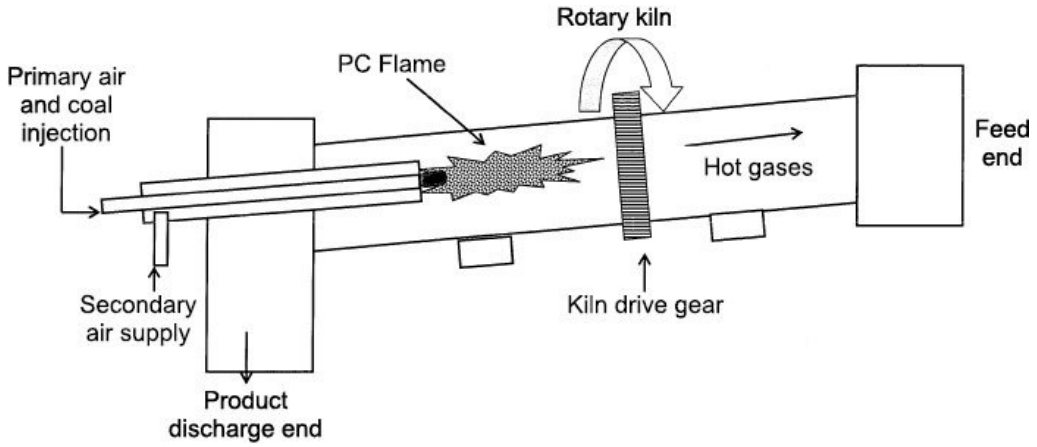


Figure 5.8 The use of PC firing in a rotary kiln furnace.

The rotary kiln is common in cement and sponge iron plants. In both cases, temperatures in the range of 1000–1150 °C are involved which is easily obtained by using PC burners and selection of suitable coal. The ash and sulphur present in coal do not pose any problem in cement making as it becomes a part of the product. However, in case of sponge iron preparation, the ash from PC burner joins the dolomite, lime (converted from charged limestone) and partially used coal which is added in excess. This mixture is separated from main product sponge iron by magnetic separator and is termed as dolo-char. The sulphur in coal is fixed by excess lime and dolomite, and the sponge iron is not seriously contaminated. Effort must be made to keep coal sulphur at lower level while selection.

(ii) Power plants

The PC burners are very commonly used in power plants for raising steam as illustrated in Figure 5.6. The PC burners have the ability to use a variety of solid fuel hence, it is very commonly practiced. The PC burners of different sizes are

used for generating required heat. These PC burners are mounted on wall in various ways to get desired flow pattern of hot gases which affect the heat transfer and steam raising rate. Figure 5.6 shows three different burner mounting positions: front wall, opposed wall and corner giving tangential flow. The PC fired boilers are used by power plants to generate power from 12 to 600 MW by appropriate number of burners, each having thermal capacity of 10 to 60 MW. The combustion efficiency in such system is very high (~ 98%).

5.3.3 SOLID FUEL COMBUSTION IN FLUIDISED BED

The fluidised bed combustion of solid fuels occurs in a bed of fuel where the particles are in gaseous space without resting on other particles. This technique offers large surface area for interaction between solid fuel and oxygen (air) giving efficient combustion.

Fluidised and fixed bed differentiation

The state of fluidisation is illustrated in Figure 5.9 to differentiate it from fixed bed on grate for combustion. In case of grate combustion, the fuel particles rest on other particle to form a fixed bed of fuel. The air passing through grate flows through voids in the fuel bed and reacts with carbon in fuel particles. The surface area available for reaction is limited by void percentage. In this case, the air velocity passing through grate is low to keep the flowing air buoyancy force (f_b) less than gravitational force (f_g) of the particle. When the air velocity is increased to a limit where the buoyancy force equals the gravitational force ($f_b = f_g$), the particles do not rest on each other and the bed gets losen. In this case, the particles remain close, but do no rest on each other. With further increase in air velocity, the particles are further moved up by higher buoyancy force of the air which exceeds much higher than gravitational force ($f_b >> f_g$). In this suspended state ($f_b >> f_g$), the inter particle distance is much more than the loose bed ($f_b = _g$). This suspended state of particles is termed as *fluidised bed* . When the velocity of air is further increased, particle density in the reactor is decreased, and a state may reach with further higher velocity that buoyancy force is too high to blow out all solid particles out of the reactor which is known as *empty tube velocity* . Thus, the air velocity has to be limited in certain range to keep particles suspended in the reactor which depends on fuel particle size and density

with air density at operating temperature.

In fluidised bed condition, the combustion reaction rate is higher than fixed bed due to high surface area availability.

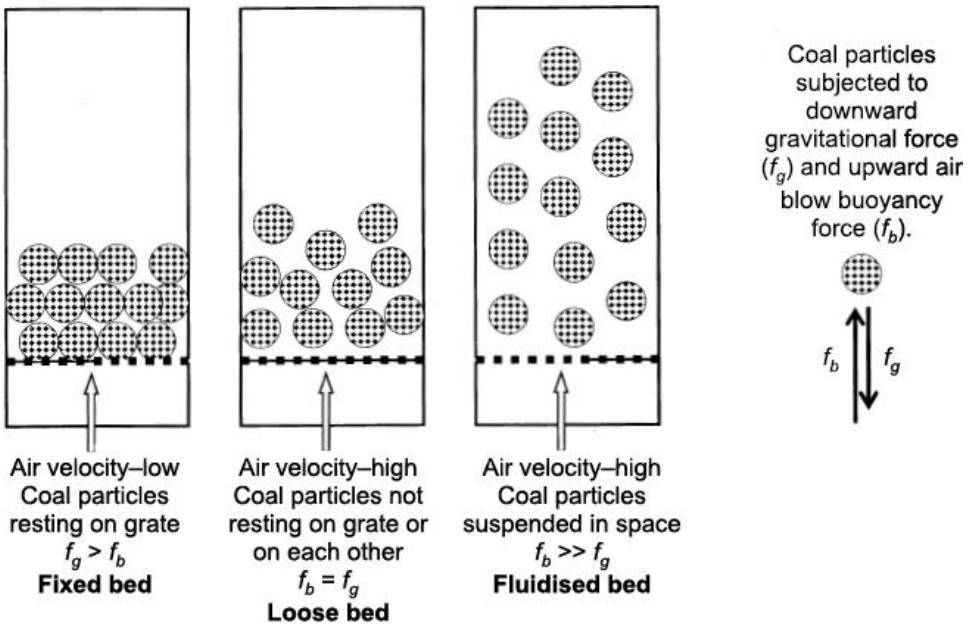


Figure 5.9 Fluidised bed differentiated from fixed bed.

Merits and limitations

Merits

(i) The expensive coal grinding process of coal is not needed. The coal has to be only sized for efficient fluidisation.

(ii) Practically, all types of non-coking coals can be used by this method.

(iii) Combustion efficiency is very good due to coal bed fluidisation.

(iv) The sulphur in coal is not a constrain as it can be fixed with ash by charging limestone with coal.

(v) The working temperature of fluidised bed boiler is less (~ 950 °C) compared with PC fired boilers (~ 1200 °C) causing lesser problems due to corrosion, erosion, etc.

(vi) Lower requirement of excess air (~ 5%–10%) compared to PC burners (15%–25%) helps in avoiding heat loss by flue gases.

(vii) Low NO_x generation during combustion due to lower (~ 950 °C) temperature

(viii) Better heat transfer to immersed water pipes for high rate of steam

generation.

(ix) Process automation is feasible.

Limitations

(i) The immersed water tubes for steam generation need frequent replacement due to erosion by closely placed combustion zone.

(ii) The air velocity has to be regulated in narrow zone for fluidisation and this needs a sized feed.

Working of a fluidised bed boiler

Figure 5.10 illustrates a power plant boiler using fluidised bed combustion. The sized coal and limestone are stored in separate bins, and then they are mixed in certain ratio according to the sulphur content in coal and charged in feed bin which feeds the mixed charge at desired rate in the reactor tower.

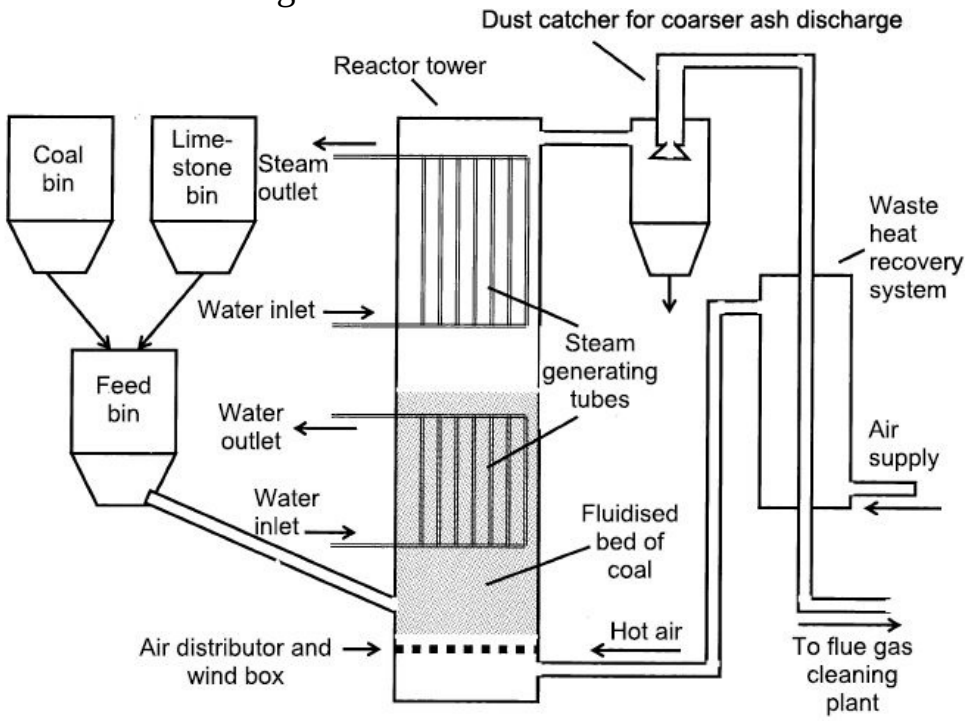


Figure 5.10 Fluidised bed boiler used in power plants (schematic).

The reactor tower is a tall structure which houses the combustion chamber and a set of steam generating tubes. The bottom end of the tower has arrangement for admitting hot air for fluidisation and combustion which is distributed through a set of nozzles. The hot air entering the reactor tower with higher velocity creates a fluidised bed of coal and limestone particles which are fed in the lower end of the reactor.

The combustion of coal particles occurs to generate heat which is transferred

to water flowing in the tubes. The heated water in the form of hot steam generated in the system is utilised for power generation. The fluidised bed combustion generates considerable amount of hot gases which have sensible heat. This sensible heat is utilised by a second set of steam generating tubes located in upper part of the tower.

The hot flue gases laden with ash particles discharged out from the tower reactor still have some sensible heat. This hot flue gas is passed through a dust catching device to retain coarser ash particles. The hot flue gases with fine ash particles passes through a heat recovery system (recuperator). The recovered heat is used to preheat the incoming air for combustion. This hot air is introduced in the tower reactor at its lower end through air distributor system. The warm flue gases leave the boiler area for its cleaning, and then discharged out to the atmosphere through chimney.

Combustion mechanism

The combustion mechanism of the coal particles is illustrated schematically in Figure 5.11 for a running system.

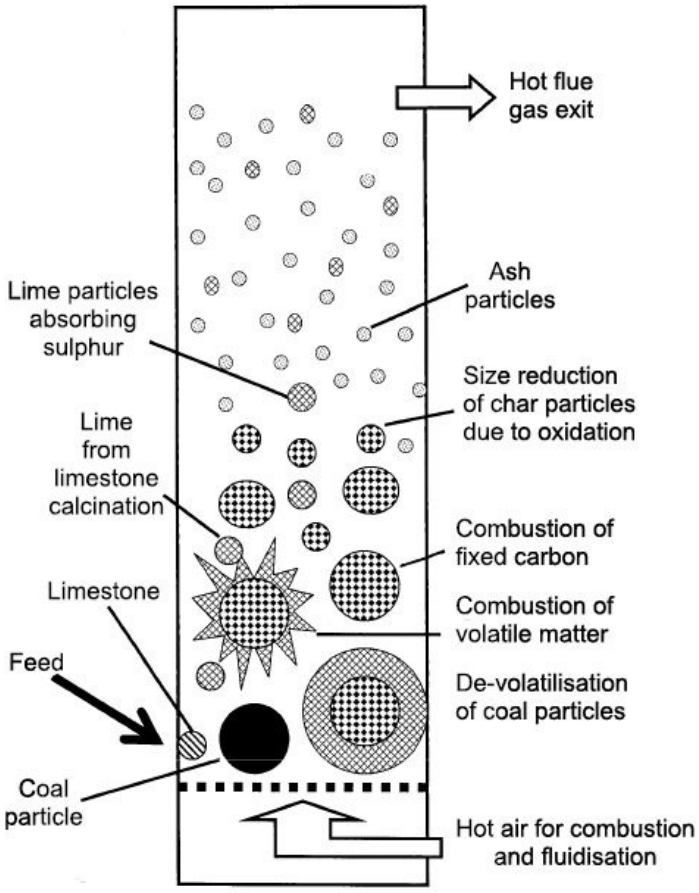


Figure 5.11 Fluidised bed combustion mechanism (schematic).

The sequence of combustion in fluidised bed is given below:

(i) The coal and limestone particles are fed in the reactor at lower end of the reactor tower.

(ii) These cold particles get fluidised by hot air and get pre-heated in few seconds due to large surface area and high radiant thermal flux in the combustion zone.

(iii) The limestone particle is calcined and gets converted to lime particle.

(iv) The coal particle during pre-heating emits volatile matter which surrounds its surface.

(v) This volatile matter is burnt by air present in the fluidising media and heat is released.

(vi) Devolatilised coal particle which can be termed as 'coal char' is now more porous and reactive. These char particles burn and generate heat. The size of char particles keep diminishing with char burning.

(vii) As the size of particles gets smaller, it is fluidised to higher level due to lower gravitational force (f_g) with constant air velocity in the reactor.

(viii) This char particle is ultimately converted to ash particle when all fixed carbon in the particle is utilised.

(ix) In the process of devolatilisation of coal and its combustion, the sulphur dioxide is generated which is absorbed by lime to form calcium sulphate.

(x) These lime particles and ash particles leave reactor tower from top end alongwith flue gases. The fly ash is separated from flue gases by dust catcher and scrubber in gas cleaning plant.

Selection of coal

The fluidised bed combustion system, in principle, can utilise a variety of solid fuels including biomass (wood). However, the design and performance of the boiler would be affected by the coal properties.

(i) *Char reactivity* : The air requirement is affected by char reactivity. The less reactive char would need more excess air and this would affect design parameters for air and charge feed point.

(ii) *Coal ash* : The larger ash in coal would mean more thermal loss by hot ash discharge and would need suitable design changes.

(iii) *Ash composition* : The ash chemistry would play role in its agglomeration in the fuel bed would need suitable changes in design. This ash nature would affect the life of boiler tubes and cost of maintenance.

(iv) *Moisture* : Higher moisture (surface and inherent) is undesirable as it would mean loss of sensible heat and larger flue gas volume. This would also affect boiler design and down side equipment.

(v) *Calorific value* : The higher calorific value of fuel is desirable which is obtained by higher fixed carbon value. This would affect air requirement (blower capacity) and furnace design. The boiler capacity and thermal efficiency is affected by calorific value of fuel.

Table 5.3 summarises the effect on the design parameters and performance.

Table 5.3 Effect of Coal Properties on the Design and Performance of the Boiler Using Fluidised Bed Combustion System

Properties of Coal	*Design Parameter*	*Performance*
Char reactivity	Air flow and feed point	CO emission and boiler efficiency
Coal ash	Ash removal system	Thermal loss and gas cleaning unit
Ash composition	Ash removal system	Agglomeration of ash in bed and boiler tube performance
Moisture	Design of cyclone and down stream equipment	Heat loss
Calorific value	Air blower capacity and furnace dimensions	Boiler capacity and thermal efficiency

5.4 LIQUID FUEL COMBUSTION AND LIQUID FUEL BURNERS

The liquid fuels offer various advantages compared with solid fuel which renders it a very popular source of heat. The handling/combustion is much easier and better controlled than solid fuel. The liquid fuel uses only one device for combustion, i.e., liquid fuel burners unlike different methods of solid fuel burning. These burners are designed in different ways to use various kinds of liquid fuel for many applications. However, all burners have two common features:

(i) They have some arrangement to atomise the liquid fuel in tiny liquid droplets which evaporate to form gas and burn.

(ii) They mix the liquid fuel with air to burn and give a desired type of flame.

5.4.1 Methods for Atomising Liquid Fuel

The liquid fuel atomisation (Figure 5.12) is a process of breaking a liquid stream into very small oil droplets. This atomisation could be done by using three

techniques:

(i) Surface tension forces: In this method, a liquid jet through orifice is created which breaks liquid into filaments and then into tiny liquid droplets due to surface tension of oil in air.

(ii) Centrifugal force: In this method, the liquid is given a swirling motion and the liquid is broken into smaller droplets by centrifugal forces.

(iii) Mechanical force: In this method, a mechanical rotating device is used to create small droplets of oil.

The liquid fuel is injected into burner under pressure or else it is carried by pneumatic systems using air/steam.

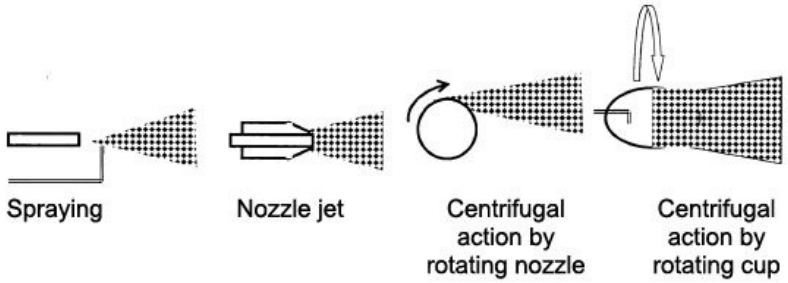


Figure 5.12 Liquid fuel atomisation techniques.

5.4.2 Types of Burner

A burner is a mechanical device that supplies required amount of fuel and air and creates condition for rapid mixing of fuel and air to produce a flame which transfers thermal energy to furnace or charge.

The liquid burners are available for variety of applications in varied sizes. These burners use following basic principle in designs:

(i) Pressure atomisation with orifice
(ii) Pressure atomisation with swirling nozzle
(iii) Pneumatic atomisation with air or steam
(iv) Atomisation with rotary cup
(v) Low pressure air atomisation

Each design has some merits and limitations. The working of these burners is illustrated in Figure 5.13 and described in the following sections.

Pressure atomisation with orifice

This is the simplest design in burner where oil under pressure is injected through a nozzle. The oil is atomised by the surface tension force and the oil mist

(droplets) emerge as a jet in conical shape. The nozzle diameter is more than 0.5 mm which gives a jet cone angle between 5–15 °. The air for combustion is entrained from the surrounding atmosphere in the jet cone due to high velocity of the jet and helps in combustion of oil vapours. The fuel atomising pressure might be as high as 3000 kPa (30 bar) for heavy fuel oil, and for light fuel oils this pressure may be as low as 600 kPa (6 bar). The use of higher pressure helps in reducing the droplet size and enhances the combustion rate.

The merits of pressure jet burners include: (i) low cost, (ii) availability with easy maintenance and (iii) reliability.

However, these burners have some limitations also. These are not suitable for heavy applications and cannot use all varieties of fuel. The burner performance is affected
by drop in pressure due to change in droplet size. The turndown ratio of such burners is
low.

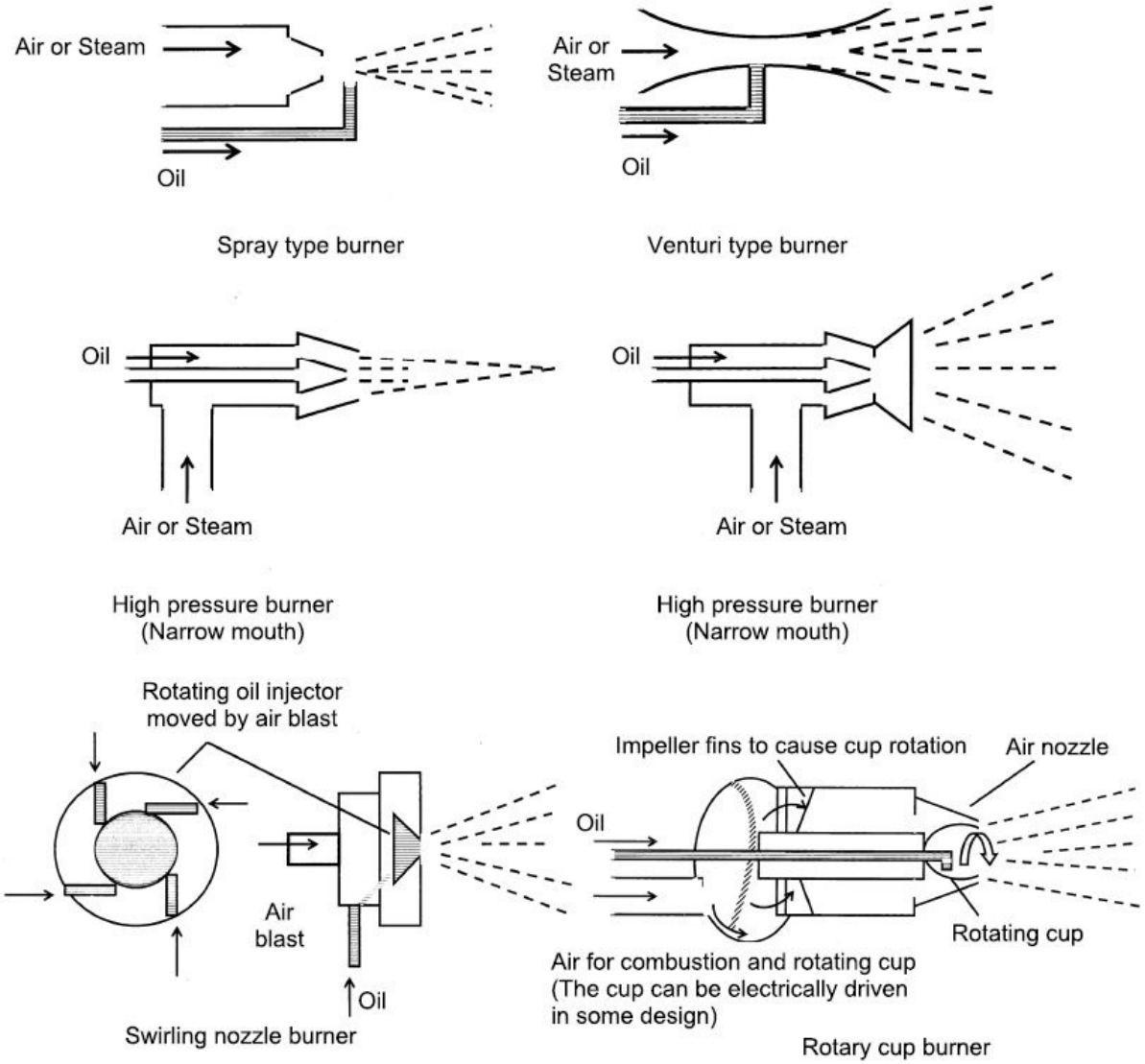


Figure 5.13 Pressure jet burners, swirling nozzle burner, and pneumatic atomisation with air or steam.

Pressure atomisation with swirling nozzle

This system uses a swirling nozzle to atomise oil. The nozzle diameter ranges 2–6 mm which gives high jet cone angle ranging 45°–90°. These burners are known for their simple design, reliability and high quality atomisation.

Pneumatic atomisation with air or steam

In this type of burner, the oil is supplied to the nozzle at lower pressure (~600 kPa or 6 bar). The steam or compressed air is injected to the nozzle for atomisation. This steam and oil get mixed in a chamber in the nozzle before ejecting out as a jet cone. The expansion of the steam/air causes atomisation of the oil.

The merits of these burners include: (i) use of variety of fuel oils, (ii) the quality changes in oil does not affect burner's function significantly, (iii) high pressure fuel pump is not needed, (iv) the lower pressure of oil and steam keeps the muzzle wear less, (v) burner design is robust and simple and (vi) the turndown ratio of such burners are better.

The limitations of such burner are: (i) higher initial cost, (ii) the nozzles are expensive, (iii) these may have ignition difficulties, (iv) these are suitable only for larger furnaces,
(v) use of burner requires a source of steam or compressed air supply.

Rotary cup burner

In this type of burner, the oil flows at low pressure (250 kPa or 2.5 bar max) onto the back of a spinning cup where it runs down the sides and is thrown off the cup rim as a very fine oil film. The rotary cup is rotated at high speed (about 4500–5000 rpm) by an electric motor. A primary air fan blows air concentrically around the outside of the cup which strikes the oil film at high velocity and atomises it into tiny droplets. The rotary cup can use oil in the viscosity range of 3.5–70 centiStokes.

These burners have the advantage that they can use a variety of oil, and small change in viscosity does not affect the burner's working. These are robust is design and working.

The limitation of such burner is its high cost and expensive maintenance. It needs daily maintenance for reliable operation.

Low pressure air atomising burners

The oil is fed at very low pressure (20–50 kPa) into a high velocity air stream. The high speed air "shears" the oil into droplets, and air turbulence further mixes and atomises the fuel. The air source is generally a high pressure blower.

The advantages of a low pressure air burner are: (i) very robust design as these can handle a large variety of fuels, (ii) these are relatively low cost burners, and (iii) they have low running costs as no steam/compressed air is required, (iv) these burners offer very good turndown ratio.

The limitations for such burner are its poor atomisation capability, and it is suitable only for hot or large furnaces like billet reheating, smelter or rotary kilns.

5.4.3 Oil Ignition Systems

The oil after atomisation requires ignition. In hot furnaces, the refractory heat itself may be sufficient to cause ignition of the oil with time delay. In a cold furnace, the oil has to be ignited by using an ‘electric spark’ or a ‘pilot flame’.

Spark ignition

Spark ignition needs a high voltage transformer. The spark is emitted through a set of electrodes, which ignites the atomising fuel oil. The electrode positioning is important. If the electrodes are set too close to the nozzle tip, the spark may jump to the nozzle, causing poor ignition. The same can be said if the electrode is in the oil path–the spray will smoother the spark, causing poor ignition.

Pilot flame ignition

A flame known as a pilot flame is directed straight on to the atomising fuel oil, causing it to ignite. The flame ignition is more reliable, and is generally used in larger burners.

5.4.4 Flame Detection

It is important to monitor the flame on all burners. If the flame fails or goes out, the oil supply to the burner must be shut down. Flame monitoring is done by either using photoelectric cell or using ionisation probe.

The *photoelectric cells* used to regulate oil flow can be of two types: Visible light and UV light.

The lower-cost burners will employ the conventional light detector, whereas the higher range burners will use the superior UV detectors. These detectors give signal for flame working, and also trigger to cut off oil supply in case of auto system.

The *ionisation probe* consists of a rod insulated by ceramic, which is immersed into the flame space. The probe gives signal to indicate whether the flame is working or extinguished. In case flame is extinguished, the oil supply is stopped under auto mode.

5.4.5 Oil Combustion Mechanism

The oil combustion is done through a burner which provides oil in atomised state alongwith air for combustion. These constituents enter the combustion space at high velocity. In a working system, the combustion space is hot, and the atomised liquid oil droplet is heated to form vapours of hydrocarbons. These hydrocarbons react with oxygen present in air and release heat and light. This

combustion occurs in dynamic state caused by high velocity of air supply to form a flame structure. The burning hydrocarbons moving in forward direction give flame till the combustion process is in progress. This visible section of flame from burner tip to end of the flame constitutes ‘flame length’. The shape of the flame will be dependent on burner nozzle design, which gives certain kind of flow pattern.

The complete combustion of oil will be indicated by a flame free from carbon monoxide or hydrocarbons. The hot gases present at the end of flame would contain only CO_2 , NO_x , SO_x and nitrogen, when the air supply is in excess to its theoretical value.

The incomplete combustion of oil would be indicated by a smoky flame with oil droplets fire falling from the flame. This is the indication of excess oil supply and poor atomisation or both, which needs correction.

Figure 5.14 shows schematic view of the flame under above two combustion conditions.

5.4.6 Flame Properties

The flame in the burner needs stability, suitable length, shape and luminosity, depending on the purpose of combustion.

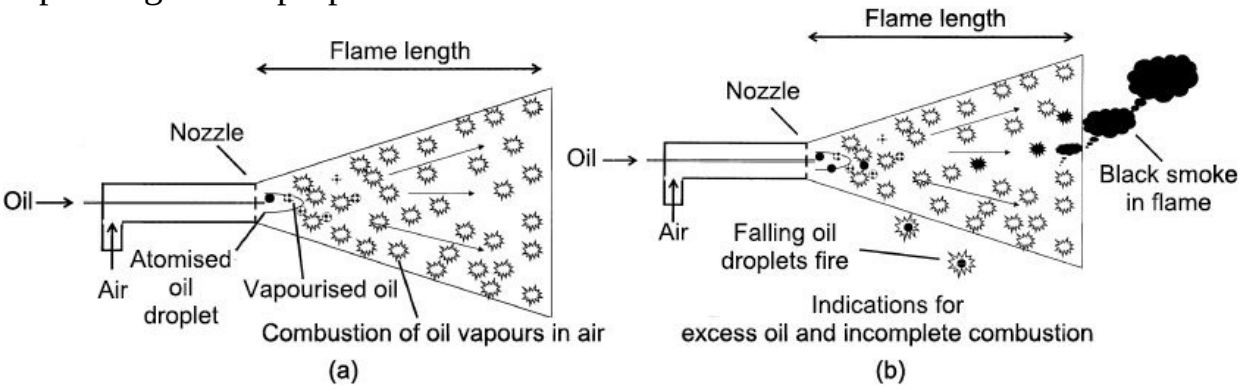


Figure 5.14 (a) Schematic view of flame under complete combustion of oil and (b) incomplete combustion condition.

Flame stability

The flame stability is given by ‘turndown ratio’ of the burner. Turndown ratio of burner is defined as the ratio of maximum heat input rate to minimum heat input rate. This can be expressed as:

$$TR = \frac{Q_{max}}{Q_{min}}$$

where,

T R is the turndown ratio,

Q_{max} is the maximum heat input rate and

Q_{min} is the minimum heat input rate.

The air and fuel are mixed in the burner and delivered in the combustion zone through nozzle. When the mixture velocity is very high than the flame velocity, then the it has a tendency to ‘lift off’ from the burner tip, and gets extinguished. In the other extreme, when the velocity is very low (less than flame velocity), then flame travels back which is termed as ‘backfiring’ or ‘flashback’. Both the conditions are undesirable for a good burner.

The turndown ratios greater than four are uncommon due to the mixing of oil and air in liquid burners.

Flame length

The increased supply rate of oil with air would offer a longer flame length. The deficiency of air will give a longer flame, but with less heat input.

Shape

The shape of the flame is provided by flow pattern of the gases depending on nozzle design and air velocity.

Luminosity

The deficiency in air supply would increase luminosity of the flame.

Oxidising or reducing flame for controling atmosphere

The excess air would give oxidising flue gases, free from CO and hydrocarbons, rich with oxidising gases. In this condition, maximum thermal efficiency is expected and adopted for heating applications.

The deficiency in air would give reducing flue gases due to increased CO and hydrocarbons in flue gases, which may be required for certain applications like heat treatment where loss of heating capacity is compromised.

5.5 GASEOUS FUEL COMBUSTION

The combustion of gaseous fuel is easy due to its ease of mixing with air. The simplest example of gaseous combustion is burning gas in a Bunsen burner (Figure 5.15). It illustrates the principle of two types of flame: the premixed flame and the diffusion flame. The inner cone is the reaction zone for a premixed flame, whereas the outer cone is due to diffusion flame. The inner cone flame,

rich in fuel, offers incomplete combustion giving carbon monoxide which burns in the outer cone as a diffusion flame with the surrounding air.

The nature of the flame as determined by the fuel to air (mixture) ratio. If fuel is present in excess, the flame would be termed ‘rich’ and appear as a yellow luminous flame. If there is excess air (or oxygen), the flame would be termed ‘lean’ and would appear non-luminous. When air to fuel ratio is present in correct propertion, the flame is termed as stoichiometric.

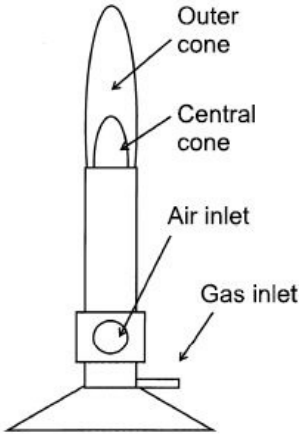


Figure 5.15 Bunsen burner.

5.5.1 Flame Propagation

The gas and air mixture will burn as flames when they are within the flammability limit, which defines the composition of the fuel-air mixture that will sustain a stable flame. There are two types of limit associated with the propagation of a laminar flame. The first is the chemical reactive capability of the mixture to support a flame, i.e., the flammability limit. The second is concerned with gas flow. Typical values for methane gas where the lower and upper flammability limits are 5 mol% and 14 mol%, the stoichiometric ratio is 9.47 mol%. In the case of *n* -heptane the limits would be 1 mol% and 6 mol% respectively, with a stoichiometric ratio of 1.87 mol%.

The combustion flame propagation depends on the gas velocity at the exit of the burner’s nozzle. The flow of gas is laminar when the velocity is less. This flow becomes turbulent with increased velocity as illustrated in Figure 5.16. In the laminar flow, the flame looks slim, and in turbulent, the flame spreads and appears wide. The length of flame is less at lower gas velocity and it increases with velocity up to a point where flow changes from laminar to turbulent. In the turbulent region, the flame length remains mostly constant.

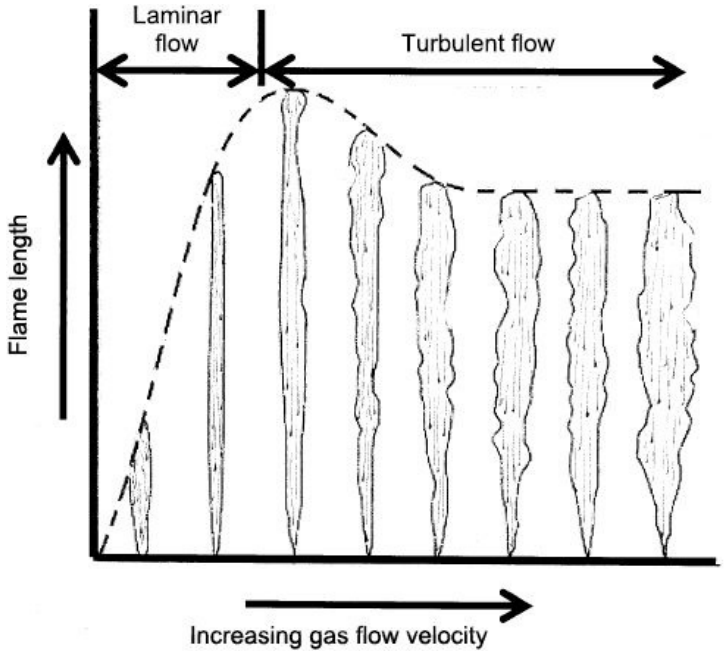


Figure 5.16 The effect of gas flow velocity on the length and shape of flame.

5.5.2 Gas Burner Types

The gas burners can be classified broadly into two types as illustrated by Bunsen burner:

Pre-mixed gas flame and diffusion gas flame. These two can have further subdivision as low gas velocity and high gas velocity. Thus, the gas burners are available for various applications which can fit in category given in Table 5.4 and is illustrated schematically in Figure 5.17.

Table 5.4 Gas Burner Classification

Gas Mixing Method	*Gas Flow Velocity*	
	Low Gas Velocity	*High Gas Velocity*
Pre-mixing gas and Air	Laminar pre-mix flame	Turbulent pre-mix flame
Diffusive air mixing during combustion	Laminar diffusive flame	Turbulent diffusive flame

Burners with pre-mixing arrangement

In this arrangement, the gas and air are mixed and burnt at burner's end. The air mixed with gas is called primary air, and secondary air is supplied in the furnace through ports located at suitable place. The pre-mixed gases react faster giving smaller flame. Such burners need less draft for mixing air/fuel, but they are sensitive to gas specific gravity in comparision to raw gas burners.

These burners are suited for small units where it can give good control of

temperature. The design of the mouth of the burner is important as the linear velocity of the issuing gas must exceed by a small amount to the flame propagation velocity for the mixture used. If the linear velocity of the gas is less, then the flame may ‘strike back’ or ‘back fire’ which is undesired. This may be avoided easily by making burner mouth narrow to increase the gas velocity. When the velocity of gas is very high, the flame may be detached and flame may ‘blow off’.

Burners with diffusive mixing arrangement

In this arrangement, the raw gas and air are delivered separately into burners. The fuel gas and air get mixed together by diffusion process after leaving the burner tip. These burners provide one combustion zone in the flame called ‘diffusion flame’.

Burners with forced draft

Figure 5.17(c) shows a simplified ‘forced draft’ burner. The air is brought into the burner by means of a forced draft blower or fan. The gas is metered into the burner through a series of valves. In order to get proper combustion, the air molecules must be thoroughly mixed with the gas molecules before they actually burn.

The mixing is achieved by burner parts designed to create high turbulence. If insufficient turbulence is produced by the burner, the combustion will be incomplete and samples taken at the stack will reveal carbon monoxide as evidence. Since, the velocity of air affects the turbulence, it becomes harder and harder to get good fuel and air mixing at higher turndown ratios, since the amount of air is reduced. Towards the highest turndown ratios of any burner, it becomes necessary to increase the excess air amount to obtain enough turbulence to get proper mixing. The better burner design will be the one that is able to properly mix the air and fuel at the lowest possible air flow or excess air.

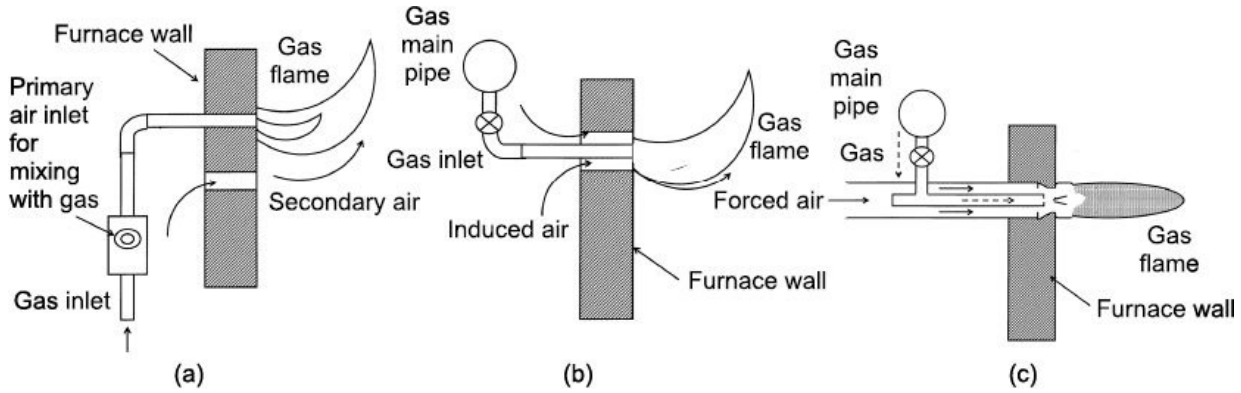


Figure 5.17 Schematic view of industrial gas burners: (a) Air-gas pre-mixing, (b) Raw gas-diffusive air mixing and (c) Forced draft.

Two stage burners

In two stage fuel burner, the combustion occurs in two steps. In the first stage, the fuel-rich combustion is made followed by second stage combustion in fuel-lean zone. The 'fuel-rich' and 'fuel-lean' zone are created by regulating fuel and air in two different ways: 'fuel-staging' and 'air-staging'. In 'fuel-staging' system, the fuel is supplied as 'primary fuel' and 'secondary fuel' to supply gas in two steps. In this burner, the flame is longer.

Low NO_x burners

These burners are designed to give low NO_x in the flue gases. In such burners, nearly 15–25% cold flue gas is recirculated alongwith combustion air to act as a diluting gas. This gas dilution causes reduction in flame temperature with minimisation of oxygen partial pressure resulting in less NO_x formation during combustion.

5.6 NUMERICAL PROBLEMS

In this section, the calculation procedure is provided by solving problems to estimate the air required for combustion, volume of flue gas generated and its composition when solid or gaseous fuels are burnt.

The combustion of solid fuels (coal, coke, etc.) occurs by reacting with air to give heat with gaseous products. This means, a solid substance is converted into gas. It is common to measure solids in terms of mass (gram, kilogram or ton) and gases in terms of volume as cubic centimeter (cc) or cubic meter (m^3). While calculating combustion products, two methods could be adopted: calculation on mass basis or volume basis. This is illustrated with a simple example of combustion of pure carbon in air.

PROBLEM 1 A bed of 12 kg graphite (100% C) is burnt in air. Calculate: (i) Theoretical air required in m^3 , (ii) Volume of products of combustion in m^3 and (iii) Flue gas per cent analysis.

Solution

(a) On mass basic

(i) The combustion of carbon by oxygen is expressed as: $C + O_2 \rightarrow CO_2$

Molecular weights of carbon = 12, oxygen = 32, and carbon dioxide =

44

Thus, 12 kg carbon would react with 32 kg oxygen to produce 44 kg carbon dioxide.

Air contains 23% oxygen and 77% nitrogen by mass.

Thus, theoretical oxygen required for combustion = 32 kg

Or theoretical air required = (32 × 100)/23 = 139.1 kg

Considering the standard air density at STP = 1.2754 kg/m^3

Volume of air required = (139.1/1.2754) = 109 m^3

(ii) The combustion product consists of CO_2 and N_2 .

Nitrogen is derived from air = 109 × 0.79 = 86.11 m^3

(Since air contains 79% nitrogen on volume basis)

Volume of 44 kg carbon dioxide (density at STP = 1.977 kg/m^3) = 22.25 m^3

Thus, the volume of product of combustion = 86.11 + 22.25 = 108.36 m^3

(iii) Volume of nitrogen gas = 86.11 m^3

Volume of carbon dioxide gas = 22.25 m^3

Volume of product of combustion = 108.36 m^3

Thus, flue gas analysis: Nitrogen gas(%) = 100 × (86.11/108.36) = 79.5%

Carbon dioxide gas(%) = 100 × (22.25/108.36) = 20.5%

(b) On volume basis

(i) The combustion of carbon by oxygen is expressed as $C + O_2 \rightarrow CO_2$

Thus, one molecule of C reacts with one molecule of O_2 to give one molecule of CO_2 .

If we convert mass in kg mol, then 12 kg C (mol. wt. 12) = (12/12) = 1 kg mol

The theoretical oxygen required for 12 kg C (1 kg mol.) combustion of = 1 kg mol

It is known that air contains 21% oxygen by volume and 1 kg mol gas at STP = 22.4 m^3

Hence, the theoretical air required = (1/0.21) = 4.76 kg mol = 4.76 × 22.4

= 106.6 m^3

(ii) Volume of 1 kg mol CO_2 at STP = 22.4 m^3

Volume of nitrogen with air at STP = 106.6 × 0.79 = 84.21 m^3

Total product of combustion = 22.4 + 84.21 = 106.6 m^3

(iii) Volume of nitrogen = 84.21 m^3 or Percentage of N_2 = 100 × (84.21/106.6) = 79%

Volume of CO_2 = 22.4 m^3 or Percentage of CO_2 = 100 × (22.4/106.6) = 21%

Volume of product of combustion = 106.6 m^3

The results summary calculated by mass and volume basis:

	Mass basis	Volume basis
(i) Theoretical air required in m^3	109	106.6
(ii) Volume of products of combustion in m^3	108.36	106.6
(iii) Flue gas per cent analysis	N_2 79.5	79
	CO_2 20.5	21

Looking at the methods of calculation done by both ways, the volume basis would appear simple and easy with less steps without remembering density data. The minor difference in answer values are due to density data approximation.

5.6.1 COMBUSTION OF SOLID FUEL

P ROBLEM 2 A pulverised coal fired furnace uses coal analysing 72% carbon, 4% hydrogen, 2% nitrogen, 4% oxygen, 2% sulphur and 16% ash on dry basis. The air used for complete coal combustion contained 10% excess air. Calculate the theoretical air required in m^3 /kg coal at STP, volume of actual air used in m^3 /kg coal at STP and dry flue gas analysis in percentage constituents.

Solution Assume 1000 kg coal is being combusted (Basis for calculation).

In order to proceed with the calculation, it is better to make a table (see Table 5.5) having 12 columns involving different steps for the calculation of coal constituents.

(i) List various coal constituents in Column 1.

(ii) Enter the coal composition (given) in Column 2.

(iii) Calculate the weight of each coal constituent in assumed coal wt. (1000 kg) burned in Column 3.

(iv) Enter the molecular weight of each coal constituent in Column 4.
(Note: The molecular weights of C(12), H_2 (2), O_2 (32), N_2 (28), S(32), etc. are often not provided in the question and needs to be memorised.)

(v) Calculate the kg mol of the coal constituent (weight/mol wt.) in Column

5.

(vi) Write the combustion reaction for each coal constituent in Column 6.

(vii) Calculate the oxygen required (theoretically) for combustion of various coal constituents and place the values in Column 7 alongwith products generated. For example, 720 kg carbon present in 1000 kg coal when converted to kg mol yields 60 kg mol (= 720/12). The chemical reaction of carbon tells us that 1 kg mol of carbon needs 1 kg mol of oxygen and generates 1 kg mol of carbon dioxide on complete combustion. Therefore, 60 kg mol carbon would need 60 kg mol oxygen and produce 60 kg mol CO_2 . Hence, place the respective values in Column 7 (oxygen required) and Column 8 (CO_2 produced).

(viii) The oxygen present in coal is available in-situ, hence the value is put in Column 7 with negative sign.

Now, add the total oxygen (theoretically) required in kg mol to burn 1000 kg coal which is found to be 69.37 kg mol (= 60 + 10 – 1.25 + 0.625 kg mol).

Since, air contains 21% oxygen by volume, hence the theoretically air needed would be = 69.375 kg mol × (100/21)

= 330.35 kg mol for 1000 kg coal

= 0.33 kg mol air needed for one kg coal

Since, 1 kg mol ideal gas at STP = 22.4 m^3

Hence theoretical air needed = 0.33 kg mol air × 22.4 m^3

= 7.39 m^3 air at STP

∴ Theoretical air needed

= ~ 7.4 m^3 air/kg coal at STP **(Answer of 1st part)**

Since, 10% excess air is provided for combustion.

Hence, actual air used = Theoretical air/kg coal + 10% excess air

= 7.4 + (0.1 × 7.4) = 8.14 m^3 air at STP

(**Answer of 2nd part**)

Now, calculate the flue gas analysis on 1000 kg coal combustion basis.

We have calculated the theoretical air = 330.35 kg mol for 1000 kg coal.

The volume of nitrogen in the theoretical air = Air volume – oxygen volume

= 330.35 – 69.37

= 260.98 kg mol –~ 261 kg mol

(ix) Place this nitrogen value (261 kg mol) in column 11 of Table 5.5 with

remark from theoretical air.

The air used in excess (10% over theoretical air) = 330.35 × (10/100)
= 33 kg mol

Since, air contains 21% oxygen by volume, therefore oxygen in excess air
= 33 × (21/100) = 6.93 kg mol

The air contains rest amount (79%) as nitrogen,
hence nitrogen in excess air = 33 – 6.93 = 26.07 kg mol

(x) Now, place the values of nitrogen and oxygen from excess air in Columns 11 and 12 in Table 5.5 with remark from excess air.

(xi) Add all values of the product of combustion in Table 5.5 to find the amount of each product of coal combustion.

Table 5.5 Calculation Table for Solid Fuel Combustion

1	2	3	4	5	6	7	8	9	10
Coal Constituents	*Coal Constituent wt. % (Given)*	*Constituent wt. in* 1000 kg *Coal Burned*	*Molecular weight of the Coal Constituents*	*Coal Constituents Burned in* kg mol	*Chemical Reaction of Combustion*	*Oxygen Required in* kg mol *for Combustion*	*Products of C in*		
							CO_2	H_2O	SO
C	72	720	12	60	$C + O_2 = CO_2$	60	60		
H	4	40	2	20	$H_2 + 0.5\ O_2 = H_2O$	10		20	
N	2	20	28	0.71					
O	4	40	32	1.25		–1.25			
S	2	20	32	0.625	$S + O_2 = SO_2$	0.625			0.62
ASH	16	160							
		Total coal burnt 1000 kg				Total oxygen needed 69.37 kg mol			

					Products of combustion in kg mol		60	20	0.62

Thus, total carbon dioxide in flue gas = 60 kg mol

Total moisture in flue gas = 20 kg mol

Total SO_2 in flue gas = 0.625 kg mol

Total nitrogen in flue gas = 0.71 kg mol from coal + 261 kg mol from theoretical air

+ 26.07 kg mol from excess air

= 287.78 kg mol

Total oxygen in flue gas from excess air = 6.93 kg mol

The total product of combustion = 60 + 20 + 0.625 + 287.78 + 6.93

.= 375 kg mol (moist flue gas for 1000 kg coal combustion)

The dry flue gas volume = Moist flue gas volume – Moisture = 375 – 20 = 355 kg mol

Once the total dry flue gas volume and its constituents are known, the dry flue gas analysis (% volume) can be calculated as given in Table 5.6 **(Answer of 3rd part)**

Table 5.6 Dry Flue Gas Analysis

Constituent	*Volume in* kg mol	*Analysis % Vol.*
Carbon dioxide	60	16.90
Sulpher dioxide	0.625	0.17
Nitrogen	287.78	81.00
Oxygen	6.93	1.93
Total	355	100.00

PROBLEM 3 A coal analyses C–84%, H – 4%, N–1.4%, O–1.8%, S–0.64% and total inorganic oxides (ash) 8.16%. This coal was burnt in pulverised form with excess air to ensure complete combustion. The dry gaseous product of combustion analysed CO_2 –15.7%, O_2 –3.6%, SO_2 –0.04% and N_2 –80.7% at STP. Calculate the following:

(i) Theoretical amount of air needed for combustion in cubic meters per kg coal

(ii) Per cent of excess air used for combustion

(iii) Total dry gaseous product of combustion in cubic meters per kg coal

Solution Given,

Coal analysis: C – 84%, H–4%, N–1.4%, O–1.8% , S–0.64% and Ash–8.16%.

Dry flue gas analysis: CO_2 –15.7%, O_2 – 3.6%, SO_2 –0.04% and N_2 –80.7%. at STP.

Assuming 100 kg coal is combusted and Y% excess air is used during combustion

Prepare a table (Table 5.7) to register all given and calculated data as explained in Problem 2. Table 5.7 gives coal constituents (Column 1), constituents weight (W) in
100 kg coal (Column 2), coal constituents molecular (M) weight (Column 3), calculated coal constituents (W/M) in kg mol (Column 4), combustion chemical reaction occurring with oxygen
(Column 5), oxygen required for combustion in kg mol (Column 6) and products of combustion in kg mol (Column 7).

(i) The sum of Column 6 in Table 5.7 gives the theoretical oxygen needed = 7.964 kg mol

Since, air contains 21% oxygen by volume

hence, the theoretical amount of air needed for combustion

= Theoretical oxygen needed × (100/21) kg mol

= 7.964 × (100/21) kg mol

= 37.923 kg mol

= 37.923 kg mol × 22.4 (since 1 kg mol gas at STP = 22.4 m^3)

= 849.5 m^3 for 100 kg coal

Or theoretical amount of air = 8.495 –~ 8.5 m^3 for 1 kg coal

∴ Theoretical air needed for combustion = 8.5 m^3 per kg coal (**Answer of 1st part)**

Table 5.7 Coal Combustion (100 kg) Using Y% Excess Air

1	2	3	4	5	6	7				
Constituents in Coal	*Const. wt. in* kg	*Mol. wt.*	*Constituents in* kg mol	*Reactions*	*Theoretical* O_2 *Needed in* kg mol	*Products of Combustion Generated in* kg mol				
						CO_2	N_2	H_2O	SO_2	O_2
C	84	12	7	$C + O_2 \rightarrow CO_2$	7	7				

H	4	2	2	$H_2 + 0.5\ O_2 \rightarrow H_2O$	1			2		
O	1.8	32	0.0562		–0.0562					
N	1.4	28	0.05				0.05			
S	0.64	32	0.02	$S + O_2 \rightarrow SO_2$	0.02				0.02	
Ash	8.16	–	–							
Total oxygen needed for combustion theoretically					**7.964**					
										# $0.07962\ Y$
							$ $0.3\ Y$			
							@ 29.96			

Oxygen from excess air calculated under Part ii
$ Nitrogen from excess air calculated under Part ii
@ Nitrogen with theoretical air calculated under Part ii

(ii) It is assumed that the excess air supplied is Y %
Hence, excess oxygen going to the product of combustion
= 7.964 × (Y /100) kg mol
= 0.07962Y kg mol (#–data is transferred to Table 5.7)
Nitrogen with excess air = (79/21) × 0.07962Y kg mol
= 0.3Y kg mol ($–data is transferred to Table 5.7)
Nitrogen with theoretical air = Theoretical oxygen needed × (79/21)
(since air contains 21% oxygen and 79% nitrogen on volume basis)
= 7.964 × (79/21) kg mol
= 29.96 kg mol (@–data is transferred to Table 5.7)
Thus, the total product of combustion (dry) = [CO_2 + N_2 + SO_2 + O_2] present in product gas

= 7 + [0.05 + 0.3Y + 29.96] + 0.02 + 0.07962Y
= [37.03 + 0.37962Y] kg mol

The percentage of CO_2 given the product gas is 15.7%,
i.e. per cent CO_2 in product gas = 15.7% = [7/(37.03 + 0.37962Y)] × 100
or 15.7 × (37.03 + 0.37962Y) = 700
or 581.37 + 5.96Y = 700
or Y = (700 – 581.37)/5.96 = 118.63/5.96 = 19.9% or say Y = 20%
∴ Excess air = 20% (**Answer of 2nd part**)

(iii) Now the value of excess air (Y) is known as 20%,

hence, total product of combustion (dry)

$= 37.03 + 0.37962Y$ kg mol

$= 37.03 + (0.37962 \times 20)$ kg mol

$= 37.03 + 7.5924$ kg mol

$= 44.622$ kg mol

$= 22.4 \times 44.622$ cubic meters

$= 999.54$ cubic meters

or Say –~ 1000 cubic meters

Total product of combustion (dry) = 1000 cubic meters per 100 kg coal

= 10 cubic meters per kg coal

∴ Total product of combustion (dry) = 10 cubic meters per kg coal (**Answer of 2nd part**)

Hence,

(i) Theoretical amount of air needed for combustion = 8.5 m^3 per kg coal

(ii) Per cent excess air used for combustion = 20%

(iii) Total dry gaseous product of combustion = 10 m^3 /kg coal

PROBLEM 4 A dry coal analysing 78% carbon, 8% hydrogen, 2% oxygen, 2% nitrogen and 10% ash was burnt in a furnace. The furnace used 10% excess air during combustion. Calculate:

(i) The amount of theoretical air needed for combustion in m^3 /kg coal

(ii) The amount of actual air used during combustion in m^3 / kg coal

(iii) Flue gas volume using excess air in m^3 /kg coal

(iv) Flue gas analysis on dry basis using excess air.

Solution Consider 100 kg coal for combustion calculation.

Now, put all the constituents of coal (Column 1), weight of coal constituents (W) present in 100 kg (Column 2), molecular wt. (M) of coal constituents (Column 3), Coal constituents (W /M) in kg mol (Column 4), combustion reactions (Column 5), Oxygen required for combustion in kg mol (Column 6) in kg mol and the products of combustion (Column 7) in Table 5.8.

(i) Total theoretical O_2 needed = 6.5 + 2 – 0.0625.

(all the required oxygen for combustion is added and available oxygen in coal is

subtracted to get net theoretical value)

= 8.4375 kg mol/100 kg coal used

It is known that air has 21% O_2 by volume,

Hence, theoretical air needed = (8.4375/0.21) kg mol/100 kg coal used

= 40.1785 kg mol/100 kg coal used

Since, 1 kg mol gas at STP = 22.4 m^3 gas at STP

Theoretical air needed = 40.1785 × 22.4 m^3 air/100 kg coal used

= 899.99 m^3 air/100 kg coal used

or say ~ 900 m^3 air/100 kg coal used

Hence, theoretical air needed = 9 m^3 air/kg coal used (**Answer of 1st part**)

Table 5.8 Calculation Table for Coal Combustion

1	2	3	4	5	6	7			
Constituent in Coal	*Coal Constituent* in kg	*Molecular wt.*	*Coal Const. in* kg mol	*Reactions*	*Theoretical* O_2 *required in* kg mol	*Flue Gas generated in* kg mol			
						CO_2	H_2O	N_2	O_2
C	78	12	6.5	$C + O_2 \rightarrow CO_2$	6.5	6.5			
H	8	2	4	$H_2 + ½O_2 \rightarrow H_2O$	2		4		
O	2	32	0.0625		–0.0625				
N	2	28	0.0714					0.0714	
Ash	10	–		Total O_2 needed	8.4375				
								@ 31.74	
								$ 3.174	
									# 0.843
	100			Total flue gas constituents		6.5	4	34.98	0.84

#–Oxygen from excess air calculated under Part iii

$–Nitrogen from excess air calculated under Part iii

@–Nitrogen with theoretical air calculated under Part iii

(ii) Actual air used = Theoretical air + 10% Excess air

= 9 + (9 × 0.1) = 9.9 m^3 air/kg coal used

Actual air used = 9.9 m^3 air/kg coal used (**Answer of 2nd part**)

(iii) Let us again take the help of Table 5.8 for calculating the values.

In Part (i) we found theoretical oxygen needed = 8.4375 kg mol/100 kg coal used and theoretical air needed = 40.1785 kg mol/100 kg coal

Thus, the nitrogen present in theoretical air

= (40.1785 – 8.4375) kg mol/100 kg coal = 31.74 kg mol/100 kg coal (@–data is transferred to Table 5.8)

Since, the actual air had 10% excess air,

therefore the amount of excess air = (40.1785 × 0.1) kg mol/100 kg coal used

= 4.017 kg mol/100 kg coal used

Oxygen present in excess air = (4.017 × 0.21)

= 0.843 kg mol/100 kg coal (#–data is transferred to Table 5.8)

Nitrogen in excess air = (4.017 – 0.843) kg mol/100 kg coal used

= 3.174 kg mol ($–data transferred to Table 5.8)

Thus, the flue gas volume = [6.5 kg mol CO_2 + 4 kg mol H_2O

+ (0.0714 + 31.74 + 3.174) kg mol N_2 + 0.843 kg mol O_2]

or = 46.32 kg mol/100 kg coal used

Flue gas volume = (46.32 × 22.4)/100 = 10.37 m^3 /kg coal used

∴ Flue gas volume = 10.37 m^3 /kg coal used (**Answer of 3rd part**)

(iv) Now, on addition the flue gas constituents in Column 7 of Table 5.8, we get

Volume of CO_2 = 6.5 kg mol

Volume of H_2O = 4 kg mol

Volume of N_2 = 34.98 kg mol

Volume of O_2 = 0.843 kg mol

Total volume of flue gas (wet) = [6.5 + 4 + 34.98 + 0.843] = 46.32 kg mol/100 kg coal used

To get the value of dry gas, the moisture content (4 kg mol H_2O) is not considered.

∴ Total volume of flue gas (dry) = [6.5 + 34.98 + 0.843] = 42.32 kg mol/100 kg coal used

Calculating the dry flue gas analysis, we get

CO_2 (%) = [6.5/42.32] × 100 = 15.35%

N_2 (%) = [34.98/42.32] × 100 = 82.65%

O_2 (%) = [0.843/42.32] × 100 = 2%

∴ Analysis of dry flue gas using excess air is as follows: (**Answer of 4th part**)

CO_2 %	N_2 %	O_2 %
15.35	82.65	2

PROBLEM 5 A coal contains 78% carbon, 4% hydrogen, 2% oxygen, 1.8% sulphur and rest as non-combustibles.

Calculate:

(i) Gross calorific value of the coal in GJ/ton using Dulong's Formula

$$337\ C + 1442\ [H – (O/8)] + 93\ S\ kJ/kg$$

where C, H, O and S are percentages of carbon, Hydrogen, oxygen and sulphur respectively.

(ii) Amount of coal needed per day to burn in a 10 MW power plant working with 32% thermal efficiency (Given 1 kWh = 3.6 MJ).

Solution

(i) Given,

Dulong's Formula: 337 C+ 1442 [H – (O/8)] + 93 S kJ/kg

where C, H, O and S are carbon, hydrogen, oxygen and sulphur (in per cent) respectively.

(ii) Using the given coal analysis, the calculated calorific value of coal

= [(337 × 78) + 1442 {4 – (2/8)} + (93 ×1.8)] kJ/kg

= [26286 + 1442 {4 – 0.25} +167.4] kJ/kg

= [26286 + {1442 × 3.75} + 167.4] kJ/kg

= [26286 + 5407.5 + 167.4] kJ/kg

= 31860.9 kJ/kg

= 31860.9 × 1000 × 1000 J/ton

= 31.86 × 1000 × 1000 × 1000 J/ton

= 31.86×10^9 J/ton = 31.89 GJ/ton

∴ The calorific value of coal = 31.86 GJ/ton (**Answer to 1st part**)

(ii) Power plant capacity = 10 MW

So, power generated per day (24 hrs) = 10 × 24 MWh/day

= 240 × 1000 kWh/day

Since, it is given that 1 kWh = 3.6 MJ = 3.6 × 1000 × 1000 J

∴ Power generated per day (24 hrs) = 240 × 1000 × 3.6 × 1000 × 1000 J/day

$= 864 \times 10^9$ J/day

= 864 GJ/day

It is given that the plant is operated with 32% thermal efficiency

∴ Total energy required by power plant = [864/0.32] GJ/day

= 2700 GJ/day

As the coal calorific value is calculated (Part i) is 31.86 GJ/ton

The coal required to get the needed energy = [2700/31.86] ton/day

= 84.74 ton/day

∴ Coal required by the power plant = 84.74 ton/day **(Answer to 2nd part)**

5.6.2 Gaseous Fuel Combustion

PROBLEM 6 A natural gas analyses as: CH_4 – 85%, C_2H_4 – 3%, C_6H_6 – 3% 5%, N_2 – 4%. It is burnt with 20% excess air. The air is moist containing 1.5% water vapour.

Calculate:

(i) the dry theoretical air needed for burning one cubic meter of natural gas,

(ii) volume of moist air used for burning including excess air and

(iii) volume of product of combustion at STP and its analysis.

Solution Consider the volume of natural gas to be 100 cubic meter. Prepare a table (Table 5.9)

having five columns and rows to record the calculation data. The steps followed for calculation are:

(i) Enter the various constituents present in the fuel gas in Column 1.

(ii) Enter the volume of each gas constituent present in 100 m^3 natural gas in Column 2.

(iii) Write down the chemical reaction for complete combustion of gas constituents with oxygen in Column 3.

(iv) As per chemical reaction, write down the volume of theoretical oxygen required in Column 4 (For example: 1 volume of CH_4 requires 2 volumes of O_2 for complete combustion, hence, 85 m^3 CH_4 would need 170 m^3 O_2). Similarly, complete Column 4 with oxygen required for all the constituents.

(v) As per chemical reaction, write down the volume of products of combustion generated in Column 5 (For example: 1 volume of CH_4 generates one volume of CO_2 and 2 volumes of moisture (H_2O), hence, 85

m^3 CH_4 would generate 85 m^3 CO_2 and 170 m^3 H_2O). Similarly, complete all sub-columns of Column 5 with product generated from combustion of all the constituents.

(vi) The addition of values of Column 4 will give total oxygen required for combustion theoretically, and addition of sub columns 5 would give the volume of each product of combustion.

Table 5.9 Calculation Table for Gaseous Fuel Combustion

1	2	3	4	5			
Constituent Present in Natural Gas	*Vol. in* m^3 *of Constituents in* 100 m^3 *Natural Gas*	*Combustion Reaction*	O_2 *Needed for* 100 m^3 *Natural Gas in* m^3	*Product of Combustion in* m^3			
				CO_2	H_2O	N_2	O_2
CH_4	85	$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$	170	85	170		
C_2H_4	3	$C_2H_4 + 3O_2 \rightarrow 2CO_2 + 2H_2O$	9	6.	6		
C_6H_6	3	$C_6H_6 + 7.5O_2 \rightarrow 6CO_2 + 3H_2O$	22.5	18	9		
H_2	5	$2H_2 + O_2 \rightarrow 2H_2O$	2.5	–	5		
N_2	4	N_2	–			4	
					@ 17.7	# 919.5	$ 40.5
		TOTAL	204	109	207	923.5	40.5

@–Moisture from moist air calculated under Part (iii)
#–Nitrogen from actual air calculated under Part (iii)
$–Excess oxygen from actual air calculated under Part (iii)

The total oxygen theoretically needed = 204 m^3 for 100 m^3 natural gas (total sum in column 4).

Air composition by volume – 21% oxygen and 79% nitrogen

Therefore, dry air theoretically needed = 204 ÷ 0.21 = 971 m^3 for 100 m^3 natural gas

or dry air theoretically needed = 9.71 m^3 for one m^3 natural gas, (**Answer of 1st part)**

given that the air used was 20% excess and had 1.5% moisture.

Therefore, excess dry air used = 9.71 m^3 × 0.20 = 1.94 m^3 for one m^3 natural

gas

and actual dry air used including excess air = Theoretical dry air + Excess dry air

$= 9.71\ m^3 + 1.94\ m^3$

$= 11.65\ m^3$ for one m^3 natural gas

The actual air used was moist (1.5% H_2O), i.e., 98.5% dry air + 1.5% moisture.

Hence the actual moist air used air = (Actual dry air ÷ 0.985)

$= 11.65 \div 0.985 = 11.82\ m^3$

Actual moist air used = 11.82 m^3 for one m^3 natural gas. (**Answer of 2nd part)**

Since, actual moist air used = 11.82 m^3 per m^3 natural gas which contained 1.5% moisture and 98.5% dry air

hence, moisture content in actual air = $11.82 \times 0.015 = 0.177\ m^3$ per m^3 natural gas

or = 17.7 m^3 for 100 m^3 natural gas (@–data is transferred to in Table 5.9)

Dry air actually used = $11.82 \times 0.985 = 11.64\ m^3$ per m^3 natural gas

or = 1164 m^3 for 100 m^3 natural gas

Nitrogen in dry air actually used = $1164 \times 0.79 = 919.5\ m^3$ (#–data is transferred to Table 5.9)

Oxygen in dry air actually used having theoretical + excess oxygen = 244.5 m^3 for 100 m^3 natural gas

The excess oxygen in flue gas = 244.5 – 204 = 40.5 m^3 for 100 m^3 natural gas ($–data transferred to Table 5.9)

The sum of products of combustion in Column 5 would give

$CO_2 = 109\ m^3$ or $[(109 \div 1280) \times 100] = 8.5\%$

$H_2O = 207\ m^3$ or $[(207 \div 1280) \times 100] = 16.1\%$

$N = 923.5\ m^3$ or $[(923.5 \div 1280) \times 100] = 72.1\%$

$O_2 = 40.5\ m^3$ or $[(40.5 \div 1280) \times 100] = 3.1\%$

As the total volume of products of combustion = [109 + 207 + 923.5 + 40.5] = 1280 m^3 for 100 m^3 natural gas

Hence flue gas volume = 12.8 m^3 for 1 m^3 natural gas

Answer of 3rd part: Volume of product of combustion = 12.8 m^3 /m^3 natural gas.

Analysis of Product of Combustion is as follows:

CO_2	8.5%
H_2O	16.1%
N_2	72.1%
O_2	3.1%

PROBLEM 7 A mixed gas containing 80% blast furnace gas and 20% coke oven gas was used in a furnace with excess air to get complete combustion. The flue gases analysed 1.46% oxygen on dry gas basis. Calculate: (i) the amount of theoretical air/m^3 of mixed gas, (ii) per cent excess air used (iii) amount of actual air/m^3 of mixed gas and (iv) flue gas analysis on dry basis.

Given the fuel gas analysis as below:

Fuel Gases	Gas Analysis, Volume %						
	CO	CO_2	CH_4	N	H_2	C_2H_4	C_6H_6
Blast furnace gas	24	12	–	63	1	–	–
Coke oven gas	6	2	32	4	46	7	3

Solution Consider 100 m^3 of the mixed gas is used for combustion which contains 80%
(or 80 m^3) blast furnace gas and 20% (or 20 m^3) coke oven gas whose gas analysis is provided in the problem.

Calculating the volume (m^3) of gas constituents present in 80 m^3 blast furnace gas,
20 m^3 coke oven gas as per given analysis (in problem), the values are presented in Table 5.10. The sum of each gas constituent will provide constituents in 100 m^3 mixed gas. This mixed gas analysis could then be used for combustion as calculated in Table 5.11.

Table 5.10 Calculation of the Composition of Mixed Gas (80% BF + 20% CO)

Fuel Gases	*Gas Volume in* m^3	*Volume of Each Gas in* m^3						
		CO	CO_2	CH_4	N	H_2	C_2H_4	C_6H_6

Blast furnace gas	80	19.2	9.6	–	50.4	0.8	–	–
Coke oven gas	20	1.2	0.4	6.4	0.8	9.2	1.4	0.6
Mixed gas (BF + CO)	100	20.4	10	6.4	51.2	10	1.4	0.6

Consider combustion of 100 m^3 of mixed gas (80% BF + 20% CO) and enter values in Table 5.11 as per following steps:

(i) List all the gas constituents present in mixed gas in Column 1

(ii) Enter the volume (m^3) of each gas constituent present in 100 m^3 of mixed gas (80% BF + 20% CO) as calculated in Table 5.10.

(iii) Write down the chemical reaction for complete combustion of each gas constituents in Column 3.

(iv) The oxygen required for complete combustion as per reaction (Column 3) is presented in Column 4.

(v) The products of combustion generated as per reaction (Column 3) is presented in sub columns of Column 5 for each product constituent in flue gas.

Now, theoretical oxygen needed for complete combustion (sum of oxygen in Column 4)

$= 36.7\ m^3 /100\ m^3$ of mixed gas

It is known that the air contains 21% oxygen by volume.

Therefore, theoretical air needed for complete combustion

$= (36.7\ m^3 \div 0.21)$

$= 174.76\ m^3 /100\ m^3$ of mixed gas

or $= 1.74\ m^3$ air/m^3 of mixed gas

∴ Theoretical air needed for combustion = 1.74 m^3 air/m^3 of mixed gas (**Answer of 1st part**)

The amount of nitrogen associated with theoretical air = Air volume – Oxygen volume

$= (174.76 – 36.7)\ m^3 /100\ m^3$ of mixed gas

$= 138.06\ m^3$, this nitrogen would join product of combustion

(@–Nitrogen data is transferred to Table 5.11 as products of combustion from theoretical air.)

Now, assume excess air used = Z%

The volume of excess air used with the theoretical air = $174.76 \times (Z /100)$

$= 1.747Z\ m^3$

Oxygen present in $1.747Z\ m^3$ excess air = $1.747Z \times 0.21$, as air contains 21%

O_2

$= 0.3668Z\ m^3$

Nitrogen present in $1.747Z\ m^3$ excess air = $1.747Z \times 0.79$, as air contains 79% N_2

$= 1.38Z\ m^3$

Table 5.11 Combustion Calculation for Mixed Gas (80% BF + 20% CO)

1	2	3	4	5			
Gases Present in Mixed Gas	*Vol.* (m^3) *of gas Burnt Present in* 100 m^3 *Mixed Gas*	*Chemical Reactions*	*Oxygen Required in* m^3 *for Complete Combustion*	*Products of Combustion (Flue Gas) generated in* m^3			
				CO_2	N_2	H_2O	O_2
CO	20.4	$CO + 0.5O_2 \rightarrow CO_2$	10.2	20.4			
CO_2	10			10			
CH_4	6.4	$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$	12.8	6.4		12.8	
N_2	51.2				51.2		
H_2	10	$2H_2 + O_2 \rightarrow 2H_2O$	5			10	
C_2H_4	1.4	$C_2H_4 + 3O_2 \rightarrow 2CO_2 + 2H_2O$	4.2	2.8		2.8	
C_6H_6	0.6	$2C_6H_6 + 15O_2 \rightarrow 12CO_2 + 6H_2O$	4.5	3.6		1.8	
		Theoretical oxygen required Total	36.7				
					@ 138.06		
					# 13.8		$ 3.66
		Total volume in m^3		43.2	203.06		3.67

@–Nitrogen in flue gas from theoretical air
#–Nitrogen in flue gas from excess air
$–Oxygen in flue gas from excess air

The total flue gas (wet) = [43.2 m^3 CO_2 + (51.2 + 138.06 + 1.38Z) m^3 N_2
+ 27.4 m^3 H_2O + (0.3668 Z) m^3 O_2]

Total flue gas (dry) = [43.2 m^3 CO_2 + (51.2 + 138.06 + 1.38Z) m^3 N_2
+ (0.3668Z) m^3 O_2]
= [232.46 + 1.7468Z] m^3

Given, the oxygen as 1.46% in dry flue gas.

Therefore, the oxygen (%) in dry flue gas
= 1.46% = (Oxygen volume ÷ Dry flue gas volume) × 100
= [(0.3668Z ÷ (232.46 + 1.7468Z)) × 100

or 1.46 × (232.46 + 1.7468Z) = 0.3668Z × 100
or 339.39 + 2.55Z = 36.68Z
or 339.39 = (36.68 – 2.55)Z
or 34.13Z = 339.39
or Z = (339.39 ÷ 34.13)
Hence, excess air used (Z %) = 9.94%, say –~ 10%

∴ Excess Air used ≃ 10% (**Answer of 2nd part**)

Now, Actual air used = Theoretical air + Excess air
In Part (i), the theoretical air is calculated as 1.74 m^3 air/m^3 of mixed gas
Using 10% excess air, i.e., 0.17 m^3 excess air/m^3 of mixed gas, we find
Actual air used = (1.74 + 0.17) m^3 /m^3 of mixed gas
= 1.91 m^3 /m^3 of mixed gas

∴ Actual air used is 1.91 m^3 /m^3 of mixed gas (**Answer of 3rd part**)

Since, the value of excess air (Z %) is now calculated as 10%, therefore

nitrogen from excess air = 1.38Z m^3 = 1.38 × 10 = 13.8 m^3 (#–data is transferred to Table 5.11)

oxygen from excess air = 0.3668Z m^3 = 0.366 × 10 = 3.66 m^3 ($–data is transferred to
Table 5.11)

Dry flue gas consists of CO_2 , N_2 and O_2 .

Total volume of CO_2 in flue gas = 43.2 m^3 (From Table 5.11)

Total volume of N_2 in flue gas = [51.2 m^3 from coal combustion
+ 138.06 m^3 from theoretical air

+ 13.8 m^3 from excess air]

= 203.06 m^3

Total volume of O_2 in flue gas = 3.66 m^3

Thus, total volume of dry flue gas = [43.2 m^3 CO_2 + 203.06 m^3 N_2 + 3.66 m^3 O_2]

= 249.96 m^3 = 250 m^3

Dry flue gas analysis is now calculated as:

CO_2 % in flue gas = (43.2 ÷ 250) × 100 = 17.28%

N_2 % in flue gas = (203.06 ÷ 250) × 100 = 81.22%

O_2 % in flue gas = (3.66 ÷ 250) × 100 = 1.46%

∴ Dry flue gas analysis: 17.28% CO_2 , 81.22% N_2 and 1.46% O_2 (**Answer of 4th part**)

Review Questions

1. What are the factors considered while designing combustion system?

2. Describe the mechanism of combustion of solid fuel in the following conditions:

(i) Fuel bed on fixed grate

(ii) Pulverised coal burner

(iii) Fluidised bed

3. How is the combustion of solid fuel affected by the quality of fuel?

4. Give the properties of solid fuel for use in the following applications:

(i) Smithy furnace

(ii) Pit melting furnace

(iii) Small boilers

(iv) Power plant PC fired boilers

(v) Cement kiln PC firing

(vi) DRI kiln PC firing

(vii) Fluidised coal bed boile

5. What are the basic components in liquid fuel burner? What are the different methods used for atomisation of liquid fuel?

6. What is the role of ignition system in an oil burner? What different ignition systems find use in practice?

7. Why a flame detection system is used in automated oil burners? How does it

work?

8. What are the different types of gas burner used in industry? Give their merits.

9. Define the following terms:

(i) Oxidation
(ii) Gasification
(iii) Wobbe Index
(iv) Turndown ratio
(v) Air fuel ratio
(vi) Flame stability

10. Differentiate between the following terms:

(i) Complete and Incomplete combustion
(ii) Combustion and Smouldering
(iii) Combustion and Explosion
(iv) Theoretical air and Excess air
(v) Primary air and Secondary air
(vi) Oxidising and Reducing flame

11. Write short notes on the followings:

(i) Furnace for smithy shop
(ii) Foundry pit melting furnace
(iii) PC fired power plant boilers
(iv) Rotary kiln for cement
(v) Rotary kiln for DRI production
(vi) Power plant using fluidised coal
(vii) Two stage gas burners
(viii) Low NO_x gas burners

6

Furnaces and its Accessories

Introduction

The furnace or oven is defined (section 1.2.1) as a chamber or working enclosure where higher temperature is maintained for the conduction of some operations related to industry, research or domestic life. The furnaces are the integral part of metallurgical industries, which fall under various group due to use of available energy resources. Section 1.2.2 gives the basic purpose of these furnaces. The basis of furnace classification (section 1.2.3), major components of furnace (section 1.2.4), and reasons to select a particular furnace (section 1.2.5) has already been discussed in Chapter 1.

This chapter is devoted to describe some of the metallurgical furnaces which use fossil fuels (coal/coke, oil and natural/manufactured/waste gases) as such or convert it to electrical energy before discussing the basic principles of furnace design, reactors, combustion system, blower/exhaust and chimney.

This chapter also gives the idea of temperature measurement and indication devices, pressure measurement and indication systems, gas analysis and control tools, gas cleaning systems, thermal shields and acoustic chambers, used as furnace accessories.

6.1 COMMONLY USED FURNACES

In metallurgical industries, the furnaces are used for applications like drying, calcinations, roasting, agglomeration, reduction/smelting, refining, melting, metal heating for hot deformation, and metal heat-treatment. In these furnaces, various energy sources are used including solid fuel, liquid fuel, gaseous fuels, electrical energy and inherent chemical energy present as carbon, sulphur, phosphorus, silicon and manganese.

In the following sections, some furnaces are described as illustration for using such different energy sources.

6.1.1 Solid Fuel based Furnaces

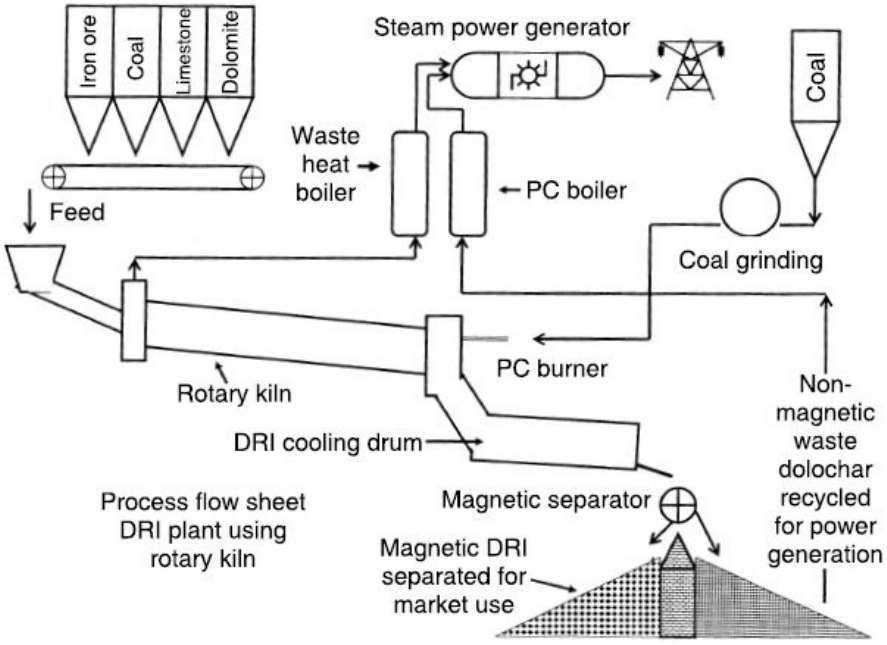
The solid fuels like coal, coke, petro-coke and charcoal find application in metallurgical furnaces as energy source to meet thermal and chemical energy needs. The furnaces using such solid fuels are illustrated in the following sections:

Coal based furnaces

(i) Sponge iron (DRI) rotary kilns

The rotary kilns have emerged as a very popular furnace for making sponge iron using non-coking coal as reductant and thermal energy source. India is the major user of such furnaces in the world due to availability of resources (rich iron ore and non-coking coal).

Design: The rotary kilns having daily production capacity of 50–500 tons by single kiln are operating in India with indigenous design. Figure 6.1 shows the major components of sponge iron (or DRI—Directly Reduced Iron) rotary kiln. The rotary kilns are horizontally laid steel cased refractory lined reactors with circular cross-section. These kilns are slightly inclined towards the discharge end to facilitate the movement of the charge due to gravity.



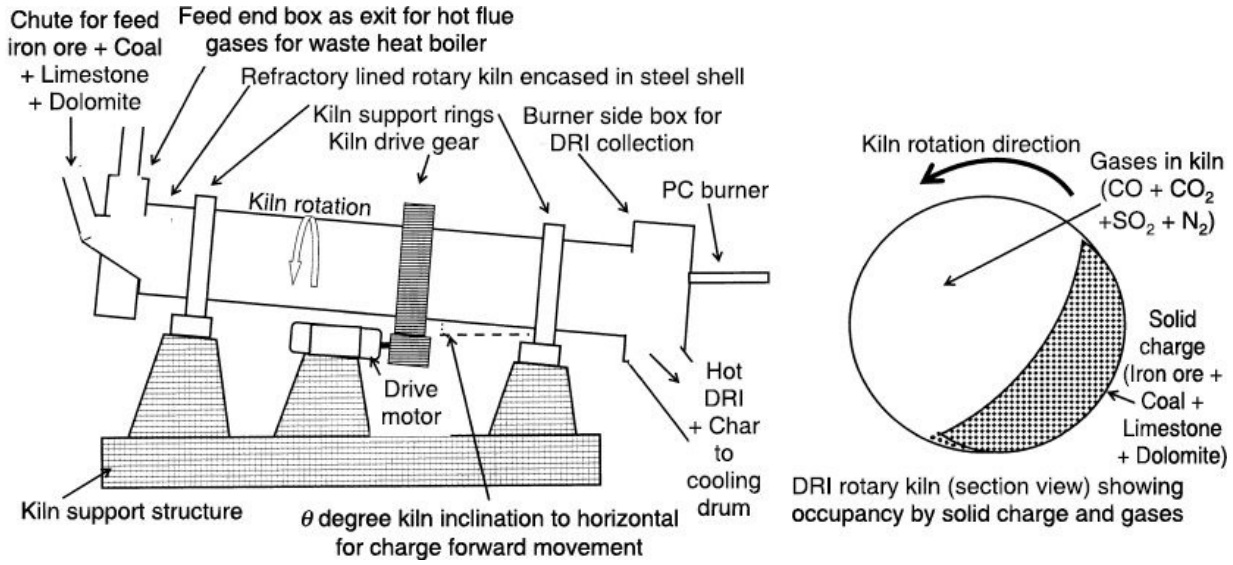


Figure 6.1 Major components in a sponge iron plant using rotary kiln (schematic).

Working: The feed consisting of lump/pellet iron ore, non-coking coal and lime stone with dolomite charged from the raised end of the kiln. This feed moves forward due to kiln rotation and downward kiln inclination. The feed undergoes drying, pre-heating with pre-reduction, heating with iron ore reduction and sintering of reduced iron to metallic iron while travelling from feed end to the discharge end. The reduced/metallised sponge iron in solid state and unused coal char mixed with lime and dolomite (dolo-char) get discharged (1100 °C) from the lower end of the kiln to the cooler drum. This rotating drum is cooled by external water spray on the drum surface. The hot sponge with dolo-char moving inside the drum loses its heat before getting discharged to the conveyer belt, which passes through a magnetic separator to separate the metallic sponge iron from non-metallic dolo-char residue.

Fuel and refractory: The sponge iron kiln is heated by using pulverised coal burner and the coal fed alongwith iron ore functions as reductant. The quality of coal selected by DRI kilns is given in section 2.12.2. The kiln is lined with fireclay bricks as the maximum temperature in the kiln is nearly 1200 °C. The kiln as such deals with solid state reduction, however, the refractory life in rotary kiln is mainly affected by ring formation, which is a fused built up due to low fusing ash with iron oxide mixture in the hot zone of the kiln. The ring formation continues with time, and requires removal mechanically after stopping the kiln operating. The continuous longer operating period of the kiln is the sign of its good functioning, which may range from 100 to 300 days/year.

(ii) COREX iron making technology

This is a new smelting reduction (SR) technology developed in 1980s as an alternative
method of iron making based on the use of coal. This SR method has distinct advantage of producing liquid hot iron unlike sponge iron (DRI) technology, which delivers solid iron and needs further melting operation. The SR technologies have been developed to get liquid iron using easily available non-coking coal, instead of scarce metallurgical grade coke. Such iron making units differ in design from conventional blast furnace. In India, this technology is adopted only by JSW Steel at Bellary.

Design and working: The COREX process design is shown in Figure 4.4 **(** Chapter 4) and its working is already described.

Fuel and refractory: The quality of coal required for the process has been described in Chapter 2 (section 2.12.3) and illustrated in Figure 2.56. The suitable refractory for use in the pre-reduction shaft would be fireclay bricks, while the refractories suitable for the smelter reactor would be different in different sections of the furnace. The hearth section requires graphite blocks to sustain high temperature with corrosive slag. The upper spherical section of the reactor faces very high temperature (~1600–1800 °C), and hence magnesite and chrome-magnesite refractory would be more suitable. However, the type of refractory actually used in this system has not been indicated in the publications.

(iii) Rotary hearth furnace for sponge iron

This is a sponge iron making furnace based on using coal fines as a reductant mixed with iron ore fines in the form of composite pellets. The main advantage of this furnace is its ability to accept weak dry ore coal mixed pellet on the hearth to cause reduction and strengthening before discharging out in one single hearth rotation. The compact nature of the furnace to produce DRI using plant waste is another advantage, responsible for its promotion by many new emerging DRI processes (Commet, ITmk3, Finmet, CPR, etc.). It is limited by its size and smaller production capacity.

Design: The furnace consists of a circular rotating hearth enclosed in a stationary circular furnace as shown in Figure 6.2(a). The hearth diameter and its rotating speed would depend on the reduction behaviour of the ore-char pellet. The hearth width would be decided depending on the production capacity of the DRI.

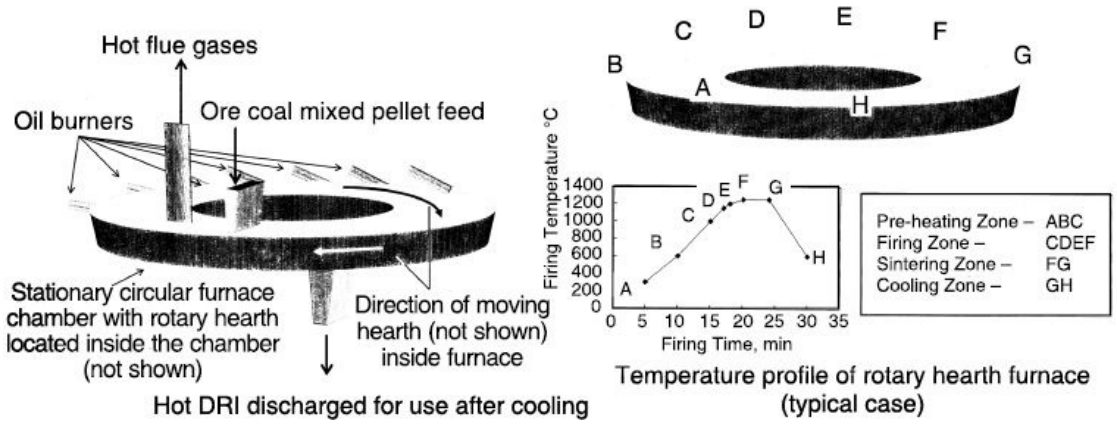


Figure 6.2 (a) Rotary hearth furnace for DRI production and (b) its firing temperature profile.

Working : The furnace is fired in a particular segment using producer gas or oil based on economics. The temperature profile in different segments of the furnace is shown in

Figure 6.2(b), which offers pellet pre-heating with pre-reduction, heating at 1050–1100 °C to cause reduction, heating at 1200–1250 °C to cause metallisation and strengthening of the reduced pellet followed by cooling down to about 600 °C before being discharged out for further cooling outside the furnace. The hot flue gases generated in the hot zone move in opposite direction of the hearth to cause pre-heating and drying of the charge, before leaving through the exit located just close to feed point. The coal fine mixed pellets are fed on the hearth in single layer or two layers due to poor pellet green strength and heat transfer limitations.

Fuel and refractory: The furnace maximum working temperature of 1250 °C permits the use of fireclay bricks as refractory. The expensive oil can be replaced by producer gas made from coal, if other gaseous energy source is unavailable.

(iv) Steam raising boilers

The boilers use coal to raise steam for various applications in metallurgical plants such as power generation, humidification of blast in blast furnace, operation of valves, power source, etc.

The steam boilers using coal are available in various capacities ranging from very smaller one using coal on grate (Figure 5.2) to larger boilers using pulverised coal combustion for power generation (Figure 5.6). The coal combustion processes in both type of boilers are described in sections 5.3.1 and 5.3.2.

The type of coal suitable for boiler use is given in Table 5.2, which can be used in lump or pulverised form. The coal must be non-caking in nature for the

combustion process.

(v) Producer gas unit

This is a coal based furnace where coal is burnt partially by limited air supply to generate gas rich in carbon monoxide alongwith some hydrocarbons evolved from coal volatile matter. The producer gas manufacturing process has been discussed in Section 4.8 and illustrated in Figure 4.5. The non-coking bituminous coals are used in the furnace which is lined with fireclay bricks.

Coke based furnaces

(i) Blast furnace

The blast furnaces are used for the production of pig iron using coke as major fuel and reductant. This is a tall shaft type reactor which is fed with ferrous burden (iron ore/iron ore sinter/iron ore pellet or their combinations), coke and lime stone from the top, and hot air is blown through tuyers in the lower part of the shaft as shown in Figure 6.3.

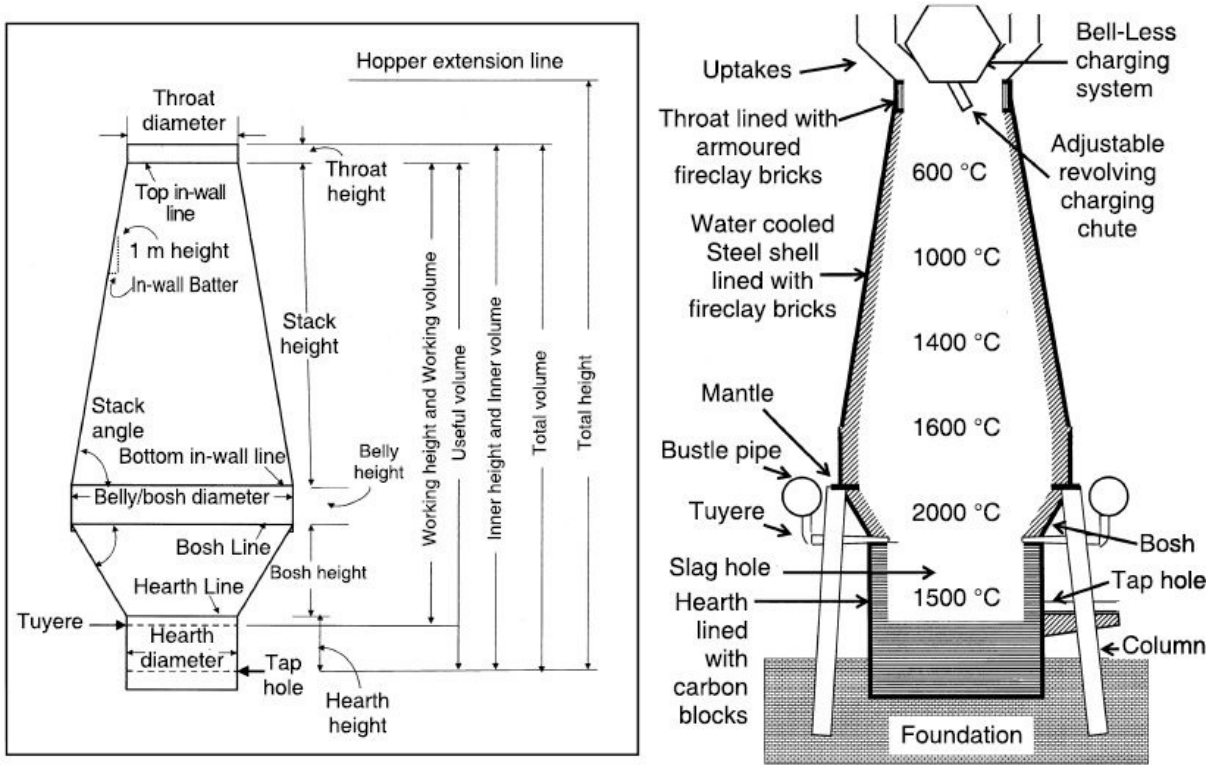


Figure 6.3 The blast furnace components and its profile.

Design: The various components of the blast furnace and its profile are depicted in

Figure 6.3. The profile of the blast furnace indicates variation in its diameter

from top to bottom. Such profile of the blast furnace has been achieved due to operational requirements. The ‘throat’ at the top is a short cylindrical section where the charging device is fitted. The upper section, known as ‘stack’, is a tall frustum of cone whose larger diameter is at lower end and matches with ‘belly/bosh’ diameter. The stack smaller diameter matches with ‘throat’ diameter. The increase in diameter size with downward height is indicated by ‘inwall batter’ in mm for every 1 m depth. The angle between sloping ‘stack’ wall and horizontal is known as ‘stack angle’. The section joining ‘stack’ and ‘bosh’ is known as ‘belly’, which is a short height cylindrical section. The lower section ‘bosh’ is again a frustum of cone with down end smaller diameter, matching with ‘hearth’ diameter and upper wider end diameter matches with ‘belly’ diameter.

The increasing stack diameter serves to provide easy solid material decent under gravitational force, and also provides extra volume to accommodate the increased volume of expanding burden due to thermal expansion and chemical reactions (iron ore swelling behaviour under reduction). The ‘belly’ is cylindrical in shape as the burden material is mostly reduced, hot and fused mass which can decent down under overburden load. The following ‘bosh’ section is inverted cone with decreasing diameter as in this section the solid reduced ferrous burden and slag gets molten due to high temperature occupying lesser volume.

The blast furnaces are designed to produce hot metal under varied conditions of raw material quality and many other considerations. These varied factors result in blast furnace having working volume ranging from 100 to 5000 m^3 and yielding ~ 300 to 10000 ton hot metal per day. The increasing size of the blast furnace increases demand for quality of raw materials including coke quality and the refractory quality, which have not only to sustain high temperature but have to bear high working load alongwith erosive and corrosive conditions prevailing inside the blast furnace due to counter current movement of solid burden materials and escaping hot reducing gases.

Working: The ferrous burden with coke and limestone descend down in the blast furnace against upward flow of hot reducing gas. This hot reducing gas, rich in carbon monoxide, is generated at tuyers level by the reaction of hot coke and oxygen in air blown into it. The reducing gas causes reduction of ferrous burden, and the iron oxide is converted into metallic iron which melts to get collected in the hearth. The unreduced oxides in the burden, ash in coke, lime, etc. combine to form slag, which is also collected in the hearth in molten form floating on the top of the liquid bath. The liquid hot metal and slag both are tapped out periodically through respective tap hole and slag notch.

Fuel: The blast furnace uses ‘metallurgical coke’ as fuel. In view of tough furnace working conditions, the coke is expected to possess many qualities, some of which are discussed below:

Ash in coke : The coke with minimum ash per cent is preferred as it affects the blast furnace slag volume, coke consumption and silicon content in hot metal.

Coke reactivity: Less reactive coke (CRI% 23–24) is preferred for blast furnace as it helps in less degradation (Figure 6.4) of coke size during its decent from top to bottom (tuyere) where it has to perform its duty of combustion, and provides bed permeability for gas movement.

Coke strength: The high shatter strength coke (70–78% Shatter Index) is needed for handling and charging in the furnace with minimum fine generation. The low CRI% offers high (64–66%) coke CSR value (Figure 2.43) which helps coke in sustaining heavy weights without breaking inside the blast furnace.

Coke size: The larger sized coke (50–100 mm) helps in providing higher coke mean size in the blast furnace which is needed for bed permeability.

The coke properties affect the blast furnace functioning in many ways, and hence maximum attention is to be paid on its quality. Some aspects are illustrated in Figure 6.4 and discussed below:

Coke Strength and Raceway depth : The deeper raceway in blast furnace is desired for better gas aerodynamics. This is possible with coke having high CSR% and low CRI%. The poor grade coke (low CSR%) would generate coke fines with decreasing raceway depth and increasing peripheral gas flow which are undesirable.

Coke strength and coke mean size: The size of coke fed in the blast furnace decreases while descending down due to mechanical wear and chemical reaction with CO_2 . The higher CSR value coke offers larger mean size coke, which is better in offering bed permeability for smoother gas movement.

Coke strength and larger blast furnace: The larger blast furnaces with 2000–5000 m^3 volume require stronger coke to sustain burden weight at high temperature. This is possible by proper selection of coal for coke making and coking at higher temperature calling for better coke ovens.

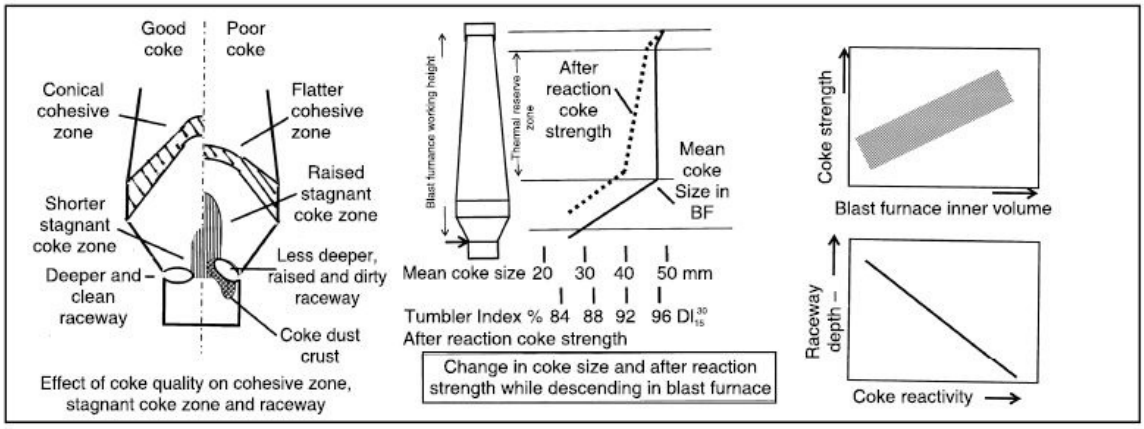


Figure 6.4 Coke quality and blast furnace operation.

Refractory: The hostile working conditions inside the blast furnace require a very careful selection of refractories. The selection of refractory becomes more important for larger blast furnaces where working load is very high together with high temperature and erosive/corrosive conditions. The different working conditions (e.g. erosion, corrosion, thermal fluctuation, high temperature, high working load, etc.) prevailing in different sections of the furnace give common working problems (e.g. wear, spalling, deterioration of brick under stress, cracking, etc.) which require the use of different refractory bricks in conventional and modern blast furnaces. The refractories used in different sections of the blest furnace are presented in
Table 6.1 in a summarized manner.

Table 6.1 Refractories Used in Different Sections of the Blast Furnace

Blast Furnace Sections	*Conditions Prevailing in the Furnace*	*Problems Faced during Working*	*Refractory used in Conventional Furnaces*	*Refractory used in Modern Furnaces*
Upper stack	Abrasion and impact, thermal fluctuations, Temperature 300–600 °C	Abrasive wear, spalling	Fireclay bricks (39–42% Al_2O_3)	Super duty fireclay (40–44 % Al_2O_3)
Middle stack	Gas erosion, thermal fluctuations, alkali attack, Temp. 900–1100 °C	Wear, spalling, deterioration of brick	Fireclay bricks (39–42% Al_2O_3)	Super duty fireclay (40–44 % Al_2O_3)
Lower stack	Erosion by gas, Thermal fluctuations, alkali attack, thermal fatigue, Temperature 1200–1400 °C	Wear, severe spalling, deterioration of brick, Shell damage and cracks	Fireclay bricks (39–42% Al_2O_3)	Super duty fireclay (40–44 % Al_2O_3)

Belly	Abrasion, gas erosion thermal fluctuations, alkali attack, Temperature 1400–1600 °C	Wear, spalling, deterioration of brick	Fireclay bricks (39–42% Al_2O_3)	Corundum, SiC-Si_3N_4
Bosh	Abrasion thermal fluctuations, slag and alkali attack, Temperature 1600–2000 °C	Wear, spalling, stress attack, deterioration of brick	62% Al_2O_3, Mullite	SiC-Si_3N_4
Hearth	Erosion from hot liquids, zinc, slag and alkali attack oxidation (water), Temperature 1450–1550 °C	Wear, deterioration of brick, hearth break out risk due to stress build up and cracking	42–62% Al_2O_3, Mullite, conventional carbon block	Carbon/Graphite block with super micro pores

(ii) Cupola

The cupola is a melting furnace for cast iron. It is the most common melting furnaces used by ferrous foundries. The cupola furnace can be easily obtained or fabricated to melt pig iron and cast iron scrap giving liquid iron (0.5–5 ton/hour) for sand casting. It is common to express cupola size as melting capacity (ton/hour) or its internal diameter (meters) size. A five ton cupola is understood to have a melting capacity of 5 ton per hour during regular melting operation.

The cupola is a widely used cast iron melting unit by ferrous foundries due to its ease of construction and low cost of operation with very low maintenance cost.

Design: It consists of a tall vertical shaft made of steel shell lined with fireclay refractory. A wind box is attached to the shaft at lower end to supply air for combustion. The cupola bottom is made of two half of a circular steel plate, which can be opened by removing hinges to drop the residual coke and metal at the end of melting operation. This drop bottom is locked before restarting the cupola, and a sloping sand bed is made to permit the flow of liquid iron out from tap hole. In some cupola, a fore-hearth is attached which consists of refractory chamber kept hot by an auxiliary oil burner. The fore-hearth acts as a hot melt buffer chamber for melt alloying, temperature control, large melt supply for larger castings, etc. Figure 6.5 shows various components of a cupola.

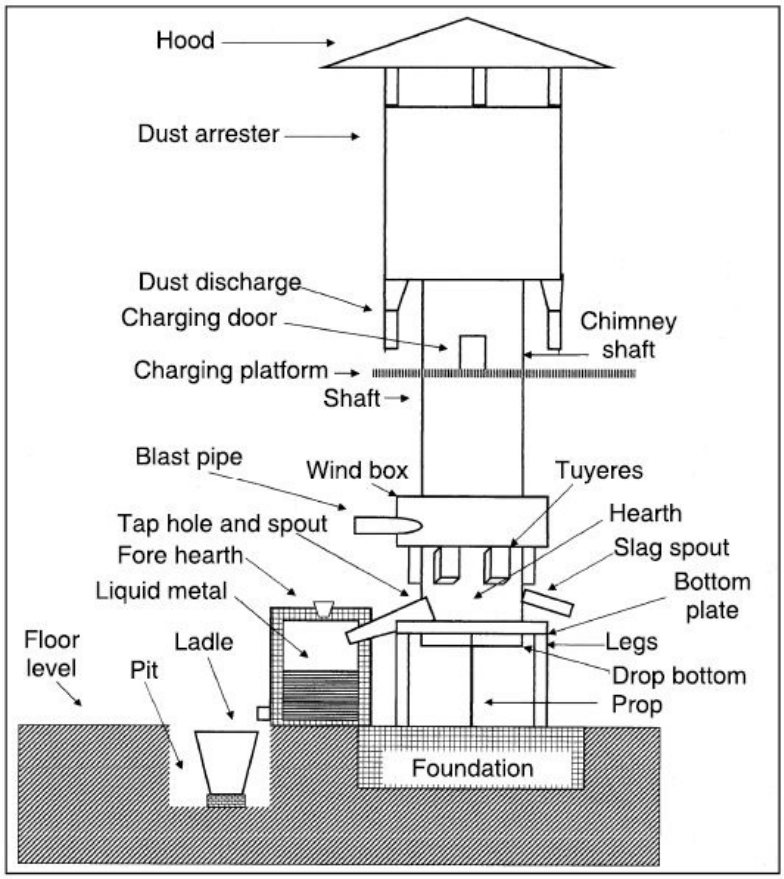


Figure 6.5 Various components of cupola furnace.

Working: The iron scrap, coke and limestone are charged from top which get heated and melted due to heat of the coke combustion at tuyere level. The cupola maintains oxidising atmosphere for maximum thermal efficiency.

Fuel and refractory: The working conditions in the cupola is not as tough as in blast furnace, being smaller in size with lower working temperature (~ 1450 °C) in the hearth region and ~ 300–400 °C at the top end. The coke having lower strength and higher reactivity would perform well under cupola working conditions. The properties of coke suitable for cupola use are given in Table 2.17. The fireclay bricks can serve satisfactorily in cupola.

Pollution control: The use of cupola is associated with environmental problems due to emission of smoke and dust, causing concern in the neighbourhood. The use of dust arrestors (Figure 6.5) and flue gas cleaning system make it environmental friendly.

(iii) Foundry pit furnace

This is a coke based melting unit in foundries for small scale (5–10 kg) use. The

melting capacity of the furnace depends on the manual handling ability of crucible filled with hot melt. The furnace is shown in Figure 5.2. Its simple construction and operation make it a popular furnace (temperature 1100–1400 °C) for melting cast iron, copper and copper alloys like brass and bronze used for making artefacts in cottage industry. The furnace uses 10–15 mm size coke in pit furnace lined with fireclay bricks.

(iv) Foundry pot furnace

This is a coke based small scale furnace for melting non-ferrous metals and alloys which melt below 600–700 °C . The metals like aluminium, aluminium base alloys, tin, lead, cadmium and low melting alloys are melted on small scale in cast iron pot heated by burning coke on grate. The melt is poured out by using spoon or pot tilting arrangement. Figure 6.6 shows a pot furnace used by non-ferrous melting units working on small scale (~ 500 kg).

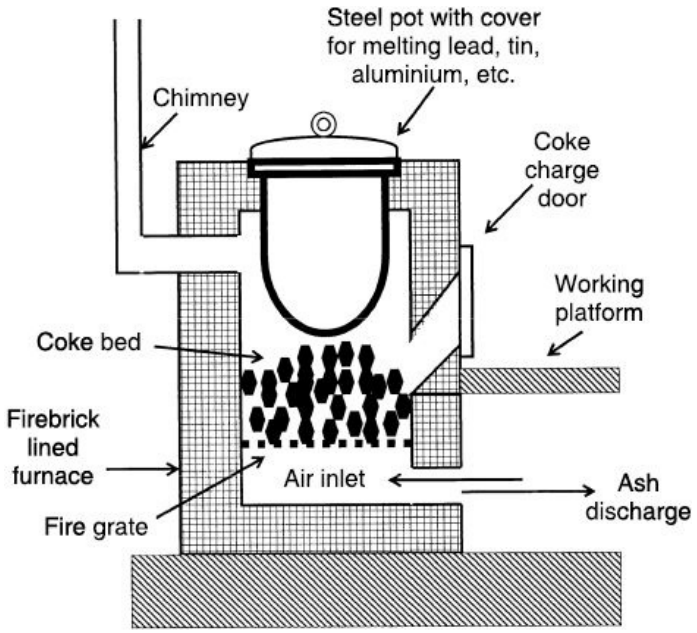


Figure 6.6 Pot furnace for melting low melting metals and alloys.

Petro-coke using furnaces

Petro-coke is a by-product of oil refineries as solid residue left after crude oil refining process. It is virtually free from ash, and has very high carbon content (~ 98%) with very low reactivity. It is used as a reductant for the production of ferroalloys like, ferrosilicon, ferromanganese, ferrochrome, ferrovanadium, etc. using submerged arc furnace (see section 6.1.4).

Charcoal using furnaces

Charcoal is a renewable energy source obtained by carbonisation of wood. It is

the best type of solid fuel and reductant having least ash content (< 4 wt. %), high fixed carbon (~ 94 wt. %) and practically very low volatile matter (~ 2 wt. %). Unfortunately, the use of charcoal is not being used due to its non-systematic production, currently rendering it as banned item in many countries. The systematic agro forestry on waste lands (desert, saline, marshy, rocky, etc.) in tropical locations having sun shine more than 300 days/year can yield solid carbon
(biomass or wood) due to photosynthesis of atmospheric carbon monoxide, moisture and solar radiation (photon) by hard wood plants. This hard wood yields very good charcoal for metallurgical use which has been studied and experimented in Brazil and India. This has a potential for use in future when metallurgical coke will be scare. The biggest limitation with charcoal is its poor crushing strength which limits the size of shaft furnace (iron blast furnace) using it as a fuel.

(i) Small iron blast furnace

The iron blast furnaces used charcoal as a fuel till 1900 AD, which were gradually replaced by metallurgical coke due to non availability of charcoal in absence of agro forestry to generate wood for commercial use. These small blast furnaces had the capacity to produce 300–600 ton iron per day. Such furnaces were used in Brazil on experimental basis using wood from agro forest. Such small scale blast furnaces are not being used currently due to economic reasons, however, they have potential in the coming time as eco-friendly renewable fuel.

(ii) Electric pig iron furnace

Tysland hole process is a special method of liquid pig iron making in a shaft type reactor using wood char as reductant and cheap abundant hydro-electrical power for providing thermal energy. Such method yielded high quality pig iron for alloy steel making and was practiced by erstwhile Mysore Iron & Steel Co (MISCO) in Bhadrawati till 1950. Such process was abandoned due to non-availability of wood char. The availability of wood char in future has potential of its revival in power rich regions.

(iii) Tribal iron making furnace

The art of iron making on kilogram scale by tribal people is well known since ages. Tribal people knew the art of reducing iron ore in small shaft type furnaces using wood char as reductant to produce semi-liquid iron. This semi-liquid iron was hot forged to squeeze out most of the slag. The retained slag get distributed

in the metal matrix due to hot working. This art of iron making is still alive in some tribes of Madhya Pradesh and Chattisgarh for making tools for their domestic use.

6.1.2 Liquid Fuel based Furnaces

The liquid fuels like furnace oil, diesel and coal tar fuels (CTF) are very commonly used in various furnaces for melting and heating applications. The various melting units (e.g. *crucible furnace*, skelner *furnace, mixer, open hearth furnaces)* and heating furnaces (e.g. *forging furnace and re-rolling mill furnaces)* are described briefly in the following sections:

Melting furnaces

(i) Crucible furnace

Oil fired crucible furnaces are common melting furnaces used by non-ferrous foundries in locations where solid fuel is not usable for reasons like lack of storage space, problem of ash disposal, high cost of transportation, availability and other difficulties for its use. In such oil fired furnaces, the heat transfer from flame to the melt is poor, since crucible acts as heat barrier resulting in very low thermal efficiency. In spite of low thermal efficiency, such furnaces, are very common in jobbing foundries working on small scale to melt non-ferrous alloys like brass, bronze, aluminium alloys, etc. These furnaces are popular with industries located in prime land areas, hilly and cold regions, isolated locations like island towns, etc.

The furnace appears like a pit furnace (Figure 6.7) with difference that it is oil fired using a burner. The size of the furnace depends on the size of crucible, which can be handled manually or by a portable crane. These furnaces provide 1200 to 1300 °C temperature, and fireclay refractory lining serves the purpose.

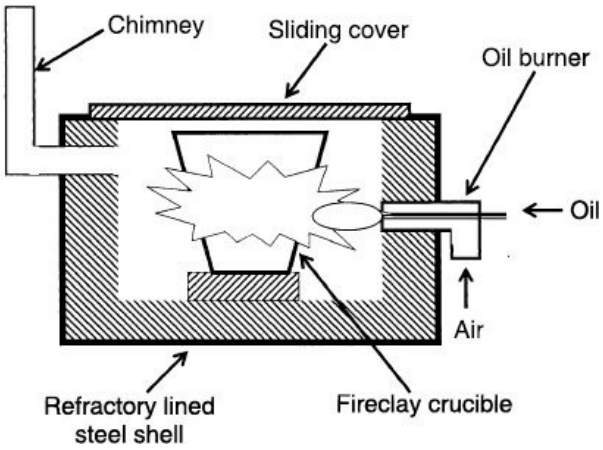


Figure 6.7 Oil fired crucible furnace.

(ii) Skelner furnace

The non-ferrous reveberatory or the Skelner furnaces are highly durable and used for large scale melting by non-ferrous foundries. These are available in manual and hydraulic tilting arrangement for pouring melt out from the furnace. These furnaces have a melting chamber lined with fireclay refractory, and equipped with burners and recuperator. The oil consumption is approximately 80–100 liter/ton of molten metal in continuous operation.

(iii) Mixer unit for liquid iron storage

The oil fired ‘mixer unit’ in integrated steel plants is used to store liquid iron produced in blast furnaces. This unit serves various functions like:

a. It stores liquid iron produced continuously by blast furnaces when the steel converters are not operating.
b. It homogenises the melt composition from various batches of liquid iron tapped to have a better converter blowing schedule.
c. In case of long shut down in steel making unit, it keeps the liquid iron hot using oil burners.
d. It also serves to remove sulphur by suitable lime slag during holding period.

The ‘mixer’ is a large cylindrical drum-shaped vessel which can be rotated by certain degree for pouring out liquid melt. The pouring in of the hot metal by ladle is done in vertical position having its spout facing the sky. The fall in temperature is checked by heat energy supply by oil burners. The holding capacity of mixers varies from 150 to 1000 ton liquid pig iron. The pig iron is

held at 1450 °C, which requires a good refractory lining. The main requirements of the refractory lining are:

a. Resistance to pig iron erosion and corrosion caused by the slag
b. Thermal shock resistance
c. Volume stability
d. Heat capacity (specific heat of the refractory material) to increase heat storage.

Such requirements are met by the use of refractories like silica-alumina, alumina or alumina-silicon carbide-carbon composite bricks.

(iv) Open hearth furnace or Siemens-Martin furnace

The oil fired open hearth furnace is an established old furnace design since 1900 AD for steel making, and it is still being retained. Currently, this furnace is mainly used by heavy steel casting units in the world due to its ability to supply quality steel melt in quantities more than 100–500 ton in one batch for making extra heavy castings like chemical reactor chamber. Such large tonnage of steel melts in one batch is not feasible by any other steel making furnace. However, these open hearth furnaces have lost their importance for common grades of steel due to their very slow steel production rate and poor thermal efficiency compared to pneumatic and electric steel making units.

The *open hearth furnaces* are also referred to as ‘Siemens-Martin furnace’, named after the British engineer Sir Carl Wilhelm Siemens and French engineer Pierre-Émile Martin, who jointly developed this furnace in 1865 AD, which became popular in 1900 AD.

The open hearth furnace has many merits and few limitations. These are discussed in the following section.

Merits

(1) It can use cold steel scrap or hot liquid melt from mixers holding blast furnace or cupola melt.
(2) It can use oil or gas burners to supply heat during steel making.
(3) It can be lined by acid or basic refractory, depending on the slag chemistry involved during steel making.
(4) It can be designed to prepare molten steel in quantity ranging 50–500 tons.
(5) The quality of steel made is very high in terms of composition and

cleanness with temperature control which is needed for large tonnage steel castings.

Limitations

a. It is a very slow process of steel making.
b. It offers very slow heat transfer rate from heat source to metal bath through insulating slag layer floating on the top of the molten steel.
c. It needs high energy input as oil or gaseous fuel.

The open hearth furnace has survived today against all odds only due to its merits, although total tonnage of steel made by this furnace is very small compared to LD and EAF.

This furnace is shown in Figure 6.8 which consists of two major parts: the roof
covered hearth for melting steel and a set of refractory brick chambers serving as regenerators. The other components like burners, ports, ducts, dampers, chimney, etc. are indicated in
Figure 6.8.

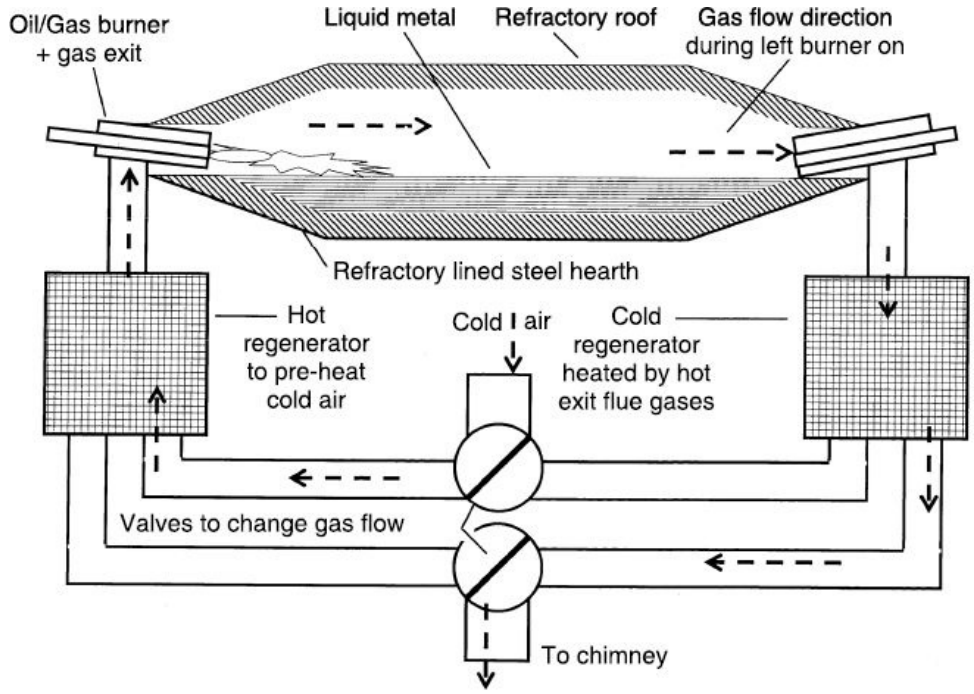


Figure 6.8 Open hearth furnace for steel making.

The various components of the furnace are described briefly below:

Hearth: The refractory lined hearth serves to hold the metal charge. The nature

of refractory lining (silica as acid or basic magnesite) depends on the steel making slag (acid or basic) practice. The hearth shape resembles a trough which is long, wide and shallow in depth. The hearth is covered with an arched roof resting on side sloping walls. One of the walls in front has doors with covers for charging raw materials (scrap, fluxes, additives, etc.) for steel making by a mechanical scoop (spoon type). The liquid melt can be poured in the furnace by ladle using a spout. The tap hole is located on the opposite side of the charging door close to the hearth floor.

Regenerators: These are the set of refractory chambers located on either end of the furnace below the hearth level. In these chambers a firebricks are arranged in such a manner that they allow gases to move freely in desired directions. The heat transfer between refractory bricks and gases occurs during its flow. Amongst two brick chambers, one cool chamber gets heated by the flow of hot gases exit from the furnace port, while the other hot chamber, which was heated in previous cycle, delivers its heat to incoming cool air (from atmosphere) to be used for combustion in the furnace. Thus, the cold air is pre-heated and gives higher flame temperature in the furnace, while the brick chamber gets cooled. The regenerator's 'heating' of one chamber and 'cooling' of another chamber proceed simultaneously for a given time, and then this cycle is reversed by actuating the duct dampers. Now, the chamber which was on 'heating' mode becomes on 'cooling' mode and vice versa. Thus, cyclic heating and cooling of regenerator chambers continue.

Burners and ports: The two longitudinal ends of the furnace serve as location for burners located in between ports. The burners provide heat using oil or gaseous fuels, while the ports provide passage to exit hot gases to the chimney via regenerator chamber. As the regenerator chambers operate in cycle of 'heating' and 'cooling', the location of fuel burning and exit of hot gases through port are also switched from 'left end' to 'right end' of the furnace. Assume, at any given time, the regenerator chamber on left end of the furnace is on heating cycle and right end chamber is on cooling cycle. In this cycle, the right end side burner would be active using hot air coming from right end chamber on 'cooling' mode. The furnace hot gases would exit from ports located on left end and pass through chamber on 'heating' mode.

Dampers: These are valves to change the direction of flow of gases in the duct such that a regenerator chamber could be put on 'heating' or 'cooling' mode.

Chimney: It is the exit for waste gases to the atmosphere.

Heating furnaces

The oil fired reheating furnaces are common in steel forging and re-rolling units, since they operate independently in locations away from integrated steel works. The LDO (light diesel oil) is the most easily available furnace oil exploited by such units due to its low sulphur content. Such furnaces operate with efficiencies as low as 7 per cent as against up to 90 per cent achievable in other combustion equipment such as boiler. This is because of the high heat losses at high operating temperature with flue gases. The furnaces of different types are adopted depending on the nature of job to be performed. Some typical furnaces are described in the following sections.

(i) Forging furnace

The oil fired forging furnaces are used for pre-heating billets and ingots to 'hot forge' temperature in the range of 1200–1250 °C. Forging furnaces use an open fireplace system, and most of the heat is transferred by thermal radiation. The typical loading in a forging furnace is ~ 5 ton with the furnace operating for 16 to 18 hours daily. Specific fuel consumption depends upon the type of material and number of 'reheats' required.

(ii) Batch type re-rolling mill furnace

The oil fired furnaces are used by steel re-rolling mills. These mills use a box type furnace
for reheating steel in batches. The furnaces basically use scrap, small ingots and billets weighing 2 to 20 kg for re-rolling. The charging and discharging of the 'rolling stock' are done manually, and the final product is in the form of rods, strips, etc. These furnaces are normally operated at ~ 1200–1250 °C with pre-heated stock load capacity of about 10–15 tons per day.

(iii) Continuous pusher type re-rolling mill furnace

This is similar to batch–type furnace with the difference that pusher type furnace is longer in length and the stock is pushed (Figure 6.9) at one end to discharge out one billet at another end for rolling. In between the fresh billet pushed in the furnace and the hot billet pushed out, there are some billets which are being pre-heated and soaked at working temperature
(~ 1250 °C). These furnaces can pre-heat ~ 20–25 ton steel stock. The thermal efficiency of these furnaces is better than batch furnace, because the hot flue gases are partially recirculated through rolling stock before exit.

The merits and limitations of these furnaces are as follows:

Merits

Low capital and maintenance costs

Heating of top and bottom face of the stock

Limitations

Frequent damage of refractory hearth and skid marks on rolling stock

Energy losses from water cooling the skids and stock supporting structure

Discharging must be synchronised by charging

Stock sizes and weights with furnace length are limited by friction

The stock pile-ups is common

Heating of the rolling stock on all sides is not possible

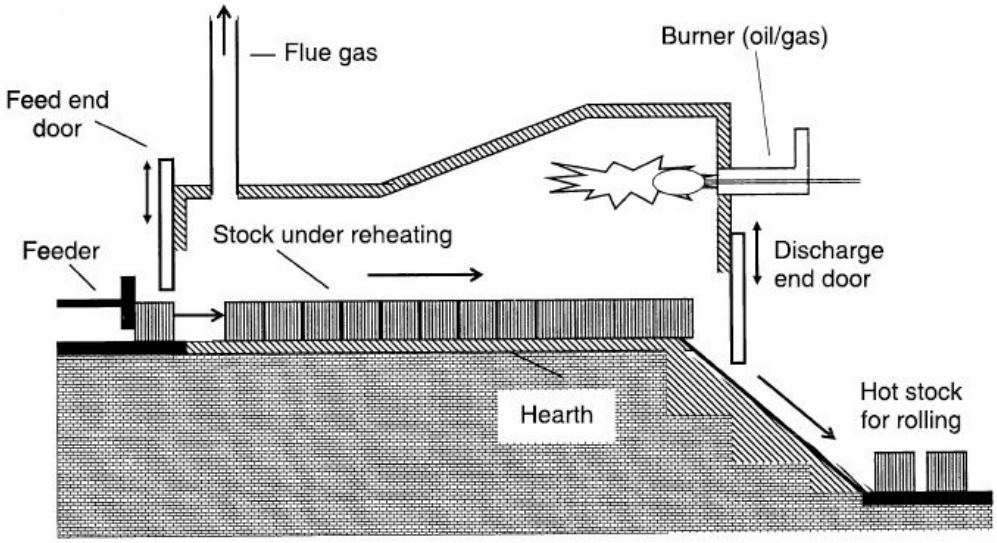


Figure 6.9 Continuous pusher type re-rolling mill furnace.

(iv) Walking hearth and walking beam furnaces

The walking Hearth and Walking Beam furnaces are furnaces where the heating stock can be moved forward by mechanical movement. The mechanism of heating is identical in both cases.

In case of *walking hearth furnace,* a section of refractory lined hearth is used to raise the rolled stock and move it towards the discharge end in walking fashion. The mechanism of moving the product is identical in both cases except the type of mechanical arrangement. These furnaces are suited for reheating alloy steel stock with thinner cross-sections. The design of such furnaces provides better heat distribution in the furnace. The capacity of such furnaces ranges from 30 to 70 ton per hour. The charge size ranges from 0.15 to 0.3 m^2 cross-section and 6 to 12 m long billets. These furnaces generally use furnace oil (32 liter per ton steel), but can be operated with CNG, coal gas or LPG. The

benefits of using such furnaces are

a. Uniform temperature in the furnace
b. Less scale loss (~ 1% wt.)
c. Absence of skid marks on the ingot/slab
d. Facility to remove stock from either side
e. The pusher required is of lower capacity and may be eliminated if needed
f. The slab of different size combination may be reheated in the furnace.

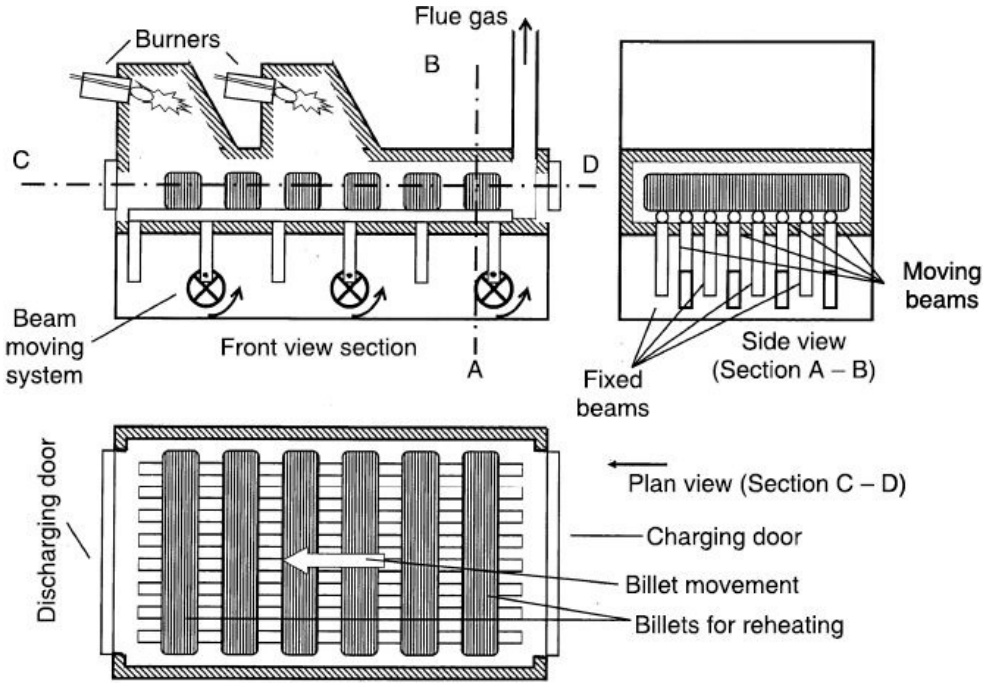


Figure 6.10 Walking beam furnaces.

In case of *walking beam furnace*, the walking beams (Figure 6.10) lift the stock and move it in the forward direction while lowering down itself. In lower stationary position, the rolling stock rests on a fixed beam. The walking beam moves underneath the rolled stock and comes to its original position ready to perform another walk.

A walking beam furnace permits the stock to be heated from all sides, whereas in the hearth furnace it got heated from the top only making them suitable for thinner sections.

6.1.3 Gaseous Fuel based Furnaces

The gaseous fuels are known for their merits (section 1.1.4), and hence are used in different types of manufacturing processes. Some applications like coke oven heating, BF stoves, soaking pit furnace, reheating furnaces and heat treatment furnaces are described in the forthcoming sections.

Coke oven heating

The coke oven utilies its own gas mixed with blast furnace gas to provide thermal energy
to coking process. The gaseous fuels are combusted in combustion chamber located between two coke ovens as shown in Figure 2.26. The coke oven heating chamber is described in Section 2.8. The coke oven heating generally uses a mixture of coke oven and blast furnace gas for the following reasons:

a. To utilise the fuel gases (coke oven and BF gas) generated in the steel plant
b. The mixing lighter coke oven gas (specific gravity 0.44) with heavy blast furnace gas (specific gravity 1.02) helps in giving better flame propagation.
c. The mixing rich coke oven gas (5100 kcal/m^3) and lean blast furnace gas (818 kcal/m^3) enhances the gas quality.

The producer gas (1450 kcal/m^3) is sometimes used when the coke oven and blast furnace gas are not available.

BF stoves

The blast furnace stoves supply hot blast to blast furnaces. These stoves work on regenerator principle.

Design

A set of three [Figure 6.11(a)] or four stoves is used to provide hot blast, where one stove is ‘on blast’ and rest are ‘on gas’ for heating. The blast furnace stoves are tall (20–35 meter in height and 6–8 meter in diameter) cylindrical furnace which has two main interior sections: combustion chamber and firebrick checkers chamber as shown in Figure 6.11(b) and (c). The top of the stove has a dome structure. The stove has a steel casing [Figure 6.11(b)] with insulating refractory layer in between case and inner refractory lining. The arrangement of air, gas, hot blast and flue gas pipe line is illustrated in Figure 6.11(d).

The combustion chamber is an open space extending the entire height of the

stove.

The checker chamber is a checker-work usually built of specially designed bricks to give maximum heating surface. The openings in the checkers allow free passage of gases for heat exchange. These checkers are built-up on cast iron shoes standing on steel grid and griders supported on cast iron columns. The grids in the stoves are made of heat resisting steel.

Working

A supply of clean blast furnace gas and air is admitted at the bottom of the chamber where the combustion occurs. The hot gases are allowed to pass through refractory checkers before leaving the stove. The hot flue gases impart their heat to the checker bricks before leaving the stoves.

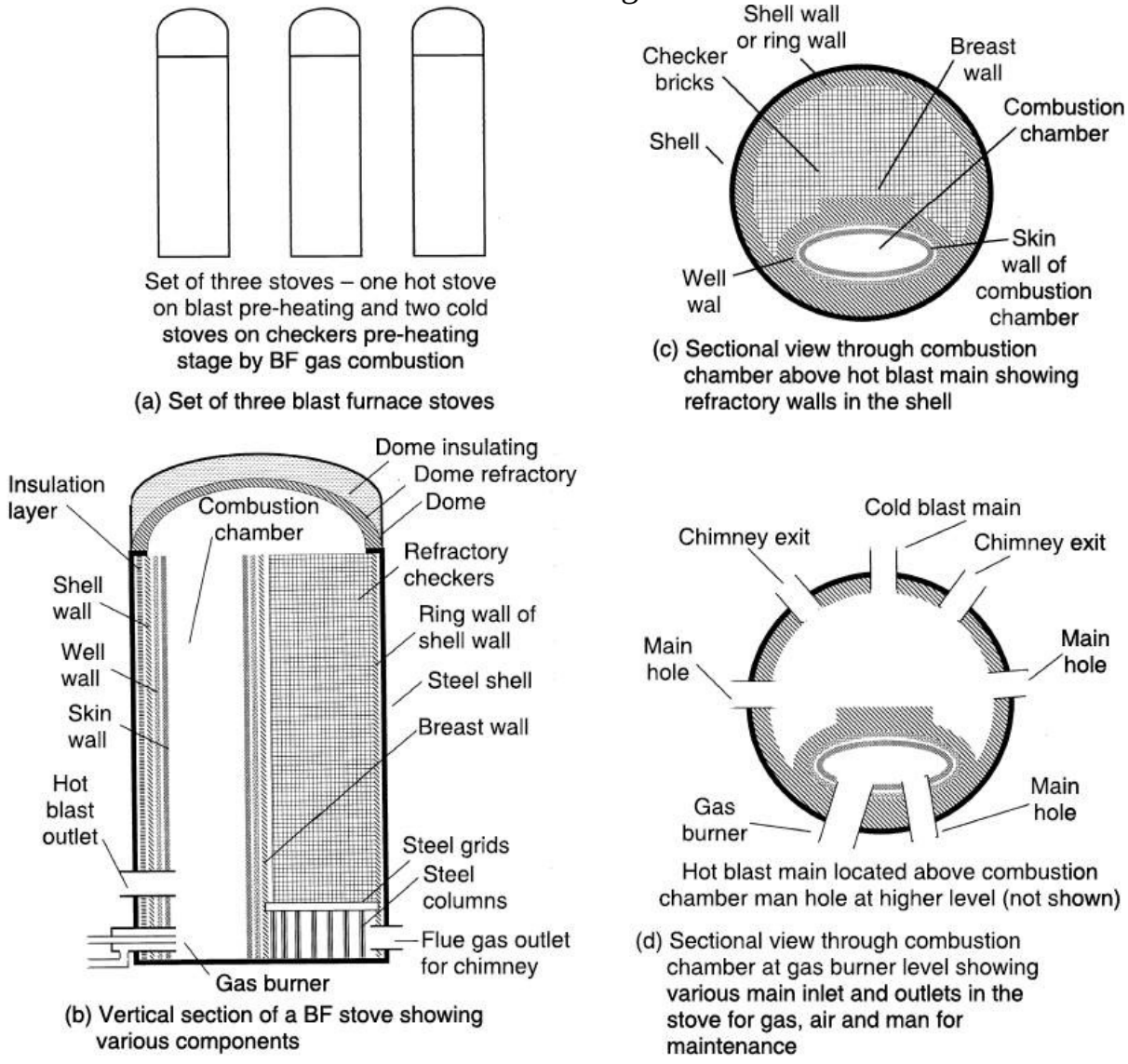


Figure 6.11 Blast furnace stoves.

Fuel and refractory

The clean blast furnace gas serves as fuel to burn and heat the checker bricks. The combustion chamber is generally lined with siliceous fire bricks as they have considerable resistance of slag attack caused by dust in blast furnace gas. Some stoves use alumina refractory also. The checker chamber uses specially designed firebricks.

Performance indices

The *hot blast temperature* and *hot blast stove specific thermal efficiency* are the two indices to judge the working of the stoves. A higher hot blast temperature is desired by the blast furnace to save coke. The *hot blast stove specific thermal efficiency* is defined as *the ratio of thermal energy available in hot blast for use to thermal energy supplied in the stove by BF gas combustion.* The higher 'hot blast stove specific thermal efficiency' provides blast furnace gas saving for heating stoves in getting desired hot blast temperature.

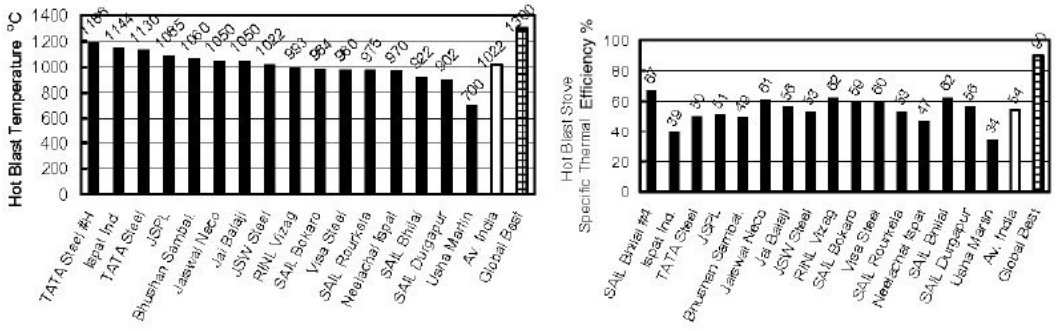


Figure 6.12 The hot blast temperature and specific thermal efficiency for Indian BF stoves.

(*Source:* Bhushan Chandra, *Into the Furnace–The Life Cycle of Indian Iron & Steel Industry* , Green Rating Project, Centre of Science & Environment, New Delhi, 2012, p. 100–101.)

These two operating indices are governed by a number of factors including: (i) BF gas calorific value, (ii) rate of supply of BF gas, (iii) period used for 'on blast' and 'on gas', (iv) use of ceramic burners, (v) checker brick design, (vi) quality of refractory used,
(vii) use of automation, etc. The value of these two indices for Indian BF stoves is shown in
Figure 6.12 according to a study pertaining 2009–10 period to indicate scope of improvement in comparison to the global best practice.

Soaking pit furnace

The soaking pits are gas fired large sized deep rectangular furnaces used for reheating steel ingots for hot working. The soaking pit furnace aims to heat large

steel ingots having uniform temperature across its cross-section without overheating the surface within minimum period with least material loss due to scale formation.

These furnaces were the part of old integrated steel plants where ingot casting was a common practice. The modern integrated steel plants having continuous billet casting or thin strip casting practice do not require such soaking pit furnaces. However, these soaking pits find use by non-integrated steel units or independent hot rolling mills in steel sector. The steel ingots made by scrap melting in electric furnaces (arc and induction) are used by hot rolling mills which need soaking pits for ingot pre-heating to hot working temperature.

Design

The shape of soaking pit is like a box having deep chamber with rectangular cross-section with movable cover on its top. The steel ingots are kept in the chamber in up-right position using a overhead crane after sliding its top cover to open position. The soaking pit is generally fired by gas burners. The hot flue gases are allowed to exit to atmosphere after passing through heat exchanger (recuperator or regenerator). Figure 6.13 shows a typical soaking pit furnace.

The burner location differs in different types of soaking pits to get different gas flow pattern giving different heating rates. The different burner locations are indicated in different types of soaking pits as shown in Figure 6.14. The different types of soaking pits used are discussed in the following section.

One way fired soaking pits (older design with regenerator): In this design, the gas burners are located on one of the short walls, and hot flue gases exit from ports located on opposite wall. This hot gas passes through regenerator before escaping to atmosphere.

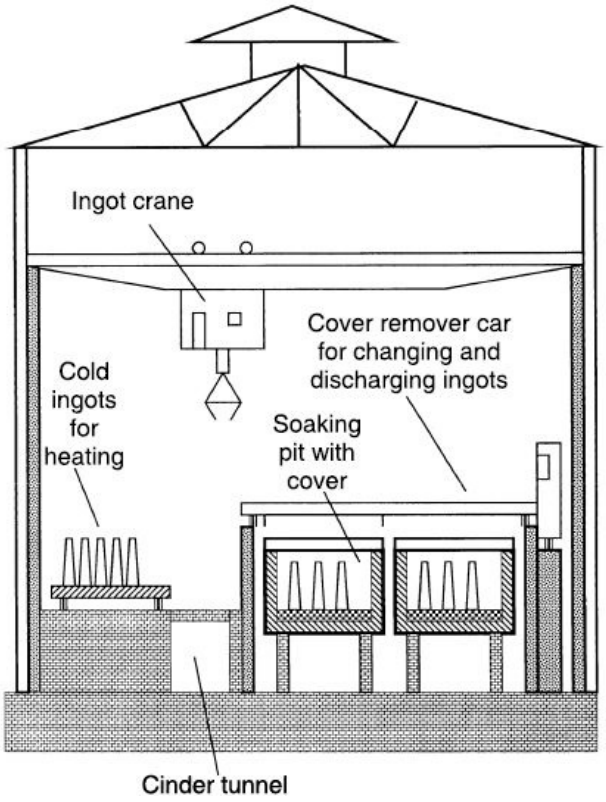


Figure 6.13 Soaking pit furnace.

One way fired soaking pits (modified design): This is an improved design with recuperator system. In this furnace, extra combustion space is given over ingots, and flue gases leave from ports located on the wall having burners.

Two way fired soaking pits: In this furnace design, the burners are located in upper part of the short wall, and the hot flue gas exits are located on all four pit corners which lead the flue gases to atmosphere through recuperators. The combustion occurs in the central aisle at the side of which ingots are placed and heated by turbulent gas flow.

Bottom centre fired or vertically fired soaking pits: In this design, the burners are located at the bottom centre and fired upward. The ingots placed around the burner get heated by circulating gas in the furnace.

Tangentially fired circular soaking pits: The circular shaped soaking pits are fired by burners placed tangentially in the lower periphery of the furnace. The hot flue gases leave through central bottom exit.

Top two way fired soaking pits: In this design, the burners are placed on opposite ends of the furnace, and the combustion space is above the ingots. The firing is done at an angle to the centre line of the pit to generate swirling gas

motion.

Fuel

The fuel source for soaking pits is gases like natural gas, blast furnace gas and coke oven gas mixture or producer gas depending on its availability. The gas calorific value is important to achieve working temperature of ~ 1350 °C in the pit to heat ingot at ~ 1250 °C.

Refractory

The requirements by refractory for use in soaking pit are high RUL value with erosion and corrosion resistance quality. The high refractoriness under load (RUL) is required to sustain high temperature (1350 °C) under ingot load alongwith heavy abrasion caused by ingot placement. The refractory must also resist corrosion by scale (iron oxide) particularly in the lower region. The upper section of the soaking pit and cover refractory must be spalling resistant due to thermal shock subjected during charging and discharging of ingots.

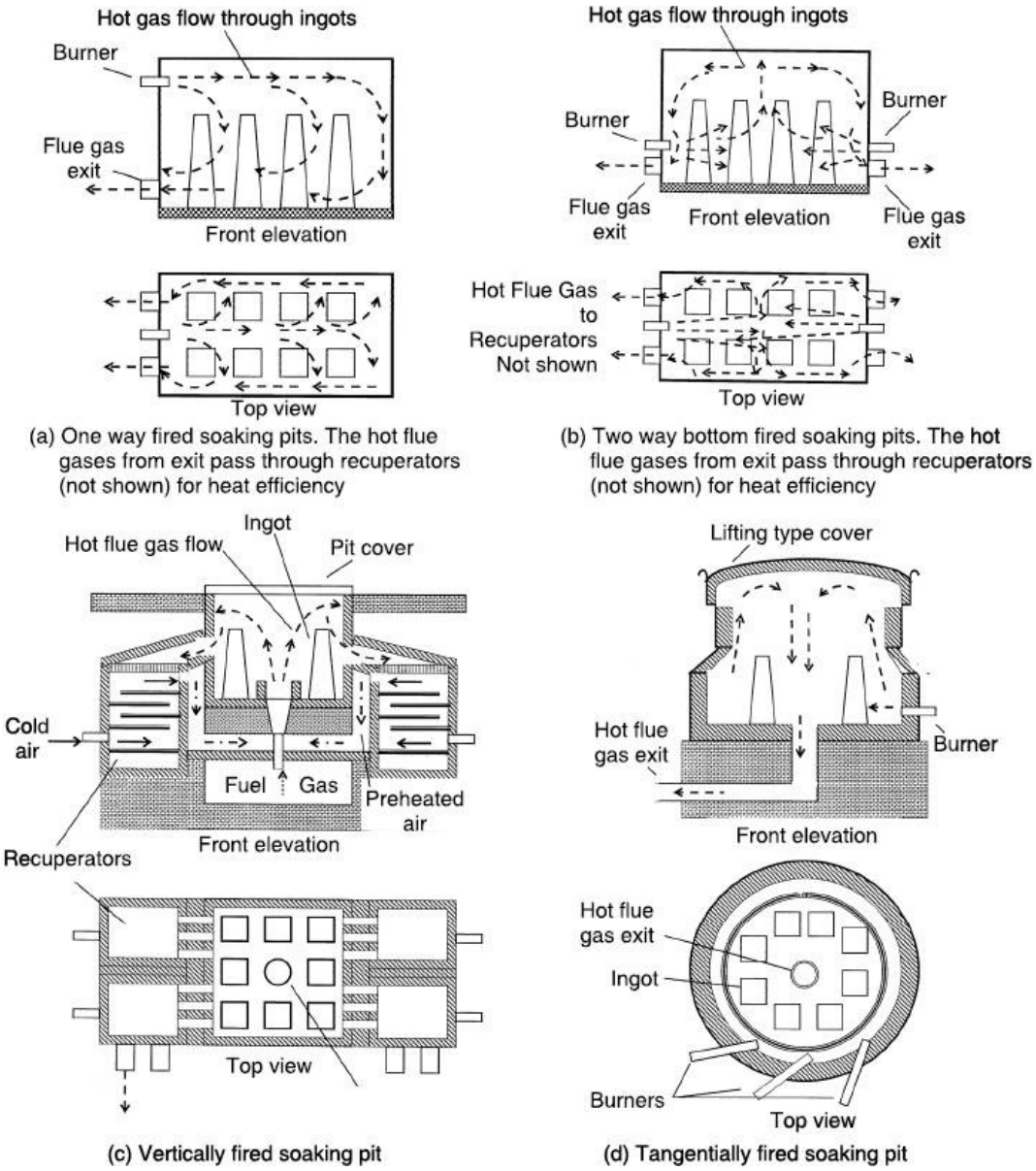


Figure 6.14 Different firing locations in soaking pits.

The refractory used in various sections differs due to the following working conditions:

a. The upper wall of the soaking pit requires silica or semi-silica bricks for better spalling resistance. The use of fireclay brick may be less satisfactory.
b. The lower region of the walls needs basic bricks to resist slag attack by falling scale (iron oxide). The magnesite brick is common for lower region of the walls.
c. The bottom of the soaking pit is made by fireclay brick while using a

thick layer of coke breeze as protecting layer from corrosion by falling scale (iron oxide). In some cases, the bottom is made by using magnesite, chrome-magnesite or high alumina bricks.

d. The cover uses semi-silica or monolithic refractory.

The gunning refractories are used for repair and maintenance of the soaking pit.

A typical example may be given of soaking pits (28 in nos.) which are used (in 2014 AD) by Bhilai Steel Plant (India) having capacity to accommodate 16 ingots/pit, where each ingot weighs nearly 9 ton. The detail of the pit furnaces is given in Table 6.2. The experiment is in progress to replace conventional fireclay brick by 70% alumina low cement castables using anchor support technique as a modern refractory practice.

Table 6.2 Soaking Pit Furnaces at Bhilai Steel Plant

Item	*Details*	
Furnace size	7.8 m	Length (long wall)
	5.5 m	Width (short wall)
	4.9 m	Depth
Refractory thickness	630 mm	Bottom
	750 mm	Long wall
	750 mm	Short wall
Refractory weight	210 ton	Total for one soaking pit
Nature of refractory	Fireclay and low cement castables	
Life of refractory	2 – 2.5 years	With 3–4 cold and 3–4 hot repairs
Capacity of Ingots	14–16 Ingots	Each ingot ~ 9 ton
Working temperature	1350 °C	
Fuel gas CV	2040 kcal/m^3	BF + Coke oven gas mix
[*Source:* Roy, I et al. (2013)]		

Reheating furnaces

Reheating furnaces sometime use gaseous fuels. These furnaces are already described in section 6.1.2.

Heat treatment furnaces

The gas fired furnace is commonly used for heat treatment due to its absence

from impurity and ability to provide easy atmospheric control. Heat-treatment furnaces are used to control structural property of the metal. The heat treating furnaces could be heated by the following three methods:

a. Directly fired
b. Firing through radiant tubes
c. Muffle or retort heated by outside gas burning

Integral quench (IQ) furnace

It is a directly gas fired furnace known as ‘work horse’ of heat treating industry. It is used for hardening or carburising process. It has a quench and cooling chamber. The furnace operates in the temperature range of 980 °C.

Tempering or draw furnace

It is a gas fired batch furnace used for pre-heating, tempering (after quench), stress-relieving and annealing applications. The operating temperature range is 200 °C to 75 0 °C. This furnace may include cooling system using air to water heat exchanger to accelerate cooling.

Quench tank furnace

The furnace is used for quenching treatment. The quenching liquid can be water, quench oil or polymer. This requires heating and cooling system to maintain the controlled quench temperature. The major concern for oil quench is fire safety. The other quenching media requires care for spilling.

Non-ferrous heat treatment furnaces

There are various types of gas fired furnaces like coil/foil annealing furnaces, rod/wire annealing furnaces, log homogenising furnaces, ingot preheating furnaces and aging furnaces. These furnaces could be direct or indirect fired (radiant tubes). The furnace temperature may range from 170 °C to 620 °C.

6.1.4 Furnaces based on Electricity

Merits and limitations

The furnaces using electrical energy are very popular in metallurgical industries for various operations like drying, heating, melting and smelting. The furnaces are associated with several merits and limitations as discussed below:

Merits

Clean energy source without any kind of pollution
Highly energy efficient
Better temperature control and uniform heating
Can be used for wide temperature processes up to 2000 °C
Concentration of high energy in small volume can result in very high temperature
Heating can be combined with other operation like electrolysis or electro-corrosion
Selective zone heating is possible by using induction coil for case hardening
Furnace can be easily automated
Less floor area requirement by the heating system

Limitations

Expensive energy source with less availability in many parts of the region
Initial high cost of installation including transformer cost, sub-station cost, cable cost, etc.
Furnace operation is subjected to power quality in terms of continuity of supply voltage, frequency, etc.
Power failure due to variety of reasons can interrupt furnace operation.

Classification of electrical furnaces

The electrical energy can be converted into thermal energy using various techniques like resistance heating, induction heating, dielectric heating, arc heating, electrolytic heating and electronic heating. These are depicted in Figure 6.15. These methods are used to design a furnace for certain application. Each conversion method of energy has its own characteristic features like heat flux density, which are summarised in Table 6.3.

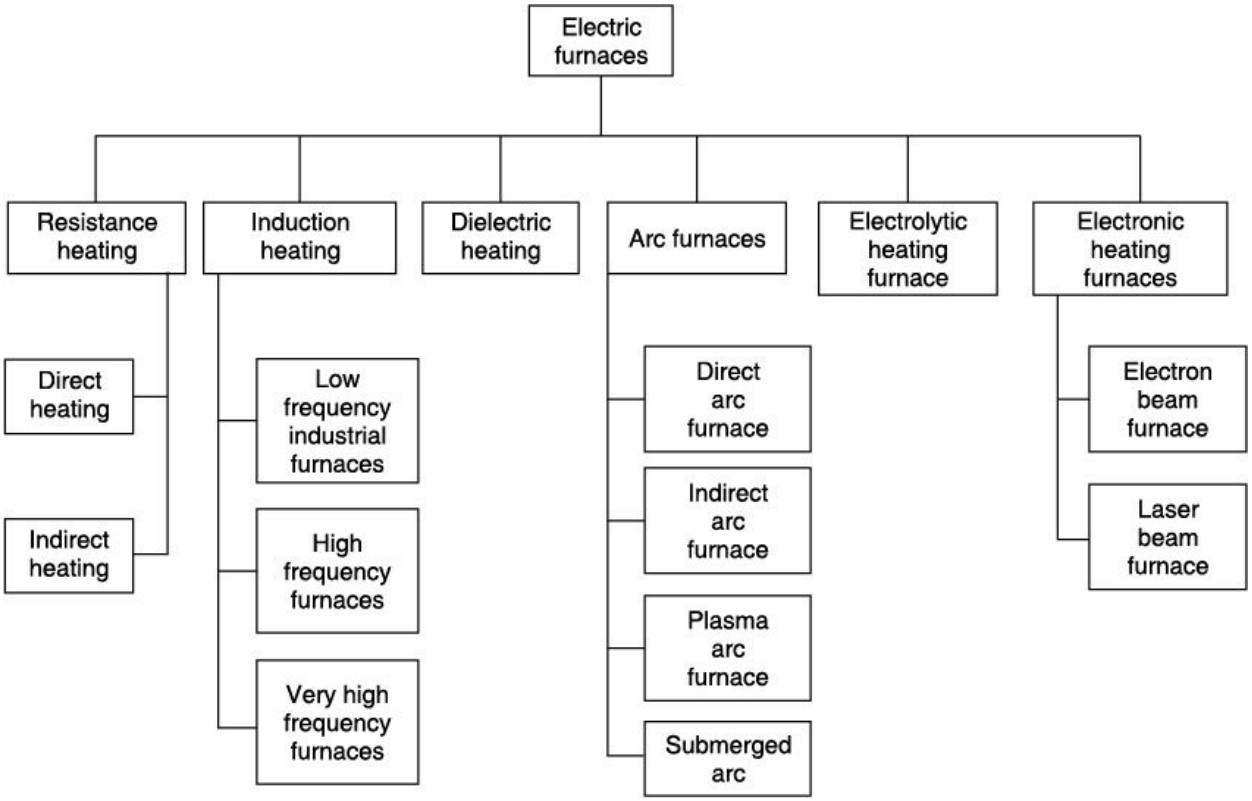


Figure 6.15 Classification of electric furnaces.

Some examples are given here to illustrate the various heating methods under different group:

(i) Resistance heating

In such furnaces, the heat is generated due to electrical resistance offered by the heating elements while a current passes through it. The heat generated could be used directly or indirectly for a given application. This duel technique of heat transfer offers two types of resistance heating furnaces as given below:

Table 6.3 Heat Flux Density of Electrical Furnaces Using Various Energy Conversion Methods

Method of Energy Conversion	*Furnace Type*	*Heat Flux Density* kW/m^2
Resistance heating	Open metallic heating elements	5–20
	Tubular heating elements	80–120
	Electro-slag furnace	2000–3000
Induction heating	Induction furnace with industrial frequency 50 Hz	700–1000
	Induction furnace with high frequency 150–250 Hz	1000–1500
	Induction furnace with very high frequency 500–3000 Hz	1500–10000

Arc heating	Direct arc furnace	2500–330000
	Plasma arc furnace	10^{6} –10^{10}
Electron beam	Electron beam melting	10^{7} –10^{8}
Laser beam	Laser melting	10^{10} –10^{12}

Direct heating: The electric pig iron furnace (Tysland hole process) is a typical example of this type of furnace, used for producing hot pig iron. The iron ore, coke/charcoal and limestone charged in a shaft furnace act as a resistor to the flow of heavy current passing through graphite electrode to generate heat to reduce iron ore to metallic iron followed by its melting.

Indirect heating: The moisture oven, muffle furnaces, heat treatment furnaces, etc. are typical example of indirect heating furnaces. In such furnaces the heat is generated by passing electrical current through heating elements, e.g. nichrome wire (80% Ni–20%Cr), kanthal wire (Fe base with 20 to 30% Cr and 4 to 7.5% Al), silicon carbide rod, etc. The object is heated indirectly through convection, radiation and conduction or a combination of these methods.

(ii) Induction heating

This is based on few basic electrical principles. When a current flows through a conductor, the magnetic field is generated around the conductor. If this conductor wire is wound into a cylindrical coil, then the magnetic field of each turn gets added producing intense magnetic field. In this intense magnetic field, caused by alternating current (AC), when an electrically conducting substance is placed, an ‘eddy current’ is generated within the conducting material which flows on its surface. The resistance offered to the flow of this ‘eddy current’ causes heat generation within the material which is used as ‘induction heating’. The induction furnaces are classified on the basis of frequency of alternating current used in the induction coil for various applications. These furnaces are described briefly in the following section:

Low fequency (50 Hz): The typical examples of such furnaces are industrial induction furnaces (core less) for steel melting (1–50 ton) and industrial induction furnaces (channel type) for melting low melting non-ferrous metals (e.g. aluminum alloys).

High frequency (up to 3000 Hz): The laboratory scale furnaces for melting 1–10 kg steel use higher frequency current as the charge used are smaller in size.

Very high frequency (195000 Hz): The levitated metal drop induction melting unit (non-refractory contact melting) needs very high frequency furnace for research purposes.

(ii) Dielectric heating

In this type of furnaces, the heat is generated by 'dielectric losses'. When a dielectric or semiconductor material is placed in a variable electrical field between the plates of a capacitor then heat is generated due to polarisation of molecules, called dielectric losses. Such furnaces are not used for metallurgical applications.

(iii) Arc heating

The electric arc furnaces use the intense thermal energy released by the electric arc struck between two electrodes while passing heavy current under low voltage. The type of electrode and arc environment provide different arrangement to produce arc heat which is exploited for different applications.

Direct arc furnace: The direct arc furnaces are used mainly for melting steel in commonly used industrial furnaces (5–50 ton). The larger furnaces (up to 200 ton) are used for special purposes like steel foundries. In such furnace, the electric arc is struck between graphite electrode and the metal charge. The number of graphite electrode depends on the nature of power supply as single or three phases. The industrial furnaces work on three phase power system, and have three electrodes. The heat generated by electric arc impinges directly on the metal to give the term 'direct arc furnace'.

Indirect arc furnace: Indirect arc furnaces are used in laboratory to melt iron and steel in smaller quantity (5–50 kg). In such furnaces, the arc is struck between two graphite electrodes and the thermal energy is radiated on the metal charge to be melted.

Plasma arc furnace: This is a special type of furnace where high temperature plasma arc is generated by passing diatomic gas like argon, hydrogen, nitrogen or carbon dioxide in arc discharge zone. Such furnaces offer various advantages over conventional arc furnace like higher temperature, lower energy consumption, lower arc noise, stable arcing with chemically active ionised gas. These furnaces are used for various applications like chemical reduction of refractory oxides (e.g. chromite), nitrogen alloying in stainless steel, nitriding steel, etc.

Submerged arc furnace: Such furnaces are used for ferroalloy (e.g. ferro-

managanese, ferro-silicon, ferro-chrome) preparation. In these furnaces, the graphite electrode is submerged in the charge consisting of metal ore mixed with carbon (petroleum coke or coke) with fluxing agent. The thermal energy is generated by the electrical resistance of the charge to reduce the metal oxides followed by their melting and alloying.

(iv) Electrolytic heating

The alumina pot cell is a typical example of this type of heating. When a direct current is passed through molten cryolite having nearly 20% alumina dissolved in the bath, the electrolysis occurs and molten aluminum is collected at graphite cathode. The passage of current through molten electrolyte keeps the bath molten.

(v) Electronic heating

These are special types of furnaces which utilise electronic devices to generate high energy electron or laser beam for generating high temperature needed to melt or shape refractory metals under vacuum in a chamber.

Electron beam heating: This method is used for melting highly reactive and refractory metals like tantalum, niobium, molybdenum, tungsten, zirconium, hafnium, etc. The furnace operating under vacuum has an electron gun to provide highly accelerated electrons which impact on the suspended refractory metal rod tip to generate high thermal energy and cause its melting. The liquid metal dropping from the melting metal rod is solidified in a water cooled mould placed below.

Laser heating: Laser radiation has high power, since the energy of all exited atoms is released simultaneously. Laser beam is coherent and strictly directed which can be focused on a very small area. The laser beam can be used for welding, cutting, hole making and melting refractory materials.

Commonly used electrical furnaces

In view of large variety of electrical furnaces, the scope of this text is limited to few commonly used electrical furnaces like resistance furnace for heat treatment of metals, induction furnace for steel melting, electric arc furnace for steel making and submerged arc furnace for ferroalloy production.

(i) Resistance heating furnaces

Construction: The main components of the furnace include (i) a refractory lined chamber encased in steel box fitted with door, (ii) heating elements, (iii) power

control system and
(iv) power supply system. The shape and size of the furnace depend on the need. The rectangular or cylindrical chambers are very common with top feeding arrangement for heat treatment applications. The small furnaces used in laboratory have front opening doors. The thickness of refractory lining depends on working temperature and furnace size. The heating elements are selected based on the temperature requirement. These heating elements may be concealed or kept open depending on the working atmosphere. The open heating elements help in offering higher temperature, but are prone to get damaged by improper working. The metallic heating wires are useful for furnaces up to 1000 °C. The silicon carbide heating elements offer temperature up to 1400 °C. Figure 6.16 shows the sketch of resistance heating furnace equipped with silicon carbide heating rods.

Operation: The operation of such furnaces is simple, mostly plug and use. The only precaution required is suitable heating rate by regulating power supply to avoid damage to the heating element.

Use: These furnaces are mainly used for heat treatment operations which are generally done below 1000 °C.

(ii) Induction melting furnace (Coreless)

Construction: The coreless induction melting furnace consists of three major components—

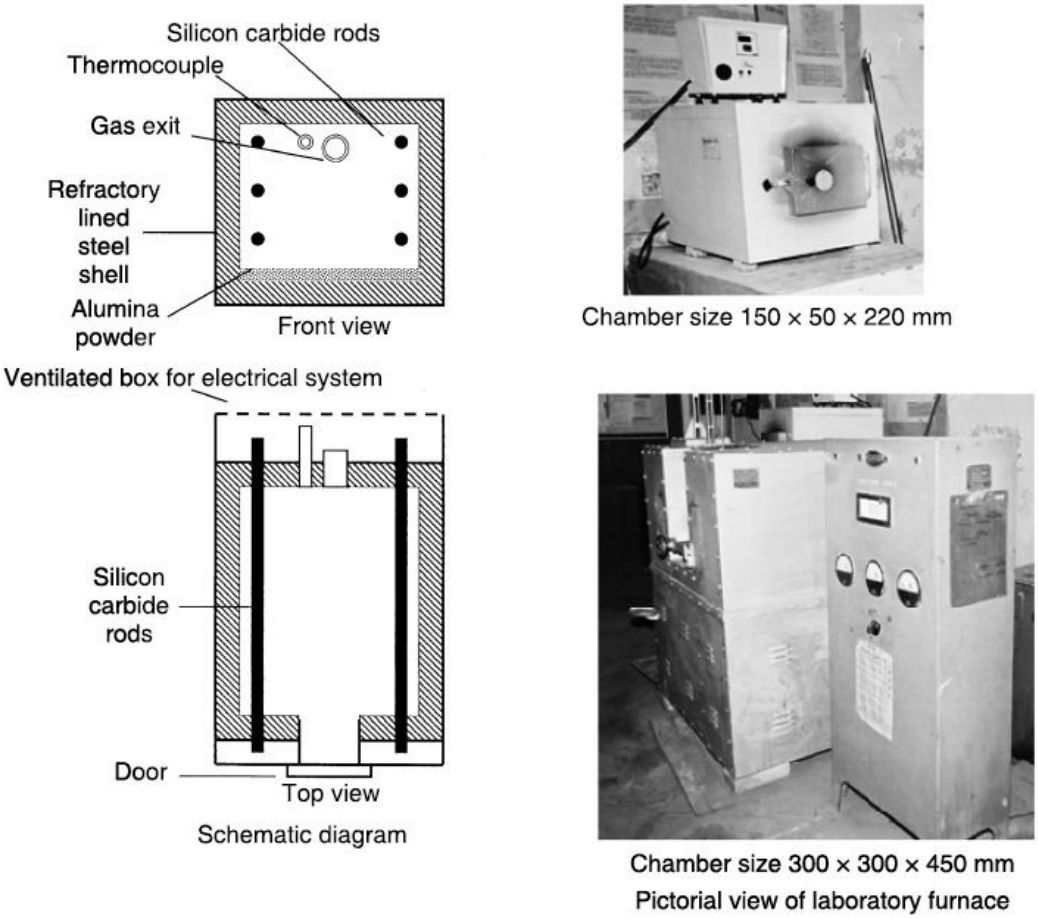


Figure 6.16 Silicon carbide resistance heating furnace.

(i) power supply system, (ii) induction coil fitted with melting crucible and (iii) cooling water supply system.

Power supply system: The induction furnace requires AC supply which is available at

50 Hz. A suitable capacity transformer is utilised to supply power to industrial induction furnace working on 50 Hz. When the induction furnace is used on smaller scale, the current frequency in the range of 1000–10000 Hz is needed. The main power supply at 50 Hz is converted into high frequency current using a frequency converter device. There are three types of frequency converting devices:

Arc gap type frequency converter: This method was in use by early induction furnaces. Some of these furnaces are working even now at some places, being simple and rugged. This system is shown in Figure 6.17. It consists of a transformer, a set of capacitors and a arc gap chamber. The arc gap chamber is made of steel having double wall to flow cooling water. The chamber has two interconnected sections and is filled with mercury up to certain height. The one

section has a water cooled copper electrode to struck arc with mercury, while the other section has a piston arrangement to change the mercury level by mechanically moving the piston. In order to prevent the mercury oxidation while arcing the atmosphere is kept reducing by regular flow of hydrogen gas. This system is switched ‘on’ after ensuring the flow of cooling

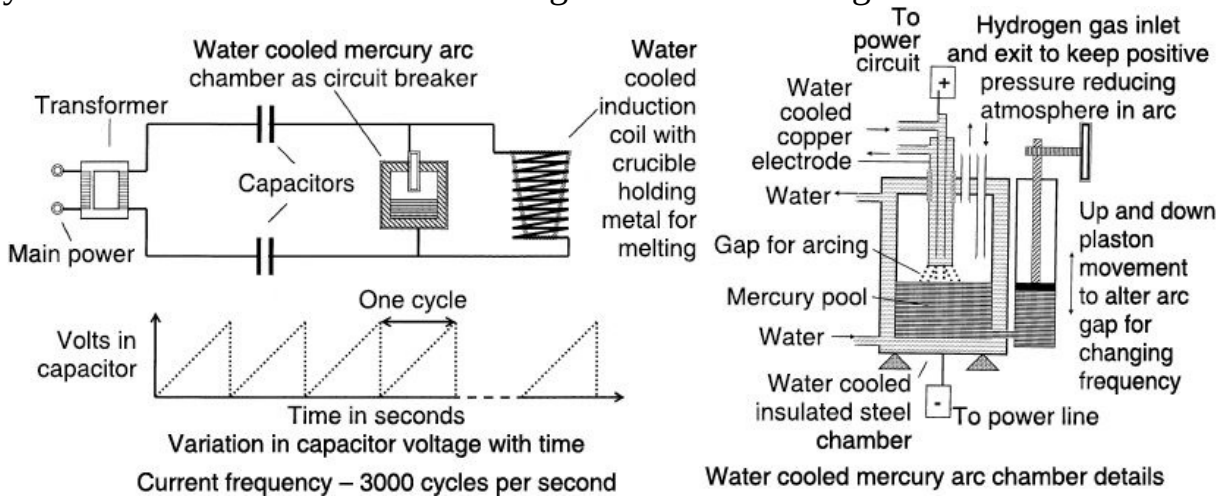


Figure 6.17 Arc gap type frequency converter.

water and flow of hydrogen in the mercury chamber which has been running for minimum 30 minutes to ensure the removal of oxygen. The current starts in the circuit with mains ‘on’. The capacitors located in series start getting charged with rise in the capacitor voltage. The arc chamber remains idle, while the capacitors are charging and current is flowing through induction coil fitted with crucible holding metal for melting. The moment the capacitor voltage reaches to arcing voltage depending on the gap between mercury and copper electrode, the current takes a short path and flows through arc chamber giving a tiny electric arc in the mercury chamber. This arcing in the mercury chamber draws all the stored energy of the capacitor causing drop in voltage and end of arcing. The current again starts flowing through capacitor and coil to repeat the cycle of capacitor charging, arcing, capacitor discharging and ending arc. The time taken to complete one such cycle depends on gap between mercury and electrode which can be adjusted to give 1000–5000 cycles per second (Hz) current.

Motor generator set: This system consists of a motor working on main supply frequency and a generator designed to give the required current frequency up to 10000 Hz. These two motor and generator are mechanically coupled. The motor switching ‘on’ rotates the shaft of the generator to give the required power supply at set frequency.

Solid state electronic converter: This is the most modern method of power

supply system using electronic circuits. These systems have several modern auto features which the older system could not provide. The power supply could be obtained up to 200000 Hz depending on the need.

Induction coil with melting crucible : The copper coil is the major component of the coreless induction furnace. This coil is made from thick section hollow tube of high purity copper, offering better electrical conductivity. The melting crucible formed inside the induction coil using refractory ramming mass. The induction coil is located within a steel frame. The copper coil is water cooled to avoid getting hot. This cooling water is recirculated after cooling in cooling tower. The refractory crucible is sintered in-situ using ramming mass (refractory powder) packed between the coil and a steel sheet drum serving as a crucible former. A nichrome wire spider is (Figure 6.18) embedded in the bottom section of the ramming mass to give a short circuit for tripping power supply, in case the liquid metal penetrates the cracked

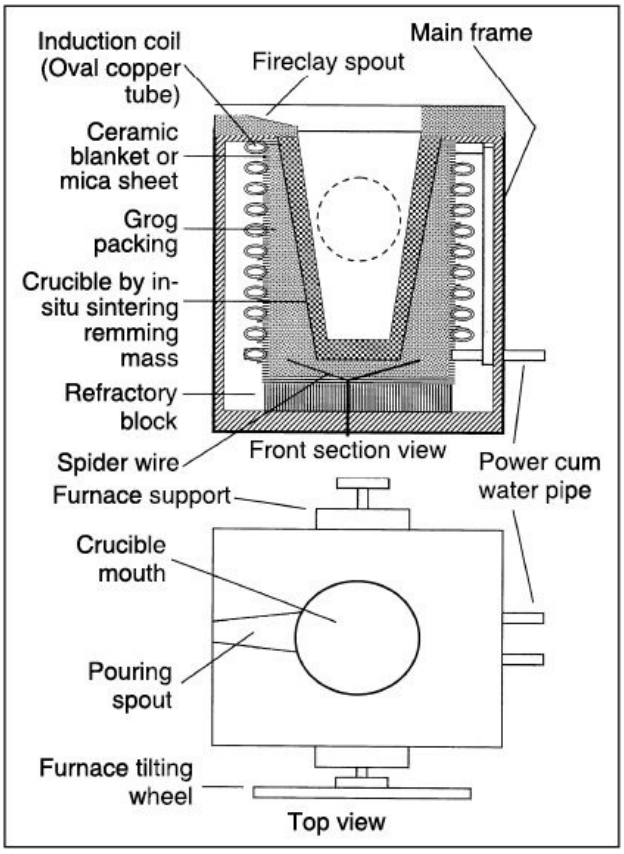


Figure 6.18 Induction furnace.

crucible. The rammed refractory mass gets sintered during pre-melt. The steel former offers the crucible shape and gets dissolved during first scrap melt. After tapping the liquid melt, a clean crucible is ready for further melting.

Cooling water supply system: The water cooling system is an integral part of the furnace system to cool various electrical and electronic systems. The quality of water is important for use. The electronic system uses distilled water free from any dissolved salts to avoid ionic conduction. The electrical system uses soft water to avoid the deposition on the cooling surface affecting cooling efficiency. The cooling water stored in overhead tank is supplied to furnace coil under pressure to have effective cooling. The hot water from furnace coil is cooled and reused. In case of power failure, the cooling water from overhead tank flows through the copper coil under gravity pressure to protect it from the heat of the melt in the crucible. The water supply system to the furnace coil is shown in Figure 6.19.

Operation: The melting of steel scrap in induction furnace involves the following steps:

a. Inspection and repair: The refractory crucible is inspected for any damage from previous heat and is repaired using refractory cement. In case of any major crack or damage, the melting is deferred till new crucible is made.
b. First charging: The steel scrap is charged in the crucible to fill the space. The remaining scrap is retained for second charge to be added after melting the initial charge.

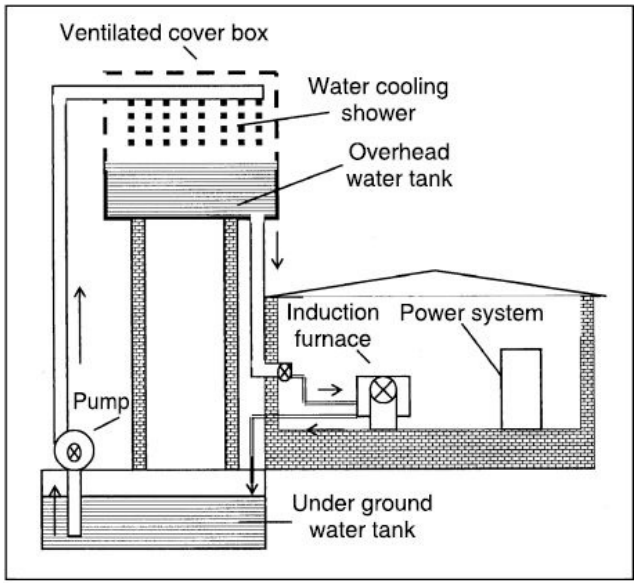


Figure 6.19 Cooling water supply system for induction furnace.

c. Water supply open: The water flow in the coil is initiated.

d. Power supply ‘ON’: The power supply main is kept on (‘ready’) position and the power is switched ‘ON’ at low power.
e. Second charging: The second charging is made in the liquid pool of the fist
charge melt. Care is taken to avoid bridging of the charge by gentle poking of the scrap.
f. Alloying and melt temperature: The alloying additions if any are added to the liquid melt. The melt temperature is adjusted by holding the melt for few minutes.
g. Power ‘OFF’ and pouring out: The power supply is switched ‘OFF’ and furnace is tilted to pour out the melt in ladle or ingot mould kept near the furnace.
h. Inspection and hot repair: The hot crucible after every melt is inspected for any damage and hot repair is done by dry ramming mass powder before making next heat.

Use: The induction furnace is used for melting ferrous and non-ferrous metals required in smaller quantity (1 kg to 10 kg) by research laboratory and industries requiring melt in wide capacity range (50 kg to 50 ton). These days the induction furnaces (5 ton – 20 ton) have become common melting units in mini-steel plants to make steel using sponge iron as metallic feed.

(iii) Vacuum induction furnace

Construction: The vacuum induction furnace is shown in Figure 6.20. In this furnace, the induction furnace is located inside a steel chamber with ingot mould to receive the liquid metal. The steel chamber is made of thick steel plate to provide high vacuum or high gas pressure during melting operation.

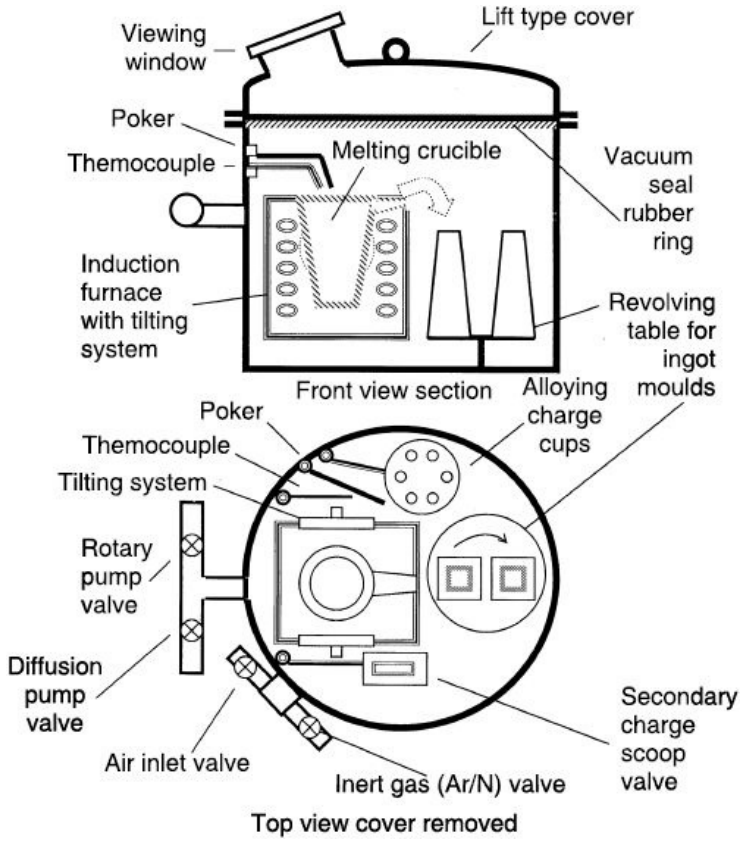


Figure 6.20 Vacuum induction furnace (schematic).

The major components of the furnace include the following:

Heavy steel chamber : This houses the induction coil with crucible and ingot mould. The steel chamber is provided with top opening or side opening heavy lid with vacuum seal. The chamber has opening with valves to connect with vacuum system and gas cylinders at high pressures. The chamber is equipped with mechanical arms for poking, alloy addition and thermocouple movement. The high temperature glass windows give a view of melting in the crucible and pouring operation from outside.

Induction coil : The induction coil is same as used in air induction melting furnace.

Power system : The modern units use electronic based power panel.

Cooling water : This is identical to system used in air induction furnace.

Vacuum system : The furnace is provided with mechanical vacuum pump for primary vacuum (1 torr or 1000 μ) and diffusion pump for secondary vacuum (0.01 torr or 10 μ).

Inert gas system : The furnace is attached with valves to connect with argon and nitrogen gas cylinders filled with gas at high pressure to be used during

melting if needed.

Operation: The system is used for remelting steel to remove dissolved gases and make nitrogen addition as alloying agent. The steel remelting operation to remove gases is described briefly as follows:

a. Furnace inspection and cleaning are done for the vacuum chamber for any undesirable objects.
b. Crucible inspection and repair are done before melting the charge to avoid crucible failure during melting.
c. Metal charging is done in the crucible to accommodate nearly 65–70% charge (cut to smaller size to fit in the crucible) and remaining charge is kept in the secondary charging scoop of the furnace for feeding at later stage.
d. Furnace lid closure is accomplished after charging, ensuring proper fit and rubber seal is placed properly.
e. Start cooling water and primary rotary vacuum pump after lid closure to remove chamber gases up to 1 torr vacuum.
f. Start secondary vacuum diffusion pump after reaching nearly 1 torr vacuum by rotary pump.
g. Power switched ‘on’ after getting 0.02 torr vacuum, and metal heating is initiated. The vacuum ensures the absence of all gases in the chamber practically.
h. Inert gas filling and melting primary charge are initiated. The chamber is filled with inert gas like argon or nitrogen (10 torr or 100 mm Hg) when the charge is heated but not melted. The power is reduced during gas filling. The inert gas is filled to avoid spurting of molten metal under vacuum. Heating is continued till melting of first metal charge. The inert gas present during melting is not harmful.
i. The remaining charge in scoop is now added in the melt pool and meting continued till all metal charge is fully melted. Mild tapping of the solid charge on the top is done to avoid any metal bridging.
j. Removal of gases from melt is done by lowering power level and starting rotary pump to get 0.4 torr (400 μ) and then starting diffusion pump to get 0.02 torr. The lowering of pressure ensures removal of all added inert gases from the chamber. As the pressure starts droping, the melt will appear boiling due to escaping dissolved gas. The boil

would end after some time when pressure is very low (0.02 torr or 20 μ), which is indicative of removal of all gases in the melt and chamber. This degassed melt is now ready for teeming.

k. Power is switched ‘off’ and melt temperature is taken when the metal is ready for teeming. The furnace is resumed with power ‘on’ if melt temperature is found less or else prepare for teeming with power ‘off’ position.
l. Teeming and ingot casting is done by tilting the crucible to pour out the melt into ingot mould under vacuum (0.02 torr).
m. Ingot cooling are continued with vacuum (0.02 torr) in chamber by sealing all valves.
n. Ingot stripping is done when ingot is cooled. The air is first admitted in the chamber to the atmospheric pressure to be able to open the lid. The cooled ingot with mould is taken out and stripped from mould.

Use: The vacuum induction melting furnace is used as secondary steel making unit to
remove gases and certain inclusions from the steel by remelting. It is also used for adding nitrogen gas as alloying addition in stainless steel to substitute nickel with nitrogen (austenite stabiliser).

(iv) Electric arc furnace

Construction: The furnace components fall under mechanical and electrical systems. The mechanical parts include: (i) furnace shell and refractory lining, (ii) furnace cover and refractory lining, (iii) furnace tilting arrangement, (iv) Metal tapping spout or Slide gate,
(v) electrode holder, (vi) graphite electrodes and fume extracting eevice or eog house. The major electrical components are: (i) transformer, (ii) heavy euty switches and (iii) electrode moving motors. These various components are very briefly described below:

Mechanical components: Furnace shell and refractory lining: The entire lower part of the furnace is housed in the steel shell made of heavy steel plates. It is cylindrical shape structure which is lined with refractory (Figure 6.21) to form the hearth of the furnace accommodating the charge material and liquid melt. The shell made of welded steel plate is common, and known as *integral type* . The *cage type* shell has welded steel structure to give access to damaged refractory for repair and replacement. The *split type* shell is useful for high

capacity furnace. The *split type* shell has two sections as lower and upper, which are joined with nuts and bolts. The lower section having bottom hearth can be replaced by another section during working if it is damaged to save relining time. The *rotating shell* used in some furnaces can rotate up to 40° angle in either direction as it is mounted on rollers. However the *rotating shell* is not popular. The *water cooled shell* used in modern furnaces offers melting in lining-less furnace. The water cooled shell is made of several double wall panels having high pressure water flow to extract heat, and a thin solid slag layer on the steel panel protects it from any mechanical erosion. These different types of shell are depicted in Figure 6.22.

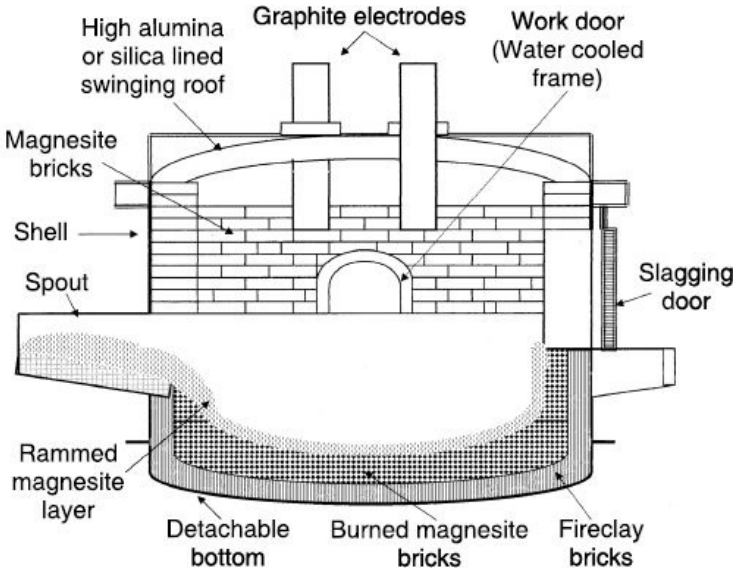


Figure 6.21 Electric arc furnace and its refractory lining.

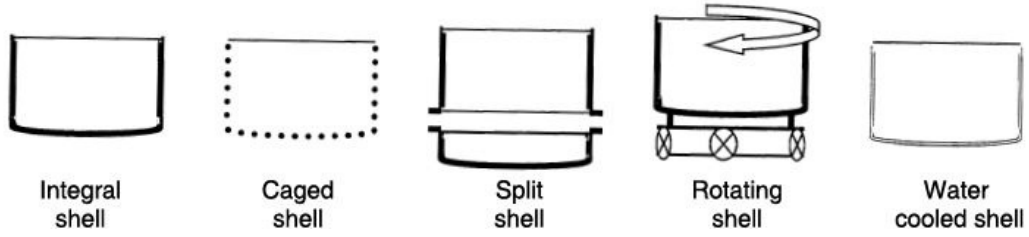


Figure 6.22 Different types of shell for EAF.

Furnace cover and refractory lining: The EAF roof serves to cover the furnace and contain its heat. It is a refractory structure supported by a steel ring. It has holes to allow electrode movement and has a hole for the exit gas movement. This roof can be lifted and swing aside to open the furnace for top charging. The roof sits on a sand seal provided on the shell of the furnace to prevent any gas leakage while working. The ‘skewback’ and ‘non-skewback’ type steel roof rings are shown in Figure 6.23 alongwith refractory lining. The

roof rings are water cooled.

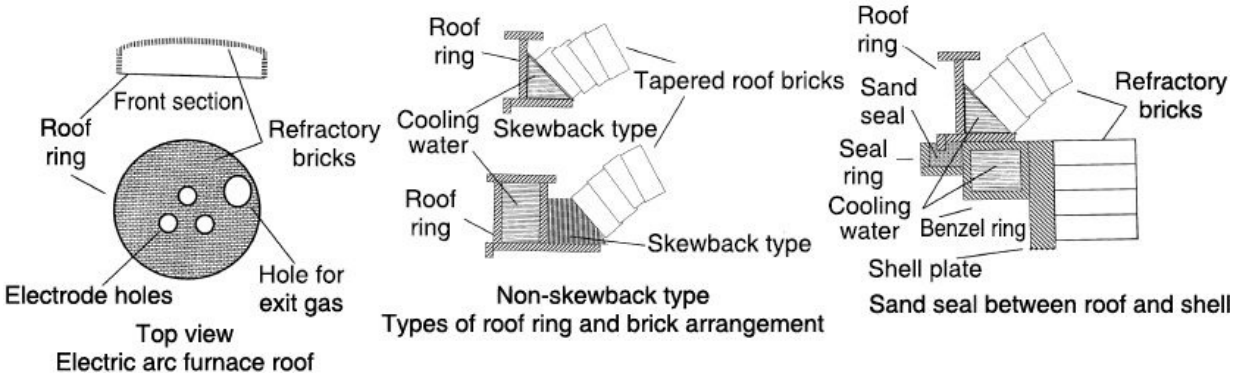


Figure 6.23 EAF roof cover.

Furnace tilting arrangement: The most common furnace tilting arrangement is rack and pinion arrangement in old furnaces. The new furnaces have pneumatic tilting arrangement as shown in Figure 6.24.

Metal tapping spout or slide gate: The older and smaller arc furnaces are fitted with spout as shown in Figure 6.21. The shell is tilted towards spout to pour out the metal using mechanical technique as illustrated in Figure 6.24. The modern and larger units have bottom tapping arrangement using slide gate (Figure 6.25). In the slide gate system, the metal is discharged by metallostatic pressure by opening the slide gate. In this method, the slag remains floating on the top of the metal during tapping and does not come out with metal which is common with spout pouring.

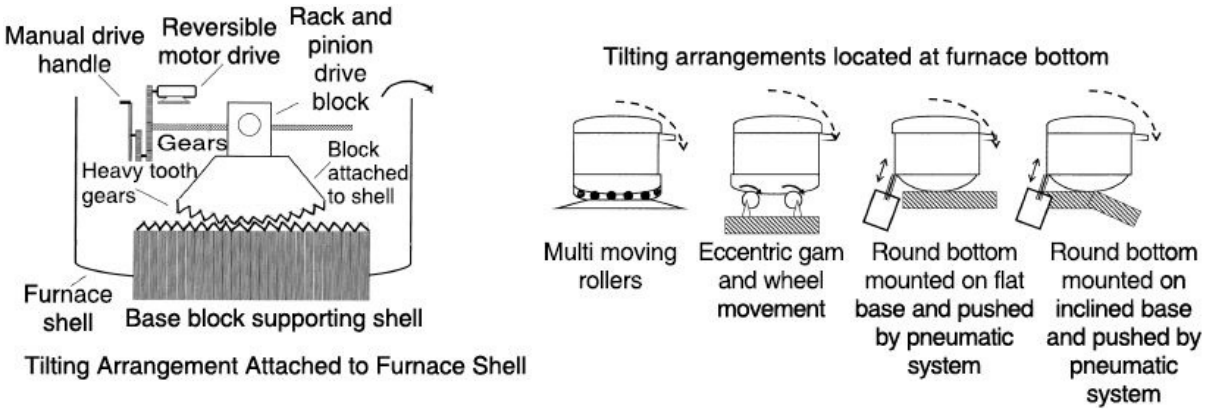


Figure 6.24 Furnace tilting and melt pouring arrangement.

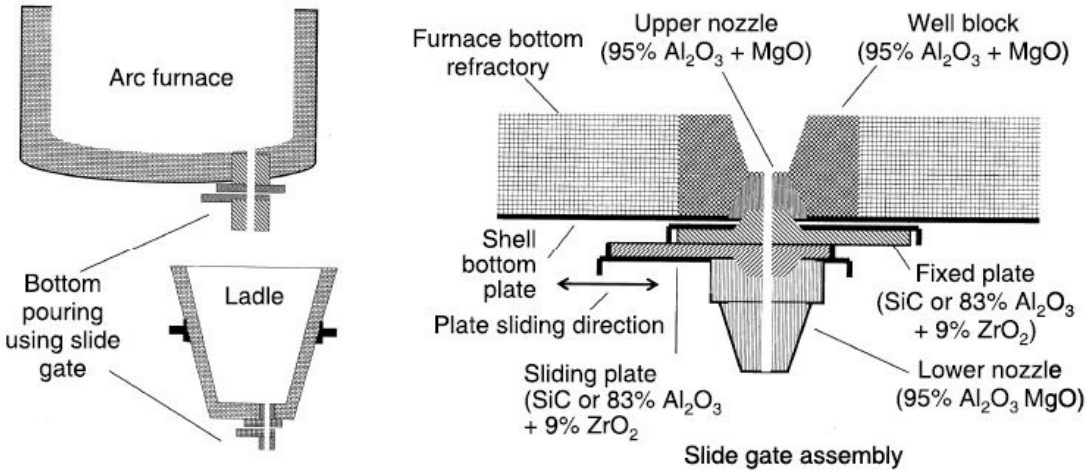


Figure 6.25 Slide gate metal tapping system.

Electrode holder: The electrode holder is a robust mechanical arm (Figure 6.26) to grip the graphite electrode. This electrode arm is fixed with moving section of telescopic column. The electrode arm can be raised and lowered by motor to adjust the arc gap.

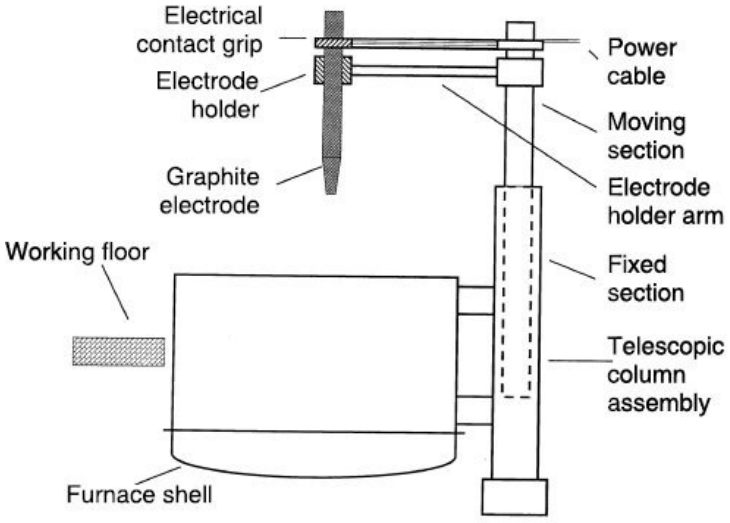


Figure 6.26 Electrode holder arm and telescopic column.

Graphite electrodes: The graphite electrode acts as an electrical conductor at high temperature to carry heavy current used for arcing.

Fume extracting device and dog house: Various types of fume extracting devices are used to remove the fumes and gases from the furnace working area as shown in Figure 6.27. The modern furnaces use a enclosure to avoid pollutants like dust, fume, heat, etc. which is known as ‘dog house’ as shown in Figure 6.28.

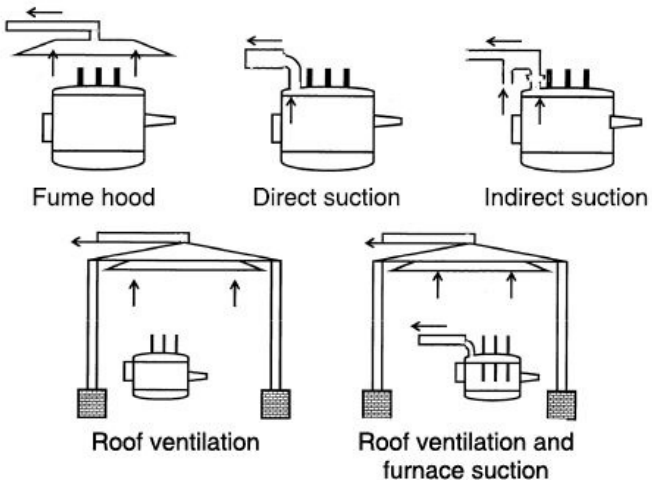


Figure 6.27 EAF fume extracting devices.

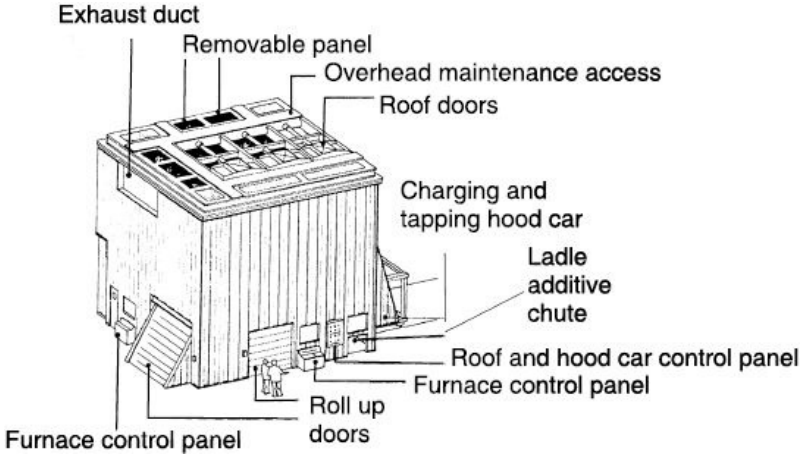


Figure 6.28 Dog house for EAF.

Electrical components: The electric arc furnace requires many electrical components to function. The major electrical components are mentioned below:

Circuit breakers: The circuit breakers are required to connect/disconnect power. This circuit breaker is actuated 5/6 times per heat. They are expected to perform arduous duty of dealing with high ampere current at high voltage. There are two types of circuit breakers: *Air-Break Switch* and *Oil Circuit Breaker* (OCB). The air-break switch is used to connect/disconnect the main power transmission line during furnace 'off' condition. The OCB can be used during furnace 'on' condition. The heat generated by arcing between switch points is absorbed by oil in which the switch is kept immersed.

Reactors: The reactors are used to limit the extent of surge when arc is struck. The surges are heaviest during melt down and get reduced as melting progresses, and the load becomes steady. A reactor inserted into line holds back the line current. The greater is the line current the greater will be the force holding it

back. Thus, the reactor limits the surge and evens out load fluctuations.

Transformer: The transformers are used to step up or step down the supply voltage. The transformer used by arc furnace is different from normal transformer, since it has to deal with non-steady or fluctuating supply condition during melting operation. The transformer immersed in oil absorbs all the heat due to fluctuating load. The capacity of the transformer is expressed in kVA. The transformer capacity depends on the furnace melting capacity. Generally, 170–650 kVA/ton charge or 780–900 kVA/m^2 hearth area is considered to estimate the capacity of required transformer. The range in capacity is given to accommodate variations in melting charges and practices.

Electrode regulators: The electrode regulators are devices obtained by combining mechanical and electrical systems to govern the arc length and power input in the furnace. The regulator performs following functions:

a. Gives speedy and instant response to changing conditions in the furnace
b. Maintains electrical contact
c. Maintains uniform power distribution on all electrodes
d. Raises the electrode in the event of failure
e. Maintains any pre-set electrical condition automatically

Operation: The electric arc furnace is used for melting steel scrap with or without oxidation of the alloying elements.

In melting practice with oxidation, the oxygen is added during the melting process through oxygen injection or iron ore addition. The elements like silicon, manganese, phosphorus and carbon get oxidised and removed. The bath is made to boil to remove carbon and non-metallic constituents float to join slag. The process for making mild steel using cold scrap involves number of steps as given below:

a. Fettling
b. Scrap charging
c. Melting scrap
d. Melt dephosphorisation
e. Boiling and melt heating
f. Slag off
g. Recarburisation

h. Deoxidation
i. Desulphurisation
j. Melt assessment: composition and temperature
k. Teeming

The melting practice without oxidation is conducted mainly for alloy steel scrap having very low phosphorus and sulphur. In this case, iron ore addition or oxygen injection is not used. The charge is melted and the oxidised alloying elements during melting are recovered back by addition of ferrosilicon. The melting process is depicted in Figure 6.29.

Use: The electric arc furnace contributes a very high share of steel production next to pneumatic steel making methods. The EAF is used for following applications:

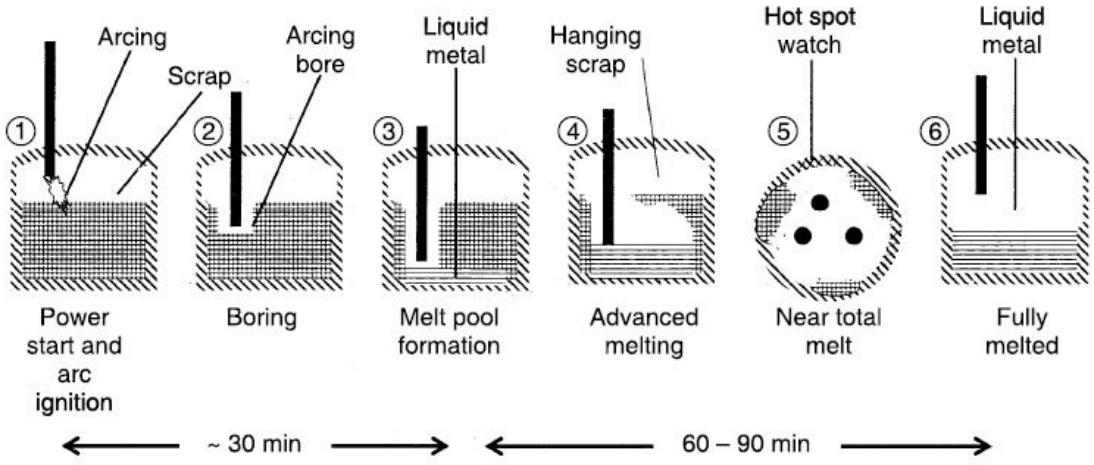


Figure 6.29 Scrap melting process in EAF.

a. Conversion of hot pig iron into steel in integrated steel plants
b. Use of hot or cold DRI for steel making in integrated steel plants
c. Use of cold scrap with or without DRI for steel making in non-integrated steel plants
d. Providing liquid steel for casings in ferrous foundries
e. Preparation of alloy steels

(v) Submerged arc furnace

The submerged arc furnace differs from arc furnace in application and construction as summarised in Table 6.4.

Table 6.4 Comparison between Arc and Submerged Arc Electric Furnace	

Arc Furnace	*Submerged Arc Furnace*
It is melting furnace used for steel and alloy steel production.	It is a smelting furnace for ferro-alloy production.
It has tilting arrangement for metal and slag removal.	It is a stationary furnace without tilting system.
It uses pre-formed sintered graphite electrode.	It uses self baking electrode.
It requires lower rated power transformers (~ 500 to 800 kWh/ton).	It requires high rated power transformers (1500 to 8500 kWh/ton).

Construction: Figure 6.30(a) gives a schematic view of submerged arc furnace process, while the Figure 6.30(b). shows the main components which are described as follows:

Furnace shell and refractory lining: It is made of thick steel plates to house the refractories as shown in Figure 6.30(b). The furnace is mainly lined with carbon blocks with backing of fireclay bricks at the bottom. The side wall has backing of fireclay brick pieces with powder.

Electrode holder: It consists of ring, clamps, bolts with nuts to hold electrode.

Supporting cylinder: Its purpose is to suspend the electrode and electrode holder through a suspended device and move the electrode during operation. The supporting cylinder has a transverse beam at its lower end, which has the connection with the chain and conducting tubes to carry the current.

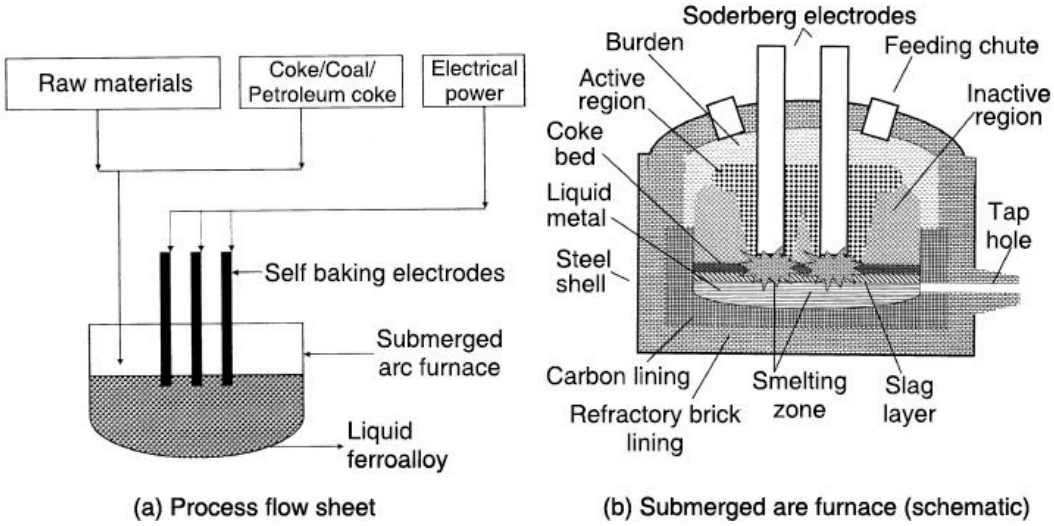


Figure 6.30 Submerged arc furnace process for ferroalloy making.

Electrode moving arm : It is a electrode moving (up and down) mechanism consisting of electrical and mechanical system for all three electrodes working on three different phases. The furnace having 750–900 mm diameter electrode has arm rising speed of 40–60 mm/min. The rate of lowering electrode is less (~ 20–25%) than that of rising.

Braking device: In working furnace, as the electrode is consumed (burnt) it has to be lowered (i.e., raising the support cylinder). At this stage, the electrode is gripped by electrode holder. The electrode is released without disconnecting the power by means of a special braking device provided to each of the three electrodes.

Water cooling: The water cooling arrangement is provided to cool parts like contact jaw, electrode holder ring, tubular suspension arm of the ring, box on the supporting cylinder and moving shoe which supplies power from flexible cable to conducting tubes.

Loading equipment: The bins, chutes and feeders are provided for continuous charging of various raw materials in the required proportion.

Ventilation fan: The dust laden gases are removed by ducts working under negative pressure. The dust particles are removed before discharging waste gases to the atmosphere.

Tap hole burning device: Ferroalloy is tapped periodically by opening tap hole located in the lower section of the shell. The tap hole is opened using a special device deploying an electric arc.

Transformer : The high power transformers are needed to provide electrical current at high ampere and low voltage. The total energy needed for melting steel in arc furnace ranges 500–800 kWh/ton, while the energy required for ferroalloy production is much high ranging from 1500 to 8500 kWh/ton as given in Table 6.5. This power is supplied by heavy transformers with capacity 7000 to 12000 kVA.

Table 6.5 Energy Consumption for Ferroalloy preparation in Submerged Arc Furnace

Alloys	*Energy Consumption,* kWh per ton
Ferro vanadium (~ 35% V)	1500
Ferro manganese (76–80% Mn)	1700
Ferro tungsten (60–70% W)	3200–3300
Ferro chromium (high C)	3200–3400
Ferro chromium (Low C)	3500–3600
Silico manganese (60–65% Mn)	4000–4100
Ferro silicon (~ 45% Si)	4500–4700
Ferro silicon (~ 75% Si)	8400–8500
Silico chrome (50% Cr)	5500–5700

Operation: The submerged arc furnace used for ferroalloy preparation work

continuously as shown in process flow sheet in Figure 6.30(a). The suitable raw materials are fed and power is supplied through electrodes. The smelted alloy collects at the hearth and tapped periodically.

Use: Table 6.6 gives the list of ferroalloys generally made in submerged arc furnace.

Table 6.6 Chemical Composition of Major Ferroalloys Prepared by Submerged Arc Furnace

Ferroalloys	*Composition, wt. %*						
	C	Si	Mn	Cr	P	S	Fe
Ferro-silicon	–	45–50	0.8	0.5	0.05	0.04	Rest
Ferro-silicon	–	70–78	0.7	0.5	0.05	0.04	Rest
Ferro-manganese	1.5–2	2	80	–	0.38	0.03	Rest
Silico-manganese	1	>20	65	–	0.1	–	Rest
Ferro-chrome	6.6–8	2–5	–	65	0.07	0.04	Rest
Ferro-chrome	0.1	0.15	–	60	0.06	0.04	Rest

6.1.5 Chemical Energy based Furnaces

There are many metallurgical operations where the chemical reactions occurring in the process are highly exothermic in nature. In such furnaces, no external energy source is required to sustain the process. The furnace only facilitates the process and allows handling of raw materials and discharging the product. The hearth roasting furnace, flash smelters, pneumatic steel making converters, alumino-thermit ovens, etc. are illustrative examples. These are described very briefly in the following sections:

Multiple hearth roasting furnace

Basic principle

Roasting is a gas-solid reaction process which can include oxidation, reduction, chlorination, sulphation, and pyrohydrolysis. In roasting, the ore or ore concentrate is treated with very hot air resulting exothermic reactions, which sustains the process without any external energy supply. This process is generally applied to sulphide minerals. During roasting, the sulphide is converted to an oxide, and sulphur is released as sulphur dioxide gas. The chemical reactions with the ores Cu_2S (chalcocite) and ZnS (sphalerite) a re expressed as:

$$2Cu_2S + 3O_2 \rightarrow 2Cu_2O + 2SO_2 + Heat$$

$$4FeS + 7O_2 \rightarrow 2Fe_2O_3 + 4SO_2 + Heat$$
$$2ZnS + 3O_2 \rightarrow 2ZnO + 2SO_2 + Heat$$

Construction

The multiple hearth roasting furnaces consist of a tall cylindrical structure having steel plate shell lined with firebricks. This tall cylindrical furnace (Figure 6.31) is divided into compartments by 9 or more hearths having a central hole for the drive shaft and a discharge hole near the wall. The central rotating shaft is fitted with arms and rabbles to move the material lying on the hearth. Each section of the hearth has a provision for air inlet and gas exit. It also has a provision for burners to pre-heat the furnace to working temperature while starting from cold stage. These burners are not needed during working period as heat evolved by the exothermic roasting reactions sustains the process. The charge is fed from top on the top most hearth which drops on the next hearth through the discharge hole. The material keeps falling on the next hearth till it reaches the bottom hearth and discharged out of the furnace. The central shaft is driven by a motor and gear drive system at a very slow speed to allow sufficient time on each hearth for chemical reaction.

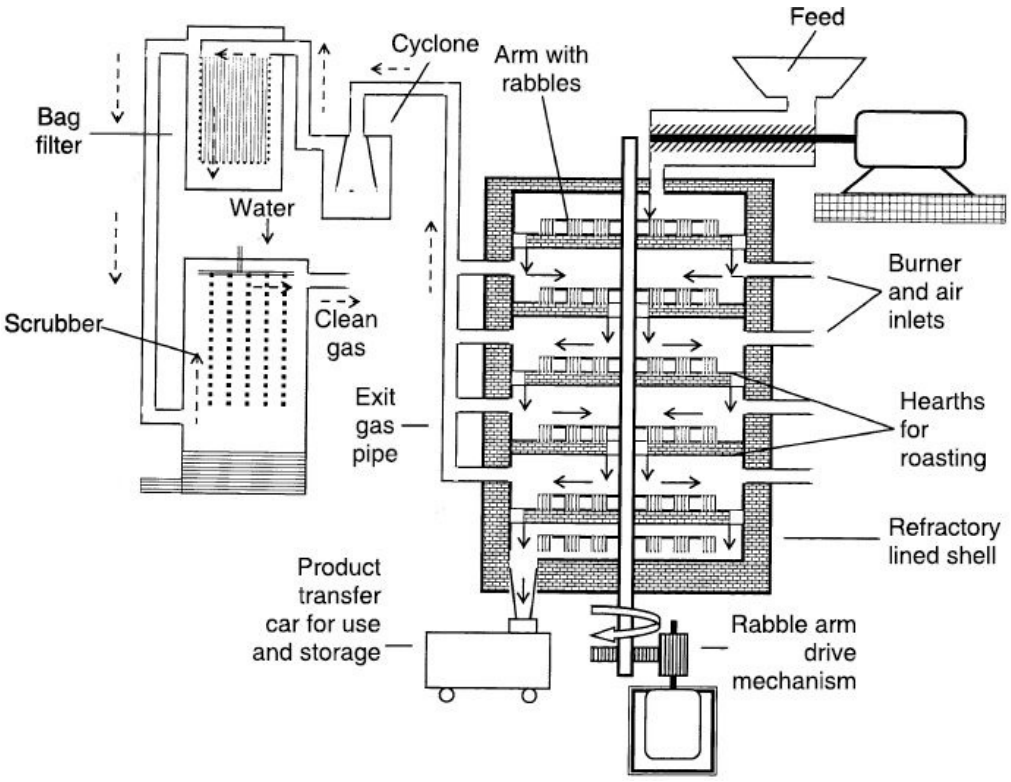


Figure 6.31 Multiple hearth roasting furnace.

Operation

The sulphide mineral concentrate fed on the pre-heated hearth having sufficient air supply causes oxidation with the release of sulphur dioxide gas and heat. The feed concentrate dropping through the furnace is first dried by the hot gases passing through the hearths, and then gets oxidised. The sulphur dioxide gas generated is collected and treated for disposal. The oxidised mineral is discharged out from bottom for further treatment.

Use

The sulphide minerals of copper and zinc are roasted first before further processing.

Flash smelting furnace

Basic principle

Flash smelting is a smelting technique for sulphur bearing mineral and its concentrates (e.g. chalcopyrite) . In flash smelting, the oxygen-enriched air is supplied to exploit sulphur as energy source meeting the thermal needs of the furnace. The concentrate is generally dried before charging in the furnace. The smelting reactions yield copper matte and iron oxide bearing slag. The copper matte is further converted into blister copper which is refined to produce copper.

There are two types of flash smelting furnace in use: Outokumpu and INCO flash furnace.

Outokumpu flash smelting

Construction: The *outokumpu* flash smelting furnace is characterised by five major components:

a. Concentrate burner which mixes dry particulate feed with oxygen-bearing blast and directs the mixture in suspension form downward into the furnace.
b. A reaction shaft where most of the reaction between oxygen and sulphide feed particles take place.
c. A settler hearth where molten matte and slag droplets collect and form separate layers.
d. An off-take for removing SO_2 bearing gases from the furnace.
e. Tap holes near the bottom of the furnace for removing matte and slag.

Operation: A schematic view of outokumpu flash furnace is illustrated in Figure 6.32.

The efficient operation of the furnace requires a good particle-gas suspension, and the maintenance of a steady flow of feed materials into the furnace. These conditions can only be obtained by the use of dry feed concentrate. The thermal balance is maintained by preheating the feed particles with direct-fired burners. These burners will use much more fuel if the furnace is operating with an air blast than if it is operating with an oxygen blast. While the smelting process is continuous, tapping of matte and slag are intermittent. Matte is tapped into ladles for transport to converters, and slag is either tapped into a cleaning furnace for copper recovery or is dried and recycled into the flash furnace with ore concentrate.

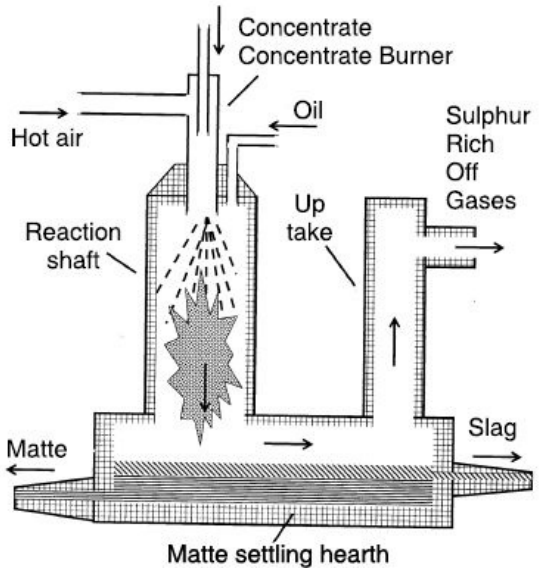


Figure 6.32 Outokumpu flash furnace.

Use: Production of copper matte.

INCO flash smelting

Merits: The principal advantage of INCO furnaces over Outokumpu furnaces is compactness, which enables them to be used to replace existing reverberatory furnaces. The reactions taking place are similar to those in an Outokumpu furnace, but without the benefit of fossil fuel combustion.

Construction: INCO flash smelting consists of blowing industrial oxygen and dry concentrate horizontally into a hearth-type furnace. A cut-away view of a typical INCO flash furnace is illustrated in Figure 6.33.

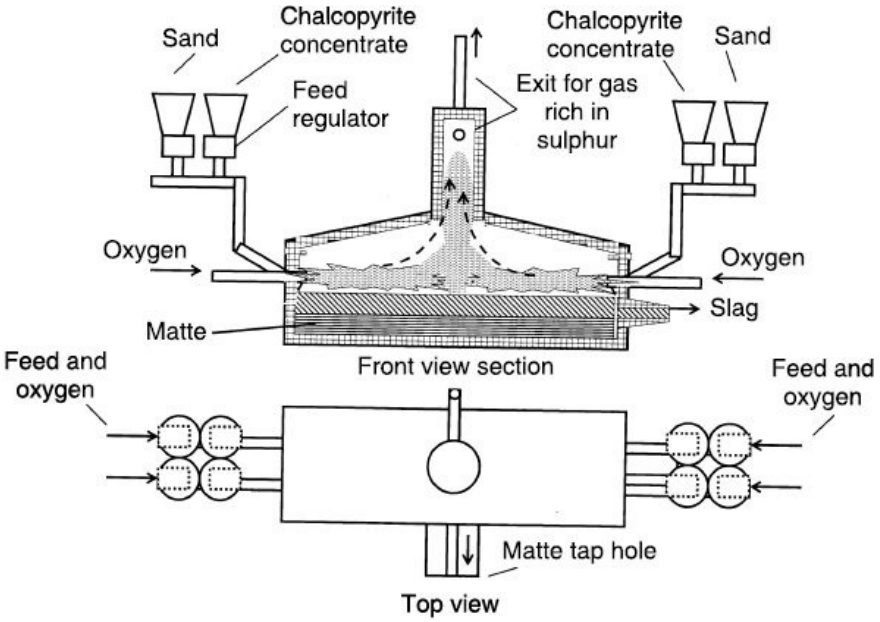


Figure 6.33 INCO flash furnace.

This type of furnace is characterised by the following four major components:

a. Concentrate burners, two at each end of the furnace, through which ambient temperature oxygen, concentrate, and flux are blown into the furnace,
b. A central gas off-take through which the off gas is withdrawn for delivery to the cooling, dust removal, and SO_2 fixation systems,
c. A long and shallow refractory lined hearth to hold the matte and slag, and
d. Matte and slag tap holes through which the liquid products are periodically removed from the furnace.

Operation: As Outokumpu furnaces, the maintenance of good gas/particle suspension and steady flow into the furnace are essential for the efficient operation of the smelter. The major difference in operating conditions is the exclusive use of industrial oxygen and the reliance on sulphur, and iron oxidation for thermal energy input. The volume of off gas is very small compared to Outokumpu furnaces, and SO_2 concentrations are much higher (~ 75%). The external fuel combustion is required at INCO furnaces only during start-up periods to bring the furnace chamber to its operating temperature. Slag produced in INCO flash furnaces do not contain more than 1% copper. This eliminates the cost of slag cleaning equipment, which is necessary to attain

similar copper recovery efficiencies with Outokumpu furnaces. The off gases from INCO furnaces are typically not routed through waste heat boilers, rather proceed through dust settling chambers and gas cleaning systems. Dust recovery of 99.99% is achieved with a combination of scrubbers, cyclones and both wet and dry electrostatic precipitators.

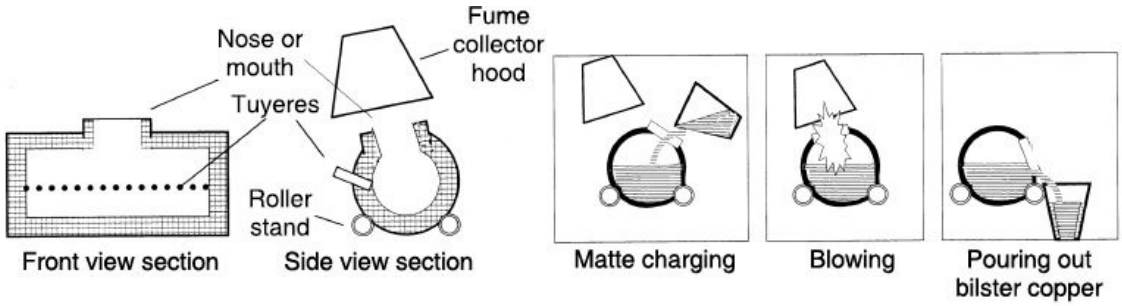
Use : Production of copper matte.

Copper converters

The matte obtained from flash smelter consists of CuS and FeS mixture. This matte is converted to blister copper by blowing oxygen through matte held in a furnace called 'copper converter'. The sulphur present in the matte serves as a source of energy.

Construction

The conversion process of matte to blister copper is carried out in a furnace called *converter* . There are various types of converter of which the horizontal converter known as *Peirce-Smith* type is more commonly used. It is a horizontally placed cylindrical vessel (4.3 to 10 m long and 2.3 to 4 m diameter) lined with refractory (magnesite bricks). The shell is mounted with two plain rims supported by roller stand, and one toothed rim is mounted which is engaged with gear and motor system. This motor and gear system cause rotation of the converter in the desired direction during conversion process. A nose or mouth on the top is provided for the purpose of the feeding matte and pouring out blister copper after conversion operation. The belt of tuyeres is placed along the axis on side of the converter. Molten matte is poured through the mouth into the converter during the feeding operation. The air is distributed to tuyeres from the tuyere collectors which are located on side of the converter. Collector pipes vary in diameter with distance from the connection to main air supply pipe to provide equal pressure of air in each tuyere. The copper converter and conversion process steps are shown in Figure 6.34.



(a) Peirce–Smith copper converter (b) Converting process steps

Figure 6.34 (a) Copper converter and (b) Converting process steps.

Operation

The copper converter operation is divided into the following steps:

a. The first step is to provide oxygen enriched air through the tuyeres to partially convert metal sulphides to oxides: $FeS + O_2 \rightarrow FeO + SO_2$ a $CuS + O_2 \rightarrow CuO + SO_2$
b. The copper oxide, thus formed, further reacts with iron sulphide, since iron is more reactive than oxygen: $CuO + FeS \rightarrow CuS + FeO$. As a result of this reaction, the copper oxide formed during first step is converted back into copper sulphide.
c. The iron oxide formed is removed as fayalite ($2FeO . SiO_2$) slag by adding silica as flux: $2FeO + SiO_2 \rightarrow Fe_2 SiO_4$ (or $2FeO.SiO_2$). This fayalite rich slag is poured out through the hood by tilting the converter.
   After removing the slag, the converter is further charged with matte, and the operation is repeated till entire converter charge is made free from FeS and FeO and left with CuS only. This stage marks the end of first step in conversion process.
d. The second step of conversion aims at oxidation of the CuS (product of first step of converting process) to produce *blister copper* through reaction: $CuS + O_2 \rightarrow Cu + SO_2$. The blister copper contains more than 95 per cent copper.
e. The slag from the copper converter, generated in its second stage, contains copper in reasonable quantity for its recovery. The sulphur rich gas from the converter is collected for preparation of sulphuric acid and avoiding its release in air due its toxic nature.

Use

Conversion of matte into blister copper.

Pneumatic steel making converters

Basic Principle

It is an important method of converting molten high carbon iron (pig iron or blast furnace hot metal) i nto steel by blowing pure oxygen. The elements like carbon, silicon, manganese and phosphorus present in pig iron are oxidised by

blowing pure oxygen in the bath to form their oxides and get removed to yield steel. The reactions of oxidation of C, Si, Mn and P are exothermic in nature, and provide sufficient thermal energy to sustain the process without needing any other heat source. These furnaces are also referred to as *basic oxygen furnace* (BOF) or *basic oxygen process* (BOP), because basic materials like dolomite or fresh lime are used as fluxes to form fluid basic slag. Such type of fluid slag is needed for the removal of products of oxidation of Si, Mn and P (i.e., SiO_2, MnO_2 and P_2O_5). This requires a basic lining of dolomite for the converter vessel. This converter is also known as LD converter named after Linz and Donawitz city of Germany, the place of its development.

Construction

The LD converter has two major components: the refractory lined converter vessel and oxygen lance.

a. The converter is a pear shaped vessel which can be designed for various capacities as given in Table 6.7. This vessel is lined with tar dolomite. The tap hole is located at the junction of cylinder and conical nose [Figure 6.35(a)] to provide clean tapping of liquid metal, while the slag remains floating on top due to its lower density.
b. The copper tipped water cooled lance serves to inject oxygen jet for creation of turbulence and reaction in the metal bath. The lance has automatic manipulator for raising and lowering as desired during oxygen blow. This lance has number of nozzles depending on the size of the converter.

Table 6.7 The Capacity and Dimensions of LD Converter

S. No.	*Capacity, ton*	*Vessel Diameter,* mm	*Vessel Height,* mm
1	50	4760	6185
2	100	6211	7810
3	150	7014	8872
4	200	7701	9701
5	250	8094	10450
6	300	8501	10911
7	350	8651	11410

Operation

The hot metal ‘pig iron’ produced in blast furnaces is kept stored in a ‘mixer’ after it is pretreated during transit from blast furnace to the ‘mixer’. This hot metal is given pre-treatment during its transit from blast furnace to minimise sulphur and silicon to a level acceptable by the converter. This hot metal is converted to steel in LD converter by oxygen lancing. The steps involved in the steel making operation is described briefly as below:

(1) *Hot metal transfer* : The hot metal held in ‘mixer’ is poured out into a ladle for transferring to the converter.

(2) *Hot metal charging or pouring* : The ladle hot metal is poured into the converter kept in tilted position. The converter is also fed with slag forming charge like fresh lime and dolomite. The converter is brought back to its vertical position for introducing oxygen lance. Figure 6.35(b) shows the converter position while charging.

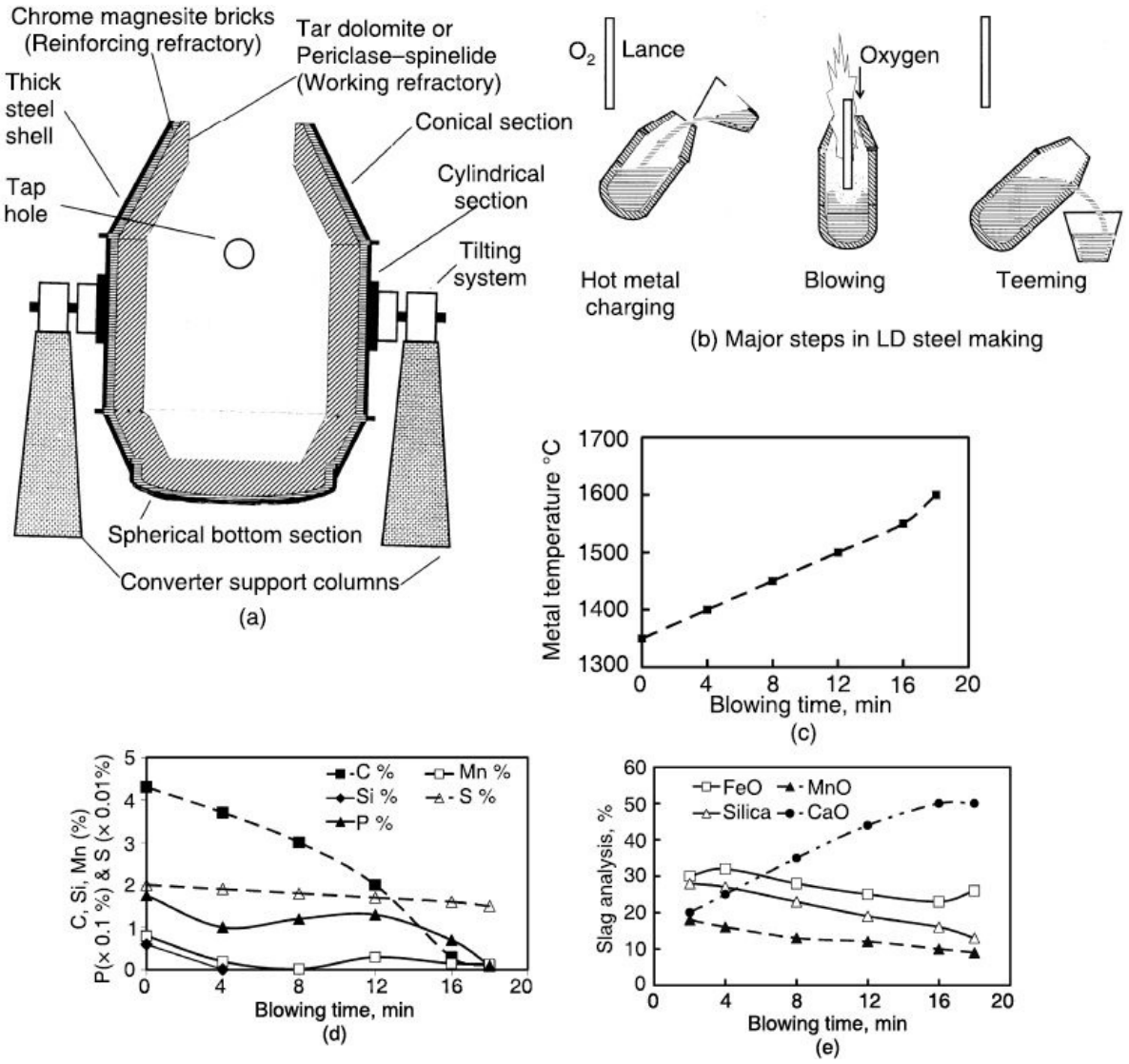


Figure 6.35 LD converter for steel making (or BOF).

(3) *Lance positioning* : The oxygen (at ~ 0.7–1. MPa, i.e., ~ 100–150 pound force/square inch) is kept ready for lancing. The water cooled lance is held suspended few meters above the hot metal bath. The oxygen is delivered in jet form by the lance with supersonic speed impinging the hot metal surface. The lance tip made of copper has 3–7 nozzles depending on the converter size.

(4) *Blowing* : The lance is lowered down over the bath to "blow" oxygen causing hot metal carbon reacting to form carbon monoxide. The 'blowing' is done for nearly 20 minutes. The highly exothermic reaction occurring during 'blowing' raises the hot metal temperature to ~ 1700 °C. This high bath temperature is lowered by adding cold steel scrap. Figure 6.35(c), (d)

and (e) show the metal bath temperature, metal chemistry (C, Si, Mn, P wt. %) and slag composition with blowing time.

(3) *Finishing* : The fluxes (burnt lime and dolomite) fed into the vessel form highly basic slag (> 3 basisity). The blowing takes about 20 minutes. The metal temperature is measured and samples are taken out. A typical blowing operation gives the metal analysis at the end of the blow as: 0.2–0.6% C, 0.05–0.1% Mn, 0.001–0.003% Si, 0.01–0.03% S and 0.005–0.03% P.

(4) *Tapping* or *Teeming* : The hot metal is tapped out by tilting the converter towards its tap hole side and hot metal is received in ladle having basic refractory lining. The deoxidisers and minor alloying additions are made in the ladle.

(5) *Cleaning:* The converted is tilted with mouth facing downward to pour out the slag. The converter lining is inspected, repaired if needed, and is kept ready to take another batch of hot metal for blowing.

Use

Conversion of liquid pig iron into steel.

Alumino-thermit ovens

Basic principle

Alumino-thermit process is a method of reduction of metallic oxides by using aluminum powder as a reducing agent. In this process, a mixture of metallic oxide (e.g. Fe_2O_3 , V_2O_5 , MoO_3 , TiO_2, etc.) and aluminum powder is place refractory crucible which is ignited by a magnesium ribbon causing a highly exothermic reaction, yielding liquid metal or alloy depending on the composition of the mixture. The reactions occurring can be expressed as:

$$3MO + 2Al \rightarrow 3M + Al_2O_3$$

Examples:

$$Fe_2O_3 + 2Al \rightarrow 2Fe + Al_2O_3$$

$$3V_2O_5 + 10Al \rightarrow 6V + 5Al_2O_3$$

Construction

The process uses a refractory crucible to hold the mixture of metal oxide and aluminium powder. The size of the crucible depends on the capacity of melt needed. It could be from 1 to 500 kg melt capacity. The crucible must be highly refractory in nature to sustain high temperature (~ 1700 °C). The crucible is

made with a hole at the bottom for discharging liquid melt. This hole is covered with a steel plate during use which gets melted by hot metal to permit liquid metal discharge. The crucible is placed on a rigid platform below which a ladle is provided to receive the liquid melt. The crucible area is provided with a safety cover wall to protect against any explosion due to moisture in the charge. The arrangement is provided for safe ignition by a magnesium ribbon held in a long arm or remotely operated rope and pulley system.

Operation

The method of alloy preparation could be described briefly as follows:

(1) *Preparation of mixture of oxides* to provide required steel composition or ferroalloy, and removal of moisture by long drying in oven at 200 °C.

(2) *Cooling the dry powder* and mixing aluminium powder in required proportion and placing in the crucible having bottom tap hole covered with a steel plate.

(3) *Ignition of the mixture* by using magnesium ribbon from distance with full care. The highly exothermic reaction yielding liquid metal gets collected at the bottom of the crucible covered with slag.

(4) The *discharging of the liquid melt* occurs due to melting of steel plate which opens the tap hole allowing flow of liquid melt in the ladle placed below the crucible. The liquid melt is poured into available mould.

Use

The process is useful for welding rail joints, welding broken heavy machine parts like rolling mill rolls and welding heavy steel components. It is also useful for producing ferroalloys on small scale without capital investment in smelting equipment.

The furnaces described in this section are only illustrative in nature as many more furnaces are used in practice whose number is very large and description of each furnace is beyond the scope of this text.

The following sections provide some information related to basic concepts of furnace design and its accessories.

6.2 BASIC PRINCIPLES OF FURNACE DESIGN

In the previous section, various types of furnaces have been given as illustration. All these furnaces are designed and fabricated to serve the purpose. The furnace design is a subject by itself and involves disciplines like mechanical engineering,

materials technology, fluid dynamics, thermal engineering, ceramic engineering, electrical engineering, electronic engineering, etc. All these various engineering groups play their role in designing a furnace system. However, such details are beyond the scope of this text.

The following section only gives a glimpse of some basic features while designing or selection of some major components of the furnace.

6.2.1 Chamber Design

The furnace chamber provides space to conduct the activity in the furnace. This chamber design has many issues like shape, size, ratio of various dimensions, refractory lining thickness and nature, furnace casing material with proper ports, etc. These factors are briefly discussed below:

Chamber shape

The furnace chamber shape could be closed rectangular (e.g. reheating furnace), narrow rectangular (e.g. coke oven), closed trough (e.g. open hearth furnace), closed hemispherical shape (e.g. electric arc furnace), open cylindrical shape (e.g. cupola), one end closed cylindrical shape (e.g. induction melting furnace), etc. The shape depends on the process activity and the mode of heat transfer desired.

Chamber size

The dimensions of rectangular shape furnace (length, width and height), cylindrical shaped (height and diameter) furnace or hemispherical shaped (section diameter and centre height) furnace depend on the scale of operation and process constrains. In case of reheating furnace, the length of the furnace will depend on the object size to be heated and burner design. The width of the furnace will be decided on the number of pieces to be heated (load) at a time, while the height will be decided by the aerodynamics of the furnace for good gas flow and heat transfer. The coke oven chamber dimensions are decided by operating factors. The coke oven length depends on the oven capacity and availability of pusher arm length, the height is decided by selection of heating chamber flue design and the minimum desired width is decided by the ability of a man to enter for construction and repair. In each case, there are compelling parameters to fix the dimensions depending on the furnace capacity.

Ratio of dimensions

In many furnaces, the design is so complex that the units are designed based on

experience and empirical equations. In case of cupola, the literature gives enough data to derive
cupola inner diameter based on melting rate in ton/hr (Figure 6.36). Once the cupola diameter is obtained, the height is derived by the empirical ratio between diameter and height
(Figure 6.37). The following expressions derived from literature give the cupola inner diameter (D_I) and effective height (H_E) in meters for a given cupola capacity (C_C) in ton per hour.

$$D_I = 0.4 \times (C_C)^{0.5} \text{ and } H_E = 1.78\, D_I + 1.88 .$$

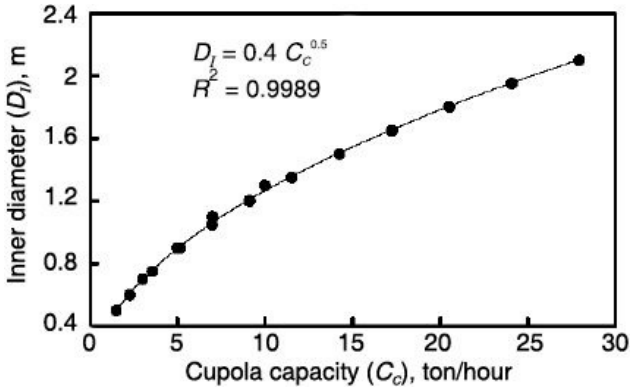


Figure 6.36 The inner diameter ($\boldsymbol{D_I}$) needed for the required cupola capacity ($\boldsymbol{C_C}$).

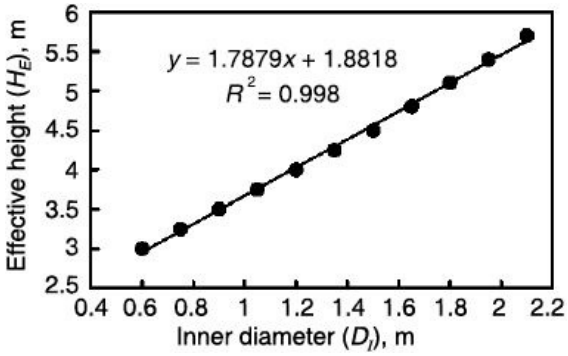


Figure 6.37 The effective cupola height ($\boldsymbol{H_E}$) for a given inner diameter ($\boldsymbol{D_I}$).

(Source : R.C. Gupta, Estimating the Cupola Dimensions, *IIM Metal News* , Vol. 13, No. 1, 2010, pp. 8–13.)

Refractory thickness and nature

The nature of refractory is decided by the maximum temperature requirements and other working conditions like chemical nature of materials in contact, working load, erosion and corrosion parameters, etc. Once the nature of refractory is decided, then the thickness of refractory layer would depend on the inner working temperature, thermal conductivity of the refractory and maximum temperature sustainable by outer metallic casing.

Furnace casing material

The furnace is generally encased in steel structure for stability, support and handling. The steel selected is generally common structural steel unless some furnace demand heat resisting steel for special applications. The steel casing thickness depends on the furnace size and load subjected. The steel casing is made sufficiently strong to sustain rough working conditions of the furnace. This casing has ports for burner, gas exit, material charging and discharging door, etc.

6.2.2 Burners

The burners are necessary to combust the fuel for generating thermal energy for its efficient utilisation in the furnace. The suitable burners are selected based on the type of fuel
(coal, oil or gas) best suited for the furnace. Various types of burners have already been described in Chapter 5.

6.2.3 Fans and Blowers

The fans and blowers are used in the furnace to provide air for combustion of fuel in the burners. The fans operated by electrical motor provide air displacement depending on its blade design. The fans provide lower (up to 1.11) specific ratio of displacement and lesser pressure (1136 mm water gauge) compared to blowers which can give higher displacement ratio
(1.11 to 1.20) and higher pressure (1136–2066 mm water gauge). This *specific ratio* of displacement is defined as the *ratio of the pressure at delivery end to the suction end pressure in fan or blower* . Various types of fans and blowers are used depending on the requirements. Different types of fans are shown in Figure 6.38.

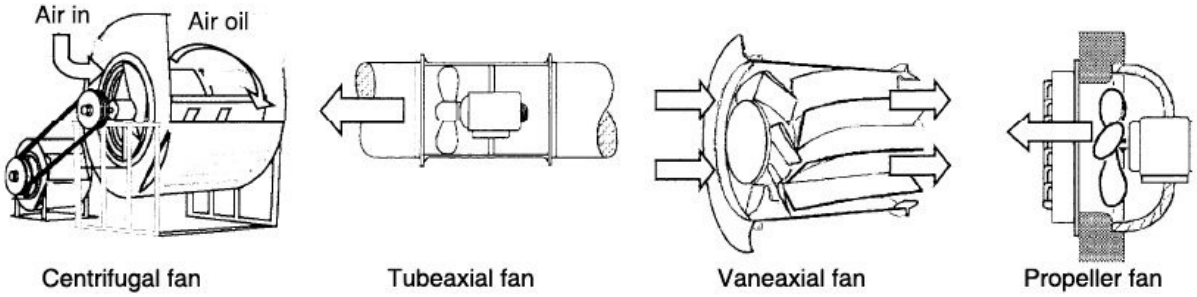


Figure 6.38 Various types of fans.

Types of fan

The fans could be categorised under two groups: *Centrifugal flow fans and Axial*

flow fans as described below:

(i) Centrifugal flow fans

In such fans, the direction of air flow is changed twice: once while entering and second while leaving the fan. The centrifugal fans are available with three types of fan blades:

Radial fans : These fans are used in industry due to their ability of providing high static pressures (up to 1400 mm WG). These fans could be used for contaminated air streams. The radial fans are suited for use at high temperatures.

Forward curved fans: These fans are used to operate at lower temperature and clean environment. These fans are suited for moving large air volumes with lower pressure.

Backward curved fans : These fans are also known as *non-overloading fans* , since changes in static pressure do not overload the motor. Such fans are found more efficient than forward curved fans.

(ii) Axial flow fans

In these fans, the air flow does not change its direction. There are various types of axial flow fans, for example:

Tube axial fans: These fans have a wheel fitted inside a housing with some clearance between blade and the housing. These fans are suitable for operation under high pressures (250–400 mm WG). The efficiency of such fans could be up to 65%.

Vane axial fans : These are similar to tube axial, but have guide vanes for better efficiency. These fans give higher static pressure up to 500 mm WG.

Propeller fans: These fans operating at lower speed work under moderate temperature. Such fans are used commonly as exhaust fans. These fans have lower efficiency (~ 50% or less).

Blowers and its types

The blowers can achieve higher pressures than fans (~ 1.20 kg/cm^2). Such fans can also be used for creating negative pressures (mild vacuum) in industrial systems. There are two types of blowers: *centrifugal and positive-displacement.*

(i) Centrifugal blowers

T hese blowers look like centrifugal pumps. The impeller is gear-driven and rotates with 15,000 rpm.

The centrifugal blowers can work against 0.3 to 0.7 kg/cm ^{2} pressures. One

characteristic feature of these blower is that flow decreases as the pressure in the system increases. Due to this disadvantage, these are suitable for applications that are not subjected to frequent clogging.

(ii) Positive displacement blowers

The positive displacement blowers push the trapped air by the moving rotors in forward direction. Such blowers keep providing regulated fixed volume of air even with fluctuating system pressure. These type of blowers are useful for systems which are prone to clogging. These blowers can produce pressure to the extent of 1.25 kg/cm ^{2} which is capable of removing clogged materials.

Basic laws of fan working

The fans operate under a predictable set of laws concerning speed, power and pressure. A change in speed (RPM) of any fan will predictably change the pressure rise and power necessary to operate it at the new RPM. These laws are as follows:

a. Flow of air (Q) is directly proportional to the rpm (N) of the fan, **(** i.e., $Q \propto N$ or $Q_1 / Q_2 = N_1 / N_2$.
   An increase or decrease in 10% rpm will cause 10% change in air delivery.
b. The fan static pressure (P) is directly proportional to the square of rpm (N^2) value of the fan,
   i.e., $P \propto N^2$ or $P_1 / P_2 = (N_1 / N_2)^2$.
   This means 10% reduction in rpm would cause 19% reduction in static pressure, while an increase in 10% rpm value would give an increase in static pressure by 21%.
c. The fan power (W) is directly proportional to the cube of rpm (N^3) value of the fan, i.e., $W \propto N^3$ or $W_1 / W_2 = (N_1 / N_2)^3$.

This means a reduction in 10% rpm value would result in 27% less power requirement, and increase of 10% fan speed (rpm) would demand 33% additional power. This basic law indicates that the fan must be operated with minimum required speed for saving energy.

Selection of fan and blower

The selection of fans depends on the air flow and outlet pressure required. These

are important for the selection of fan type and size.

The air flow requirement depends on the system process needs. This is determined from heat transfer rate or combustion air requirements or generated flue gas quantity to be handled. The system pressure requirement is usually more difficult to compute or predict. Detailed analysis is required to determine pressure drop across the length, bends, contractions and expansions in the ducting system, pressure drop across filters, drop in branch lines, etc. These pressure drops should be added to any fixed pressure required by the process. Generally, a very common approach is adopted allocating large safety margins resulting in over-sized fans which operate at flow rates much below their design values. This gives very poor efficiency.

The selection of fan type for any given application depends on the level of flow and static pressure needed . The speed of fan operation varies with the application. High speed small units are generally more economical because of their higher hydraulic efficiency and relatively low cost. However, at low pressure ratios, large, low-speed units are preferable.

The following informations are helpful to enable right fan selection:

(i) Designed operating point of the fan – volume and pressure

(ii) Normal operating point of the fan – volume and pressure

(iii) Maximum continuous power rating

(iv) Operating load range: This is particularly essential for units which wish to increase load with time.

(v) Ambient temperature: Minimum and maximum values are to be specified to the supplier. This will help in right fan material selection to offer required creep strength.

(vi) Composition of the gas: This is very important for choosing the material of construction of the fan to guard against oxidation and corrosion.

(vii) Dust concentration and nature of dust: Information regarding the dust concentration and nature of dust are required to consider erosion of the fan material.

(viii) The proposed control mechanisms that are going to be used for controlling the fan.

(ix) The operating power frequency, since this has a direct effect on the speed of the fan.

6.2.4 Chimney

The chimney is a structure (Figure 6.39) which provides draft for hot flue gases from a boiler, stove, furnace or fireplace to the atmosphere. The chimneys are tall vertical structure to provide exit to flue gas or waste gas from a furnace system.

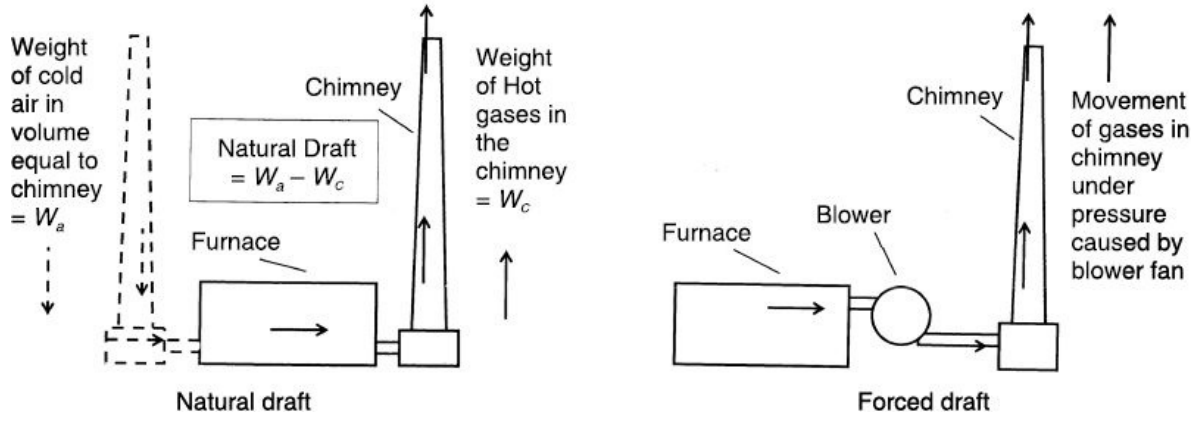


Figure 6.39 Furnace chimney.

The operating principle of the chimney depends on the type of method adopted for the draft of gases, i.e., ‘natural draft’ or ‘forced draft’.

The *natural draft* chimney works under draft due to buoyancy created by the hot gases in the chimney. The furnace exit gases are hot and have density lower than gas at lower temperature. The hot gases with lower density have upward movement in the chimney which creates a natural draft and cold gas (air) from the atmosphere enters the furnace system due to negative pressure (draft) created by hot rising gases. The rate of flow of gases would depend on the draft (pressure difference) created and area of cross-section of the chimney. The typical example of using such chimney is building red brick kilns which require slow draft for gradual combustion of coal and slow firing rate of clay bricks.

The *forced draft* is common with industrial furnace where large volumes of flue gases have to be removed and discharged at higher heights for diffusing the gases in the atmosphere to minimise pollution effect. This requires blower fans of suitable capacity to force the gases in the chimney under pressure greater than atmospheric pressure to cause movement in tall chimneys.

The height of a chimney influences its ability to transfer flue gases to the external environment due to forced draft effect. The dispersion of pollutants at higher altitudes helps in reducing their impact on the immediate surroundings. In the case of chemically aggressive output, a sufficiently tall chimney can allow for partial or complete self-neutralisation of air-borne chemicals before they reach ground level. The dispersion of pollutants over a greater area can reduce

their concentrations and facilitate compliance with regulatory limits.

The chimney structure is made of steel or steel-cement-concrete depending on the nature of flue gases and structural considerations, keeping seismic factor in view for safety.

6.3 FURNACE INSTRUMENTS

The furnace operation and control require many instruments and indicators for various functions. The temperature, pressure and flow rate are major parameters which need suitable instrument to measure and indicate on the control panel. Instrumentation is an important subject and its various aspects are beyond the scope of this book. However, the basic principles of some instruments are given in this text.

6.3.1 Temperature Measuring Devices

The temperature is a numerical measure of thermal state of a body. The measuring scales commonly used for temperature are centigrade (°C), Fahrenheit (°F) and kelvin (K). They are equated according to equation:

$$(°C) = \{(°F) - 32\} \times \frac{5}{9} = (K) - 273$$

The furnace temperatures are generally monitored by using thermocouples, which are incorporated as furnace part. The hand held pyrometers (optical and infrared) are useful to monitor molten metal temperature from safe distance as non-contact measuring device. These three types of temperature measuring devices are discussed below:

Thermocouple

It is a temperature measuring device which c onsists of two dissimilar metallic conductors, one in contact with the hot end to produce an electrical voltage, and the other is kept at cold temperature as shown in Figure 6.40.

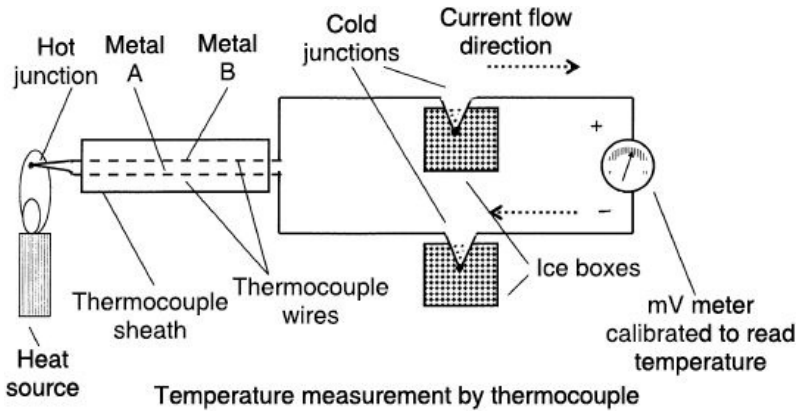


Figure 6.40 Temperature measurement by thermocouple based on thermoelectric effect or Seebeck effect.

Working principle

The thermocouples work on the principle of *thermoelectric effect* or *Seebeck effe* which may be defined as *when any conductor is subjected to a thermal gradient, a voltage is generated across its ends* . This observation was first made by Thomas Johann Seebeck, a German scientist, in 1821.

Construction

The thermocouple systems of measuring temperature consist of three main components:

a. Sensor, i.e., thermocouple wire,
b. Connecting lead wire and
c. Indicator/controller

These three components are described in the following section:

(1) ***Thermocouples and its types:*** Thermocouple wires are made of specific alloys, which have a predictable and repeatable relationship between temperature and voltage (milli volts) due to Seebeck effect. Thermocouples made of different alloys are useful in different temperature range and working conditions as given in Table 6.8. Amongst various thermocouples, the Chromel-Alumel is widely used due to its low cost and wide temperature range of usage. These thermocouples are available in various lengths with different wire gauges encased in suitable refractory or metallic sheath depending on the working temperature and atmosphere.

(2) ***Connecting leads:*** These are copper wires connecting the thermocouple to the indicator. The resistance of these wires is compensated by suitable circuit.

(3) *Temperature indicators/controller:* The emf (in milli volts) generated by thermocouples are indicated through analogue or digital milli-voltmeters. The emf signal could also be used to regulate power supply of the furnace for regulating the furnace temperature using suitable electrical/electronic devices (temperature controllers).

Table 6.8 Types of Thermocouples Used for Various Temperature Ranges

Thermo-couple	*Type*	*Positive Wire*			*Negative Wire*			*Thermo-couple emf Output* µV/ °C	*Usage Temp. Range* °C
		Name	*Composition*	*Property*	*Name*	*Composition*	*Property*		
Copper-Constantan	T	Copper	100 Cu	Red colour and Soft	Constantan	44 Ni 55 Cu	Whitish red, hard and non-magnetic	43	–200 to 370
Chromel – Constantan	E	Chromel	90 Ni 10 Cr	White, hard and non-magnetic	Constantan	44 Ni 55 Cu	Whitish red, hard and non-magnetic	68	−110 to 140
Iron - Constantan	J	Iron	99 Fe	Soft and magnetic	Constantan	44 Ni 55 Cu	Whitish red, hard and non-magnetic	50	−40 to 750
Chromel-Alumel	K	Chromel	90 Ni 10 Cr	White, hard and non-magnetic	Alumel	95 Ni 2 Al, 2 Mn, 1 Si ,	White, hard and magnetic	41	−200 to 1350
Platinum-10 Rhodium and Platinum	S	Pt-10 Rh	90 Pt 10 Rh	White and hard	Platinum	100 Pt	White and soft	10	up to 1600
Platinum-30 Rhodium and Platinum-6 Rhodium	B	Pt-30 Rh	70 Pt 30 Rh	White, hard and non-magnetic	Pt-6 Rh	94 Pt 6 Rh	White, hard and non-magnetic	10	up to 1800

Operation

The thermocouple connected to voltmeter gives the value of voltage (mV) generated and it can be converted to temperature knowing the relationship between temperature and voltage for any given thermocouple (Figure 6.41) using standard milli volt-temperature tables.

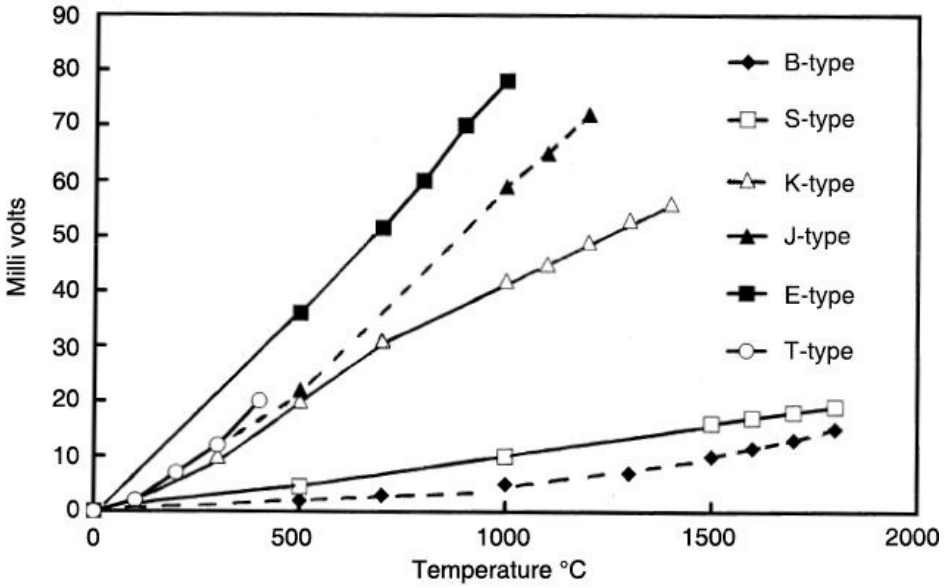


Figure 6.41 Pattern of mV generated by various thermocouples in different temperature range.

Thermocouple voltage is not only sensitive to the temperature difference between two points but also to their common temperature. To measure an unknown temperature, one of the junctions, nominally called the 'cold junction' is maintained at a controlled reference temperature, and the other junction is at the temperature to be sensed. The thermocouple voltage difference between the known cold junction temperature and the standard table reference temperature can be calculated (from standard table for temperature-to-voltage), and the appropriate correction is applied as an offset from measured temperature.

Uses

Thermocouples are fitted permanently in all electrical furnaces to monitor and control temperature. The coal, oil and gas fired units use it to monitor temperature or regulate fuel firing if having automation. The liquid melt temperature can be taken by disposable dip thermocouples having ceramic sheath. Such disposable thermocouples are used for single reading only.

Optical pyrometer

It is a non-contact temperature measuring device which compares the brightness of the hot object with the glow of an electrically heated metallic filament.

Basic principle

The flow of electrical current in the metallic filament causes its heating due to resistance resulting in filament glow with certain colour. This filament colour varies with the rise in filament temperature, which is calibrated with current and

is taken as an index of temperature. The comparison of filament glow with the brightness of hot object in furnace offers a means to know the hot object's temperature. The use of an optical telescope to view the hot object gives its name.

Construction

The optical pyrometer consists of a telescope fitted with a filament at the focal point of the eye piece. The telescope has focusing arrangement to view hot object. This filament is connected with a standard voltage battery, and the circuit has a variable resistance with a meter to indicate current flowing through the filament. This meter is calibrated to indicate hot object temperature directly. Figure 6.42 gives a sketch to show the working principle of optical pyrometer.

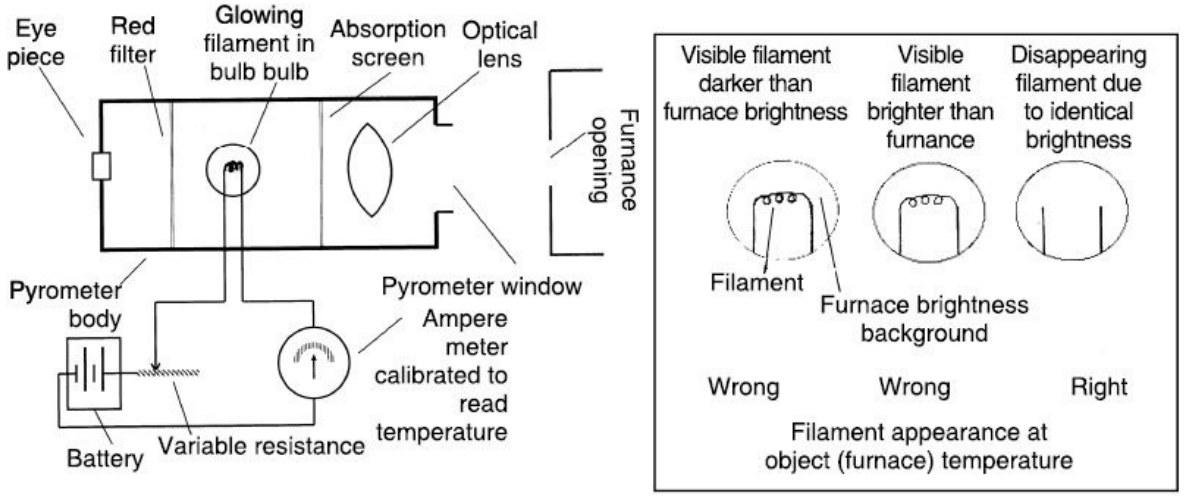


Figure 6.42 Optical pyrometer.

Operation

This is a manually operated equipment. The telescope held in hand is directed to the hot object for measuring its temperature (furnace peep hole, liquid melt in furnace or ladle, hot ingot, etc). The image is focused and battery supply is activated to flow current in the filament. The circuit resistance is varied to change current flow adjusting the glow of the filament. When the filament disappears in the background of the hot object, then the current reading is noted which is calibrated to give hot object's temperature.

Merits and limitations

The optical pyrometer has several merits with some limitations as follows:

Merits

(i) It can be used from safe distance, and no physical contact of the

instrument is required between measuring instrument and the temperature source.

(ii) The accuracy is acceptable for high temperature furnaces as ± 5 °C.

(iii) When a proper sized image of the hot object is obtained in the instrument, the distance between the instrument and the temperature source does not matter.

(iv) The instrument is easy to operate.

Limitations

(i) Temperature of more than 700 °C can only be measured, since glow of the temperature source is a must for measurement.

(ii) Since it is manually operated, it cannot be used for the continuous monitoring and controlling purpose.

(iii) The dust, smoke or vapour haze can affect the observation.

Uses

It is useful to measure temperature of molten metals, and measuring temperature of furnace and hot bodies from safe distance without contact.

Infrared pyrometer

Infrared (IR) pyrometer is a non-contact temperature measuring device based on infrared radiation.

Basic principle

All hot objects emit infrared energy. The molecules in hotter object are very active and emit more infrared energy. An infrared thermometer houses optics that collects the radiant infrared energy from the object and focuses it onto a detector. The detector converts the energy into an electrical signal which is amplified and displayed in terms of temperature.

Construction

The infrared (IR) pyrometer (Figure 6.43) has three main components: (1) Optics and window, (2) Detectors and (3) Display with interfaces.

(1) ***Optics and window:*** The optical system of an IR thermometer picks up the infrared energy emitted from a circular measurement spot and focuses it onto a detector. The target must

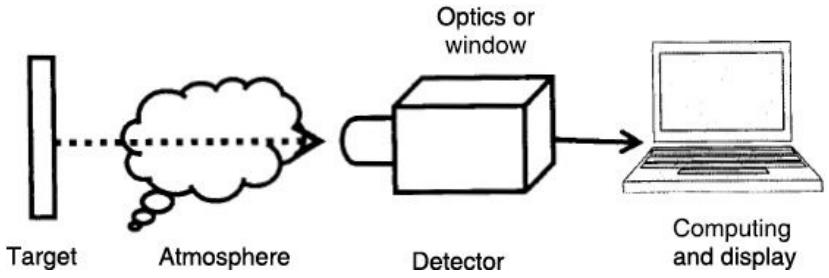


Figure 6.43 Infrared pyrometer measuring system (schematic).

completely fill this view spot, otherwise the IR thermometer will "see" other temperature radiation from the background making the measured value inaccurate. The performance of the optics (e.g. telephoto lens) is similar to a photo camera which determines what size target can be viewed or measured. The distance ratio (distance from object : diameter of spot) characterises the performance of the optics in an IR measuring device. The projected spot must be completely filled for an exact measurement of the target to give result. In order to have easier alignment, the optics is equipped with a through-the-lens sighting device, or with laser pointers. If protective windows between the measuring device and the target are necessary, the right window material must be chosen. In this case, wavelength range and operating conditions play a significant role.

(2) ***Detectors:*** The detector is the main part of the IR thermometer. It converts the infrared radiation received into electrical signals which are then displayed as temperature values by the electronic system. In addition to reducing the cost of IR thermometers, the most recent developments in processor technology have meant increase in system stability, reliability, resolution, and speed. Infrared detectors fall into two main groups: quantum detectors and thermal detectors. Quantum detectors (photodiodes) interact directly with the impacting photons, resulting in electron pairs, and therefore an electrical signal. Thermal detectors change their temperature depending upon the impacting radiation. The temperature change creates a voltage, similar to a thermocouple. Thermal detectors are much slower as it takes few milliseconds (10^{-3} s) compared to fast quantum detectors, which detects in nanoseconds (10^{-9} s) or fermi-seconds (10^{-15} s).

(3) ***Display and interfaces:*** Some devices, especially hand-held ones, have a directly accessible display and control panel combination which can be considered as the primary output of the measuring device. Analog or digital outputs control the additional displays in the measuring station or can be used for regulating purposes. It is also possible to connect data loggers, printers, and

computers directly.

Types of IR pyrometers

Two types of IR pyrometers are common: hand held portable type for multiple point use and mounted type for fixed one point use.

Hand held infrared thermometers: Hand held infrared thermometers are most commonly used for portable multi-point measuring applications. Some models also have feature to provide integral tripod mount.

Fixed or mounted infrared pyrometer: Fixed or mounted infrared pyrometers are useful for industrial processes, where the pyrometer is mounted in a fixed position at specified location to monitor continuously. The output from such IR pyrometer is made local or remote display alongwith an analog output which could be used for another display or control loop.

Operation

The operation of IR pyrometers is simple and depends on the type of equipment used. The hand held equipment is directed towards the object to focus it in the optical window and detector is switched on. The rest is done automatically by the equipment after setting the options for target conditions. The temperature is displayed on the screen. The mounted type is connected to the processing circuit to work as data-logger or system regulator working continuously.

Advantages of IR pyrometers:

(i) It is a non-contact pyrometer.
(ii) It is a fast reading pyrometer giving response time in milli second range.
(iii) It provides a means to measure temperature of moving items like ingots, hot rolled sheets, etc.
(iv) It is very useful in temperature measurements at hazardous or physically inaccessible objects like high-voltage electrical parts and non-accessible points in furnace.
(v) Measurements of high temperatures (greater than 1300 °C) with ease where thermocouples cannot be used or have a limited life.
(vi) There is no interference and no energy loss from the target.
(vii) The measurement of temperature is fairly accurate with no distortion of measured values, as compared to measurements with contact thermometers.
(viii) There is no risk of any contamination or mechanical marking on the surface of the object. The soft surface temperatures can also be measured.

Limitations of IR pyrometers:

(i) The target must be optically (infrared-optically) visible to the IR thermometer.

(ii) High levels of dust or smoke make measurement less accurate.

(iii) The obstacles like closed metallic reaction vessel allow for only outer surface measurement. The inside temperature of the reactor cannot be measured.

(iv) The optics of the sensor must be protected from dust and condensing liquids.

(v) Normally, only surface temperatures can be measured.

Uses

To measure molten metal temperature, hot ingot temperature, hot spots on the blast furnace, hot points in the electrical panel, flame temperature, etc.

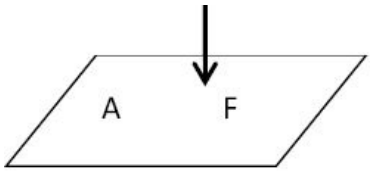
6.3.2 Pressure Measuring Equipment

Basic principles

Pressure (*p*) is defined as *force* (*F*) per unit *area* (*A*) applied in a direction perpendicular to the surface of an object which is mathematically expressed as:

$$p = F/A \text{ or } dF_n/dA$$

The unit (SI) for measuring pressure is pascal (Pa) which amounts one newton per square metre (N/m^2). Several methods are used for pressure and vacuum determination . These instruments are known as ‘pressure or vacuum gauge’ . The pressure measurements are made in comparison with atmospheric air pressure. In some cases, these measurements are reported in comparison to vacuum or some other specific pressure.



The following terms are commonly used to distinguish different pressure measure-ments:

(1) *Absolute pressure* indicates in reference to zero-pressure under a perfect vacuum state and thus it is equal to atmospheric pressure plus gauge pressure.

(2) *Gauge pressure* indicates in reference to ambient air pressure. It is estimated by deducting atmospheric pressure from absolute pressure. In case of negative pressure the term "vacuum" may be appended or the gauge may be called "vacuum gauge."

(3) *Differential pressure* gives the pressure difference between two points.

The gauges are of two types: vented and sealed. In vented type gauge, the pressure is measured in reference to barometric pressure. In sealed type, the gauge is sealed. Such sealed gauges are used for measuring presure (high ranges) in hydraulic systems where change in atmospheric pressure does not cause any problem in accuracy due to its large span of scale.

The symbol for atmosphere 'at' technically refers to 1 kilogram force/cm ^{2} (98 kPa or 14.223 psi), while the symbol ' atm' is an established constant which is approximately equal to typical air pressure at earth mean sea level, and it is taken as 101 kPa.

1 atm ≡ 760 torr ≡ 101 kPa ≡ 14.7 psi (pounds per square inch)

Classification of pressure measuring devices

Various equipment are available for measuring pressure. These devices can be classified according to measuring principle as follows:

(i) Hydrostatic gauges (e.g. Manometers)
(ii) Aneroid gauges (e.g. Bourdon gauge)
(iii) Electronic pressure sensors (e.g. Piezo-resistive straing)
(iv) Thermal conductivity (e.g. Pirani gauge)
(v) Ionisation gauge
  – Cold cathode (e.g. Penning gauge)
  – Hot-cathode (e.g. Bayard-Alpert gauge)

These pressure gauges are useful at different pressure ranges as summarised in Table 6.9.

Pressure measuring devices

The various commonly used pressure measuring devices are described briefly in the following section:

Table 6.9 Pressure Gauges and Their Measuring Range

Type	*Gauge*	*Pressure Measuring Range*
Hydrostatic gauges	Manometers	Few torr to

		few atmospheres
	McLeod gauge	10^{-4} to 10^{-6} torr
Aneroid gauges	Bourdon gauge	Few torr to few atmospheres
Thermal conductivity	Pirani gauge	0.5 to 10^{-4} torr
Ionisation gauge	Cold-cathode Penning gauge	10^{-2} to 10^{-9} torr
	Bayard-Alpert hot-cathode	10^{-3} to 10^{-10} torr

(i) Manometers

Working principle: It is based on Bernoulli's principle. It essentially consists of a 'U'- shaped glass tube (Figure 6.44), which is filled with some liquid, typically oil, water, or mercury. The one end of the U-tube is kept open to the atmosphere, while the other end is connected to the system for measuring pressure (e.g. flue gas in the duct of a furnace). The manometers could be positioned vertically or inclined, depending on the degree of accuracy needed.

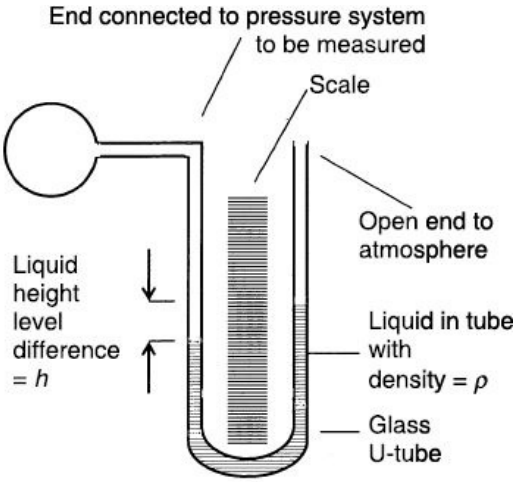


Figure 6.44 U-tube manometer.

Construction and operation

Vertical U-tube manometer: The pressure difference in such manometer can be expressed as $p_d = \gamma h = \rho g h$, where p_d = pressure, γ = specific weight of the fluid in the tube (kN/m^3),

ρ = manometer fluid density (kg/m^3), g = acceleration due to gravity (9.81 m/s^2),

h = manometer liquid height (m). The specific weight of water, which is the most commonly used fluid in U -tube manometers, is 9.81 kN/m^3 . It is also

common to express pressure in terms of mm water height (or mm water gauge).

Inclined U-tube manometer: The measurements in systems such as furnace air ventilation system give low column heights, and to increase the accuracy of reading they are kept inclined. The pressure difference in a inclined *U* -tube can be expressed as

$p_d = \gamma h \sin\theta$, where θ = angle of column relative the horizontal plane.

Use: It is used to measure low pressures.

(ii) *Bourdon gauge*

Working principle: It uses the principle of an elastic body as transducer (bourdon tube) which gets deflected when subjected to a pressure. The bourdon tube movement is directly proportional to the tube pressure in a calibrated gauge

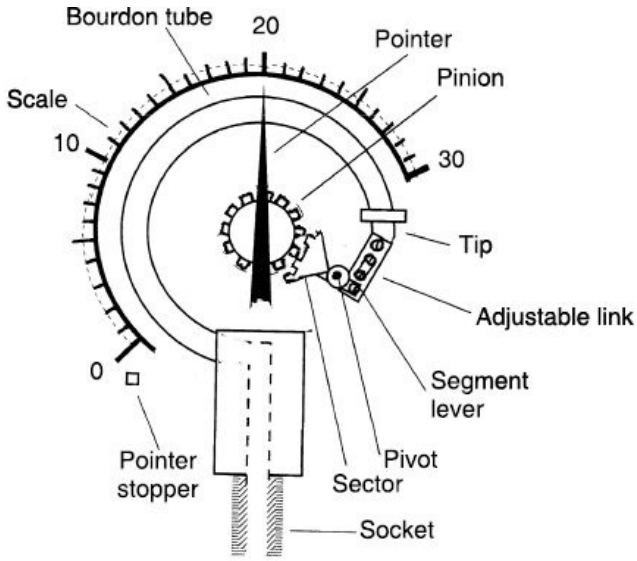


Figure 6.45 Bourdon gauge.

Construction: The major components (Figure 6.45) of this gauge are : (1) bourdo tube,
(2) adjustable link, (3) sector and (4) pinion. The bourdon tube acts as an elastic transducer. The pressure receiving end is open and rigid, but other end is closed and is free to deflect. The bourdon tube has elliptical section. The tube is bend in circular arc shape of which one end is free for movement. This free end is attached with a link which is made adjustable and fitted with sector and pinion . The pinion shaft moves the pointer over a calibrated circular scale to indicate pressure.

Operation: The system requiring pressure measurement is connected to the rigid end of the tube to allow pressure application. The applied pressure acting on the

inner surface of the bourdon tube causes change in its cross-section from its elliptical section to circular shape. The change in tube's cross-section causes straightening of bourdon tube giving movement to the closed and free end. This movement of the closed free end of the tube is dependent on the exerted pressure. This tube movement is indicated by a moving pointer on the circular scale for direct reading for pressure.

Uses: They are used to measure pressure of gas cylinders, boilers, pressure chambers, etc. having medium to very high pressures.

(iii) Pirani gauge

This instrument is used to measure low pressure created by vacuum system.

Working principle: This gauge determines the filament temperature through a measure of filament resistance. Filament excitation and resistance measurement both are performed with a bridge circuit. The response of resistance versus pressure is highly non-linear. This type of gauge was invented in 1906 by Marcello Pirani.

Construction: A Pirani gauge (Figure 6.46) consists of a tungsten or platinum wire (~ 0.02 mm dia) open to the system for pressure measurement. This wire is mounted in a tube which is attached to the system whose vacuum is to be measured. This filament wire is heated by an electrical current which is surrounded by gas causing its cooling. The temperature of the filament under equilibrium condition depends on equilibrium of heating and cooling process. When the gas pressure is low, the cooling is minimised rendering increase in filament temperature and change in its electrical resistance. This allows measuring pressure in terms of electrical resistance.

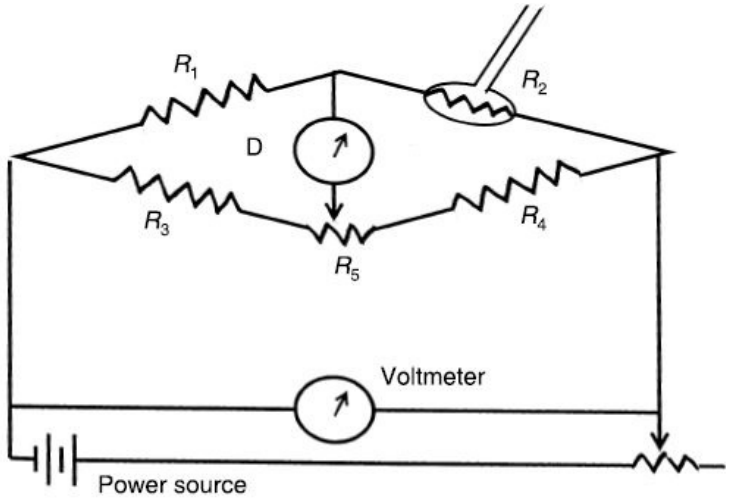


Figure 6.46 Pirani gauge.

Operation : The gas molecules surrounding the filament collide with the wire and take away its heat. When the gas pressure is low, the number of molecules present in gas will fall proportionately and the wire will lose heat more slowly. The measurement of the heat loss is an indirect method of pressure measurement. The electrical resistance of a wire varies with its temperature, and it helps in indicating the temperature of wire. In some systems, the wire is maintained at a constant resistance R by controlling the current through the wire. The resistance can be set using a bridge circuit. The power delivered to the wire is $I^2 \times R$ and the same power is transferred to the gas. The current required to achieve this balance in the bridge circuit is taken as a measure of the vacuum. The heating current is about 10–100 mA.

Uses: The gauge may be used for pressures between 0.5 torr and 10^{-4} torr. The vacuum induction melting furnace control panel is generally equipped with this type of gauge.

(iv) Penning gauge

This is an ionisation type vacuum gauge which operates with cold discharge and is known as cold-cathode or Penning vacuum gauge. This is used to indicate very low pressure created by vacuum systems.

Working principle : It is a cold cathode ionisation vacuum gauge. The high DC voltage (~ 2000 volt) maintained between unheated cathode and anode gives a cold discharge and continues at very low pressure. This is achieved by using a magnetic field to make the path of the electrons long enough so that the rate of their collision with gas molecules is large to give the number of charge carriers for maintaining the discharge.

Construction: The Penning gauge (F igure 6.47) consists of three distinct parts: filament, grid and collector. The filament is used for the production of electrons by thermionic emission. A positive charge on the grid attracts the electrons away from the filament; they circulate around the grid passing through the fine structure many times until they collide with the grid. Gas molecules inside the grid may collide with circulating electrons. The collision can result in the ionization of the gas molecule. The collector inside the grid is negatively charged and attracts positively charged ions. Likewise, they are repelled away from the positive grid at the same time.

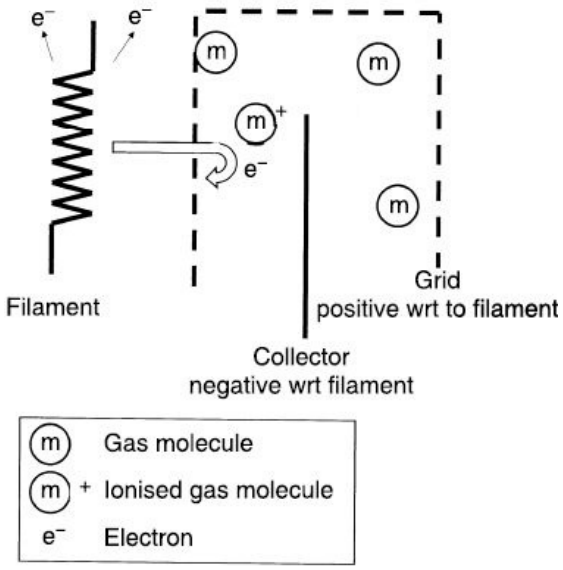


Figure 6.47 Penning gauge working principle.

Operation: The number of ions collected by the collector plate depends on the number of molecules present inside the vacuum. The measurement of collected ions by this method in the form of current gives a direct reading of the pressure.

Uses: This type of gauge is useful in measuring low pressure (vacuum) 10^{-2} to 1^{-9} torr which is simple and robust in design. The sensitivity of the gauge is gas specific, and therefore it needs suitable cell for specific application.

6.3.3 Flow Rate

The measurement of flow rate for fluids (flue gas and cooling water) is needed during furnace operation. The turndown ratio for a flow measuring instrument provides its measuring range with acceptable accuracy. When the limiting gas flow measurement is between 10^5 and
10^6 m^3/day, the flow meter for the specific application must have turndown ratio of 10 : 1.

The flow meters are based on the following measuring principles:

a. Fluid differential pressure
b. Fluid velocity
c. Fluid positive displacement
d. Fluid mass

These are described very briefly in the following section:

Differential pressure flowmeters

In such device, the fluid flow is estimated by measuring the drop in pressure across resistance created in the fluid flow. These flow meters are based on the Bernoulli's principle, where the drop in pressure and the further measured signal are dependent on the square of the flow speed.

The Bernoulli's equation, valid at any arbitrary point along a streamline , is given as:

$$(V^2/2) + hg + (P/\rho) = \text{Constant}$$

where,

V is the fluid flow speed at a point on a streamline
g is acceleration due to gravity
h is the elevation of the point above a reference plane
P is the pressure at chosen point
ρ is the fluid density at all points

The differential pressure is created at two points by placing some resistance in the fluid flow. This resistance in the flow causes lower pressure in downstream of the flow than upstream.

The various methods (Figure 6.48) used to create resistance in the flow to measure the flow rate are:

(i) Orifice plates

The orifice plates are standard sized circular plate with cut hole in centre. These orifice plates are simple and cost less. These can be used for many applications made from suitable material. The fluid flow measurement is made by observing the pressure difference from the inlet side to the outlet side of the orifice.

(ii) Nozzles

It consists of a restriction with an elliptical contour approach section that terminates in a cylindrical throat section. Pressure drop between the locations one pipe diameter upstream and one-half pipe diameter downstream is measured. These are useful for gas flow measurement on industrial scale. The flow nozzle is relatively simple and cheap. These nozzles are made of different materials for different applications.

(iii) Venturi tubes

The venturi tube is similar to an orifice flowmeter, but it is designed to nearly eliminate boundary layer separation. The change in cross-sectional area in the venturi tube causes a pressure change between the convergent section and the

throat, and the flow rate can be determined from this pressure drop. It is more expensive than orifice plate.

All these flow meters using orifice plate, nozzle or venture have a *turndown ratio*
of 3 : 1.

The fluids after passing through flow meter measuring devices try to recover their pressure near the exit. The extent of permanent pressure drop due to the device by using different size fractions of pipe is shown in Figure 6.48.

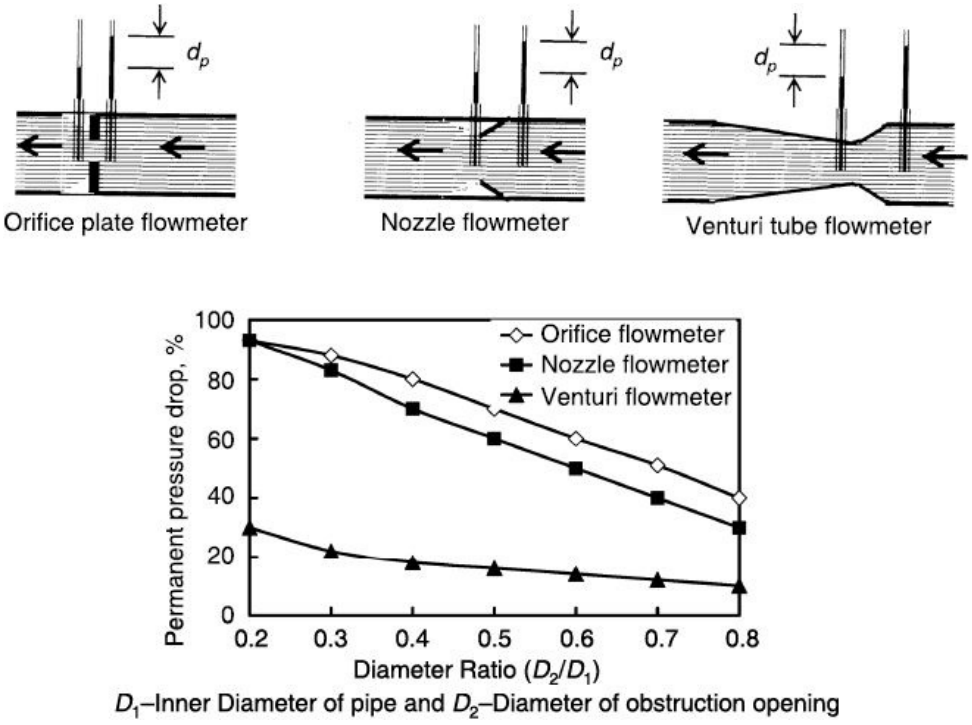


Figure 6.48 Working principle of differential pressure flow meters and r elative differential pressure drops.

(iv) Rotameter

These are (Figure 6.49) made of glass (or plastic) tube vertically placed with top end wider than lower end . This tube has a float for flow indication which is free to float within the



Figure 6.49 Rotameter.

tube. The fluid flow pressure raises the float in the tube due to upward pressure of the fluid (buoyancy) overcomes the gravitational downward pull. The float's rise in height in the tube directly indicates the flow rate. The rotameter tube can be graduated in suitable flow units. These flowmeters have a turndown ratio up to 12 : 1. The floats of magnetic material can be used for giving alarm and signal transmission.

Velocity flowmeters

In a velocity flow meter, the fluid flow is determined by metering the fluid speed at various points in the fluid flow.

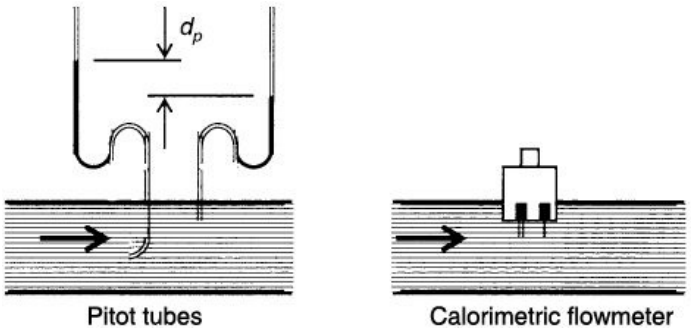


Figure 6.50 Pitot tube and calorimetric flowmeters.

(i) Pitot tubes

These are commonly used to determine fluid flow particularly for air ventilation. The kinetic energy of the flow gets converted into potential energy by the inserted pitot tube (Figure 6.50) in the fluid flow which is useful in measuring fluid velocity.

(ii) Calorimetric flowmeter

In such instruments, the fluid flow measurement is made by two temperature sensors located in proximity (Figure 6.50) and immersed in the fluid but thermall insulated from each other . One sensor is continuously heated and the heat loss by flowing fluid is measured to monitor the flow rate. When the fluid is stationary (no flow), there is a fixed temperature drop between the two thermal sensors . With the increase in fluid flow, the thermal energy is removed from the heated sensor and the temperature drop gap between the sensors is minimised. This reduction in temperature is dependent on the flow rate of the fluid .

(iii) Turbine flowmeter

In turbine flow meter, the fluid movement in a pipe drives the vanes of a turbine

to cause the turbine rotation. The rate of turbine rotation is measured to estimate the fluid flow. The turndown ratio of such flow meters is high (100 : 1), if the meter is calibrated for a specific fluid and used under constant operating conditions.

Positive displacement flowmeters

In such type of flow meters, fixed gas volumes are moved between the rotors. The rotation of the rotors is directly dependent on the volume of the fluid moved. The number of rotor rotations is metered by an electronic pulse transmitter and it is converted to volume or flow rate. These positive displacement flowmeters give turndown ratio of 70 : 1.

Such flowmeters are useful for non-abrasive fluids such as lubrication oils, heating
oils, etc.

6.4 MAJOR FURNACE ACCESSORIES

The furnaces are provided with various accessories for better working conditions required by present day environmental regulations. These include waste gas collecting and cleaning systems, noise control chambers and heat shields. These are described briefly in the following sections:

6.4.1 Waste Gas Cleaning Systems

The waste gas cleaning devices include dust catcher, bag filters, scrubber and electrostatic precipitator.

Dust catchers

A dust catcher is a system for collecting dust and other solid particles from exit gases from a unit. It is designed to handle heavy dust loads. The dust catchers work on the principle of reducing the velocity of gases and thereby promoting the particle settling under gravity.

The three primary designs of inertial separators are:

(i) Settling chambers
(ii) Baffle chambers
(iii) Cyclone dust catcher

These three types of dust catching devices are shown in Figure 6.51.

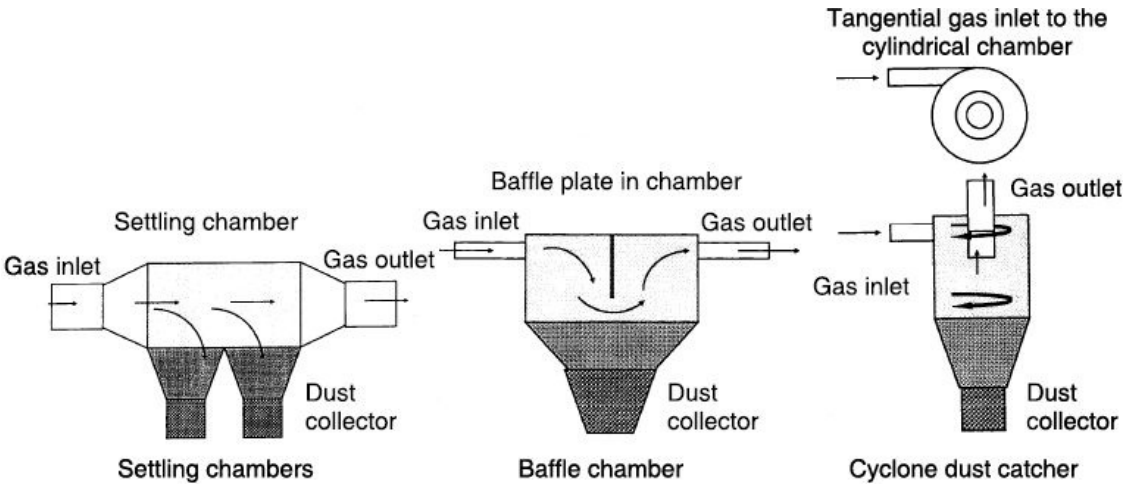


Figure 6.51 Dust catching devices.

(Adopted from R.C. Gupta, *Energy and Environmental Management in Metallurgical Industries* , PHI Learning, Delhi, 2012.)

Bag filters

The bag filters use fabric filtration to remove dust particulates from gases laden with dust

(Figure 6.52). The bag filters are considered as most efficient and cheaper type of dust catching system. These dust cleaning system can offer 99 per cent cleaning efficiency for very fine particulates. The gases laden with dust enter the bag house and pass through fabric filters. The fabric filter bags could be made of cotton, synthetic, or glass-fiber material in tube or envelope shape.

The maximum operating temperature is decided by the material used for filters (Table 6.10). The fabric pores get blocked during use by dust adhering on its surface. This dust is dislodged to keep the pores open for filtration. The bag filters use different mechanisms to dislodge the dust adhering on the filter fabric.

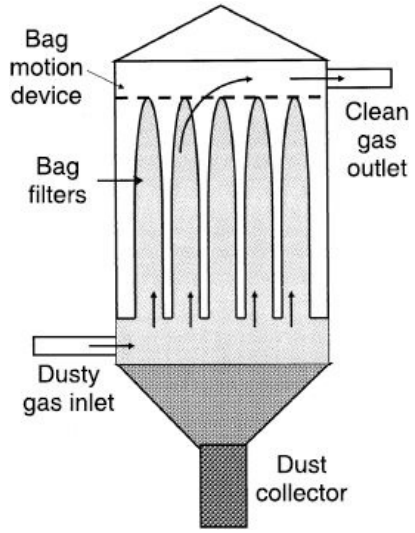


Figure 6.52 Bag filters.

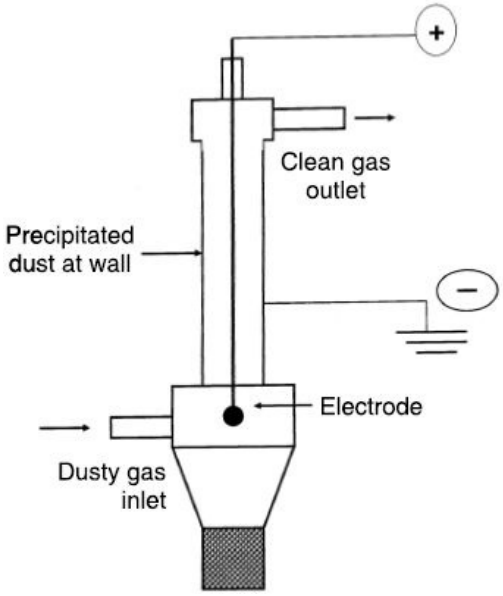


Figure 6.53 Electrostatic precipitator.

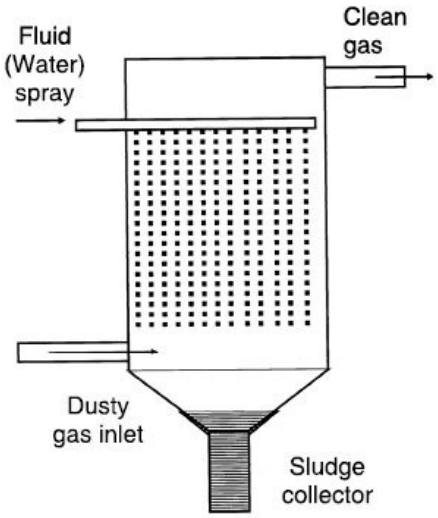


Figure 6.54 Wet scrubber.

(Adopted from R.C. Gupta, *Energy and Environmental Management in Metallurgical Industries* , PHI Learning, Delhi, 2012.)

Table 6.10 Properties of Some Bag Filter Materials

Filter Material	*Usable Temperature,* ° C (max.)	*Remark*
Cotton	80	Low cost
Wool	95	Fairly abrasion resistant
Nylon (Polyamide)	100	Easy to clean and excellent abrasion resistant
Polyester (Dacron)	135	Easy to clean
Teflon (Tetrafluoroethylene)	260	Expensive
Glass	280	Poor resistance to abrasion

Electrostatic precipitators (ESP)

This method is shown in Figure 6.53. The fine particulate matters in exhaust gases are removed by electrostatic force. Several high (50–100 kV) DC voltage charged electrodes are placed between collecting electrodes which are grounded. The particulates in gases get
ionised while flowing through collecting electrodes . The airborne dust particles get
positively charged while passing through the ionised field between the electrodes. The
charged dust particles are attracted by a grounded (negative) electrode and adhere on to its surface. The collected material on the electrodes is separated by mechanical tapping at fixed time interval.

Scrubbers

Scrubber is a device to remove dust from gases by washing the gas stream using a liquid or dry reagent. These are used as primary dust cleaning device to regulate gaseous emissions, especially having acidic gases. The scrubbers could be operated in wet and dry condition.

(i) Wet scrubbing

The wet scrubber (Figure 6.54) is used to remove pollutants like dust and gases present in flue gases. The wet scrubber uses water for removing dust or a solution of some reagents could be used as washing media that specifically targets certain compound.

The exhaust gas sometimes contains gases like hydrogen chloride (HCl) or ammonia (NH_3) which are toxic and corrosive . These gases are treated well by a wet scrubber. The cleaning efficiency of pollutants is improved by increasing residence time in the scrubber or by increasing the surface area of the scrubbing action by using a spray nozzle, packed towers or an aspirator. The wet cleaning may increase the water content in the exit gas resulting in a visible stack plume.

(ii) Dry scrubbing

In dry scrubbing system, flue gas stream is treated without moisture. In some cases, little amount of moisture used is removed with the flue gas . The dry scrubbing is done to remove acidic gases (e.g. SO_2) mainly from combustion systems. The dry absorbent use involves the spray of an alkaline material (e.g. hydrated lime or soda ash) into the gas stream for reaction with the acidic gases. The absorbent materials can be injected directly at several different locations, e.g. in the combustion system, in the flue gases (before dust control device), or in a reaction chamber (if available).

6.4.2 Waste Gas Collecting Systems for Melting Units

The metallurgical furnaces like cupola, arc furnace, induction furnace, etc need suitable devices for collecting and removing the undesirable gases from the working area. The devices used by cupola and steel melt shop are discussed as follows:

Cupola melting

The cupola operators may adopt single equipment or their combination to have maximum efficiency with minimum investment. The systems used by cupola

based foundries include: (i) mechanical arrester, (ii) dry electrostatic precipitators/bag filters and (iii) wet scrubber with wet electrostatic precipitator. These are shown in Figure 6.55. The use of mechanical arrester by providing hood on cupola top is common in smaller units, while the bag filters, electrostatic precipitator and scrubber are used by bigger units.

Steel melting

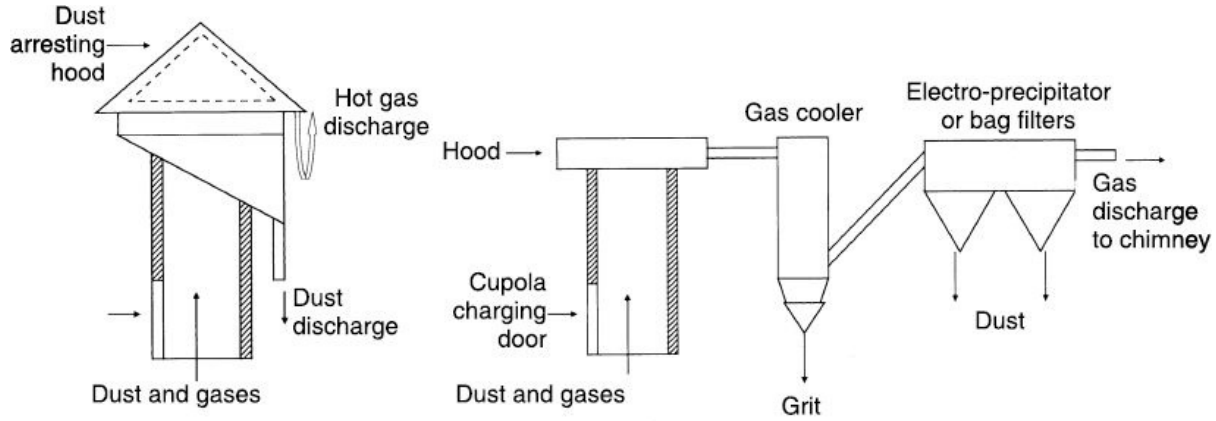
The steel making shop may have LD converter, EAF or induction melting units. The main issues in this area are dust, fume, odour, noise and heat. The dust and fumes generated during melting are extracted through various collecting systems like:

Hood system

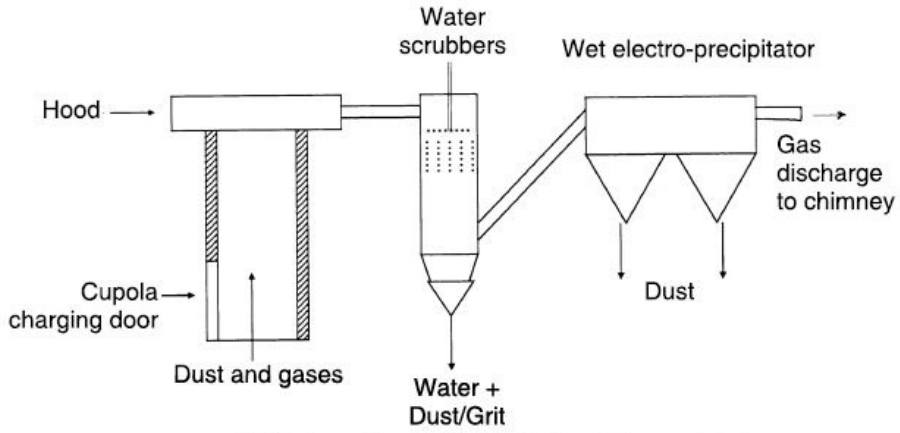
Suction hood is located above arc furnace to collect dust and fumes.

Direct extraction system

The suction device is attached with the furnace.



(a) Mechanical arrester (b) Electrostatic precipitators or bag filters



(c) Wet scrubber and wet electrostatic precipitator

Figure 6.55 Systems for collecting dust from cupola.

Semi direct extraction system

The suction device is located close to furnace outlet. This gives chance to burn CO gas at the exit of furnace itself.

Roof ventilating system

The suction hoods are located on the roof to collect gases from furnace and dust generated in the area.

Furnace and roof combines system

In this system, the fumes from furnaces and dust from the furnace area are collected. The gases from furnace are burnt in a combustion chamber before being mixed with gases from roof. These gases are then taken to dust removal chamber and gas is discharged through chimney.

All the above systems are shown in Figure 6.27. The collected gases are cleaned by using a combination of dust catchers to remove bigger particles followed by bag filters and electrostatic precipitators. The scrubbers are provided when sulphur dioxide in waste gas is high which is not common in steel melting units.

The suction could be generated using fans. The dust cleaning devices are provided before the gas is discharged through chimney. During oxidation process, the carbon in the melt is removed as carbon monoxide (CO) gas. This gas being toxic it is burnt in a combustion chamber at gas collection point with excess air.

6.4.3 Thermal Shields

The thermal shields are used to protect the worker from thermal radiations from the furnace when the temperature is very high as in the case of steel melting shop. These shields made of heat resisting sheet mounted on steel frame give a cover while working in the front of the hot furnace. The slot made in the shield gives working and peep hole to the worker.

6.4.4 Acoustic Chambers

Acoustic chambers is an enclosure housing the complete furnace systems (e.g. electric arc furnace, LD converter, etc.) and termed, *dog house*. The dog house for EAF is shown in Figure 6.28. It has all controls of the system located outside

the enclosure. The operators can perform the melting operation from outside without being affected by heat and noise. All the dust and fumes are withdrawn through ducts, and separated before gas discharge to atmosphere. This kind of system provides remedy for all kind of pollution problems like dust, fumes, noise and heat.

Review Questions

1. What are the various iron making furnaces which can use coal as a energy source? Which property of coal is considered important for the use and why?

2. What is the basic difference in reactor design used for reduction of iron ore by DRI kiln, COREX and rotary hearth process? Give the merits of each design.

3. Why are open hearth furnaces not commonly used these days for steel making?

4. Electrical energy is an expensive source, but it is used by many furnaces. Why?

5. How can you classify the various types of electrical furnaces used in industry?

6. What is the order of heat flux generated in various types of electrical furnaces? Give their applications.

7. How does induction melting furnace work? Draw a neat sketch of the furnace to illustrate its working and give its basic principle of heat generation.

8. What are the applications of vacuum induction furnace? Draw a neat sketch to show various components and describe a melting procedure in such a unit.

9. What is the basic principle of flash smelting? Give its application.

10. What is ‘matte’? How ‘matte’ is converted into blister copper?

11. What is the function of oxygen lance in LD converter? Draw a sketch of LD converter and describe the process of a ‘blow’ giving changes in metal temperature, and composition with blow time.

12. What are the merits of alumino thermit process of metal extraction? Give its application.

13. What are the various factors considered in designing furnace chamber?

14. What are basic laws governing fan design?

15. What are the various factors which must be considered while selecting fan or blower for a furnace?

16. What are the various systems used for collecting dust from cupola gases? Draw neat sketches showing the devices.

17. Give brief answer to the followings:

(i) Why the open hearth furnaces are retained today only by big steel foundries?

(ii) What is the function of spider wire in induction melting furnace?

(iii) What is the difference between arc furnace and sub-merged arc furnace?

(iv) What are the merits of INCO furnaces over Outokumpu furnaces?

18. Give the source of energy in the following furnaces with the reason for their selection:

(i) Sponge iron rotary kilns

(ii) COREX iron making technology

(iii) Rotary hearth furnace for sponge iron

(iv) Blast furnace

(v) Cupola

(vi) Mixer unit for molten iron storage

(vii) Open hearth furnaces

(viii) Forging furnace

(ix) Electric pig iron furnace

19. Differentiate between the following terms:

(i) Blast furnace working volume and total volume

(ii) Blast furnace stack angle and bosh angle

(iii) Blast furnace bosh diameter and hearth diameter

(iv) Foundry pit furnace and pot furnace

(v) Regenerators and Recuperators

(vi) Flue gas and Fuel gas

(vii) Walking hearth and Walking beam reheating furnace

(viii) Two way fired soaking pits and vertically fired soaking pits

(ix) Direct arc and Indirect arc furnace

(x) Water quality for cooling induction coil and electrical components

(xi) Induction furnace and Vacuum induction furnace

(xii) Integral type and split type shell for arc furnace

(xiii) Skewback and Non-skewback type arc furnace roof

(xiv) ‘Air-break Switch’ and ‘Oil Circuit Breaker’

(xv) Peirce-Smith copper converter and LD converter

(xvi) Fan and Blower

(xvii) Natural draft and Forced draft
(xviii) Vertical and Inclined U-tube manometer
(xix) Pirani and Penning vacuum gauge
(xx) Differential pressure flowmeters and Rotameter

20. Write short notes on the following:

(i) Pot melting furnace
(ii) Skelner furnace
(iii) Continuous pusher type Re-Rolling mill furnace
(iv) Arc furnace roof
(v) Arc furnace tilting devices
(vi) Slide gate tapping device
(vii) EAF fume extracting device
(viii) Dog house
(ix) Soderberg electrode
(x) Graphite electrode life
(xi) Multiple hearth roasting units
(xii) Chimney
(xiii) Thermocouples
(xiv) Optical pyrometer
(xv) Infrared pyrometer
(xvi) Bourdon Gauge
(xvii) Dust catching devices
(xviii) Electrostatic precipitator
(xix) Wet scrubber
(xx) Thermal shields

21. Draw neat sketches of the following furnaces showing the refractory used in various parts of the furnace:

(i) Blast furnace
(ii) Cupola
(iii) Blast furnace stoves
(iv) Soaking pit
(v) Arc furnace

7

Refractories

Introduction

The refractory is an essential requirement for any furnace to sustain high temperature. These refractory materials must possess sufficiently high fusion temperature to retain their shape at working temperature. Further, such materials must have required porosity, strength at high temperature, thermal conductivity, resistance against corrosion and erosion with many other properties at affordable cost. The production of quality refractory with low cost has always posed challenge to ceramic industries. The larger high temperature metallurgical units (e.g. blast furnaces producing more than 4000 ton hot metal per day) constructed these days for economic reasons, demand very stringent quality of refractory materials.

The definition and functions of refractory, its classification based on chemical nature and on other considerations, forms (shaped and monolithic), applications and factors responsible for performance are already discussed in Chapter 1.

This chapter focuses on the properties of refractory and its testing methods, e.g. refractoriness (PCE value and RUL test), porosity, density, etc. together with preparation of refractory bricks and components.

7.1 PROPERTIES OF REFRACTORY

The refractory materials are required to possess many properties. Refractory materials should have the ability to:

(i) withstand high temperature
(ii) withstand corrosive action of molten slag and hot gasses
(iii) withstand abrasion and erosion by moving solid charge, flowing liquids and blowing gases
(iv) withstand working load during service

(v) retain dimensional stability at working temperatures
(vi) sustain repeated thermal cycling
(vii) sustain thermal shock (sudden change in temperature)
(viii) conduct/resist heat flow as needed during use
(ix) store heat in the system

In addition to the above properties, the availability of refractory at suitable cost would be a desirable factor for its use.

7.1.1 High Temperature Behaviour

The refractory materials are required (Table 1.3**)** to serve at high temperature, and hence they must have sufficient strength at working temperature to retain their shape and size. This high temperature strength becomes more important when the size of the furnace is large and load on the hot refractory structure becomes high. It must be noted that strength measured at room temperature is not the indication for its fitness to use the refractory at high temperature. As we know that any solid material when heated starts becoming soft at some temperature due to fusion/melting at grain boundaries, and eventually it becomes liquid at its melting point. This requires the knowledge of maximum temperature for safer use of the refractory. This high temperature behaviour of the refractory is tested by measuring the following properties:

a. PCE (Pyrometric Cone Equivalent) value
b. RUL (Refractoriness Under Load) value
c. Creep at high temperature
d. High Temperature Modulus of Rupture (HMOR)
e. Thermal shock resistance
   – Spalling test
   – Loss in MOR strength
f. Reversible thermal expansion
g. PLC (Permanent Linear Change) test

PCE (Pyrometric Cone Equivalent) value

(i) Definition

It is the measure of refractory's ability to sustain high temperature without fusion or deformation. This is measured by heating a standard size cone made of the

material to be tested in a furnace alongwith another standard cone having refractoriness very close to the test material (determined by a pre-test), and noting the furnace temperature at bending (9′ or 3′ o'clock positions viewed upside down) of the cone inclined at one end due to its own weight (Figure 7.1). The furnace end-point temperature is expressed as PCE number as given in Table 7.1 on Orton (American and British Standard) or Segar (German Standard) scale. The Indian cone standards for cone numbers with temperature are given in Table 7.2. However, the users and manufacturers can use any standard value to designate refractoriness.

(ii) Significance

This is the most important value for selection of any refractory material for a given application in the furnace. The maximum working temperature in the furnace is always kept below the PCE value to avoid refractory failure.

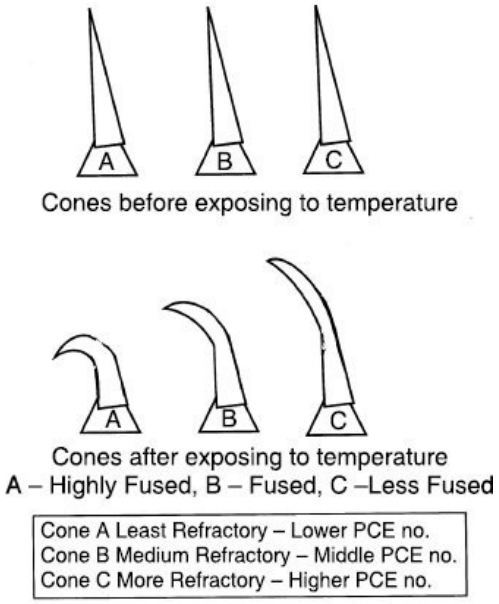


Figure 7.1 PCE value test cones.

Table 7.1 PCE Values and Temperature (Orton and Segar Scale)

Cone No./ PCE Value	*Orton Scale (ASTM and British Standard) Temperature,* ^{o} C	*Segar Scale (German Standard) Temperature,* ^{o} C	*Cone No./ PCE Value*	*Orton Scale (ASTM and British Standard) Temperature,* ^{o} C	*Segar Scale (German Standard) Temperature,* ^{o} C
12	1337	1375	–	–	–
13	1349	1395	31	1683	1695
14	1398	1410	$31\ ^{1}/_{2}$	1699	–
15	1430	1440	32	1717	1710

16	1491	1470	$32\ ^{1}/_{2}$	1724	–
17	1512	1490	33	1743	1730
18	1522	1520	34	1763	1755
19	1541	1530	35	1785	1780
20	1564	1540	36	1804	1805
23	1605	1560	37	1820	1830
26	1621	1585	38	1850	1855
27	1640	1605	39	1865	1875
28	1646	1635	40	1885	1900
29	1659	1655	41	1970	1940
30	1665	1680	42	2015	1980

(iii) Test method

The testing of PCE value is done according to the following six steps:

Step 1. *Sample preparation* : The refractory to be tested could be available in pre-formed shape or dry monolithic form. The sample preparation for both materials are given below:

Pre-formed bricks: Several bricks are taken to have good representation of the refractory, and broken into smaller size (5–10 mm). Out of the total mass, nearly 1 kg sample is taken, and ground to have –200 μm particles for making cone.

Dry monolithic form: The ramming mass, refractory cement, etc. may be already in powder form and further grinding may not be required. This powder may be sieved to have –200 μm particles for making cone.

Table 7.2 Indian Standards for Cone Numbers with Temperature

Cone No.	*Temperature,* ^{o} C	*Cone No.*	*Temperature,* ^{o} C
ISO 150	1500	ISO 166	1660
ISO 152	1520	ISO 168	1680
ISO 154	1540	ISO 170	1700
ISO 156	1560	ISO 172	1720
ISO 158	1580	ISO 174	1740
ISO 160	1600	ISO 176	1760
ISO 162	1620	ISO 178	1780
ISO 164	1640	ISO 180	1800

Step 2. *Cone moulding:* The powder mixed with binder (dextrine or glue) and water is cast into a cone shape using a metal mould. The cone dimensions must be in accordance with standard followed. The cone is tetrahedron in shape with some inclination to one side. The Indian standard (IS) 1528: 2010 prescribes 82° for cone with 8 mm base and 25 mm high.

Step 3. *Cone heat hardening:* The green moulded cone is dried and heat hardened at 1000 °C to make cone strong enough for handling.

Step 4. *Mounting cone for test:* The prepared cone for testing and a standard cone are mounted on a refractory plate with the help of a refractory paste which will not affect the fusion behaviour of the test cone.

Step 5. *Heating cones in high temperature furnace:* The high temperature furnace used for the purpose must be capable of reaching the expected temperature. The test cone mounted plate is inserted in the furnace and heating is initiated keeping oxidising atmosphere. In case of gas fired furnace, the flames must not have any impact on cones. In case of electrical heating, the plate must be in central zone with constant temperature. The furnace is initially heated slowly to reach 200 °C in approximately two hours, and then it is heated at the rate of 2.5 °C per minute.

Step 6. *Softening point temperature and PCE value:* The furnace temperature is allowed to attain the expected temperature to begin observing the sagging of cone through peep hole using suitable dark glass filter to avoid radiation. The temperature must be noted at which the test cone tip sags to 9′ or 3′ o'clock position depending on cone mounting angle. This temperature must be matched with Tables 7.1 and 7.2 to get equivalent cone number on a given scale. Suppose, one is using Indian Standard and he expected fusion temperature ~1620 °C, since he used a cone

ISO–162 however, the actual test cone indicated fusion at 1610 °C compared to standard cone which was not fully fused. This means the PCE number for the test cone is between ISO 160 (fusion point 1600 °C) and 162 (fusion point 1620 °C). Similarly, if the standard cone number 26 (Orton Scale–ASTM and British Standard) was chosen and the test cone fused at 1610 °C, then the cone number would be between 23 (fusion point 1605 °C) and 26 (fusion point 1621 °C) on Orton Scale. The PCE value range for common refractory bricks and shapes is indicated in Figure 7.2, however, the actual value may be little different according to refractory grade and make.

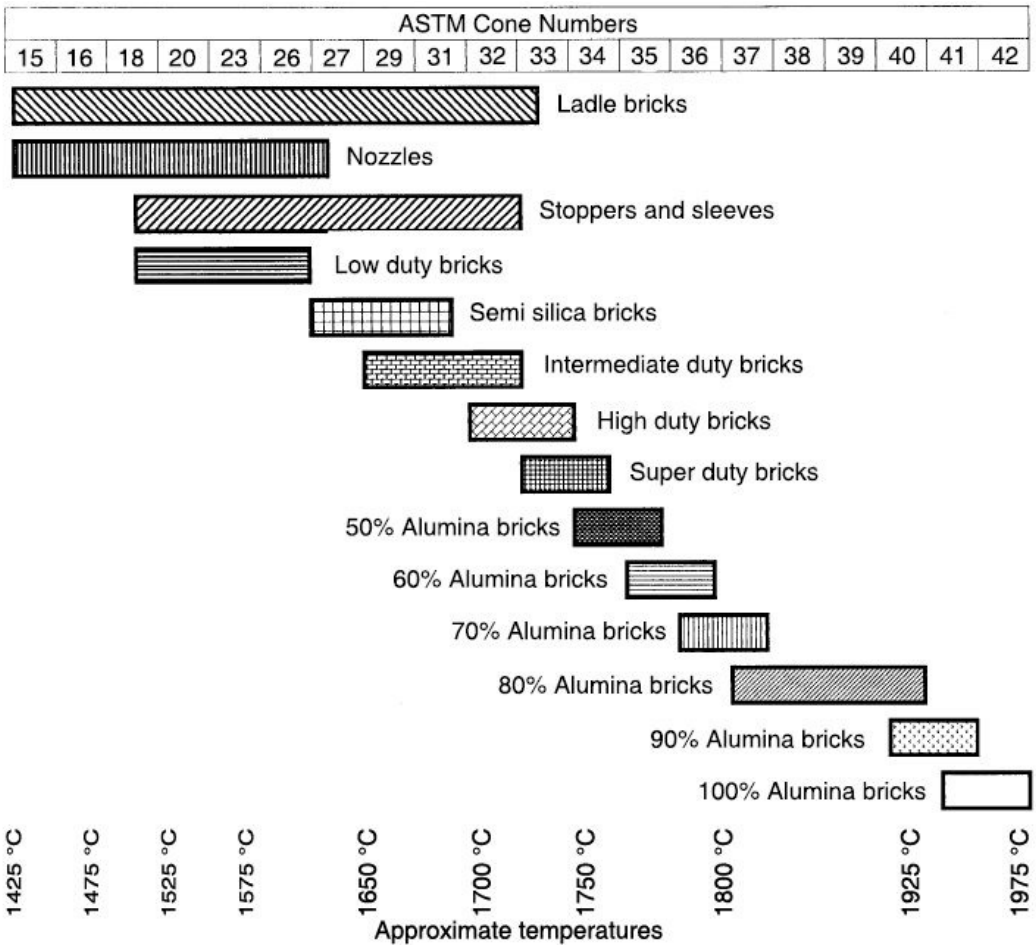


Figure 7.2 The PCE values for common refractory bricks and shapes.

(*Source* : Making Shaping and Treating of Steel, US Steel, 1964.)

RUL (Refractoriness Under Load) value

(i) Definition

It is the capability of a brick to sustain itself without breaking at high temperature under pressure of overlying load. This working load could be due to burden, liquid metal or its own structural weight. In simple words, RUL is the crushing strength of a brick at elevated temperature. The crushing strength of the refractory brick is lowered at elevated temperature due to fusion/melting of grain boundaries.

(ii) Significance

This RUL value is more important for brick which is heated from different sides as in case of coke oven heating chamber, checker brick work, etc. compared to brick which is facing heat from one side as in the case of a melting furnace. Nevertheless the RUL value is a guiding parameter to use the brick at high

temperature with safety against brick failure due to pressure at high temperature.

(iii) Test method

It is tested in a similar manner as crushing strength with the difference of maintaining high temperature around test sample. The RUL testing procedure is given under ISO 1893. It is described briefly in the following sections.

Sample preparation: A cylindrical test sample (50 mm diameter and height) with a coaxial bore (12.5 mm) is prepared by cutting and drilling process.

Test unit: Figure 7.3 shows the schematic diagram of the test unit. The unit essentially consists of loading device, furnace to provide desired atmosphere and temperature to the test sample, monitoring/control/recording systems for furnace temperature, load and linear expansion/shrinkage of test sample.

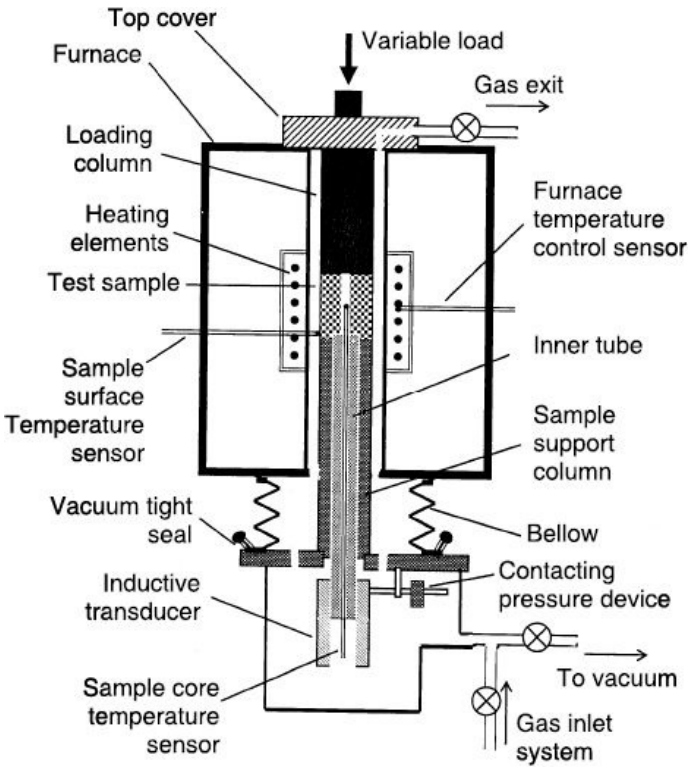


Figure 7.3 RUL/CIC testing apparatus.

The essential equipment details are as follows:

1. Furnace working temperature range – room temperature to 1700 °C
2. Heating elements – super kanthal
3. Test atmosphere – Ambient air (inert gas optional)
4. Loading range – 1 N to 1000 N

5. Sample deformation measuring range – 20 mm (minimum resolution 0.005 mm)

The actual details of the equipment may vary depending on the equipment manufacturer and model.

***Test procedure* :** The testing procedure involves the following steps:

Step 1: A defect free test sample is placed on the ram slab and lower the loading column. The furnace is brought in a position to keep the test specimen in constant temperature zone.

Step 2: The load is applied on the test piece. This load would give 0.2 N/mm^2 stress to a dense sample. The porous samples may be given a load to give 0.05 N/mm^2 stress.

Step 3: The furnace temperature is raised at the rate of 15 °C/minute to reach 1000 °C and then further heated at the rate of 8 °C /min.

Step 4: The change in sample height with temperature is noted and plotted as per cent height change with temperature as shown in Figure 7.4.

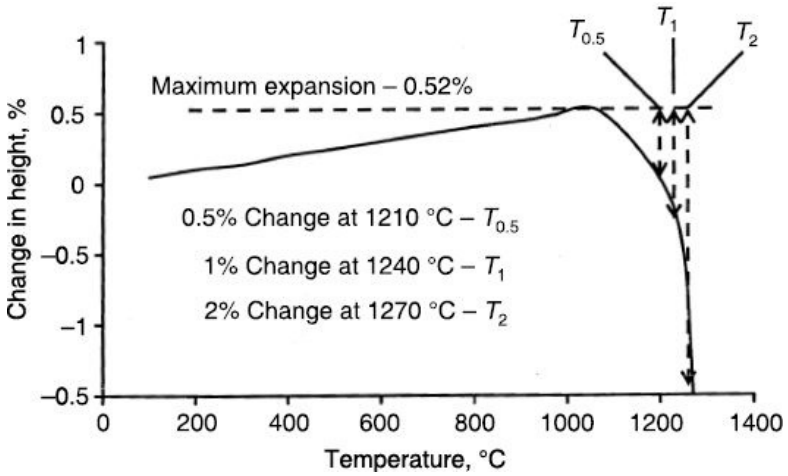


Figure 7.4 Plot of percentage change in sample height with furnace temperature.

Step 5: The temperatures for 0.5% ($T_{0.5}$), 1% (T_1) and 2% (T_2) negative change in sample height are reported. The temperature $T_{0.5}$ indicates initiation of failure under load and T_2 gives failure of the refractory under load.

Creep at high temperature

(i) Definition

Creep is a property which indicates deformation of the refractory at high temperature which is subjected to stress for longer period.

(ii) Significance

This phenomenon is significant for refractories at high temperature. The refractory materials must maintain dimensional stability under extreme temperatures (including thermal cycling) and constant corrosion from very hot liquids and gases. The refractory tested for creep under compression (deformation at a given time and temperature under stress) for normal working conditions of load and temperature should not exceed 0.3% change in the first 50 hours of the test.

(iii) Test method

The equipment used for RUL test is also useful for creep in compression (CIC) test. This test is done according to ISO 3187. In this text, the sample preparation, its size and test procedure are given briefly as.

***Sample preparation* :** The cylindrical test sample of 50 mm diameter and height with a coaxial bore (12.5 mm) is made by cutting or drilling process by equipment used during RUL test.

***Test equipment* :** Same as used for RUL test (Figure 7.3) with suitable device for measuring change in sample height (dial gauge or length transducer) capable of measuring 0.005 mm change in sample height.

***Test procedure* :** The various steps of the test are as follows:

Step 1: A defect free test sample is placed on the ram slab with two refractory discs (5–10 mm thick 7.50 mm diameter with a bore in centre) to protect the ram from sticking in case of fusion as illustrated in Figure 7.5. The disc material must be compatible with test refractory. The high fired alumina or mulite disc is used for silica/alunino silicate and magnesia for basic refractories. Further, a platinum or platinum/rhodium disc (0.2 mm) may be put between sample and disc to ensure no chemical reaction occurs between test sample and discs.

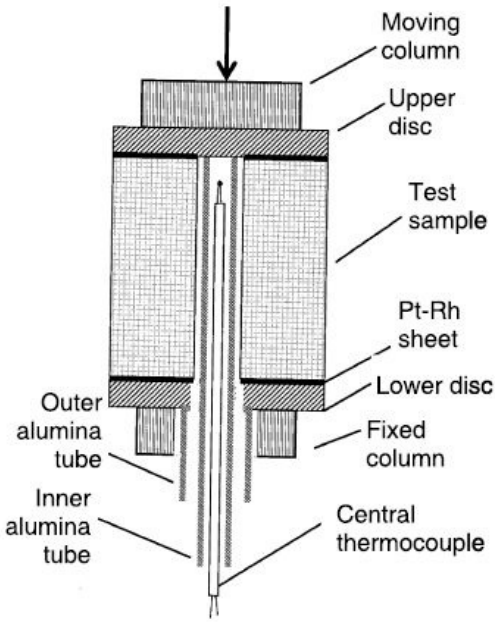


Figure 7.5 Arrangement of creep test piece, columns, discs and tubes.

Step 2: The furnace is located in position to keep the test specimen in constant temperature zone. The load is applied on the test piece. This load would give 0.2 N/mm^2 stress to a dense sample. The porous samples may be given a load to give 0.05 N/mm^2 stress.

Step 3: The furnace is switched 'ON' and temperature is raised at the rate of 10 °C/min up to 500 °C and then further heating is done at 5 °C/min till the desired temperature is arrived and remains constant.

Step 4: The change in sample height is noted for 25 hours after achieving test temperature. The plot between change in height (%) and time (hours) subjected to high temperature stress gives the creep behaviour (Figure 7.6) of the material.

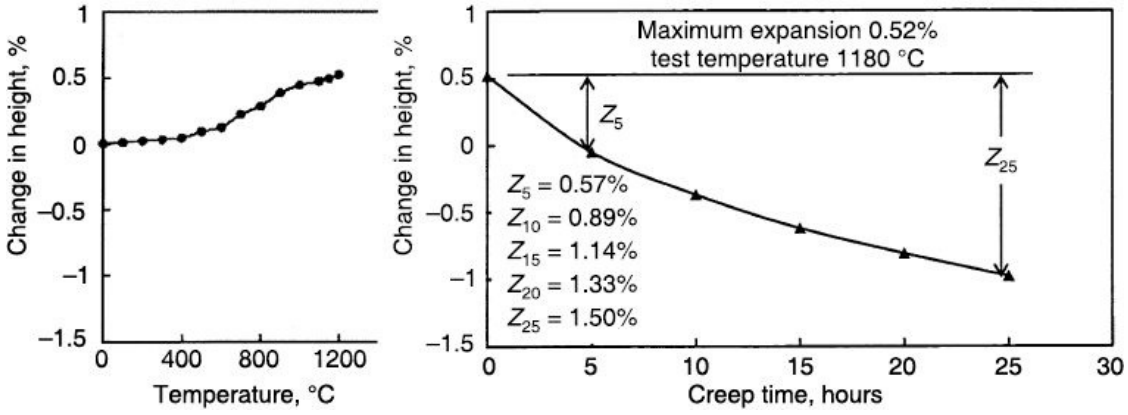


Figure 7.6 Change in sample height with time at high temperature under stress.

High Temperature Modulus of Rupture (HMOR)

(i) Definition

It is the maximum stress that a rectangular test piece of defined size can withstand when it is bent in a three point bending device (Figure 7.7). It is expressed as N/mm^2 or MPa.

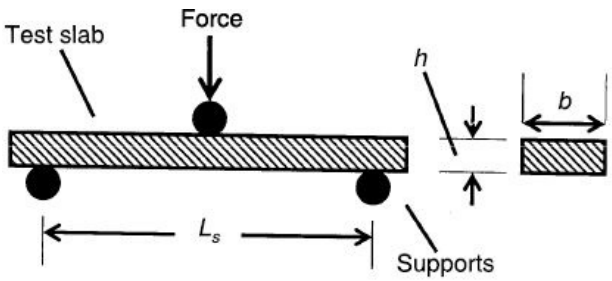


Figure 7.7 Refractory slab subjected to three point loading.

HMOR (σ_F) is expressed as the ratio of bending moment at the point of failure (M_{max}) to the moment of resistance W (the section modulus) at working temperature. It is expressed as *Hooke's law* for elastic materials as follows:

$$\sigma_F = \frac{M_{\max}}{W} = \frac{3}{2} \times \frac{F_{\max} \times L_s}{b \times h^2}$$

where,

F_{max} is the maximum force exerted

L_S is the distance between points of support

b is the breadth of test sample

h is the height of test sample.

(ii) Significance

The furnaces have openings for various applications and these openings have a slab supporting the top layers of refractory. This slab must be strong enough to sustain the stress at high temperature when loaded in manner illustrated in Figure 7.7.

(iii) Test method

The testing method follows ISO 5013 code. The sample size, testing unit and procedure are given briefly in the forthcoming sections.

Sample size: A refractory slab of size 150 mm × 25 mm × 25 mm is used for testing.

Test unit: The testing unit has two basic components—furnace and loading device. The test sample is heated in the furnace to a desired temperature and then

it is internally moved on alumina rollers to a point where loading device is located. The unit can pre-heat a fixed number of samples to test in sequence. The loading device can have arrangements for measurement of load and deformation together with device for loading with constant deformation rate. The details of equipment may depend on its manufactures and model. A typical test unit has the following features:

Furnace maximum temperature – 1500 °C
Furnace heating element – Silicon carbide
Loading range – 0 to 1250 N
Loading rate – 2, 4, 8 12 N/s (4 speed)

Test procedure: The test sample pre-heated to the desired temperature is transported within the unit using alumina rollers to the loading point where loading is done till fracture. The maximum load is noted and MOR is calculated as per Hooks law and expressed as N/mm^2 or Pa. The result must be given with test conditions, e.g. average value for number of test, test piece size and loading details (N/mm^2 /second), test temperature, heating rate, soaking time, etc.

Thermal shock resistance

(i) Definition

Thermal shock resistance is a measure of refractory property when it is exposed to alternate heating and cooling. This thermal shock leads to breaking of refractory particles which is termed as ‘spalling’ and loss of strength due to micro-cracks and is noted as MOR value after thermal treatment.

(ii) Significance

It is an important property for a refractory material. Many refractory components in high-temperature processes undergo heating and cooling. The refractory grains and the grain bonding material expand while being heated, and contract during cooling. The different expansion and contraction behaviour of grains and the bond material lead to breaking away and development of micro cracks. The nature and magnitude of the cracks would decide the thermal shock resistance of the material.

The metallurgical furnaces often undergo heating and cooling during practice, and in cases of rapid thermal cycling, the refractory experiences stresses which may lead to its failure. The refractory materials with high thermal expansion are generally prone to failure due to thermal shock and refractories with lower thermal expansion behaviour are considered safe.

(iii) Testing method

The thermal shock resistance is tested in two ways: Spalling test and loss in Modulus of Rupture (MOR) strength.

Spalling test: This test (IS 1528-3, 2010) is conducted by water quenching or air cooling.

Water quenching test : The test is conducted with cylindrical refractory sample (50 mm dia and 50 mm height) free from apparent defect. The sample is dried at 110 °C till constant weight to expel any moisture present. The dried sample is heated in furnace at 950° ± 5° C for 15 minutes and then quenched in water (10 – 30 °C) for 3 minutes. The sample is withdrawn and put in moisture oven (110 °C) for 30 minutes to make it dry. This heating, quenching and drying constitute one cycle of operation. This heating, quenching and drying cycle is repeated till the sample breaks into pieces. This test is terminated after 30 cycles if the refractory fails to break.

Air cooling test: Three test pieces of prism shaped (75 mm high and 50 mm square base) are taken for this test. The samples are dried at 110 °C before test. The samples are heated at 1000° ± 5 °C for 30 minutes and withdrawn to place on a brick floor for 10 minutes cooling having no air draught. The heating and cooling constitute one cycle. This heating and air cooling cycle is repeated till the sample break. The number of cycle required to cause breaking is reported as spalling number.

***Loss in MOR strength* :** This test requires a pair of sample (80 mm × 30 mm × 30 mm). One sample is given five cycles of heating and cooling, and then both samples (unheated and heated) are tested for MOR. The per cent loss of MOR value is taken as index for spalling. The lower MOR loss per cent represents better resistance to thermal shock. More pairs are tested for better result.

Thermal expansion

(i) Definition

The increase in volume of the material due to heating is called thermal expansion. This expansion process is reversible in nature, and material regains its size on cooling, hence, it is also called *reversible thermal expansion* . It is the inherent property of all the materials. This property is measured as linear expansion with heating due to practical reasons. Figure 7.8 shows the thermal expansion of some refractory items.

(ii) Significance

The knowledge of thermal expansion is needed while selecting the refractory for a given application, designing the furnace system particularly at places where the refractory type is

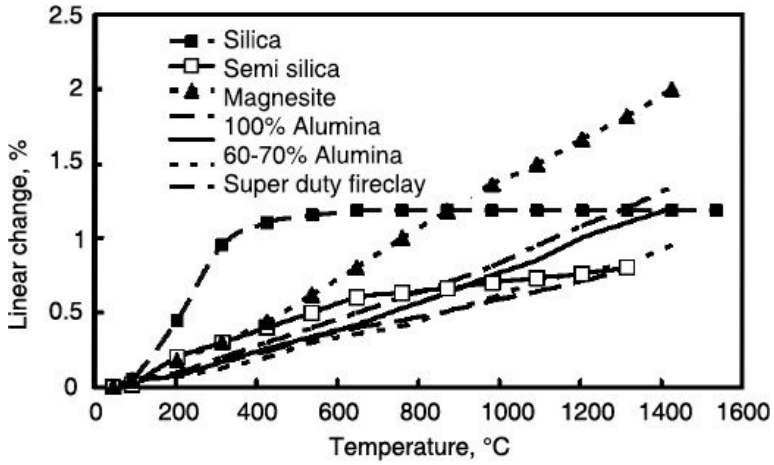


Figure 7.8 Linear change in refractory with temperature due to thermal expansion.

different at two points due to the furnace requirement. The materials having uniform expansion rate with temperature present less difficulty when furnace temperature fluctuates widely. The refractories with lower expansion rate are less likely to thermal spalling (e.g. fireclay). The silica bricks possess different proportions of its three phases (cristobalite, tridymite and unconverted quartz) depending on the firing cycle (time-temperature) practiced during manufacturing stage. Such typically fired silica bricks possess their own characteristic expansion. As most of the expansion occurs below 600 °C, hence if care is taken during heating and cooling below dull red-heat, the silica bricks behave admirably. The silica bricks work well as refractory for doors and covers (e.g. EAF swinging roof) undergoing frequent thermal fluctuation during opening and closing.

(iii) Test method

The test can be done by using two methods: Dial Gauge method and Telescopic/video method.

Dial gauge method: This method uses mechanical dial gauge to monitor expansion in test sample mounted in vertical [Figure 7.9(a)] or horizontal set-up (not shown). The test apparatus consists of a one end closed silica tube enclosed in a removable furnace. The silica tube is rigidly

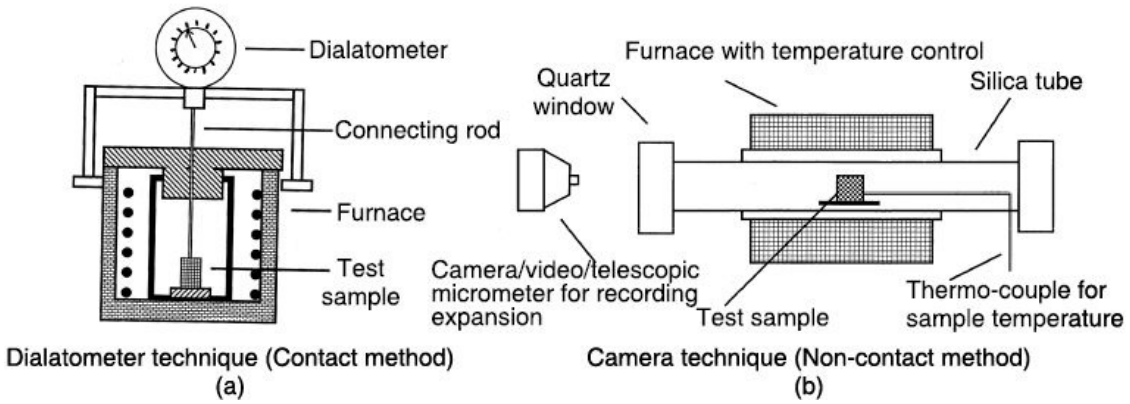


Figure 7.9 Methods for measuring thermal expansion.

mounted while a refractory rod transmits the expansion to the dial gauge for observing the change in length. The test sample (50 mm long and 10 mm diameter) is mounted in the set-up after making initial measurements. The furnace is heated at 3–4 °C per minute to 1000 °C and the change in length is noted with a fixed interval of temperature rise. The plot of linear expansion with time indicates the nature of expansion. This method has a limitation that dial indication for expansion depends on the sensitivity of mechanical system, and is prone to error. The weight of the refractory rod connecting the dial gauge counters the expansion force to some extent.

Telescopic/Video method: This method overcomes the demerits of dial gauge method. The expansion is measured in sample without subjecting any kind of pressure due to contact

less technique. The sample (10 mm long and 10 diameter) is placed on a flat platform

[Figure 7.9(b)] in a horizontally placed silica tube in a tube furnace. The two ends of the silica tube is kept open and a telescope fitted with travelling micro-scale is placed at one end focussing the top edge of the sample on the cross-wire. The other end of the tube is provided with a light source to help in viewing the sample when tube is dark at low temperatures. The increase in linear height of the sample with temperature can be noted by telescope micro-scale. The light source would not be needed after the thermal glow at ~ 400–500 °C. This can be automated by replacing telescope with video camera and computing system network to record thermal expansion with rising temperature with time automatically. The change in sample height could be computed by image analysis.

PLC (Permanent Linear Change) test

(i) Definition

The materials expand on heating, but they regain original shape on cooling (reversible thermal expansion). The permanent linear/volume change refers to non-reversible expansion in the refractory materials due to heating process.

This permanent linear/volume changes could be due to the following reasons:

1. *Phase changes* in the refractory due to allotropic forms having different specific gravity.
2. *Chemical reactions* causing formation of new compound having different specific gravity. This could be due to chemical attack by gas or slag in the system leading the formation of different compounds with changed properties.
3. *Sintering* of the material causing densification and shrinkage.
4. *Melting* of some phase causing densification and shrinkage.

(ii) Significance

The permanent change in refractory could alter the furnace structure and may cause its failure. This phenomenon of permanent volume change is significant in case of silica brick manufacture. The silica undergoes phase changes, and it is desirable to allow completion of the changes at manufacturing stage such that their use is made without trouble and is more assured during use. However, this is not practical due to long time required for phase change, which the manufacturers are not able to afford for economic reasons. This requires checking and care during use.

(iii) Test method

Sample for test: Two test samples (60 mm × 50 mm × 50 mm) are cut from the refractory block. The square (50 mm × 50 mm) faces are ground to make them parallel and smooth.

Apparatus: An electrical furnace giving uniform 1500 °C temperature over a 200 mm × 200 mm floor area is needed for heating. The measuring tools are needed to know the sample dimensions accurate to 0.05 mm.

Test procedure: The test is conducted as per the following steps:

Step 1: The dimensions between two parallel surfaces are measured at many points to consider the average value accurately (reading up to 0.05 mm).

Step 2: The two test pieces are placed in the constant temperature zone area of the furnace vertically or horizontally 25 mm apart for free flow of air.

Step 3: The furnace temperature is raised to 500 °C and then heated with 5–6

°C/min to the desired temperature and soaked for one hour.

Step 4: The Furnace is then cooled to 200 °C in 30 minutes and allowed to cool in air overnight.

Step 5: The cooled test samples are withdrawn and the dimensions are measured again to note the difference expressed as PLC%. The test sample's physical appearance is also noted and reported as unchanged, wrapped or bloated.

7.1.2 Corrosion Resistance

Definition

It is the wear and tear of refractories caused by static chemical attack of slag. The eating away of refractory material due to chemical reaction between refractory and molten fluid (slag) at high temperature is termed as 'refractory corrosion'.

Significance

Such corrosive behaviour of the refractory material is undesirable as it would cause refractory failure. The corrosive action by hot slag can eat away the refractory to cause pits. This pit could become the point of stress concentration and may lead to brick failure. The corrosive failure of the brick could be easily avoided by proper selection of the chemical nature (acid/basic/neutral) of the brick material which is not affected by working slag nature.

Test method

The metallurgical operating conditions are complex and vary from process to process. Thus, the standardisation of this test is difficult. However, various test methods are in practice, e.g. cone test, pill test, suspended rod test, powder impact test, etc. In this text, only cone test and pill test are given.

Cone test

It consists of making a cone of mixture from different quantities of powdered slag with refractory material. This cone is heated in a furnace and its fusion behaviour is observed. The interval between softening and flattening of the cone is supposed to indicate the critical range of deformation of refractories in contact with slag.

Pill test

It is used when the quantity of slag is less as compared to the quantity of

refractories for the test. The slag in the form of a pill is placed on the refractory body and heated in a furnace. The depth of penetration of the slag inside the refractory, the spread of the molten mass and also the corrosion or bloating behaviour is observed. These are the indications of chemical reaction between slag and refractory.

7.1.3 Erosion Resistance

Definition

The ability of a refractory to sustain the mechanical erosive action of sliding burden, moving products (liquid melt and slag), flowing gases (e.g. hot flue gases laden with solid particles) is termed as ‘erosion resistance’.

Significance

The flowing fluids (liquids/gases) cause erosion of the refractory due to mechanical friction between solid (refractory) and solid (burden) or solid (refractory) and fluid (molten metal/slag or gases). This mechanical erosion becomes more aggressive when the flowing fluids are laden with solid particles then the solid-solid abrasion causes more erosion. This mechanical erosion of the refractory becomes the cause of its failure during service. The erosion of refractory could be improved by regulating the mechanical properties of the refractory material (e.g. porosity, density and grain bonding strength). In some cases, the erosion is prevented by using *armoured brick* . The steel armour plate provided to the brick surface can sustain the working temperature below 400 °C and prevent brick being eroded by hot gases laden with dust particles.

Test method

The abrasion behaviour of the refractory is tested at room temperature and assessment is made for its suitability for a given application. The test method determines the volume of refractory material abraded from a flat surface of a test piece placed at right angles to a nozzle through which 1 kg sized graded silicon carbide particles are blasted by compressed (450 kPa) air in ~ 450 seconds.

Abrasion media

Silicon carbide (80% 300 μm + 20% 600 μm size)

Test apparatus

The test is done in a air tight chamber fitted with arrangement to blast abrasive powder (SiC) through a nozzle onto a refractory test sample (100 mm × 100 mm

× 25 mm) from top located at 200 mm from sample surface (100 mm × 100 mm). The test conditions are maintained as per IS 1528-23 standard (Indian ISO 16282–2007).

Test procedure

The refractory sample is exposed to blasting of 1 kg SiC particles in 450 seconds using
450 kPa compress air. The loss in refractory weight (gram) due to erosion is reported as abrasion index.

7.1.4 Thermal Conductivity

Definition

Thermal conductivity is defined as the quantity of heat that will flow through a unit area in a direction normal to the surface area in a given time with a known temperature gradient under steady state thermal conditions. It is indicative of heat flow characteristics of the refractory and depends upon the nature of mineralogical constituents as well as the physical properties of the refractories as shown in Figure 7.10.

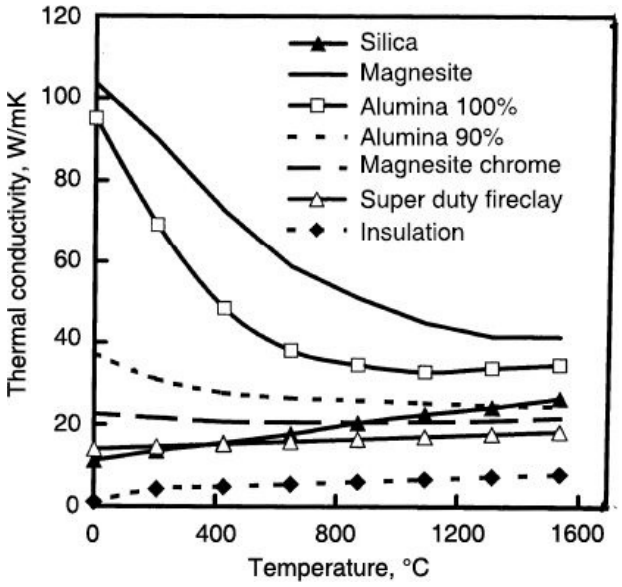


Figure 7.10 Thermal conductivity of some refractory materials.

Significance

The thermal conductivity of the refractory is needed to decide the wall thickness for obtaining desired temperature gradient across refractory lining section in the furnace. High thermal conductivity in refractories are required for some

applications where good heat transfer is essential such as coke oven walls, regenerators, muffles and water cooled furnace walls. Lower thermal conductivity refractory materials are preferred for applications where heat flow has to be minimised to conserve heat energy. In addition to refractory material's own thermal conductivity, the porosity in the brick is an important property to regulate the heat flow through refractory material. The thermal conductivity of a refractory decreases with increasing porosity. The extent of brick porosity can be regulated by brick manufacturing parameters.

Test method

The hot wire method is commonly adopted, which is an absolute method for direct determination of thermal conductivity. It is based on the measurement of the temperature increase of a linear heat source/hot wire (known as cross wire technique ISO 8894-1) or at a specific distance from a linear heat source (called parallel wire technique ISO8894-2).

The hot wire and thermocouple both are embedded between two test pieces, which make up the actual test assembly. The time dependent temperature increase after the heating current is swithched on is a measure of the thermal conductivity of the material being tested.

7.1.5 Porosity

Definitions

Porosity is a measure of the vacant space as pores and voids/cavities in the refractory material. The *pores and cavities* could be differentiated on their length to diameter ratio. The pores have longer length and their length to diameter ratio is more than the cavity.

The pores present in refractory are of three types: *open pores, inter-connected pores and sealed pores.* These are explained in the following sections:

Open pores

These have one of their ends on the outer surface of the particle. This open end allows the movement of fluids (gas/liquid) to the interior location of the particle permitting chemical reaction and adsorption/absorption processes. The liquid metal may penetrate under pressure and get solidified to cause refractory failure. The refractory with large sized open pores are undesirable for places facing liquid metal or slag.

Interconnected pores

These have both of their ends opening to the outer surface of the refractory. This allows a free movement of fluids (gas/liquid) and offers site for chemical reactions and adsorption/absorption of fluids. Such pores are useful in manufacturing ceramic filters, but are not desirable in refractory brick used in furnaces which may cause leakage of gases in the furnace.

Sealed pores

There are deep seated and do not open up to the surface of the particle. These sealed pores do not offer any site for chemical reaction nor allow adsorption/absorption of fluids. However, these sealed pores act as a good thermal barrier and increase the heat insulating power of the material. Such sealed pores are useful while making heat insulating materials.

The apparent porosity in refractory is determined by knowing volume of open pores including interconnected pores. The ratio of open pore volume to bulk volume of the refractory is expressed as apparent porosity which is commonly called as porosity. The true porosity includes all three types of pores and is determined by measuring apparent density and true density of the refractory material. The sealed porosity is known by the difference between true porosity and apparent porosity. Thus, we can express these three porosities in the following manner:

$$\text{The Apparent porosity (\%)} = \frac{\text{Open pore volume}}{\text{Total bulk volume}} \times 100$$

$$\text{The true porosity (\%)} = \left(1 - \frac{\text{Apparent density}}{\text{True density}}\right) \times 100$$

The sealed pores (%) = True porosity (%) – Apparent porosity (%).

In literatures, it is common to express the apparent porosity value as porosity only without using any suffix.

Significance

High porosity materials tend to be highly resistant to the thermal flux flow due to the presence of air in the pores as air is a very poor thermal conductor. The denser bricks having low porosity are generally used in the hotter zones, while the highly porous bricks are commonly used for thermal insulation in outer layer of the furnace. The porous refractory bricks are not used at place which is in contact with liquid metal or slag as its penetration in the pores may cause refractory failure. The porous bricks are also not used at places having toxic gas

at pressure as it may leak through pores and may cause hazard.

Testing method

The pore volume can be determined by three methods: boiling water method, mercury porositometer and nitrogen gas adsorption. These are described briefly in the following section:

Boiling water method

A piece of solid dry sample is weighed in air (W_1). This solid material is then dipped in boiling water for 30 minutes. The boiling action will cause expansion of air bubbles trapped in the pores and lead to its expulsion. Once the heating is stopped, water cools and enters into the pores to fill it completely. The weight (W_2) of the water saturated sample is taken while dipped fully under water (Figure 7.11). The sample is now taken out and surface water is removed by soaking with cotton cloth. The weight of water saturated sample is taken in air (W_3).

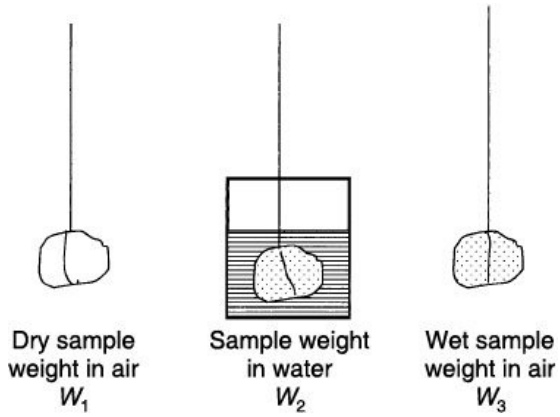


Figure 7.11 Determination of apparent density and porosity.

Now, the weight of water absorbed in open pores = $(W_3 - W_1)$ g

Or, volume of water absorbed in open pores = $[(W_3 - W_1) \times \rho]$ cc

where ρ is the density of water.

The loss in weight of the sample due to buoyancy while being immersed in water

$$= (W_3 - W_2) \text{ g}$$

or the volume of sample = $[(W_3 - W_2) \times \rho]$ cc

Hence,

The apparent porosity (%) = $\dfrac{W_3 - W_1}{W_3 - W_2} \times 100$

The true porosity (%) = $\left(1 - \frac{\text{Apparent density}}{\text{True density}}\right) \times 100$

The sealed pores (%) = True porosity (%) − Apparent porosity (%).

This method is simple, direct and accurate to determine apparent porosity. The procedure for knowing apparent density and true density is given in the forthcoming sections.

Mercury porositometer

This is a costly and sophisticated research instrument used to measure pore volume and pore size distribution in the range of 300 μm to 0.0035 μm pore diameter for variety of materials. The sample introduced in the system is first subjected to vacuum to remove all gases present in pores, and then the mercury is filled in the chamber under pressure. The volume of mercury penetrating with increase in pressure is noted. The software provided with the equipment gives the total open pore volume and its distribution with pore size. It is non-destructive test and all the mercury introduced is removed under reduced pressure. This method is useful for developing ceramic filters.

Nitrogen gas absorption

This method is used to determine very fine pores (< 0.09 μm) in solid materials. The material is first subjected to high vacuum and then provided with nitrogen atmosphere to cause adsorption of nitrogen on the walls of the pore. The volume of adsorbed nitrogen is measured, and the pore volume and its size are determined. This is a sophisticated instrument and is used for research purposes.

7.1.6 Density

Definitions

The refractory is a porous material, and therefore its density is seriously affected by pore volume. Following three terms are used to differentiate various types of density values:

True density

This refers to the ratio of mass to volume of solid particle without any pores or cavities.

Apparent density

It refers to the ratio of mass to volume of a single solid particle including closed

pores (i.e., volume of solid material + volume of closed pores within the particle).

Bulk density

It refers to the ratio of bulk mass to total bulk volume (solid volume + pore volume + void volume) of the refractory brick.

Significance

True density value reflects the characteristic property of the refractory. It helps in identifying the nature of refractory material. The apparent density value indicates the extent of porosity. The apparent density value decreases with increasing porosity in the brick. High density bricks with low porosity are good for heat facing locations, while low density bricks are good for heat insulation applications. The bulk density of the brick is useful in assessing its mass for the purpose of knowing total weight for choosing transport means, assessing handling and transport cost, designing civil structures for supporting the furnace weight, etc. It also helps in assessing heat retention capacity of the furnace structure.

Testing method

True density

This refers to the ratio of mass to volume of solid particle without any pores or cavities. The *solid refractory is crushed in powder form* (–72 # or 200 μm) to test its true density. The powder state of the material renders it free from any porosity, thus, the density value determined represents its *true density* . A pycnometer (pyknometer) or specific gravity (empty) bottle is taken, cleaned and dried before taking its weight (W_1) with stopper. Then, nearly 10 to 15 g refractory powder is poured in the bottle and weighed (W_2) with powder and stopper in position. Now, a liquid of known density is selected which should not react with refractory and filled in the bottle to its capacity. The weight of the bottle with stopper, powder and fluid is taken (W_3). To ascertain the volume of bottle noted on it, the bottle is filled with liquid and weighed (W_4).

The density of the powder is calculated in the following way:

Mass of the refractory powder = $(W_2 - W_1)$ g

Mass of the powder and fluid in bottle = $(W_3 - W_1)$ g

Hence, mass of the fluid = $[(W_3 - W_1) - (W_2 - W_1)]$ g

$= (W_3 - W_2)$ g

Therefore, the volume of fluid = $\frac{W_3 - W_2}{\rho_f}$ cc,

where ρ_f is the density (g/cc) of the fluid used.

The total volume of the bottle (V) = $\frac{W_4 - W_1}{\rho_f}$ cc

Volume of powder = $V - \frac{(W_3 - W_2)}{\rho_f}$

∴ True density of the powder = $\frac{(W_2 - W_1)\,\rho_f}{(W_4 - W_1) - (W_3 - W_2)}$ g/cc

This method is used commonly to determine the true density of minerals, ores, powdered materials and chemicals.

Apparent density

A small piece of material is taken and tied with a thread to be suspend in a chemical balance. The weight of the sample suspended in air is taken (W_1). Then the sample is taken out and kept in boiling water for 30 minutes to enable water soaking in all the open pores. The water saturated sample is taken out from boiling water and its weight (W_2) is taken while keeping it suspended in cool water at room temperature held in a beaker. This water filled beaker is kept on a wooden bench without touching the balance pan. Now, the wet sample is taken out and surface water is soaked out with cotton, and water saturated wet sample is weighed in air (W_3). The density of the material is now calculated in the following way:

Mass of sample = W_1 g

Volume of sample = Loss in weight (Buoyancy) in water

$= (W_3 - W_2) \times \rho_W$

$= (W_3 - W_2)$ cc (Considering ρ_W as 1 g/cc)

Apparent density = $\frac{W_1}{W_3 - W_2}$ g/cc

Bulk density

It refers to the ratio of bulk mass to total bulk volume (solid volume + pore volume + void volume) of the refractory brick.

Regular Shaped Refractory: The bulk density of brick shaped refractory could be determined by weighing one brick to know its mass, and measuring its dimensions to calculate its bulk volume. The ratio of mass, to its bulk volume would give its bulk density.

Unshaped Refractory: The refractory material in unformed state is used as ramming mass or filler mass. Such refractory materials have mixture of different size particles. The bulk density of such unformed refractory is determined by knowing its mass and bulk volume (including pores in refractory and inter-particle voids) in a steel container. The steel container with 400 ± 2 mm inner diameter and 250 ± 2 mm height is used to measure mass (kg) of the material held in the container (0.0314 m^3). The mass (kg) per unit volume (m^3) could be calculated. This confirms IS-584 (1970) standards.

7.1.7 Cold Crushing Strength (CCS)

Definition

The cold crushing strength (CCS) represents the ability of a refractory to resist failure under compressive load at room temperature. The compressive load is applied on the refractory block till its fracture. The CCS is then calculated as total load applied divided by the surface area.

Significance

The cold crushing strength of the brick may not be useful in assessing its performance during service, but it does help in assessing its behaviour during storage and transportation. The high cold crushing strength value of the brick is useful in sustaining the rigorous condition during transportation without breakage. It can also be a useful indicator to the adequacy of firing giving suitable bulk density and porosity to provide abrasion resistance.

Test method

Test sample

Six cylindrical samples (50 mm diameter and 50 mm height) are cut or drilled out from the refractory block. The circular faces in the sample must be parallel, and samples are dried before testing.

Test equipment

Any mechanical or hydraulic compressive testing machine could be used for the purpose.

Test procedure

The test samples are loaded on the flat surface till its fracture following uniform loading rate. The average of six tests is taken as CCS value.

7.2 RAW MATERIALS FOR REFRACTORY MANUFACTURE

The refractory preparation exploits natural resources together with synthetic materials. These refractory raw materials can be broadly divided into two categories: clay based and non-clay based.

7.2.1 Clay based Refractory Raw Materials

The naturally occurring clays having high percentage of refractory constituents find use in refractory industry. These include fireclay and high alumina clays.

Fireclay

It is generally defined as a “mineral aggregate composed of hydrous silicates of aluminium ($Al_2 O_3 .2SiO_2 .2H_2 O$) with or without free silica”. It is also known as kaolinite. It is generally found as white in colour, but sometimes red, blue or brown tints come from impurities.

It has specific gravity as 2.16–2.66 and mohs scale hardness as 2–2.5. The chemical

composition typical for fireclays are 23–34% $Al_2 O_3$, 50–60% SiO_2 and 6–27% loss on ignition together with various amounts of $Fe_2 O_3$, CaO, MgO, $K_2 O$, $Na_2 O$ and TiO_2 as impurities. High grade fireclays can withstand temperatures of 1775 °C, but to be referred to as a “fireclay” the material must withstand a minimum temperature of 1515 °C. Fireclay refractories can be low, medium, high, or super-duty based on their resistance to high temperature or refractoriness. Fireclay refractories are used to produce bricks, insulating refractories, and ladle brick.

High alumina clay

It is composed of bauxite riched or other raw materials that contain 50 to 87.5% alumina. High alumina refractories are generally multipurpose, offering

resistance to chipping and higher volume stability. High alumina refractories are used to produce brick and insulating refractories.

7.2.2 Non-clay based Refractory Raw Materials

These refractory materials are prepared from naturally occurring minerals and synthetically processed materials. The properties of some refractory materials are given in Table 7.3 and described in following sections:

Magnesite

It is a mineral with the chemical formula $MgCO_3$ (magnesium carbonate). It is found as colourless, white, pale yellow, pale brown, faintly pink, lilac-rose mineral having conchoidal fracture, possessing hardenss of 3.5–4.5 on mohs scale. The mineral lusture is vitreous giving white streak and possesses specific gravity of 3.0–3.2.

Table 7.3 Properties of the Raw Materials Used for Refractory Manufacture

Property → Mineral/ Material	*Formula*	*Colour*	*Fracture*	*Hardness Mohs*	*Luster*	*Streak*	*Specific Gravity*	*Temperature, °C*	
								Fusion	*Melting point*
Fireclay kaolinite	$Al_2O_3.2SiO_2.2H_2O$	White (red, blue or brown tints from impurities)		2 to 2.5	Pearly to dull earthy	White	2.16–2.66	1775	
Magnesite	$MgCO_3$	White (pale yellow, pale brown, faintly pink)	Conchoidal	3.5 to 4.5	Vitreous	White	3.0–3.2		2570
Dolomite	$(CaMg)(CO_3)_2$	White (gray to pink)	Conchoidal	3.5 to 4	Vitreous to pearly	White	2.84–2.86		2570
Iron Chromite	$(Fe)Cr_2O_4$	Black to brownish black	Uneven	5.5	Submetallic	Brown	4.5–4.8		2190–2270
Quartz	SiO_2	Colorless through various colors to black	Conchoidal	7	Vitreous – waxy to dull when massive	White	2.65		1670 °C (β tridymite) 1713 °C β cristobalite)
Zircon	ZrO_2	Reddish brown, yellow, green, blue, gray, colorless; in	Conchoidal		Vitreous to adamantine;		4.6 –		

Sand	.SiO_2	thin section, colorless to pale brown	to uneven	7.5	greasy when metamict .	White	4.76		2100
Alumina Powder	Al_2O_3	White	–	–	–	–	3.95 – 4.1		2072
Silicon Carbide	SiC	Grey	–	9.2	–	–	3.2		2250 – 2730

Extra-high alumina

It is prepared predominately from bauxite or alumina (Al_2O_3). The extra-high alumina refractories contain 87.5% to 100% alumina and offer good volume stability. They are typically poured into special shapes using a fused casting process.

Mullite

Mullite ($Al_6Si_2O_{13}$) is made from kyanite, sillimanite, and alusite, bauxite or mixtures of alumina silicate materials. The mullite refractories contain ~ 70% alumina. It possesses specific gravity of 3.11–3.26 and hardness 6–7 on Mohs scale. They maintain a low level of impurities and high resistance to loading in high temperatures.

Silica

The quartz mainly containing silica is used for this purpose. The silica refractories
are characterised by a high coefficient of thermal expansion between room temperature
and 500 °C. Silica bricks are prepared in three grades: super-duty (low alumina and alkali), regular, and coke oven quality. Silica compositions can be used for hot patching, shrouds, and bricks.

Silicon carbide

These are produced by the reaction of sand (silica) and coke in an electric furnace. The silicon carbide (mp 2730 °C) refractories are used to make special shapes, such as kiln furniture to suport ceramic ware as it is fired in kilns. It has high thermal conductivity, good load bearing characteristics at high temperatures, and good resistance to changes in temperatures.

Zircon

The *zircon sand* containing zirconium silicate (ZrO_2SiO_2) is used for refractory

purpose. The zircon refractories maintain good volume stability for extended periods or exposure to high temperatures. Zircon refractories are widely used for glass tank construction.

Graphite

Mineral graphite is used for making carbon-based refractory.

Petroleum coke

The petroleum coke generated in oil refinery is used for making carbon based refractory and graphite electrodes.

7.3 REFRACTORY MANUFACTURING PROCESS

Refractory manufacturing process basically consists of four steps:

(i) Raw material processing

This step involves crushing and grinding of raw materials obtained from various sources followed by their classification according to particle size by screening and sieving. These raw materials also sometimes need washing, calcinations and drying operations to meet the chemical specifications. The dry refractory powder of one size is mixed with other size to meet specific grain size distribution alongwith other chemical constituents desired for specific need. The dry refractory powder is packed and marketed as such for various applications. This dry refractory powder mass with specific size mix serves as feed for making refractory bricks and other components.

(ii) Shaping

The dry powder is mixed with water and other additives to prepare wet dove for giving shape to the refractory using different types of machines and technique. The shaped refractory is air dried before firing.

(iii) Firing

The shaped refractory is subjected to firing to cause heat hardening by ceramic bonds and bring desired phase changes to have a stabilised refractory. This firing is done in kilns having high temperature caused by combustion of fuels mostly gaseous in nature for better quality product.

(iv) Final processing

The final processing step includes milling, grinding, and sand blasting of the

final product to give finished and desired surface quality. The certain products may also need impregnation with tar/pitch or armouring by some other material like steel sheet. Finally the products are packaged for safe transportation.

These steps are illustrated in Figure 7.12.

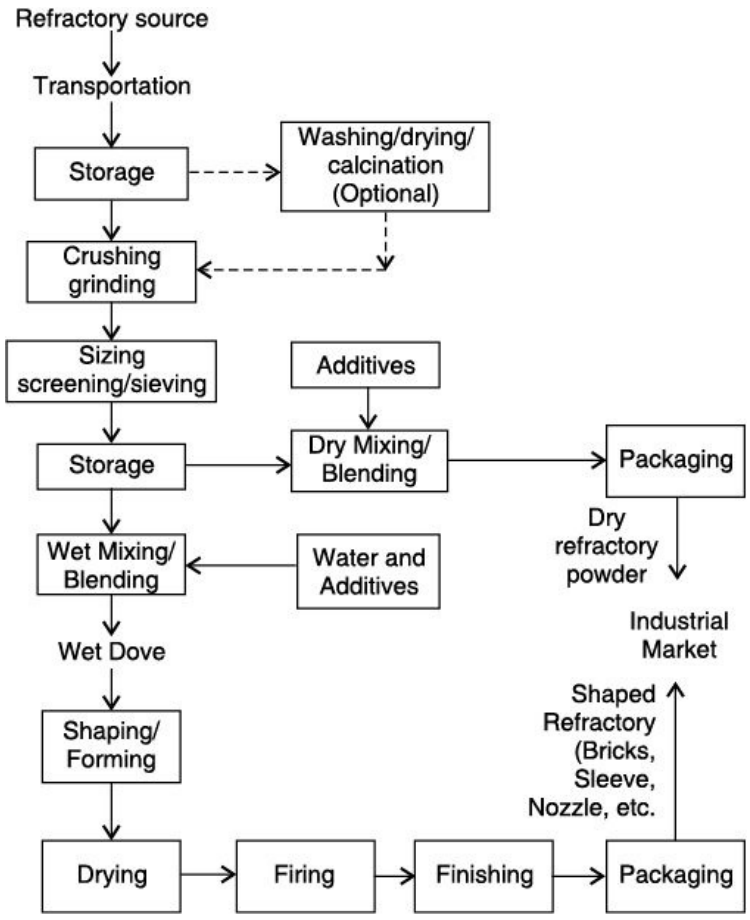


Figure 7.12 Flow sheet of refractory manufacturing process.

7.4 COMMONLY USED EQUIPMENT IN REFRACTORY INDUSTRY

The refractory manufacturing process needs heavy equipment to handle and process large quantities of rocks and minerals. These mineral processing equipment are similar to those used in ore preparation and washing. These are: (i) Crushing and Grinding Equipment, (ii) Sizing Equipment, (iii) Mixing Machines, (iv) Kneading Machines, (v) Shaping Machines, (vi) Firing Kilns and (vii) Finishing Equipment.

7.4.1 Crushing and Grinding Equipment

The breakers and crushers are used to reduce large sized rocks into smaller size particles. The grinding unit is used to further reduce the particle size as dust.

Crushers

The crushers are of two types based on crushing property: Primary crusher and secondary crushers.

(i) Primary crushers

The primary crusher (Figure 7.13) mainly refers to the gyratory crusher and jaw crusher. They reduce 1.5 meter feed to approximately 10–20 cm particles. The crusher selection is based on the nature of mineral, its hardness and humidity, production capacity (ton/hr) and the desired granularity or the particle size distribution of the finished products.

Gyratory crusher: A gyratory crusher consists of a concave surface and a conical head. Both these surfaces are typically lined with manganese steel plates. The inner cone has a slight circular movement, but it does not rotate. The movement is generated by an eccentric arrangement. The material travels downwards between the two surfaces being progressively crushed until it is small enough to fall out through the gap between the two surfaces. It can be used to break soft to hard rocks without any abrasion problems. It can yield a reduction ratio of 4 : 1 to 7 : 1.

Jaw crusher: A jaw or toggle crusher consists of a set of vertical jaws. One of the jaws is fixed, and the other being moved back and forth relative to it by cam or pitman mechanism. The gap at the top of the jaws are more than at the bottom forming a tapered chute so that the material is crushed progressively smaller and smaller as it travels downwards until it is small enough to escape from the bottom opening. The movement of the jaw can be quite small, since complete crushing is not performed in one stroke. It can be used for breaking soft to hard rock without any abrasion problem. It can yield a reduction ratio of 3 : 1 to 5 : 1.

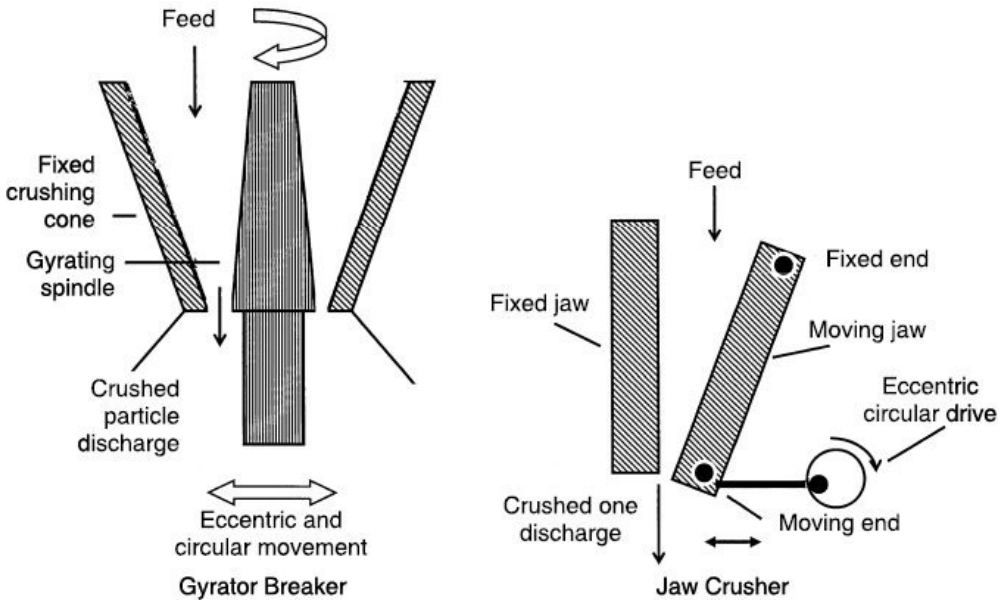


Figure 7.13 Primary crushers.

(ii) Secondary crushers

It mainly handles rocks of smaller particle size that have already been impacted and crushed from their original size. These are used to reduce particle size 250 mm to 30–50 mm. The cone crusher and roll crushers are common for the purpose.

Cone crusher: It is used as a secondary crusher. It is similar to gyratory crusher with a difference that it has a shorter cone and a smaller receiving opening. It rotates faster (two times) than gyratory crusher and produces more uniform size product. This can convert 250 mm size rocks into smaller fragments to give average 30–50 mm (some particle may range 100 mm to 0.1 mm) size particles.

Roll crusher: It consists of two hard steel rolls mounted on heavy cast iron frames, and driven by electrical motor and gear arrangement in opposite direction. The gap between roll decides the product size. The maximum size of the feed depends on the roll diameter which controls the nip angle. The maximum particle size (D mm) in roll crusher is given by the expression: $D = 0.085\ R + C$, where R is the roll radius and C roll setting (product size) in mm.

Grinders

The grinding mill used for producing fine sized particles use alloy steel balls and rod as grinding media, and thus named accordingly as ball mill and rod mill. This grinding can be performed in dry or wet state.

(i) Ball mill

The ball mill consists of cylindrical or conical drum mounted horizontally and driven by motor and gear arrangement (Figure 7.14). The drum is partially filled with alloy steel or alloy cast iron balls as grinding media. In case of iron free ceramic powder, the flint balls are used as grinding media. The feed is made from one end, and it is discharged from the other end by gravity in case of wet grinding. In case of dry grinding, the discharge is made by pneumatic system. The product is subjected to wet/dry classification system to return the coarser particles for further grinding. The ball mill and classification unit are operated in close circuit.

(ii) Rod mill

The rod mill uses a cylindrical drum with large numbers of alloy steel rods in the drum as grinding media. It is operated identical to ball mill.

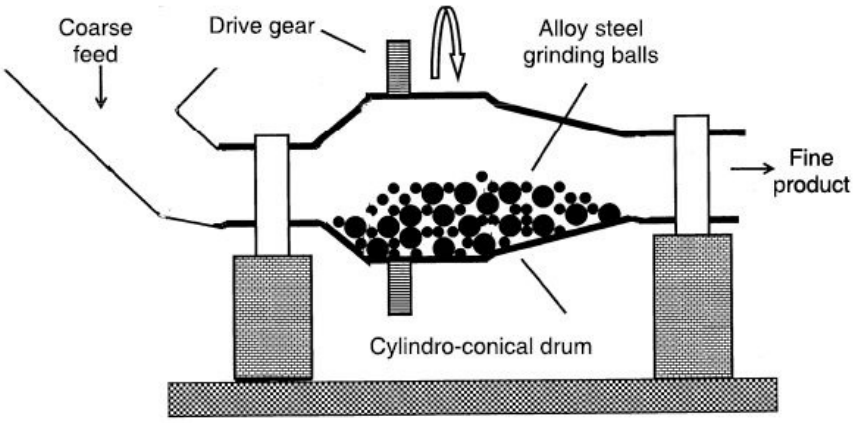


Figure 7.14 Ball mill.

7.4.2 Sizing Equipment

The vibrating screen, trammel and sieves are used to separate the coarser particles while classifiers are used for finer (100 to 400 mesh) particles. Figure 2.14 in Chapter 2 gives various sizing equipment for coal which are also used for other materials including refractory materials.

7.4.3 Mixing Machines

The mixing machines are used to homogenise the mineral powders obtained from two or more sources to have uniform composition. The additives, if any, required in small quantity is also added to get uniformly distributed in the mass. The various types of mixers are used depending on the requirement and production capacity. Some of these machines (Figure 7.15) are briefly described

below:

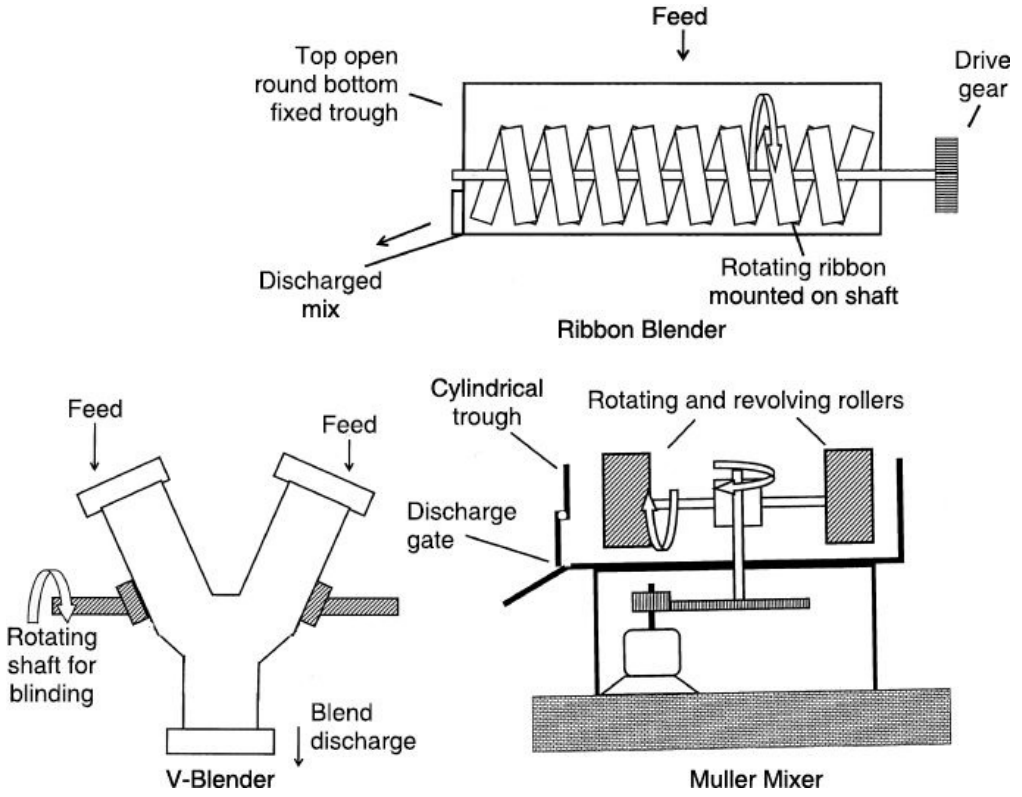


Figure 7.15 Mixing machines.

Ribbon blender

It is a kind of horizontal mixer to mix different types of powders. This consists of a U-shaped trough fitted with steel ribbons mounted on the horizontal shaft located at bottom which is driven by a motor. This mixer functioning depends mainly on three major dimensions: Diameter of the helical ribbon, ribbon width and its pitch. It is effective in distributing very small amount of additive added to the powders. Powder is subjected to rotary as well as horizontal motion in positive direction to get effective blending which is caused by inner and outer ribbons moving helically.

V-blender

It consists of two wide tubes joined in V-shape, and mounted to rotate along central shaft. The ingredient fed in the tubes gets mixed by dropping from top to bottom while being rotated. The mixed mixture is discharged out from the bottom end of V-shaped tube.

Mullar mixer

It consists of a bowl fitted with two free moving mulling roller wheels mounted

on a central shaft to cause a rotary motion. The work forces are applied via weight of the mulling wheels. The weight, and thereby the mixing efficiency, is controlled through a spring suspension arrangement on the wheel that is fully adjustable, and allows the user to increase or decrease the amount of work that is applied to the mixture via the mulling wheel. This type of mixer provides additional mixing forces over that of other conventional mixers to assure that the total mixture prepared has uniform consistency. Unlike other mixers, mulling provides forces that incorporate kneading, shearing, smearing, and blending of materials for total uniform consistency. This process produces enough pressure to move, intermingle and push particles into place without crushing, grinding, or distorting the ingredients. The resultant mixture is of truly uniform consistency in both physical and chemical structure.

7.4.4 Kneading Machines

These are also a kind of mixer having heavy duty blades and rotary system to mix powder with liquid (e.g. water) to make a viscous paste. The paste consistency is assured by the blade design and rouged nature of the rotating system. This is used to make dough of ceramic powders to give them shape.

7.4.5 Shaping Machines

The dough of ceramic powders with moisture is pressed or extruded to get desired shape. Press of different types (Figure 7.16) are used to make brick shaped refractory, while extrusion (Figure 7.17) is used for making cylindrical shaped objects.

Pressing machines

The pressing machines shown in Figure 7.16 are used to make regular shaped refractory like bricks. These machines can be operated manually or designed to operate in semi-automatic or fully automatic mode. The moist refractory mixture in powder or dough form is held in a metallic mould and given a pressure by the machine to take the shape of the moulds before being ejected out for drying and firing operation. The different methods to impart pressure to mould bricks are classified in the following way:

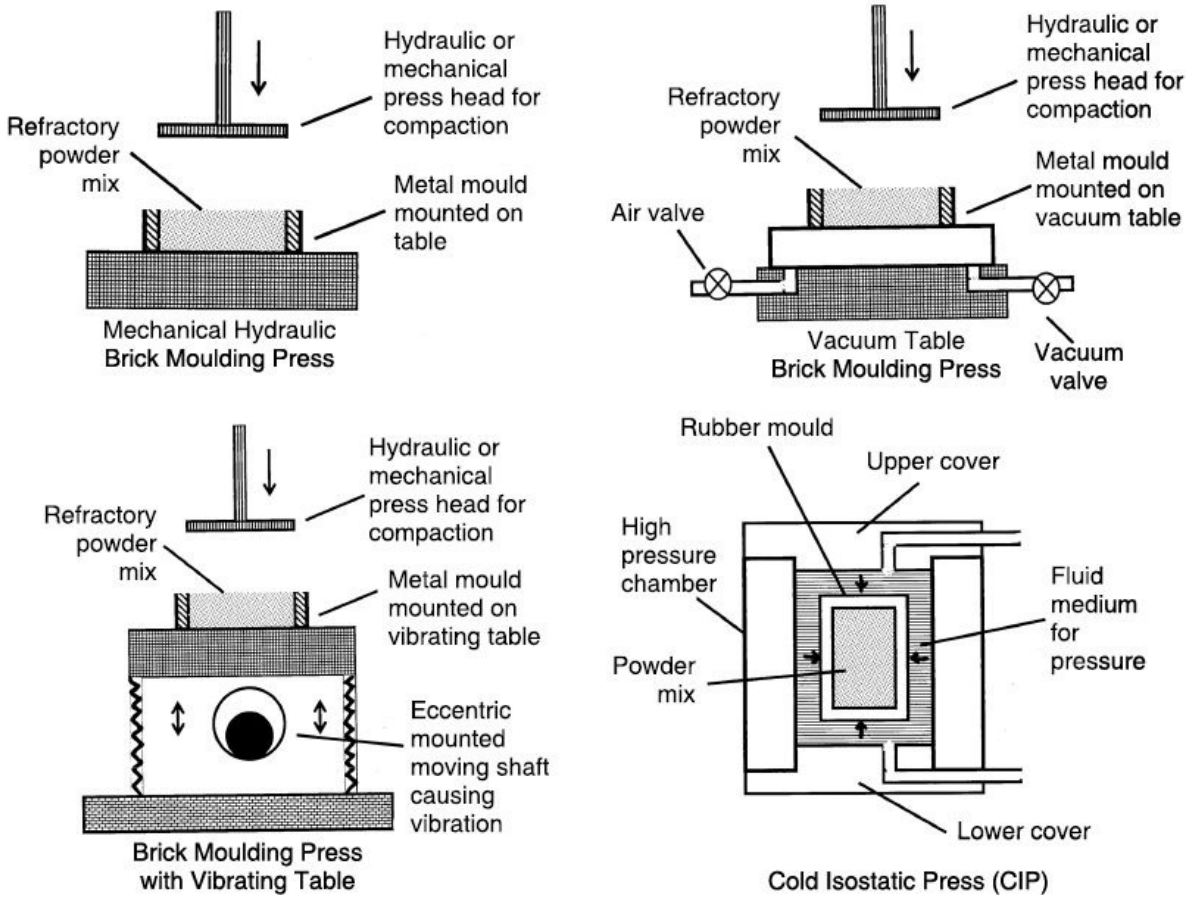


Figure 7.16 Press for shaping refractory bricks and blocks.

Mechanical/Hydraulic press

Such machines are capable of giving impact or apply static pressure. These may be equipped with a vacuum de-aerator which on release of valve gives an impact and applies squeezing action giving pressure to shape the bricks in the mould. Impact press provides higher allowable maximum compacting force than static presses. However, static presses are finding increasing application for the production of sophisticated refractories such as submerged nozzles, shrouds and industrial ceramics. Bricks formed with static presses are flat, uniform and compact.

Vibrating press

Vibrating presses could be of two types using air cylinder and hydraulic cylinder. The vibrator in the air cylinder type is attached to the press table and the air cylinder causes compaction of refractory mix held in the mould. The hydraulic vibrating press is constructed with the hydraulic pulse generator attached to the pressure block and the hydraulic cylinder causes compaction in the refractory

mixture held in the mould. Vibrating presses are typically used for the compaction of complexly shaped ceramic items.

Cold Isostatic Press (CIP)

In this method, homogeneous hydrostatic pressure is provided over entire surface of a rubber mould filled with refractory powder mix with suitable binder. The binder gives green and fired strength. This method is also known as *hydrostatic press* or *rubber press* . In this technique, the high fluid pressure is applied to a powder mass at ambient temperature causing compactness with desired shape. Water or oil is commonly used as a fluid medium for the application of pressure. The moulding of complex shape is made possible by this method.

Extruding machines

The extrusion machine (Figure 7.17) consists of a cylindrical chamber (vertical or horizontal) fitted with a piston and hydraulic system to apply pressure. The cylindrical chamber is fitted with a metallic die to get desired cross-section of the extruded material. The plastic dough of refractory mass is kept in the cylindrical chamber, and pressure is applied to cause the flow of plastic dough through the die and yield a desired shape in highly compacted form. The length of the shape is obtained by shearing or cutting the long extruded bar coming out from the die.

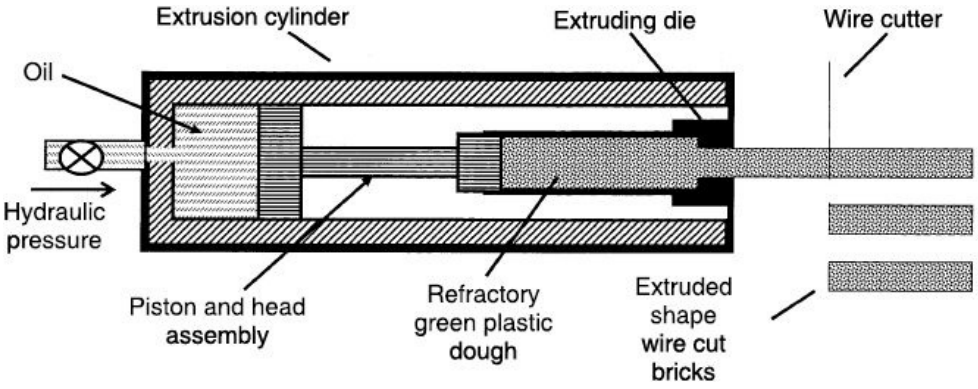


Figure 7.17 Extrusion process.

Machines for finishing green refractory shapes

The moulded or extruded shapes sometimes need machining to get some desired features like wedge, cut, hole, taper, etc. to meet the application requirements. These operations are conducted using conventional machines like cutter, lathe, drill, etc. The green compact is strong enough to permit such machining

operations.

7.4.6 Firing Kilns

The shaped green refractory bricks are stored in dry airy place for few days to remove the moisture partially before firing in kiln at higher temperature to develop ceramic bonding offering all required properties in the refractory, e.g. thermally stable phase, porosity, density, strength, etc. Various types of kiln are used to fire the refractory depending on the type of fuel, firing temperature and production capacity.

Tunnel kiln

It is the most popular type of firing system used in the industry. It consists of furnace which appears like a tunnel and the refractories mounted on bogies move on rails from entry to exit.

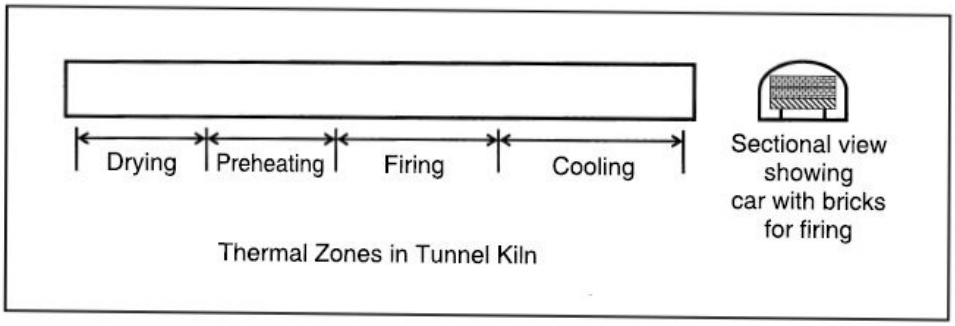


Figure 7.18 Tunnel kiln furnace for brick firing.

The furnace (Figure 7.18) has different heating zones marked as pre-heating zone, heating zone and cooling zone. The furnace is heated commonly by gaseous fuel (e.g. producer gas) in the heating zone and the hot gases are utilised in pre-heating zone before exiting as flue gas. In the cooling section, the heat of the hot refractory is recovered by recuperators to preheat ingoing air for being used as hot blast to burn fuel in combustion zone.

Circular kiln

Circular kilns are typically used to fire silica bricks. These kilns can be used to fire large refractory products that cannot be fired in a tunnel kiln and can easily accommodate changes in production.

Shuttle kiln

The design of a shuttle kiln resembles the firing zone of a tunnel kiln. Shuttle

kilns effectively store heat and are used to fire fireclay and specialty bricks.

7.4.7 Finishing Equipment

The fired refractory products are given finishing operation by blasting, grinding, etc. to have desired surface finish in some cases. Some refractories need tar impregnation or armouring by steel sheet to meet specific needs. Finally, all the products are given packaging for safe transport. Various suitable equipment are used for specific operation.

7.5 PREPARATION OF COMMONLY USED REFRACTORY BRICKS

The metallurgical furnaces use a variety of refractory bricks, however bricks made of
silica, fireclay (dense and porous), magnesite, chromite and graphite are very common. This section is devoted to describe the manufacturing process for such commonly used refractory bricks.

7.5.1 Silica Bricks

Quality of bricks

The silica bricks are required to possess certain properties for its use in metallurgical furnaces. The properties required are as follows:

Chemical composition: The silica content in the bricks must be more than 94% with alumina content as 1.5% (max).

PCE value: Not less than 31 number cone (ASTM)

RUL value : Not less than 1670 °C

App. porosity: 27% (max)

True specific gravity : 2.35 (max)

PLC value: 1% (max)

CCS value: 30 MPa (300 kgf/cm^2)

Table 7.4 Mineral Properties of Quartz

S. No.	*Item*	*Properties*
1	Chemical Form	Oxide of silicon – SiO_2
2	Colour	Colourless through various colours to black

3	Fracture	Conchoidal
4	Tenacity	Brittle
5	Hardness Mohs scale	7 (lowered by impurities)
6	Lustre	Vitreous – waxy to dull when massive
7	Streak	White
8	Specific gravity	2.65; variable 2.59–2.63 in impure varieties
9	Melting point	1670 °C (β - tridymite) 1713 °C (β - cristobalite)

Raw materials needed

The major raw material is quartz (Table 7.4) occurring in nature as rock and river sand. The raw materials used are expected to have minimum 97% silica (SiO_2) and maximum 1% alumina (Al_2 O_3) with alkalies not exceeding 0.3%. The other minor impurities could be titania (TiO_2), iron oxide (FeO) and lime (CaO). The effect of impurities on silica quality is given briefly in the following sections.

Effect of alumina

The presence of alumina is not desired as it reacts with silica and lowers the melting
point considerably by forming compound as shown in SiO_2 -Al_2 O_3 binary phase diagram (Figure 7.19). The five per cent alumina lowers the melting point of quartz (SiO_2) from 1730 to 1549 °C.

Effect of titania

The behaviour of titania is similar to alumina and its presence is not desired in quartz. The presence of 10% titania (TiO_2) can lower the melting point to 1540 °C. This is shown in Figure 7.19.

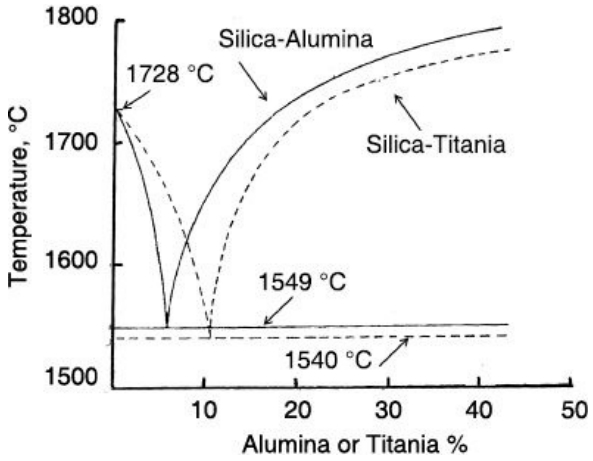


Figure 7.19 Effect of alumina and titania on the melting point of silica.

Effect of lime

The presence of lime does not affect the melting point of the brick, but it should not be present in larger quantity as it may pose problem during use by reacting with acidic slag. The binary phase diagram of SiO_2 -CaO shows (Figure 7.20) that melting point is not lowered by lime up to 30%.

Effect of FeO

The presence of FeO in quartz is also not found to affect the melting point when present up to 40% (Figure 7.20). However, the presence of FeO in quartz may give colour which may not be accepted by user. Hence, the presence of FeO is avoided while selecting quartz.

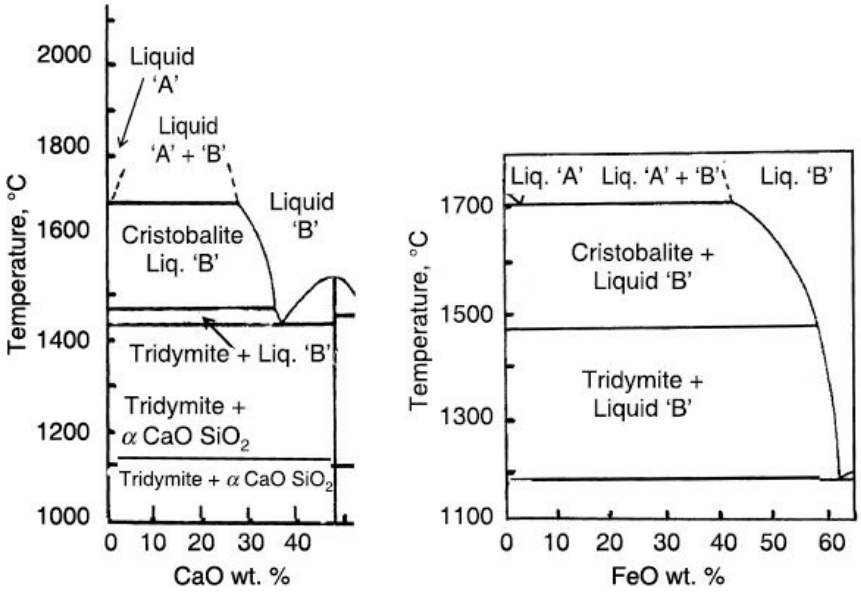


Figure 7.20 Effect of lime and FeO on the melting point of silica.

Structure of silica

The preparation of silica bricks requires considerable care. This needs understanding the structure of silica. The silica has various crystalline forms (Figure 7.21) which changes with heating process. These are as follows:

α-Quartz: It has rhombohedral (trigonal) structure. The helical chains making individual single crystals optically active.

β-Quartz: It has hexagonal structure. The α-quartz converts to β-quartz at 575 °C.

α-Tridymite: It is a metastable phase under normal pressure having orthorhombic structure.

β-Tridymite: It has hexagonal structure. The β-quartz gets converted to β-tridymite at 867 °C (1140 K).

α-Cristobalite: It is a metastable phase under normal pressure having tetragonal structure.

β-Cristobalite: It has cubic structure. β-tridymite converts to β-cristobalite at 1470 °C. β-cristobalite melts at 1723 °C to give vitreous silica.

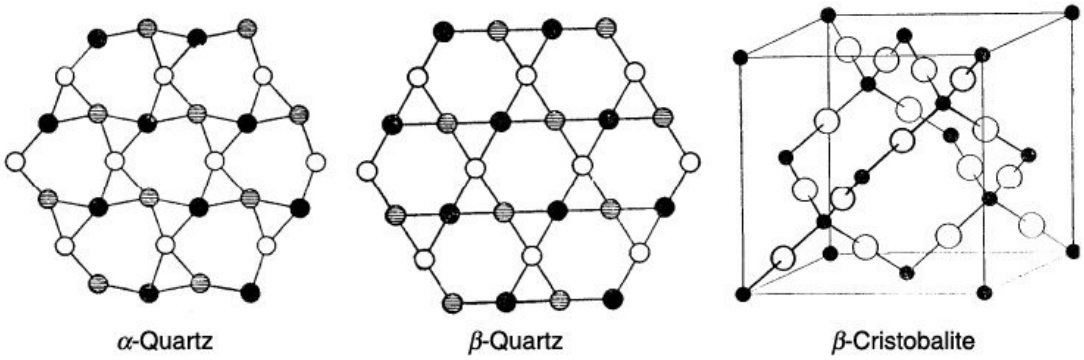


Figure 7.21 Crystal structure of silica.

True density of silica

The different crystalline forms of silica are characterised by its different true density. The true density of silica in different forms is given in Table 7.5. This change in specific gravity could be noticed during heating of silica rocks obtained from different sources as shown in

Figure 7.22. The specific gravity change pattern is different for different rock sources, may be due to the presence of other minor constituents. This specific gravity change in silica could offer a simple means to indicate its structural nature during firing silica bricks in addition to XRD test.

Table 7.5 Density of Various Crystalline Forms of Silica		

S. No.	Crystalline Form	True Density
1	α -Quartz	2.648
2	β -Quartz	2.533
3	β -Tridymite	2.265
4	β -Cristobalite	2.334
5	Quartz glass	2.210

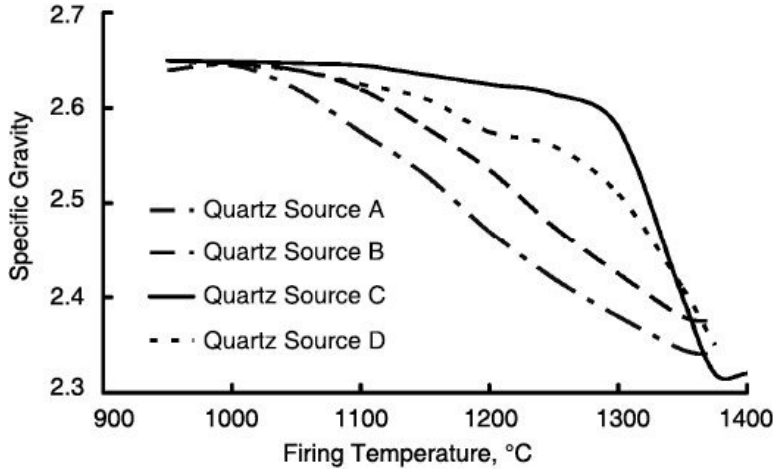


Figure 7.22 Change in silica brick specific gravity with firing temperature prepared using quartz from different sources.

Volume change with temperature

The volume change in silica occurs due to its phase change. When α-Quartz is heated volume expansion occurs at 575 °C (rhombohedral to hexagonal) due to the formation of β-Quartz.

On further heating (870 °C), very little volume expansion occurs due to the formation of β-tridymite (hexagonal). The conversion of β-tridymite to cristobalie (at 1470 °C) is associated with shrinkage (hexagonal to cubic). The total volume expansion from quartz to cristobalie is ~12–13%.

Silica brick making process

The preparation of silica bricks involves the following steps (Figure 7.23).

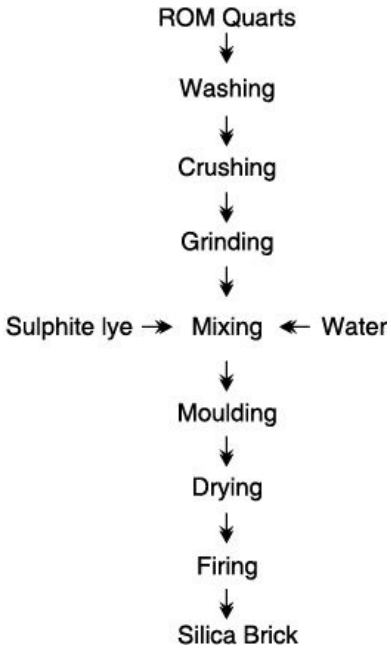


Figure 7.23 Flow sheet for silica brick manufacture.

Washing : The silica rocks mined from its source are washed to remove clay impurities adhering on its surface.

Crushing : The run-of-mine (ROM) rocks are crushed to 50 mm size in jaw crusher and then further crushed to –20 mm in a cone crusher.

Grinding : The crushed quartz is further ground to fine size depending upon the requirement. The quartz being hard mineral the wear of grinding media is high. The dry grinding process is highly hazardous due to dust generation. The wet grinding will need dewatering and drying operation and added cost.

Mixing : The dry silica powder is mixed with sulphite lye (paper industry waste) and water to give green strength to the bricks. The addition of 0.25% sulphite lye provides good dry strength to the bricks.

Moulding : The wet silica powder and sulphite lye mix is moulded in brick shape using suitable machines.

Drying : The moulded bricks are stored in air for some time for drying. In some case, the waste heat of the firing unit is used to dry the bricks.

Firing : The dry moulded bricks are fired in kilns. The kiln has pre-heating, heating and cooling zones. The rate of heating is done in controlled manner to avoid defects due to expansion. In the firing process, quartz granules could be noticed up to 750 °C. The quartz converts to crisobalite when the firing temperature reaches 1200–1300 °C. The crisobalite changes to tridymite with soaking time at 1300–1350 °C. The full conversion to tridymite requires considerable soaking time and energy. The reduction in firing period to

economise the cost may result in residual cristobalite which will need change to tridymite during service period causing change in its volume and damage to the furnace structure.

Quality control

The preparation of good silica bricks poses challenge due to conversion of quartz into less denser form due to firing. The property obtained in silica brick is due to combined effect of various parameters. The following properties are generally obtained:

Porosity : 22–26% porosity in bricks is common.

True density : The specific gravity of fully fired silica bricks ranges from 2.31 to 2.33.

Bulk density : This depends on the porosity of bricks. The soft firing gives high bulk density.

Permanent Linear Change (PLC) value : The hard fired silica brick give little expansion on reheating and offers low PLC value (less than 1%).

PCE value : The silica bricks offer PCE 32–34 cone number (ASTM).

RUL value : The RUL value is seriously affected by alumina and alkali value. A good RUL value expected is 1670 °C.

Thermal Conductivity : Silica bricks offer good thermal conductivity value.

Applications

The silica bricks are used in furnaces requiring following properties:

High Refractoriness Under Load (RUL) : The silica bricks offer good refractoriness
under 0.344 MPa (50 psi) load up-to fusion point 1710–1730 °C temperature.

High resistance to attack by iron oxide and lime : The iron oxide and lime are common as flux and dust in steel plant. The silica bricks are ideal to resist chemical action. Used in all acid steel making furnaces.

High Thermal Shock Resistance : It is resistant to thermal shock in the temperature
range 600–1700 °C and thus suitable for furnace door and cover refractory (e.g. EAF swinging cover).

Good thermal conductivity at higher temperature : Its thermal conductivity increases with temperature which is helpful in using coke ovens.

Special issues

The silica dust is injurious to health as it causes *silcosis disease* . This requires a

very good dust management in such manufacturing units.

7.5.2 Fireclay Bricks

Fireclay bricks represent a type of alumino-silicate brick which ranges from silica to alumina. Fireclay is the most common refractory which is used for a wide range of applications. This brick is prepared from natural clay found in various parts of the world.

The clay is defined as weathered products of silicate rocks containing sufficient hydro-silicate of alumina in the softened condition to produce a plastic or semi-plastic mass when mixed with water. The clay minerals include kaolenite, nacrite, dickite, montmorillonite, and illite in different proportions occurring in various regions. These minerals differ in properties.

Quality of bricks

The fireclay bricks have wide range of applications and are required to fulfil certain properties including chemical composition, refractoriness, and other physical properties. These bricks are classified accordingly. The ASTM system classifies them in five classes as: Super-Duty, High-Duty, Medium-Duty and Low-Duty. In Indian system, they are termed as ‘moderate heat duty’ and ‘high heat duty’ fireclay bricks. The properties of such bricks are given in Table 7.6.

Table 7.6 Properties of the Fireclay Bricks

Type of Firebrick Properties	*Low Duty*	*Moderate Heat Duty or Medium Duty*		*High Heat Duty or High Duty*		*Super-Duty*
		Type 1	*Type 2*	*Type 1*	*Type 2*	
Alumina (%) min.		30	30	38		40–44
Silica (%) max.		65	65	38		
PCE no (ASTM)	15–27	30	30	32	32	33 min
Apparent porosity (max. %)		25	23–25*	25–27*	23–25*	20
Cold crushing Strength, MPa min.		20	22.5–17.5*	20–15*	25–20*	20
RUL ° C min.		1300	1300	1400	1425	1450
PLC at 1350 ° C at 1 hr, (max. %)		1	1	1.5	1	0.4

* Hand moulded bricks.

Raw materials needed

The list of raw materials includes: (i) fireclays (plastic and non-plastic), (ii) refractory grog (broken fire bricks) and (iii) high alumina minerals, e.g. bauxite,

kyanite and sillimanite.

Fireclay

The fireclay occurring in nature is obtained for making fireclay bricks. The selection of fireclay is made on the basis of properties like chemical composition, refractoriness (PCE no.), plasticity, drying shrinkage, firing shrinkage, etc. The fireclay selection is further based on its impurity content as follows:

1. *Silica* present as raw quartz must be lesser in quantity.
2. *Iron oxide* present in small quantity can affect the quality of fireclay bricks by lowering its melting point. Its presence may be avoided.
3. CaO, MgO and TiO_2 present in small quantity has less harmful effect.
4. Presence of *alkali* in small quantity (1–2%) is harmful as it causes vitrification, shrinkage and spalling of the brick during service.

Grog

The grog is added (0–90%) in natural fireclay to regulate quality of the firebrick. The fireclay brick property depends on grog ratio and its size. The desired grog is obtained from two sources:

The broken fireclay bricks: These are used after crushing and grinding. The grog quantity from this source is unpredictable.

Manufactured grog: These are prepared by firing raw fireclay in rotary kiln. This source provides desired quality grog with predictable quantity.

Bauxite

It is used in small quantity to regulate alumina content in the fireclay bricks. It consists mostly of the minerals, e.g. gibbsite $Al(OH)_3$, boehmite γ-AlO(OH) and diaspore ∝-AlO(OH) mixed with iron oxides goethite and hematite, the clay mineral kaolinite and small amounts of TiO_2 .

Sillimanite and kyanite

Sillimanite and kyanite are an alumino-silicate mineral with the chemical formula $Al_2\ SiO_{5.}$. The kyanite and sillimanite are added in small quantity as a source of alumina.

Preparation Method : The preparation of fireclay bricks illustrated in Figure 7.24 involves the following steps:

Raw material sourcing and storage

The various raw materials obtained from different sources are stored in marked yards.

Raw material preparation

All the raw materials are crushed, ground and sized to be kept ready for blending.

Preparation of grog

The grog required for the brick making is prepared by crushing and sizing of broken firebricks in the plant. The large mechanised plants generate less damaged bricks as rejects and they

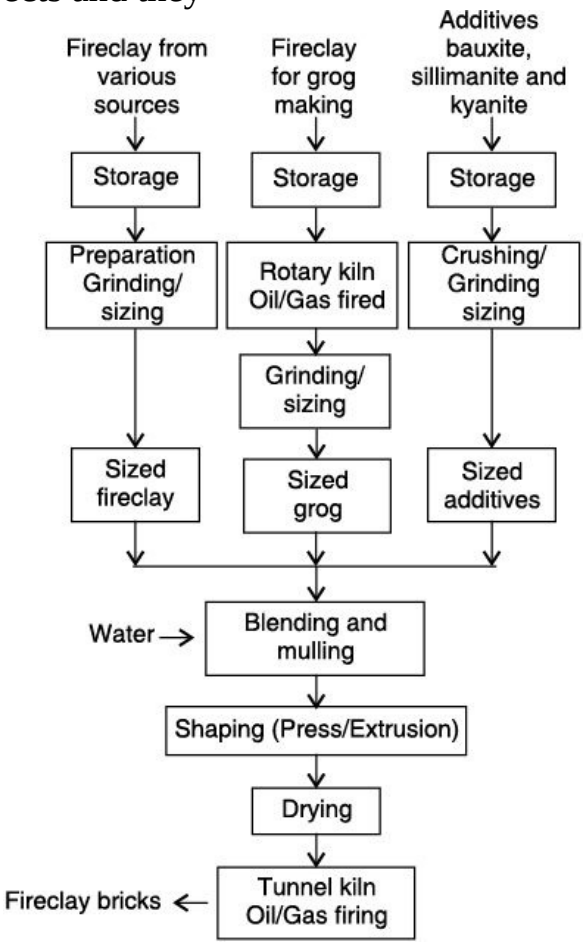


Figure 7.24 Flow sheet for fireclay brick manufacture.

opt for firing raw fireclay in rotary kilns within the plant. The grog amount, its size and particle size distribution are important to achieve desired property in the firebricks. The finely ground grog added in small quantity with hard firing yields fireclay bricks suitable for high slag resistance. The larger quantity of grog is added to get high porosity fireclay bricks.

Blending and mulling

The fireclay from various sources is mixed in the desired ratio, and minor ingredients are added to blend properly. This fireclay mixture is mulled with moisture added in quantity depending on the next step. The dry press moulding requires 5–8% moisture while this is raised to 10–15% for the wet moulding process. The addition of right quantity of water and mulling is important to have the desired brick quality with lesser defects by uniformly distributing the moisture on the surface of the clay particles.

Shaping

The bricks are shaped using two techniques: Dry moulding and Wet moulding.

Dry moulding: The clay mixture having 5–8% moisture which flows as powder is poured into the moulding box and then pressed using mechanical or hydraulic press machines. The press machine with vacuum is useful in removing trapped air within clay mixture.

Wet moulding: The clay mixture with high moisture (10–15%) prepared in a pug mill and the plastic dough are then extruded through auger machine, sometimes using vacuum, to the desired shape and long in size. This longer shape is cut into small pieces by wire cutter. This small sized brick shape is further repressed to give any special contour or feature on the brick surface, edges or corners.

Drying

The green bricks made by dry moulding may not need this step and may be sent for next step of firing. However, the green bricks made by wet moulding needs slow drying to remove excess moisture. The green bricks placed on wooden pallets are stored in drying room for certain period which have steam heated floors. Alternately, the firing kiln may be designed to have extended zone for drying using the exit hot gases.

Firing

The tunnel kilns are commonly used for firing firebricks. These kilns are heated by combusting oil or gas depending on the economics. The tunnel kilns have three heat zones— pre-heating, heating and cooling. The heating zone temperature may range from 1100 to 1400 °C depending on the quality of the bricks desired. The fireclay with lower refractoriness is fired at lower temperature.

Applications

The character and quality of the bricks made utilise different proportions of clays in the blend to yield fireclay bricks with following uses:

1. Super-duty fireclay bricks find applications where good strength and volume stability at high temperatures alongwith resistance to spalling is needed caused by rapid temperature change.
2. High-duty fireclay bricks are used in bulk quantities for range of applications due to their better resistance to thermal shock. The high-duty fireclay brick offers better economy than medium-duty brick for the linings of furnaces operated at moderate temperatures for longer durations.
3. Medium-duty bricks are suitable for use where refractory is exposed with moderate conditions. These bricks can withstand abrasion better than other bricks of the high-duty category.
4. Low-duty fireclay bricks find use as 2nd layer backing brick with 1st layer consisting of higher refractoriness bricks. These are also suitable for other services where relatively lower temperatures prevail.

7.5.3 Burnt Magnesite Bricks

It is an important refractory brick used in steel industry. This is made by using magnesia (MgO), which is obtained from magnesite or sea water. Magnesite is a mineral with the chemical formula $MgCO_3$ (magnesium carbonate). Similar to the production of lime, magnesite can be burnt in presence of coal to produce MgO, which in the form of a mineral is known as periclase.

Quality of bricks

The burnt magnesite bricks properties are given in Table 7.7. These bricks are associated with the following properties:

1. *Thermal Conductivity* : This is very good at 300 °C, but decreases with increasing temperature (Figure 7.10).
2. *Electrical Conductivity* : This is low at room temperature, but high at 1500 °C which is helpful in making electrical connection in hearth furnaces.
3. *Thermal Expansion* : These bricks show high (1.2–1.4) thermal expansion when heated to 1000 °C.
4. *Slag resistance* : very good
5. RUL value: These bricks fail in narrow temperature range due to fusion of

the bonding constitutent (forsterite $2MgO.SiO_2$ or monticellite $MgO.CaO.SiO_2$). These are solid at given temperature and with few degree rise in temperature become liquid causing brick failure.

6. *Permanent Linear Change value* : Higher firing temperature 1700 °C gives lower PLC value brick.

Table 7.7 Properties of a Typical Dead Burnt Magnesite Brick	
Characteristics	*Value*
Apparent porosity, per cent, max.	20
Apparent density, g/cc	3.52–3.56
Bulk density, g/cc	2.83–2.86
Refractoriness under load at ° C, min.	1600
Spalling resistance, cycles, Min	30
Permanent linear change (PLC) % max. (Heating at 1500 ° C for 2 hr)	1
Cold crushing strength, MPa, min.	55

Table 7.8 Properties of Magnesite Mineral	
Characteristics	*Properties*
Chemical formula	$MgCO_3$
Colour	Colorless, white, pale yellow, pale brown, faintly pink, lilac-rose
Crystal system	Trigonal-Hexagonal
Fracture	Conchoidal
Mohs scale hardness	3.5–4.5
Luster	Vitreous
Streak	white
Specific gravity	3.0–3.2

Raw materials needed

The major raw material for the manufacture of magnesite brick is magnesia (MgO). The chemical analysis of dead burnt magnesite produced by two different methods is given in Table 7.9.

Table 7.9 Chemical Analysis of dead burnt Magnesite produced from different Sources and Methods		
Constituents	*Produced from*	*Produced from*

	Natural Mineral	*Sea Water*
MgO	90.81	91.5
CaO	2.6	2.5
SiO_2	5.4	2.5
Fe_2O_3	0.7	2
Al_2O_3	0.4	0.5

The two methods to prepare magnesite using natural mineral magnesite ($MgCO_3$) and sea water through chemical method are described briefly in the forthcoming sections:

Use of natural mineral (Magnesite)

Magnesite is a naturally occurring mineral. The mineral properties are given in Table 7.8. The mined magnesite is converted directly into magnesium oxide by calcinations. This is done by firing the lumps in horizontal rotary kilns using oil or gas as fuel. The temperature and duration of the calcination process determines the respective reactive properties (grades) of the magnesium oxide. Decomposition of magnesium carbonate ($MgCO_3 \rightarrow MgO + CO_2$) to form magnesium oxide and carbon dioxide begins at a temperature slightly above 400 °C (Figure 7.25). The firing temperatures between 500–1000 °C produce magnesium oxide with a relatively high specific surface area and good reactivity. These react readily with water and even fairly vigorously with diluted acid solutions. The firing at temperatures above 1600 °C produces ‘dead burnt magnesite’. Dead Burnt Magnesite means magnesite with unreactive properties. These grades are principally used as a refractory material.

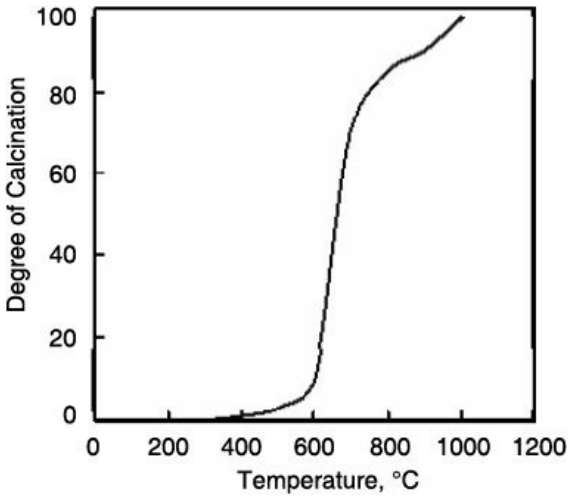


Figure 7.25 The completion of magnesite calcination with temperature.

Preparation of magnesia by chemical method from sea water

The magnesium oxide produced from calcinations of mineral magnesite may not meet all the requirements concerning purity and activity. The chemical processes, therefore, have been developed to produce magnesium oxide. Magnesium oxide produced this way from sea water is called *precipitated* , *chemical* or *synthetic magnesia* .

The sea water containing Mg (1300 ppm) as $MgCl_2$ is utilised to precipitate out magnesium as $Mg(OH)_2$ using lime milk solution. The process of making dead burnt magnesite from sea water is shown Figure 7.26 which involves the following steps:

Step 1: Collection of sea water in a reservoir.

Step 2: Filtration of sea water to remove sand etc. and its storage in tanks.

Step 3: The cleaned water is given softening treatment to minimise the precipitation of impurities e.g. bicarbonates. The pH level 4 is maintained.

Step 4: This soft sea water is treated with calcined dolomite (CaO + MgO) to precipitate out $Mg(OH)_2$ according to the following reaction

$$MgCl_2 + Mg(OH)_2 + Ca(OH)_2 \rightarrow 2Mg(OH)_2 + CaCl_2$$

Step 5: The precipitated $Mg(OH)_2$ is allowed to settle in thickener and the slurry is dewatered to get $Mg(OH)_2$ as cake.

Step 6: The wet $Mg(OH)_2$ cake is fired in a rotary kiln (1700 °C) to get dead burnt magnesite (MgO).

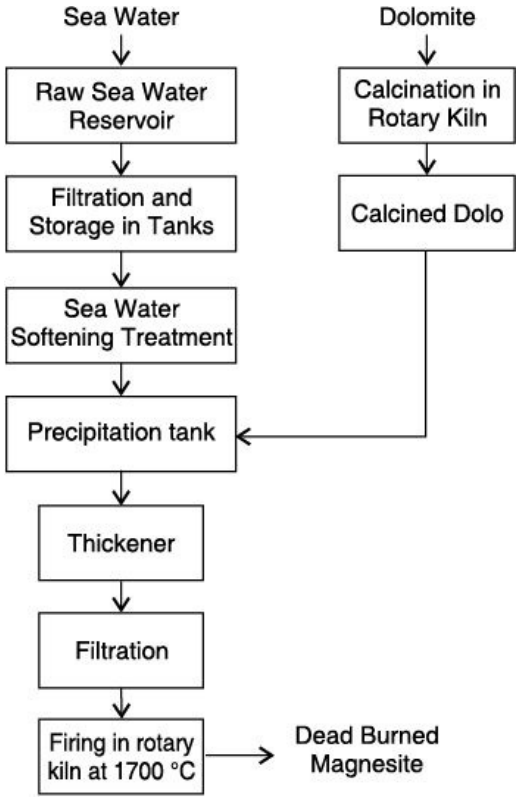


Figure 7.26 Flow sheet for dead burned magnesite from sea water.

Brick preparation method

The magnesite brick is prepared using the dead burnt magnesite produced from any of the two methods just described. This brick preparation involves the following steps (Figure 7.27):

Grinding

The dead burnt magnesite is ground and sieved to generate two or three sized fractions as coarse, medium and fines. These sized fractions are again mixed to get a desired particle size distribution for preparing brick with desired porosity. The denser bricks are desired for steel melting furnace hearth bottom, while less denser bricks are needed for furnace roof applications.

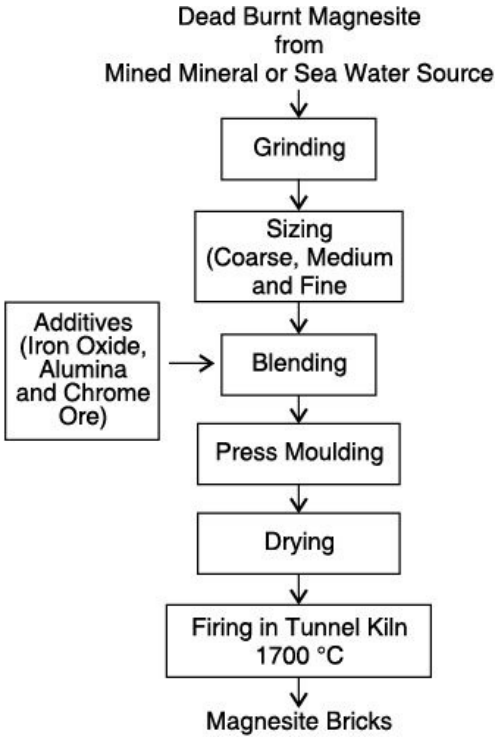


Figure 7.27 Flow sheet for magnesite brick manufacture.

Additives

The additives are added to get the following specific property:

1. Iron oxide in small quantity is added to get higher density.
2. Alumina in small quantity is added to give increased thermal shock resistance.
3. Chrome ore is added to get chromme magnesite brick.

Moulding

The mixed particle size of dead burnt magnesite powder is mixed with 5% water and then pressed in brick shape using mechanical, hydraulic or hammer type press. The effect of increased moulding pressure in lowering the porosity of the bricks is shown in Figure 7.28. The use of nearly 70 MPa pressure is common.

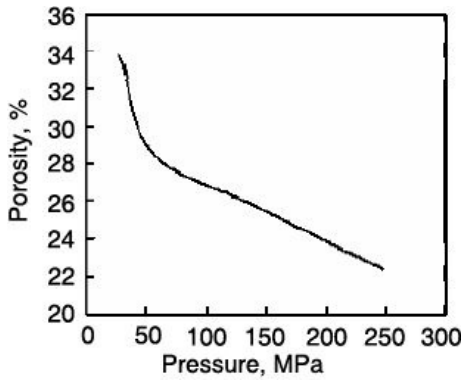


Figure 7.28 Effect of moulding pressure on brick porosity on magnesite bricks.

Drying

The bricks are dried and care is taken to avoid excessive hydration which may cause volume change and develop cracks specially in bigger sized blocks.

Firing

The bricks are fired in tunnel kiln using oil or gas as fuel. The increased temperature in kiln up-to 1400 °C does not cause much sintering as can be seen in the Figure 7.29 showing changes in specific gravity with temperature and firing time. The raised temperature to
1650 °C causes increase in specific gravity which is indicative of grain fusion and bonding. The increased soak period of 30 minutes gives the desired specific gravity in the brick. This needs furnace to be fired at 1700 °C.

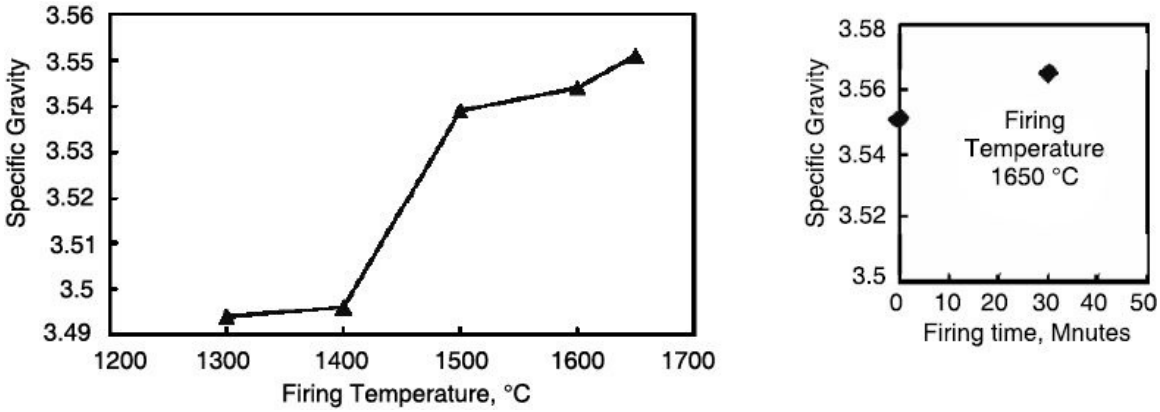


Figure 7.29 Effect of firing temperature and time on magnesite brick specific gravity.

Applications

The dead burnt magnesite bricks are used for making hearths of melting furnaces (open hearths and electric arc furnaces). These are used in steel plant mixers holding the liquid iron. The heating furnaces front and end walls are made of

magnesite.

7.5.4 Dolomite Bricks

Dolomite is a naturally occurring carbonate mineral of calcium and magnesium ($CaMgCO_3$). Its properties are given in Table 7.10.

Table 7.10 Properties of Dolomite Mineral

Characteristics	*Properties*
Chemical formula	$CaMg(CO_3)_2$
Colour	White, gray to pink
Crystal system	Trigonal
Fracture	Conchoidal
Tenacity	Brittle
Mohs scale hardness	3.5 to 4
Luster	Vitreous to pearly
Streak	White
Specific gravity	2.84–2.86

Dolomite is used as a refractory material in form of calcined powder or stabilised bricks.

Dolomite bricks are highly porous and suffer from the following two problems during use:

1. *Perishing:* The free lime in calcined bricks reacts with water (moisture in air) and break down into pieces.
2. *Dusting:* The β-dicalcium silicate formed at high temperature either during brick firing or during service tends to revert to γ-dicalcium silicate during cooling with 10% increase in volume. The stress caused by expansion causes brick to disintegrate in pieces which is termed as ‘dusting’.

There problems are solved by ‘stablisation’ of dolomite bricks using the following three methods:

1. The calcined dolomite is mixed with pitch to minimise the ‘perishing’ in bricks.
2. Conversion of free lime to a silicate or ferrite to prevent hydration during storage or use.
3. Addition of boric acid, phosphate or other stabiliser to prevent

inversion from β to γ dicalcium silicate.

Quality of bricks

The dolomite brick properties are given in Table 7.11.

Raw materials needed

The major raw material used is mineral dolomite obtained from mines. This composition depends on the local occurrence conditions. The typical dolomite properties are given in
Table 7.12. The ratio of CaO to MgO does not affect the refractoriness of dolomite as the lowest melting point is 2300 °C for 33% CaO and 67% MgO. The melting point is higher for any other ratio.

Table 7.11 Properties of Dolomite Bricks

Characteristics	*Values*
Chemical composition	
CaO %	40
MgO%	40
SiO_2 %	14.4
Fe_2O_3 %	3.4
Al_2O_3 %	1.5
Porosity (%)	22–24
Bulk density, g/cc	2.53–2.58
App. Density, g/cc	3.30–3.36
Cold crushing strength, MPa	35–55
Permanent Linear Change (PLC)	0.088–0.12
RUL, ° C	1600
Thermal Shock Resistance, no of cycles	2–3
Thermal Conductivity at 300 ° C	2.16 W/mK
Specific heat (20–750 ° C range)	025
Slag resistance to FeO	Less than pure MgO

Table 7.12 The Properties of a typical ROM Dolomite

Characteristics	*Values*
Chemical Composition	
CaO %	30–31
MgO%	19–21
SiO_2 %	0.3–2
Fe_2O_3 % + Al_2O_3 %	0.5–3.6
LOI%	45–47
Bulk density, g/cc	2.4–2.7
Specific gravity	2.81–2.87
Porosity (%)	2–13

Preparation method

The following steps are involved in making dolomite bricks:

1. *Preparation of mined mineral:* The mined mineral is broken and crushed either at mine or at plant to make them suitable for calcinations in rotary kilns.
2. *Stabilisation of dolomite:* The dolomite (75%) and serpentine (25%) are heated in rotary kiln to produce stabilised ‘doloma.’

$$6(CaCO_3 .MgCO_3) + 3(MgO + 2SiO_2 .H_2O) \rightarrow 2(3CaO.SiO_2) + 9MgO + 2CO_2 + 2H_2O$$

75% Dolomite + 25% Serpentine → Stabilised Doloma

The low temperature calcinations of dolomite would give very reactive and porous ‘doloma’ (Figure 7.30). This doloma is further fired at 1700 °C to reduce the porosity to
~ 17% and make doloma clinker more stabilised.

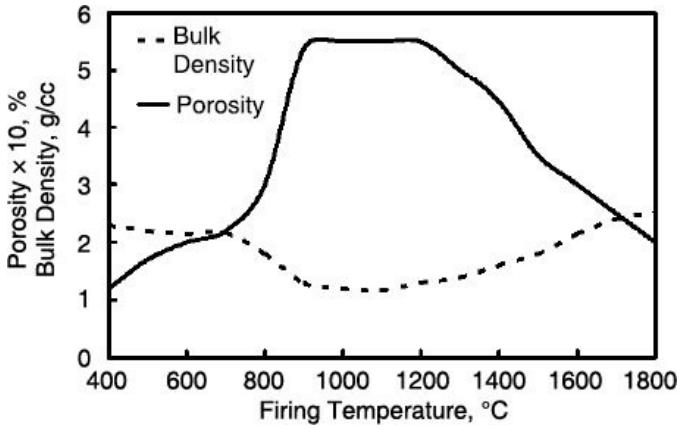


Figure 7.30 Effect of temperature on porosity and bulk density of doloma.

3. *Grinding of clinker:* The ‘doloma’ clinker produced is ground and classified into two or three sizes as coarse, medium and fine.
4. *Mixing:* The ground doloma powder is mixed (60% coarse, 10% medium and 30% fines) with very little (~ 4%) water.
5. *Moulding:* The mixed powder is pressed into moulds using 70–100 MPa pressure in the desired shape.
6. *Drying:* The pressed bricks or blocks are dried below 60 °C in air.
7. *Firing:* The bricks are fired in circular or rectangular furnaces using oil/gas as fuel. The bricks are fired at 1350–1450 °C, and then soaked at 1450 °C for 24 hours to minimise free lime.

Applications

The stabilised dolomite bricks are used in top sub-layer of hearth furnaces (open hearth, electric arc furnaces, etc.). This is useful in ladle and tap hole making in basic furnaces. It is a cheap substitute for magnesia bricks.

7.5.5 Chromite Bricks

The usefulness of chromite as a refractory is based on the following four factors:

1. *High refractoriness* : It has high melting point spinals ($MgO{\cdot}Al_2O_3$ – m.p 2105 °C, $MgO{\cdot}Cr_2O_3$ – m.p. 2400 °C and $FeO{\cdot}Cr_2O_3$ – m.p. 2160 °C)
2. *Moderate thermal expansion* : Chromite has a linear expansion of about 1.3% at 1400 °C, which is almost 50% of that of magnesia (MgO). As a consequence, when added to magnesia refractories, chromite will improve the thermal shock resistance of the refractory.
3. *Neutral chemical behavior* : In addition to refractoriness, a lining material must be compatible with the process slag chemistry. Figure 7.31 shows the range of slag lime-to-silica ratios with which magnesia, mag-chrome and high-alumina refractories are compatible. Chromite-containing materials can tolerate slag ranging from slightly acid to basic, and can be used in place of tabular-alumina brick or magnesia brick in most applications.
4. *Relatively high corrosion resistance* : Chromite has exceptionally good resistance to pyro-metallurgical slag. The acidic slag containing high levels of silica-rich fayalite ($2FeO{\cdot}SiO_2$) attack rapidly on alumino-silicate refractories but the chromite brick has high resistance. Such fayalitic slags are common in many non-ferrous metallic smeltiocesses and chromite

brick offers exceptional service.

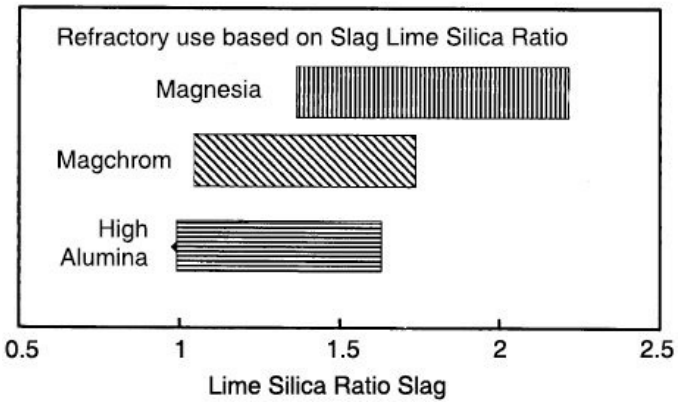


Figure 7.31 Refractory use as a function of slag lime-to-silica ratio.

[*Source:* N. McEwan et al. (2011)]

Quality of bricks

The properties of typical chromite bricks are given in Table 7.13.

Table 7.13 Properties of Chromite Bricks

Properties	*Values*
Chemical composition Cr_2O_3 % MgO % Fe_2O_3 % Al_2O_3 % SiO_2 % CaO%	33–38 18–30 20–21 11–16 4–8 0–0.6
Apparent porosity (%)	22–28
Apparent density, g/cc	3.9–4
Bulk density, g/cc	2.8–3.1
Permanent Linear Change	–
Refractoriness under load (RUL), ° C	1470
Thermal shock resistance, no. of cycles	8–11

Raw materials needed

The main raw material for brick preparation is chromite ore. Table 7.14 gives the chemical analysis of a typical chromite ore.

Table 7.14 Chemical Analysis of a Typical Chromite Ore

Constituents	*Wt. %*

Cr_2O_3 %	~ 45
Fe_2O_3 %	~ 15
FeO %	~ 7
Al_2O_3 %	~ 13
SiO_2 %	~ 1
CaO%	0.1
MgO%	0.2
TiO_2 %	0.3
LOI%	3

Preparation method

The preparation of chromite bricks involves the following steps:

1. *Crushing and Grinding:* The chromite ore is crushed and wet ground using water.
2. *Mixing:* The wet ground chromite ore is mixed with binder (clay) in small quantity.
3. *Moulding:* The green mass is given shape by moulding in a press machine.
4. *Drying:* The green bricks are dried before firing.
5. *Firing:* The dried bricks are fired at 1500 to 1700 °C.

Applications

1. Their most important use is in separating acid and basic refractory linings so as to prevent their interaction even at high temperature (e.g. between acid roofs of basic open hearth furnaces and the basic bricks of side walls).
2. Another use is as bottom refractory of soaking pits.

Special issues

There are environmental issues associated with chrome-containing refractories. Chromium exists in a number of different oxidation states which give it the ability to modify other chemical compounds, or to act as a catalyst in promoting chemical reactions. Hence, it is widely used in the chemical industry. The most important oxidation states are as follows:

Cr(III)—trivalent chromium

Trivalent chromium is the most stable oxidation state of chromium. Trivalent chromium compounds are stable, generally have low solubility in water, and do not present a significant environmental hazard. The most common example of trivalent chromium is green chrome oxide (Cr_2O_3), which is widely used as a pigment in paints and as a component in alumino-silicate refractories. Chromium in chromite is also in the trivalent form.

Cr(IV)

The Cr(IV) oxide (CrO_2) is a black, conducting, ferromagnetic compound used i the production of audio and video tapes.

Cr(VI)—hexavalent chromium

Common examples of hexavalent chromium compounds are chromic acid and di-chromates of sodium and potassium, which are used in the chemical industry and in surface treatment of steels to improve corrosion resistance. Hexavalent chromium compounds are soluble, toxic, and are known to increase the risk of respiratory cancer.

When chrome-based refractory materials are exposed to high temperatures and pressures, it combine with certain chemical phases with the possibility of forming toxic by-products. In particular, the transition in the oxidation state of the chrome from Cr^{3+} to Cr^{6+} is a matter of concern, as hexavalent chromium compounds are classified as carcinogenic and harmful to health. As chromite comes in contact with alkali and alkaline earth oxides, the transition from Cr^{3+} tc Cr^{6+} is accelerated. The reaction in chromium-containing refractories begins along the grain boundaries and thus can spread throughout the structure of the refractory at a fairly rapid rate where circumstances and the environment favour it. The Cr^{6+} content, following the CaO- Cr_2O_3 phase diagram, increases with exposure to temperatures below 1022 °C and with an increase in CaO (from 0 to 42% CaO). In the case of magnesia-chrome refractories temperature, basicity (the CaO to SiO_2 ratio) and the chromite grain size play a role in Cr^{6+} formation Thus, the formation of Cr^{6+} can be minimised by carefully controlling the levels of CaO in the refractory and by avoiding the use of fine chromite during brick making. The use of fused magnesia-chrome or chrome-magnesia grains will also help minimising the potential to form Cr^{6+} within the refractory structure.

Because of the likely formation of Cr^{6+} , when exposed to alkali or CaO environments, there has been a move away from chromium-containing

refractories in those applications where these chemical and certain physical conditions exist. This move has also taken place in other industries and applications where the formation of Cr^{6+} is not at all likely, but a view has been taken that chromium based refractories are environmentally damaging and could be harmful to health. The move to replace chrome-containing refractories has led the development of several other possibilities. These include magnesia-alumina spinels, spinel bonded magnesia, very high alumina materials, zirconia-containing materials, and various fused-cast products.

Exposure limits to Cr^{6+}

Occupational exposure limits to hexavalent chromium range from 1.0 to 0.01 mg/m^3 on an eight hour TWA (time weighed average, values vary from one country to the other). The exposure limit soon to be adopted by the European Union will probably be 0.01 mg/m^3 . The limit in South Africa is 0.05 mg/m^3 . If the maximum nuisance dust level of 10 mg/m^3 is assumed of a material at a hexavalent-chromium level of 450 ppm (unused chromium-bearing refractories vary between 20 and 200 ppm) exposure to hexavalent chromium would be 0.005 mg/m^3 , which is well below the TWA maximum.

Limits for landfill disposal are typically—

1. 0.5 mg/L Cr(VI) in the leachate (Germany)
2. 1.5 mg/L Cr(VI) in the leachate (Japan)

7.5.6 Chrome Magnesite Bricks

The chrome magnesite bricks were developed to remove difficulties faced by chromite bricks in early days. The chromite bricks used to burst and crumble due to alternate exposure to oxidising and reducing atmospheres. They also indicated shrinkage and softening behaviour at high temperatures. These difficulties were solved by the addition of magnesia. The chrome-magnesite series of refractories were initiated during 1930s. The effect of a silicate melt on brick behaviour was investigated in 1950–1960, and became popular in the steel industry due to lower SiO_2 bricks for open hearth and electric-arc furnaces.

Table 7.15 Properties of Chrome Magnesite Bricks

Characteristics	*Magnesite Chrome and Chrome Magnesite Bricks*		
Chemical composition			

Cr_2O_3, min	22.1	27.6	31.7
MgO, min	51.6	41.2	43.1
SiO_2	3.2	5.5	4.6
Fe_2O_3 %	10.2	9.9	9.6
Al_2O_3 %	9.5	12.3	8.0
CaO%	1.7	1.5	0.9
App. porosity, %	18	25	20
App. density, g/cc	3.8	3.88	3.98
Bulk density, g/cc	3.1	2.9	3.1
Refractoriness under load 28 psi at 1600 ° C,	1.4–4.2% deformation after 1 hr	5% deformation after 1 hr	3.3–4.3% deformation after 1 hr
Spalling resistance, cycles, min.	30+	30+	30+
Re-heat linear change, % max. (Heating at 1650 ° C for 2 hr)	No change	–1%	+0.5%
Cold crushing strength, MPa, min.	27.5	30.8	26.7

Chrome magnesite refractories are divided on the basis of chrome oxide content as follows:

1. Magnesite-chrome brick (< 30 Cr_2O_3 %)
2. Chrome-magnesite brick (> 30 Cr_2O_3 %)

Quality of bricks

The properties of some typical chrome magnesite bricks are given in Table 7.15.

Raw materials needed

The main raw materials required for the preparation of chrome magnesite brick are dead burnt magnesite and chromite ore. Table 7.16 gives the properties of two major raw materials used for brick making.

Table 7.16 Raw Materials used for making Chrome Magnesite Bricks

Raw Materials	*Dead Burnt Magnesite*			*Chromite Ore*
Source	*Mine A*	*Mine B*	*Plant C (Sea water)*	*Mine D*
Chemical analysis %				
	–	–		52–57

Cr_2O_3 %				
MgO%	90.5	89.4	99.0	13.6–14.0
SiO_2 %	5.8	2.5	0.2	2.2–4.6
Al_2O_3 %	1.0	1.4	0.1	13.8–14.3
Fe_2O_3 %	0.5	4.2	0.1	12.0–13.0
CaO%	1.8	1.4	0.4	0.1
LOI%	0.4	1.1	0.1	1.1–1.8
Other properties				
CaO /SiO_2 ratio	0.29	0.52	1.99	0.02–0.05
App. Porosity, %	3.2	1.9	0.2	0.3–2.3
App. Density, g/cc	3.5	3.5	3.5	4.2–4.0
Bulk Density, g/cc	3.1	2.9	3.4	4.2–3.9

Preparation method

Five types of chrome magnesite bricks are manufactured by using different binding materials:

Silicate bonded: The magnesia crystallites and chromite grains are bonded together by silicates. These bricks have limited refractoriness, but can have good thermal shock resistance and high pressure flexibility.

Direct bonded: The lower impurity content with high-temperature firing, a direct-bonded brick is prepared. In such bricks, the chromite reacts with the MgO to form a highly refractory spinel $MgO{\cdot}(Al, Cr, Fe)_2O_3$.

Chemically bonded: These are unfired bricks moulded with the use of magnesium salts.

Co-burned : These bricks are prepared by sintering magnesia clinker with chromite grains followed by grinding.

Fusion cast : In such bricks, the magnesia clinker and chromite grains are fused before brick-making process.

Applications

1. All pyro-metallurgical extraction processes for Cu, Ni and Pt.
2. The steel industry in vacuum degasser
3. CLU converters in the ferroalloy industry

Special issues

Environmental issues related to chromite use and manufacture are same as given under chromite bricks.

7.5.7 Insulation Bricks

Insulating refractories are used as thermal barrier that minimises the heat loss from furnace and thus help in saving energy. The cost of energy has been increasing in the recent past giving more importance to insulating refractories. All the furnaces used for melting, heat treatment, heat regeneration or for any other purpose demand maximum heat conservation so as to minimise heat losses for maximum thermal efficiencies and minimum fuel consumption with high production rate resulted by high working temperature. The justification of using insulation brick would depend on the following factors:

1. Comparison of fuel cost saving with added insulating refractory cost
2. Change in furnace output
3. Cost of design alteration to provide insulating layer specially in old working furnace

In general, the insulation bricks have been found to justify their use by saving energy cost, which is the major cost parameter for many products.

Quality of bricks

The insulation bricks are classified in three grades depending on the maximum temperature of use:

1. Grade A – Suitable for temperature up to 1500 °C
2. Grade B – Suitable for temperature up to 1250 °C
3. Grade C – Suitable for temperature up to 850 °C

The desired properties of such bricks as per Indian standard are given in Table 7.17.

Table 7.17 Properties of Insulating Bricks (Indian Standard IS 2042-2006)

Characteristic	*Grade A*	*Grade B*	*Grade C*
Pyrometric cone equivalent, min. ° C	1 717	1640	–
Bulk density, g/cc, max.	1	0.9	0.75

Apparent porosity, % min.	60	60	65
Cold crushing strength, kgf/ cm^2 , min.	20	15	7
Permanent change after reheating for 12 hr, max. at 1500 ° C , %	–1.5	– 1.5	–2.0
Thermal conductivity at 600 ° C w/mk at hot face, max.	0.52	0.35	0.28

Raw materials needed

Various raw materials can be used for making insulating bricks. e.g. diatomite, fireclay, silica sand, asbestos, vermiculite, etc. The properties of bricks made by using these materials are given in Table 7.18.

Diatomite: It is a naturally occurring mass of aquatic plant deposits found on sea bed and lakes in some countries. The diatomite analyses as 73% silica, 8.5% alumina, 2% iron oxide, 1% lime, 0.83% magnesia, 0.3% alkali and 7.7% organic matter.

Fireclay: It is the most commonly used material and its quality is same as used for making fireclay bricks (section 7.5.2).

Silica sand: Silica sand used for making silica bricks can be used for making high porosity silica bricks as insulating brick.

Asbestos: It is a naturally occurring fibrous silicate mineral (chrysotile) with formula $Mg_3 Si_2 O_5 (OH)_4$. Its use is very limited due to health hazard posed by its manufacture and use.

Vermiculite : It is a hydrated biotite (magnesia-iron mica) having chemical formula
$(OH)_2 .(Mg.Fe)_3 .(Si,Al,Fe)_4 .O10.4H_2 O$. It is a flaky solid mineral, and on heating the flakes burst in number of flakes giving air gap.

Table 7.18 Properties of Insulating Bricks made by using different Materials

Properties	*Insulation Bricks Made by Using Different Raw Materials*				
	Diatomite	*Fireclay*	*Silica*	*Asbestos*	*Vermiculite*
Suitable temperature for use, ° C	1000–1200	1200–1400	1200–1400	800	1150
Thermal conductivity, W/m K	0.21	0.21–0.37	0.44–0.5	0.08	0.18
Cold crushing strength, MPa	1.2	2–4.1	3.4–6.9	0.4	0.8
Bulk density, g/cc	0.5–0.9	0.7–1	0.8–1	0.4	0.5
Porosity, %	65–75	65–75	55–65	80	80

Preparation method

The properties of insulating bricks depend on two major factors:

1. The properties of base material used which decides the heat capacity of the insulating bricks.
2. The extent of porosity in the brick which enhances the total brick thermal conductivity in addition to the thermal conductivity of the material used.

Table 7.19 Properties of some typical Insulating Bricks made in India

Properties	*Temperature for Using Insulation Brick*			
	1200 °C	1300 °C	1400 °C	1500 °C
Chemical composition AI_2O_3 SiO_2 Fe_2O_3 CaO	 40 55 1.3 0.4	 40 55 1.3 0.4	 41 54 1.4 0.2	 68 30 0.9 0.8
Bulk density, g/cc	0.78	0.78	0.87	0.96
Thermal conductivity, W/m K	0.24	0.26	0.28	0.34
Cold crushing strength, MPa	2.7	2.7	3.2	3.6
Reheat shrinkage for 8 hrs	0.0% at 1200 ° C	0.50% at 1300 ° C	0.60% at 1400 ° C	0.90% at 1500 ° C
Modulus of rupture, MPa	2.3	1.7	2.0	2.0
Thermal expansion% at 1000 ° C	0.50	0.50	0.48	0.50

The various methods are adopted to generate porosity in the insulation brick include the following techniques:

1. Incorporation of natural or synthetic material having low density.
2. Addition of combustible material to leave pore after its removal during firing, e.g. saw dust, rice husk, etc.
3. Production of cellular structure by mechanical beating the slurry using

a frothing chemical.

4. Formation of gas bubbles in semi fluid medium by a chemical reaction.
5. Other methods.

The green brick making method differs depending on the technique of pore creation, but ultimately the bricks are dried and fired in a manner similar to other bricks. However, care is taken to avoid over firing which may destroy pores and affect the brick quality. The properties of insulation bricks made by a typical Indian manufacturer are given in Table 7.19.

Applications

The insulations bricks are used on outer wall in a wide variety of furnaces. The selection of brick follows guideline as :

1. High thermal insulating capability with low bulk density
2. *Sufficient mechanical strength with good surface* . The cold compressive strength is less important compared to the hot properties of the brick. In general, the mechanical loads are not high. The strength of insulating fire bricks is fully sufficient. Approximately 0.5 N/mm^2 are required as minimum strength. This value ensures safe transport, handling and installation work. Often, a compromise between strength, bulk density and thermal conductivity has to be made.
3. *High thermal resistance under a variety of atmospheric conditions* . Reducing furnace atmospheres require bricks with low iron content (carbon bursting). Higher shrinking occurs in reducing atmospheres.
4. *Resistance to temperature shocks and changes* . The different insulating fire bricks vary in their thermal shock behaviour due to their specific composition
   and porosity. High (> 10%) cristobalite contents have a negative effect on thermal shock resistance. When cristobalite content is below 10%, other criteria are more essential.
5. *Shrinkage* should not exceed 2%, after being subjected to heat on all sides for 24 hours. CaO-bonded bricks are sensitive to overheating due to lower sintering temperatures. Sulphuric gases can attack the bricks.

7.5.8 Graphite based Refractory

Graphite based refractory being neutral in nature is useful for high temperature applications. These are made by using natural or manufactured graphite.

Properties of graphite

The properties of commercial grade graphite are given in Table 7.20.

Table 7.20 Properties of Commercial Grade Graphite

Bulk density (g/cm^3)	1.3–1.95
Porosity (%)	0.7–53
Modulus of elasticity (GPa)	8–15
Compressive strength (MPa)	20–200
Flexural strength (MPa)	6.9–100
Coefficient of thermal expansion ($\times 10^{-6}$ ° C)	1.2–8.2
Thermal conductivity (W/mK)	25–470
Specific heat capacity (J/kgK)	710–830
Electrical resistivity (Ωm)	$5 \times 10^{-6} – 30 \times 10^{-6}$

The other properties of graphite are listed below:

1. It is grey in colour.
2. It possess high crushing strength.
3. It can withstand high temperature (provided not exposed to air).
4. It burns is air when heated.
5. It is not attacked by either acid or basic slag.
6. It is practically infusible, insensitive to spalling.
7. It is close textured and can withstand under fluctuation of temperature.
8. It can withstand attack by corrosive slag, etc.

Raw materials needed

Graphite based refractory products are made using natural and synthetic graphite.

Natural graphite

It is naturally occurring carbon as mineral. It is mined as carbon mineral containing other minerals as impurity which requires beneficiation process like froth floatation. It is a good conductor of electrical current. It is stable over wide

temperature ranges for use as refractory material. It is chemically inactive to many liquids, and is preferred as hearth lining material for liquid metals. This can be obtained in three forms: amorphous, flakes and crystalline.

Amorphous Graphite: These are carbon deposits which have undergone minimum graphitisation process. The word amorphous is a misnomer. The crystallite size is very small during initial period.

Flake Graphite: This carbon form represents intermediate stage which has undergone graphitisation for some time. Flake graphite is generally found in metamorphic rocks.

Crystalline Graphite: This is highly graphitised form of carbon which has undergone considerable time, temperature and pressure resulting crystalline form.

Synthetic graphite

The synthetic graphite can be prepared from coke and pitch. Synthetic graphite consists mainly of graphitic carbon that has been obtained by graphitisation and heat treatment of non-graphitic carbon, or by chemical vapour deposition from hydrocarbons at temperatures above 2100 K. There are essentially two types of synthetic graphite.

1. The first is electro-graphite, which is pure carbon produced from calcined petroleum coke and coal tar pitch heated in an electric furnace.
2. The second type of synthetic graphite is produced by heating calcined petroleum pitch to 2800 °C.

Preparation method

The preparation methods of various products are briefly given here:

Carbon refractories from coke

Carbon bricks are made from metallurgical coke by crushing and grinding mixed with tar (as binding material). The finely ground coke mixed with tar is passed through pug mill followed by heating in a steam jacket for few hours. After steam heating, the mixture is moulded into the bricks which are first dried in cool room and then fired in kilns from 1100 to 1300 °C .

Graphite bricks

The pure graphite is crushed, finely powdered and then mixed with fireclay as binder. This mixture is then processed (shaped, dried and fired) for the preparation of the graphite bricks like fireclay bricks.

Graphite electrode

The high purity graphite is mixed with pitch as binder and compacted in the electrode shape and is then baked to gain strength. This baked electrode is heat-treated (2600 °C – 3300 °C.) to convert carbon in-to graphite which is termed as 'graphitising'. During the graphitising process, the more or less pre-ordered carbon (turbostratic carbon) is converted (see
Figure 2.45**)** into an ordered graphite structure. Depending on the raw materials and the processing parameters, various degrees of conversion to the ideal structure of graphite is achieved. Since graphitisation increases the lattice order and produces smaller inter layer distance (see Figure 2.47), it simultaneously leads to a considerable growth of ordered domains. However, the degree of order that can be reached depends largely on the crystalline pre-order of the solid used. These reduced lattice layer distances are macroscopically noted as a contraction in volume. This graphitisation-shrinkage is approximately 3 to 5%. Due to this shrinkage, density of the graphite increases (see Figure 2.35 a similar phenomenon in case of coke making).

Applications

The high temperature stability and chemical inertness graphite renders it as a good refractory material. Various products are made by using graphite refractory in the metal industry. These are as follows:

1. In the production of pig iron, graphite blocks are used to form part of the lining of the blast furnace. Its structural strength at high working temperature, thermal shock resistance, high thermal conductivity, low thermal expansion and good chemical resistance are of paramount importance in this application.
2. The graphite electrodes in electric arc furnaces are used for providing electric arc struck between metal charge and graphite electrode generating thermal energy needed for steel making.
3. It is used in the production of carbon bricks and in the production of magnesia–carbon refractory bricks (mag-carbon).
4. Graphite is also used to manufacture crucibles, ladles and moulds for molten metals.

5. Graphite blocks are used in non-ferrous metal industry (copper, aluminium and lead smelting furnaces) for making hearth.
6. Additionally, graphite is one of the most common materials used in the production of functional refractories for the continuous casting of steel. In this application, graphite flake is mixed with alumina and zirconia and then isostatically pressed to form components such as stopper rods, subentry nozzles and ladle shrouds used both in regulating flow of molten steel and protecting against oxidation.

7.5.9 Zirconia Bricks

The high melting point and excellent chemical properties of zirconia render its use as a neutral refractory material. However, the tetragonal-monoclinic phase transformation and the associated volume change become the main reason of using it after stabilising zirconia with MgO.

Raw material

The zircon sand is used as main raw material whose properties are given in Table 7.21. MgO is used in small amount to stabilise the zircon.

Table 7.21 Properties of Zircon

Bulk density (uncompacted), kg/m ^{3}	2643–2804
Specific gravity	4.60–4.71
Mohs hardness	7.0–7.5
Melting point, ° C	2100–2300
Coefficient of linear expansion, cm/cm ° C	7.2×10^{6}

Properties of zirconia bricks

These bricks can be used up to 2000 ° C but it can be used with load (3.5 kg/cm^2) up to 1500 °C. These bricks have low thermal expansion behaviour. These are quiet resistant to thermal shock. The properties of zirconia bricks are given in Table 7.22 prepared from two different quality of raw materials.

Preparation method

MgO is added as a stabilising oxide in the desired amount to the zirconia, typically 6 mol%. The mixture is briquetted and fired to a temperature above 1600 °C. This converts the zirconia into cubic phase. The fired briquettes are

then ground in a ball mill (< 10 mm) using steel grinding media. This powder is then washed with dilute hydrochloric acid to remove impurities and form a casting slip (pH 3). The wet mass is shaped in desired size and dried. The drying process results in shrinkage of 2–4%. The dried shape is fired at 1900 °C to get the zirconia bricks. The firing causes a further contraction of ~ 15%.

Table 7.22 Properties of Zirconia Bricks

Raw Material Used Properties	*Zircon Sand*	*High Purity Zircon Sand*
Chemical Analysis		
Al_2O_3 (%)	>1	1.0
ZrO_2 (%)	63.0	65.0
Fe_2O_3 (%)	0.5	0.3
App. porosity (%)	20	17
Bulk density (gm/cm^3)	3.60	3.7
C.C.S (kg/cm^2)	600	800
RUL (°C)	1600	1700

Applications

Zirconia bricks are costly and hence are used only where high temperature is maintained. The applications include:

1. Ladle lining, non-ferrous metal smelting furnaces and steel furnaces
2. Zirconia brick is also suitable for transition region between silica brick and magnesia brick, areas of crown, burner, thermal couple, peep hole, and secondary layer of melter bottom and its back lining, etc.
3. Zirconia brick is also suitable for special region of glass tank, such as paving part and secondary layer of paving bottom, back lining, wall and bottom of fore hearth, flowing spout and spinning portion and melter, etc.

7.5.10 Silicon Carbide Bricks/Blocks

Silicon carbide is a compound of silicon and carbon with chemical formula SiC. It occurs in nature as extremely rare mineral moissanite. In view of its wide applications, the silicon carbide powder has been mass-produced since 1893. Grains of silicon carbide can be bonded together by sintering to form very hard ceramics that are widely used in applications requiring high endurance, abrasion resistance and temperature resistance.

Raw material

The silica sand and coke are the two major raw materials for preparing silicon carbide.

Preparation method

Silicon carbide is made in an electric furnace at temperature of 1500 ° C from sand and coke with the addition of some sawdust and a little amount of a salt. The combustion of sawdust gives gases, which increases the porosity of the charge. The added salt reacts with iron and similar impurities present in raw material forming volatile chlorides, and escape from furnace. This increases the purity of the final product. The silicon carbide thus produced is mixed with bonding agent like clay or silicon nitride and shaped by press moulding and fired at approximately 1400 to 2000 ° C in electric furnace. Recently, self bond type silicon carbide bricks have been prepared; in this silicon carbide particles are mixed with a temporary binding agent such as glue followed by press moulding and firing at 2000 ° C rendering the formation of inter-crystalline bond of silicon carbide which gives strength and other desired properties.

Properties of silicon carbide bricks

The properties of silicon carbide bricks are given in Table 7.23 and described briefly as follows:

Table 7.23 Properties of Silicon Carbide Bricks

Properties	*Data*
Chemical composition	
SiC%	78
Si_3N_4 %	18
(Al_2O_3 + Fe_2O_3 + CaO)%	0.5
(SiO_2 + Si_2ON_2) %	2

Colour	Grey
Bulk density, g/cc	2.64
Porosity, %	17
Cold crushing strength, MPa	160
Thermal expansion (200–1000 ° C) µm/ m ° C	4.3

1. Silicon carbide bricks are dark grey and blue black in colour.
2. They have high thermal conductivity and very low co-efficient of expansion.
3. Clay bonded bricks can be used up to 1750 ° C.
4. Nitride bonded bricks have a high strength and superior thermal shock resistance than clay bonded bricks.
5. Self bonded products have high refractoriness, superior strength, high density, high abrasion resistance and high chemical resistance.
6. However, silicon carbide bricks tend to oxidise to silica when heated in air at temperature of 900 to 1000 ° C, but this drawback is overcome by coating them with thin layer of zirconium.

Applications

They are used for partition walls of chamber kilns, coke ovens and muffle furnaces due to their hardness, great strength and toughness.

7.6 COMMON MONOLITH REFRACTORIES

In steel industry, the grog, dead burnt magnesite, ramming mass, alumina powder, fireclay, fire cement, etc. as monolith refractory finds application in furnace construction and repair of the furnace in hot and cold condition. These are briefly described below:

7.6.1 Grog

Grog is used to fill the vacant space in the furnace during construction and repair in steel industry. The grog preparation has been described in section 7.5.2 during fireclay brick preparation. These are broken pieces of fireclay bricks (used/unused). These are also prepared by firing fireclay in kilns and then crushed to size (Figure 7.24).

7.6.2 Dead Burnt Magnesite

The dead burnt magnesite granules are used for hot repair of the furnace. The composition, preparation methods, etc. are given in section 7.5.3 while discussing brick making.

Table 7.24 Ramming Mass

Property	*Acid Ramming Mass*	*Basic Ramming Mass*
Chemical composition		
SiO_2 %	99	2
Al_2O_3 %	0.02	2
MgO%	–	93
Fe_2O_3 %	–	1.
CaO%	–	2
Granulometric analysis		
–4.00 mm to + 1.00 mm size %	33	35
–1.00 mm to + 0.20 mm size %	30	30
–0.20 mm to + 0.06 mm size %	17	15
–0.06 mm size %	20	20
Max. temperature use, °C	1700	1700
Bulk density, g/cc	2 – 2.2	2.75
PCE value ASTM No.	31–32	37–38
Application area	Induction furnaces	Launder L.D. converter Electric arc furnace, Induction furnace melting (mild/stainless Steel/Mn-Steel)

7.6.3 Ramming Mass

The ramming mass is used for hot repair of the furnace and preparation of induction furnace melting crucible by in-situ sintering process.

The ramming mass can be made or purchased in ready to use form for acid and basic lining both. These are prepared by blending suitable particle sizes of quartz (acid) or dead burnt magnesite (basic) particles with binders like boric

acid. Such ramming mass mixture when gets exposed to high temperature, it gets sintered and offers good refractory conditions needed during steel melting process.

Table 7.24 gives the composition and other details of the ramming mass.

7.6.4 Alumina Powder

The alumina powder is sometimes used to protect the floor of small muffle heating furnaces. It is also used as a packing material to fill in the voids while constructing furnaces. The properties of alumina powder is given in Table 7.25

Table 7.25 Properties of Alumina Powder

Property	*Values*
Chemical form	Al_2O_3
Density, g/cc	3.95–4.1
Melting point, ° C	2072
Thermal conductivity, $Wm^{-1}K^{-1}$	30

7.6.5 Fireclay

The fireclay is naturally occurring clay which is used for fireclay (section 7.5.2) refractory brick making. The same fireclay is used as mortar and repair material.

7.6.6 Fire Cement

Fire cement is a high alumina refractory (cements/mortars) which is suitable for joining, coating, and patching in all high temperature applications from 1450 °C to 1860 °C. They are air-setting in nature with outstanding bonding properties at ambient and operating temperatures. Table 7.26 gives its properties and applications.

7.7 CASTING PIT REFRACTORIES

The metal casting practice requires various refractory components which are specially made for the purpose having desired shape and quality. The commonly used components are discussed in the forthcoming sections.

Table 7.26 Properties of High Alumina Fire Cement

Properties	*High Alumina Refractory Cements*			
Service temperature, °C	1700	1750	1810	1860
Chemical analysis				
Al_2O_3 %	44.2	74.0	81.0	88.0
Fe_2O_3 %	0.7	1.3	0.7	0.1
Bond type	Air setting	Air setting	Air setting	Air setting
Applications	Foundry ladles, Foundry furnaces, Kilns and kiln cars in ceramics	Steelworks and foundries where high temperatures are encountered such as setting high alumina bricks for safety linings in pouring ladles and setting bricks, purging nozzles in continuous casting, tundishes, etc.	Higher temperature alloys and treatment vessels	Setting sliding gate plates, purging nozzles and setting pre-cast shapes

7.7.1 Ladle Components

Steel ladles are required in a steel plant to perform the following (Figure 7.32) functions:

1. Receive liquid steel from steel making furnace and transport it to casting facility
2. Serve as a container during secondary steel refining including temperature control, degassing, deoxidation, composition adjustment by addition of ferro-alloys, etc.

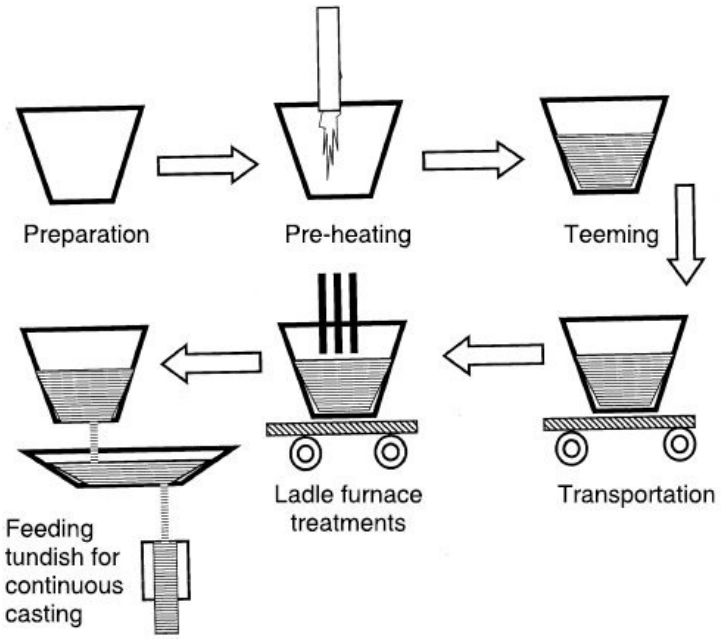


Figure 7.32 Ladle service cycle.

The ladle component refractories are expected to sustain:

(i) high temperature (1600 to 1650 °C) for longer duration,
(ii) mechanical erosion by falling liquid metal,
(iii) slag attack and
(iv) thermal shock while receiving the metal

The ladle design used by steel plants depends on the steel making practice. The conventional old ladles have nozzle, stopper and stopper rod assembly fitted to regulate metal flow during casting practice as shown in Figure 7.33. The newer plants use ladles equipped with slide gate arrangements which is shown in Figure 7.34. All these components are described briefly in the following section.

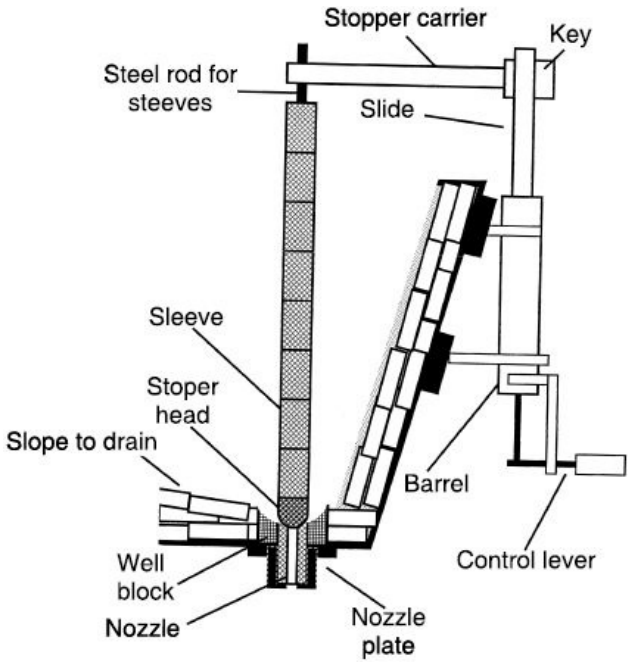


Figure 7.33 Ladle with nozzle and stopper.

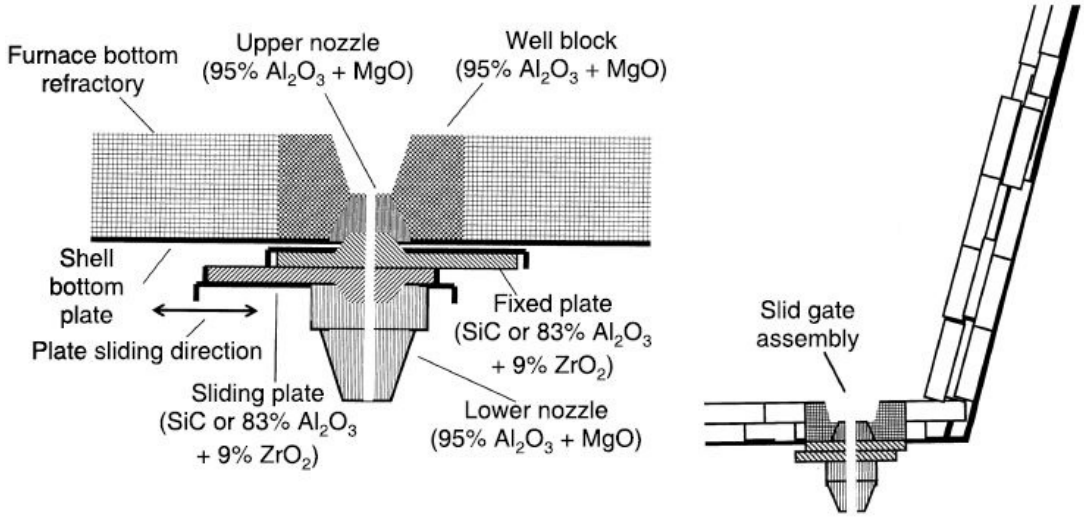


Figure 7.34 Ladle with slide gate.

Nozzle

It allows the liquid metal flow with regulated rate controlled by gap between nozzle seat and stopper head. The nozzle block is fitted at the bottom of the ladle and can be replaced in case it gets damaged or worn out.

Stopper

The stopper sitting on the nozzle mouth regulates liquid flow. The gap between stopper head and nozzle mouth is regulated by a lever fitted to the stopper rod.

Stopper rod sleeve

The sleeves on the stopper rod are provided to protect steel rod.

Slide gate

The slide gate system has been developed to control liquid flow for use in bottom pouring electric arc furnace (discussed in Chapter 6 and shown in Figure 6.25) or steel casting ladle. The basic function of the slide gate in ladle is to regulate the flow of the liquid steel from the ladle to the tundish. The slide gate being a two plate linear, hydraulically driven, gate system the opening is regulated by moving the sliding plate against the fixed plate. This sliding mechanism system has several advantages compared with conventional stopper rod mechanism as given below:

1. Slide gate refractory contact steel liquid only in the casting process, and therefore not subject to longer duration of time which gives a longer gate service life.
2. The casting speed can be controlled accurately, and thus helps in improving the quality of cast steel.
3. Sliding mechanism is mounted on the steel sliding gate outside of the package which renders easy and safe ladle operation giving better work conditions.
4. Sliding mechanism offers remote operation to adopt automated casting operating practice.

Table 7.27 gives the refractory quality used for making nozzle, stopper and sleeves whereas the quality of slide gate refractory components and their properties are given in Table 7.28.

Table 7.27 Refractory Quality for Nozzle, Stopper and Sleeves

Component Properties	*Nozzle*	*Stopper*	*Sleeve*
Chemical analysis			
SiO_2 %	54.5	54	62.2
Al_2O_3 %	38.9	39	30.0
Fe_2O_3 %	3.2	3.5	4.4
TiO_2 %	1.3	1.2	1.2
CaO%	0.9	1.0	0.1

MgO%	0.2	0.3	0.7
Physical properties			
Apparent porosity,%	21–25	16	22
Apparent density, g/cc	2.66	2.58	2.60
Bulk density, g/cc	2.00	2.10	2.03
Permanent linear change,% (Heating at 1500 ° C for 2 hr)	+ 5.3	+ 6.4	+ 2.7
Refractoriness under load			
Initial softening, ° C	1130	1100	–
Rapid softening, ° C	1410	1470	–
10% deformation, ° C	1480	1520	1660
Thermal shock resistance, nos	20 +	26 +	–

Table 7.28 Slide Gate Components Refractory Properties

Components Properties	*Slide Plates*	*Slide Gate Nozzles*	*Well Block*	*Seating Block*
Chemical analysis				
Al_2O_3 %	92 min	90	95	95
MgO%				
Fe_2O_3 %			1 max.	0.5
SiO_2 %			2 max.	0.5
Cr_2O_3 %				3–4
Physical properties				
Apparent porosity,%	5	8	16	14
Bulk density, g/cc	3.1	3	3	3
Cold crushing strength, MPa	150	60	60	65
HMOR at 1400 ° C, 0.5 hr, MPa	20	15	16	18

7.7.2 Tundish

The tundish acts as a buffer between the ladle and mould (Figure 7.35) in the continuous casting process. The functions of tundish are as follows:

1. Serves as metal reservoir providing a constant ferro-static pressure to

ensure a constant flow rate of liquid metal to the mould of continuous casting (concast) machine.

2. Prevention of ladle slag entering the concast mould.
3. Division of the liquid metal stream into many concast strands.
4. Allows separation of non-metallic pieces.

The tundish is provided to deliver the molten metal to the concast mould evenly, and at a designed throughput rate having temperature without any contamination or inclusions. It distributes molten steel in continuous casting moulds, and is typically operated at a constant

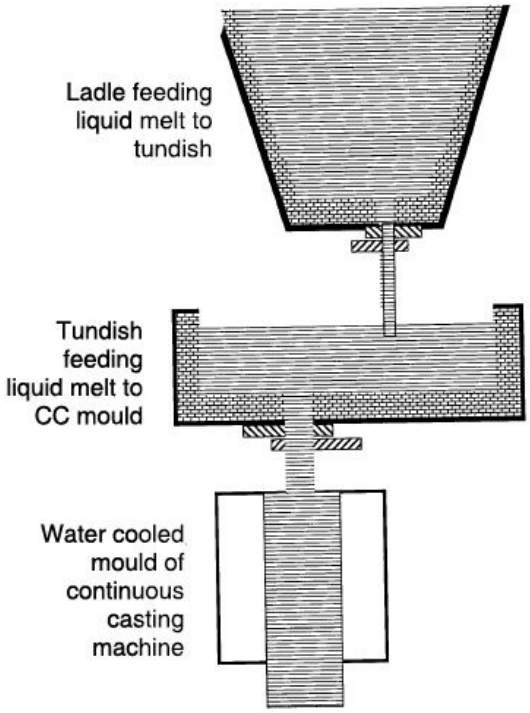


Figure 7.35 Tundish as a melt reservoir between ladle and mould.

bath depth to ensure a constant feed rate into the mould required to achieve a constant throughput. In the continuous casting process, the tundish directly controls the molten steel in its last stage of processing, and the refractories used here are therefore, required to have high stability and special properties. Tundish is one of the most important areas of refractory application and is also one of the biggest ‘cost controling parameter’ in the continuous casting process.

There are different tundish lining practices which can be classified into following five major types:

1. Brick lined tundish
2. Refractory powder gunning
3. Pre-formed tundish lining
4. Spray lined tundish
5. In-situ dry refractory forming

These are briefly discussed below:

Brick lined tundish

The continuous casting practice started around 1960s, and initially the refractory brick lining technology was used as practiced in other metal containing vessels. These bricked linings were of high alumina type and they were used in direct contact with liquid steel after intense pre-heating.

Refractory powder gunning

This technique was developed to solve the problems of brick lining. The alumino-silicate based powder was used in the beginning to make a refractory layer by gunning technique. Later magnesite powder or basic refractory powder was found attractive. Such refractory gunning practice provided a monolithic joint-free lining and improved the de-skulling nature.

Pre-formed tundish lining

This new type of pre-formed board tundish lining was introduced in 1970s. Such pre-formed board type lining were having low density, highly insulating, disposable and pre-cured refractory lining. They were found to be easy de-skulling requiring no equipment, and its low cost made it attractive among many users. The silica-based pre-formed boards permitted only ‘cold start’ practice, but the magnesite-based boards could be pre-heated to give ‘hot start’ for rendering low hydrogen in steels.

Spray lined tundish

This technique uses a refractory spraying machine to spray deposit thick refractory slurry to give joint free lining. This method provided the advantage of better lining density, thickness and refractory composition compared to gunned technique. This method used compressed air for atomising the slurry.

In-situ dry refractory forming

In this method, the refractory powder is mixed with resinous bonding material

which gets activated at low temperature (~ 160 °C). The dry refractory powder and resin binder mix is filled in the gap between a tundish former and tundish permanent lining. The refractory powder is heated by hot air (400 °C) for ~ 50 minutes followed by cooling (~ 30 minutes). The main advantage of this method is absence of moisture. This methods gives good de-skulling rendering prolonged tundish lining.

7.7.3 BF Runner

Blast furnace (BF) runners are designed to carry molten iron (hot metal) and slag, during tapping and hot metal transfer to ladle. The runners also facilitate metal and slag separation during flow. The runner refractory lining reacts with iron, slag and air, especially at the metal- slag and slag-air interfaces. Abrasion of the refractory lining is also encountered, especially at the impact area of the main trough and the tilting runner. Runner system must also meet the expectation of BF operators, i.e., long and predictable campaign life, ease of installation, mechanised dismantling and installation processes, safe working conditions, rapid drying capability, campaign life without intermittent repairs and above all reduced operating costs.

Sand with small amount of clay and coke, bonded by tar, did suffice in the past as trough lining material. The modern BF plants use alumina-based formulations with carbon and SiC for runner lining.

Review Questions

1. What are the various properties needed by a material to be selected as a refractory for a furnace?
2. What are the various high temperature properties tested for a refractory material? Give the significance of each test.
3. What are the various scales used to give PCE no.? Which scale is the most commonly used?
4. What are the different techniques used for testing thermal expansion of a refractory? Give their merits and limitations.
5. What are the various steps involved in making refractory bricks? Describe the steps briefly.
6. What are the various mixing equipment used to blend the refractory constituents while making bricks? Give a brief description of such

equipment.

7. What is the effect of alumina, titania, lime and FeO content on the quality of silica brick?
8. What structural changes occur during firing of silica bricks? How the specific gravity of the silica brick could be used to assess the structural changes with firing temperature?
9. How can you increase the alumina content in fireclay brick during its preparation? Give some options with reason.
10. What is grog? Where is it used and why? What are the methods of preparing grog?
11. What are the different methods of preparing dead burnt magnesite? What is
    the difference in quality of dead burnt magnesite prepared by two different
    methods?
12. How does the degree of calcinations of magnesite change with increasing calcinations temperature?
13. How the specific gravity of the magnesite bricks is affected by brick moulding pressure and firing temperature?
14. What are the limitations with dolomite bricks? How are the dolomite bricks ‘stabilised’?
15. What are the environmental problems related with chromite brick manufacturing and use?
16. What are the properties of insulation bricks? What additives are needed to prepare insulation brick?
17. Draw the flow sheet for the manufacture of following refractory bricks and describe the various steps briefly:
    (i) Silica bricks
    (ii) Fireclay bricks
    (iii) Insulation bricks
    (iv) Magnesite bricks
18. Differentiate between the followings:
    (i) Corrosion and erosion resistance of the refractory
    (ii) Room temperature and working temperature crushing strength of the refractory

(iii) Open pores and Sealed pores
(iv) True density and Apparent density
(v) Fireclay and high alumina clay
(vi) Magnesite and Dolomite
(vii) Mixing and kneading operation
(viii) Brick press machine with or without vacuum table
(ix) Pressing and extrusion process of brick making
(x) Super-duty and High duty firebrick
(xi) Magnesite chrome and Chrome magnesite bricks
(xii) Natural graphite and Synthetic graphite
(xiii) Graphite bricks and Graphite electrode
(xiv) Silicon carbide brick and Zirconia brick
(xv) Fireclay and Fire cement
(xvi) Nozzle and Stopper

19. Write short notes on the followings:
    (i) PCE (Pyrometric Cone Equivalent) value
    (ii) RUL (Refractoriness Under Load) value
    (iii) Creep at high temperature
    (iv) High Temperature Modulus of Rupture (HMOR)
    (v) Tundish
    (vi) Runner
    (vii) Ladle
20. Give the application of the following refractories:
    (i) Silica bricks
    (ii) Silicon carbide blocks
    (iii) Carbon blocks
    (iv) Ramming mass
    (v) Fire cement
    (vi) Alumina powder

8

Heat Transfer and Energy Management

Introduction

The three main subjects mentioned in this book ‘Fuels’, ‘Furnaces’ and ‘Refractories’ are designed to offer maximum thermal efficiency in ‘heat transfer’ with best ‘energy management’. The thermal energy released by fuel combustion is directed towards the object to be heated. This thermal energy reaches the object using various modes of heat transfer (‘conduction’, ‘convection’ and ‘radiation’) to offer a certain ‘degree of thermal utilisation’ which ranges from 3 to 30%, and the remaining energy is lost in the process as ‘thermal capacity of the refractory system’, radiation loss to atmosphere, thermal loss with water cooling systems and various other operational losses. The ‘heat recovery systems’ like ‘regenerators’ and ‘recuperators’ are used to utilise waste heat to the extent practicable and try to increase the ‘degree of thermal utilisation’ of the fuel energy. These important energy related aspects become more significant in period of human history when energy demand is increasing with depleting natural resource. This subject gains further importance when environmental laws restrict the improper use of fossil fuels due to its possible relation with global warming.

The subjects ‘Heat Transfer’ and ‘Energy Management’ are very exhaustive and various books are available to justify the subject. In view of the limited scope, in this text only some salient features of these two major subjects are discussed very briefly.

8.1 MODES OF HEAT TRANSFER

Consider a case of billet heating in directly fired furnace as illustrated in Figure 1.1. The thermal energy released by the combustion of fuel through a burner is

used for heating the steel billet. The thermal energy from burner reaches the billet by the following three modes of heat transfer: (i) The thermal energy travels directly from flame to billet surface by ‘radiation’ process.

(ii) The hot gases in flame flow in the furnace space depending on the design of exit, and in the process some amount of heat is transferred by hot gases to the billet surface, which is termed as ‘convective heat transfer’. This mode of heat transfer is dependent on flow pattern of gas in the system.

(iii) When the billet surface gets heated by radiation and convection process, the thermal energy starts moving to the interior of the billet by ‘thermal conduction’ process due to thermal gradient existing between billet surface and interior.

The three modes of heat transfer, i.e., conduction, convection and radiation are illustrated in Figure 8.1. These three modes of heat transfer are discussed briefly in the forthcoming sections.

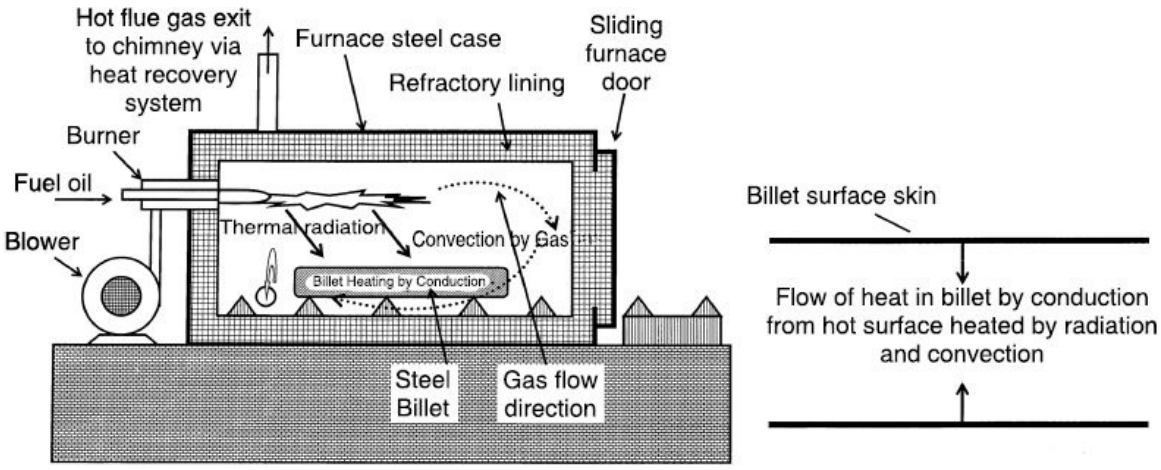


Figure 8.1 Modes of heat transfer in a billet reheating furnace.

8.1.1 Thermal Conduction

Physics of heat transfer

The thermal conduction is a process of transfer of internal energy within a body due to temperature gradient . Thermal conduction between two materials occurs when placed together in contact. The thermal energy gets transferred from one object to the other object placed in contact when the exited atoms in one object collide with atoms in other object. This energy transfer could also occur due to free electrons movement in the hotter body to the colder object in contact.

The metallic materials have the characteristic property of providing free

electron movements which is not possible in materials having ionic or covalent bonds. This free electron flow in metals gives thermal energy transfer through conduction process in metallic materials (e.g. gold, platinum, copper, etc.).

Basic terms related to conduction

The basic terms related to the conduction are as follows:

(i) *Heat Flow* : Thermal energy always flows from a region of high temperature to lower temperature.

(ii) *Temperature:* It is the thermal state of a body. It characterises the substance giving degree to which it is heated or it is the degree of its hotness.

(iii) *Steady State or Stationery Temperature* : It is the temperature of the substance which does not change with time.

(iv) *Transient or Non-stationery Temperature* **:** The temperature keeps changing with time.

(v) *Rate of Heat Flow* (*Q*): It is the quantity of transferred heat. It is referred as energy flow per unit time (hour or second). It is expressed in kcal/hr or kcal/s.

(vi) *Specific Rate of Heat Flow* (*q*): It is the rate of heat flow per unit area. It is also called thermal load. It is expressed in kcal/m^2 hr.

(vii) *Thermal Conductivity* (λ)*:* It determines the quantity of heat flowing per unit time per unit area at a temperature drop of 1 °C per unit length with material, and it further depends on various other conditions e.g. material structure, its volume and weight. The atmospheric conditions, e.g. humidity, pressure and temperature also affect the heat transfer.

In view of many parameters affecting thermal conductivity, care is needed to select a value from literature which is applicable to the case of study. In important cases, it is better to determine the thermal conductivity experimentally before proceeding for thermal assessment. The literature presents thermal conductivity data for variety of materials. The range of values of some group of materials are given below.

Thermal conductivity of gases

It ranges from 0.005 to 0.5 kcal/m hr °C. The value of λ increases with temperature, and practically does not depend on pressure with the exception for high (> 2000 atm) or very low (< 20 mm Hg) pressure.

Thermal conductivity of liquids

It ranges from 0.08 to 0.6 kcal/m hr °C . In most cases, λ decreases with increasing temperature, the exception being the water and glycerine.

Thermal conductivity of insulating and refractory materials

The value of λ ranges from 0.02 to 2.5 kcal/m hr °C. The change in value of λ for refractory materials with temperature is illustrated in Figure 7.10. The thermal conductivity of silica rich bricks increases while others show a decreasing trend with rising temperature.

Thermal conductivity of metals

Metals are good conductor of heat. The value of λ ranges from 2 to 360 kcal/m hr °C. The best conductor being silver (λ = 360), followed by copper (λ = 340), gold (λ = 260) and aluminium (λ = 160). The thermal conductivity of metals is affected by impurity and structure as illustrated in Table 8.1

Table 8.1 Thermal Conductivity of Metals Affected by Impurity and Structure

Metal	*State*	*Thermal Conductivity* kcal/m hr °C
Copper	Pure	340
Copper	As in trace	122
Steel (0.1% carbon)	Soft	45
Steel (1.0% carbon)	Soft	34
Steel (1.5% carbon)	Soft	31
Steel (0.1% carbon)	Hardened	40

Fourier's law

The quantity of transferred heat is proportional to drop in temperature, time and area perpendicular to the direction of heat flow. It can be expressed as follows: $q = -\lambda \text{ grad. } t$ (8.1)

where,

q is the heat transfer (kcal/m ^{2} hr)

λ is the thermal conductivity of the material (kcal/m hr °C)

t is the temperature (°C)

The thermal conductivity of some materials is given in Table 8.2 for reference.

Table 8.2 Thermal Conductivity of Some Materials (Metals and Refractories)

Metals (Thermal	*Thermal Conductivity*	*Heat Insulating Materials and*	*Thermal Conductivity*

Conductors)			*Refractories*		
	W/mK	kcal/m hr °C		W/mK	kcal/m hr °C
Aluminium	186	160	Asbestos-cement board	0.744	0.64
Brass	109	93.7	Asbestos fiber	0.08	0.07
Bronze	110	94.6	Balsa wood	0.048	0.041
Cadmium	92	79.1	Building brick	0.6–1.0	0.5–0.8
Chromium	94	80.8	Cement, portland	0.29	0.25
Copper	401	340	Diatomite	0.21	0.18
Carbon as diamond	1000	860	Diatomaceous earth	0.06	0.05
Carbon as graphite	25–470	20–400	Dolomite brick	2.16	1.85
Cast iron	55	47	Earth, dry	1.5	1.29
Gold	302	260	Fireclay powder	0.21–0.37	0.18–0.31
Lead	35	30	Fireclay brick at 500 °C	1.4	1.2
Magnesium	156	116	Glass	1.05	0.9
Mercury, liquid	8.3	7.1	Insulation brick at 600 °C	0.28–0.52	0.24–0.44
Nickel	91	78	Magnesite	4.15	3.56
Platinum	70	60	Mica	0.71	0.61
Silver	418	360	Quartz mineral	3	2.57
Steel, carbon 1%	40	34	Sand, dry	0.15–0.25	0.12–0.21
Steel, carbon 0.1%	52	45			
Stainless steel (18 Cr/8 Ni)	16	13.7			
Tin	67	57			
Titanium	22	19			
Tungsten	174	150			
Zinc	116	100			

[1 W/(mK) = 1 W/(m °C) = 0.85984 kcal/(h m °C) = 0.5779 Btu/(ft h °F) = 0.048 Btu/(in h °F)]

Heat flow through furnace wall

Fourier's law could be used to calculate heat flow under various situations applicable to furnace systems. Some simple cases of heat transfer under two conditions are illustrated in the following sections: (i) Heat conduction through plane furnace wall

(ii) Heat conduction through composite plane furnace wall

(i) Heat conduction through plane furnace wall

Let us consider the following conditions of heat flow:

1. The wall is homogeneous in nature having width δ.
2. The faces of the wall have steady state condition of heat flow having temperatures t_1 and t_2 which do not change with time.
3. Temperature t_1 is higher than t_2 and the heat flow direction is from surface temperature t_1 to t_2 .
4. This is a case of one dimensional heat flow with isothermal surface. In such case, the temperature is changing only in one direction (say x - axis) perpendicular to wall.

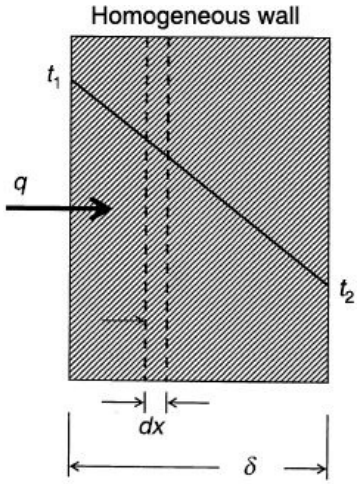


Figure 8.2 Heat flow through plane wall.

The heat flow direction, wall thickness and surface temperatures are illustrated in
Figure 8.2 for better understanding.

Now, let us consider *a* small thickness of wall (dx) is located at distance x from the wall having temperature t_1 . The rate of heat flow per unit area through

this thin layer (thickness *dx*) is given by Fourier's Law as:

$$q = \lambda \ (dx/dt) \tag{8.2}$$

This can be written as, $dt = -(q/\lambda)\ dx$ (8.3)

The integration of equation (8.3) gives

$$t = -(q/\lambda)\ x + c \tag{8.4}$$

The constant c can be determined by using boundary conditions, i.e., when $x = 0$, then $t = t_1$ Substituting the boundary conditions in equation (8.4), we get

$$c = t_1 \tag{8.5}$$

When the value of $x = \delta$, then $t = t_2$. Substituting these values of x and t along with value of c in equation (8.4), we get

$$t_2 = -(q/\lambda)\delta + t_1 \tag{8.6}$$

Thus, the rate of heat flow per unit area through the wall can be expressed by rearranging equation (8.6) as

$$q = -(\lambda/\delta)\ (t_1 - t_2\ ) \tag{8.7}$$

The ratio (λ/ δ) is known as 'thermal conductance' and the ratio (λ/ δ) is termed as 'thermal resistance' of the wall.

Using equation (8.7), the total quantity of heat transferred (Q) through a plane wall having surface area A (in m^2) in τ hours is given by

$$Q = q\ .\ A\ .\ \tau$$

$$Q = -(\lambda/\delta)\ A\ .\ \tau\ .\ (t_1 - t_2\ ) \text{ kcal} \tag{8.8}$$

(ii) Heat conduction through composite plane furnace wall

The walls of furnaces and other heat devices are generally made of wall having two, three or more layers of different materials to have better furnace efficiency. It is common to have a refractory layer backed with insulating bricks on the outer side. The heat flow in such cases can be done with the following assumptions (Figure 8.3**)** to simplify the calculation:

1. The composite wall under consideration has three layers of different materials.
2. The thicknesses of 1st, 2nd and 3rd layer walls are δ_1 , δ_2 are δ_3 respectively.
3. The thermal conductivities of 1st, 2nd and 3rd layer are λ_1 , λ_2 and λ_3 respectively.

4. The temperatures t_1 (inner higher temperature) and t_4 (outer lower temperature) are known.
5. The layers in the wall are in close contact with each other and adjacent junction surfaces have same temperature, but the values of t_2 and t_3 are not known.
6. The rate of heat flow per unit area under steady state condition is same for all the layers.

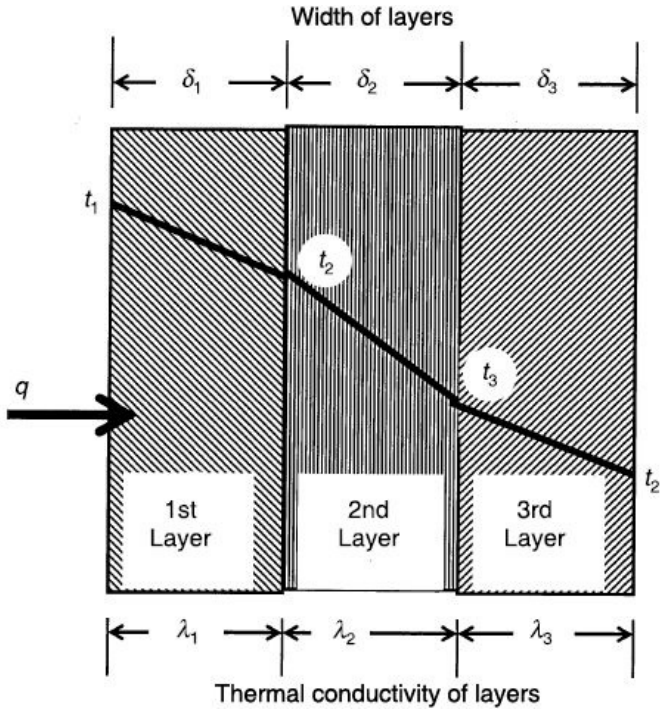


Figure 8.3 Heat flow through composite wall.

Under these assumptions the rate of heat flow for all these layers could be written (using equation (8.7) as:

$$q = -(\lambda_1/\delta_1)(t_1 - t_2) \quad (8.9)$$

$$q = -(\lambda_2/\delta_2)(t_2 - t_3) \quad (8.10)$$

$$q = -(\lambda_3/\delta_3)(t_3 - t_4) \quad (8.11)$$

Equations (8.9), (8.10) and (8.11) help in knowing temperature difference at each layer, hence we can write them as:

$$(t_1 - t_2) = q(\lambda_1/\delta_1) \quad (8.12)$$

$$(t_2 - t_3) = q(\lambda_2/\delta_2) \quad (8.13)$$

$$(t_3 - t_4) = q(\lambda_3/\delta_3) \quad (8.14)$$

The sum of temperature difference at each layer is the temperature difference of the composite wall

i.e., $$(t_1 - t_4) = (t_1 - t_2) + (t_2 - t_3) + (t_3 - t_4) \quad (8.15)$$

Equation (8.15) can be written as:

$$(t_1 - t_4) = q[(\delta_1/\lambda_1) + (\delta_2/\lambda_2) + (\delta_3/\lambda_3)] \quad (8.16)$$

Hence, the rate of heat flow,

$$q = \frac{t_1 - t_4}{[(\delta_1/\lambda_1) + (\delta_2/\lambda_2) + (\delta_3/\lambda_3)]} \text{ kcal/m}^2 \text{ hr} \quad (8.17)$$

By analogy, the rate of heat flow for wall having n number of layers can be written as:

$$q = \frac{t_1 - t_{n+1}}{[(\delta_1/\lambda_1) + (\delta_2/\lambda_2) + (\delta_3/\lambda_3) + \cdots + (\delta_n/\lambda_n)]} \text{ kcal/m}^2 \text{ hr} \quad (8.18)$$

8.1.2 Numerical Problems

Thermal Conductivity Calculation

PROBLEM 1 The heat loss of 100 kcal/m^2 hr is occurring from a 50 mm thick wall with its two surfaces having 50 °C temperature difference. What is the thermal conductivity of wall material?

Solution: The heat flow from a single layer wall is expressed as

$$q = -(\lambda/\delta)(t_1 - t_2) \text{ kcal/m}^2 \text{ hr}$$

Given q = 100 kcal/m^2 hr, $(t_1 - t_2)$ = 50 ^{o} C, wall thickness δ = 50 mm = 0.(

Hence, $\lambda = q \cdot \delta/(t_1 - t_2)$

= (100 × 0.05)/50

= 0.1 kcal/m hr ^{o} C

Calculation of heat flow from a wall

PROBLEM 2 A plane wall is made of steel (thermal conductivity 70 W/m °C) having 50 mm thickness and 1 square meter surface area. The temperature is 150 °C on one side while the other face has 80 °C temperature. Calculate the amount of heat being transferred through steel wall.

Solution: According to Fourier's law, the rate of heat loss,

$$q = -(\lambda/\delta)(t_1 - t_2) \text{ kcal/m}^2 \text{ hr}$$

Given, λ = 70 W/m °C = 60.18 kcal/m hr °C (since 1 W/m °C = 0.85984 kcal/m hr °C)

δ = 50 mm = 0.05 m

and $(t_1 - t_2) = 150° - 80° = 70$ °C

∴ The conductive heat transfer can be calculated as:

$q = (60.18/0.05) \times 70$

$= 84.25$ kcal/m^2 hr

or

$= 98000$ W/m^2 (since 1 kcal = 1163 Wh)

$= 98$ kW/m^2

Calculation of energy loss through walls in terms of oil

PROBLEM 3 Calculate the hourly heat loss through a furnace wall 5 m long, 3 m high and
300 mm thick. The working temperature in the furnace is 900 °C and outer wall temperature
is 50 °C. The thermal conductivity of the brick used in the furnace is 0.6 kcal/m hr °C.
Express the heat loss in terms of oil (CV 10000 kcal/kg).

Solution: According to Fourier's law, the rate of heat loss,

$$(q) = [\lambda/\delta] \times [t_1 - t_2] \text{ kcal/m}^2 \text{ hr}$$

where,

λ is the thermal conductivity of the brick = 0.6 kcal/m hr °C (Given)

δ is the brick thickness = 300 mm = 0.3 m (Given)

$(t_1 - t_2)$ is the difference in temperature on the two sides of wall = 900 – 50 = 850 °C

Hence, $q = [0.6/0.3] \times [850] = 2 \times 850 = 1700$ kcal/m^2 hr

Wall surface area (A) = 5 m × 3 m = 15 m^2

Rate of heat loss from furnace wall surface, $Q = q \times A = 1700 \times 15 = 25500$

kcal/hr

Given that the oil calorific value = 10000 kcal/kg

Hence, heat loss rate in terms of oil = [25500]/[10000]

= 2.55 kg oil/hr

8.1.3 Heat Convection

Process of heat transfer

The process of heat transfer by convection is a means of heating solid by a moving fluid (liquid/gas) in direct contact, or in other words, convection is a heat energy transfer method between a surface and a moving fluid at different temperatures. In convection process, the thermal energy is transferred by convection and conduction simultaneously, but the combined process of heat transfer is termed *convection* . The convection process of heat transfer requires a liquid or gas as a medium where particles could be displaced.

The heat transfer by conduction in fluids (liquid/gas) is determined by its thermal conductivity and temperature gradient as in the case of solids. The process of heat transfer by convection is very complex as several factors influence this process. These factors are described briefly in the following sections: (i) Fluid flow origin

The fluid flow can occur due to natural convection or forced convection.

***Natural convection* :** The fluid flow motion is solely due to difference in density of hot and cold fluids.

***Forced convection* :** This type of convection process occurs under the influence of some external means for flow like fan, pump, wind, etc.

(ii) Fluid flow type

The fluid flow can have different patterns due to fluid velocity.

***Laminar flow* :** In this type of flow, the fluid flows parallel to the wall of passage.

***Transitional flow* :** The fluid flow starts moving in random direction when the fluid velocity is equal or more than critical value.

***Turbulent flow* :** The fluid movement direction is random when its velocity is more than critical value.

The pattern of fluid flow is shown in Figure 8.4. A thin layer near wall exhibits laminar flow pattern due to fluid viscosity even when the fluid pattern is

turbulent. This thin layer is called ‘boundary layer’.

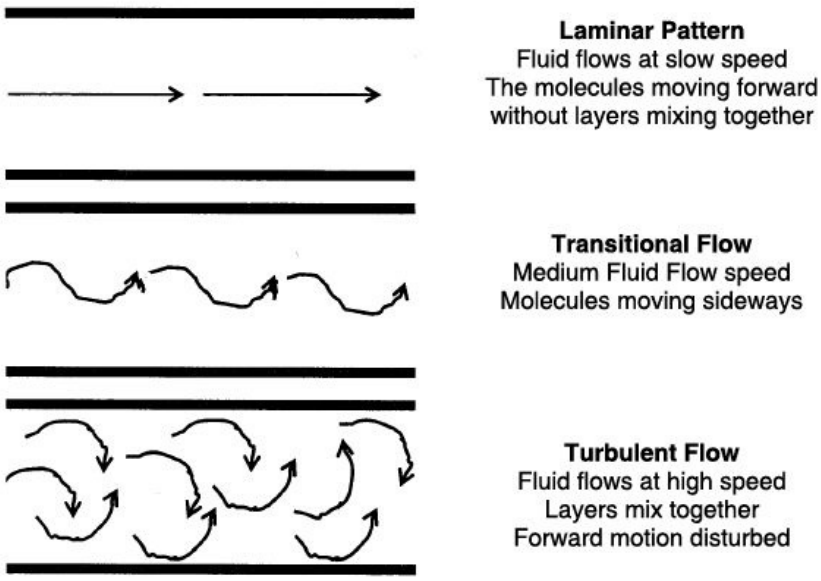


Figure 8.4 Fluid flow type with change in its velocity.

(iii) Physical properties of fluids

The physical properties of the fluid like thermal conductivity, density, thermal diffusivity, viscosity, etc. are found to affect the heat transfer by convection process.

Thermal conductivity (λ kcal/m hr °C): It is the ability of a substance to conduct heat. Its value decides the quantity of heat passing per unit time per unit area at a temperature difference of 1 °C per unit length.

Density (ρ kg/m^3): It is the mass per unit volume.

Thermal diffusivity (α m^2 /hr): It characterises the rate of change in temperature in transient heat transfer process. The higher thermal diffusivity of the substance will give higher temperature propagation.

$$\text{Thermal diffusivity } (\alpha) = (\lambda)/[C_p \gamma] \text{ m}^2 \text{/hr} \quad (8.19)$$

where, λ is the thermal conductivity

C_P is the specific heat and

γ is the specific gravity

Viscosity *(* μ Pa.s)*:* Viscosity or absolute viscosity is the internal frictional force offering resistance to flow. All liquids exhibit viscosity. According to Newton’s law, the force applied to unit area is proportional to velocity gradient. In SI units, absolute viscosity is expressed as pascal second (Pa.s).

$$1 \text{ Pa.s} = 1 \text{ kg/ms} = 10 \text{ P (poise)}$$

Kinematic viscosity (ϕ) = (Absolute viscosity/density) = (μ/ ρ) m^2 /s (8.20)

(iv) Shape and size of the heat transfer surface

The heat transfer surfaces are generally shaped as plate or tube. This surface could be vertical, horizontal or inclined giving different conditions of heat transfer.

(v) Heat transfer coefficient (h_c)

It is the quantity of heat transferred in unit time through unit area at a temperature difference of 1 °C between solid and fluid. It determines the intensity of heat transfer. It is expressed as kcal/m^2 hr °C.

The heat transfer coefficient (h_c) is a complex function as it is dependent on many factors such as surface shape, dimension, fluid velocity, fluid temperature, properties of the fluid, e.g. thermal conductivity, heat capacity, viscosity, etc. In view of the complexity the values of heat transfer coefficient (h_c), it has to be determined theoretically or experimentally for a given condition.

Heat transfer laws

The transfer of heat from surface by convection process was first derived by Newton. This *law* of heat transfer can be expressed as:

$$q = h_c A\, dT \quad (8.21)$$

where,

q is the thermal energy transferred per unit time (W)

A is the heat transfer area of the surface (m^2)

h_c is the convective heat transfer coefficient of the process (W/m^2 K)

dT is the temperature difference between the surface and the bulk fluid (K or °C)

Typical convective *heat transfer coefficient* for common fluids are given below:

(i) Free convection–air, gases and dry vapours: 0.5–1000 (W/(m^2 K))

(ii) Free convection–water and liquids: 50–3000 (W/(m^2 K))

(iii) Forced convection–air, gases and dry vapours: 10–1000 (W/(m^2 K))

(iv) Forced convection–water and liquids: 50–10000 (W/(m^2 K))

(v) Forced convection–liquid metals: 5000–40000 (W/(m^2 K))

1 W/(m^2 k) = 0.85984 kcal/(hm^2 ° C)

8.1.4 Thermal Radiation

Physics of heat transfer

Heat can be radiated as an electromagnetic energy produced by the movement of the charged particles in heated body. The material having temperature higher than absolute zero emits thermal radiation due to inter atomic collisions causing the kinetic energy of the atoms or molecules to change resulting in charge acceleration and/or dipole oscillation. The thermal radiation has wavelength from 0.4 to 40 microns (μ m) in contrast to visible light ranging 0.4–0.8 microns. The thermal radiation is known as 'heat rays' and its thermal radiation propagation is called 'radiation'.

Laws governing thermal radiation

(i) Radiant power and Planck's law

The radiant power of a body (E) is defined as *the amount of energy emitted by unit surface area per unit time for electromagnetic waves of length (λ) ranging from* λ *to* λ + *d* λ *referred to the interval of wavelength d* λ. Hence,

$$E_{\lambda} = (dE/d\lambda) \quad (8.22)$$

This E_{λ} is called *spectral intensity* or simply *radiation intensity* expressed in kcal/m^2 hr micron.

Planck determined theoretically the radiation intensity as a function of wavelength for a black body as:

$$E_{0\lambda} = (c_1 .\lambda^{-5})/[e^{(c_2/\lambda T)} - 1] \quad (8.23)$$

where,

λ is the wavelength in m

T is the body temperature in ° K (° C + 273 = ° K)

e is the natural logarithmic base

c_1 is the constant (3.17×10^{-16} kcal/m^6 hr)

c_2 is the constant (1.44×10^{-2} m °K)

(ii) Distribution of incident radiation

The radiations emitted from a source reach another surface which may be partially absorbed, reflected and transmitted. The behaviour of a surface with radiation incident upon it can be described by the following quantities: α = absorptance—fraction of incident radiation absorbed

ρ = reflectance—fraction of incident radiation reflected

τ = transmittance—fraction of incident radiation transmitted

The total sum of three coefficients is unity, i.e.

$$\alpha + \rho + \tau = 1 \quad (8.24)$$

(iii) Black body

The body that absorbs all radiation falling on its surface is known as black body, giving absorptance α = 1.

A black body is a hypothetic body that fully absorbs all wavelengths of thermal radiation falling on its surface. The black bodies do not radiate or reflect light, and thus appear dark when their surface temperatures are low enough so as not to be self-luminous. The black bodies when heated to a specific temperature emit thermal radiation.

(iv) Stefan-Boltzmann law

The radiation energy per unit time from a body is proportional to the fourth power of the absolute temperature and can be expressed as:

$$E_b = \sigma T^4 \quad (8.25)$$

where ,

E_b is the Emissive power (kcal/cm^2 hr), the gross energy emitted from an ideal surface per unit area per unit time.

σ = 4.9 × 10 $^{-8}$ (kcal/m ^{2} ° K) the Stefan-Boltzmann constant

T is the absolute temperature, (K)

The radiation energy emitted by ideal surface (black body) at different temperatures is shown in Figure 8.5.

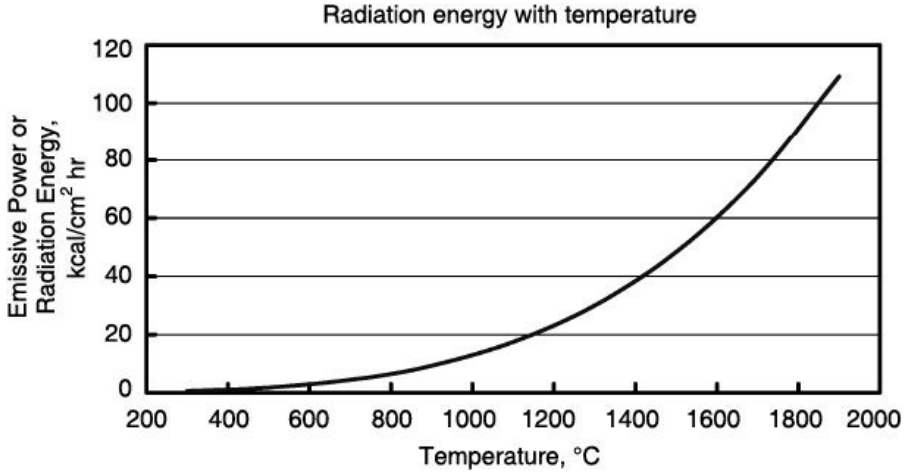


Figure 8.5 Emissive power from ideal surface (black body) at different temperatures.

(v) Kirchhoff's law

It establishes the relationship between emissivity and absorptivity of a body. It states that the ratio of emissive power to absorptivity is same for all bodies, and equal to emissive power of black body at the same temperature. It can be expressed as: $(E_1 / \alpha_1) = (E_2 / \alpha_2) = (E_3 / \alpha_3) = \ldots = (E_0 / \alpha_0) = E_0$ (8.26)

where,

E_1 , E_2 , E_3 , ... are emissive power of bodies 1, 2, 3, …

α_1 , α_2 , α_3 , ... are absorptivity of bodies 1, 2, 3, …

E_0 is the emissive power of black body

$\alpha_0 = 1$ is the absorptivity of black body

(vi) Lambert's law

The Stefan-Boltzmann's law determines the energy emitted by a body in all directions. Each direction is given by an angle Φ which emitted ray form with the normal to the surface. Lambert's law defines the variation of radiation in individual direction.

The rate of radiation from surface element dA_1 in the direction (Figure 8.6) of the surface element dA_2 is proportional to rate of radiation along the normal dQ_r multiplied by the solid angle $d\Omega$ and cos, Φ , i.e.,

$$dQ_\Phi = dQ_n \, . \, d\Omega \, . \cos \Phi \quad (8.27)$$

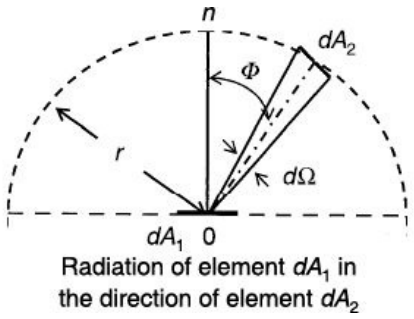


Figure 8.6 Radiation in a given direction by Lambert's law.

where,

dQ_Φ is the rate of heat radiation from surface element dA_1 to element dA_2

dQ_n is the rate of heat radiation from surface element dA_1 to its normal direct

$d\Omega$ is the solid angle formed by heat receiving element dA_2 with element dA

Φ is the radiation direction angle from normal to radiating surface element dA

The radiation laws are helpful in estimating the heating process of steel

billets, heat loss from furnace surface walls and openings.

8.2 THERMAL EFFICIENCY OF FURNACES

The thermal efficiency of any furnace is the ratio of heat energy utilised and fuel (energy) used.

$$\text{Therefore, thermal efficency of the furnace (\%)} = \frac{\text{Heat utilised in heating steel stock}}{\text{Heat delivered by fuel/electricity used}} \times 100 \quad (8.28)$$

The quantity of heat (Q_s) used by the steel stock is given by:

$$Q_s = W_s \,.\, C_p \,.\, (t_1 - t_2) \quad (8.29)$$

where,

W_s is the weight of the stock in kg

C_p is the mean specific heat of the stock in kcal/kg °C

t_1 is the final temperature of the stock in °C

t_2 is the initial temperature of the stock in °C

The total heat delivered by fuel/electrical power (Q_f) in heating the steel stock is given by

$$Q_f = W_f \times \text{CV kcal} \quad (8.30)$$

where,

W_f is the fuel burnt in heating the steel stock in kg or m^3

CV is the calorific value of fuel in kcal/kg or kcal/m^3

or Q_f = (860 × electrical energy used in kWh) kcal [since 1 kWh = 860 kcal]

The thermal efficiency of the furnace is affected by a number of design and operating parameters. The common thermal efficiency observed for industrial furnaces is given in
Table 8.3.

8.3 SOURCES OF HEAT LOSS IN A FURNACE

The objective of designing and operating any furnace is to achieve maximum thermal efficiency as it directly affects the cost of the process. However, the thermal efficiency of most industrial furnaces is very low ranging from 5 to 35%. The tunnel furnace can give higher efficiency
(up to 80%) if operated carefully due to its better heat utilisation of hot waste

gases in long kiln for pre-heating and drying operation.

Table 8.3 Thermal Efficiency for Some Industrial Furnaces

Furnace Type	*Operating Temperature, °C*	*Operating Nature*	*Thermal Efficiency %*
Oil fired crucible melting	700–1000	Batch	4–5
Coil anneal (bell) radiant type	700–900		5–7
Strip anneal muffle	700–900		7–12
Reheating furnace (forge)	1000–1200	Pusher, Rotary	7–15
Reheating furnace (forge)	1000–1200	Batch	5–10
Cupola	1300–1450	Batch	14–15
Heat treatment furnaces	550–1000	Batch type	15–25
Heat treatment turnaces	550–1000	Continuous	20–30
Ovens	20–350	Direct fired	35–40
Induction melting	1400–1550	Batch	~ 40
Arc melting	1400–1500	Continuous	~ 40
Tunnel furnace	1000–1500	Continuous	20–80

The low thermal efficiency of furnace is mainly due to various sources of heat loss as illustrated in Figure 8.7. These furnace losses include the followings: (i) Heat stored in the furnace refractories

(ii) Thermal losses from the furnace outer walls or structure
(iii) Heat loss through load conveyors, fixtures, trays, etc.
(iv) Thermal loss through radiation from openings, hot exposed parts, etc.
(v) Heat carried away by the cold air infiltration in the furnace
(vi) Heat loss by hot flue gases and excess air used for combustion in the burners.
(vii) Heat loss by cooling water

These sources of heat loss and methods of their prevention are discussed briefly in the forthcoming sections.

8.3.1 Heat Stored in Furnace Structure and its Loss

The furnace structure consists of refractory walls encased in steel casing. The refractory wall could be single layer or multiple layers of different refractory materials depending on its size and nature of furnace working. This structure absorbs considerable amount of thermal energy and is lost on cooling after closer of the furnace work. The extent of loss would depend on frequency of start and closing of the furnace in a given period (daily, weekly, monthly or yearly). The increased number of furnace closer in a given period would mean more loss of stored structural energy giving higher energy (fuel) cost.

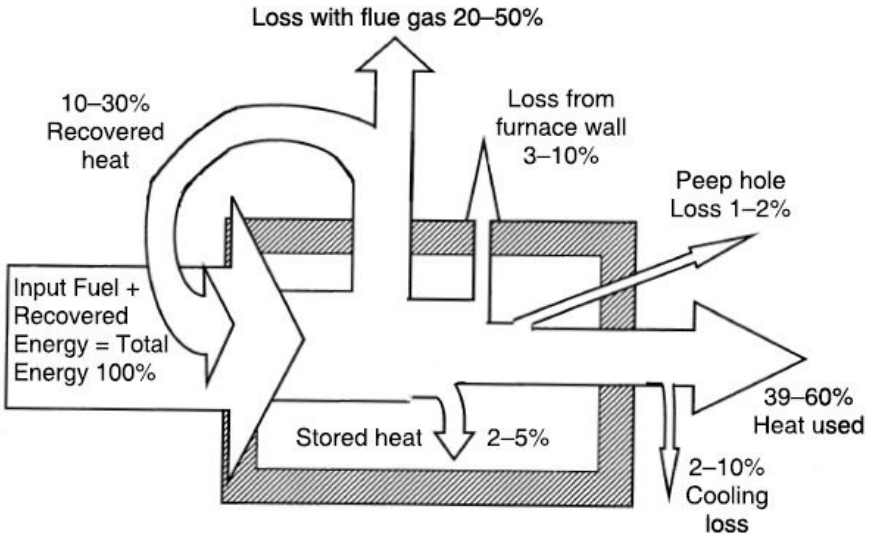


Figure 8.7 Sources of heat loss from furnace.

The loss due to structural stored energy could be minimised by adopting the following measures: (i) Designing optimum furnace wall thickness to have minimum stored energy.

(ii) Minimise the number of furnace closers in a given period.

(iii) Design optimum size of the furnace for a given work load.

8.3.2 Thermal Losses from the Furnace Outer Walls or Structure

The outer walls of the furnace and roof radiate heat to the atmosphere. The outer wall surface temperature depends on the nature of refractory and insulation used. This outer wall temperature could be minimised by proper selection of material for insulation and thickness.

The heat loss from outer surface is further increased by flowing air due to convection depending on the location of furnace. This could be avoided by

creating wind barrier to avoid direct impingement of blowing wind on the furnace surface.

8.3.3 Heat Loss through Furnace Components

The conveyer belts, conveyor cars, trays, etc. are used to handle hot objects in the furnace. These get heated to working temperature along the object they carry. The stored heat in such fixtures is lost to the atmosphere after being discharged from the furnace. These fixtures get heated to lose their heat every time they are used. The quantity of heat they carry to lose depends on their design and material used. Such losses are unavoidable, but can be optimised by paying attention at the design stage.

8.3.4 Thermal Loss from Furnace Walls and Openings

The furnace has several openings like door, peep hole, hole for fixing some instruments, etc. In addition, there could be cracks in roof or other walls in uncased furnaces due to poor maintenance. All such openings provide passage for thermal radiation and heat loss. The
extent of loss would depend on furnace temperature. This could be substantial in high temperature (> 1000 °C) furnaces as emissive power of furnace wall is higher at high temperature (Figure 8.5).

These losses could be minimised by adopting good operating practices, e.g.

(i) Adopting proper furnace maintenance
(ii) Keeping the peep hole and door closed when not needed
(iii) Closing the gap in fixtures hole by using suitable insulating materials like asbestos, ceramic blanket, etc.
(iv) Avoid charging longer objects in the furnace which may obstruct closing the furnace door.

8.3.5 Heat Carried Away by the Cold Air Infiltration in the Furnace

The cold air in the atmosphere entering in the furnace through openings, door gap, cracks, etc. would first get heated and then leave the furnace though exhaust carrying furnace heat. This loss of heat can be avoided by avoiding air infiltration by adopting positive pressure in the furnace. The few millimeter higher water gauge pressure in the furnace would prevent cold air infiltration in

the furnace. In the case of positive furnace pressure, the hot air will be moving out from the openings avoiding cold air infiltration. The furnace positive pressure must be kept just to stop cold air infiltration with minimum heat loss through hot gases leaking out.

8.3.6 Heat Loss by Hot Flue Gases and Excess Air Used for Combustion in the Burners

The flue gases are generated as a result of fuel combustion with air. The use of excess air is common to ensure complete combustion. The hot flue gases leaving the furnace represent loss due to flue gases as they carry thermal energy with them. The loss due to hot flue gases depends on the following factors: Air/fuel ratio used for combustion, i.e., use of excess air

In Figure 5.1 (section 5.2.2), it has been shown that excess air is required for complete combustion giving maximum thermal efficiency. The higher use of excess air is detrimental. It causes decrease in thermal efficiency, since the excess air carries away sensible heat of the furnace along with flue gases.

Furnace temperature used

The higher furnace temperature gives higher temperature flue gases which carry higher quantity of sensible heat and result in more energy loss from furnace.

Type of fuel used (Hydrogen per cent)

The oil and gaseous fuel contain hydrogen which on combustion yields moisture. This moisture is converted into superheated steam depending on the furnace temperature and leaves with flue gases. This superheated steam carries away sensible heat as superheated steam and latent heat in steam. The higher hydrogen content gives more steam and results in more loss of energy. This hydrogen content is the cause for lower calorific value (net CV) of fuels. Such losses could be minimised by selection of fuel for the furnace.

Moisture content in fuel oil

The oil sometimes contains small quantity of moisture due to poor storage and transportation problem. This moisture would become steam during combustion process, and would cause heat loss in a manner explained above. This loss can be avoided by proper storage and handling of oil.

8.3.7 Heat Loss by Cooling Water

Many components in furnace need water cooling to avoid damage due to high temperature. The typical example is cooling of coils in induction furnace, electrical clamps in high temperature area, high temperature metallic structures, etc. The heat carried away by cooling water is an unavoidable loss to the furnace system. It can be optimised by proper design, maintenance and operation.

8.4 WASTE HEAT RECOVERY

In all furnace operation, considerable amount of heat is lost by different means. This waste
heat if recovered would increase the thermal efficiency of the furnace. The feasibility of recovering this waste heat depends on various factors, and it is adopted only after assessing its economic viability. The waste heat recovery technique is affected mainly by the following two factors: Quality of waste heat
The quality of waste heat is assessed by the following factors:

(i) Degree of thermal energy (temperature)

The higher temperature of the material offers more thermal gradient for heat exchange and encourages heat recovery. The heat exchange becomes unattractive when this temperature gradient is low.

(ii) Nature of material containing this thermal energy

The material holding heat could be solid, liquid and gas. The thermal exchange method is affected by selecting heat exchanging media. Some examples could be cited as: (a) use of inert gas media to extract heat from hot coke (solid), (b) cold air/water as media to extract heat from hot flue gas from furnaces and (c) water/air flowing in metallic tubes to extract radiated heat from hot billet or hot iron ore sinter (solid).

(iii) Thermal conductivity of the material

The thermal conductivity of the material containing heat is important in designing the heat recovery system.

(iv) Chemical nature of the material

The chemical nature of hot body is important for selecting the media for heat exchange. The reactive material like hot coke requires an inert gas (nitrogen) to exchange heat. Use of reactive gas could defeat the purpose. Recovery of heat

from hot steel billet cannot be made by blowing air as it would cause oxidation.

(v) Cycle of heat availability

Availability cycle of waste heat would help in designing the waste heat recovery system. The waste heat could be available on continuous basis like flowing flue gas or it could be intermittent discharge of hot object like hot rolled steel plate.

Quantity of waste heat

The quantity of heat (Q) available in a given time period is necessary to judge the viability of heat recovery. This will depend on volume (V) of the fluids (hot flue gases, hot water, etc.) or mass (W) of the solids (hot slag, hot steel, hot coke, hot sinter, etc.) available for heat recovery.

Heat content $$Q = [V \times \lambda \times C_P \times \Delta T] \text{ kcal for fluids} \quad (8.31)$$

or $$Q = [W \times C_P \times \Delta T] \text{ kcal for solids} \quad (8.32)$$

where,

V is the volume of the fluid in m^3

W is the mass of the solid in kg

ρ is the density of the fluid in kg/m^3

C_p is the specific heat of the substance in kcal/kg °C

ΔT is the temperature difference in ° C

The value of total heat (Q) is very much dependent on temperature and specific heat of the waste object. The specific heat of some common metals, refractories, materials and
gases are given in Table 8.4. The higher exit flue gas temperature, high cooling water temperature and higher temperature of solids offer good opportunity of heat recovery. The value of total heat available based on its mass or volume must justify the heat recovery using viable methods.

Table 8.4 Specific Heat of some common Materials and Gases related to Metal Industry

Gaseous Substances				*Solid Substances*			
Gases	*At Temp.* °K	*Specific Heat*		*Refractory/Ore/ Coke/Slag/Steel*	*At Temp.* °K	*Specific Heat*	
		kJ/m ^{3} °C	kcal/m ^{3} °C			kJ/kg °C	kcal/kg °C
Air	273	1.296	0.309	Fireclay	1273	1.25	0.298
Air	1273	1.409	0.337	Fireclay	1473	1.28	0.305
Air	1473	1.432	0.342	Silica	1273	1.26	0.301

O_2	273	1.305	0.312	Silica	1473	1.22	0.291
O_2	1273	1.476	0.352	Magnesite	1273	1.25	0.298
O_2	1473	1.499	0.358	Magnesite	1473	1.28	0.305
N_2	273	1.294	0.309	Coke	1473	1.53	0.365
N_2	1273	1.391	0.332	Magnetite	273	0.92	0.219
N_2	1473	1.413	0.337	Hematite	1473	0.902	0.215
H_2	273	1.276	0.305	Sinter 54% Fe, (Lime/Silica = 1)	1473	1.09	0.260
H_2	1273	1.328	0.317	Pellets	473	0.63	0.150
H_2	1473	1.342	0.320	Pig Iron	1423	0.73	0.174
CO_2	273	1.599	0.382	Steel 0.03C	1783	0.70	0.167
CO_2	1273	2.202	0.526	Steel 0.8 C	1758	0.69	0.165
CO_2	1473	2.262	0.540	Steel Scrap	273	0.57	0.136
CO	273	1.298	0.310	BF Slag 1*	1753	1.24	0.296
CO	1273	1.412	0.337	BF Slag 2*	1713	1.25	0.299
CO	1473	1.434	0.342	BF Slag 3*	1603	1.16	0.277

[1 kJ/cubic meter = 0.239 kcal/cubic meter]

**Compositions*	*Silica%*	*Alumina%*	*Lime%*	*MnO%*	*S%*
BF Slag 1	37	7.8	50	1.3	2.4
BF Slag 2	30	25.7	39	1.14	1.64
BF Slag 3	41	14	39	1.44	1.6

8.4.1 Classification of Waste Heat Source

The various potential sources of waste heat in the metallurgical industries could be identified based on temperature which could be arbitrarily classified in three groups: (i) High temperature (more than 1000 °C), (ii) Moderate temperature (300–1000 °C) and (iii) Low temperature (below 300 °C). These different sources of waste heat are listed in Table 8.5.

Table 8.5 Sources of Waste Heat in Metallurgical Plants

Group	*Heat Carrier Nature*	*Source of Heat*	

			Waste Gas Temperature in °C
High Temperature	Flue gas	LD steel	1200–1500
	Flue gas	EAF steel	1200–1300
	Flue gas	Non-recovery coke oven	1200–1300
	Flue gas	Nickel refining	1300–1650
	Solid	Hot iron ore sinter	1200–1300
	Solid	Hot coke	1200
	Liquid	Hot slag	1400
	Solid	Hot rolled billet	1100
	Solid	Hot DRI	1050
Moderate Temperature	Flue gas	Copper refining	760–815
	Flue gas	Aluminium refining	650–750
	Flue gas	Zinc refining	700–1000
	Flue gas	Open hearth	600–700
	Flue gas	Steel reheating	900–1000
	Flue gas	Heat treatment	400–600
	Flue gas	DRI kilns	300–500
Low Temperature	Flue gas	Drying and baking ovens	150–250
	Flue gas	Annealing furnaces	60–200
	Water	Water from steam condenser	80–90
	Water	Furnace cooling water	50–80

8.4.2 Merits and Limitations in Heat Recovery

The heat recovery process has the following merits and limitations:

Merits

The merits of using a waste heat recovery unit are as follows:

(i) Energy saving to increase the thermal efficiency of the furnace
(ii) Saving of fuel cost by recovering some energy which was lost otherwise
(iii) Minimising thermal pollution in the environment

Limitations

The limitations of using a waste heat recovery unit are as follows:

(i) The heat recovery methods are capital intensive
(ii) Heat recovery methods becomes more expensive in dealing with reactive

objects like hot coke or hot steel billet (iii) Heat recovery methods may not be possible due to design constrain in older units

(iv) These methods are suited best in new upcoming plants

8.4.3 Waste Heat Recovery Devices

Various types of waste heat recovery units are used in industry depending on the process requirements. The different heat recovery devices are described in the following sections.

Regenerator

(i) Definition

It is a high temperature heat exchanging device where thermal energy is stored in solid refractory to be exchanged with gaseous media.

(ii) Working principle

This device uses stored thermal energy in solid refractory having high heat capacity
(e.g. fireclay brick) for exchange with air or gas for combustion purposes. This system operates in cyclic manner undergoing thermal storage due to heating by waste hot gas or burning gaseous fuel in one part of the cycle. In second part of the cycle, the stored heat is delivered to desired gaseous media (air/fuel gas) and undergoes cooling process.

(iii) Heat transfer method

The heat transfer mode includes conduction within solid body up to its surface, and then convection by flowing gaseous media close to surface. In order to enhance convection process, the refractory bricks are specially designed to have more surface area by creating slots in the body.

(iv) Construction and working

Such devices need a set of minimum two chambers (A and B) having refractory checker
work for thermal storage (Figure 8.8). These two refractory chambers are used in cyclic manner. One of the two chambers (say A) serves as heat source to preheat cold air useful for combustion in any system, and the other chamber (B) is heated by using sensible
and/or potential heat of the available waste flue gases in 1st half cycle. The role of these two chambers is reversed after a given time. In 2nd half cycle, the

chamber (A) which was pre-heating air is now cool and is heated by using waste flue gases. The Chamber B which is now hot, serves to preheat air in 2nd half cycle. The change in cycle is automated in a fixed period to work continuously.

In case the air and gas both are required to be pre-heated, then two sets of chambers would be required. One set of two chambers serves to pre-heat air, while another set of two chambers serves to pre-heat gas. The fuel gases containing hydrocarbons are not pre-heated as they breakdown in smaller molecules with loss in their heating value.

In most of the cases, only a set of two chambers is used to pre-heat air by recovering heat of waste flue gases.

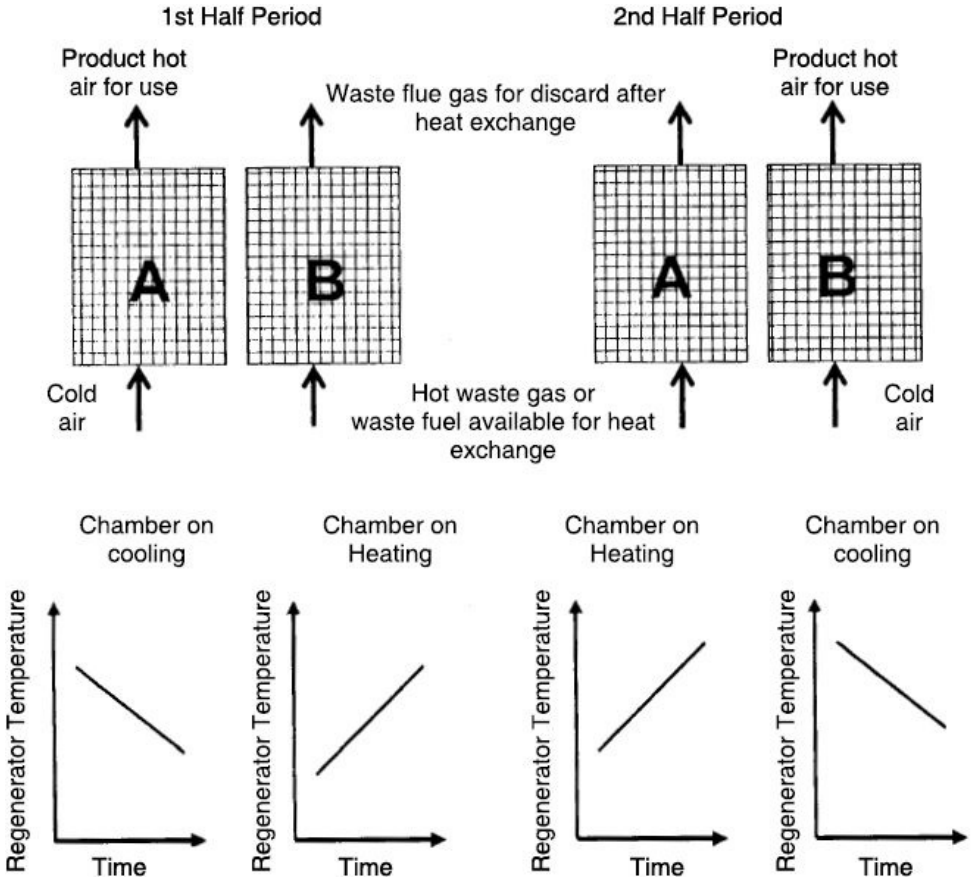


Figure 8.8 Working principle for one set of regenerator chambers.

(v) Applications

The regenerators are used in coke ovens to pre-heat air for combustion. Figure 2.29 shows its location in coke oven. Figure 6.8 shows the location of regenerators in open hearth furnaces where it is used to preheat air in case of oil fired furnaces. If the open hearth uses blast furnace or producer gas as fuel, then it uses two sets of regenerators. The blast furnace stoves, also working on

regenerative principle of waste blast furnace gas use is illustrated in Figure 6.11. In this case, theoretically only two stoves can operate in a cycle of heating and cooling,but the number of stoves generally provided is three and sometimes it is four. This is done to get high air blast temperature. The heating cycle time is more than cooling time and larger number of stoves help in providing higher air blast temperature. Further, in case one stove undergoes shutdown for repair, the heating process for the blast furnace goes unabated with remaining (one or two) stoves with little lower heating capacity.

Recuperator

(i) Definition

It is a continuous heat exchanging device using fluid (water/air) flowing in tubes.

The device is useful at comparatively lower temperature using two metallic or ceramic tubes. The recuperators could be radiation or convective type.

Radiation recuperator working principle: In this system, the thermal energy radiated from hot source could be used to pre-heat air for use in combustion process or raise steam for power generation. The hot sources like hot sinter on sinter bed, hot flue gas leaving furnace, hot rolled steel slabs, hot DRI in tunnel kiln, hot fired iron ore pellets, etc. may be used to recover waste energy.

The radiated heat is received by metallic tubes for good heat conduction to flowing fluid (air/water) inside the tubes. The tube system is designed according to available space and thermal flux.

Convective recuperator working principle: The device consists of two tubes fitted in each other to exchange thermal energy through metallic/ceramic wall of the tubes while the fluids are moving in the respective tubes over certain length to give time for heat exchange.

The heat in bulk hotter fluid is transferred to fluid boundary layer by convection process. This thermal energy reaches metallic/ceramic wall of the tubes by conduction through fluid boundary layer which is practically stationary. The thermal energy conducted by metallic/ceramic wall of the tube is delivered to boundary layer of the colder fluid and further conducted to the bulk colder fluid which is carried away by convection current. Thus, both conduction and convection process play role in heat exchange which is dependent on thermal conductivities of metallic/ceramic tube material and fluids.

(ii) Design of the convective recuperators

The process of heat exchange is further affected by design of the recuperator system, where the fluids exchange thermal energy under three different fluid flow directions: (i) Counter current flow, (ii) Co-current or parallel flow and (iii) Cross flow. These three design principle of recuperators is illustrated in Figure 8.9.

Counter current recuperators: In this arrangement, the tube carrying hot fluid (gas or liquid) is encased by a larger diameter tube carrying colder fluid (gas/liquid). The length of concentric tubes depends on the recuperator design. The flow direction of the fluids is counter current defining nature of heat exchange mechanism. The temperature profile of the two fluids is also shown in Figure 8.9. In this figure, hot waste gas entering at Face 1 is heat donor, and cool air entering at Face 2 is heat receiver flowing in opposite (counter current) direction. The temperature of cold air entering at Face 2 keeps increasing as it moves towards Face 1 for exit. The temperature of hot waste gas entering at Face 1 keeps decreasing over the length of the recuperator as a result of heat exchange till its exit at Face 2. This arrangement offers heat transfer as air entering at Face 2 which is gradually pre-heated and the exit temperature at Face 1 is little lower than hot gas temperature.

Co-current or parallel flow recuperators: This is identical in design used for counter current flow recuperator with only difference that the flow direction is same for donor hot fluid and receiver cold fluid. In Figure 8.9, both fluids are shown to enter the recuperator at Face 2 at widely different temperature. In the time period of passing through recuperator length, the heat exchange occurs and fluid temperature difference becomes less making cold fluid hotter and hot fluid colder at the exit Face 1.

Cross flow recuperators: In this recuperator design, the fluid flow is made to cross each other. The hot and cold fluids enter at 90 degrees, and exit after heat exchange at 90 degrees.

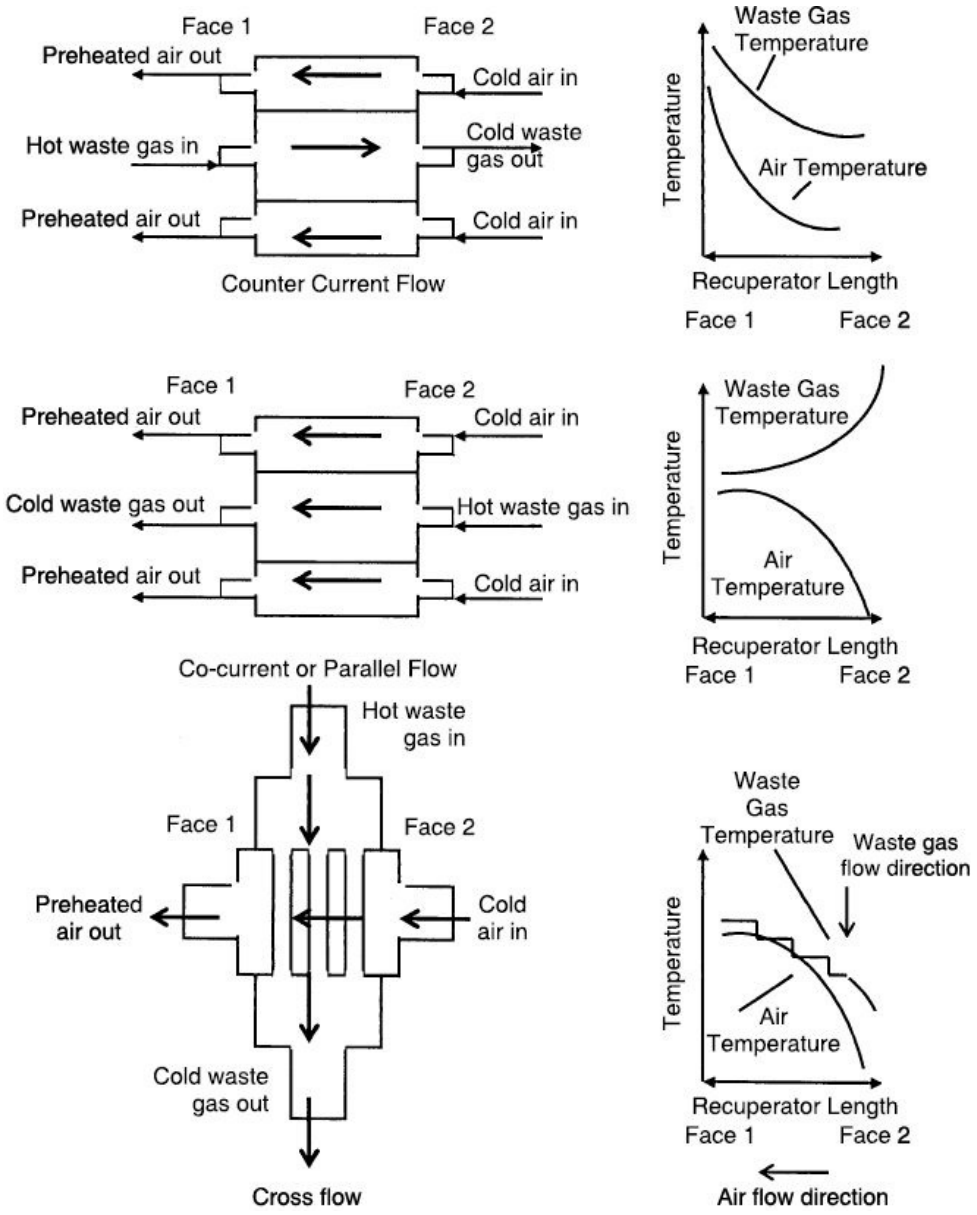


Figure 8.9 Arrangement of heat exchanging tubes in recuperators.

The cold air temperature keeps increasing as it crosses hot gas tubes and emerges as warm air. The hot waste gas temperature in tube at cold air entry side is lower than warm air exit side. These waste gases after donating their thermal energy would get mixed and emerge out as less warm air.

(iii) Application

Recuperators are used in most of the furnaces to pre-heat air for combustion in the burners to get higher flame temperature.

Waste heat boilers

It is a device to utilise waste heat in flue gases to raise steam. Waste heat boilers

are ordinarily water tube boilers in which the hot exhaust gases from furnaces pass over a number of parallel tubes containing water. The water is vapourised in the tubes and collected in a steam drum from which it is drawn off for use as heating or processing steam. Generally, the exhaust gases are in the medium temperature range and in order to conserve space, a compact boiler can be designed with finned water tubes to increase the effective heat transfer area on the gas side. Figure 8.10 shows a typical boiler design. The steam pressure and rate of steam generation depend on the temperature and flow rate of flue gas. In case the sensible heat in the exhaust gases is insufficient for generating the required amount of process steam, then auxiliary burners are provided to compensate the required heat energy. Waste heat boilers are built in wide ranging capacities from 25–30000 m^3 /min of exhaust gas.

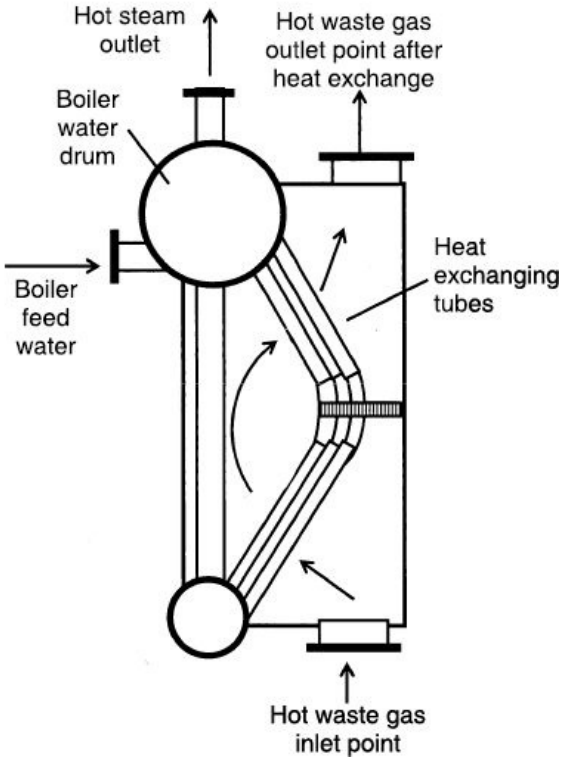


Figure 8.10 Waste heat boiler.

The waste heat boilers form integral part of many rotary kiln DRI plants to utilise the thermal energy of out going hot flue gases.

Economiser

It is a kind of cross flow heat exchanger to use low temperature waste gas for pre-heating water or air. The economisers are provided to pre-heat the boiler

feed water (Figure 8.11). The rise in feed water temperature by 6 °C through an economiser nearly saves 1% of fuel in the boiler.

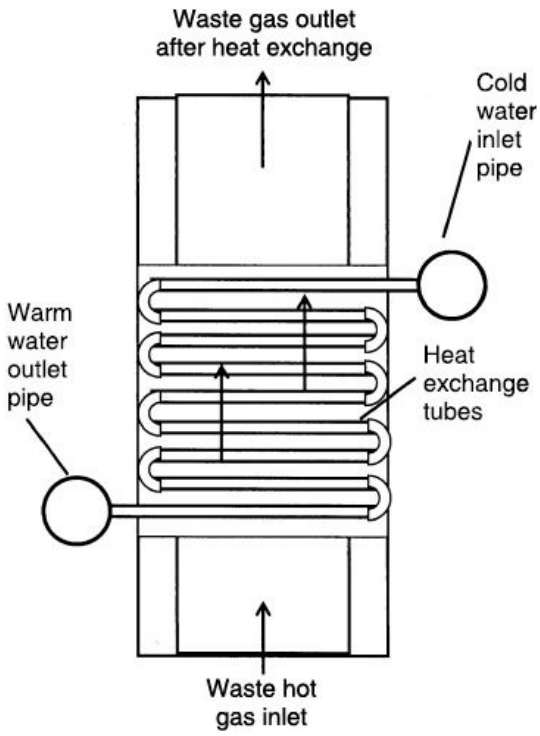


Figure 8.11 Economizer.

Special direct heat exchanging devices

In addition the mentioned methods of heat exchange, there are special direct heat exchanging devices for a specific purpose. Such devices are illustrated in the following sections: (i) Coke dry quenching (CDQ)

This is a device to recover sensitive heat of hot coke during its cooling process to raise steam for power generation. This device has been described in Chapter 2 (Figure 2.31), giving its merits and limitations. Nearly 0.5 ton steam per ton hot coke can be recovered by this equipment. The generation of 0.5 ton steam amounts approximately to 150 kWh energy.

(ii) Sinter coolers

It is a device to recover heat from sintering machine cooler. The hot sintered ore (500 °C to 700 °C) is cooled down to about 200 °C to 400 °C. The device contains a boiler and economiser. After heat exchanging with sintered ore in the cooler, the hot air is led to the boiler economiser resulting in generation of steam. The heat amounting 60000 kcal per ton sintered iron ore could be recovered by such device.

(iii) Scrap preheating by hot EAF gases

In steel melting by EAF, the hot gases could be utilised to pre-heat the scrap by adopting a double shell for melting. While main shell holding scrap is under melting process, the hot gases are allowed to escape after passing through auxiliary shell holding scrap charge. The out going hot gases deliver their heat to pre-heat scrap in the auxilliary shell. When the melting is over in main shell, the EAF cover is moved to the auxiliary shell holding pre-heated scrap to begin the melting process. The main shell after discharging its liquid metal is ready to receive the scrap charge which will be pre-heated by hot gases coming out from melting in auxiliary shell. Such double shell device in EAF is helpful in lowering power consumption for melting due to use of waste heat of outgoing gases.

8.5 ENERGY AUDIT

8.5.1 Definition

An energy audit is an activity that seeks to identify conservation opportunities of an energy savings program. Energy audit attempts to balance the total energy inputs with its use. It also serves to identify all the energy sources in the system and quantifies the energy use according to their function.

8.5.2 Aim of Audit

The aim of energy audit includes the following:

(i) The quantity, quality and cost of various input energy sources
(ii) Assessment of current practice of energy consumption
(iii) Identification of potential areas of energy economy
(iv) Highlighting the sources of energy waste in the system
(v) Fixing targets for energy saving potential
(vi) Implementation of measures for energy saving

8.5.3 Audit Procedure

The process of conducting energy audit is very elaborate and involves considerable manpower and effort. In brief, this could be presented as work done in the following steps: (1) Collections of data on operational parameters and energy consumption through a detailed questionnaire.

(2) Study of the existing plant operations to assess plant performance.

(3) Study of the specific energy consumption (both thermal and electrical) unit wise and plant as a whole.
(4) Collection of requisite data and identification of specific areas with potential for conservation of thermal and electrical energy.
(5) Study of limitations, if any, in the optimal use of thermal and electrical energy.
(6) Preparation of techno-economic feasibility report for recommended measures.
(7) Preparation of cost benefit analysis in terms of savings of energy consumption per unit of production.
(8) Formulation of tentative time schedule for implementation of the recommendations.
(9) Follow-up with the industry on periodic basis to ascertain the level of implementation of recommendation and assist, if required, in implementation of the measures to achieve energy user efficiency.

When such energy audit is conducted for various plants, units or furnaces, the possible areas could be identified for making savings.

8.5.4 Presentation of Energy Audit

The energy assessment report could be summarised in various ways to understand the entire flow pattern of energy. These methods could use tables, charts or Sankey diagrams.
The energy audit conducted for a reheating furnace is presented as illustration in three
different ways, i.e., tabular form (Table 8.6), bar chart (Figures 8.12), and Sankey diagram (Figure 8.13).

Table 8.6 Energy Balance of a Billet Reheating Furnace

Energy Input			*Energy Output Use/Loss*		
Input Source	Gcal/hr	*%*	*Sources*	Gcal/hr	*%*
Oil used in burner	3.78	100	Used in billet heating	0.869	23
			Loss due to moisture in oil	0.045	1.2
			Loss due to moisture from hydrogen% in oil	0.245	6.5
			Loss due to opening in the furnace	0.313	8.3
			Loss due to radiation from furnace walls	0.094	2.5
			Loss due to sensible heat of flue gases	2.007	53.1

			Loss due to unknown sources	0.204	5.4
Total input	3.78	100	Total output	3.78	100

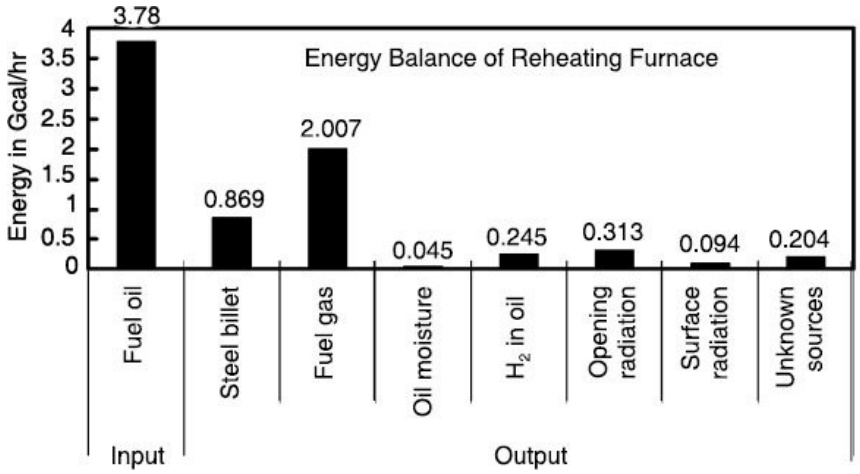


Figure 8.12 Bar chart showing energy balance of billet reheating furnace.

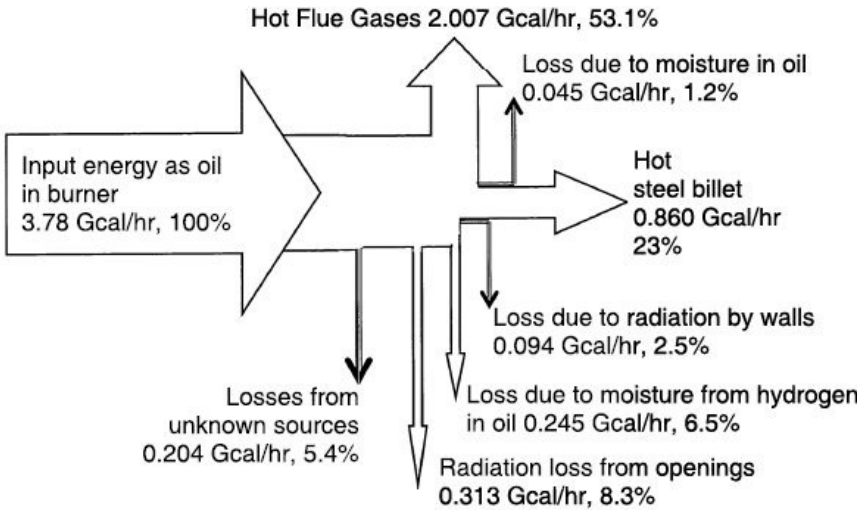


Figure 8.13 Sankey diagram showing energy balance of billet reheating furnace.

8.5.5 Numerical Problems

PROBLEM 4 A steel billet reheating furnace was supplied energy by burning oil at the rate of 20 liters per hour (calorific value 9000 kcal/liter). 25% of the total energy was used for heating the steel billets. The energy lost through various sources were as follows: 7% through conveyor system, 10% radiation losses through doors, 6% conduction losses through walls, 34% loss through hot flue gases. 18% energy is recovered from recuperative system to preheat air and recycled in the system. Draw a Sankey diagram showing the furnace energy balance and label the values in J/hr.

Solution

Given,

Energy in form of pre-heated air = 18%

Since, input energy = 100%

Hence, energy input in form of oil = 82% (= 100–18)

As energy with oil = 20 lit/hr = (20 × 9000 kcal/hr) = 180000 kcal/hr

As 1 kcal = 1000 × 4.186 joules

Therefore, oil energy = $180000 \times 1000 \times 4.186$ J/hr = $18 \times 4.186 \times 10^7$ J/hr

= 753.48×10^6 J/hr = 82% of total energy

Thus, total input energy = $(753.48 \times 10^6)/0.82 = 918.8 \times 10^6$ J/hr

Energy with Hot Air = $(918.8 - 753.48) \times 10^6 = 165.32 \times 10^6$ J/hr

Now, putting all input energy values in the table and calculating the values for output energy distribution, we get values as given in Table 8.7. The energy balance thus calculated is also given as Sankey diagram (Figure 8.14).

Table 8.7 Energy Balance Sheet

Input Energy			*Output Energy*		
Sources	10^6 Js/hr	%	*Sources*	10^6 Js/hr	%
Oil Burnt	753.48	82	Steel billet heat	229.70	25
Energy with preheated air	165.32	18	Loss with conveyor system	64.30	7
			Radiation loss	91.88	10
			Conduction losses	55.10	6
			Loss with flue gases	312.4	34
			Heat used for air preheat	165.32	18
Total energy	918.8	100	Total energy	918.7	100

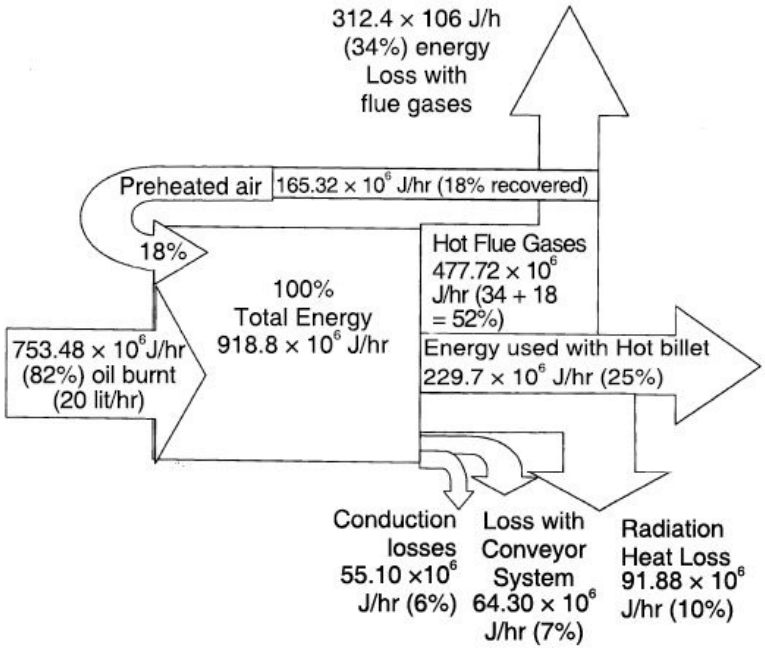


Figure 8.14 Sankey diagram showing energy balance.

Review Questions

1. What are the various mechanisms of heat transfer from burner to the ingot under heating process?

2. What are the basic principles which regulate conduction process?

3. What is Fourier's Law? Derive an expression for heat transfer through a plane wall.

4. What are the sources of heat loss in a furnace? What precautions are required to minimise the thermal loss.

5. What is waste heat? What are the factors considered before recovering the waste heat?

6. What is the objective of regenerator? How does it work? Give example of its use in metal industry.

7. What is the function of a recuperator? How many types of recupeators are used? Give their merits and limitations.

8. Why do we need energy audit? How is it conducted?

9. What is the purpose of energy balance sheet? What is the difference between bar chart and Sankey diagram for showing energy balance?

10. Define the following terms:

(i) Temperature

(ii) Thermal conductivity
(iii) Plank's law
(iv) Black body
(v) Stefan-Boltzmann law
(vi) Kirchhoff's law
(vii) Emissive power
(viii) Lambert's law
(ix) Thermal efficiency
(x) Air/Fuel ratio

11. Differentiate between the following terms:

(i) Thermal load and Thermal conductivity
(ii) Natural convection and Forced convection
(iii) Laminar flow and Turbulent flow
(iv) Absorptance and Transmittance
(v) Regenerator and Recuperator

9

Furnace Atmosphere Control and Environmental Issues

Introduction

This chapter deals with two different atmospheric aspects of the furnace. The first part is devoted to regulating the nature of atmosphere within the furnace conducive to the nature of activity processed in the furnace, while the second part gives the methods of controlling atmospheric pollution prevailing outside the furnace affecting work condition and human life.

The atmosphere within the furnace is characteristic of the nature of fuel used to burn and generate heat to conduct activities like heating, melting, heat treatment, etc. The atmosphere present in the furnace affects the quality of work being conducted, and hence needs to be regulated to suit the nature of work.

The flue gases generated by the combustion process are discharged to the atmosphere. These exit gases contain harmful and toxic gases which affect the working place and endanger the health of the persons in the proximity of the furnace. The discharge of exit gases is made through tall chimney after removing harmful constituents by suitable cleaning systems.

9.1 FURNACE ATMOSPHERE—NATURE AND APPLICATION

9.1.1 Definition

The word *furnace atmosphere* is used to define the nature of gases present in the working chamber of the furnace.

The furnaces are heated by the combustion of fuel (coal, oil or gas). The atmosphere within the furnace would be constituted by the products of

combustion including CO, CO_2 , $C_x H_y$, N_2 , O_2 , NO_x , SO_x , and $H_2 O$. In common electrical heated furnace, only air (O_2 and N_2) is present in the furnace atmosphere, except vacuum furnace where all gases are removed. In such electrically heated vacuum furnace, large amount of gas is removed and only trace amount of gas remains depending on the level of vacuum. In some furnaces, gases like H_2 , Ar, CH_4 are added in furnace chamber for specific purposes.

9.1.2 Properties of Different Gases

The different gases present in the furnace behave according to their nature. The nature of these gases is discussed in the following sections: Carbon monoxide (CO)
The presence of carbon monoxide in the furnace atmosphere is indicative of excess fuel or insufficient air for combustion. It is reducing in nature and highly toxic for human health. It has no smell or colour to give physical indication of its presence.

Carbon dioxide (CO_2)

The complete combustion of fuel gives CO_2 as end product. It is colourless, odourless and non-toxic gas. This is mildly oxidising in nature. It can oxidise iron at various temperatures forming FeO or $Fe_3 O_4$ according to the following chemical reactions:

$$CO_2 + Fe \rightarrow FeO + CO$$

$$CO_2 + 3FeO \rightarrow Fe_3 O_4 + 3CO$$

Carbon dioxide gas can also cause decarburisation of steel by reacting with carbon or cementite ($Fe_3 C$) present in its structural phase as follows:

$$CO_2 + Fe_3 C \rightarrow 2CO + 3Fe$$

$$CO_2 + C \rightarrow 2CO$$

Moisture ($H_2 O$)

Moisture is present in the furnace atmosphere from different sources. It is a product of fuel combustion due to presence of hydrocarbons ($C_x H_y$). It could be present in air (humidity) used for combustion of fuel and sometime moisture is added in the furnace atmosphere for certain reasons. Moisture causes oxidation

of steel.

Sulphur dioxide (SO_2)

Sulphur dioxide is formed during combustion by the oxidation of sulphur present in the solid and liquid fuels. Generally, gaseous fuels do not have sulphur dioxide as they are removed during their preparation. This gas has pungent, irritating and rotten odour giving pale white colour smoke. It is highly corroding gas for steel structures. It is toxic in nature and may cause deterioration in its quality.

Nitrogen (N_2)

Nitrogen is derived from the air used for combustion of fuel. It is an inert gas and normally does not cause any harm to objects or human body.

Hydrocarbons ($C_x H_y$)

Small amount of hydrocarbons may be present in the furnace atmosphere due to high fuel/air ratio, giving black smoke. The carbon soot in the exit gas gives its visibility and is harmful for respiration due to tiny carbon particles present in air. The deposition of soot on the refractory surface creates problem in the furnace.

Oxides of nitrogen (NO_x)

The oxides of nitrogen (nitric oxide –NO and nitrogen dioxide –NO_2) are commonly called NO_x . The nitrogen oxides (mainly NO_2) are generated from high temperature combustion. Nitrogen dioxide is a reddish-brown toxic gas with typical pungent odour. Nitrogen dioxide is a major air pollutant.

Oxygen (O_2)

Oxygen in the furnace atmosphere mainly comes from two sources. The main source is excess air needed for complete combustion of fuel in the furnace. The other source is leakage from openings. The atmospheric air infiltrates in the furnace operating under negative pressure. The oxygen present in the furnace atmosphere can cause oxidation of metal at high temperature.

Hydrogen (H_2)

Hydrogen in furnace atmosphere is provided from a source to have reducing atmosphere in the furnace. It is a highly flammable gas and needs care while use.

Argon (Ar)

It is an inert gas and is provided in the furnace for preventing oxidation of the metal at high temperature. Argon is colourless, odourless, nonflammable and non-toxic gas. Argon is chemically inert under most conditions, and forms no compound at room temperature.

Helium (He)

It is an inert gas and used in the furnaces for purging and creating protective atmosphere. It is the lightest gas with no toxicity.

Hydrogen and helium are gases having low density, high specific heat capacity and high thermal conductivity compared with nitrogen and argon. This property makes hydrogen and helium suitable for better heat transfer. These gases may be useful for rapid heating or cooling process during treatments in the furnace. The physical properties of few gases are given in Table 9.1.

Table 9.1 Physical Properties of Few Gases

Gas	*Density* kg/m ^{3}	*Specific Heat Capacity* J/kg K	*Thermal Conductivity* W/m K	*Dynamic Viscosity* $\times 10^{-6}$ Ns/m ^{2}
Hydrogen	0.084	14300	0.1750	9
Helium	0.167	5190	0.1536	20
Nitrogen	1.170	1040	0.0255	18
Argon	1.669	523	0.0173	23

9.1.3 CLASSIFICATION OF ATMOSPHERIC GASES

The various gases having different characteristics can be classified in the following manner according to their behaviour in the furnace.

Oxidising atmosphere

The gases like oxygen, carbon dioxide and steam provide oxidising atmosphere, which is present in most of the furnaces burning fuel for heating purposes.

Reducing atmosphere

The gases like hydrogen and carbon monoxide provide highly reducing conditions in the furnace needed for specific purposes like chemical reduction of oxides, heat treatment of steel, etc.

Inert or neutral atmosphere

The gases like nitrogen , argon and helium are used to provide protective inert atmosphere for heat treatments and heating of reactive metals.

In addition to the three common types of atmosphere used in most of the furnaces, the heat treatment furnaces use the following atmosphereres for particular type of treatment: Carburising atmosphere

The gases like carbon monoxide and hydrocarbons (C_x H_y) are used for carburisation of steel.

Decarburising atmosphere

The gases like carbon dioxide, oxygen and steam which are oxidising in nature, used for removing surface layer carbon by slow oxidation treatment known as *decarburisation* .

Nitriding atmosphere

Nitrogen is considered inert for most of the alloys, but it is active for some metals like stainless steel and titanium. Nitrogen is added by diffusion at high temperature in stainless steel to cause change in its properties.

9.1.4 Vacuum as Atmosphere

The vacuum atmosphere is created by expelling most of the gases from the chamber by using vacuum pumps. The degree of vacuum created will give the extent of gases present in the furnace chamber. Such vacuum atmosphere is used for melting metals and alloys for preparing melt free from any gas. The vacuum system is also useful for heat treating reactive metals and alloys. The extent of vacuum depends on the need or vacuum system used. The terms commonly used to express the degree of vacuum are given in Table 9.2. The use of vacuum system while conducting melting or heat treatment does not imply vacuum during entire operation. It only implies that the operation is conducted with the help of vacuum system, and suitable gaseous atmosphere is maintained during the period when vacuum is not necessary to meet the objectives while operating the process. This is illustrated in Figure 9.1 showing the cycle of furnace pressure, furnace temperature and object’s temperature during a typical heat treatment cycle.

Table 9.2 Level of Vacuum and Common Terms Used in Practice

Term Used for Vacuum Level	*Pressure*	
	Pa	torr

Rough vacuum	$1.3 \times 10^{2} - 1.3 \times 10^{4}$	1 – 100
Fine vacuum	$1.3 \times 10^{-1} - 1.3 \times 10^{2}$	$10^{-3} - 1$
High vacuum	$1.3 \times 10^{-5} - 1.3 \times 10^{-1}$	$10^{-7} - 10^{-3}$
Ultra high vacuum	$< 1.3 \times 10^{-5}$	$< 10^{-7}$

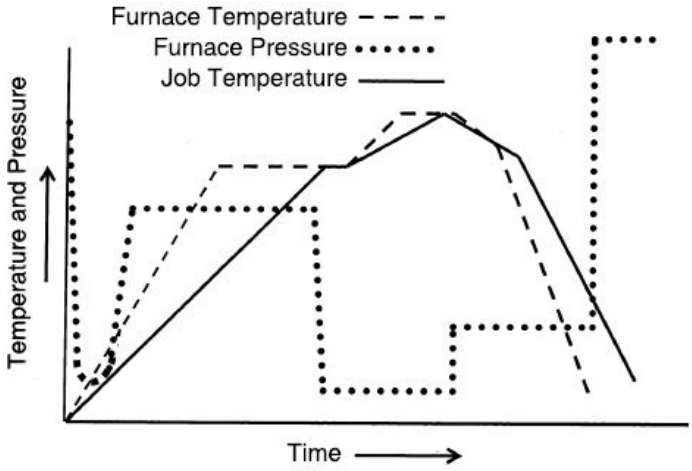


Figure 9.1 A typical heat treatment cycle showing vacuum and temperature changes.

9.2 METHODS TO GENERATE FURNACE ATMOSPHERE

In industrial furnaces, the required gaseous atmosphere is generated by mixing the supplied gas in-situ in the furnace. In many cases, two or more gases are needed to meet the required equilibrium in atmosphere. In case of external generators, the gases are generated outside the furnace and then supplied to the furnace. These two methods have their merits, and both are practiced.

9.2.1 In-situ Methods of Atmosphere Generation

Method

In this system, the gases are supplied by separate pipes in the furnace which get mixed in-situ. The furnace atmosphere may require one, two or more gases depending on the requirement. The furnace is provided separate pipelines to supply these different gases through regulators indicating respective gas flow rate. The example of feeding nitrogen and hydrogen by separate pipeline may be given to have atmosphere consisting of nitrogen and hydrogen in the desired

ratio. Similarly, methanol (dissociating in carbon monoxide and hydrogen) and nitrogen
may be supplied to have mixture of nitrogen, carbon monoxide and hydrogen in the furnace. Table 9.3 gives the supply line for various gases to provide desired atmosphere.

Table 9.3 Gas Pipe Systems for in-situ Atmosphere Generation

Gas Supply Lines in the System			*Furnace Atmosphere Created*
Line 1	*Line 2*	*Line 3*	
Nitrogen	–	–	Nitrogen
Hydrogen	–	–	Hydrogen
Argon	–	–	Argon
Helium	–	–	Helium
Nitrogen	Hydrogen	–	$N_2 + H_2$
Nitrogen	Cracked ammonia gas	–	$N_2 + H_2$
Argon	Hydrogen	–	$Ar + H_2$
Nitrogen	Natural gas	–	$N_2 + C_x H_y$
Nitrogen	$C_2 H_6$ gas	–	$N_2 + C_x H_y$
Nitrogen	Methanol	–	$N_2 + CO + H_2$
Nitrogen	Ethanol	Steam	$N_2 + CO + H_2$

Merits

This method has the following merits:

(i) The gas mixture can be altered at will to suit the process needs depending on alloy nature and heat treatment cycle.

(ii) The flow rate of the gases can be controlled precisely to have desired gas composition in the furnace atmosphere.

(iii) The starting time required for conditioning the furnace is less compared to external gas generators.

(iv) The maintenance and supervision of this system is easy.

(v) It gives better safety during operation.

(vi) Quality and productivity of the treatment in the furnace is improved due to better atmosphere control.

Gas procurement and supply

The gases are procured in different forms (compressed gas and liquefied gas), and then converted to gas at required pressure for supply in different units for use. These are given very briefly here in the following sections: (i) Nitrogen
The nitrogen gas is obtained in the following manner:

Cylinders: High purity nitrogen gas at high pressure for use in smaller furnace

Liquid nitrogen tanks: Suitable for high purity nitrogen demand with 5 ppm impurity (oxygen + moisture) meeting flow rate 10–200 m^3 /h without any capital installation.

Nitrogen from membrane unit installed on site: Suitable for 5–1000 m^3 /h flow rate demand with less purity 90–99%.

Nitrogen plant (pressure swing adsorption) on site: Suitable for larger flow rate (10–2000 m^3 /h) demand providing 99–99.99% gas purity.

Nitrogen plant (cryogenic) on site: Suitable for high flow rate (250–2000 m^3 /h) demand with high purity (5 ppm impurity O_2 + H_2 O) gas. The plant is capital intensive and justified for larger units.

(ii) Hydrogen

It is procured in three ways:

(1) Cylinders
(2) Liquid hydrogen
(3) On site plant using electrolysis, natural gas reformation by steam, ammonia dissociation or methanol dissociation technique.

(iii) Argon

It is procured as gas in cylinders and as liquid in cryogenic tankers with high purity (5 ppm impurity O_2 + H_2 O).

(iv) Helium

It is obtained in cylinders.

(v) Methanol

It is obtained as liquid in tankers. This is dissociated as CO and H_2 by the following reaction:

$CH_3OH \rightarrow CO + 2H_2$

CO and H_2 gas are mixed with nitrogen to get any composition of CO, H_2 and N_2 gas. The methanol is injected in the furnace above 700 °C. At lower temperature methanol may
give soot. The different methods of injection of methanol in the furnace are illustrated in Figure 9.2.

9.2.2 External Atmosphere Generators

The external atmosphere generators (Figure 9.3) use hydrocarbons (natural gas or propane) to allow controlled reaction with air to produce gas known as endogas (RX), exogas (DX) and monogas (HNS). The cracked ammonia gas (DA) is also generated for certain applications. Table 9.4 gives the composition of such gases.

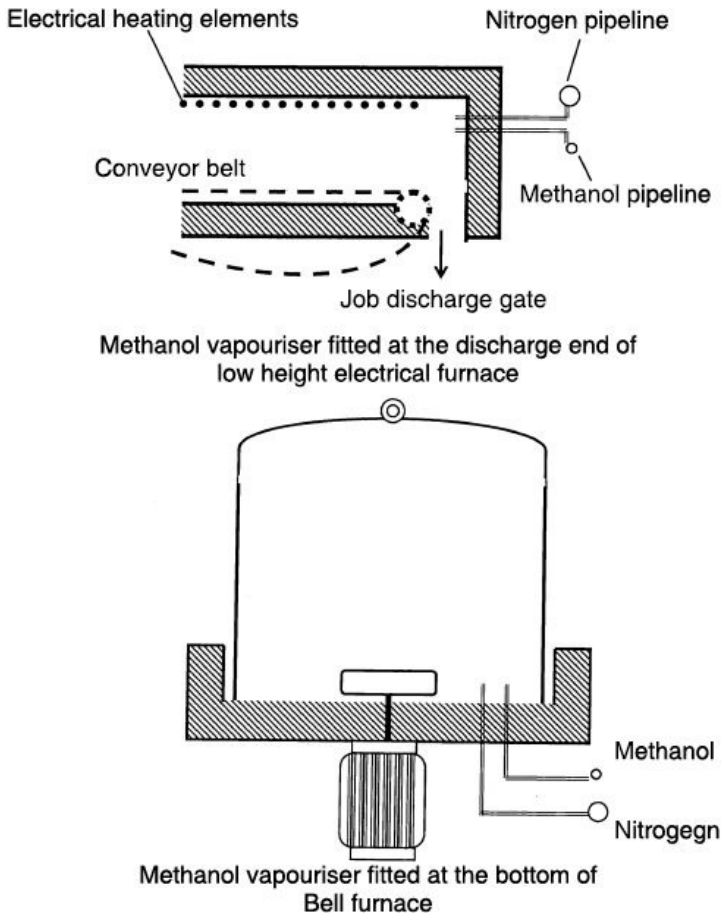


Figure 9.2 Injection places of methanol in the furnace.

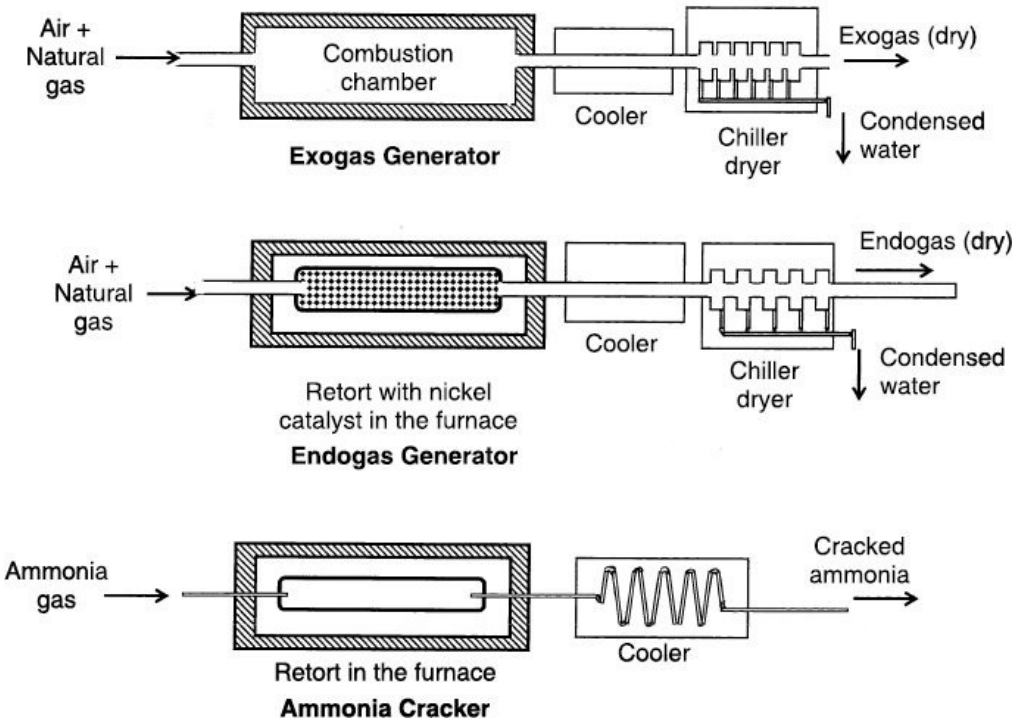


Figure 9.3 Gas generators for atmosphere control.

Table 9.4 Composition and Use of Gas Prepared in External Generators

Type of Gas	*Gas Composition (% Vol.)*					**Dew Point,* °C	*Use*
	N_2	H_2	CO	CO_2	CH_4		
Lean exothermic gas or Lean exogas	86	1.2	1.5	10.5	–	4.5	Bright annealing of copper and sintering of ferrites
Rich exothermic gas or Rich exogas	71	12.5	10.5	5	1	10	Bright annealing low C steel, silicon steels/copper brazing, sintering
Endothermic gas or Endogas	40	34	20	0.5	0.5	–10 to 10	Hardening, carburising with CH_4, sintering brazing
Monogas nitrogen	87	7	5	0.5	–	–60	Neutral atmosphere for annealing
Cracked Ammonia	25	75				–50 to 60	Brazing, sintering and bright annealing

* The "dew point" indicates the amount of water vapour present in the flue gases. Dew point gives the temperature at which flue gas gets saturated with moisture (Relative humidity–100%). The concentration of H_2, H_2O, CO and CO_2 in the furnace atmosphere depends on 'water gas reaction' ($CO + H_2O \rightarrow CO_2$).

Exothermic gas or exogas

The 'exogas' is prepared by combustion (complete or partial) of fuel gas like natural gas and propane with air. The moisture formed during combustion is

absorbed by using activated alumina/silica for its removal to get a desired dew point for the gas. The composition of the lean and rich exogas is given in Table 9.4. In lean exogas, the ratio of CO_2 /CO is greater than a rich exogas. The 'exogas' is useful for sintering iron and non-ferrous metal powders and bright annealing of steel items.

Endothermic gas or endogas

The 'endogas' is produced from a lean mixture of gaseous fuel (natural gas/propane)
with air. This mixed gas is led through blower to a heated (1000 °C) retort. The retort
contains nickel as catalyst to enable reaction to produce CO and H_2 according to the following reactions:

Propane $C_3 H_8 + 7.2$ Air $(0.21O_2 + 0.79N_2) \rightarrow 3CO + 4H_2 + 5.7N_2$

Natural gas $CH_4 + 2.4$ Air $(0.21O_2 + 0.79N_2) \rightarrow CO + 2H_2 + 1.9N_2$

The catalyst and heat are needed to promote the combustion reaction. The temperature of 'endogas' thus generated is lowered to avoid the cracking of CO gas as.

$$2CO \rightarrow CO_2 + C$$

The 'endogas' is useful for heat treatment of steel items without any problem of carburisation or decarburisation. This gas is also used as carrier gas for gas carburising/carbonitriding and copper brazing.

Cracked ammonia gas

Ammonia gas dissociation is used to prepare high purity nitrogen which is free from oxygen. The liquid ammonia is vapourised into a heat exchanger and is fed to dissociate in a reactor. The decomposition of ammonia to nitrogen and hydrogen begins at 300–320 °C. The rate of decomposition increases with rise in temperature. It is mainly used for bright annealing of metals such as silicon to obtain electrical properties. The ferrous and non-ferrous metals both are bright annealed using cracked ammonia gas. Bright silver brazing and copper brazing of steel also make use of this gas.

Monogas

This is high purity nitrogen gas with low concentrations of water vapour and carbon dioxide. This is obtained by cleaning exogas with respect to oxidising

gases. The equipment cost is high and also needs high maintenance. This is used for providing a neutral atmosphere for annealing treatments.

9.3 SELECTION OF ATMOSPHERE IN THE FURNACE

The selection of suitable atmosphere in the furnace is dependent on the following factors:

9.3.1 Alloy under Treatment and its Requirement

In case of treating ferrous and non-ferrous metals, it is desired that oxidation must not occur. This gives a limitation on oxygen concentration in gas decided by the nature of metal being treated. In case of steel, it is also desired that carburisation or decarburisation must not occur during treatment, which needs gas to be free from such gases. In some cases, the nitrogen and hydrogen may be undesirable and these gases must be absent.

9.3.2 Chemical Properties of the Atmosphere

The furnace gas atmosphere is selected as reducing, neutral or oxidising on the basis of treatment to be performed. The following care may be taken while selecting gas for the furnace atmosphere: (i) The reducing atmosphere would require lowest oxygen activity, which would be obtained by using pure hydrogen, mixture of N_2 and H_2 or Ar and H_2 having high hydrogen content with some hydrocarbon (C_x H_y). The reducing nature must not be kept very high unless needed. Ten per cent hydrogen with nitrogen can give very bright surface on steel and copper. Pure (100%) nitrogen may be used if protection is needed from oxidation, but it may not give bright surface. While using natural gas as a source of carbon, it may be kept around 5 per cent to avoid the formation of soot and its deposition.

(ii) Hydrocarbons should be introduced in the furnace when the temperature is more than 400–500 ° C.

(iii) Decarburisation free annealing may be conducted in very dry and oxygen free nitrogen or N_2 /H_2 atmosphere.

(iv) In alloys where nitrogen is detrimental, the Ar/H_2 or pure Ar may be used in place of nitrogen. Pure helium or vacuum treatment may be

alternative in some cases if possible.

Table 9.5 gives the use of gases for various treatments of alloys.

Table 9.5 Furnace Atmosphere for different Heat Treatments of Some Alloys

Heat Treatment	*Alloys*	*Furnace Atmosphere*
Annealing	Steels (low carbon)	Nitrogen or Hydrogen
	Steel (medium carbon)	$N_2 + CO + H_2$
	Steel (high carbon)	$N_2 + CO + H_2$
	Tool steel	$N_2 + CO + H_2$
	Stainless steel	$N_2 + H_2$ or Hydrogen
	Copper	$N_2 + H_2$ or Nitrogen
	Brass/Bronze	$N_2 + H_2$ or Hydrogen
	Aluminium	Nitrogen
	Nickel	$N_2 + H_2$
	Chromium	$N_2 + H_2$ or Hydrogen
	Titanium	$N_2 + H_2$ or Hydrogen
Hardening	Steel (medium carbon)	$N_2 + CO + H_2$
	Steel (high carbon)	$N_2 + CO + H_2$
	Tool steel	$N_2 + CO + H_2$
	Stainless steel	$N_2 + H_2$ or Hydrogen
Vacuum treatment	Steel	N_2, Ar, He or H_2
	Titanium	Ar or He
	Ni-Cr alloys	Ar, He or H_2

9.3.3 Reactions with Respect to Temperature and Heat

Transfer

The gases like hydrocarbons and hydrogen are flammable in nature. These gases need extra care during use. While introducing such gases in the furnace, the temperature must be above ignition temperature or oxygen content should be very low (below flammability range). The hydrocarbons also pose the risk of soot formation and affect the quality of the product. For example, methanol injected below 700 °C would give soot. If rapid heating is necessary, then hydrogen or helium may be better for higher heat conductivity (Table 9.1).

9.3.4 Restriction with Regard to the Furnace

The furnace type and design also put certain restriction in using gases. The factors affecting use may be as follows: (i) Availability of exhaust gas ignition system

(ii) Batch or continuous operation
(iii) Loading in hot or cold furnace
(iv) Leakage in the furnace system, etc.

9.3.5 Restrictions with Regard to Product Quality

The quality of atmosphere control is stricter at final stage of the product than intermediate stage of production. For example, the annealing treatment requires strict control after final cold rolling than intermediate hot rolling operation.

9.4 MONITORING FURNACE ATMOSPHERE

The furnace atmosphere provided in the furnace requires monitoring for good result. The monitoring process may depend on the scale of operation and nature of instruments used. This monitoring process could be the followings: (i) Indicating panel instruments

(ii) Auto control system
(iii) Visual observations

9.4.1 Indicating Panel of Instruments

The various instruments installed in the furnace are helpful in monitoring the atmosphere in the furnace. This type of system has two components: gas sensors

and indicators. These systems can monitor (i) humidity (%), (ii) CO and CO_2 (%), (iii) oxygen (%), (iv) hydrogen (%), (v) carbon potential and (vi) any other specific gas.

The sensors are placed at critical points, and connected to display panel. The gas flow rate is regulated manually by observing the control panel. Figure 9.4 shows schematic diagram of a continuous annealing furnace equipped with sensors for different gases to indicate on a display panel. This type of system would cost less, but would have limitation of gas control accuracy and subject to operators working skill.

9.4.2 Auto Control System

In units requiring better atmosphere quality, the atmosphere is controlled through auto regulation system. This consists of three components: sensors, gas analyser and gas flow regulator. The gas analyser and gas flow regulator are interfaced for dynamic control. This is shown schematically in Figure 9.5 for an illustrative continuous annealing furnace. The nitrogen and hydrogen gas supplied from respective source are mixed in a mixer in the desired ratio, and then supplied to various points in the furnace in regulated manner. The sensors placed in the furnace at various locations analyse the gases in the furnace. This gas analysis data is interfaced with gas flow regulator for necessary correction in flow rate automatically based on the required ratio.

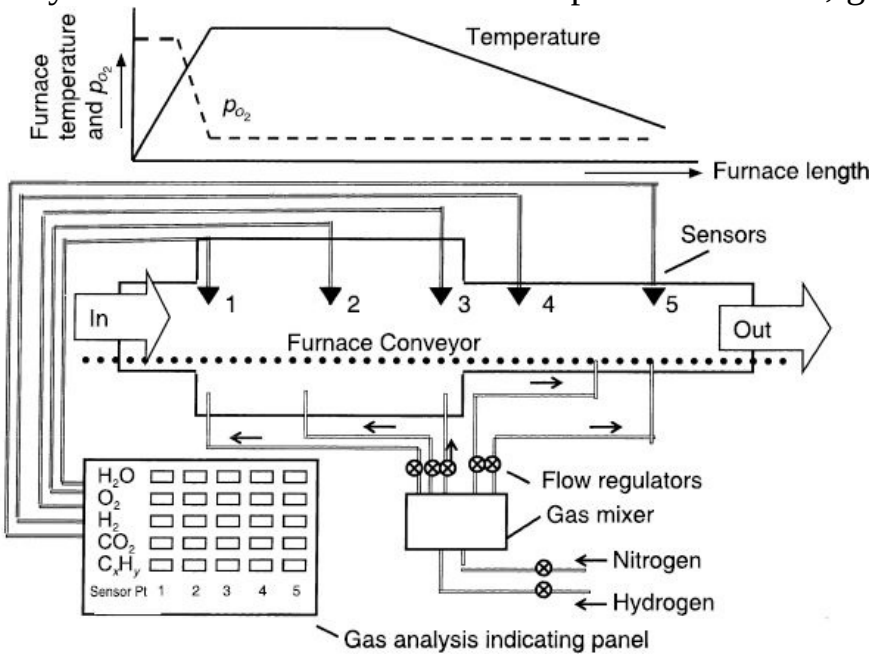


Figure 9.4 Gas analysis panel for indication percentage at sensing points in illustrative continuous annealing furnace.

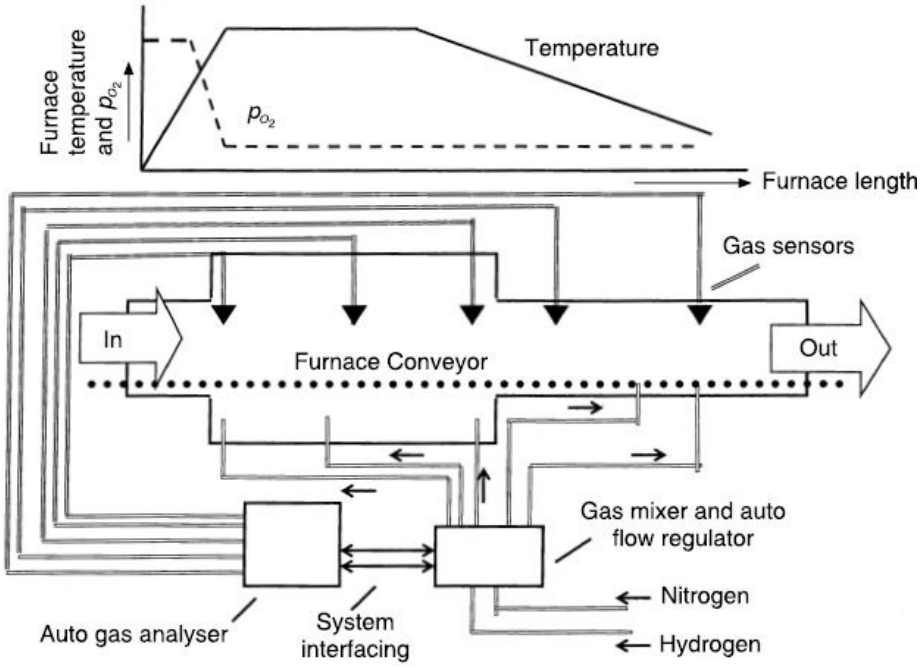


Figure 9.5 Auto gas analysis and control system in illustrative continuous annealing furnace.

9.4.3 Visual Observations

The visual observation of the product and furnace components is always helpful to monitor the progress in plants having indicating instruments or auto controlled furnaces. It is the only way to monitor the atmosphere quality in small scale units which do not have any instruments. The visual observation is simple and low cost method for atmosphere control, but needs trained workers.

The presence of oxidising gases like oxygen, moisture and carbon dioxide would cause oxidation of furnace components and items undergoing heat treatment. This oxidation would cause change in colour of the surface layer due to oxide formation. A close watch on the surface nature of the product and furnace components may help in identifying the problem which can be rectified by due adjustment of gas atmosphere. The following two simple visual observations can help in regulating the furnace atmosphere.

Copper and steel sheet method

Two metallic sheets of copper and low carbon steel with bright surface are put on the conveyor system of the furnace at the entry end, and taken out while emerging from exit for observing the change in brightness and colour of the surface. The copper would get oxidised by oxygen, but not by water vapour. The steel is oxidised by oxygen and water vapour both. The extent of oxidation

would be an indication of presence of oxidising gases. In muffle type furnace, the sheets could be left for a given time to oxidise before its observation. The degree of oxidation would be affected by temperature, time and gas concentration.

Paper method

The ordinary paper held in a dish type container exposed to furnace atmosphere would yield residue when furnace temperature is high enough to cause charring of the paper. In a reducing atmosphere, this residue would appear black char due to carbonisation of the paper. The same paper in presence of oxygen would yield white ash as residue due to combustion of carbonaceous matter.

9.5 SAFETY DURING USING GAS

The common hazards of using gas in the furnace could be the following:

(i) Fire/Explosion
(ii) Harmful/Toxic gas leakage
(iii) Cold burn while using cryogenic gas

The hazard due to fire and explosion is common and needs care during operation. This hazard can be avoided by taking care of the following: (i) Fuel handling

(ii) Absence of oxygen
(iii) Ignition source

Fuel handling

The gases like hydrogen, carbon monoxide and hydrocarbons are highly flammable
(Table 9.6), and require care during use. The mixing of gas with air forming flammable mix must be handled carefully.

Table 9.6 Flammability Range of Gases

Gas	*Flammability Range in Air, %*	*Auto Ignition Temperature,* °C
Hydrogen	4 – 75	560
Carbon monoxide	12 –74	620
Methane	4 – 15	595
Ammonia	15 – 30	630

Methanol	5 – 45	455

Absence of oxygen

The absence of oxygen can avoid such incidences, and the given guidelines must be followed: (1) Maintaining positive pressure in the furnace to avoid infiltration of air from leaking points.

(2) Vocation of the furnace gas by controlled combustion of exit gas.

(3) Using good natural ventilation when controlled combustion of exit gas cannot be assured.

(4) Use pilot burners at the exhaust when temperature below 750 °C does not automatically ignite the flammable mixture.

Ignition source

The leaking gas must not come in contact with any ignition source for combustion to occur. This can be avoided by strict control of external ignition sources.

9.6 FUELS, FURNACES AND ENVIRONMENTAL ISSUES

The subjects fuels, furnaces and environmental issues are very much inter-related. Fuels including solid, liquid and gas are used to generate energy in the form of heat for wide applications, e.g. boilers for power generation, heating metals for hot working, heat treatment and firing ceramic items. In metallurgical furnaces, coal, coke and natural gas are used as chemical energy source to extract metal from their oxides.

In all such furnaces, the use of fuel yields flue gases after reaction with oxygen in air or metal minerals. The flue gases thus generated are discharged in the atmosphere causing air pollution. The various components of the furnace need cooling to protect it from thermal damage. The hot cooling water along with dissolved chemicals is discharged in the natural water bodies causing water pollution. The ash generated from the combustion of coal in power plants is mostly discharged as fly ash and some quantity as bottom ash. In smelting unit, the ash combined with flux is discharged as molten slag. The disposal of this large quantity of solid waste (fly ash, bottom ash and slag) poses problem of disposal due to lack of land fill site in many locations. The thermal radiations from the furnace make working atmosphere near furnace very difficult for

workers.

All these issues of emission of flue gas, discharge of waste hot water, solid waste and thermal radiations raise various concerns related to ecological sustainability and hazard for the living bodies including flora and fauna of the region.

The use of energy is undoubtedly essential for meeting the needs of the society while sustaining ecosystem including land, water and air is equally necessary for the existence of living body on this planet earth. This requires a good understanding of resulting problems due to various emissions generated during the use of fuels. A judicious balance between the exploitation of fuels and impact of its emissions is required for sustainability.

9.6.1 Impact Area of Pollutants

The emissions from furnace migrate to different distances before they are diluted by natural process rendering it non-hazardous. The pollutants thus could be divided in the following three groups based on their impact zone: (i) Pollutants affecting local zone ranging up to 5–10 km radius, (ii) Pollutants migrating to some larger distance affecting a regional zone extending up to 10–200 km and (iii) Pollutants affecting ecosystem on much wider range extending to global reach. These three different groups of pollutants are given in Table 9.7.

Table 9.7 Impact Zone of Pollutants from Furnace

Impact Zone		*Pollutants*
Group	*Impact Zone Radius*	
Local pollutants	Up to 5–10 km	Solid particulates (dust)
		Toxic gases, e.g. CO, Cl, NH_3, cyanides
		Bad odour
		Heat and noise < 500 meters
		Liquid discharge with toxic chemicals
		Solid wast e, e.g. fly ash
Regional pollutants	Up to 10–200 km	NO_x and SO_x
Global pollutants	Global	CO_2

9.6.2 Airborne Pollutants

The air around us supports our life. The quality of natural air is important for a safe living. The quality standard prescribed by government administration differs from nation to nation keeping national policy in view. The Indian Ambient Air Quality Standard (2009) is given in Table 9.8. In this table, various airborne constituents are presented with their annual average value in air which is the maximum permissible limit for residential and industrial areas. These air borne constituents originate by the use of fuels in the furnaces and industrial activities. The health hazard caused by each constituent is briefly described in the following sections.

Table 9.8 Indian Ambient Air Quality Standard (2009)

Pollutants	*Concentration of Ambient Air*	
	Industrial Area, Residential, Rural and Other Area	*Sensitive Area*
Particulate matter # (size less than 10 µm)	60 µg/m ^{3}	60 µg/m ^{3}
Particulate matter # (size less than 2.5 µm)	40 µg/m ^{3}	40 µg/m ^{3}
Sulphur dioxide (SO_2) #	50 µg/m ^{3}	20 µg/m ^{3}
Oxides of Nitrogen (NO_2) #	40 µg/m ^{3}	30 µg/m ^{3}
Ozone #	100 µg/m ^{3}	100 µg/m ^{3}
Ammonia (NH_3) #	100 µg/m ^{3}	100 µg/m ^{3}
Carbon monoxide $	2.0 mg/m ^{3}	2.0 mg/m ^{3}
Benzene #	5 µg/m ^{3}	5 µg/m ^{3}
Lead as Pb #	0.50 µg/m ^{3}	0.50 µg/m ^{3}
Benzo pyrene (BaP) #	1 ng/m ^{3}	1 ng/m ^{3}
Arsenic (As) #	6 ng/m ^{3}	6 ng/m ^{3}
Nickel (Ni)	20 ng/m ^{3}	20 ng/m ^{3}

Annual average, $:8 hours average

(*Source:* Ministry of Environment and Forest, GOI, 16 th Nov. 2009 notification.)

Particulate matter (Dust)

These are fine solid particles originating from ash present in the fuel. The ash particles join the flue gases after combustion of solid fuels like pulverised coal. The gas and oils are considered ash free though minor quantities may be present in some cases. These fine solid particles also get mixed with air during handling and transportation of solid fuels. These particulate matters are classified according to their size as given in Table 9.9. The particulate matters are the cause of various ailments, e.g. altered lung function, lung cancer and heart diseases. The intake of these fine particles leads to cardiopulmonary disease.

Table 9.9 Particulate Matter (PM) Classification based on Size

Fraction	*Abbreviation Used*	*Size / Range*
Larger particles (thoracic)	PM_{10}	< or = 10 μ m
Fine fraction	$PM_{2.5}$	< or = 2.5 μ m
Very fine fraction	PM_{1}	< or = 1 μ m
Ultra fine fraction	UFP or UP	< or = 0.1 μ m
Mixed fraction	$PM_{10} - PM_{2.5}$	2.5 μ m – 10 μ m

Sulphur dioxide (SO_2)

The fuels (coal, coke and oils) often contain sulphur derived from their origin. This elemental sulphur yields sulphur dioxide after combustion causing metal corrosion and becoming health hazard (Table 9.10) to human being depending on gas concentration and exposure duration. The presence of this gas is irritating in nature due to its bad smell. The sulphur dioxide discharged in air forms sulphuric acid (H_2SO_4) which comes on surface as acid rain causing environmental damage.

Table 9.10 Health Hazard of Sulphur Dioxide

Exposure Period	*Concentration in Air,* ppm	*Effect on Workers*
Long	1–2	Irritation
Long	5–10	Severe bronchial spasm
Short	20	Not harmful

Short	500	Fatal

Oxides of nitrogen (NO_x)

Oxides of nitrogen are formed at high temperature during combustion of fuel. It causes health problem and is considered as ozone destroyer. The oxides of nitrogen react with other constituents present in air such as water vapour, ammonia and some other compounds to form nitric acid fumes and similar particles. Such fine sized particles enter human body through breathing and damage sensitive tissues in lung. This may result in worsen respiratory diseases like emphysema or bronchitis, aggravation of existing heart disease and premature death in some cases.

Carbon monoxide (CO)

The carbon monoxide is produced due to partial combustion of carbon present in coal, oil or gas. It is highly toxic gas, and can affect human health exposed for short durations. The CO gas inhaled by human body reacts with blood hemoglobin to form carboxyl-hemoglobin (HbCO). The dissolution of CO in blood reduces its carrying capacity of oxygen leading to oxygen deficiency (hypoxia). The intake of CO gas containing 100 ppm or more could be fatal to human health as indicated in Table 9.11.

Table 9.11 Effect of Carbon Monoxide Exposure on Human Health

Effect of Carbon Monoxide Exposure on Human Health	*Exposure*	*Reaction Time*	*CO Level* (ppm)
Headache and dizziness	Constant	6–8 hr	35
Slight headache in two to three hours	Constant	2–3 hr	100
Slight headache with loss of judgment	Short	2–3 hr	200
Frontal headache	Short	1–2 hr	400
Dizziness, nausea, and convulsions loss of sense	Short	45 min –2 hr	800
Headache, tachycardia, dizziness and nausea death	Short	20 min– < 2 hr	1600
Headache, dizziness and nausea death	Very short	5–10 min– 30 min	3200
Headache and dizziness. Convulsions, respiratory arrest, and death	Very short	1–2 min– < 20 min	6400
Death	2–3 breath	< 3 min	12800

Volatile Organic Compound (VOC)

The volatile organic compounds (VOCs) are a group of chemicals that contain

organic carbon and readily evaporate in air. These are evolved during heating of coal (e.g. coke making). The VOCs may affect liver or kidney depending on the exposure level and gas concentration. At higher concentrations, breathing some of these VOCs may cause irritation of the respiratory tract. The reproductive and developmental effects of these contaminants have been poorly studied. The health scientists do not have firm observation about these chemicals causing cancer in human being, but the public health officials take a cautious approach to set conservative standards.

Ozone (O_3)

The ozone gas is composed of three oxygen atoms. The ozone layer found in the upper atmospheric layer (stratosphere) protects the living bodies on earth from solar (ultraviolet) radiations. However, the same ozone gas present near the earth surface which provides oxygen for breathing (troposphere) acts as an air pollutant causing serious health problems.

The ozone is formed by the interaction of solar radiations and VOC, NO_x and CO discharged by the furnaces (Figure 9.6).

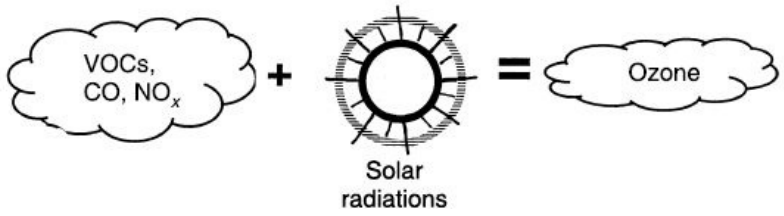


Figure 9.6 Formation of ozone in the atmosphere.

The ozone is found to cause many health problems as studied by the US–EPA (American Environmental Protection Agency). These health issues are as follows: (1) Ozone is found to damage respiratory system resulting in COPD (Chronic Obstructive Pulmonary Disease) or worsened asthma.

(2) The short- and long-term exposure of ozone is reported to cause early death.

(3) Ozone can cause cardiovascular damage (e.g. heart attacks, strokes, heart disease and congestive heart failure).

(4) Ozone is found harmful to the central nervous system.

(5) Ozone exposure may cause reproductive and developmental problems in human beings.

Carbon dioxide (CO_2)

The carbon dioxide is formed by the complete combustion of carbon in the fuel. The atmospheric air contains about 390 ppm carbon dioxide. It is not toxic at low concentrations, but its higher concentration and longer exposure may cause serious health problems as indicated in
Table 9.12. The carbon dioxide is known to cause green house effect on the earth which is a serious global concern due to its devastating impact.

Ammonia (NH_3)

It is a colour less gas with characteristic odour. The compressed gas may explode if heated, since it is a flammable gas. The high concentration of ammonia could be a fire hazard, in confined space. It can decompose at higher temperatures forming very flammable hydrogen gas. It is very toxic in nature and could be fatal if inhaled. It is corrosive to the respiratory tract. Its corrosive nature causes severe skin burns and eye damage. Its high concentration exposure may cause frostbite .

Benzene ($C_6 H_6$)

It is a constituent of crude petroleum and could be present up to 4g/lit. It is released in the atmosphere during processing of petroleum products, coking of coal, production of toluene, xylene and other aromatic compounds. Its use as a chemicals, petrol (gasoline) and heating oils also releases it in the atmosphere. The discharge of industrial waste containing benzene adds to atmospheric concentrations.

The human health is affected by exposure to benzene. The acute industrial exposure to benzene may cause narcosis like headache, dizziness, drowsiness, confusion, tremors and loss of consciousness. This toxic effect is aggravated under alcoholic conditions. It causes moderate eye irritation and is a skin irritant. The benzene is a well-established cause of cancer in human beings. The evidences indicate that benzene may also cause acute and chronic lymphocyte leukaemia

Table 9.12 **Effect of Carbon Dioxide Exposure on Human Health**

Effect on Human Health	*Exposure*	CO_2 *(%) in Air*
Drowsiness	Prolonged	1
Mildly narcotic and causes increased blood pressure and pulse rate, and reduced hearing	Mild	2

Stimulation of the respiratory center, dizziness, confusion and difficulty in breathing accompanied by headache and shortness of breath. Panic attacks may also occur at this concentration	Mild	5
Headache, sweating, dim vision, tremor and loss of consciousness	5–10 min	8

Benzo (a) Pyrene (BaP)

Benzo(a)pyrene is a polycyclic aromatic hydrocarbon found in coal tar with the formula C_{20} H_{12} . The BaP compound is one of the benzopyrenes formed by a benzene ring fused to pyrene. The BaP is formed due to incomplete combustion of coal at temperatures between
300 and 600 °C. This compound is found in all smoke resulting from the combustion of organic material.

The International Agency of Research in Cancer (IARC) has classified Benzo (a) pyrene under carcinogen chemicals in ‘Group 1’. BaP is mutagenic agent which changes the genetic material like DNA of an organism and known for highly carcinogenic effects.

Arsenic (As)

The coal combustion is one of the sources for arsenic in air. The arsenic present in coal as mineral matter is released during combustion, and joins with flue gases and partly with fly ash. The flue gases from smelting furnaces may also contain arsenic based on the nature of solid fuel being used. The World Health Organisation (WHO) has published the adverse health effects of arsenic on human beings. The effect due to acute short term exposure and long term exposure has been given in the following sections: (i) Effects of acute short-term exposure
The arsenic intake by human body is reflected by the signs of poisoning causing vomiting, diarrhoea and pain in abdomen. The numbness and mussel cramping occur with higher dose intake which may follow death in some cases.

(ii) Effects of long-term exposure

The longer exposure of gases having high concentrations of inorganic arsenic results in changes in the skin. The skin pigmentation change follows with hard skin patches on the hand palms and feet sole. The long-term exposure of high inorganic arsenic also causes peripheral neuropathy, gastrointestinal symptoms, diabetes, conjunctivitis, enlarged liver, renal system effects, depressed bone marrow, increased blood pressure and cardiovascular ailments.

Nickel (Ni)

Nickel in air is mainly released by power plants and trash incinrators. This nickel

in air is brought to the ground by gravity and entrapment in rain water droplets. The nickel entering in human body through breathing process or contaminated water/food items can harm in many ways. Nickel can create the following problems to human health: (1) Sickness and dizziness after inhaling air containing nickel particles

(2) Increasing chances of lung cancer, nose cancer, larynx cancer and prostate cancer (3) Problem of lung embolism

(4) Failure of respiratory system

(5) Source of asthma and chronic bronchitis

(6) Skin rashes due allergic reactions mainly from nickel based artificial jewelry or spectacles frame

9.6.3 Waterborne Pollutants

Water is used in furnaces as cooling media and cleaning gas (scrubbers). This water gets contaminated with soluble chemicals giving colour, odour, taste and pH value. The unsoluble solids remain as suspended particles giving turbidity. This contaminated water needs treatment before being discharged to natural water bodies. The hot water from furnace cooling system needs cooling to minimise the thermal pollution affecting aquatic life in water bodies. Further, the solid waste in the landfills is leached by rain water and joins the ground water as well as the nearby water drainage leading to rivers. This requires care while discarding solid waste in landfills by providing suitable liners. In the rainy reason, the soil contaminated with industrial dust and discarded waste gets washed and joins the river water.

Thus, the various constituents dissolving in natural water affect its properties, e.g. colour, odour, taste, pH, etc. These various polluting constituents affect its use and sometime make it unfit for human consumption. Table 9.13 gives the impact of various pollutants on its use and human health along with water treatment techniques needed to make it fit for use. The water quality for drinking and irrigation is also given in Table 9.14 as prescribed by law.

9.6.4 Solid Pollutants

The power plants use coal as fuel and yield ash as solid waste. The steel plants use coke and coal for iron making and yield slag. The slag is also generated during steel making. All such solid waste generated form the use of solid fuels is discarded which amounts several million ton per year.

The iron making slag fortunately finds use as raw material cement and is fully utilised. The fly ash and bottom ash from power house are partially used for making cement and building bricks. Unfortunately, the amount of ash generated is so high that it cannot be fully utilised and is dumped in adjoining areas. The fly ash contains many elements which are leached out and join the water causing harmful effect to human settlements.

The seriousness of the issue could be illustrated with thermal power plants using coal as one example. In India, the installed capacity of power plant was about 70000 MW which consumed 218 million tons of coal in 1999–2000. The quality of coal used by different plants would differ but the coal used by Singrauli Super Thermal Power Plants is reported to contain mercury to the extent of 0.41 mg/kg in one of the units (in 2000). Use of such coal discharges mercury in the atmosphere through fly ash and flue gas. This mercury is reported to be causing serious health problem in the region. The impacts of various pollutant form the industry are often reported by the media to draw public attention and seek remedial action to keep balance between industrial development and ecological sustainability. The media reporting (http://www.downtoearth.org.in/content/india-s-minamata) on large scale health impacts of mercury from thermal power plants in Sonbhadra region is an illustrative case and alarming in nature which needs care for using such coal.

Table 9.13 Water Pollutants Source, Impact and Treatment

Item	*Source*	*Impact of Pollutants*	*Water Treatment*
Colour	Iron, Copper, Manganese Natural deposits	Visible tint, Decreased acceptance	Filtration, Distillation, Ozone treatment RO (Reverse osmosis)
Odour	Chlorine, Hydrogen sulphide, Organic matter, Septic contamination, Methane gas	Bad feel	Activated carbon, Air stripping, Oxidation, filtration
Temperature	Furnace cooling	Thermal pollution to aquatic life in natural water body	Water showering or fountain in pond
pH value	Natural	Low pH – corrosion, metallic taste High pH – bitter/soda taste, deposits	Increase pH by adding soda ash, Decrease pH by adding white vinegar or citric acid
Hardness ($CaCO_3$)	Dissolved Ca and Mg from soil and aquifer minerals containing limestone or dolomite	Scale in utensils and hot water system, soap scum	Water softener, ion Exchanger, Reverse osmosis
Total Dissolved Solids (TDS), mg/l	Septic system, Landfills, nature of soil, Hazardous waste landfills, Dissolved minerals, iron and manganese	Hardness, scaly deposits, sediment, cloudy and stain giving coloured water, salty in taste, pipes and fittings showing corrosion	Reverse Osmosis, Distillation, Deionisation by ion exchange
Alkalinity	Pipes, landfills, Hazardous waste	Low alkalinity (i.e., high acidity) causes	Neutralising agent

	landfills	deterioration of plumbing and increases the chance for many heavy metals in water (present in pipes, solder or plumbing fixtures).	
Iron (Fe)	Leaching of cast iron pipes in water distribution systems, Natural	Blackish colour, rusty sediment, tasting bitter or metallic, giving brownish green stain mark	Oxidising filter, Green-sand Mechanical filter
Manganese (Mn)	Landfills, Deposits in rock and soil	Brownish colour, black stains on laundry and fixtures. At 2 mg/l level-bitter taste, altered taste of water-mixed beverages	Ion exchange, Chlorination, Oxidising Filter, Green-sand, Mechanical filter
Chloride (Cl)	Industrial wastes, Minerals, Seawater	Giving salty taste, showing corrosion spots in pipes and fixtures, blackening and pitting of stainless steel	Reverse osmosis, Distillation, Activated carbon
Fluoride (F)	Industrial waste, Geological	Brownish discolouration of teeth, bone damage	Activated alumina, Distillation, Ion exchange treatment, RO (Reverse Osmosis)
Arsenic (As)	Previously used in pesticides (orchards), Improper solid waste disposal or product storage of glass or electronics, Mining rocks	Weight loss, depression, lack of energy, skin and nervous system toxicity	Filtration by activated alumina, Distillation RO (Reverse Osmosis), Chemical precipitation (lime softening)
Chromium (Cr)	Septic systems, Industrial discharge, Mining sites, Geological	Skin irritation, skin and ulcer in nose, tumors in lung, gastrointestinal effects, damage to the nervous system, bones, spleen, kidney and liver	Ion exchange, Reverse osmosis, Distillation
Copper (Cu)	Industrial and mining waste, wood preservatives, Natural deposits	Giving bad taste (bitter or metallic) and bluish-green mark on fixtures, Causing anemia, digestive disorder, harm to liver/kidney and gastrointestinal disorders	Ion exchange, Reverse osmosis, Distillation
Cyanide (CN)	Fertiliser Electronics, Coke ovens, Steel, Plastics, Mining	Thyroid, nervous system damage	Ion exchange, Reverse osmosis, Chlorination
Lead (Pb)	Paint, diesel fuel combustion Pipes and solder, old car/truck batteries, paints, leaded petrol, Natural deposits	Causes mental problems like retardation, affects kidney and neurological systems, blood disorders, hypertension and death at high intake levels	Distillation, ion exchange Treatment, Activated carbon, RO (Reverse Osmosis)
Mercury (Hg)	Fungicides, Batteries, Mining, Electrical bulbs and components, Coal power plants, pulp and paper and Natural deposits	Mental disorder (deterioration in intellectual property), loss of sight, kidney failure, nervous system disorders, death at high levels	Distillation RO (Reverse Osmosis)
Zinc (Zn)	Leaching of galvanised pipes and fittings, Paints, Dyes Natural deposits	Metallic taste	Ion exchange, Water softeners, Reverse osmosis, Distillation
Coliform bacteria	Livestock facilities, Septic systems, Manure lagoons, Household waste water	Gastrointestinal diseases	Chlorination, Ultraviolet, Distillation, Iodination
E. coliform bacteria	do	do	do
Aluminum		Neurological disorders, Alzheimer’s disease	

Cadmium		Highly toxic; causes ‘itai-itai’ disease—painful rheumatic problems, affects cardiovascular systems, upsets intestinal functions and causes hypertension	
Nitrate		Blue baby disease (methemoglobinaemia)	
Sulphate		Taste affected, laxative effect, gastrointestinal irritation	

Table 9.14 Quality of Water for Drinking and Irrigation

Parameter	*Units*	*Drinking Water Desirable #*	*Drinking Water Permissible*	*Land Water for Irrigation*	*Inland Surface Water*
Colour	Hazen	5	25	–	–
pH value		6.5–8.5	No relaxation	5.5 to 9.0	5.5 to 9.0
Hardness ($CaCO_3$)	mg/l	300	600		
Temperature, max.	°C				40
Turbidity (suspended solids)	NTU	5	25	200 mg/l	100 mg/l
Total Dissolved Solids (TDS)	mg/l	500	2000	2100	2100
Alkalinity	mg/l	200	600		
Iron (Fe)	mg/l	0.3	1		
Manganese (Mn)	mg/	0.1	0.3		
Oil and grease, max.	mg/l	Nil	Nil	10	10
Total residual free chlorine	mg/l	0.2	–		1.0
Chloride (Cl)	mg/l	250	1000	600	1000
Fluoride (F)	mg/l	1	1.5	–	2.0
Arsenic (As)	mg/l	0.05	No relaxation	0.2	0.2
Chromium (Cr)	mg/l	0.05	No relaxation	–	2.0 max.
Copper (Cu)	mg/l	0.05	1.5	–	3.0 max.
Cyanide (CN)	mg/l	0.05	No relaxation	0.2 max	0.2 max.
Lead (Pb)	mg/l	0.05	No relaxation	–	0.1 max.
Mercury (Hg)	mg/l	0.001	No relaxation	——	0.01 max.
Zinc (Zn)	mg/l	5	15	——	5.0 max.
Total coliform bacteria	coliform/100 ml	10			
E. coliform bacteria	coliform/100 ml	Nil	No relaxation		

Biochemical oxygen demand (5 days at 20 °C)	mg/l	–	–	100 max.	30 max.
Chemical oxygen demand	mg/l	–	–	–	250 max.
Ammonical nitrogen (as N)	mg/l	–	–		50 max.
Total Kjeldahl nitrogen (as N)	mg/l	–	–		100 max.
Free ammonia (as NH_3)	mg/l	–	–		5.0 max.
Cadmium (as Cd), mg/l, max.	mg/l	–	–	–	2.0 max.
Hexavalent chromium (Cr^{+6})	mg/l	–	–	–	0.1 max.
Selenium (Se),	mg/l	–	–	–	0.05 max.
Nickel (Ni)	mg/l	–	–	–	3.0 max.
Boron (B)	mg/l	–	–	2.0 max	2.0 max.
Residual sodium carbonate	mg/l	–	–	5.0 max	–
Dissolved Phosphates (P)	mg/l	–	–	–	5.0 max.
Sulphate (SO_4)	mg/l	–	–	1000 max	1000 max.

BIS (IS: 10500: 1991)

9.6.5 Thermal Radiation

The furnaces give thermal radiation from their outer walls and openings. The thermal radiation from furnace is more when the doors are open for charging or discharging the products in the furnace. The example may be given from steel making furnaces, soaking pits and heating furnaces which radiate considerable amount of heat during such operations. The hot liquid metal and slag held in ladle or moving out from furnaces radiate considerable amount of heat to the surroundings. In the hot rolling mill large amount of radiation comes out from the hot ingot and slab and makes the working atmosphere worst. In all such areas, the workers are exposed to this thermal radiation and get affected.

The thermal radiation exposure can cause thermal illness depending on exposure and person's health. The thermal illnesses may appear in the following manner:

(i) Heat stroke— Giving symptoms like dry skin, rapid strong pulse and dizziness.

(ii) Heat exhaustion—Indicated by heavy sweating, rapid breathing weak pulse.

(iii) Heat cramps—Giving muscle pains or spasms.

(iv) Heat rash—Skin irritation from excessive sweating.

(v) Heat tetany (stress)—Symptoms like hyperventilation, respiratory problems, numbness or tingling or muscle spasms may be noted.

9.6.6 Noise

The noise in furnace area could be due to fans, blowers, burners, etc. The high level noise is harmful to health, and due precautions are needed as safeguard.

This unwanted noise can damage physiological and psychological health. Noise pollution can cause annoyance and aggression, hypertension, high stress levels, tinnitus, hearing loss, sleep disturbances, and other harmful effects. High noise levels can also contribute to cardiovascular effects.

9.7 POLLUTION ABATEMENT DEVICES

The furnaces are provided with pollution abatement devices as legal pre-condition for industrial activity making the working surrounding safer and encouraging to work. These devices are summarised in Table 9.15.

9.7.1 Devices to remove Airborne Pollutants

The various devices for cleaning flue gases have already been described in Chapter 6
(section 6.4.1). These are repeated here again briefly for the purpose of text continuity.

Dust catchers

These devices (Figure 6.51) are used to collect ~ 90% coarser (50 μm) dust particles present in flue gases. In these devices, the flue gas velocity is arrested by creating mechanical obstructions which cause the settlement of particle attracted with higher gravitational force than lifting force due to gas velocity.

Bag filters

These devices (Figure 6.52**)** use fabric filters to retain most of the dust particles before releasing flue gases to the atmosphere. Bag filters have the ability to remove 100% coarser (50 μm) particles and 99% fine (1–5 μm) solid particles from the gases. However, this can be used when the flue gas has been cooled and its temperature is below 250 °C. The filters made of cotton can be used up to 80 °C. The gases having temperature > 80 °C would need special fabric. The type

of filter material with temperature of use is given in Table 6.10.

Table 9.15 Pollution Abatement Devices

Pollutant Media	*Pollutant*	*Pollution Abatement Devices*
Airborne	Dust	Dust catchers: Settling chambers, baffle chambers and cyclone dust catcher
Airborne	Dust	Bag filters: Shaking, reverse air, pulse jet and sonic
Airborne	Dust	Electrostatic precipitators
Airborne	Dust	Scrubbers: Wet scrubbing and dry scrubbing
Airborne	SO_2	Fluegas desulphurisation (FGD)
Airborne	NO_x	Low NO_x Burners
Waterborne	Heat	Cooling systems: Ponds, cooling towers and cogeneration
Waterborne	Suspended solids	Settling tanks
Waterborne	Oils and grease	Settling chambers with oil and scum collector
Waterborne	Biodegradable organics	Water aeration: Aeration tank with solid settling chamber and trickling filter
Waterborne	pH value	Mixers: Increase pH–add soda ash and to decrease pH–add citric acid
Waterborne	Hardness ($CaCO_3$)	Water softener: Ion exchanger and reverse osmosis
Waterborne	Iron (Fe)	Filtration: Oxidising filter and green-sand mechanical filter
Waterborne	Fluoride (F) Arsenic (As) Chromium (Cr) Copper (Cu) Lead (Pb)	Water softeners: Ion exchanger, reverse osmosis and distillation
Waterborne	Cyanide (CN)	Water treatment: Chlorination
Soil	Solid waste	Lining of land fill: Clay liners and cement liners
Thermal	Radiations	Thermal shields and dog house
Noise	Noise	Noise protecting devices and dog house

Electrostatic precipitators

In this method (Figure 6.53), electrostatic force is used to remove fine dust particles from flue gases. Several charged electrodes at high (50–100 kV) DC voltage are placed in between collecting electrodes. The gases laden with dust particles which flow through the gap between the charged and collecting

electrodes get positively charged. These positively charged particles are attracted by a grounded (negative) electrode and remain attached to it. This type of device is used to remove very fine dust particles (1–5 μm) with nearly 99% efficiency.

Scrubber

In this device (Figure 6.54), the gas is scrubbed (washed) with some liquid or showering dry solid particles. The liquid or solid is selected to absorb some pollutant present in the gas. Water can remove dust particle by trapping it and also absorbing some soluble gases like HCl, ammonia, chlorine, etc. In dry scrubbing, the hydrated lime or soda ash powder is sprayed to react with acidic gas and remove it from flue gases.

Flue-gas desulphurisation (FGD)

This is a kind of scrubber using lime dust to remove SO_2 gas and produce calcium sulphite ($CaSO_3$) as by-product. The calcium sulphite is further oxidised to produce marketable gypsum ($CaSO_4 \cdot 2H_2O$).

Low NO_x burners

These are specially designed burners to produce less NO_x during combustion (see
section 5.5.2).

9.7.2 Devices to Treat Waste Water

The water gets contaminated with various solid particles and chemicals during its use in the furnace. This contaminated water is treated to remove all possible pollutants before its reuse or discharge to natural water body. The equipment used are very briefly described in the following sections.

Settling tanks for removing suspended particles

These are large tanks where waste water is discharged in central section pipe which rises slowly to get discharged out overflowing the top rim. The slow water movement allows suspended solid particles enough time to settle down in the bottom of the tank and clear water overflows out from tank for further treatment. The flocculants may be added to help in settling of fine particles.

Removal of oil and grease

The cooling water coming in contact with moving parts lubricated with oil and

grease gets contaminated. Sometimes the oil leaking from some source may join water and needs cleaning. The oil and grease are immiscible with water and floats on the surface due to lower density. This floating oil layer is skimmed out as shown in Figure 9.7.

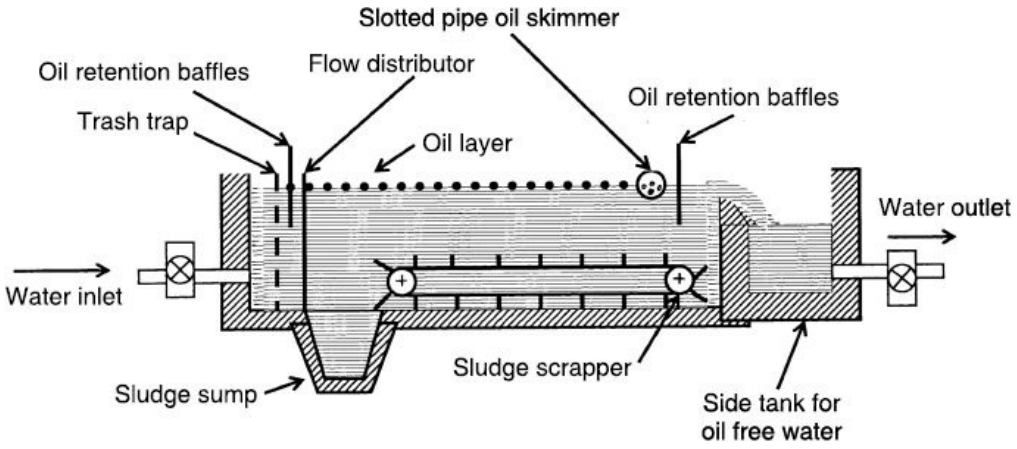


Figure 9.7 Oil and grease removing system from waste water.
(Adopted from R.C. Gupta, "Energy and Environmental Management in Metallurgical Industries", PHI Learning, Delhi, 2012.)

Water aeration for removing bio-degradable organics

The waste water may contain plant matter or animal waste which is bio-degradable. Such contaminants can be removed by aeration process which oxidises such organic matter.

Figure 9.8 shows trickling filter process for biochemical oxidation. In this filter, the waste water is sprayed on a filter bed through which air flows for oxidation of bio-compounds. The clean water collected at bottom is suitable for reuse for industrial application.

Oxidising filter

The iron and manganese in water can be removed by filtration process after they are oxidised to a insoluble state. Ferrous iron is oxidised to ferric iron, which readily forms the insoluble iron hydroxide complex $Fe(OH)_3$. The reduced manganese Mn^{2+} is oxidised to Mn^{4+} which forms insoluble MnO_2 . The common oxidising chemicals for water treatment are chlorine, chlorine dioxide, potassium permanganate, and ozone. Oxidation with chlorine or potassium permanganate is commonly used on small scale. The water is filtered to remove the precipitate containing iron and manganese.

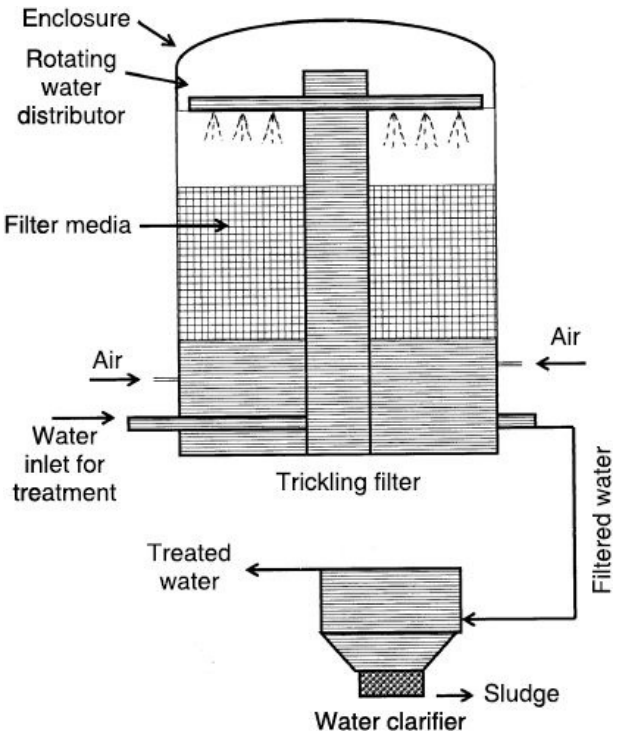


Figure 9.8 Trickling filter process for biochemical oxidation.
(Adopted from R.C. Gupta, "Energy and Environmental Management in Metallurgical Industries", PHI Learning,
Delhi, 2012.)

Water distillation for removing dissolved chemicals

This device is useful in removing many dissolved chemicals. In this unit, the water is heated to form steam which gets condensed on a cooling coil to drip down as water droplet in the collecting chamber. This is shown in Figure 9.9.

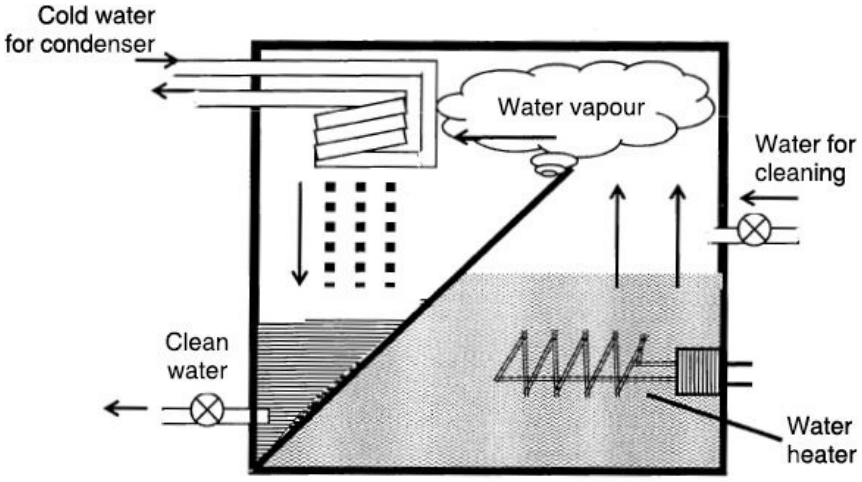


Figure 9.9 Water distillation unit.

Ion exchanger

An ion exchange column is a popular water treatment system in industries. It is also known as a water softener. This cation exchange system has the ability to make water free from Ca and Mg salts. The Ba and low concentrations of Fe and Mn soluble salts also get removed. An anion exchange unit can also be installed to remove nitrate and fluoride salts.

Reverse osmosis (RO) Purifier

Reverse osmosis is a filtration process that uses a membrane having micro pores to filter water. This membrane only allows water free from dissoleved salts to pass through. This membrane is called a semipermeable membrane as it allows only clean water to pass through, but retains any water with dissolved and suspended constituents. The RO purifier can give up to 95 per cent clean water free from inorganic and some organic compounds. However, RO unit cannot remove any dissolved gases like H_2S.

Review Questions

1. What is the significance of furnace atmosphere? Why it needs to be controlled?

2. How the furnace atmosphere is classified? Give the significance of each group of atmosphere in the furnace.

3. What do you mean by in-situ method of creating furnace atmosphere? Give its merits and describe the methods of atmosphere generation.

4. What are the various methods of generating atmosphere externally? Describe them briefly.

5. What factors influence the selection of atmosphere for a furnace? Describe briefly.

6. What are the various methods of monitoring furnace atmosphere? Give their merits and limitations.

7. How can you physically check whether the atmosphere in the furnace is oxidising or reducing in nature?

8. What are the various environmental issues concerned with the use of furnace?

9. What are the health issues with regard to following pollutant present in the flue gas:

(i) Dust particles

(ii) Sulphur dioxide

(iii) Carbon monoxide
(iv) Oxides of nitrogen
(v) Volatile Organic Compounds (VOCs)
(vi) Benzo(a) Pyrene (BaP)

10. Differentiate between the following terms:

(i) Carburising and Decarburising atmosphere
(ii) Nitrogen and Nitriding atmosphere
(iii) Oxidising and Reducing atmosphere
(iv) High vacuum and Ultra high vacuum
(v) Local pollutant and Regional pollutant

11. Give the source, impact and treatment method of the following pollutants in water:

(i) Colour
(ii) Acidity
(iii) Hardness
(iv) Total dissolved solids
(v) Iron
(vi) Fluorides
(vii) Cyanide
(viii) Zinc
(ix) Mercury
(x) Lead

12. Write short notes on the followings

(i) Atmosphere control safety
(ii) Environmental issues
(iii) Thermal radiation
(iv) Noise
(v) Dust catchers
(vi) Bag filter
(vii) Electrostatic precipitator
(viii) Oil and grease removal from water
(ix) Oxidising filter
(x) Water distillation unit

10

Fuels, Furnaces and Refractories

Indian Scenario

Introduction

The fuels, furnaces and refractories are the essential components of many industries dealing with metal extraction, metal shaping, chemicals, power generation, cement, glass, pharmaceutics, refractory manufacturing, etc. The fuel as an energy source is used in various forms. The various energy sources used in India along with world are shown in Figure 10.1 which indicates 87% of world energy is based on fossil fuels (coal 30%, crude oil 33% and natural gas 24%). The pattern in India also indicates an identical energy consumption, i.e., consumption of fossil fuels (coal 55%) is more than oil (29%) and natural gas (8%). The global and Indian energy use pattern indicate common feature as both depend on fossil fuels with very little from other sources like hydro, nuclear and renewable sources (like wind, solar, biomass, etc.).

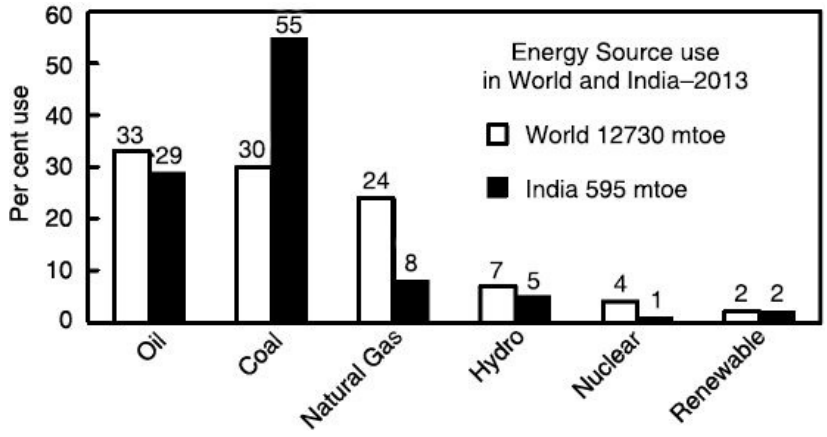


Figure 10.1 Pattern of energy use in World and India (2013).

This chapter focuses on the industrial scenario in India for three commodities —Fuels, Furnaces and Refractories.

10.1 NATURAL RESOURCES OF COAL IN INDIA AND ITS AVAILABILITY

Coal is the major energy source in India which is the 5th largest country in the world having coal deposits. India was considered as the 3rd largest producer and consumer of coal among the nations in 2012.

10.1.1 Coal Reserves in India

It is estimated (in 2014) that a cumulative total of ~ 300 billion tons of coal reserves are available (Figure 10.2) in India. Out of this total coal reserves, the amount of proved (~ 126 billion ton) deposits are available for extraction, while the indicated (142.5 billion ton) and inferred (33 billion ton) deposits remain for future use. The proved deposit in various states of India is shown in Figure 10.3, which indicates that 98.8% coal deposits are present in few Indian states including Jharkhand, Odisha, Chattisgarh, West Bengal, Madhya Pradesh, Andhra Pradesh and Maharashtra. The proved coal deposits in India are mostly non-coking type
(Figure 10.4) with very little deposit as prime coking coal which is needed by steel industry.

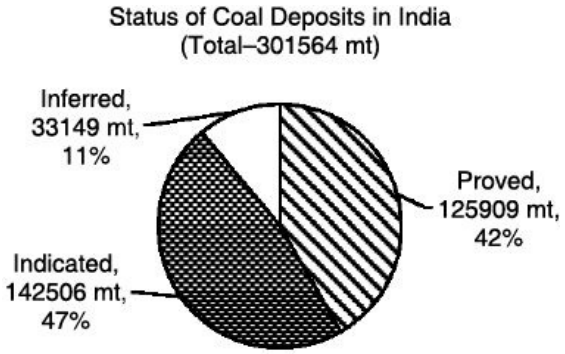


Figure 10.2 Status of coal deposits in India.

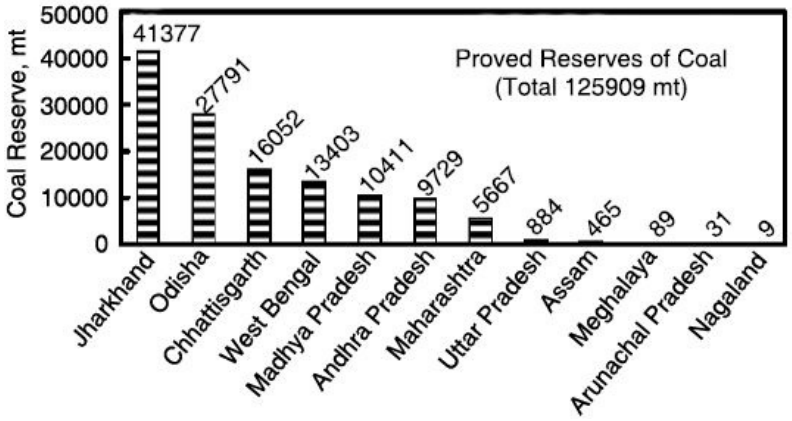


Figure 10.3 Proved coal deposits in various states of India.

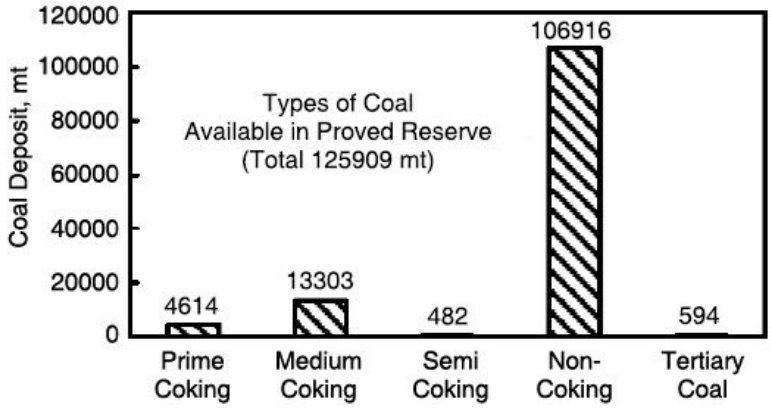


Figure 10.4 Types of coal available in proved coal deposits of India.

10.1.2 Coal Demand and Supply in India

The total production of coal and its demand in India are shown in Figure 10.5 which indicates the demand of coal is much higher than supply. The major user industries of coal are shown in Figure 10.6, which shows power industry as the major (75%) users along with industry captive power (6.3%), sponge iron (1.8%), steel (1.7%), cement (1.2%), fertiliser (0.5%) and others (13.3%). India has large coal deposits, but it has high ash content. India also has limited reserves of coking coal. This limitation in coal and its limited supply are supplemented by imports of low ash non-coking and coking coals. India imports steam coal mainly from Indonesia and South Africa. The coking coal is mainly obtained from Australia. India imported nearly 180 million ton coal in 2012. The share of coal import from different countries is shown in Figure 10.7.

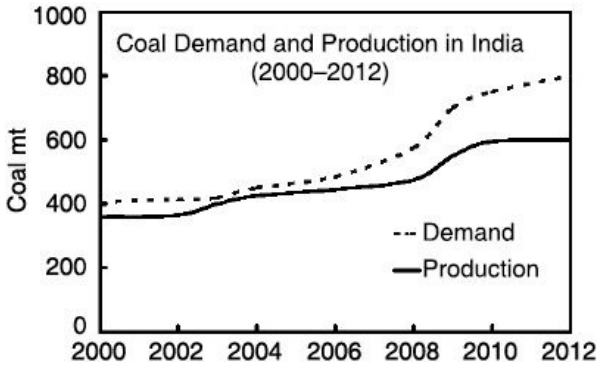


Figure 10.5 Demand and supply of coal in India.

10.1.3 Coal Producing Companies in India

The coal mines in India were nationalised in 1973, and Coal India Ltd. (CIL) was established to produce coal under state directive. The national mineral policy was amended in 1993 to

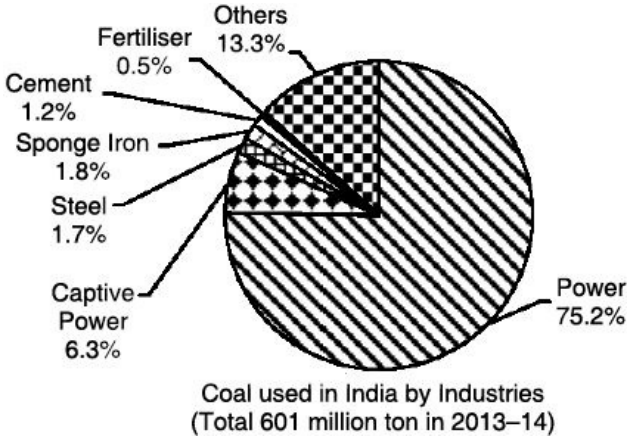


Figure 10.6 Coal user industries in India.

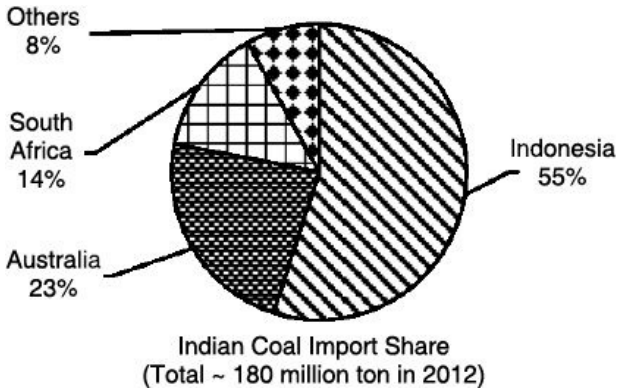


Figure 10.7 Coal import in India from nations.

allow private and foreign investment in coal mining. Currently, the Coal India Ltd. (CIL) is the largest coal producer in India.

Coal India Ltd. is a government owned company having seven subsidiary companies. It operates 470 coal mines out of which 164 mines practice open cast mining, while 275 have underground mines and remaining 31 practice mixed mining operations. It employs nearly 3,60,000 workers and produces ~ 80% coal mined in India.

The Singareni Collieries Company Limited (SCCL) is another government, owned mine, currently operating 15 opencast and 34 underground mines in 4 districts of Telangana with a manpower around 65,354. It produces nearly 9% of India's production.

In addition to these two national companies (CIL and SCCL), there are small units under private control which produce nearly 9% coal.

Table 10.1 gives the production details of all Indian coal mines for year 2012–13.

10.2 NATURAL RESOURCES OF OIL IN INDIA AND ITS AVAILABILITY

The oil reserves in India are under exploration, and it is difficult to estimate total oil reserves. India is the major consumer (4th largest in 2013) of oil in the world who meets its demand by importing oil from different nations.

Table 10.1 Coal Producing Companies in India

Coal Producing Companies in India	*Abbreviated*	*Production 2012–13 in million ton*			*India Share (%)*
		Coking Coal	*Non-coking Coal*	*Total*	
Subsidiary Companies of Coal India Ltd.	CIL				
Eastern Coalfields Limited	ECL	0.04	33.87	33.9	6.1
Bharat Coking Coal Ltd.	BCCL	27	4.2	31.2	5.6
Central Coalfields Limited	CCL	16.1	31.9	48.1	7
Northern Coalfields Limited	NCL	–	70.0	70.0	12.7
Western Coalfields Limited	WCL	0.3	41.9	42.3	7.5
South Eastern Coalfields Ltd.	SECL	0.16	118.0	118.2	21.7
Mahanadi Coalfields Limited	MCL	–	107.9	107.9	19.8
North Eastern Coalfields	NEC	–	0.6	0.6	0.1
Total CIL		43.6	408.5	452.2	81
Singareni Collieries Co Ltd.	SCCL		53.19	53.2	9.4
Other minor mines			52.31	52.31	9.3
Total		**43.656**	**514.05**	**557.7**	**100**

10.2.1 Production and Consumption of Crude Oil

The crude oil production in India is limited through its own reserves which are not fully explored. The exploration work is in progress, and it is expected to yield dividend in future. At present, India meets its needs through import from different nations. The known oil reserves and trend of crude oil production and consumption are shown in Figure 10.8, indicating the wide gap between production and consumption. In 2013–14, the Indian oil consumption was 222 million ton against only 38 million ton production. The gap between production and consumption was met by imports.

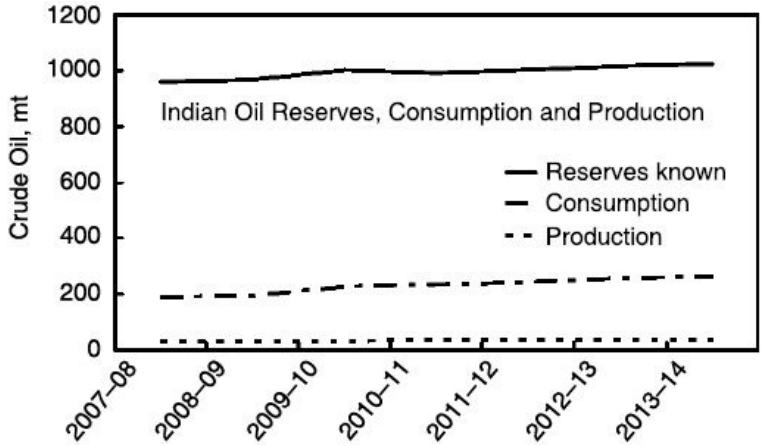


Figure 10.8 Crude oil production and consumption in India.

The oil import from different countries shows (Figure 10.9) India's dependence on other nations which is not appreciable for its self sustenance. The present oil production in India is through its offshore oil rigs (~ 50% share) and in-land oil wells located mainly in Rajasthan, Gujarat, Assam, Nagaland and Andhra Pradesh, which is shown in Figure 10.10.

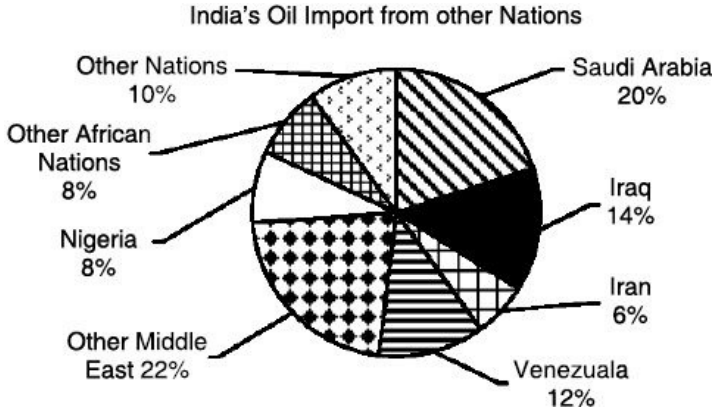


Figure 10.9 Oil import by India from other nations.

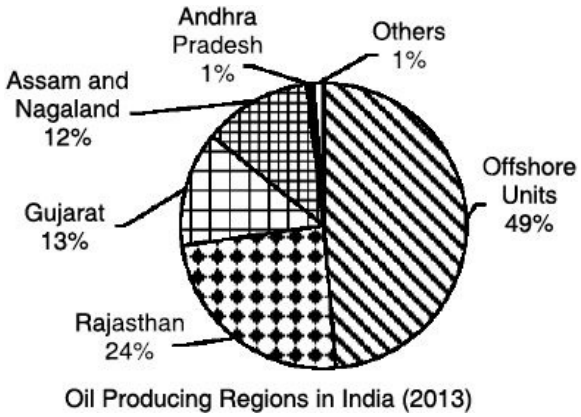


Figure 10.10 Oil producing regions in India.

Globally, India is the 4th largest consumer of oil after USA, China and Japan. In 2013, its consumption was 3.7 million barrels per day against production of 1 million barrels per day. It is reported that by 2040 the demand may rise to 8.2 million barrels per day. In order to meet such high demand, Indian energy companies have purchased some oversea oil fields in South America, Africa, South East Asia and Caspian Sea region to enhance their oil reserve capacity in addition to import and home production.

10.2.2 Oil Refineries in India

The oil produced and imported in India are refined to produce various oil products. The government of India has promoted refining sector and it became a net exporter of petroleum products in 2001. There are several world-class refineries in India owned by private and public sector refining companies.

The Indian refining industry is an important part of India's economy. Indian refinery capacity was 4.35 million barrel/day in 2013, which is the second largest refiner nation in Asia after China. Reliance Industries own two largest crude refineries located in the Jamnagar complex in Gujarat which have world-class facilities. The oil refinery at Jamnagar accounts for 29% Indian oil production capacity. The various oil refining units with their capacity are listed in Table 10.2.

10.2.3 Export of Oil Products by India

India meets its oil demand by importing crude oil from other nations as shown in Figure 10.9 but it has now become exporter **(** Figure 10.11**)** of petroleum products by its world class oil refineries and earns a good return to meet its import cost.

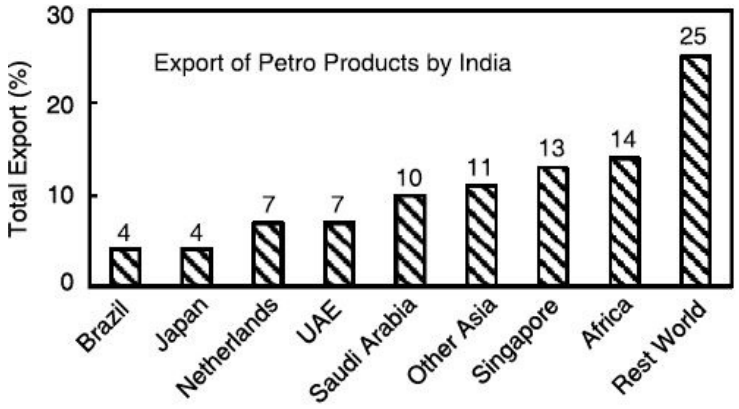


Figure 10.11 Export of petroleum products by India in 2013.

Table 10.2 Oil Refining Facility in India

Indian Company	*Location*	*State*	*Capacity × 1000 barrel/day*	*Total (%)*
Indian Oil Corporation	Barauni	Bihar	120	3
Indian Oil Corporation	Bongaigaon	Assam	47	1
Indian Oil Corporation	Digboi	Assam	13	0.03
Indian Oil Corporation	Guwahati	Assam	20	0.05
Indian Oil Corporation	Haldia	WB	151	3
Indian Oil Corporation	Koyali	Gujarat	275	6
Indian Oil Corporation	Mathura	UP	160	3.7
Indian Oil Corporation	Panipat	Haryana	301	7
Hindustan Petroleum Corporation	Mahul	Mumbai	131	3
Hindustan Petroleum Corporation	Visakhapatnam	AP	166	4
Bharat Petroleum Corporation	Mahul	Mumbai	241	6
Bharat Petroleum Corporation	Kochi	Kerala	191	4
Chennai Petroleum Corporation	Manali	Chennai	211	5
Chennai Petroleum Corporation	Nagapattinam	Tamil Nadu	20	0.03
Numaligarh Refinery Ltd.	Numaligarh	Assam	60	1
Mangalore Refinery and	Mangalore	Karnataka	302	7

Petrochemical				
Oil and Natural Gas Corporation Ltd.	Tatipaka	AP	1	0.002
Bharat-Oman Refinery Ltd.	Bina	MP	120	3
HPCL-Mittal Energy Ltd.	Bhatinda	Punjab	180	4
Reliance Industries Ltd.	Jamnagar	Gujarat	660	15
Reliance Industries Ltd.	SEZ, Jamnagar	Gujarat	580	13
Essar Oil Ltd.	Vadinar	Gujarat	405	9
Total			**4351**	**100**

The Essar Oil and Reliance Industries are designed for export, and they sell their products like naphtha, motor gasoline, and gas oil in the international markets of Singapore , Saudi Arabia , United Arab Emirates and Netherlands. Th Reliance Industries also target the US markets and have leased storage space in New York harbor in 2008.

10.2.4 Consumers of Petroleum Products

The various petroleum products used by consuming sectors are shown in Figure 10.12 for the year 2013–14. The values may differ in different years, but the pattern may not show much change. The major consumer for each petroleum product by specific using sector could be easily noted from this figure.

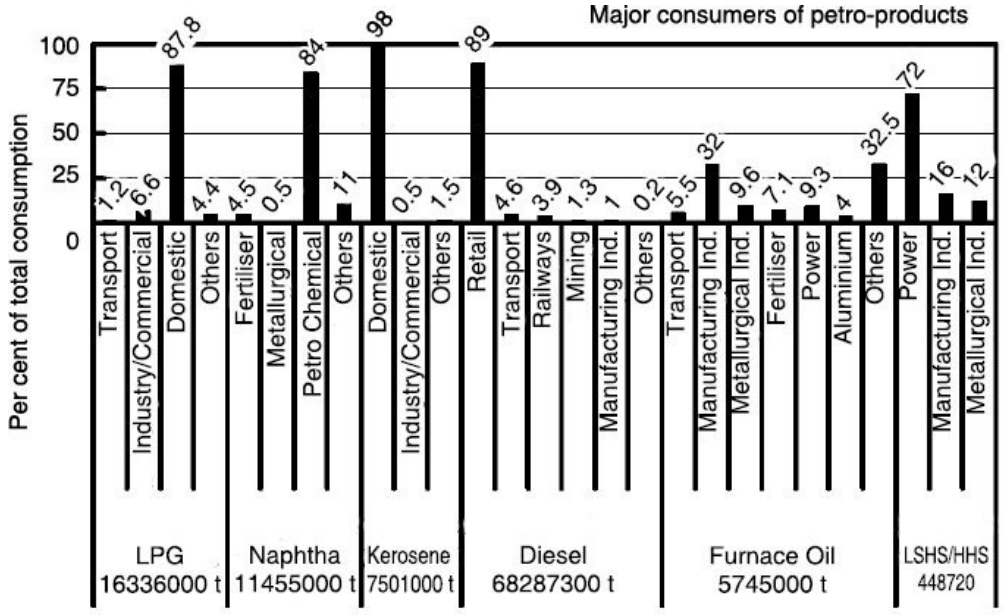


Figure 10.12 Major consumers of various petroleum products in India during 2013–14.
(LPG–Liquefied Petroleum Gas, LSHS–Low Sulphur Heavy Stock, HHS–Hot Heavy Stock)

10.3 RESOURCES OF NATURAL GAS IN INDIA AND ITS AVAILABILITY

The natural gas reserve in India is found in many regions including Bombay high sea, Krishna Godavari Basin, Assam, Rajasthan, Gujarat, etc. The total known natural gas reserve is reported to be approximately 1330×10^9 m^3 in the year 2014. This natural gas reserve is expected to increase further **(** Figure 10.13**)** with the exploration work which is in progress.

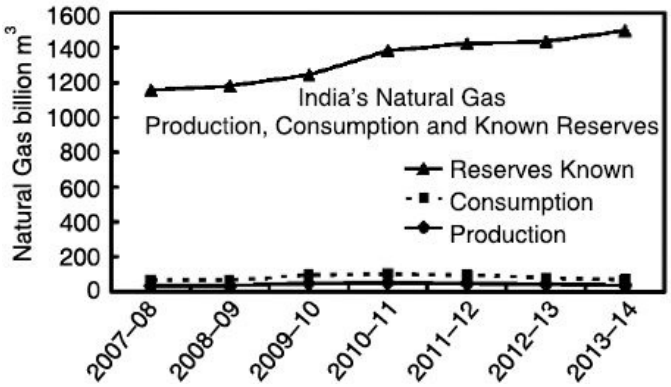


Figure 10.13 Production, consumption and known reserves of natural gas in India.

All the natural gas in India is mainly owned by two state-owned companies, oil and Natural Gas Commission and Oil India. Among the total known Indian reserves of natural gas, nearly 66% deposits are located in offshore area and only 34% deposits occur on land.

10.3.1 Production and Demand of Natural Gas

India was self-sufficient in natural gas till 2004. It started import of liquefied natural gas (LNG) from Qatar in 2005 as it was not been able to produce sufficient natural gas infrastructure on a national level or produce adequate domestic natural gas to meet domestic demands. India was the world's fourth-largest LNG importer in 2013 following Japan, South Korea, and China. India consumed nearly 6% of the global market. The trend of natural gas consumption and production is shown in Figure 10.13.

10.3.2 Natural Gas Consumers in India

The natural gas is mainly used by power, fertiliser and steel industries along with domestic fuel consumers. Figure 10.14 shows demand pattern of major consumers of natural gas projected up to 2030.

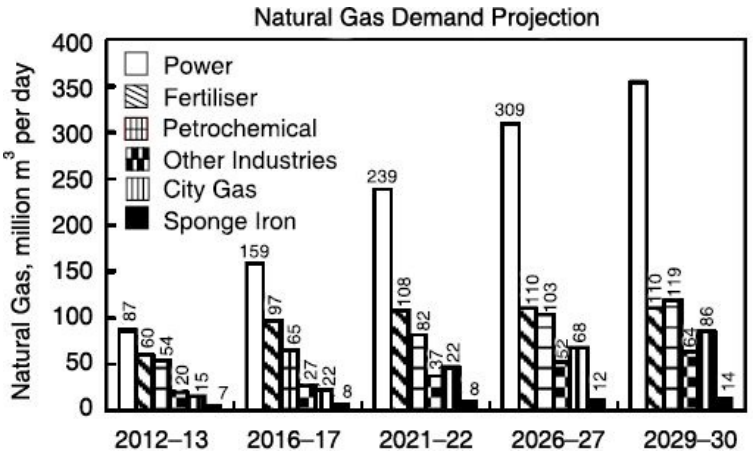


Figure 10.14 India's natural gas demand projection.

10.4 STATUS OF ELECTRICAL ENERGY IN INDIA

The electrical energy is used by many industrial furnaces for heating applications, metal melting, metal heat treatment, etc. This electrical energy is generated by using fossil fuels (coal, oil and natural gas) and nuclear fuel. In addition, various renewable energy sources like water, wind, solar, biomass, etc. are also exploited to generate electrical energy.

10.4.1 Installed Power Plant Capacity

The total installed power plant capacity in India was 237743 MW in 2014 of which ~ 70% was based on thermal plants using coal, oil and natural gas as natural energy source. The contribution of nuclear energy was only 2% of the total installed capacity. The renewable energy sources like hydro power (17%) and other plants based on wind, biomass, micro-hydro projects, solar, etc. contribute significantly (12%) by having installed plant capacity of ~30000 MW power in India (Figure 10.15).

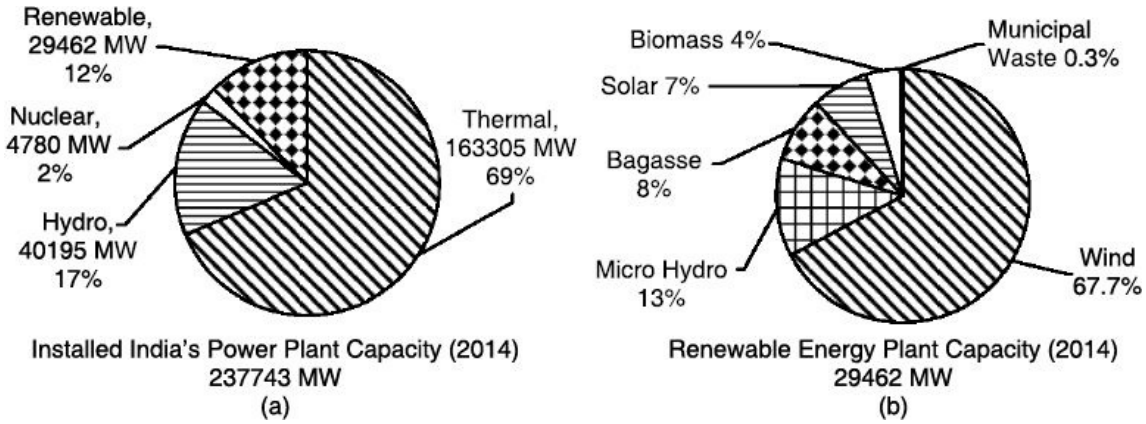


Figure 10.15 Power plant installed capacity in India based on various energy sources (2014).

The power plants in India are owned by central government (~ 40%), state governments (~ 40%) and private companies (~ 20%) using various energy sources which are illustrated in Figure 10.16. It can be observed that central government, state government and private owned plants generate power using various sources except nuclear energy which is operated by central government only for obvious reasons.

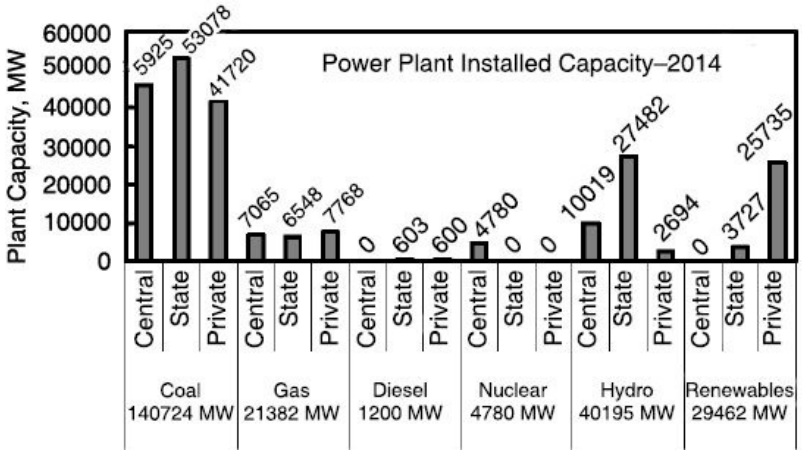


Figure 10.16 Power plant installed capacity owned by different sectors in India (2014) using different energy sources.

10.4.2 Demand and Supply Status

In India, the demand of power is higher than the supply. India suffers from severe power shortages and this becomes a major issue during peak demand hours. In many cases, it leads to shut-downs. There are several reasons for this power shortage which includes infrastructure, plant efficiency, distribution system (line loss), etc. In view of this power shortage, many industries have their own captive power supply to meet the essential services which are generally

based on coal (heavy industries) and oil (medium and small units).

10.4.3 Users of Electrical Energy

The major consumers of electrical energy are industries, domestic users, agriculture (irrigation), commercial units and railway traction which are shown in Figure 10.17 (2009–14). This figure is based on sale of power to various sectors as reported by government publication

10.4.4 Major Companies in Power Sector

The power sector has companies running under public (Central/State) and private ownership, but it is dominated by public sector. Amongst several Indian power companies, only few major companies are mentioned in the following sections:

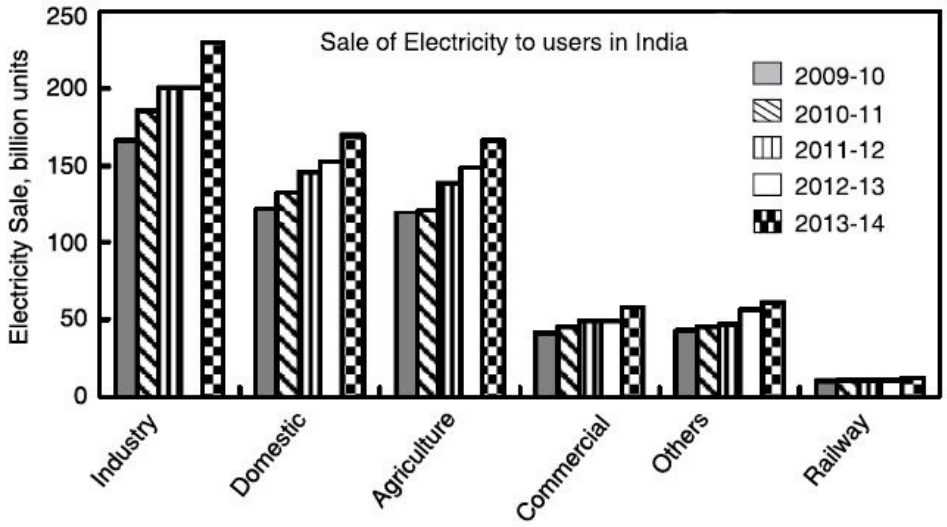


Figure 10.17 Users of electrical energy in India.

National Thermal Power Corporation (NTPC)

It is a public sector undertaking with a capacity to generate nearly 33 GW of power, and by the end of 2015 the company aims to double its capacity. The power generation by this company is mainly based on coal/gas, but now they are planning to exploit other energy sources like hydel power, nuclear power and solar power.

National Hydroelectric Power Corporation (NHPC)

It is a hydro power based company with total installed power capacity of 4271

MW.

Tata power

Tata Power is one of the few major power and energy companies in the private sector, and it is engaged in the production of power using energy resources like coal, hydro, solar and wind. Its production capacity is 3 GW and it is in the process of building a number of power transmission and power generation plants in India.

Reliance power

It is a subsidiary of the Reliance Group of Companies. This unit of Reliance proposes to build and operate power plants in India and other nations. In India, it has programme for 13 medium and large-sized power plants with total 33480 MW installed capacity.

Adani power

It is the business subsidiary of Adani Group (Ahmedabad, Gujarat). The company is one of the largest private power producer in India with capacity of 8620 MW and it is the largest solar power producer of India with a capacity of 40 MW.

Damodar Valley Corporation (DVC)

It is a public company which operates several power stations in Damodar River area of West Bengal. The company operates both thermal power station and hydro-power dams under the Ministry of Power (GOI). It has 7610 MW installed capacity thermal power plants (coal based) and 147.2 MW installed capacity hydro-power plants.

Lanco Infratech

It is Andhra Pradesh based private sector power generation company with a capacity of 2 GW power.

Satluj Jal Vidyut Nigam (SJVN)

It is the second largest hydro-power generation company in India. This company was established through an agreement between the Government of India and Government of Himachal Pradesh.

10.5 FURNACE DESIGN AND MANUFACTURING

IN INDIA

10.5.1 History of Furnace Development

The history of furnace development is associated with the history of steel making which needs variety of furnaces for smelting, melting, heating, reheating, heat-treatment, finishing, etc. The history of furnace design and its use can be traced back to ancient period as India was known destination for making metals like steel and zinc as evidenced by furnace remains in south and north Indian archaeological sites.

The history of furnace making starts from 1830 AD when first attempt was made to make iron from a shaft furnace at Porto Novo by Joshua Marshall Heath. In 1874, the Bengal Iron Works (BIW) started making pig iron at Kulti, near Asansol in West Bengal. The Indian Iron & Steel Co (IISCO), established in 1918, started producing pig iron at Burnpur in 1922. The BIW was taken over by IISCO in 1936. The credit of modern iron making practice is given to Jamshetji Nusserwanji Tata who established Tata Iron & Steel Co. (TISCO) in 1908 and operated its first blast furnace in 1911. The Mysore Iron & Steel (MISCO) started in 1923 and became the first in India to make electric pig iron using charcoal as fuel in 1952 which operated till 1970. The three plants (TISCO, IISCO and MISCO) established in pre-independence period were able to produce nearly 1 million ton steel in 1950s. India witnessed rapid growth in steel industry after independence by establishing integrated steel plants at Bhilai, Bokaro, Rourkela and Durgapur with international help during 1955–60 under the flag of Hindustan Steel Ltd. The Steel Authority of India (SAIL) was established in 1973 to manage all public steel plants. It took over the plants at Burnpur (IISCO) in 1976 and Bhadrawati (MISCO) in 1989. With the liberalised Indian policy, the real growth of steel industry occurred and it has become the 4th largest steel producer in the world
(Figure 10.18) in 2013 by producing 81.2 million ton steel through different routes of steel making. In addition to this total crude steel, it also produces pig iron and sponge iron for sale to iron foundries in India which is illustrated in Figure 10.19.

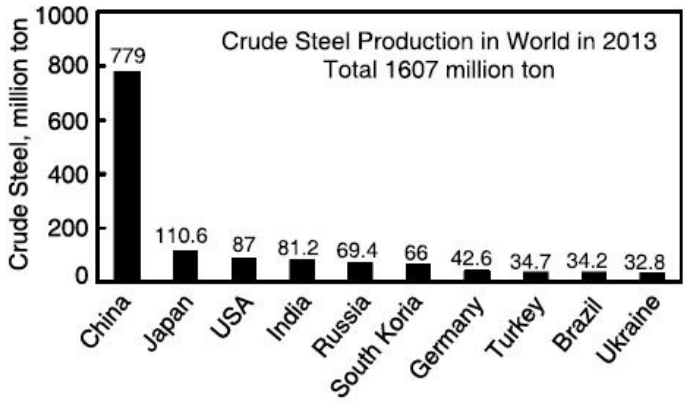


Figure 10.18 Major steel producing countries in the world .

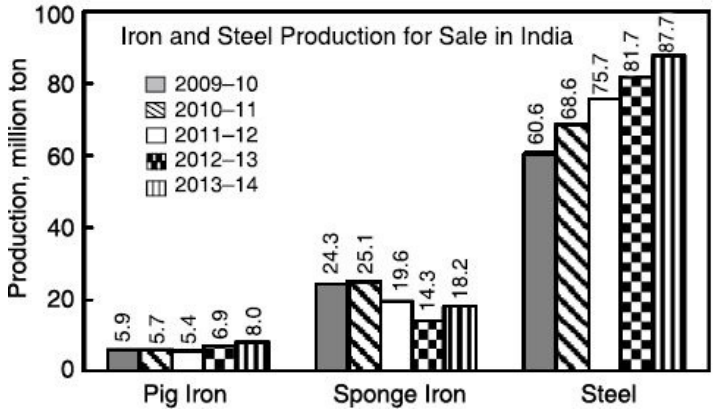


Figure 10.19 Production of iron and steel in India

10.5.2 Types of Furnaces Used in India by Steel Industry

The steel industry is one of the largest users of furnaces with variety of designs as it produces steel through different routes such as:

(1) Blast furnace iron making and basic oxygen furnace (LD Converter) steel making
(2) Rotary kiln DRI (coal based)–Electric arc/Induction melting
(3) Shaft DRI (gas based)–Electric arc/Induction melting
(4) Scrap (reuse)–Electric arc/Induction melting

These four routes are commonly referred as BF-BOF, DRI (Coal)—EF, DRI (Gas)—EF and Scrap—EF and shown in Figure 10.20. Their contribution in steel production is mainly dictated by raw material availability. It may be observed that in 2010–11 the BF-BOF route contributed maximum (46% production share) followed by DRI (Coal)–EF with 27% share in steel production. This

trend is expected to change in future (2030–31) with nearly 58% production by DRI (Coal) – EF route followed by BF-BOF route (30% share). The other two routes also contribute in steel production with lesser share.

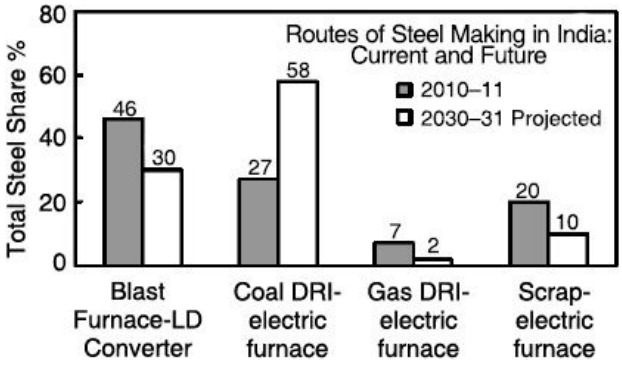


Figure 10.20 Steel production using different furnaces in India.

The trend of steel production route is directly indicative of use of different types of iron making facility namely blast furnaces, rotary kilns (coal based) DRI and Shaft (gas based) DRI units.

10.5.3 Iron Making Furnaces

The hot iron in India is produced mainly by blast furnaces, and only 1.6 million ton hot metal is obtained through two furnaces based on COREX technology at JSW (Bellary). The sponge iron is produced by using coal in rotary kilns and shaft furnace designed by MIDREX work on natural gas.

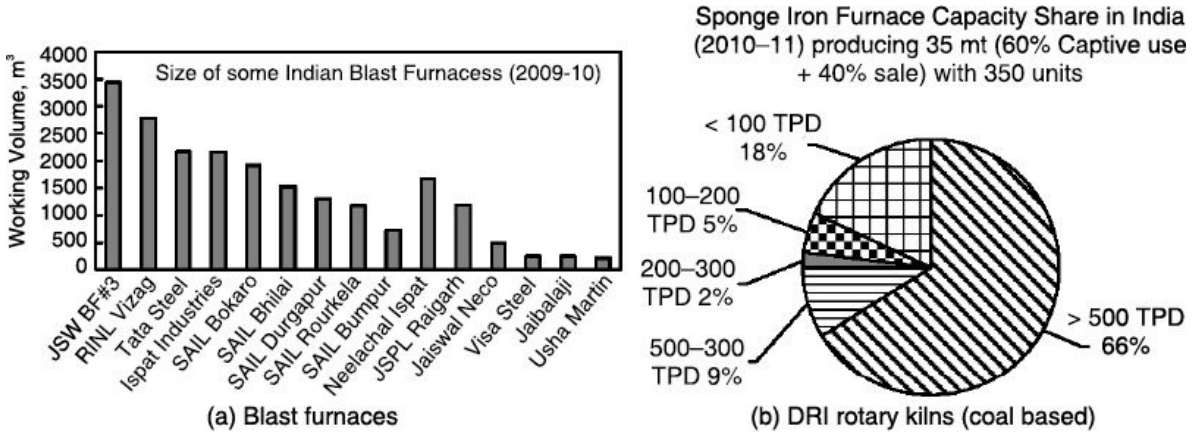


Figure 10.21 Size of Indian iron making units (a) Blast furnaces and (b) DRI rotary kilns.

Blast furnaces

The blast furnaces act as major source of hot metal producer in India. These furnaces are designed and constructed mainly by Indian companies. The blast

furnaces of various sizes ranging from small (200–300 m^3) to big (3000–4000 m^3) working volume are operating in Indian steel plants. Figure 10.21(a) gives the size of the some blast furnaces operating in integrated steel plants. The major companies like M N Dastur (Kolkata) and MECON (Ranchi) serve as design consultants, while HEC (Ranchi) provides heavy equipment and L & T carries out commissioning work along with many other companies in India. The Indian steel industry obtained technical assistance for design, fabrication and erection work from various global firms, but presently it has the competence to carry out most of the activities by itself.

COREX furnace

The COREX units (2 in number) each having capacity to produce 0.8 million tons hot metal per year has a reduction shaft of 600 m^3 volume coupled with melter gasifier unit
(Figure 6.2) having 2200 m^3 volume. The COREX unit design is developed and provided by Austrian company Siemens VAI.

Coal based DRI rotary kilns

The sponge iron is mainly produced in rotary kilns using coal as evident from Figure 10.20 compared to gas based DRI. Figure 10.21(b) gives the size of rotary kilns adopted by Indian DRI units. This figure indicates the use of wide size range furnaces requiring very less capital compared to blast furnaces. These rotary kilns are designed and fabricated by many Indian manufacturers on turn key basis in many parts of India.

Gas based DRI plants

The gas based sponge iron plants which contribute a small share in steel production
(Figure 10.20) are mostly based on MIDREX technology (USA) except one plant which is based on HyLIII technology (Mexico). The capacities of various gas based DRI modules are shown in Figure 10.22. The furnaces are designed and supplied by the MIDREX and HyL and commissioned with the help of local venders.

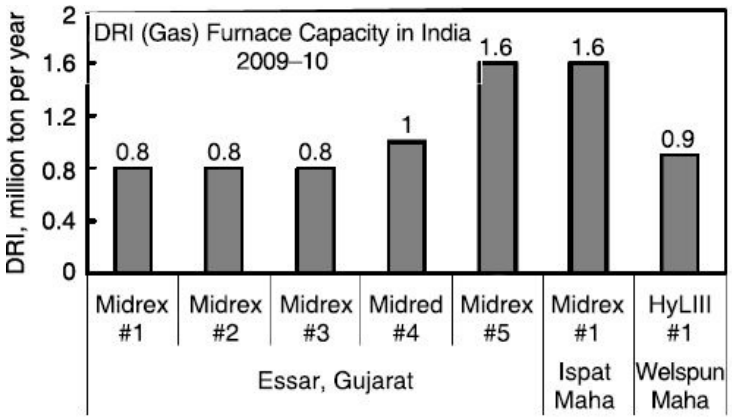


Figure 10.22 Gas based DRI furnace capacity in India.

10.5.4 Steel Making Furnaces

The iron obtained from various sources like blast furnace (hot metal or pig iron), sponge iron (lump or pellet) from DRI plants and recycled scrap (steel and cast iron) are used to make steel in different types of furnaces depending on working condition. The different types of furnaces used during recent period (2005–11) are shown in Figure 10.23. This figure indicates the use of basic oxygen furnace (45–50% share) more than electric arc (~ 20% share) or electric induction (~ 30% share) furnace in recent period (2005–11). The data given in
Figure 10.20 presents a different picture for future which projects use of more electric furnaces (arc and induction) during 2030–31. This increased use of electric furnace is based on the fact that India imports most of its coke whose cost is increasing while the non-coking coal is available in plenty within the country. This fuel scenario is likely to impact negatively on iron making by blast furnace (coke based) while promoting DRI (coal based) production. The increased DRI production is likely to enhance the use of electric furnaces in coming times.

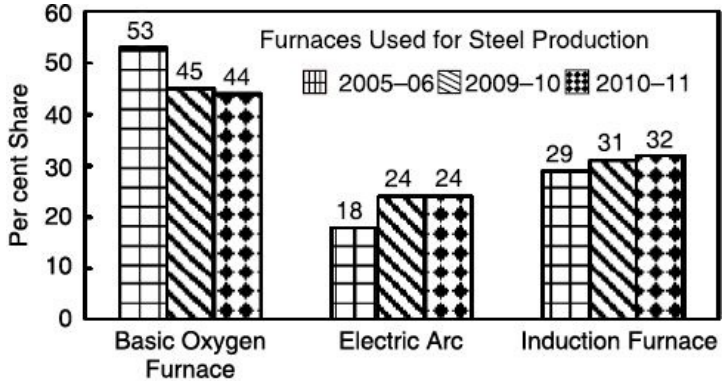


Figure 10.23 Steel making furnaces used in India.

Basic oxygen furnaces (LD converters)

The size of some LD converters used by Indian steel plants is shown in Figure 10.24, which indicates the use of converters having 100–150 ton/heat capacity. The use of large (300 ton/heat) converters is made only at Bokaro which is comparable to largest vessel (375 ton/heat) used in the world. The converters are provided by mostly overseas firms like Siemens VAI though Indian firms like Mukund, etc. also have their market share.

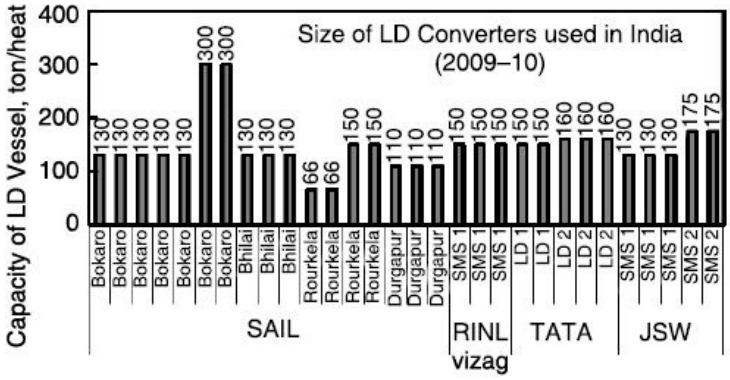


Figure 10.24 Size of some LD converters (BOF) used in India.

Electric arc furnaces

The electric arc furnaces were essentially adopted in early days to melt the cold scrap for reusing steel. With the development of DRI technology, the electric arc furnaces have become an essential requirement to utilise DRI for steel making. The electric arc furnaces are viable means of making steel using wide range of sizes (2 to 150 ton per heat). The smaller furnaces are used by foundries requiring limited liquid hot metal, while large furnaces are used by integrated steel plants for making structural steels. Figure 10.25 shows the size of some bigger (40–150 ton per heat) EAF units used by integrated steel plants. These electric arc furnaces were imported earlier, but now many Indian manufacturers like Electrotherm are competing with global firms.

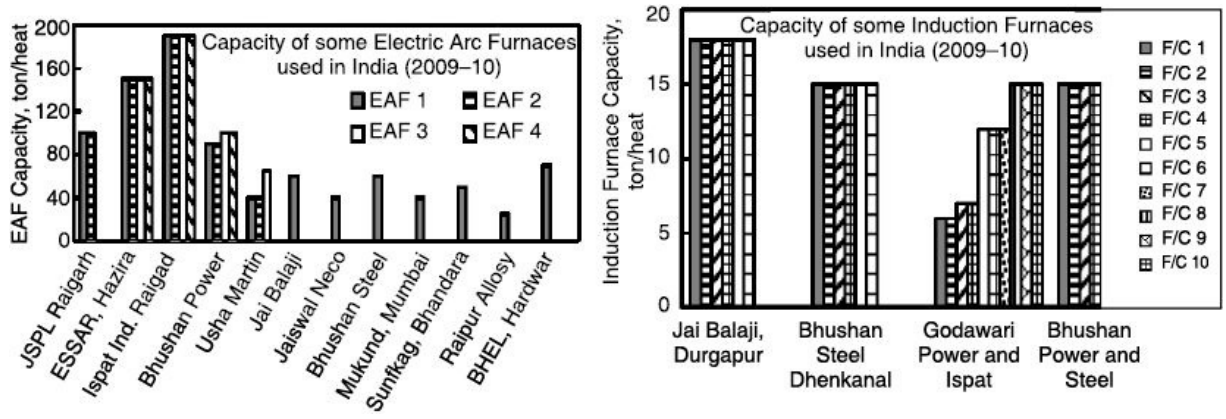


Figure 10.25 Size of some electric furnaces (arc and induction) used by steel plants.

Induction furnaces

The induction furnaces were earlier used by ferrous and non-ferrous casting units due to various advantages in melting process. Now, this induction furnace has become a common tool to use the sponge iron for making structural grades of steel in bulk. These induction furnaces are adopted by many integrated steel makers as shown in Figure 10.25. These furnaces are now available in wide range of melting capacity ranging from 0.5 to 20 ton/heat. There are a large number of Indian manufacturers (e.g. Inductotherm, Megatherm, Electrotherm, etc.) who are doing very good business in view of large demand.

10.5.5 Heating Furnaces

The big heating furnaces like soaking pits, ingot heating furnaces, billet reheating furnaces are the part of integrated steel which are used to heat the steel ingot/billet before hot rolling. The use of such furnaces has declined in the recent past due to increasing use of continuous casting technique where ingot making and heating are totally avoided. The advent of thin slab casting and thin strip casting has further removed the need of billet/slab reheating furnaces. These new steel casting technologies have affected in minimising the total specific energy consumption of finished steel.

This changed scenario of modern steel casting technologies are likely to minimise the need of reheating furnaces in coming time.

10.5.6 Furnaces for Foundries

The foundries require furnaces for melting metals (ferrous/non-ferrous), ovens for baking sand cores and facilities for conducting heat treatments. In the recent

years, India has emerged as a major player in meeting global cast product requirement, specially, in automobile sector. The cast product production has shown increasing trend as evident from Figure 10.26. It is reported that there are nearly 46000 units of different sizes spread across India having clusters in Batala, Jalandhar, Ludhiyana, Delhi, Agra, Howrah, Mumbai, Rajkot, Kolhapur, Coimbatore, Belgaum, and Chennai. These foundries serve various industries of which auto sector occupies special space.

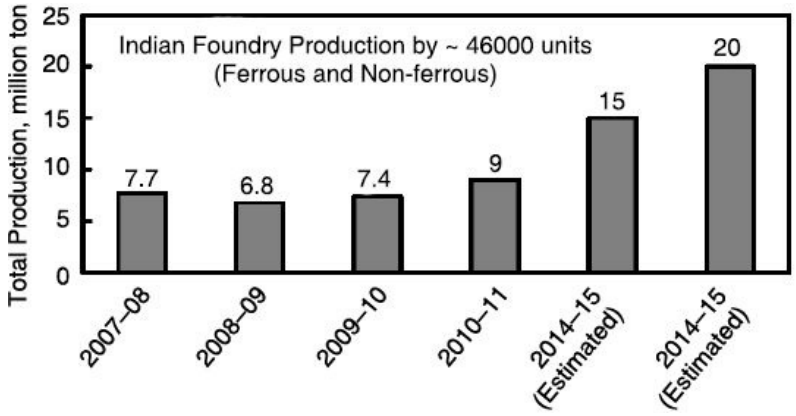


Figure 10.26 Foundry's production in India.

The growing foundries give business opportunity to furnace industries to meet their needs for melting and heat treatment operations. Many companies in India are now manufacturing wide range of melting equipment using electrical energy, oil and gas. The firms like Inductotherm, Electrotherm, Megatherm, Bright Engineer, Balaji Engineer, etc. supply furnaces for melting and heat treatment.

10.5.7 Furnaces for Electrical Power Plants

The need for electrical power is increasing in India with rapid industrialisation. Figure 10.15 shows the type of plants with total installed capacity (237743 MW) in 2014. Out of this total capacity ~ 70% power plants are based on fuel combustion using coal, oil and natural gas. The power plant capacity (163305 MW) is designed to generate power using 86% coal, 13% gas and only 1% oil as shown in Figure 10.27. The coal burnt in pulverised coal burners gives energy forming steam to run turbine in generating electricity. The pulverised coal fired boilers are manufactured and supplied by many Indian firms.

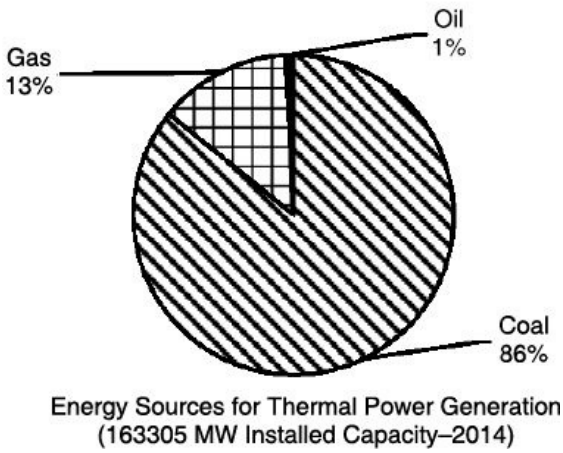


Figure 10.27 Energy sources for thermal power generation.

10.6 REFRACTORY INDUSTRIES IN INDIA

10.6.1 History of Refractory Industry

The development of steel making technique and recovery of zinc metal from its ore by ancient Indians are now well documented. The archaeological evidences available in South India and Zawar in Rajasthan are the testimony of this fact. The extraction of metal and knowledge of refractory material for making furnace and crucible go together. This information is indicative of the fact that ancient refractory industry in India could be traced up to 300 BC.

The modern history of refractory in India could be considered from 1874, when the first iron company (Bengal Iron Works- BIW) was established to make pig iron at Kulti, near Asansol in West Bengal. In order to meet the refractory bricks requirement of industries in West Bengal like railway workshops, Bengal Iron Works, foundries, Calcutta mint, etc., the first refractory unit was established at Raniganj by Burn & Company (now Burn Standard Co. Ltd.) . Later on, when TISCO and IISCO were being established in 1908 and 1918 with integrated facility for iron and steel, the demand for refractory increased. This led to the establishment (1905) of another refractory company called KFS (Kumardhubi Fireclay and Silica Works) located in Chirkunda (near Dhanbad). This could be the beginning of Indian refractory industry which went on expanding with the expansion of metallurgical industries. There were only three integrated steel plants (TISCO, IISCO and MISCO) before India became independent from British rule in 1947. The industries started taking shape under 2nd five years plan of independent India, and establishment of four integrated

steel plants at Bhiali, Bokaro, Rourkela and Durgapur demanded refractory at much higher rate. This higher demand of refractories was met with expansion of Burn & Co. Ltd. which added more units in West Bengal, Bihar, MP and Tamil Nadu. The demand of refractories led to the establishment of several small and medium refractory units around Asansol, Durgapur, Chirkunda, Dhanbad belt (viz. Bihar Pottery at Rupnarainpur, National Refractory at Salanpur, Hindustan Refractory at Durgapur, India Refractories [later on Kesoram Refractories and now ORIND Bengal] at Kulti, Harry Refractories at Kalubathan, Maithan Ceramics and Valley Refractories at Chirkunda, etc.).

The establishment of few large scale refractory plants were made during 1958, e.g., Belpahar Refractories (named as Tata Refractories Limited and now as TRL Krosaki Refractories Ltd.), Orissa Cement (now called OCL India Ltd.), Orissa Industries (ORIND), ACC Refractories (Ace Refractories Ltd.), India Firebricks & Insulation, etc.

In 1970, plants like Bokaro Steel Plant underwent modernisation/expansion giving further increased demand of refractories. This added some more units in private and public sectors like Ipitata Refractories (now Nilachal Refractories), Raasi Refractories Ltd., Indo Flogate (IFGL), Bharat Refractories, etc.

The steel making technologies underwent change globally during 1960–1990 (Figure 10.28), The dominant open hearth steel making technology was replaced by newly developed LD converter and the already existing electric steel technology to melt scrap was now used to melt DRI and scrap or only DRI/scrap. Indian steel industry technology also adopted global pattern. This technology change created the demand of different types of refractories mainly magnesite.

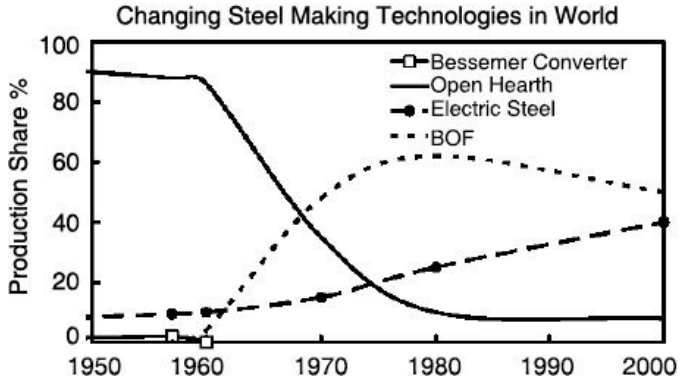


Figure 10.28 Global changes in steel-making technology during 1960–1980.

The new steel making technologies also demanded sophisticated refractories to increase lining life and cut down steel production cost. In addition to steel

industries, other consumers like DRI plants, aluminum plants, cement, glass, etc. were also demanding new generation refractories. Further, the demand for more refractory increased with the increasing production of steel **(** Figure 10.29) particularly after liberalisation (1990) of Indian industrial policy. This led to expansion of refractory industry in India by opening newer plants, collaboration of existing plants with MNCs and acquisition of plants overseas.

The major Indian refractory industries are listed in Table 10.3 with their place of production and year of commencing business.

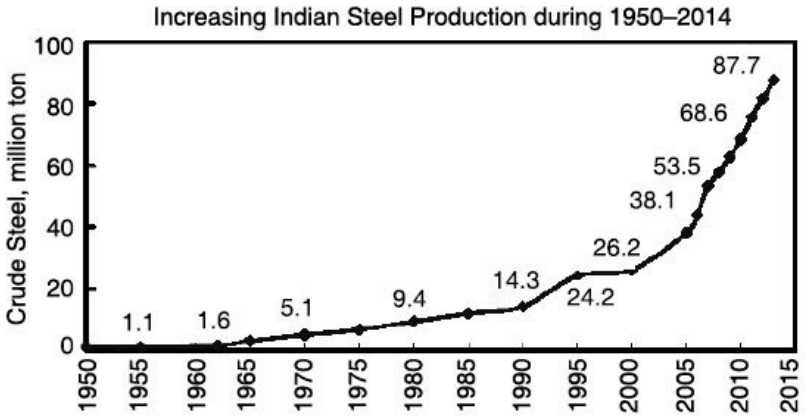


Figure 10.29 Increasing steel production in India during 1950–2014.

Table 10.3 Refractory Industries in India

Company	*Owner*	*Place*	*Established in Year*
Burn & Co (now Burn Standard Co.)	Private	Raniganj	1874
Kumardhubi Fireclay and Silica Works	Private	Chirkunda	1905
Parashuram Pottery Works	Private	Morvi	1934
Brick Making at TISCO	Private	Jamshedpur	1940
Harry Refractories	Private	Kallobathan Dhanbad	1954
OCL India with German Otto & Co.	Private	Rajgangpur, Odisha	1954
TRL Krosaki Refractories Limited (formerly Tata Refractories Limited)	Private	Belpahar –Odisha (District Jharsuguda)	1958
Dalmia Refractories (earlier SNCCIL)	Private	Dalmiapuram, Tamil Nadu	1960
Maithan Ceramics	Private	Chirkunda, Dhanbad	1965
Valley Refractories	Private	Chirkunda, Dhanbad	1970
Carborundum Unioversal	Private	Katrasgargh.	1973
SAIL Refractory Unit (SRU) Erstwhile Bharat Refractories Limited	Private	Bokaro	1974

Orient Abrasive	Private	Porbandar Gujarat and Bhiwadi Rajasthan	1974
Neelachal Refractories (formerly IPITATA Refractories)	Private	Dhenkanal, Odisha	1977
Dalmia Refractories (earlier SNCCIL)	Private	Khambalia, Gujarat	1980
IFGL Refractories	Private	Sundergarh, Odisha	1984
Mahakoshal Ceramics	Private	Katni, MP	1989
Perfect Fire Bricks	Private	Jabalpur, MP	1992
Vishva Vishal Engg.	Private	Bhilai, Chattisgarh	2004
Raasi Refractory	Private	Laxmipuram, Nalgonda, AP	2009
Dalmia Refractories (earlier SNCCIL)	Private	Katni, MP	2010

10.6.2 Current Scenario of Refractory Industries

The refractory industries operating currently in India is around 100–130 in number of which nearly 10% are in large sector, 25% in medium scale sector and rest 65% belong to small scale refractory units (Figure 10.30). These units produce refractory products for Indian consumers of which nearly 75% belong to steel industries as shown in Figure 10.31.

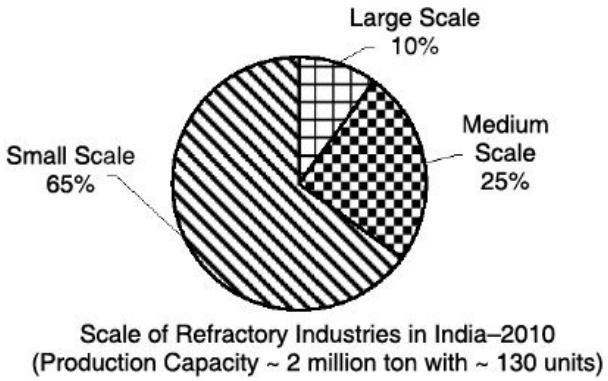


Figure 10.30 Indian refractory units scale.

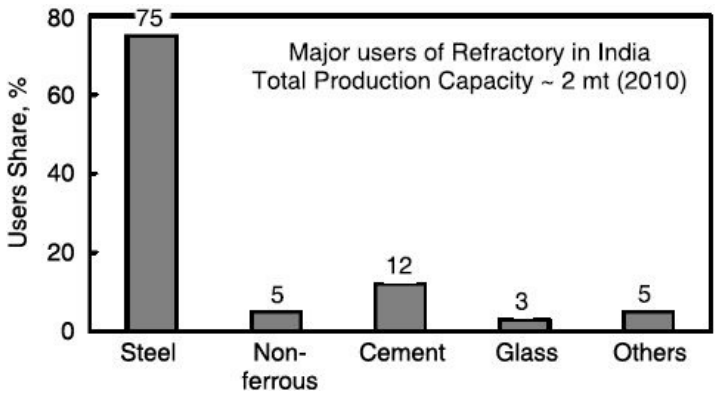


Figure 10.31 Refractory Users in India.

The refractory industries in India have the capacity to produce ~ 2 million tons refractory every year, however, they operate with nearly 60% production capacity and have been producing **(** Figure 10.32**)** around 1.2 million ton during past five years (2008–13) having a trade of nearly ` 6000 crores per year (1 billion $/year). This makes India a very promising market for refractory, attracting global attention.

10.6.3 Consumption Rate of Refractory by Steel Industry

The rate of refractory consumption in 1990 was average 30 kg/ton steel which has been reduced to average 12–13 kg/ton steel in 2010. This consumption rate is only 7–8 kg/ton steel for some very efficiently operated plants. Considering an average value of 12 kg/ton steel, the refractory requirement for steel sector alone can be estimated as 2.4 million ton for projected

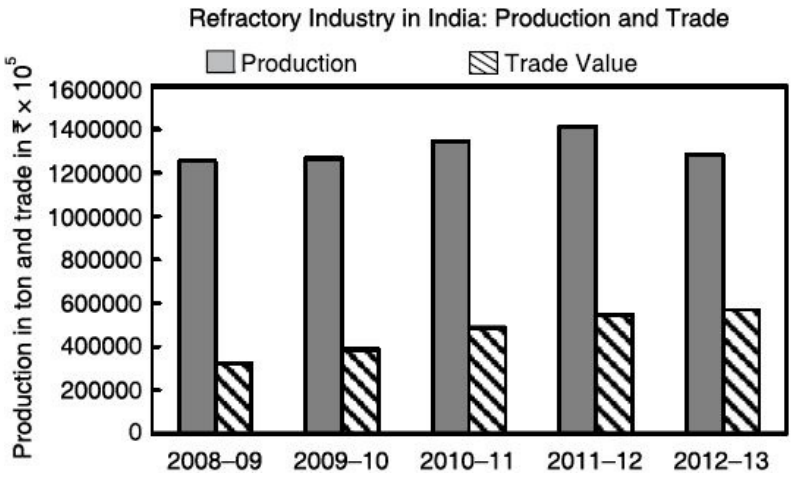


Figure 10.32 Indian refractory industry production and its trade value.

steel production of ~ 200 million ton by 2020. This presents India as a very promising market for refractory industry.

10.6.4 Major Refractory Industries in India

Figure 10.30 gives a picture of refractory industry in India which indicates that there are nearly 10–14 big refractory plants owned in public/private sector, and remaining units belong to private sector of which some are multi nationals. It is reported that nearly 20–25% supply of refractory is met by imports. The

remaining market (75–80%) is divided with some major companies like TRL Krosaki Refractories Limited (formerly Tata Refractories Limited), SAIL Refractory Unit-SRU (erstwhile Bharat Refractories Limited), OCL India, IFGL Refractories, Orient Abrasive, Maithan Ceramics, Carborundum Unioversal, Shri Natraj Ceramic, etc. along with major MNCs like RHI (Austria), Vesuvius (Belgium), French giant Calderys (France), Pohang (South Korea), etc.

The major refractory import from China is for magnesia based products. Only few industries manufacture magnesia carbon bricks in India. Some Indian refractory manufacturers have magnesia carbon brick plants located in China – like Vesuvius, RHI, Tata Krosaki Refractories, OCL, etc. for sale in India. There are some companies in India who import magnesia carbon brick from Chinese firms.

The total refractory produced in India constitutes 75% in shaped form and 25% as monolithic.

The major refractory units in India are described briefly in the following sections:

TRL Krosaki Refractories Limited (formerly Tata Refractories)

Tata Refractories Limited is the largest refractory (2013) manufacturing private company in India with a wide range of products like basic, dolomite, high alumina, monolithics and silica refractories having a total installed capacity of 0.3 million ton per annum (2010). It was established in 1958 which has pioneered itself in refractory production in India. Its main consumers are the steel, cement, glass, copper and aluminium industries. Its main production unit is located at Belpahar (District Jharsuguda, Odisha). During the year 2010–11, the company has achieved the distinction of being the first Indian refractories company to cross ` 1000 crores consolidated turnover. After acquisition of 51% shares of Tata Refractories Limited by Krosaki Harima Corporation (KHC-Japan) from Tata Steel, the Tata Refractories Limited has changed its name to TRL Krosaki Refractories Limited. Tata Steel continues to hold 26.62% equity stake in TRL Krosaki. With the association of KHC, a leading refractory player with global presence and advanced technology, TRL Krosaki is able to access latest technology and diversify its product offering.

SAIL Refractory Unit–SRU (Erstwhile Bharat Refractories Ltd.)

Bharat Refractories Limited is the largest public sector unit producing refractory which was established in 1978 to serve Bokaro Steel and other units under Hindustan Steel Limited (HSL). The HSL was converted to public enterprise as

Steel Authority of India Ltd. (SAIL) under the Steel Ministry. The Bharat Refractory Ltd. got merged with SAIL in 2007 to become SAIL Refractory Unit (SRU).

The SRU is one of the largest manufacturers of refractories in India at present with an annual turnover exceeding ` 350 crores. SRU comprises several units equipped with a wide range of manufacturing facilities at the following places:

(i) Bhandaridah

SRU main Bokaro unit is located in Bhandaridah on the bank of the Damodar river at distance of 40 km from Bokaro city. The plant has installed capacity of 26000 tonnes. This unit is a pioneer in manufacturing tap hole mass, trough ramming mass and ultra low cement castables for application in blast furnaces.

(ii) Bhilai

SRU unit at Bhilai (Chhattisgarh) is situated near Bhilai Steel Plant. The unit produces entire range of basic and silica refractories. It also carries out calcination of lime in its high capacity rotary kiln, which is further used by Bhilai Steel Plant for iron and steel production.

(iii) Ramgarh

SRU unit at Ramgarh is located 50 km away from Ranchi and 90 km from Bokaro. The installed capacity of this unit is 7500 ton producing superior quality magnesia carbon bricks.

(iv) Ramgarh SRU

IFICO unit is also situated in Ramgarh with an installed capacity of 42000 ton refractory product. This unit produced all types of alumino-silicate refractories and various other special products.

OCL India

The Orissa Cement Limited which is known as ‘OCL’ was established in 1949, located in Rajgangpur (Odisha). It diversified and started making refractories from 1954. It is one of the largest (0.1 mt/yr) refractory plants in India producing wide range of products for use in the industries related to steel, cement, aluminum, glass, copper, chemicals and hydrocarbons. The refractory products range in year 2014 includes: (i) silica refractory (30000 ton/yr) for coke ovens, high temperature blast furnace stoves and glass industries, (ii) high alumina refractory for blast furnace stoves (25000 ton/yr), (iii) basic refractories (22000 ton/yr), (iv) magnesia carbon bricks (8000 ton/yr), (v) continuous casting

refractory (2000 ton/yr), (vi) new generation high performance castable and precast blocks (11000 ton/yr) for various applications, (vii) slide gate refractory (2000 ton/yr), basic, silica and high alumina ramming masses/mortars (6400 ton/yr).

IFGL refractories

The IFGL Refractories is one of the largest refractory manufacturer in India located in Sundergarh (Odisha). IFGL started (1984) to manufacture specialised refractory products for ferrous industry. They also initiated slide gate refractory production in 1984. They started making continuous casting refractories in 1993 with Japanese technology. The IFGL Exports Limited is subsidiary company located in Kandla (Gujarat) which is also engaged in
the manufacture of continuous casting refractories. It is multinational company having collaboration with several global partners and has manufacturing facility in other countries. Major products of IFGL include: (i) slide gate refractories, (ii) continuous casting refractories, (iii) magnesia carbon tap-hole sleeves, (iv) tundish spraying mass, (v) refractory darts,
(vi) casting filters, (vii) feeders, (viii) SiC chill plates and pouring systems, (ix) mono block stoppers, (x) high grade fire-proof refractory shapes, etc. The reported trade in 2013–14 was ~ ` 777 crores.

Orient abrasives

This plant was set up in 1974 in technical collaboration with Karborundum, Bentueky, Czechoslovakia Company. The plant manufacturing facilities are located in Porbandar, Gujarat and Bhiwadi, Rajasthan. In its four decades of existence, it has become one of the largest refractory plant in 2014 and considered biggest for calcined and fused products in India. This unit offers a wide range of refractory and monolithic products for the iron and steel industries. The product range of the plant includes high alumina raw materials like Calcined bauxite, brown fused alumina, white fused alumina, pink fused alumina, white fused mullite, high alumina refractory cement, zirconia mullite (Zirmul) and alumina magnesia. The shaped and monolithic refractory items produced by the plant include isostatically pressed continuous casting refractories, slide gate plates, nozzles and well blocks, tundish nozzles, bottom purging refractories and top purging lances, slag arresting darts and basic spray mass for tundish working lining castables.

Maithan ceramics

The Maithan Ceramic Limited was established in 1963 at Chirkunda in Dhanbad. In this fifty years of business, it has now become a major refractory unit in India. It produces various value added refractories like resin bonded magnesia carbon bricks, magnesia carbon refractories, alumina magnesia carbon refractories, magnesite bricks, dense magnesite bricks up to 92% MgO, low iron magnesite for glass industries, magnesite chrome, chrome magnesite, high grade magnesite chrome and magnesia alumina spinel.

Corundum abrasives

The Corundum Abrasives, established in 1954, is located at Southern India in Chennai. It is one of the largest units in India. Its basic products are abrasives, but it also deals in refractories. The refractory products include brown fused alumina, white fused alumina, silicon carbide, mullite, castables, insulators, kiln furniture, fused alumina, semi friable and sintered alumina.

Dalmia refractories

Dalmia Refractories is the new name given in 2014 to its original company ‘Shri Nataraj Ceramic And Chemical Industries Limited’ established at Dalmiapuram (Tamil Nadu) in 1960, Khambalia Unit (Gujarat) in 1980 and Katni Unit (MP) in year 2010. It had the capacity to produce 0.12 million refractory from all its three units in 2014. The product range includes fireclay bricks, clay bricks, refractory bricks, high alumina bricks, refractory bricks for cement plant, high alumina fire bricks, special castables, fire cement, aluminous cement and refractory cement.

Raasi refractories

Raasi Refractories, established in 2009, is located in Hyderabad (AP). It produces basic refractories, monolithics, Fireclay, high alumina and insulation bricks.

Vishva Vishal

This unit is a part of Bhilai Engineering Corporation which was established in 2004 at Bhilai (Chattisgarh). This unit made a beginning with cast house refractories and later started making other products like porous plug, impact pad, ramming and gunning masses, castables and various shaped products.

In addition to the above few major Indian units, there are medium scale unit set up by MNCs to supply in Indian market in addition to large number of small scale units.

Review Questions

1. What is the pattern of using energy sources in India compared to global practice?

2. What is the scenario of coal reserves, production and demand in India?

3. India has sufficient coal reserves, but it is importing coal from other countries. Why? Name the countries who are supplying coal to India.

4. Name the major industries in India using coal. Give their usage pattern.

5. Give the Indian scenario of oil reserve, production and consumption.

6. Name the oil resources in India and list major oil supplying nations to India. How does Indian oil import practice affect metallurgical industries?

7. Name the Indian states producing oil and name few major oil refineries in India giving their locations.

8. India is dependent on oil import for its use then how it is able to export oil to other advanced nations in the world?

9. What is the situation of natural gas reserves, production and consumption in India?

10. Give the name of user industries for natural gas in India.

11. What are the sources of energy for generating electrical power in India? Give their pattern of exploitation.

12. What are the renewable energy sources exploited in India to generate electrical power?

13. Who are the major users of electrical energy in India? Give their usage pattern.

14. List five major power generating companies in India and give their energy source and mention their owner as private or public.

15. What is the current status of steel industry in India? How steel industry growth is related to furnace industry?

16. Give the size ranges of blast furnaces and DRI kilns used in India.

17. The capacity of induction furnaces per heat is smaller than electric arc furnaces. Give reasons.

18. What is the scenario of foundries in India which demand melting furnaces?

19. Give briefly the history of refractory industry in India.

20. What is the current status of refractory industry in India?

APPENDIX I

Mathematical Formulae

Triangle (sides a , b , c)

$$\text{Area} = \frac{1}{2}bc\sin A = \sqrt{s(s-a)(s-b)(s-c)}$$

where, $s = a + b + c$

Circle (radius r)

Area = $p\,r^2$

Perimeter = $2\,p\,r$

Ellipse (axes $2\,a$, $2\,b$)

Area = $p\,ab$

Perimeter = $2\pi\sqrt{\frac{1}{2}(a^2 + b^2)}$

Cylinder (radius r , height h)

Area = $2\,p\,r\,(h + r)$

Volume = $p\,r^2\,h$

Cone (base radius r , slant height l , vertical height h)

Total surface area = $p\,r\,(l + r)$

Curved surface area = $p\,rl$

Base area = $p\,r^2 = A$

Volume of cone = $\frac{1}{3}A\,h = \frac{1}{3}\pi r^2 h$

Frustum of pyramid and cone (areas a, b , height h)

Volume = $\frac{h}{3}\left[a + b + \sqrt{ab}\right]$

Pyramid frustum curved surface area = $\frac{1}{2}$ (sum of perimeters of ends) × slant height

Cone frustum curved surface area = $p\,(\,r_{\,1} + r_{\,2}\,)\,l$

where, $r_{\,1}$ and $r_{\,2}$ are radii of two ends and l is slant height.

APPENDIX II

Useful Data

Elements with Increasing Density			Elements with Increasing Melting Point		
S. No.	*Elements*	*Specific Gravity*	*S. No.*	*Elements*	*Melting Point, °C*
1.	Lithium	0.53	1.	Mercury	–38.8
2.	Sodium	0.97	2.	Lithium	180.6
3.	Magnesium	1.74	3.	Tin	232
4.	Aluminium	2.69	4.	Bismuth	271.4
5.	Titanium	4.54	5.	Cadmium	321
6.	Vanadium	6.11	6.	Lead	327.5
7.	Antimony	6.68	7.	Zinc	419.6
8.	Zinc	7.13	8.	Antimony	630.5
9.	Chromium	7.15	9.	Magnesium	650
10.	Tin	7.28	10.	Aluminium	660
11.	Manganese	7.44	11.	Silver	960
12.	Iron	7.874	12.	Gold	1064
13.	Niobium	8.570	13.	Copper	1084.9
14.	Cadmium	8.69	14.	Manganese	1246
15.	Nickel	8.91	15.	Silicon	1410
16.	Copper	8.93	16.	Nickel	1455
17.	Bismuth	9.80	17.	Cobalt	1495
18.	Molybdenum	10.22	18.	Iron	1535
19.	Silver	10.50	19.	Titanium	1670
20.	Lead	11.34	20.	Platinum	1769
21.	Mercury	13.53	21.	Chromium	1857
22.	Uranium	18.95	22.	Vanadium	1910
23.	Tungsten	19.25	23.	Niobium	2468
24.	Gold	19.282	24.	Molybdenum	2623

25.	Platinum	21.46	25.	Tungsten	3410

Elements with Increasing Boiling Point		
S. No.	*Elements*	*Boiling Point,* °C
1.	Mercury	357*
2.	Arsenic	614*
3.	Cadmium	765
4.	Zinc	906
5.	Magnesium	1110
6.	Lithium	1320
7.	Antimony	1440
8.	Bismuth	1560
9.	Lead	1740
10.	Manganese	2100
11.	Silver	2210
12.	Tin	2267
13.	Aluminium	2470
14.	Chromium	2482
15.	Copper	2600
16.	Nickel	2730
17.	Cobalt	2900
18.	Gold	2970
19.	Iron	3027
20.	Titanium	3257
21.	Vanadium	3400
22.	Platinum	3820
23.	Molybdenum	5560
24.	Tungsten	5930
* Sublimes		

Metals with Increasing Electrical Resistivity		
S. No.	*Metals*	*Electrical Resistivity* (Ω m $\times 10^{-8}$)
1.	Silver	1.47
2.	Copper	1.72
3.	Gold	2.44

4.	Aluminium	2.82
5.	Tungsten	5.6
6.	Iron	10
7.	Platinum	11
8.	Lead	22
9.	Mercury	98
10.	Carbon	3500

Alloys with Increasing Electrical Resistivity

S. No.	*Alloys*	*Electrical Resistivity* (m × 10^{-8})
1.	Brass	8
2.	Constantan	49
3.	Nichrome	110

Elements by Atomic Number and Weight

Atomic Number	*Elements*	*Symbol*	*Atomic Weight*
1.	Hydrogen	H	1
2.	Helium	He	4
3.	Lithium	Li	6.9
4.	Beryllium	Be	9
5.	Boron	B	10.8
6.	Carbon	C	12
7.	Nitrogen	N	14
8.	Oxygen	O	16
9.	Fluorine	F	19
10.	Neon	Ne	20
11.	Sodium	Na	22.9
12.	Magnesium	Mg	24
13.	Aluminium	Al	27
14.	Silicon	Si	28
15.	Phosphorus	P	30.9
16.	Sulphur	S	32
17.	Chlorine	Cl	35
18.	Argon	Ar	39.9

19.	Potassium	K	39
20.	Calcium	Ca	40
21.	Scandium	Sc	44.9
22.	Titanium	Ti	47.8
23.	Vanadium	V	50.9
24.	Chromium	Cr	52
25.	Manganese	Mn	55
26.	Iron	Fe	55.8
27.	Cobalt	Co	58.9
28.	Nickel	Ni	58.7
29.	Copper	Cu	63.5
30.	Zinc	Zn	65
31.	Gallium	Ga	69.7
32.	Germanium	Ge	72.6
33.	Arsenic	As	74.9
34.	Selenium	Se	78.9
35.	Bromine	Br	79.9
36.	Krypton	Kr	83.8
37.	Rubidium	Rb	85
38.	Strontium	Sr	87.6
39.	Yttrium	Y	88.9
40.	Zirconium	Zr	91
41.	Niobium	Nb	92.9
42.	Molybdenum	Mo	95.9
43.	Technetium	Tc	98
44.	Ruthenium	Ru	101
45.	Rhodium	Rh	102.9
46.	Palladium	Pd	106
47.	Silver	Ag	107.8
48.	Cadmium	Cd	112
49.	Indium	In	114.8
50.	Tin	Sn	118.7
51.	Antimony	Sb	121.7
52.	Tellurium	Te	127
53.	Iodine	I	126.9
54.	Xenon	Xe	131
55.	Caesium	Cs	132.9

56.	Barium	Ba	137
57.	Lanthanum	La	138.9
58.	Cerium	Ce	140
59.	Praseodymium	Pr	140.9
60.	Neodymium	Nd	144
61.	Promethium	Pm	145
62.	Samarium	Sm	150
63.	Europium	Eu	151.9
64.	Gadolinium	Gd	157
65.	Terbium	Tb	158.9
66.	Dysprosium	Dy	162.5
67.	Holmium	Ho	164.9
68.	Erbium	Er	167
69.	Thulium	Tm	168.9
70.	Ytterbium	Yb	173
71.	Lutetium	Lu	174.9
72.	Hafnium	Hf	178.5
73.	Tantalum	Ta	180.9
74.	Tungsten	W	183.8
75.	Rhenium	Re	186
76.	Osmium	Os	190
77.	Iridium	Ir	192
78.	Platinum	Pt	195
79.	Gold	Au	196.9
80.	Mercury	Hg	200.6
81.	Thallium	Tl	204
82.	Lead	Pb	207
83.	Bismuth	Bi	208.9
84.	Polonium	Po	209
85.	Astatine	At	210
86.	Radon	Rn	222
87.	Francium	Fr	223
88.	Radium	Ra	226
89.	Actinium	Ac	227
90.	Thorium	Th	232
91.	Protactinium	Pa	231
92.	Uranium	U	238

93.	Neptunium	Np	237
94.	Plutonium	Pu	244
95.	Americium	Am	243
96.	Curium	Cm	247
97.	Berkelium	Bk	247
98.	Californium	Cf	251
99.	Einsteinium	Es	252
100.	Fermium	Fm	257
101.	Mendelevium	Md	258
102.	Nobelium	No	259
103.	Lawrencium	Lr	262

Appendix III

Unit Conversion Tables

Table A Length

Inch (in)	*Foot* (ft)	*Yard* (yd)	*Centimeter* (cm)	*Meter* (m)	*Kilometer* (km)	*Mile* (mi)	*Fathom*
1	0.0833	0.02777	2.54	0.0254	2.54×10^{-5}	1.57×10^{-5}	0.01388
12	1	0.33333	30.48	0.3048	30.48×10^{-5}	18.93×10^{-5}	0.1666
36	3	1	91.44	0.9144	91.44×10^{-5}	56.8×10^{-5}	0.5
0.3937	0.03280	0.01093	1	0.01	0.00001	0.621×10^{-5}	0.00546
39.37	3.2808	1.0936	100	1	0.001	62.1×10^{-5}	0.546
39370	3280.8	1093.6	100000	1000	1	0.6213	547
63360	5280	1760	160934	1609.34	1.609344	1	880
72	6	2	182.88	1.8288	0.00182	0.00113	1

Angstrom (A)	*Nanometer* (nm)	*Micrometer* (μm)	*Meter* (m)
1	0.1	10^{-4}	10^{-10}
10	1	10^{-3}	10^{-9}
10^{4}	10^{3}	1	10^{-6}
10^{10}	10^{9}	10^{6}	1

Table B Area

Square Meter (m^2)	*Hectare*	*Square* km (km^2)	*Square inch* (sq	*Square Foot* (sq	*Square Yard* (sq	*Acre* (acre)

	(ha)		in)	ft)	yd)	
1	1×10^{-4}	1×10^{-6}	1550	10.764	1.1959	2.471×10^{-4}
10^{4}	1	10^{-2}	15.5×10^{6}	10.764×10^{4}	1.1959×10^{4}	2.471
10^{6}	100	1	1550×10^{6}	10.764×10^{6}	1.1959×10^{6}	247.15
6.4516×10^{-4}	6.4516×10^{-8}	6.4516×10^{-10}	1	0.69445×10^{-2}	7.7154×10^{-4}	0.159419×10^{-6}
9.29×10^{-2}	9.29×10^{-6}	9.29×10^{-8}	144	1	0.1111	22.9×10^{-6}
0.836127	0.836127×10^{-4}	0.83619×10^{-6}	1296	9	1	206.6×10^{-6}
4046.8	0.40468	0.004046	6272640	43560	4840	1

Table C Volume

Fluid Ounce (fl oz)	*Litre* (L)	*Standard Imperial Gallon Gal*	*Crude Oil Barrel* (b)	*Cubic Meter* m^3 *or* (cu m)
1	0.0284	62.48×10^{-4}	0.1786×10^{-3}	2.841×10^{-5}
35.2	1	0.22	6.29×10^{-3}	1×10^{-3}
160	4.546	1	28.57×10^{-3}	4.546×10^{-3}
5600	159	35	1	0.1589×10^{-3}
35200	1000	220	6.29	1

1 standard imperial gallon = 1.2 US gallon

Table D Mass

Gram (g)	*Ounce* (oz)	*Pound* (lb)	*Kilogram* (kg)	*Hundred Weight* (cwt)	*Metric Ton* (t)
1	35.2×10^{-3}	2.2×10^{-3}	10^{-3}	19.685×10^{-6}	10^{-6}
28.4	1	6.25×10^{-2}	28.4×10^{-3}	0.56×10^{-3}	28.4×10^{-6}
453.6	16	1	0.4536	8.95×10^{-3}	453.5×10^{-6}
1000	35.2	2.2	1	19.685×10^{-3}	10^{-3}
50.8×10^{3}	1792	112	50.8	1	0.05
	35200	2200	1000	19.684	1

10^{6}					

1 metric ton (t) = 0.9842 long ton (ton) = 1.1023 short ton (sh tn) = 19.684 Hundred weight (cwt)

Table E Force

N ewton (N)	*D yne* (dyn)	*K ilogram–force kp* (kilopond)	*Pound–force* (lbf)	*P oundal* (pdl)
1	10^{5}	≈ 0.10197	≈ 0.22481	≈ 7.2330
10^{-5}	1	≈ 1.0197×10^{-6}	≈ 2.2481×10^{-6}	≈ 7.2330×10^{-5}
9.80665	= 980665	1	≈ 2.2046	≈ 70.932
≈ 4.448222	≈ 444822	≈ 0.45359	1	32.174
0.138255	13825	≈ 0.014098	≈ 0.031081	1

1 newton (N) = 1 kg m/s²
1 dyne (dyn) = 1 g cm/s²

1 poundal (pdl) = 1 lb ft /s²

1 kilogram–force, (kp) = g_n (1 kg) (kilopond)

1 pound–force (lbf) = g_n (1 lb)

Table F Pressure

P ascal (Pa)	*B ar* (bar)	*Technical Atmosphere* (at)	*Atmosphere* (atm)	*Torr* (torr)	*Pound–force/ Square Inch* (psi)
1	10^{-5}	1.0197×10^{-5}	9.8692×10^{-6}	7.5006×10^{-3}	145.04×10^{-6}
100,000	1	1.0197	0.98692	750.06	14.504
98,066.5	0.980665	1	0.96784	735.56	14.223
101,325	1.01325	1.0332	1	760	14.696
133.322	1.3332×10^{-3}	1.3595×10^{-3}	1.3158×10^{-3}	1	19.337×10^{-3}
6894.7	0.068947	0.070307	0.068046	51.71	1

1 pascal (Pa) = 1 N/m^2
1 bar (bar) = 10^6 dyn/cm^2
1 technical atmosphere (at) = 1 kgf/cm^2
1 atmosphere (atm) = 14.696 psi
1 Torr; (torr) = 1 mm Hg
1 mm water gauge (wg) = 0.073556 mm Hg

Table G Energy

Joule	*Calorie*		

(J)	(cal)	*Kilo Watt Hour* (kWh)	*British Thermal Unit* (BTU)
1	0.2389	2.778×10^{-7}	9.478×10^{-4}
4.186	1	1.163×10^{-6}	3.968×10^{-3}
3.6×10^{6}	8.6×10^{5}	1	3412
1055	252	2.93×10^{-4}	1

1 Ton Oil Equivalent (TOE) = 41.87×10^{9} J

= 10^{10} cal

= 1.163×10^{4} kWh

= 3.968 10^{7} BTU

Table H Celsius Temperature Conversion Formulae

	From Celsius	*To Celsius*
Fahrenheit	[°F] = [°C] × 9/5 + 32	[°C] = ([°F] − 32) × 5 / 9
Kelvin	[K] = [°C] + 273.15	[°C] = [K] − 273.15
Rankine	[°R] = ([°C] + 273.15) × 9/5	[°C] = ([°R] − 491.67) × 5 /9

For temperature *intervals* rather than specific temperatures,

1 °C = 1 K = 1.8 °F = 1.8 °R

Table I Multiplication Factor for Numerals

Multiplication Factor	10^{n}	*Prefix*	*Symbol*
1000 000 000 000	10^{12}	tera	T
1000 000 000	10^{9}	giga	G
1000 000	10^{6}	mega	M
1000	10^{3}	kilo	k
100	10^{2}	hecto	h
10	10^{1}	deca	da

0.1	10^{-1}	deci	d
0.01	10^{-2}	centi	c
0.001	10^{-3}	milli	m
0.000 001	10^{-6}	micro	μ
0.000 000 001	10^{-9}	nano	n
0.000 000 000 001	10^{-12}	pico	p
0.000 000 000 000 001	10^{-15}	femto	f
0.000 000 000 000 000 001	10^{-18}	atto	a

Numerals commonly used in India

1 lack = 1000 00 = 10^{5}

1 million = 1000 000 = 10^{6}

1 crore = 1000 000 0 = 10^{7}

1 billion = 1000 000 000 = 10^{9}

Table J Sieve Sizes (British and USA –Tyler Standard)

British Standard Mesh	*USA Tyler Mesh*	*Microns* (μm)	*Inches* (in)	*British Standard Mesh*	*USA Tyler Mesh*	*Microns (* m m)	*Inches* (in)
–	3	6680	0.2630	–	32	495	0.0195
–	4	4699	0.1850	36	–	422	0.0166
–	5	3962	0.1560	–	35	417	0.0164
5	–	3353	0.1320	44	–	353	0.0139
–	6	3327	0.1310	–	42	351	0.0138
6	–	2812	0.1107	52	48	295	0.0116
–	7	2794	0.1100	60	–	251	0.0099
7	–	2411	0.0949	–	60	246	0.0097
–	8	2362	0.0930	72	–	211	0.0083
8	–	2057	0.0810	–	65	208	0.0082
–	9	1981	0.0780	85	–	178	0.0070
10	–	1676	0.0660	–	80	175	0.0069
–	10	1651	0.0650	100	–	152	0.0060
12	–	1405	0.0553	–	100	147	0.0058

–	12	1397	0.0550	120	115	120	0.0049
14	–	1204	0.0474	150	150	104	0.0041
–	14	1168	0.0460	170	–	89	0.0035
16	–	1003	0.0395	–	170	88	0.0035
–	16	991	0.0390	200	–	76	0.0030
18	–	853	0.0336	–	200	74	0.0029
–	20	833	0.0328	240	–	64	0.0025
–	24	701	0.0276	–	250	63	0.0025
22	–	699	0.0275	300	270	53	0.0025
25	–	599	0.0236	350	325	44	0.0017
–	28	589	0.0232	–	400	37	0.0015
30	–	500	0.0197				

Table K Vacuum Chart

Vacuum (%)	*Torr or* mm *of Mercury*	*Microns*	psi	*Inches Mercury Absolute*	*Inches Mercury Gauge*
0.00	760	760000	14.7	29.92	0.00
1.3	750	750000	14.5	29.5	0.42
1.9	735.6	735600	14.2	28.9	1.02
7.9	700	700000	13.5	27.6	2.32
21	600	600000	11.6	23.6	6.32
34	500	500000	9.7	19.7	10.22
47	400	400000	7.7	15.7	14.22
50	380	380000	7.3	15.0	14.92
61	300	300000	5.8	11.8	18.12
74	200	200000	3.9	7.85	22.07
87	100	100000	1.93	3.94	25.98
88	90	90000	1.74	3.54	26.38
89.5	80	80000	1.55	3.15	26.77
90.8	70	70000	1.35	2.76	27.16
92.1	60	60000	1.16	2.36	27.56
93	51.7	51700	1.00	2.03	27.89
93.5	50	50000	0.97	1.97	2.7.95
94.5	40	40000	0.77	1.57	2.8.35
96.1	30	30000	0.58	1.18	28.74
97.4	20	20000	0.39	0.785	29.14
98.7	10	10000	0.193	0.394	29.53
99	7.6	7600	0.147	0.299	29.62

99.8	1	1000	0.01934	0.03937	29.88
99.9	0.75	750	0.0145	0.0295	29.89
99.99	0.10	100	0.00193	0.00394	29.916
99.999	0.01	10	0.00019	0.00039	29.919
100	0.00	0	0	0	29.92

Table L Sheet and Wire Gauges

SWG	*Sheet Thickness* (mm)	*Wire Diameter* (mm)	*Wire Diameter* (in)	*Wire Cross Sectional Area* (mm^2)
0000000	12.70	12.70	0.5000	126.6767
000000	11.7856	11.7856	0.464	109.092
00000	10.9728	10.9728	0.432	94.5637
0000	10.160	10.160	0.400	81.073
000	9.4488	9.4488	0.372	70.12
00	8.8392	8.8392	0.348	61.36
0	8.23	8.23	0.3240	53.19
1	7.62	7.62	0.3000	45.60
5	5.38	5.38	0.212	22.73
10	3.25	3.25	0.128	8.296
15	1.83	1.83	0.072	2.630
20	0.9144	0.9144	0.036	0.6567
25	0.508	0.508	0.020	0.2027
30	0.3150	0.3150	0.0124	0.07791
35	0.213	0.213	0.0084	0.03563
40	0.1219	0.1219	0.0048	0.011675
45	0.071	0.071	0.0028	0.003959
50	0.025	0.025	0.0010	0.000491

Table M Mohs Scale of Mineral Hardness

Mohs Hardness	*Mineral Name*	*Chemical form*	*Sclerometer Hardness*
1	Talc	$Mg_3Si_4O_{10}(OH)_2$	1
2	Gypsum	$CaSO_4 \cdot 2H_2O$	2
3	Calcite	$CaCO_3$	9
4	Fluorite	CaF_2	21

5	Apatite	$Ca_5(PO_4)_3(OH^-,Cl^-,F^-)$	48
6	Orthoclase Feldspar	$KAlSi_3O_8$	72
7	Quartz	SiO_2	100
8	Topaz	$Al_2SiO_4(OH^-,F^-)_2$	200
9	Corundum	Al_2O_3	400
10	Diamond	C	1500

Table N Hardness of Common Materials on Mohs Scale

Material	*Hardness Mohs Scale*
Finger nail	2.5
Pure gold	2.5–3
Pure silver	2.5–3
Copper coin	~3.5
Knife blade	5.5
Glass	6
Steel file	6.5
Hardened steel	7–8

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