CHAPTER 47

ENGINE-DRIVEN HEATING AND COOLING EQUIPMENT

COMBUSTION ENGINES are used to drive space conditioning, liquid chilling, and refrigeration equipment. In many areas of the United States, the operational cost of an engine-driven system is less than the cost for an electric-driven system because the average cost of energy from fuel or natural gas is less per equivalent unit of energy than electricity. In addition, operation of engine drives, especially during the peak time of the day when electric demand charges are highest, result in additional savings. However, initial and maintenance costs are greater.

Technical advances in materials and engine design have resulted in the production of relatively small, long-lived, reliable engines with sufficient output to drive residential and small commercial/industrial systems. These engines provide lower fuel consumption, noise, and space requirements.

The overall efficiency of an engine-driven system is significantly improved when heat from the engine coolant and exhaust gas is recovered to meet auxiliary heat requirements such as space heating, hot water heating, process heat, domestic hot water, desiccant dehumidification, etc. State-of-the-art engine-driven equipment is designed for minimal service and maintenance. State-of-art controls permit efficient variable-speed operation and proper sequencing of the running characteristics.

This chapter presents the technical and operating data to assist an engineer in making an appropriate choice of equipment and system design based on cost and application. The section on Design and Installation in Chapter 7 includes additional information on engine-driven chillers and heat pumps.

The preparation of this chapter is assigned to TC 7.4, Combustion Engine Driven Heating and Cooling Equipment.

CHILLERS

An engine-driven chiller is driven in a conventional vapor compression mode by a natural gas, gasoline-derivative, or diesel-derivative engine rather than an electric motor. The components and thermodynamic cycle on the refrigeration side of the chiller are those common to all vapor compression chillers: a compressor, an evaporator, a condenser, and an expansion device (Figure 1). The prime movers are external to the compressor. Natural gas powered engines have the benefits of:

- Variable speed and capacity modulation capability
- High part-load efficiency
- Ability to efficiently recover high temperature waste heat for domestic water heating, steam generation or process use
- Reduced total operating costs

CHILLER COMPONENTS

Engines

Engines for chiller can be categorized into two types: diesel-derivative and gasoline-derivative. With diesel-derivative engines, the engine block and crankshaft remain in place for the life of the chiller. Most other components are replaced over time based on a schedule prescribed by the manufacturer. Gasoline-derivative engines are generally low power engines (less than 150 horsepower) that are fully replaced after a top end overhaul. Figure 2 provides a reference to estimate the engine size required for a given chiller capacity. Typically, about 1 horsepower per ton of cooling capacity is required.

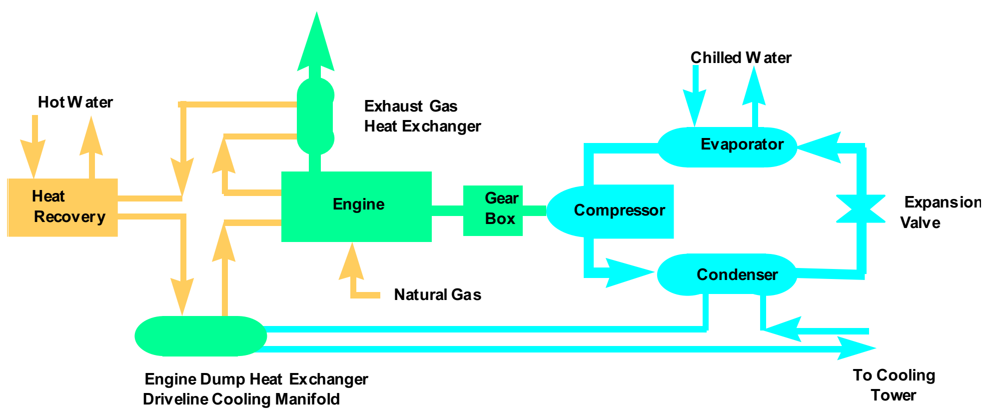

Fig. 1 Engine Driven Chiller with Heat Recovery

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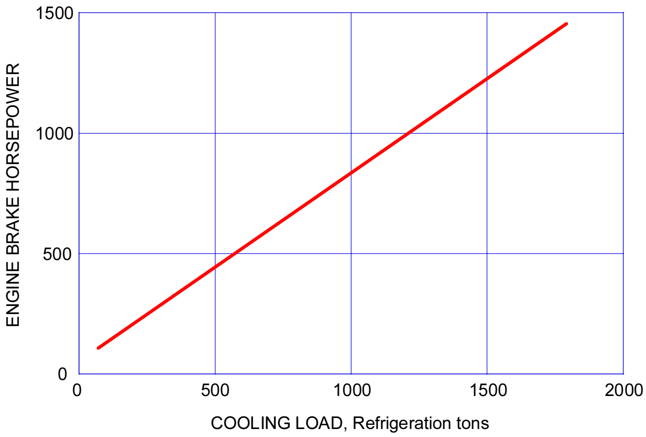

Fig. 2 Relationship Between Cooling Load and Engine Size

Table 1 Characteristics of Compressors for Engine-Driven Chillers

	Centrifugal	Screw	Reciprocating
Capacity range, tons	400 to 6000	100 to 4000	<200
Shaft speed range, rpm	3000 to 14000	1000 to 4000	1200 to 1800
Type of gear box	Speed increasing	Speed increasing	Direct drive or speed decreasing
Capacity control	Guide vanes	Slide valve	Cylinder unloading

Compressors

Three types of engine driven compressors for chiller application are available, differing usually by the cooling capacity:

Reciprocating compressors are generally used in applications of 200 tons of cooling or less. Part-load capacity is controlled by modulating engine speed down to about 30 to 50% of rated speed, which improves fuel economy. Some reciprocating engine chillers also use cylinder unloading to reduce capacity further.

Screw compressors are available in capacities from 100 to 1250 tons. Capacity control is achieved by varying the engine speed and adjusting the slide valve on the compressor.

Centrifugal compressors are most appropriate for large capacity systems and are available in sizes from 400 to over 2000 tons. Speed increasers operate the compressors at significantly higher speeds than the engine. Capacity is controlled by varying the speed of the compressor and/or by compressor inlet guide vane control. Table 1 summarizes the basic characteristics of the three types of chiller compressors. Chapter 34 has more information on compressors.

Engine Compressor Gear Boxes

Engines are typically mated to the compressor through a gear box, which may be internal or external to the compressor. Depending on the shaft speed of the compressor, a speed increasing or a speed decreasing gear box is used. Typical compressor shaft speeds as well as the type of gear box are indicated in Table 1.

Reciprocating engines are typically designed to operate between 1200 to 2400 rpm depending on the size of the engine. The larger the engine the slower the rated speed. The speed is kept as low as possible to extend the life of the engine.

Clutch

The clutch allows the engine to warm up before engaging and loading the compressor. The clutch also allows the engine to complete a cool down sequence as recommended by the engine manufacturer without the compressor being engaged. The clutch can be air-actuated or electric-actuated.

Table 2 COP of Engine-Driven Chillers

Heat Recovery Option	COP at Full Load
No heat recovery	1.2 to 2.0
Jacket water heat recovery	1.5 to 2.25
Jacket water and exhaust heat recovery	1.7 to 2.4

Dump Heat Exchangers

A dump heat exchanger transfers heat from the engine water jacket, engine oil, and compressor oil loops to the cooling tower. Both shell-and-tube or plate heat exchangers are used; but because plate heat exchangers have narrow passages, shell and tube heat exchangers are more commonly used to avoid plugging with debris from open cooling systems such as cooling towers.

RATING AND PERFORMANCE

Both engine-driven and electrically-driven chillers are rated according to ARI *Standard* 550/590 conditions as follows:

Chilled Water Conditions
44°F chilled water supply temperature
54°F chilled water return temperature
2.4 gpm/ton chilled water flow
Water-Cooled Condensers
85°F condenser water supply temperature
95°F condenser water return temperature
3.0 gpm/ton chilled water flow
Air-Cooled Condensers
95°F air supply temperature
20°F temperature differential between air supply and the condensing refrigerant
2°F refrigeration system heat loss to the condenser

Manufacturers offer performance curves for other than ARI standard conditions. As with any chiller, performance is largely a function of design conditions for the condenser and chilled water supply temperatures.

Table 2 provides a typical range of engine-driven chiller COPs with and without heat recovery. The COP is the cooling energy output divided by the fuel energy input. Engine fuel input is based on the higher heating value (HHV) of the fuel. For natural gas, the average HHV is 1020 Btu/ft^3.

The heat recovered from the jacket coolant and exhaust gas is added to the cooling load produced by the chiller, thereby increasing useful thermal output and the COP. Because no standards have been approved on how to calculate the COP of an engine-driven chiller when considering heat recovery, most manufacturers present COPs with and without heat recovery.

Typical COPs at part-load operation for engine-driven chillers are shown in Figure 3 and Figure 4. The variable speed provides a significant part-load performance advantage over single-speed chillers. The high part-load performance results in a higher integrated part-load value (IPLV) as defined by ARI *Standard* 550/590 as follows:

$$\text{IPLV} = 0.01A + 0.42B + 0.45C + 0.12D$$

where

Chiller Load, %	Entering Cond. Water Temp., °F	Manufacturer Rated COP	Part-Load Hours, %
100	85	A	1
75	75	B	42
50	65	C	45
25	65	D	12

The IPLV for engine chillers is significantly higher than its rated load performance. As an example, the full-load COP for a typical

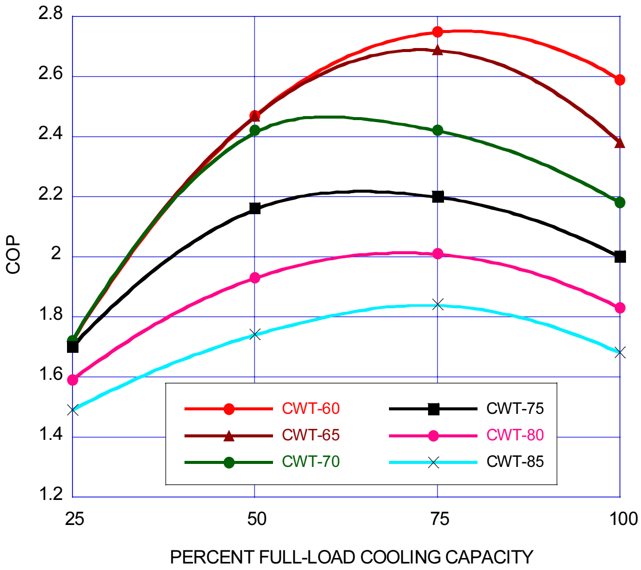

Fig. 3 Typical Engine-Driven Screw Chiller (500 Ton) COP Versus Part-Load and Entering Condenser Water Temperature (CWT)

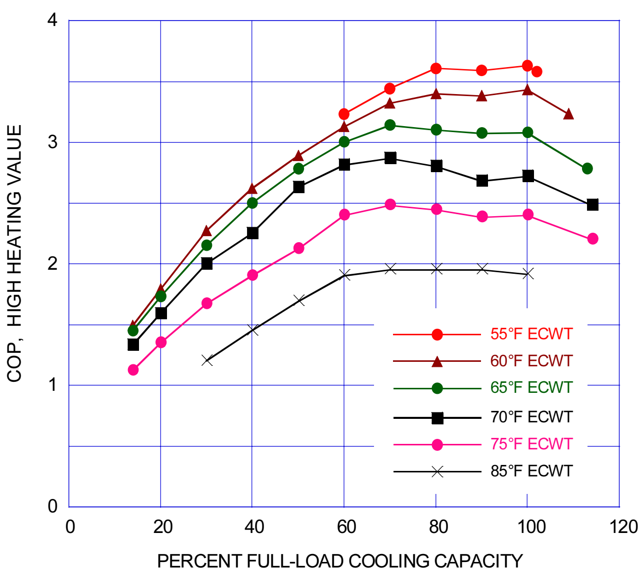

Fig. 4 Typical Engine-Driven Centrifugal Chiller COP Versus Part-Load and Entering Condenser Water Temperature (ECWT)

150 ton engine-driven screw compressor chiller would be 1.3 while the IPLV would be 1.8.

Engine Heat Rejection and Recovery

Energy in the fuel is released during combustion and is converted to shaft work and heat. The shaft work drives the compressor, while the heat is liberated from the engine through the coolant, exhaust gas, and surface radiation (see Figure 5). Approximately 75% of the total energy input is converted to heat. Much of this heat can be recovered from the engine exhaust and jacket coolant. The heat can be used to generate steam or hot water, or it can be used directly in certain industrial applications. To be cost effective, a heating load must be coincident with the cooling load. Examples of applications where this is possible include service water heating in hospitals, hot water for dish washing in restaurants, and a heat source for regenerating a desiccant cooling system. Other uses for recovered heat include space heating, reheating return air, preheating boiler water, and absorption chilling.

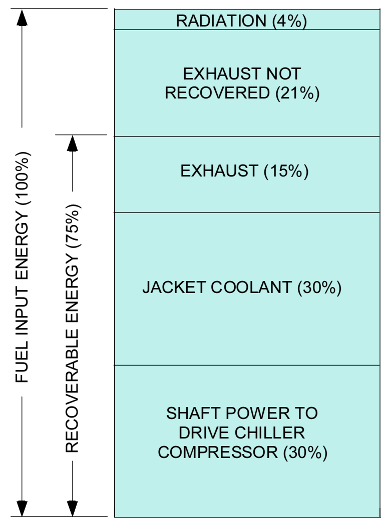

Fig. 5 Engine Energy Balance

Heat recovered from the engine jacket accounts for up to 30% of the energy input and is capable of producing 180°F hot water. To avoid thermal stress, the coolant temperature difference between inlet and outlet generally should not exceed 15°F. Almost all of the heat transferred to the engine coolant can be recovered, limited only by the efficiency of the heat exchanger, and assuming that there is a demand for the heat.

The other major source of heat is the engine exhaust. Exhaust temperatures of 850 to 1200°F are typical. Only a portion of the exhaust heat can be recovered because exhaust gas temperatures are generally kept above condensation thresholds. Most heat recovery units are designed for a 300 to 350°F exhaust outlet temperature to avoid the corrosive effects of condensation in the exhaust piping. Exhaust gas can generate hot water to about 230°F or low pressure steam of 15 psig.

By recovering heat in the jacket water and exhaust, approximately 75% of the fuel's energy can be effectively used. Figure 5 shows typical percentages of energy that can be recovered from the engine based on the fuel's heat content.

MAINTENANCE AND SERVICE

Engine-driven chillers, like any other type of cooler, require routine and preventive maintenance. Maintenance of the compressor is similar to the maintenance of electric-drive units, with the exception of the periodic changing of the gear box oil and the operation and care of the external lubricating pumps.

Engines require periodic servicing and parts replacement, depending on the severity of use and the type of engine. Maintenance and service tasks for engines are usually scheduled as a function of operating hours and equivalent full load hours (EFLH). Operating hours (run hours) are defined as the accumulated time of engine operation. EFLH indicates the severity of chiller operation and is defined as

$$\text{EFLH} = \frac{\text{Total ton-hours/year}}{\text{Max. continuous design capacity (tons)}}$$

Table 3 Typical Service and Overhaul for Diesel Engine

Daily
Walkaround Inspection – Inspect for leaks and loose connections
Lubrication System – Check crankcase oil level and oil filter diff. pressure
Cooling System – Check coolant level
Engine Air Cleaner – Check service indicator, Clean dust collector (if equipped)
Air Starting Motor (if equipped) – Check lubricator level/Empty collector jar
Aftercooling System – Drain condensate; Check intake manifold air temp.

Every Two Weeks or 250 Hours*
Batteries (if equipped) – Clean/Check electrolyte level

Every Month or 750 Hours*
Scheduled Oil Sampling (S-O-S) Analysis – Obtain
Lubrication System – Replace oil and filters
Auxiliary Oil Filter System – Replace oil
Crankcase Breather – Clean
Cooling System – Test for coolant additive concentration; Inspect/Clean radiator fins (if equipped)
Engine Valve Lash – Check/Adjust
Exhaust Valve Takeup and Cylinder Pressure Blowby (Crankcase) – Measure/Record
Carburetor/Governor Control Linkage – Check/Adjust/Lubricate
Spark Plugs – Clean/Check/Adjust gap
Ignition System – Inspect/Check/Adjust timing, inlet manifold temperature and air/fuel ratio
Gas Pressure Regulator – Drain water from drip leg; Check diff. pressure
Air Inlet and Exhaust Piping – Inspect
Belts and Hoses – Inspect/Replace
Fan Drive – Lubricate bearing
Engine Mounts – Inspect
Crankshaft Vibration Damper – Inspect

Every Month or 750 Hours (continued)*
Engine Protection Devices – Inspect for proper operation; Inspect wiring harness
Magnetic Pickups/Sensor (at first oil change only) – Check/Clean
Turbocharger – Inspect for proper operation
Aftercooler – Check for proper operation; Drain condensate; Clean fins

Every Two Months or 1500 Hours*
Auxiliary Oil System Filters – Replace elements

Every Six Months or 4000 Hours
Generator (if equipped) – Lubricate bearing
Magnetic Pickups/Sensor – Check/Clean
Driven Equipment – Inspect/Check/Lubricate as recommended by manufacturer
Jacket Water Pump – Inspect for proper operation
Starting Motor – Inspect for proper operation
Alternator – Inspect for proper operation

Top End and Overhaul – 12,000 to 15,000 Hours
Cylinder Head Assembly – Rebuild or Exchange
Cooling System – Clean/Flush coolant; Replace thermostats and lines
Water Pumps – Rebuild or Exchange
Oil Cooler and Aftercooler Cores – Clean/Test
Ignition Transformers – Test resistance
Carburetor – Inspect/Replace
Gas Pressure Regulator – Inspect/Replace
Prelube Pump – Inspect for proper operation
Turbochargers – Rebuild or Exchange
Exhaust Bypass Valve – Inspect/Clean

Overhaul – 24,000 to 30,000 Hours
Cylinder Head Assembly and Cylinder Packs – Rebuild or Exchange
Crankshaft, Camshaft, Camshaft Followers and Bearings, Damper, Gear Train Gears and Bushings, and Driven Unit Alignment – Inspect

*First perform previous service hour items.

For a typical chiller duty cycle, the EFLH is roughly one-half that of the total operating hours. Suggested maintenance schedules for two different manufacturers of natural gas-powered engine-driven chillers are presented in Table 3 and Table 4.

A preventive maintenance program should inspect for

- Leaks (a visual inspection facilitated by a clean engine)
- Abnormal sounds and odors
- Unaccountable speed changes
- Condition of fuel and lubricating filters

An analysis of lubricating oil is a low-cost method of determining the physical condition of the engine and a guide to maintenance procedures. Commercial laboratories routinely provide this service which includes measuring the concentration of various elements in the lubricating oil such as bearing metals, silicates, calcium, suspended and nonsuspended solids, water, and oil viscosity. The laboratory can assist in interpreting the readings and alert the user to impending problems.

CONTROLS AND OPERATION

Engine-driven chillers can be controlled locally or from a remote location equipped with a computer or a local area network. The control system performs a series of pre-start checks to verify that pressures, temperatures, and flows are within normal limits. After the readiness of these parameters is confirmed, the engine is started and allowed to reach normal operating temperature. During warm-up, engine speed is low and compressor loading is minimal. When the engine reaches normal operating temperature, loading on the compressor is gradually increased, maintaining the desired chilled water set point.

The microprocessor control maintains the set point by controlling both engine speed and compressor loading, a combination that gives many engine chillers a high turndown ratio (5:1 or greater). As the cooling demand decreases, engine speed is reduced until its low limit is reached. Further decreases in chilled water demand cause the compressor to be unloaded (in a reciprocating compressor, the cylinders are unloaded; in a screw compressor, the slide valve is closed; in a centrifugal compressor, the guide vanes are closed).

The control system also monitors key parameters to ensure safe operation. Safety shutdowns are generally initiated if low or high temperatures or pressures occur in the refrigerant, compressor oil, condenser water, or engine oil or coolant. Engine chiller shutdown follows an orderly, predetermined sequence of events including a reduction in engine speed and load in order to reduce thermal and stress shocks on the equipment.

Engine chiller controls may have a graphical interface to allow on-board diagnostics, monitoring of operating and performance parameters, and set-point control and scheduling. Most controls also provide an operating history of alarms and shutdowns to simplify service and troubleshooting. The ability to remotely monitor the chiller's operation and performance is another feature offered by some manufacturers.

DESIGN AND APPLICATION ISSUES

Noise and Vibration Control

Engine-driven machines installed indoors, even where the background noise is high, usually require noise attenuation and isolation from adjoining areas. Noise can be (1) airborne noise created by the engine, compressor, exhaust, and intake; and (2) structure-borne noise created by engine vibration transmitted through the floor and through pipes supported by the wall or ceiling.

Table 4 Typical Service and Overhaul for Gasoline Engine

Service Category	Interval, the First of …	Item	Action	Est. Hours to Perform
A	750 EFLH or 1500 operating hours	Air filter	Replace	2
		Battery	Inspect	
		Timing	Check and adjust if necessary	
		Carburetor	Check and adjust if necessary	
		Exhaust drains	Check	
		Spark plugs	Replace	
		Ignition wires	Replace	
		Coupling	Inspect	
		Engine mounts	Inspect	
		Engine oil filter	Replace	
		Compressor shaft seal	Evaluate leak rate	
		Compressor oil level	Check	
		Dump heat exchanger strainer	Clean	
		Filter dryer cores	Replace (first season only, then as required)	
		General	Check for leaks and tighten electrical connections	
B	1500 EFLH or 3000 operating hours	Engine lube oil	Replace oil drum and drain pan	2 to 4
		PCV valve	Replace	
		Distributor cap	Replace	
		Rotor	Replace	
		Engine evaluation	Blowby and compression test (may be omitted first B service)	
		Dump heat exchanger	Check, clean if necessary	
		Condenser	Check, clean if necessary	
		Compressor lube oil	Take sample and log	
		Filter dryer	Check upstream moisture indicator	
C	6000 EFLH or 12,000 operating hours	Cylinder heads	Replace	8
D	7500 to 10,000 EFLH or 15,000 to 20,000 operating hours	Engine	Replace	16
E	Seasonal	Start-up	Follow procedure in manual	2 to 4
		Shutdown	Follow procedure in manual	2 to 4
F	As required (no set interval)	Engine valves	Adjust	1
		Compressor shaft seal	Replace	4
		Compressor oil	Replace	4
		Compressor oil filter	Replace	1
		Thermo mixing valve(s)	Replace elements	1

Table 5 Sound Reduction

		Approx. Sound Reduction, dBA
	Original machine (90 to 98 dB)	0
	Vibration isolators	2
	Baffle	5
	Absorption material only	5
	Rigid sealed enclosure	15 to 20
	Enclosure and isolators	25 to 30
	Enclosure, absorption, and isolators	35 to 40
	Double wall enclosure, absorption, and isolators	60 to 80

Sound levels measured in accordance with ARI *Standard* 575.

Exhaust noise is commonly attenuated with a silencer, which typically reduces the noise by 15 dB when measured 10 ft from the exhaust outlet. The muffler manufacturer can evaluate such factors as the number of cylinders and engine speeds to predict the specific effects of a muffler.

Vibration created noise can be minimized with engine vibration isolator mounts and flexible connections for piping. Sound absorbing materials or double wall construction can be applied to room enclosures to reduce noise. The approximate noise reduction level for various approaches is shown in Table 5.

Emissions and Permitting

Depending on local regulations, exhaust emissions from internal combustion engines is a concern of the equipment manufacturer. The emission characteristics of an engine are primarily affected by the ratio of air to fuel during combustion. In stoichiometric combustion, fuel reacts with the exact amount of air required to oxidize all carbon and hydrogen in the fuel. The combustion by-products include carbon dioxide, water, nitrogen dioxides, and sulfur dioxide. The exhaust theoretically contains no unburned fuel or unreacted oxygen. Because the air and fuel can never be completely mixed, combustion is never complete. Therefore, other contaminants such as unburned hydrocarbons and carbon monoxide become part of the exhaust emissions. Based on theoretical calculations, approximately 16 lb of air are required to burn 1 lb of natural gas. This ratio represents stoichiometric combustion. Chapter 18 of the *ASHRAE Handbook—Fundamentals* has more information on combustion.

A common method to represent the air-to-fuel ratio is to define the **relative air-to-fuel ratio** as

$$\lambda = \frac{\text{Operating air-fuel ratio}}{\text{Stoichiometric air-fuel ratio}}$$

A λ value of 1 indicates that the engine is operating at stoichiometric conditions. For values of λ less than 1.0, the engine is said to run rich because more fuel is in the cylinder than the air can theoretically oxidize. For values of λ greater than 1.0, the engine is said to run lean because more air is present than is required to theoretically oxidize the fuel.

Atmospheric Contaminants. Contaminants that can be produced in natural gas engines are classified in the following categories: NO_x, CO, HC, SO_x, and PM_{10}.

NO_x: Oxides of nitrogen consist of NO and NO_2 which are formed when N_2 and O_2 from the air react. The level of the reaction primarily depends on combustion temperature. A low combustion temperature will result in low NO_x levels, and vice versa, a high combustion temperature will result in high NO_x levels.

CO: Carbon monoxide is formed by incomplete combustion of the fuel, which occurs when air is insufficient or poorly mixed with the fuel to develop complete combustion.

HC: Hydrocarbons are unburned fuel (hydrogen and carbon). Hydrocarbons are the result of incomplete combustion because of inadequate air, insufficient mixing of the air and fuel, and inadequate combustion temperature. Natural gas is made up of several hydrocarbon gasses including methane, ethane, propane, and butane. Methane is the primary hydrocarbon representing about 95% of natural gas.

HC emissions are typically broken down into two categories: total hydrocarbons (THC), which include all HC gases in the exhaust stream; and non-methane hydrocarbons (NMHC), are the portion of the total hydrocarbons that does not include methane. Most regulating agencies only regulate non-methane hydrocarbons because they react with NO_x in the lower atmosphere, acting as the precursor in the formation of photochemical smog. NMHC gases are considered volatile organic compounds (VOCs) or reactive organic compounds (ROCs).

SO_x: Oxides of sulfur are formed when sulfur containing compounds in the fuel and air are oxidized in the combustion chamber. Sulfur levels in natural gas are negligible, therefore SO_x emissions from natural gas engines are extremely low. Oxides of sulfur enter the atmosphere and combine with water in the air forming H_2SO_3 (sulfurous acid) and H_2SO_4 (sulfuric acid).

PM_{10}: Particulate matter is formed during combustion of liquid fuels and engine lubricating oil. Particulates are often seen as black smoke coming from diesel truck engines. Particulate emissions from gaseous fueled engines are extremely low.

Figure 6 shows how the relative amount of each contaminant qualitatively changes with air/fuel ratio.

The two most common strategies used to meet emission regulations are (1) lean burn combustion and (2) stoichiometric combustion with three-way catalyst after-treatment.

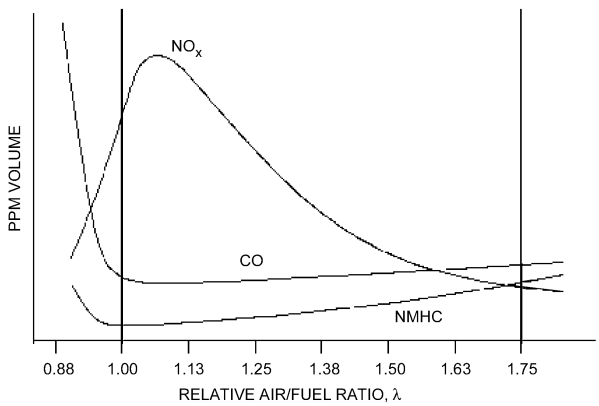

Fig. 6 Natural Gas Engine Emission Characteristics

Lean Burn Combustion. To the rich side (λ < 1.0) of stoichiometry, NO_x decreases significantly due to the lack of oxygen in the combustion chamber and the lower combustion temperature. On the lean side (λ > 1.0), the NO_x reaches a peak because the combustion temperature remains high and oxygen is abundant. At increasingly lean air/fuel ratios, the combustion temperature continues to fall, thus reducing NO_x levels.

Carbon monoxide levels are also lower in a lean combustion engine when compared to a stoichiometric engine because the fuel has plenty of oxygen to react with. Operation to the rich side causes a significant increase in CO because of the lack of sufficient oxygen to complete combustion. At a slightly lean point, CO output reaches a minimum because oxygen is sufficient and combustion temperatures are high. At leaner combustion air/fuel ratios, CO gradually increases due to poor combustion from low combustion temperatures and the lower flammability of the fuel.

Like CO, emissions of NMHC are higher at points rich of stoichiometry because of a lack of sufficient oxygen for combustion. NMHC emissions reach a minimum at a point slightly lean of stoichiometry, but gradually increase at higher air/fuel ratios due to poor combustion as a result of low combustion temperatures.

Overall, a lean combustion engine operating with λ between 1.0 and 1.5 allows the most effective combustion of the fuel and results in lowest overall levels of contaminants.

Stoichiometric Combustion with a Three-Way Catalytic Exhaust After-Treatment. Emissions from an engine can be reduced by chemically converting these contaminants into harmless, naturally occurring compounds. The most common method for achieving this is through the use of a catalytic converter. In a catalytic converter, the catalyst will either act as an oxidizing agent or a reducing agent.

A three-way catalyst contains both reduction catalyst materials and oxidation catalyst materials and converts NO_x, CO, and NMHCs to N_2, CO_2, and H_2O. Typical emission conversions for a three-way catalyst operating on a stoichiometric engine are

- 90%+ decrease in NO_x
- 80%+ decrease in CO
- 50%+ decrease in NMHC

These emission levels are satisfactory to meet the most stringent regulations, including the California South Coast Air Quality Management District. However, a very narrow air/fuel ratio operating range is necessary to maintain these percentages. Electronic air/fuel ratio controls are often required. In addition, stoichiometric combustion is necessary to provide exhaust gas temperatures high enough for effective catalyst operation.

Engine Room Ventilation and Combustion Air Requirements

Three to six percent of the fuel consumed by a gas engine is lost as heat radiated to the surrounding air. Additionally, heat lost from exhaust piping can easily equal engine radiated heat. Engine room ventilation must be sufficient to meet three basic requirements:

1. Limit the engine room temperature to less than 110°F in order to maintain rated engine power and reasonable temperatures for the engine operator and service personnel. The ventilation requirement can be calculated following the procedures in Chapter 29 of the *ASHRAE Handbook—Fundamentals* or estimated from Table 9 in Chapter 7.
2. Meet the requirements of ASHRAE *Standard* 15, Safety Code for Mechanical Refrigeration
3. Provide enough air for proper combustion. Ventilation air must be adequate to provide the engine with sufficient combustion air. About 4 cfm per brake horsepower is satisfactory.

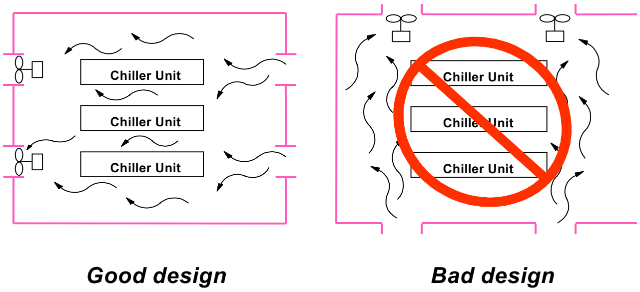

Fig. 7 Plan View of Engine Room Ventilation

As shown in Figure 7, proper ventilation provides an airflow path around the units. Also, cool air should enter low around the engines and remove the heated air from above the engines to encourage as much circulation as possible.

Technical Specifications

Engine-driven chiller manufacturers offer equipment with the same footprint as an electric chiller. The typical engine chiller can weigh up to 50% more than a conventional electric chiller depending on the type of prime mover. Diesel-derivative engines built for high combustion pressures add the greatest weight. Sound levels from engine chillers typically range from 90 to 100 dBA at full load without any enclosure. A removable sound enclosure reduces the full-load sound to that of a conventional electric chiller. Depending on the chiller operating load profile, a sound enclosure may not be needed in many cases because most of the operating time is spent at reduced engine operating speeds with lower noise levels.

Economics

An economic analysis by GRI (1997a) found that installing a mix of gas and electric chillers rather than all-gas or all-electric chillers provided the most attractive economics in most of the cities analyzed. The natural gas engine-driven chillers are operated at maximum capacity during periods with high peak electric demand charges, while the electric units operate during off-peak hours when electric rates are traditionally low.

Although engine chillers are premium priced products, they can be attractive investments yielding a return on investment of 20 to 50% in areas of the country with high electric rates and demand charges (GRI 1997b). Hospitals, colleges/universities, and manufacturing operations that require cooling are prime candidates for these products.

HEAT PUMPS AND AIR CONDITIONERS

EQUIPMENT DESCRIPTION AND DESIGN

Engine-driven heat pumps use an internal (reciprocating, Wankel, etc.) or external (Stirling) combustion engine to drive the compressor in a standard vapor-compression refrigeration cycle. Heat recovered from the engine jacket water and exhaust gas can be used to provide additional heating, dehumidification, or defrost capabilities. The inherent variable-speed capability of engines coupled with variable-speed or multi-speed indoor fans allow engine-driven heat pumps to modulate system heating and cooling capacities to closely match building loads and maintain reasonable indoor humidity levels.

Engine-driven heat pumps are commercially available in residential, light commercial, and commercial sizes and for use with natural gas and propane fuel. They are available with single or multiple indoor packages or units coupled to one outdoor unit.

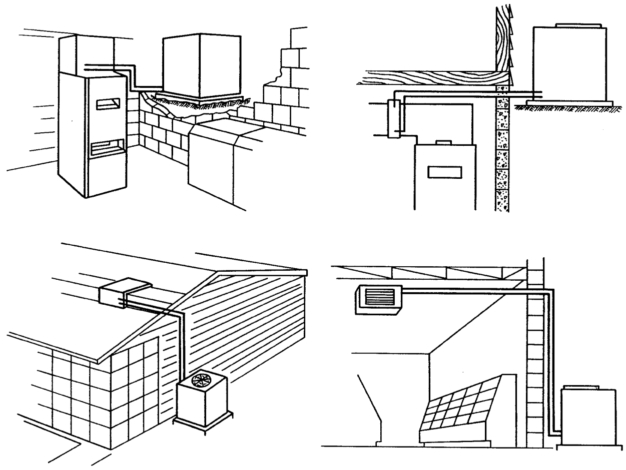

Fig. 8 Residential Engine-Driven Heat Pumps

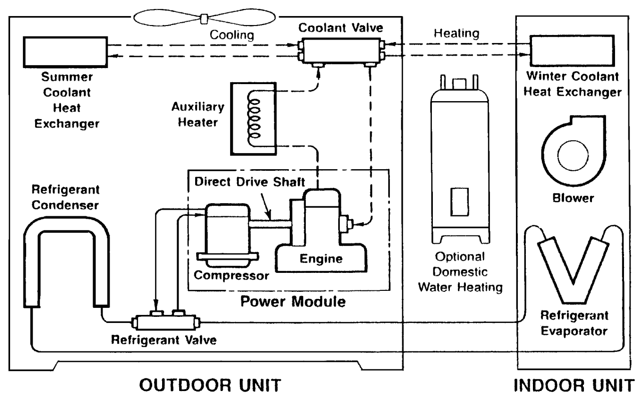

Fig. 9 Four-Pipe Heat Pump

A cross section of a typical engine-driven heat pump is shown in Figure 8. The outdoor unit houses the engine, compressor, and outside heat exchangers. The engine and compressor, combined with associated hardware (e.g., the exhaust gas recuperator, oil reservoir, intake air silencer, exhaust muffler, and auxiliary heater) are located in a common enclosure to reduce noise. This enclosure is ventilated to maintain reasonable internal air temperatures.

Engine-driven heat pumps use either a two-pipe or a four-pipe strategy, referring to the number of pipes running between the indoor and outdoor units. In a two-pipe system, only refrigerant circulates between the indoor and outdoor units. In a four-pipe system, a coolant also circulates between the indoor and outdoor units to carry heat recovered from the engine jacket water and exhaust gas (see Figure 9).

The indoor unit(s) houses the air handler and inside heat exchangers. A coolant-to-air heat exchanger is located downstream of the refrigerant coil for four-pipe systems. A multispeed or electronically commutated blower motor is controlled so that indoor airflow varies in direct proportion to engine speed. In the cooling mode, variable airflow is needed to provide a comfortable split between latent and sensible control of the indoor air. In the heating mode, variable indoor airflow allows the heat pump to deliver a constant air temperature throughout the operating range.

Except for the fuel piping and the coolant loop piping required for a four-pipe system, the installation of an engine-driven heat pump is similar to that of other split-system air-source heat pumps.

The compressor in the outdoor unit is either directly coupled to or belt driven by the engine. Engines vary in design, some having been designed specifically for use in engine-driven heat pumps and others having been modified from automotive engine designs. The engine/compressor suspension system is tuned to avoid resonances and to isolate vibrations throughout the normal operating speed range, which is generally between 1000 and 3000 rpm.

Reciprocating, automotive scroll-type, and rotary compressors are used in engine-driven heat pumps based on the design of specific units. The engine has inherent load-matching capability. Because engine speed can be varied over a broad range, the engine-driven heat pump can modulate output to meet the load. Modulation substantially reduces the cycling required compared to a fixed-capacity system. In addition, because cycling occurs at low-capacity operation, cycling rates are considerably lower (1.5 cycles per hour at 50% on-time) than those exhibited by single-speed systems (3.0 cycles per hour at 50% on-time).

RATINGS AND PERFORMANCE

Test procedures specific to engine-driven heat pumps are included in ANSI *Standard* Z21.40.4/CGA 2.94 (CSA International 1996). A diagram of test points for variable-speed engine-driven heat pumps is shown in Figure 10.

The test procedures for engine-driven heat pumps (CSA International 1996) were derived primarily from those previously developed for electric-motor-driven heat pumps. A study by Talbert et al. (1998), which was funded by ASHRAE, evaluated the relevance of engineering assumptions inherent in the electric heat pump procedures to the engine-driven heat pump test procedures. Several changes in the ANSI test procedures were recommended to better represent the performance characteristics of engine-driven heat pumps. The study also found that gas engine heat pumps are very tolerant of oversizing or undersizing because of their variable-speed operation.

Figure 11 shows the performance characteristics of a typical split-system engine-driven heat pump with one indoor unit. Figure 12 shows performance characteristics of a system with multiple

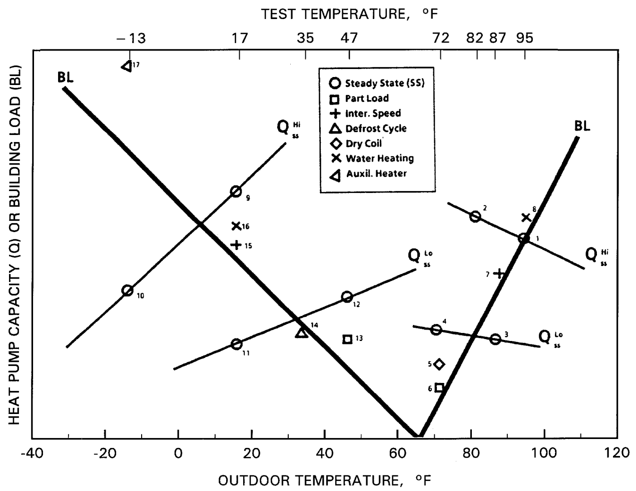

Fig. 10 Test Points for Variable-Speed Engine-Driven Heat Pumps (GRI 1986 and Talbert et al. 1987)

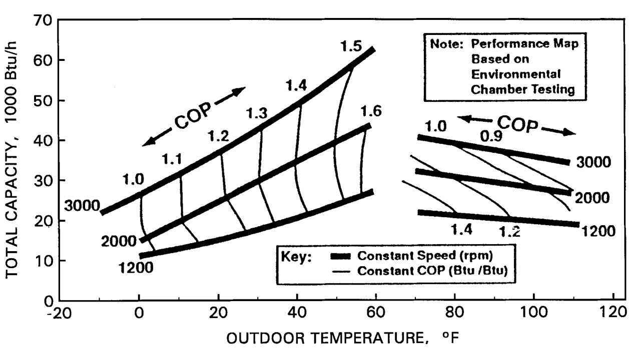

Fig. 11 Performance Characteristics of Split-System Engine-Driven Heat Pumps (GRI 1986)

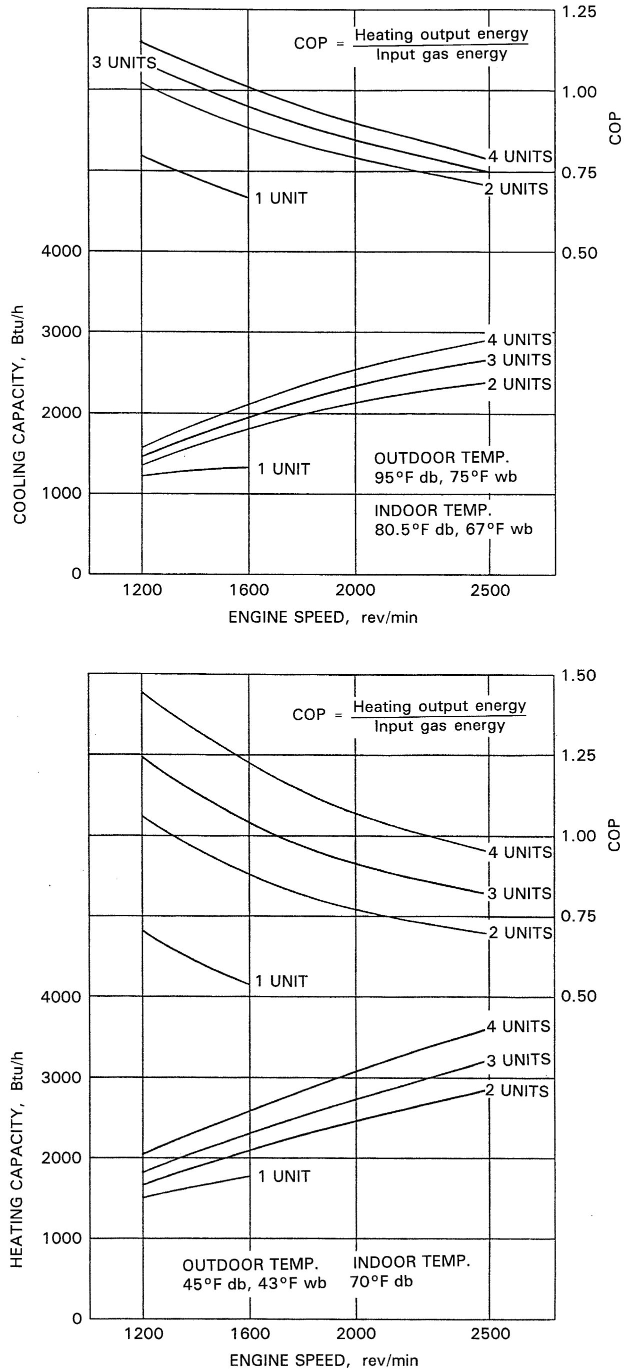

Fig. 12 Performance Characteristics of Multisplit Engine-Driven Heat Pump

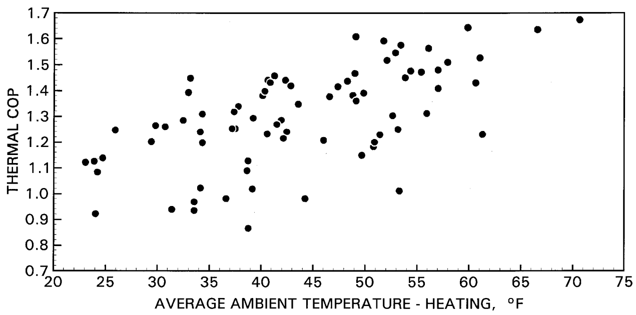

Fig. 13 Field Test Heating Performance (One Site)

indoor units. Heating and cooling capacities increase with increased engine speed and indoor fan speed. Efficiency, measured in terms of COP, is a strong function of outdoor temperature (COP is defined as the heating or cooling energy output divided by the energy input). As illustrated by the heating mode field test data in Figure 13, part-load operation at moderate ambient temperature yields the highest COP (GRI 1993). The same trend is true in the cooling mode; COP decreases as ambient temperature increases. Supplemental heating may be required in areas with severe cold climates, but it is not necessary in most climates if jacket and exhaust heat are used.

ENGINE HEAT REJECTION AND RECOVERY

An important feature of the engine-driven heat pump is the ability to recover heat energy from the engine jacket water and exhaust gas. In a two-pipe system in the heating mode, heat recovered from the engine is transferred to the refrigerant circuit through a double-walled heat exchanger, thus increasing the temperature and heat energy of the refrigerant. In a four-pipe system, a separate coolant circuit transports engine heat recovered through an exhaust gas-to-coolant recuperator in the outdoor unit to a coolant-to-air heat exchanger located in the indoor unit(s), thus increasing the heating capacity of the system.

Recovering engine heat increases the system heating output by as much as 25%. Due to the increased heating capacity and load matching with variable-speed capabilities, the balance point at which supplemental heating is required is 10 to 15°F lower than that of conventional, single-speed, air-source heat pumps.

In the cooling mode in a two-pipe system, engine heat is transferred to the refrigerant through the same double-walled heat exchanger used in the heating mode. The heat is then rejected through the outside heat exchanger along with heat carried by the refrigerant from the indoor air. In a four-pipe system, engine heat is transferred to a coolant loop connected to a second heat exchanger in the outside unit, where it is then rejected to the outside air.

MAINTENANCE AND SERVICE

Special maintenance tasks include checking oil and coolant levels, belt tension, and valve clearance; and changing spark plugs, oil, and air filters. A typical engine maintenance schedule is shown in Table 6. Maintenance intervals and tasks should follow those specified by the equipment manufacturer. Maintenance tasks should be performed by a trained service technician.

CONTROLS AND INSTALLATION

The installation should follow the manufacturer's instructions. Because the supply air from a heat pump is usually at a lower temperature (typically 90 to 100°F) than most heating systems, ducts and supply registers should control air velocity and throw to minimize the perception of cool drafts.

Table 6 Typical Maintenance Schedule for Engine-Driven Gas Heat Pump

	Recommendations	
Items	**Check**	**Change**
Oil level	—	1 year
Oil filter	—	1 year
Coolant level	1 year	5 years
Air filter	—	1 year
Spark plug	—	1 year
Valve clearance[a]	1 year	—
Indoor unit air filter	1 month	6 months

[a]Not necessary if engine is equipped with hydraulic valve lifters.

Low-voltage heating/cooling thermostats control heat pump operation. Models that switch automatically from heating to cooling operation and manual selection models are available. Usually, heating is controlled in two stages. The first stage controls heat pump operation, and the second stage controls supplementary heat. When the heat pump cannot satisfy the first stage's call for heat, supplementary heat is added by the second-stage control. The amount of supplementary heat is often controlled by an outdoor thermostat that allows additional stages of heat to be turned on only when required by the colder outdoor temperature.

Microprocessor technology has led to night setback modes and intelligent recovery schemes for morning warm-up on heat pump systems (Chapter 46 of the *ASHRAE Handbook—Applications* has further information).

A standard method of defrost is to briefly reverse the refrigeration cycle to send hot refrigerant gas through the outside heat exchanger to defrost the coil. For a two-pipe system with engine heat recovery, the defrost frequency is reduced because the average temperature in the outdoor unit's heat exchanger is higher. A hot-coolant defrost strategy uses a second heat exchanger located adjacent to the outdoor unit's heat exchanger. Coolant that has picked up heat from the engine is circulated through the secondary heat exchanger to defrost the main refrigerant heat exchanger.

In a four-pipe system, simultaneous heating and cooling can be used to counteract problems with cold air delivery during defrost operation. In defrost mode, the refrigerant cycle is reversed and operated in the cooling mode, providing hot refrigerant gas to the outdoor coil. The coolant loop between the indoor and outdoor units continues to operate in the heating mode, offsetting any cooling effect experienced due to the reversed refrigerant cycle.

DESIGN AND APPLICATION ISSUES

Heat pump yearly operating hours are often up to five times those of a cooling-only unit. In addition, heating extends over a greater range of operating conditions at higher stress conditions, so the design must be thoroughly analyzed to ensure maximum reliability. Improved components and protective devices contribute to better reliability, but the equipment designer must select components that are approved for the specific application.

For a reliable and efficient heat pump system, the following factors must be considered: (1) outdoor coil circuitry, (2) defrost and water drainage, (3) refrigerant flow controls, (4) refrigerant charge management, and (5) compressor selection.

Outdoor Coil Circuitry

The outdoor coil operates as an evaporator when the heat pump is used for heating. The refrigerant in the coil is less dense than when the coil operates as a condenser. To avoid an excessive pressure drop during heating, the circuitry is usually a compromise between optimum performance as an evaporator and optimum performance as a condenser.

Defrost and Water Drainage

During colder outdoor temperatures, usually below 40 to 50°F, and high relative humidities (above 50%), the outdoor coil operates below the frost point of the ambient air. The frost that forms on the surface of the coil is usually removed by the reverse-cycle defrost method. In this method, the refrigerant flow in the system is briefly reversed, and hot gas from the compressor flows through the outdoor coil, melting the frost. A typical defrost takes 4 to 10 min. The outdoor fan is normally off during defrost. Because the defrost is a transient process, capacity, power, and the pressures and temperatures of refrigerant in different parts of the system change throughout the defrost period (Miller 1989, O'Neal 1989a).

The performance of the heat pump during the defrost cycle can be enhanced in several ways. Improved defrost times and water removal can be achieved by ensuring that adequate refrigerant is routed to the lower refrigerant circuits in the outdoor coil. Properly sizing the defrost expansion device is critical for shorter defrost times and reducing energy use (O'Neal 1989b). If the expansion device is too small, suction pressure can be below atmospheric, defrost times become long, and energy use is high. If the expansion device is too large, the compressor can be flooded with liquid refrigerant. During the conventional reverse-cycle defrost, there is a significant pressure spike at defrost termination. Prestarting the fan 30 to 45 s before defrost termination can minimize the spike (Anand et al. 1989). In cold climates, the cabinet should be installed above grade to provide good drainage during defrost and to minimize snow and ice buildup around the cabinet. During prolonged periods of severe weather, it may be necessary to clear ice and snow from around the unit.

Several methods are used to determine the need to defrost. One of the more common, simple, and reliable control methods is to initiate defrost at predetermined time intervals (usually 90 min). Demand-type systems detect a need for defrosting by measuring changes in air pressure drop across the outdoor coil or changes in temperature difference between the outdoor coil and the outdoor air. Microprocessors are applied to control this function, as well as numerous other functions (Mueller and Bonne 1980). Demand defrost control is preferred because it requires less energy than other defrost methods.

Refrigerant Flow Controls

Separate refrigerant flow controls are usually used for the indoor and outdoor coils. Because the refrigerant flow reverses its direction between the heating and cooling mode of operation, a check valve bypasses in the appropriate direction around each expansion device. Capillaries, fixed orifices, thermostatic expansion valves, or electronically controlled expansion valves may be used; however, capillaries and fixed orifices require that greater care be taken to prevent excessive flooding of liquid refrigerant into the compressor. A check valve is not needed when an orifice-type expansion device or a biflow expansion valve is used. The reversing valve is the critical additional component required to make a heat pump air-conditioning system.

Refrigerant Charge Management

Refrigerant charge management requires extra care to control compressor flooding and the storage of refrigerant in the system during both heating and cooling. The mass flow of refrigerant during cooling is greater than during heating. Consequently, the amount of refrigerant stored may be greater in the heating mode than in the cooling mode, depending on the relative internal volumes of the indoor and outdoor coils. Usually, the internal volume of the indoor coils ranges from 70 to 110% of the outdoor coil volume. The relative volumes can be adjusted so that the coils not only transfer heat but also manage the charge.

When using capillaries or fixed orifices, the refrigerant may be stored in an accumulator in the suction line or in receivers that can remove the refrigerant charge from circulation when compressor floodback is imminent. Thermostatic expansion valves reduce the flooding problem, but storage may be required in the condenser. Use of accumulators and/or receivers is particularly important in split-system products.

To maintain performance reliability, the amount of refrigerant must be checked and adjusted in accordance with the manufacturer's recommendations, particularly when charging a heat pump. Manufacturer's recommendations for accumulator installation must also be followed so that good oil return is assured.

Compressor Selection

Compressors are selected on the basis of performance, reliability, and probable applications of the unit. In good design practice, equipment manufacturers often consult with compressor manufacturers during both design and application phases of the unitary equipment to verify proper application of the compressor. Compressors in a heat pump operate over a wide range of suction and discharge pressures; thus, their design parameters, such as refrigerant discharge temperatures, pressure ratios, clearance volume, and motor-overload protection require special consideration. In all operating conditions, compressors should be protected against loss of lubrication, liquid floodback, and high discharge temperatures.

REFRIGERATION EQUIPMENT

Engine-driven refrigeration equipment use the same mechanical vapor compression cycle as the engine-driven chillers discussed previously. This equipment is available from various manufacturers as custom and/or standard packaged products. Although engine-driven chillers are typically not operated to deliver fluid temperatures below 40°F, some manufacturers allow chillers with screw compressors to be operated to temperatures as low as 10°F. Figure 14 shows a typical effect of low temperature operation on the chilling capacity and energy input to the machine.

Because refrigeration equipment operates at low evaporator temperatures (+20 to –70°F), refrigerants such as ammonia and other cycles that provide improved efficiency over single-stage cycles are used. Besides the standard, single-stage vapor compression cycle, a multistage refrigeration cycle or cascade refrigeration cycle may be chosen. The multistage cycle is the most common cycle used to efficiently provide refrigeration from –10 to –70°F. The section on

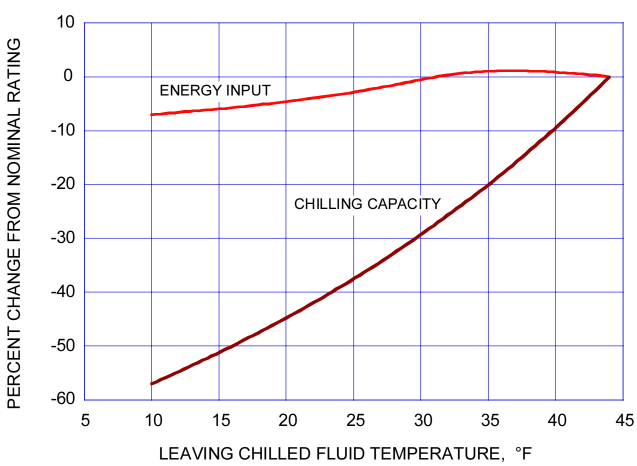

Fig. 14 Effect of Low Temperature Chilling on Nominal Rating of Engine-Driven Chiller with Screw Compressor

Table 7 Typical Efficiency of Engine-Driven Refrigeration Equipment (Ammonia Screw Compressor) (AGCC 1999)

	Sat. Suction Temp./Sat. Discharge Temp.		
	–40/95°F	–12/95°F	+20/95°F
Electric COP	1.32	2.66	4.62
Engine-driven COP without heat recovery	0.44	0.78	1.32
Engine-driven COP with jacket water heat recovery	0.74	1.08	1.62
Engine-driven COP with jacket water and exhaust heat recovery	0.89	1.23	1.77

Compression Refrigeration Cycles in Chapter 1 of the *ASHRAE Handbook—Fundamentals* describes this cycle.

A cascade system is used when two (or more) refrigerants in the same system provide an operating and/or capital cost advantages. Chapter 38 and Chapter 39 of the *ASHRAE Handbook—Refrigeration* describe cascade cycles in more detail.

As was the case with engine-driven chillers, heat recovery from the jacket coolant and exhaust gas boosts overall energy use and efficiency. Table 7 lists the coefficient of performance and impact of heat recovery for a range of conditions found in the industry.

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