CHAPTER 36

REFRIGERATION IN THE CHEMICAL INDUSTRY

CHEMICAL industry refrigeration systems range in capacity from less than one ton of refrigeration to thousands of tons. Temperature levels range from those associated with chilled water through the cryogenic range. The degree of sophistication and interrelation with the chemical process ranges from that associated with comfort air conditioning of laboratories or offices to that where the production of reliable refrigeration is vital to product quality or to the safety of the operation.

Two significant characteristics identify most chemical industry refrigeration systems: (1) almost exclusively, they are engineered one-of-a-kind systems, and (2) equipment used for normal commercial application may be unacceptable for chemical plant service.

This chapter gives guidance to refrigeration engineers in working with chemical plant designers so they can design an optimum refrigeration system. Refrigeration engineers must be familiar with the chemical process for which the refrigeration facilities are being designed. An understanding of the overall process is also desirable. Computer programs are also available that can calculate cooling loads based on the gas chromatographic analysis of a process fluid. These programs accurately define not only the thermodynamic performance of the fluid to be chilled, but also the required heat transfer characteristics of the chiller.

Occasionally, because the process is proprietary, refrigeration engineers may have limited access to process information. In such cases, chemical plant design engineers must be aware of the restrictions this may place on providing a satisfactory refrigeration system.

FLOW SHEETS AND SPECIFICATIONS

The starting point in attaining a sound knowledge of the chemical process is the flow sheet. Flow sheets serve as a road map to the unit being designed. They include such information as heat and material balances around the major system components and pressures, temperatures, and composition of the various streams within the system. Flow sheets also include refrigeration loads, the temperature level at which refrigeration is to be provided, and the manner in which refrigeration is to be provided to the process (such as via a primary refrigerant or via a secondary coolant). They indicate the nature of the chemicals and processes to be anticipated in the vicinity in which the refrigeration system is to be installed. This information should indicate the need for special safety considerations in the design of the refrigeration system or for construction materials that resist corrosion by process materials or process fumes.

Different portions of a process flow sheet may be developed by different process engineers; consequently, the temperature levels at which refrigeration is specified may vary by only a few degrees. A study of such a situation might reveal that a single temperature is satisfactory for several or even all of the users of refrigeration, which could reduce project cost by eliminating multilevel refrigeration facilities.

Most process flow sheets indicate the design maximum refrigeration load required. The refrigeration engineer should also know the minimum design load. Process loads in the chemical industry tend to fluctuate through a wide range, creating potential operational problems.

Flow sheets also indicate the significance of the refrigeration system to the overall process and the desirability of providing redundant systems, interlocking systems, and so forth. In some cases, refrigeration is mandatory to ensure safe control of a process chemical reaction or to achieve satisfactory product quality control. In other cases, loss or malfunction of the refrigeration system has much less significance.

Other sources of information are also valuable. A properly prepared set of specifications and process data expands on flow sheet information. These generally cover the proposed process design in much more detail than the flow sheets and may also detail the mechanical systems. Information regarding the design principles, including continuity of operation, safety hazards, degree of automation, and special start-up requirements, is generally found within the specifications. Equipment capacities, design pressures and temperatures, and materials of construction may be included. Specifications for piping, insulation, instrumentation, electrical, pressure vessels and heat exchangers, painting, and so forth are normally issued as part of the design package available to a refrigeration engineer.

It is imperative that refrigeration engineers establish effective communication with chemical process engineers. The refrigeration engineer must know what information to request and what information to give to the chemical process engineer for design optimization. The following sections outline some of the significant characteristics of chemical industry refrigeration systems. A full understanding of these peculiarities is of value in achieving effective communication with chemical plant designers.

REFRIGERATION—SERVICE OR UTILITY

Refrigeration engineers unfamiliar with the chemical industry must understand that unless the chemical process is cryogenic in nature, chemical plant designers probably consider refrigeration merely as a service or utility of the same nature as steam, cooling water, compressed air, and the like. Chemical engineers expect the reliability of the refrigeration to be of the same quality as other services. When a steam valve is opened, chemical engineers expect steam to be available instantly, in whatever quantities demanded. When steam is no longer required, the engineer expects to be able to shut off the steam supply at any time without adversely affecting any other steam user or the source of steam. The same response from the refrigeration system will be expected. This high degree of reliability is usually so strongly implied that no specific mention of it may be made in specifications.

Because refrigeration is frequently considered a service, process designers spend insufficient time analyzing temperature levels, potential load combinations, energy recovery potentials, and the like. The potential for minimizing the size of the refrigeration system, the total plant investment, or both, by providing refrigeration at

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a minimum number of temperature levels, is frequently not investigated by process engineers. Likewise, the potential for power recovery is frequently overlooked.

Part of the reason for this attitude is that refrigeration facilities represent only a minor part of the total plant investment. The entire utilities installation for the chemical industry usually falls in the range of 5 to 15% of the total plant investment, with the refrigeration system only a small portion of the utilities investment. Process requirements may be overruling, but process engineers must recognize legitimate process necessities and avoid unnecessary and costly restrictions on the refrigeration system design.

LOAD CHARACTERISTICS

Flow sheet values generally indicate direct process refrigeration requirements and do not include heat gains from the equipment or piping. Flow sheet peaks and average loads generally do not allow for unusual start-up conditions or off-normal process operation that may impose unusual refrigeration loads. This information must be gained by a thorough understanding of the process and by discussing the potential effect on refrigeration system design for off-normal process conditions with the process engineer.

Once the true peak loads are established, the duration and frequency of the peaks must be considered. For some simple processes this information is fairly straightforward; however, if the plant is designed for both batch operation and multiproduct manufacture, this can be an enormous task. Computer simulation of such a combination of processes has led to optimization of not only the refrigeration equipment but also the process equipment. Computer simulation ensures that the refrigeration machine, secondary coolant storage tanks, and circulating pumps are properly sized to handle both average and peak loads with a minimum investment. Few applications require computer simulation, but a thorough understanding of the relationship of peak loads to average loads and their influence on refrigeration system component sizing is vital to good design.

Sometimes unusually light load conditions must be met. If the process is cyclic and an on-off operation is undesirable, the refrigeration system may run for significant periods under a very light load or even a no-load condition. Light loads often require special design of the system controls, such as multistep unloading and hot-gas bypass with reciprocating compressors, a combination of suction throttling or prerotation vanes and hot-gas bypass with centrifugal compressors, and slide valve unloading and hot-gas bypass with screw compressors. A secondary coolant system might require a bypass arrangement.

The investment in refrigeration equipment can be kept to a minimum when only a few levels of refrigeration are required. Checking the specified temperatures to be sure they are based on some process requirement may show that fewer temperature levels than shown on the flow sheet are necessary. If multiple levels of refrigeration are required, a compound system should be evaluated. The evaluation must consider the limited ability of a compound system to provide the precise temperatures required of some processes.

Production Philosophy

The specifications generally indicate whether a chemical process is in continuous or batch operation, but further research may be required to understand the required continuity of service for the refrigeration facilities. The chemical industry frequently requires a high degree of continuity; plant production rates are often based on 8000 h or more per year. In general, the refrigeration equipment is worked extremely hard, with no off-peak period because of seasonal changes, and any unscheduled interruption of refrigeration service may create large production losses. In most cases, scheduled maintenance shutdowns are not only infrequent but also highly vulnerable to cancellation or delays because of production requirements.

As a result, reliability is key in the design of chemical industry systems. Equipment that is satisfactory in commercial or light industrial service is frequently unfit where high service rates and minimum availability for maintenance are the rule. In some cases, duplicate systems are justified. More often, multiple part-capacity units are installed so that a refrigeration system breakdown will not create a total process production loss. Major equipment and hardware items that require minimal maintenance or that permit maintenance with the refrigeration system in operation should be selected (for instance, dual lube oil pumps, oil filters, and in many cases dual oil coolers, compressors, and bypasses around control valves to allow operation during service of control valve and other components; many systems are built to American Petroleum Institute (API) specification. Particular attention should be paid to equipment layout, so that adequate access, tube pullout space, and laydown space are available to minimize refrigeration system maintenance time. In some cases, overhead steel supports for rigging heavy equipment, or permanent monorails, are justifiable.

Flexibility Requirements

The chemical industry constantly develops new processes; consequently, the usual chemical plant undergoes constant modification. On occasion, total processes are rendered obsolete and scrapped before design production rates are ever reached. Thus, flexibility should be designed into the refrigeration system so it may be adaptable to some process modification. Designing for optimum flexibility is difficult; however, a study of the potentials or probabilities of process modifications and of the expected life of the process facility will help in making design decisions.

SAFETY REQUIREMENTS

Most chemical processes require special design to ensure safe operation. Many raw materials, intermediates, or finished products are themselves corrosive or toxic or are potential fire or explosion hazards. Frequently, the chemical reactions involved in the process generate extremes of pressure or temperature that must be properly contained for safe operation. Refrigeration engineers must be aware of these potential hazards as well as any abnormal hazards that may develop during start-up, unscheduled shutdown, or other upset within the chemical process. When designing modifications or expansions for an existing facility, the possibility that certain construction or maintenance techniques may be safety hazards must be considered.

Corrosion

The shell, tubes, tube sheets, gaskets, packing, O rings, seal materials, and components of instrument or control hardware must be properly specified. The potential hazards of leakage between the normal process side and the refrigeration side of heat exchange equipment must be investigated, because an undesirable chemical reaction may occur between the process material and the refrigerant.

An additional corrosive hazard may result from leaks, spills, or upsets within the process area. Safe chemical plant design must anticipate the unusual as well as the usual hazards. For example, if refrigerant piping will run adjacent to a flanged piping system containing a highly corrosive material, special materials for the piping and insulation systems may be justified.

Toxicity

If the refrigeration system indirectly contacts a toxic material via heat exchange equipment, flanges and such elements as gaskets, packing, and seals in direct contact with the toxic material must be designed carefully. The possibility of a leak in equipment that might allow refrigerants or secondary coolants to mix with process chemicals and cause a toxic or otherwise dangerous reaction must also be considered. In some cases, the potential for toxic leaks may be so high that a special ventilation system may be required, double tube sheets are used, or the tubes are welded and rolled into the tube sheets of shell-and-tube heat exchangers. Intermediate reboilers may also be used to isolate the process.

Even though containment and ventilation can handle toxic materials under normal process conditions, toxic material may need to be vented in abnormal situations to avoid the hazards of fire or explosion. In such cases, the toxic material is frequently vented or diluted through a flare stack so that ground or operating level concentrations do not reach toxic limits. Refrigeration engineers should evaluate the desirability of locating the refrigeration equipment itself or its controls outside the operating areas. An alternative is to ventilate either the refrigeration system or its controls with a system that has a remote air intake.

The hazards of toxicity are not confined to the chemical process itself. Some common refrigeration chemicals are toxic in varying degrees. Because of the chemical industry's interest in safety, refrigeration engineers are required to treat some of the common refrigerants and secondary coolants with much more caution than required for the usual commercial or industrial system.

Fire and Explosion

Plant specifications normally define the area classifications, which determine the need for special enclosures for electrical equipment. For areas designated as being in an explosionproof environment, standard components are grouped in a single large explosionproof cabinet. Intrinsically safe control systems, which eliminate the need for explosionproof enclosures at all end devices, are also used. Intrinsically safe shutdown systems eliminate arcing at the end device by using low-voltage signals controlled by a microprocessor. Control equipment can also be mounted in standard or weatherproof cabinets and kept at a positive pressure with an inert gas purge system.

Items other than the electrical system may require special consideration in areas of high fire or explosion hazard. The use of flammable materials should be carefully reviewed. Stainless steel instrument tubing should be chosen rather than unprotected plastic tubing, for example. Both insulation materials and insulation finish systems should minimize flame spread in the event of a fire. In some extremely hazardous areas, nonflammable refrigerants or secondary coolants may be required, rather than flammable materials that would provide otherwise superior performance.

In areas of high explosion potential, modification of the usual refrigeration system design may be required. Design pressures for refrigeration vessels or piping may be determined by process considerations as well as refrigeration system requirements. Special pressure relief systems, such as rupture disks in series with relief valves, dual full-sized relief valves, or a parallel relief valve and rupture disk with transfer valves between them, are often required, using API relief valves.

Refrigeration System Malfunction

A malfunction can itself be a significant safety hazard, whether the upset is caused by an internal failure of the system or by fire, explosion, or some other catastrophe. Some process areas designated as being in a hazardous environment are protected by automatic gas-detection systems that shut down the refrigeration system when explosive mixtures are detected in an area. Loss of refrigeration may permit a process reaction to run out of control and cause loss of product, fire, explosion, or the release of toxic material in an area remote from the original source of trouble. Thus, one or several degrees of redundancy may be needed to minimize the consequence of refrigeration system malfunction.

Storage of cold coolant, ice, or cold eutectic, or an alternative emergency supply of cooling water may be necessary to meet emergency peaks. Alternative sources of electric power to the refrigeration system may be desirable. Dual drive capability by either electric motor or steam turbine might even be justified. Uninterruptible power systems may also be used for control systems.

Frequently, special facilities are used to protect against the extreme consequences of refrigeration system malfunction. One example is the quenching of the process reaction by an inhibiting or neutralizing chemical introduced to the process in the event of an unusual pressure or temperature rise. Another simpler and more common example requires closing one or more process valves in the event of a loss of refrigeration.

Maintenance

In an operating chemical plant, because of hazards frequently encountered, the normal maintenance procedures may not be permitted. Because welding, burning, or the use of an open flame is often prohibited throughout large areas of a chemical plant, maintenance flanges or screwed connections are used to permit replacement of piping and equipment. Sometimes extra access space or handling facilities (such as monorails) are provided to permit efficient removal of machinery to an area where welding, burning, and the like is permitted.

EQUIPMENT CHARACTERISTICS

Automation

In chemical plant operations, instrumentation represents a significant percentage of the plant investment. For this reason, most chemical plant designers insist on standardization of instrumentation throughout the plant. These requirements may not include familiar refrigeration components and may create problems in the refrigeration design. Therefore, it is vital that the refrigeration engineer and the chemical or instrumentation engineer agree on the instrument requirements early in the design phase.

A second concept frequently adopted is the control and monitoring of all plant operation from a single central control room. It is not unusual to operate a multimillion-dollar processing facility with two central control room operators and perhaps a single roving operator. This concept influences the refrigeration system in several ways. Refrigeration system controllers and alarm and shutdown lights are mounted in the distributive control system (DCS) panel, as are recorders or indicators that display refrigeration system temperatures, pressures, flows, and so forth.

Even with DCS operation, a local panel is required for starting, stopping, displaying, or recording additional information that can aid in troubleshooting an emergency shutdown. Frequently, start-up control is available only at this local panel, to ensure that start-up is not attempted unless an operator is present to witness the operation of major items of refrigeration equipment. The DCS-mounted hardware should certainly conform to the standards of the process instrumentation to minimize operator confusion either in reading informative devices or in operating control devices. Most plants now use centralized computer or microprocessor controls. In most cases, the refrigeration unit is controlled from the local PLC or microprocessor.

When applying a DCS concept, it is important to determine exactly how much information and control are to be provided at the control room and how much are to be provided locally. Transmission of unnecessary information to the DCS can be costly, but if sufficient information is not available, serious process upsets are inevitable. Most process operators are not trained to understand the intricacies of refrigeration machinery. The DCS system must permit monitoring of the refrigeration system performance and control of that performance to suit process needs.

Operators require alarms to indicate abnormal conditions for which they can make corrections, either at the DCS or in the field, and to indicate a system malfunction or shutdown. They also require a locally mounted manual shutdown station in the event of an emergency. Devices such as sequencing alarms and lube oil or bearing temperature recorders, which are troubleshooting aids, can be checked or logged by the local PLC.

Designing for a minimum of operator attention with personnel who are not refrigeration specialists is yet another reason that a high degree of reliability is required for a chemical industry refrigeration system.

Outdoor Construction

Another chemical industry characteristic is outdoor construction. The chemical industry installs sophisticated process and auxiliary facilities outdoors all over the world. Whether the problems are those imposed by low temperatures, heavy snows and freezing rain, dust storms, baking heat, or hurricane-force winds with salt-laden rains, they are generally unfamiliar to the uninitiated refrigeration engineer. For example, explosionproof electrical construction is not necessarily weather resistant. Lube oil heaters and a prestart-up circulation of heated lube oil may be required for compressors or other rotating machinery. In areas with high winds, special attention must be paid to the detailed installation instructions for insulation jacketing applied to pipe or vessels.

Winter operation of cooling towers may require multiple-cell construction, two-speed or reverse rotation cooling-tower fans, or even facilities for steam heating the cooling-tower basin. Instrument air for transmission of signals or power to pneumatic operators should be dried to a dew point (under pressure conditions) lower than anticipated ambient conditions to avoid condensate or ice from forming in the instrument air lines or in the instruments themselves. In fact, the almost-standard expectation is that the instrument air provided is both oil-free and dried to a low dew point. The effect of ambient temperature, as well as radiation from the sun, should be considered in determining system design pressures, especially when equipment may be idle. Ambient temperatures up to 120°F and vessel skin temperatures of 165°F can be experienced in hot climates. To determine whether purchased equipment meets the requirements for outdoor installation, a detailed check of vendors' drawings, specifications, descriptive literature, and vendor-procured components is required.

Energy Recovery

Both the installed cost and the operating costs for the refrigeration system of some chemical processes can be reduced by the intelligent use of energy recovery techniques. If the process requires large quantities of low-pressure steam, the use of back-pressure turbines to drive the refrigeration compressors could significantly reduce refrigeration system energy costs. On the other hand, if the process generates an excess of low-pressure steam, an absorption system may provide an overall saving. For processes with an excess of low-pressure steam only during the summer months when heating requirements are at a minimum, a condensing turbine may be economical if it is sized to operate at the low steam pressure when the excess is available and at a higher pressure during the heating season.

Other energy imbalances occurring within a chemical process can be advantageous. A waste heat boiler installed in a high-temperature gas stream may provide a source for low-cost steam. If the gas stream is at a moderate pressure as well as a high temperature, the possibility of a gas-driven power recovery turbine should be considered.

Another means by which operating costs frequently can be reduced is the reuse of once-through cooling water. Frequently, turbine-driven centrifugal refrigeration machines can use cooling water from the refrigerant condenser to condense the turbine exhaust steam, either in a shell-and-tube or a low-level jet condenser. Another possibility is the reuse of refrigeration system cooling water in process heat exchangers. Again, a thorough understanding of the process is a prerequisite for understanding the energy recovery potential, and a flow sheet should be helpful.

Performance Testing

Frequently, a requirement for performance testing of the refrigeration facilities is included within the contract for a chemical industry processing unit. Agreement should be reached as early as possible between the owner and the contractor regarding the exact procedure to be used for testing. If the test is to be run at some condition other than design conditions, both parties must agree on the methods of converting the test results to design conditions. Approximation techniques, such as those outlined in Air-Conditioning and Refrigeration Institute (ARI) *Standard* 550, are usually unacceptable in the chemical industry. The refrigeration engineer must be ensured that adequate facilities for an equitable test are designed into the refrigeration system. This may require additional flow-metering devices or more accurate temperature-measuring devices than are required for normal plant operation.

Insulation Requirements

The service conditions imposed by the chemical industry on both piping and equipment insulation are frequently more exacting than those experienced in the usual commercial or industrial installation. Not only must the initial integrity be as near perfect as possible, but it must also resist the high degree of both physical and chemical abuse that it is likely to incur during its lifetime. To achieve both a minimum permeability and a maximum resistance to abuse, multi-component finish systems may be required. In some cases, a vapor barrier mastic coating system (which usually includes reinforcing cloth) is covered with aluminum, stainless steel, or an epoxy-coated carbon steel jacket to protect against physical and chemical abuse. Piping and equipment insulated under ideal shop working conditions must be designed to withstand loading and unloading and erecting into position on the job site without damaging the vapor barrier.

Because the fire hazard is generally high and the potential loss of personnel and investment resulting from a fire is prohibitive, a strict limit is usually placed on insulation systems having a high flame-spread rating, particularly in indoor construction.

The frequent use of stainless steel in the chemical industry for piping and equipment creates another problem with regard to insulation system design. Many stainless steels fail when they are exposed to chlorides. Stress corrosion cracking can occur in a matter of hours. Consequently, chloride-bearing insulation materials must not contact stainless steels even in minute quantities and should not be used anywhere in the system unless a valid vapor retarder is interposed. Chapter 24 of the *ASHRAE Handbook—Fundamentals* and Chapter 32 of this volume cover the general subject of thermal insulation and water vapor retarders.

Nonflammable insulation material is usually used, such as foam glass (even though it has a much lower resistance to heat flow).

Design Standards and Codes

Relatively few suppliers of refrigeration equipment regularly manufacture to meet codes or standards that apply to the chemical industry. Another variation from commercial or industrial design practice is the use of company standards. For the usual commercial or industrial plant, the client will at best provide performance specifications and a statement of what is to be done, leaving the preparation of detailed specifications for equipment, piping, ducting, insulation, and painting to the designer. However, many such items are covered by company standards, which, though established primarily for use in the process cycles, can yield corporate benefits if they are also used in design of the refrigeration systems. A request for all applicable company standards at the start of the design and an effort to use them will avoid costly rework of the design following a review by the client.

START-UP AND SHUTDOWN

Processes are most hazardous during start-up and shutdown. Although present in batch or discontinuous processing units, the problem is usually more severe in continuously operating units for the following reasons:

- Instrumentation and control must be designed for the normal condition, and the cost of features intended for use only during start-up or shutdown often cannot be justified. Frequently, conditions at start-up or shutdown fall outside the range of the operating instruments and control, so that manual control is necessary.
- The same argument holds for much of the process equipment, so that extraordinary measures, such as severely throttled flow, minimum-flow bypasses, and recycling may be needed.
- The operators go through these conditions only infrequently and may have forgotten the techniques of operation at the time they are most needed.
- The process conditions at start-up and shutdown are usually not recorded on flow sheets or in descriptions because they occur so infrequently and usually vary continually as the units are brought on and off stream. Consequently, designers tend to overlook them and concentrate on the conditions in the operating range.

Refrigeration engineers must inquire whether start-up or shutdown is likely to impose any special conditions on the refrigeration system. Start-up and shutdown is a special burden in this respect, since operators are particularly busy with the processing equipment and cycle during these times and generally cannot monitor or adjust the operation of what they regard as a service system. Therefore, process engineers must be made thoroughly aware of the precise limitations that start-up or shutdown of the refrigeration system may impose on process operation.

REFRIGERANTS

Such factors as flammability, toxicity, and compatibility with proposed construction materials may influence the final selection of a refrigerant more than in other applications. Special attention should be paid to the consequences of leakage between the process materials and the refrigerant or the secondary coolant. Chapters 19 and 21 of the *ASHRAE Handbook—Fundamentals* discuss refrigerants and secondary coolants in detail.

In addition to traditional refrigerants, other refrigerants used in the petrochemical industry are hydrocarbons. Produced in many refineries and readily available, they are very good refrigerants, but are flammable. When hydrocarbons are used as a refrigerant in a plant, the area around the system is process-classified as flammable. The most common hydrocarbon refrigerants are propane, propylene, ethane, and ethylene; they are used in many cases where the process stream involves them as constituents. A number of cryogenic processes use a mixed hydrocarbon cycle.

Because of their nontoxic, nonflammable properties, halogenated hydrocarbons have been used predominantly, but recent environmental concerns have reduced their application throughout the chemical industry.

Of the secondary coolants, calcium and sodium chloride brines have been used most often, although glycols and such halocarbons as methylene chloride, trichloroethylene, R-11, and R-12 also have been frequent choices. Again, environmental concerns predicate against the use of R-11 and R-12 in new facilities.

Many of the same factors that influence refrigerant selection must be considered in choosing a secondary coolant. Corrosivity, toxicity, and stability are of special significance in determining suitability for chemical plant service.

REFRIGERATION SYSTEMS

An indirect system, in which brine or chilled water is circulated to air washers, cooling coils, and process heat exchangers from a central refrigeration plant, is much more prevalent in the chemical industry than in the food industry or in residential or light commercial comfort air conditioning. This is particularly true where large capacities or low temperature levels are involved. An indirect system permits centralization of the refrigeration equipment and associated auxiliaries, which may offer significant advantages in operation and maintenance, particularly if remote location of the refrigeration equipment permits design, operation, and maintenance in a nonhazardous location. It also may permit the installation of a minimum number of large units rather than many small units located in remote areas. For low-temperature systems of significant capacity, an indirect brine cooling system installed in the process area close to the process users is common.

Where the number of process heat exchangers requiring cooling and the length of piping can be kept to a minimum, a direct system, which uses the refrigerant in the process heat exchange equipment, often is the optimum design, particularly for small or medium loads. Because an indirect heat exchanger is not required in this case, a higher operating suction pressure and consequent lower operating and investment costs may be possible. Direct systems are also used when a refrigerant is involved in the manufacturing process stream, as in the production of ammonia or many petrochemicals. Here, the length of refrigerant lines, with possible high refrigerant losses because of leakage, is a less significant factor in system selection. Direct systems are usually of the flooded evaporator design; flooded coil systems of the gravity feed or pumped liquid overfeed design are relatively uncommon.

Direct systems for larger-capacity, low-temperature, multiple-user service have advantages and disadvantages that must be considered for proper system selection. Some of the disadvantages are the following:

- Maintaining an extensive refrigeration piping system free of leaks is difficult. Leakage from piping for secondary coolants is frequently less objectionable than the refrigerant gases. Checking for refrigerant leaks or repairing them in certain high explosion hazard process areas can be a problem because electronic leak detectors may not be permitted and burning or welding may not be possible without a plant shutdown. If air or moisture leaks into a system operating at vacuum conditions, extensive icing and corrosion problems can result.
- Higher piping costs are often involved when all items are considered, including large and expensive vapor and liquid-control valves at individual heat exchangers. Generous refrigerant knockout separators are necessary at each stage. Both refrigerant and secondary coolant lines require insulation to prevent capacity losses, sweating, and icing. Refrigerant lines are about the same size as vapor return to the compressor.
- No system reserve capacity is available as is the case with a secondary coolant, particularly if the latter is designed as a storage system. Process upsets can directly and suddenly increase the load on the refrigeration unit, causing rapid cycling of the equipment. For some processes, meeting short, sharp load peaks is of paramount importance to avoid off-standard quality and unsafe operating conditions.
- Constant temperature control is sometimes more difficult or costly to maintain with direct refrigeration than with a secondary coolant.
- Initial pressure testing of an extensive direct refrigeration system may be a significant problem. Testing must be done pneumatically rather than hydrostatically to prevent problems associated with water left in the refrigerant system. Pneumatic testing is considered a hazardous operation and is avoided where possible in some

chemical plants. The alternative of extensive posttesting dehydration is usually both expensive and time consuming.
- The initial cost for refrigerants is usually much lower in a system using hydrocarbons in an extensive direct refrigeration system than in a secondary coolant system operating at temperatures most frequently encountered in the chemical industry. In the case of system leaks, the costs of makeup coolant are generally about the same as the costs of makeup primary refrigerant.

Some of the advantages offered by direct refrigeration systems include the following:

- Careful control of corrosion inhibitors may be necessary to keep secondary coolants stable so that they do not cause extensive equipment damage.
- Less equipment and maintenance may be required; secondary coolant circulation and control or coolant mixing and makeup facilities are not needed.
- Power costs are generally lower because of higher suction pressures and, in some designs, because pumps are not required.
- Damage because of equipment freezing is not likely. Such damage can occur in a secondary coolant system if the coolant condition or the refrigeration plant is not properly operated.

Thus, the broad scope of refrigeration applications within the chemical industry permits the use of virtually any refrigeration system under the proper process conditions.

REFRIGERATION EQUIPMENT

For the most part, the refrigeration equipment used in the chemical industry is identical to, or closely parallels, the equipment used in other industries. The chemical industry is unique, however, in the wide variety of applications, the large temperature ranges covered by these applications, the diversity of equipment usage, and the variation of mechanical specifications required. Where possible, the chemical industry uses standard equipment, but this is frequently impossible because of the particularly rigorous demands of chemical plant service. Therefore, this section only briefly describes the application and modification of refrigeration equipment for chemical plant service.

Compressors

Refrigeration engineers may find difficulty in applying conventional refrigeration compressors to chemical plant service. Most process engineers are familiar with heavy duty, forged steel, high-pressure, single- or double-throw reciprocating gas compressors; they are uncomfortable with the high-speed, cast iron or steel compressors that are standard to the refrigeration industry. Another difference between commercial and chemical plant usage is the greater use of open-drive equipment in the chemical plant.

The large capacities and low temperatures frequently encountered in chemical plant duty have led to wide use of either centrifugal compressors or high-capacity rotary or screw compressors. These large machines vary from standard commercial equipment principally in the amount and complexity of controls or other auxiliaries provided. Load control devices such as multistep unloaders or hot-gas bypass systems are often required to permit a compressor turndown to 10% of full load or, in some cases, to permit no-load operation without either compressor surge problems or on-off operation. Most systems with large multistage centrifugal compressors use economizers to minimize power and suction volume requirements. Compressor lube oil systems are often provided with auxiliary oil pumps, dual oil filters, dual oil coolers, and the like to permit routine maintenance without shutdown and to minimize shutdown frequency. Compressor control and alarm systems are frequently tied into central control room panel boards to permit monitoring and/or control of compressors.

Compressors for hydrocarbon gas refrigerants find their greatest use within the chemical industry, particularly in the field of petrochemicals. The relatively low cost and ready availability of pure hydrocarbons and hydrocarbon mixtures frequently dictate their use. Many offer the additional advantage of positive-pressure operation throughout the entire refrigeration cycle.

Because refrigeration systems within the chemical industry are often required to operate for a year or more without shutdown, standby compression equipment is frequently installed. Even the larger refrigeration loads sometimes require 100% standby protection. Special controls may be required to provide rapid and automatic start-up of the standby equipment. The main drive is commonly an electric motor and the standby drive may be either a steam turbine or an internal combustion engine. Provisions must be made via nonelectric drivers or emergency generating equipment to keep all necessary auxiliaries and controls operative during an electrical outage. Oversized crankcase heaters may be required, as well as electric or steam tracing of various lubricant system components.

High in-service requirements, plant standardization, explosion hazards, and corrosive atmospheres all require special controls. Often, the copper instrument tubing normally used on commercial equipment must be replaced with steel or stainless steel tubing more suitable to the proposed plant atmosphere. Lubricant piping must be stainless steel with nonferrous valves, coolers, and filters. This requirement is primarily to minimize expensive delays in initial plant start-up that may result when rust or scale within lubricant systems causes damage to bearings or seals in high-speed centrifugal or screw compressors.

Absorption Equipment

Chapter 1 of the *ASHRAE Handbook—Fundamentals* and Chapter 41 of this volume discuss absorption equipment in detail. Absorption equipment has seen little recent use in chemical plants, even though plant waste heat may be available to operate it, because of the proximity of the heat source to the refrigeration requirement.

By special design and reselection of materials, hot streams of many fluids can be used as the energy source instead of using hot water or steam. Direct-fired units are available. Hot condensable vapors can also be used as the energy source.

Lithium bromide absorption equipment must be modified to permit outdoor operation. Manufacturers' recommendations should be followed regarding changes necessary to prevent freezing on the water side and solution crystallization on the absorption side of the equipment, particularly during shutdown.

Condensers

Water-Cooled Condensers. Units for chemical plant service require relatively minor design changes from those provided for industrial installations. Since cooling water is frequently of low quality, special materials of construction may be required throughout the tube side. An example is the necessity to switch from copper to a cupronickel when cooling water comes from a brackish source that is high in chlorides. If the cooling water is high in mud or silt content, it is sometimes justifiable to install piping and valving that will permit backflushing the condenser without requiring a refrigeration machine shutdown. Chemical plant requirements normally dictate shell-and-tube condensers of the replaceable tube type. Process engineers may insist on conservative tube-side velocities (8 fps or less as a maximum for copper tubes) and removable bundles. The long hours of required operation without opportunity for cleaning and the types of cooling water used frequently require that a higher water-side fouling factor be assumed than on industrial installations.

Air-Cooled Condensers. With increasing restrictions on the use of water for condensing, air-cooled condensing systems have been used in many instances, even in larger centrifugal-type plants. These have usually been installed in humid locations where the increase in condensing pressure (temperature) over that from the use of cooling tower water or once-through water systems is minimal.

Air-cooled condensers for chemical plant service are normally fabricated to one of the API standards for forced-convection coolers. Care must be taken when specifying these coolers so that the manufacturer understands the type of duty associated with a condensing refrigerant. The service required of an air-cooled condenser in a chemical plant atmosphere dictates either the use of more expensive alloys in the tube construction or conventional materials of greater wall thickness to give acceptable service life. Air coolers may be more difficult to locate because recirculation of hot discharge air or fouling by hot process exhaust gases must be avoided.

Evaporative Condensers. Evaporative condensers, particularly for smaller refrigerating loads, are used extensively in the chemical industry, and they should become more prevalent as more emphasis is placed on the reduction of thermal contamination of rivers, lakes, and streams. In a few larger installations, the combination of an air cooler and an evaporative condenser operating in series satisfies the condensing requirements.

In most cases, the commercial evaporative condenser is totally unsuitable for chemical plant service, but satisfactory results can be obtained if this equipment is carefully specified. The major items of concern are the atmospheric conditions to which such equipment may be exposed and the long in-service requirements of the chemical plant. The chemical plant atmosphere, which may abound in vapors or dusts that are corrosive in themselves, can be an even more serious problem when these vapors and dusts are passed over surfaces that are constantly being wetted. Another problem is that dusts from nearby raw material storages or grinding operations may infiltrate the water recirculating system and plug the spray nozzles. The problems of water treatment and winter freeze protection are usually much more severe in chemical plant service because of the lower-quality water that is frequently available and the demand for both year-round operation and a high turndown ratio. Light load operation in freezing weather calls for extreme care in design to avoid freezeup.

Two other areas of commercial evaporative condenser design that must frequently be strengthened for chemical plant duty are the electrical equipment, which must be satisfactory for the plant environment, and the fans, dampers, and recirculating pumps, which must be suitable for long-life, low-maintenance service.

Evaporators

The general familiarity of chemical plant design personnel with heat exchanger design and application may sometimes lead them to suggest that refrigeration evaporators for the chemical plant should be designed similarly to evaporators in nonrefrigeration service. While the general laws of heat transfer apply in either case, there are special requirements for evaporators in refrigeration service which are not always present in other types of heat exchanger design. Refrigeration engineers must coordinate the process engineers' experience with the special requirements of a refrigeration evaporator. To do so, the standards of the Tubular Exchanger Manufacturers Association (TEMA) should be consulted to ensure that the end product is familiar to the plant engineer while still performing efficiently as a refrigeration chiller.

Paramount in these special requirements are the proper treatment of oil circulation in the refrigeration evaporator and proper evaluation of liquid submergence as it may affect low-temperature evaporator performance. When the evaporator in chemical plant service is being used with reciprocating and rotary screw compression equipment, continuous oil return from the evaporator must normally be provided. If continuous oil return is not possible, an adequate oil reservoir for the compression equipment, with periodic transfer of oil from the low side of the system, may be needed. On evaporators used with centrifugal compression equipment, continuous oil return from the evaporators is not necessary. In general, centrifugal compressors pump very little oil, so oil contamination of the low side of the system is not as serious as with positive displacement equipment. However, even with centrifugal equipment, the low-side evaporators eventually become contaminated with oil, which must be removed. Most centrifugal systems operate for several years before oil accumulation in the evaporator adversely affects evaporator performance. Newer tube surfaces with porous coatings may be more sensitive to the presence of oil in the refrigerant than would be conventional finned surfaces. For newer surfaces, a continuous oil return system may be essential for centrifugal systems.

Flooded shell refrigeration evaporators operating at extremely low temperatures and low suction pressures may build up an excessive liquid head, which can create higher evaporating pressures and temperatures at the bottom of the evaporator than at the top. Spray-type evaporators with pump recirculation of refrigerant eliminate this static head penalty.

Special materials for evaporator tubes and shells of particularly heavy wall thickness are frequently dictated to cool process streams of a highly corrosive nature. Corrosion allowances in evaporator design, which are seldom a factor in the commercial refrigeration field, are often required in chemical service. Ranges of permissible velocities are frequently specified to prevent sludge deposits or erosion at tube ends.

Process-side construction suitable for high pressures seldom encountered in usual refrigeration applications is frequently necessary. Choice of process-side scale factors must also be made carefully without overstatement.

Differences between process inlet and outlet temperatures of 100°F or more are not uncommon. For this reason, special consideration must be given to thermal stresses within the refrigerant evaporator. U-tube or floating tube sheet construction is frequently specified in chemical plant service, but minor process side modifications may permit the use of less expensive standard fixed tube sheet design. The refrigerant side of the evaporator may be required to withstand pressures resulting from maximum process temperature or the evaporator must be able to bypass the process stream under certain high-temperature conditions (e.g., in a refrigeration system failure).

Relief devices and safety precautions common to the refrigeration field normally meet chemical plant needs but should be reviewed against individual plant standards and local statutory requirements. Forged steel relief valves are becoming more common as they meet the applicable refinery piping codes. In hazardous service, relief valves are sized for emergency discharge in the event of fire. The effect of chemical vapors on the downstream (outlet) internal parts of relief valves may call for special materials or trapped outlet piping with isolating liquid seals.

Process requirements frequently call for sudden or unexpected load changes on the refrigeration evaporator. Possible thermal shocks, with attendant stresses, must be evaluated, and the evaporator must be designed to meet any such conditions.

Evaporators in chemical plant duty normally require inspection and cleaning on an annual basis. For this reason, they should be located for accessibility and ease of tube replacement. Possible contamination of the process stream or the refrigerant side, because of leakage, should be evaluated. Special means of leak detection from one side of the evaporator to the other may be justified on occasion.

Low-temperature refrigeration in the chemical industry often creates extremely high viscosities on the process side of the equipment. Special evaporator designs may be needed to minimize pressure drops on the process side and to maintain optimum heat transfer performance. Small tube diameters may not be compatible with the process stream because certain processes may call for extra-large tubes. For extremely low-temperature and high-viscosity duties, evaporators are sometimes provided with rotating internal wall scrapers to ensure flow of high-viscosity fluids through the evaporators. Similarly, jacketed process vessels are used to cool highly viscous materials, while rotary scrapers keep the vessel walls clean.

For proper process flow, evaporators usually are remote from the other refrigeration equipment to minimize piping and pumping costs. Because remotely located evaporators place special emphasis on proper refrigerant piping practices, secondary coolant systems may be used. Chemical plants frequently use flooded refrigeration systems, which pump refrigerant from the central compressor station to remote evaporators. The use of these systems often reduces the design difficulties in ensuring adequate oil return, and special provisions must be made at the central refrigeration station to protect the compressor against liquid carryover in the suction gas. The system must have an adequate accumulator to ensure dry gas to the compressor.

Standard air-side evaporators may require modification, mainly to solve special corrosion problems in handling air or process gases that attack standard coil materials. Occasionally, process requirements demand coil designs that do not match standard commercial air-side pressure drops, air-side design temperature range, or both. Coils of special depth and finning may be required and coil casings and fan casings of alloy steel are common.

Instrumentation and Controls

Since the heart of the chemical plant is its instrument control system, it follows that instrumentation and control is much more advanced in the chemical industry than in commercial or usual industrial refrigeration applications. As previously discussed, chemical industry refrigeration instrumentation hardware is much more sophisticated in design, particularly in regard to providing increased safety, reliability, and compatibility with process instrumentation devices. This sophistication extends to the application and design of individual hardware items. The chemical industry seldom settles for integral control devices such as self-contained pressure regulators or capillary-actuated thermal control valves. The usual chemical industry control loop consists of a sensing device, a transmitter, a recorder/controller, a positioner, and an operator, all pneumatically or electrically interconnected. Many plants use central computer and microprocessor controls. Interfacing between the refrigeration system and control system may be necessary.

Cooling Towers and Spray Ponds

In a refrigeration system that uses water-cooled rather than air-cooled or evaporative condensers, heat may be rejected to once-through cooling water, spray ponds, or cooling towers. The chemical industry uses mechanical draft towers almost exclusively. These are generally of the induced draft design and are about evenly divided between crossflow and counterflow operation. Although a familiarity with these items is necessary, chemical plant engineers are usually responsible for their design.

Miscellaneous Equipment

Pumps. Refrigeration system pumps are usually of a high-quality centrifugal design, the primary exception being small positive-displacement pumps for compressor lube oil systems. In the past, heavy-duty design was the rule rather than the exception, and secondary coolant and chilled water units were usually of a horizontal split-case design, patterned after boiler-house or water plant construction. Chemical process designers have advocated standard chemical plant pump designs, which usually have a vertically split case and an end suction. If the selection is made carefully, this design is successful in many applications, and the resultant savings in pump costs, space requirements, and spare parts stocking requirements make it economically attractive.

For pumped materials difficult to contain, such as most refrigerants and many secondary coolants, mechanical shaft seals of various designs are frequently used. As a result of their highly successful use in pumping difficult process fluids, canned or sealless pumps are used in such applications as liquid overfeed systems using halocarbons. Because the pumping of difficult fluids is a common problem, chemical process designers can be of invaluable assistance.

Piping. As a consequence of several factors, including low fluid temperatures, large pipe sizes, congested pipe alley space, and the industry's reluctance to use expansion joints for high-duty service and in corrosive atmospheres, piping flexibility problems are much more complex. Expansion joints are frequently prohibited, which increases space requirements dramatically. Secondly, piping and valve standards that apply to both process and service facilities are frequently established by the process designer. The engineer who is accustomed to using carbon steel piping systems with tongue and groove flanging and valves may find that plant standards call for a welded nickel steel system with raised face flanges, spirally wound stainless steel gaskets, and cast steel valving.

Most piping construction problems resulting from the difference between expectations of the process engineer and the experience of the refrigeration engineer can be resolved by constructing the system to meet ASME *Standard* B31.3. The ASME B16 series of standards that defines the flanges and fittings of the process industry should also be followed. Chapters 1 through 4 also discuss piping sizing for various refrigeration systems.

Tanks. Chemical plants use storage tanks for both refrigerants and secondary coolants more frequently than most commercial or industrial plants. In chilled water or brine circulation systems, storage tanks often serve a dual purpose: (1) to store secondary coolants during operation to provide a reserve capacity and thus smooth out short-term peak requirements and (2) to store secondary coolants during a maintenance shutdown of process evaporators. In some cases, brine mix and storage facilities are provided, so that any brine lost due to leakage or unusual maintenance demands can be quickly replaced, thus minimizing unscheduled process outages. In many cases, refrigerant pumpout compressors and storage receivers can minimize loss of the refrigerant and unscheduled outage time because of refrigeration system failures on the refrigerant side.

The chemical industry designs all pressure vessels in accordance with the ASME *Boiler and Pressure Vessel Code*, in particular Section VIII, Division 1, for unfired pressure vessels, regardless of local government regulations requiring such design. In most plants, standards are established regarding such items as pressure relief devices, manhole design, insulation supports, and tank supports. A thorough knowledge of the plant standards to be applied should be gained before specifications and design details are established for refrigeration system tankage.

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