CHAPTER 43. LIQUID-CHILLING SYSTEMS

LIQUID-CHILLING systems cool water, brine, or other second- ary coolant for air conditioning or refrigeration. The chiller may be either factory-assembled and wired or shipped in sections for erection in the field. The most frequent application is water chilling for air conditioning, although brine cooling for low-temperature refrigeration and chilling fluids in industrial processes are also common.

The basic components of a vapor-compression chiller include one or more compressor(s), liquid cooler (evaporator), condenser, compressor drive(s), liquid-refrigerant expansion or flow-control device, and control center. It may also include a receiver, economizer, expansion turbine, and/or subcooler. In addition, auxiliary components may be used, such as a lubricant cooler, lubricant separator, lubricant-return device, purge unit, lubricant pump, refrigerant transfer unit, refrigerant vents, and/or additional control valves.

For information on absorption equipment, see Chapter 18 of the 2014 *ASHRAE Handbook—Refrigeration*.

1. GENERAL CHARACTERISTICS

1.1 PRINCIPLES OF OPERATION

Liquid (usually water or water/glycol mixture) enters the cooler, where it is chilled by liquid refrigerant evaporating at a lower temperature. The refrigerant vaporizes and is drawn into the compressor, which increases the pressure and temperature of the gas so that it may be condensed at the higher temperature in the condenser. The condenser cooling medium is heated in the process. The condensed liquid refrigerant then flows back to the evaporator through an expansion device, where some of the liquid refrigerant changes to vapor (flashes) as pressure drops. Flashing cools the liquid to the saturated temperature at evaporator pressure. The following modifications (sometimes combined for maximum effect) reduce flash gas and increase the net refrigeration per unit of power consumption.

Subcooling. Condensed refrigerant may be subcooled below its saturated condensing temperature in either the subcooler section of a water-cooled condenser or a separate heat exchanger. Subcooling reduces flashing and increases the refrigeration effect in the chiller.

Economizing. This process can occur either in a direct-expansion (DX), an expansion turbine, or a flash system. In a **DX system**, the main liquid refrigerant is usually cooled in the shell of a shell-and-tube heat exchanger, at condensing pressure, from the saturated condensing temperature to within several degrees of the intermediate saturated temperature. Before cooling, a small portion of the liquid flashes and evaporates in the tube side of the heat exchanger to cool the main liquid flow. Although subcooled, the liquid is still at the condensing pressure.

An **expansion turbine** extracts rotating energy as a portion of the refrigerant vaporizes. As in the DX system, the remaining liquid is supplied to the cooler at intermediate pressure.

In a **flash system**, the entire liquid flow is expanded to intermediate pressure in a vessel that supplies liquid to the cooler at saturated intermediate pressure; however, the liquid is at intermediate pressure.

Flash gas enters the compressor either at an intermediate stage of a multistage centrifugal compressor, at the intermediate stage of an integral two-stage reciprocating compressor, at an intermediate pressure port of a screw compressor, or at the inlet of a high-pressure stage on a multistage reciprocating or screw compressor.

Liquid Injection. Condensed liquid is throttled to the intermediate pressure and injected into the second-stage suction of the compressor to prevent excessively high discharge temperatures and, in the case of centrifugal machines, to reduce noise. For screw compressors, condensed liquid is injected into a port fixed at slightly below discharge pressure to provide lubricant cooling.

1.2 COMMON LIQUID-CHILLING SYSTEMS

Basic Chiller

The refrigeration cycle of a basic chiller is shown in Figure 1. Chilled water enters the cooler at 54°F, for example, and leaves at 44°F. Condenser water leaves a cooling tower at 85°F, enters the condenser, and returns to the cooling tower near 95°F. Condensers may also be cooled by air or evaporation of water. This system, with a single compressor and one refrigerant circuit with a water-cooled condenser, is used extensively to chill water for air conditioning because it is relatively simple and compact.

Multiple-Chiller Systems

A multiple-chiller system has two or more chillers connected by parallel or series piping to a common chilled-liquid distribution system. Multiple chillers offer operational flexibility, standby capacity, and less disruptive maintenance. The chillers can be sized to handle a base load and increments of a variable load to allow each chiller to operate at its most efficient point.

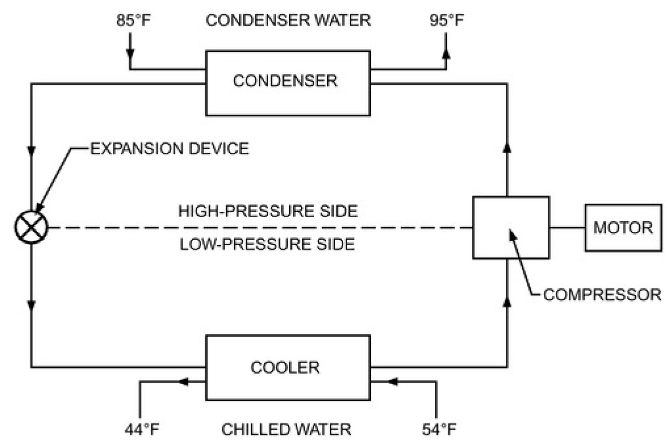

Figure 1. Equipment Diagram for Basic Liquid Chiller

Multiple-chiller systems offer some standby capacity if repair work must be done on one chiller. Using multiple smaller chillers rather than one larger chiller may reduce starting in-rush current as well as power costs at partial-load conditions. Maintenance can be scheduled for one chiller during part-load times, and sufficient cooling can still be provided by the remaining unit(s). These advantages require an increase in installed cost and space, however. Traditionally, flow was held constant through the chillers for stable control. Today, variable-flow chilled-water systems are preferred in many applications. Both variable-flow and primary/ secondary hydronic systems are discussed in further detail in Chapter 13.

In the parallel arrangement, when design chilled-water temperature is above about 45°F, all units should be controlled by the combined exit liquid temperature or by the return water temperature (RWT), because overchilling will not cause dangerously low water temperature in the operating machine(s). Chilled-water temperature can be used to cycle one unit off when it drops below a capacity that can be matched by the remaining units.

When the design chilled-water temperature is below about 45°F, each machine should be controlled by its own chilled-water temperature, both to prevent dangerously low evaporator temperatures and to avoid frequent shutdowns by low-temperature cutout. The temperature differential setting of the RWT must be adjusted carefully to prevent short-cycling caused by the step increase in chilled-water temperature when one chiller is cycled off. These control arrangements are shown in Figures 2 and 3.

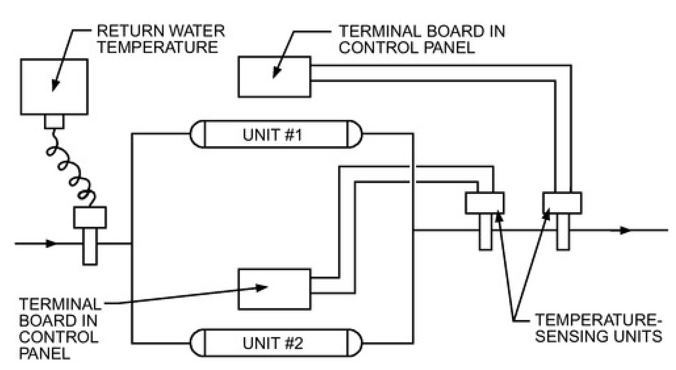

Figure 2. Parallel-Operation High Design Water Leaving Coolers (Approximately 45°F and Above)

In the **series arrangement**, the evaporator vessel must handle the entire system flow in both chillers, so they should be selected with the combined pressure drop in mind. No overchilling by either unit is required, and compressor power consumption is lower than for the parallel arrangement at partial loads. Each chiller provides part of the overall system temperature differential. Because the first chiller operates at a higher evaporator temperature (meaning lower lift), it operates more efficiently than the second chiller, thereby improving overall system efficiency. In addition, because evaporator temperature never drops below the design value (because no overchilling is necessary), the chances of evaporator freeze-up are minimized. However, the chiller should still be protected by a low-temperature safety control. If operating flexibility, standby capacity, or ability to operate on one chiller during maintenance of the other are desired, the piping must be arranged such that all flow can bypass either chiller and the system can operate on the non-bypassed chiller. This means that each chiller should be specified to be able to provide the overall system temperature differential.

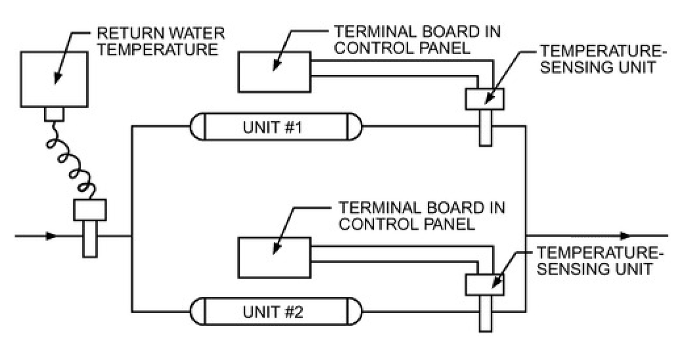

Figure 3. Parallel-Operation Low Design Water Leaving Coolers (Below Approximately 45°F)

If the condenser water side of the chillers is to be designed in series, the condensers are best piped in a counterflow arrangement so that the first machine is provided with warmer condenser and chilled water and the second machine is provided with colder entering condenser and chilled water. Refrigerant compression for each unit is nearly the same. If about 55% of design cooling capacity is assigned to the first machine and about 45% to the second machine, identical units can be used. In this way, either machine can provide the same standby capacity if the other is down, and the machines may be interchanged to equalize the number of operating hours on each.

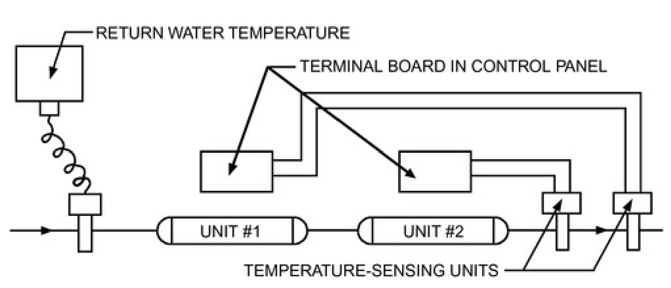

Figure 4. Series Operation

A control system for two machines in series is shown in Figure 4. Both units are modulated to a certain capacity; then, one unit shuts down, leaving less than 100% load on the operating machine.

One machine should be shut down as soon as possible, with the remaining unit carrying the full load. This not only reduces the number of operating hours on a unit, but also leads to less total power consumption because the coefficient of performance (COP) tends to decrease below full-load value when unit load drops much below 50%.

1.3 SELECTION

The largest factor that determines total liquid chiller owning cost is the cooling load size; therefore, the total required chiller capacity should be calculated accurately. The practice of adding 10 to 20% to load estimates is unnecessary because of the availability of accurate load estimating methods, and it proportionately increases costs of equipment purchase, installation, and the poor efficiency resulting from wasted power. Oversized equipment can also cause operational difficulties such as frequent on/off cycling or surging of centrifugal machines at low loads. The penalty for a small underestimation of cooling load, however, is not serious. On the few design-load days of the year, increased chilled-liquid temperature is often acceptable. However, for some industrial or commercial loads, a safety factor can be added to the load estimate.

Use the life-cycle cost (discussed in Chapter 37 of the 2015 *ASHRAE Handbook—HVAC Applications*) to minimize overall purchase and operating costs. Total owning cost is comprised of the following:

- **Equipment price.** Each machine type and/or manufacturer's model should include all necessary auxiliaries such as starters and vibration mounts. If these are not included, their price should be added to the base price. Include associated equipment, such as condenser water pump, tower, and piping.
- **Installation cost.** Factory-packaged machines are both less expensive to install and usually considerably more compact, thus saving space. The cost of field assembly must also be evaluated.
- **Energy cost.** Using an estimated load schedule and part-load power consumption curves furnished by the manufacturer, a year's energy cost should be calculated.
- **Water cost.** With water-cooled towers, the cost of acquisition, water treatment, tower blowdown, and overflow water should be included.
- **Maintenance cost.** Each bidder may be asked to quote on a maintenance contract on a competitive basis.
- **Insurance and taxes.**
- **Regulatory/codes.** Changes in regulations could require replacement of chiller fluids, upgrades of electronics, or improvements in efficiencies.

For packaged chillers that include heat recovery, system cost and performance should be compared in addition to equipment costs. For example, the heat recovery chiller installed cost should be compared with the installed cost of a chiller plus a separate heating system. Also consider the following factors: (1) energy costs, (2) maintenance requirements, (3) life expectancy of equipment, (4) standby arrangement, (5) relationship of heating to cooling loads, (6) effect of package selection on sizing, and (7) type of peripheral equipment.

Condensers and coolers are often available with either **liquid heads**, which require water pipes to be disconnected for tube access and maintenance, or **marine-type water boxes**, which allow tube access with water piping intact. The liquid head is considerably less expensive. The cost of disconnecting piping must be greater than the additional cost of marine-type water boxes to justify using the latter. Typically, an elbow and union or flange connection can be installed immediately next to liquid heads to facilitate removing heads. By making sure that all specialty piping components (valves, controls, strainers, etc.) fall outside the tube bundle boundary, the liquid heads can be removed with very minimal pipe disassembly.

Figure 5 shows types of liquid chillers and their ranges of capacities.

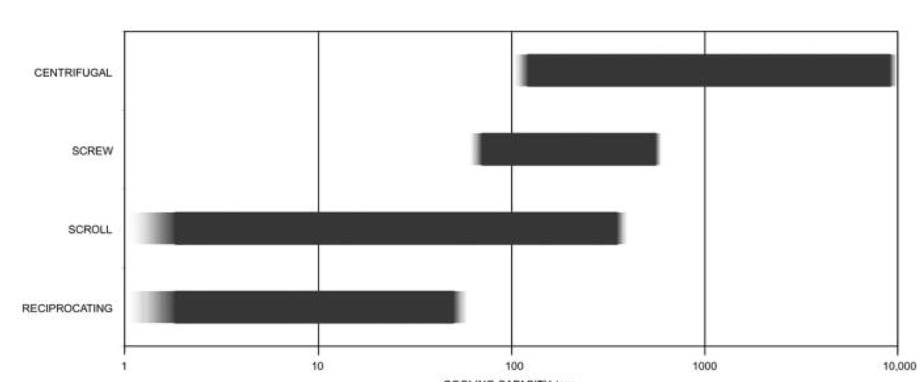

Figure 5. Approximate Liquid Chiller Availability Range by Compressor Type

For air-cooled condenser duty, brine chilling, or other high-pressure applications from 80 to about 200 tons, scroll and screw liquid chillers are more frequently installed than centrifugals. Centrifugal liquid chillers (particularly multistage machines), however, may be applied quite satisfactorily at high pressures.

Advancements in technology, refrigerants, and manufacturer offerings all affect which compression technology is best suited for a given liquid chiller application. Centrifugal packages are typically available to about 3500 tons, and field-assembled machines to about 10,000 tons.

1.4 CONTROL

Liquid Chiller Controls

The **chilled-liquid temperature sensor** sends an air pressure (pneumatic control) or electrical signal (electronic control) to the control circuit, which then modulates compressor capacity in response to leaving or return chilled-liquid temperature change from its set point.

Compressor capacity is adjusted differently on the following liquid chillers:

Reciprocating chillers use combinations of cylinder unloading and on/off compressor cycling of single or multiple compressors.

Centrifugal liquid chillers, driven by electric motors, commonly use adjustable prerotation vanes, which are sometimes combined with movable diffuser walls. Turbine and engine drives and inverter-driven, variable-speed electric motors allow use of speed control in addition to prerotation vane modulation, reducing power consumption at partial loads.

Screw compressor liquid chillers include a slide valve that adjusts the length of the compression path. Inverter-driven, variable-speed electric motors, turbines, and engine drives can also modulate screw compressor speed to control capacity.

In air-conditioning applications, most centrifugal and screw compressor chillers modulate from 100% to approximately 10% load. Although relatively inefficient, hot-gas bypass can be used to reduce capacity to nearly 0% with the unit in operation.

Reciprocating chillers are available with simple on/off cycling control in small capacities and with multiple steps of unloading down to 12.5% in the largest multiple-compressor units. Most intermediate sizes provide unloading to 50, 33, or 25% capacity. Hot-gas bypass can reduce capacity to nearly 0%.

The **water temperature controller** is a thermostatic device that unloads or cycles the compressor(s) when the cooling load drops below minimum unit capacity. An **antirecycle timer** is sometimes used to limit starting frequency.

On centrifugal or screw compressor chillers, a **current limiter** or **demand limiter** limits compressor capacity during periods of possible high power consumption (such as pulldown) to prevent current draw from exceeding the design value; such a limiter can be set to limit demand, as described in the section on Centrifugal Liquid Chillers.

Controls That Influence the Liquid Chiller

Condenser cooling water may need to be controlled to avoid falling below the manufacturer's recommended minimum limit, to regulate condenser pressure. Normally, the temperature of water leaving a cooling tower can be controlled by fans, dampers, or a water bypass around the tower. Tower bypass allows water velocity through the condenser tubes to be maintained, which prevents low-velocity fouling.

A flow-regulating valve is another common means of control. The orifice of this valve modulates in response to condenser pressure. For example, reducing pressure decreases water flow, which, in turn, raises condenser pressure to the desired minimum level.

For air-cooled or evaporative condensers, compressor discharge pressure can be controlled by cycling fans, shutting off circuits, or flooding coils with liquid refrigerant to reduce heat transfer.

A reciprocating chiller usually has a thermal expansion valve, which requires a restricted range of pressure to avoid starving the evaporator (at low pressure).

An expansion valve(s) usually controls a screw compressor chiller. Cooling tower water temperature can be allowed to fall with decreasing load from the design condition to the chiller manufacturer's recommended minimum limit.

Screw compressor chillers above 150 tons may use flooded evaporators and evaporator liquid refrigerant controls similar to those used on centrifugal chillers.

A thermal expansion valve may control a centrifugal chiller at low capacities. Higher-capacity machines may use a pilot-operated thermal control valve, an electronically controlled valve, fixed orifice(s), a high-pressure float, or even a low-side float valve to control refrigerant liquid flow to the cooler. These latter types of controls allow relatively low condenser pressures, particularly at partial loads. Also, a centrifugal machine may surge if pressure is not reduced when cooling load decreases. In addition, low pressure reduces compressor power consumption and operating noise. For these reasons, in a centrifugal installation, cooling tower water temperature should be allowed to fall naturally with decreasing load and wet-bulb temperature, except that the liquid chiller manufacturer's recommended minimum limit must be observed.

Safety Controls

Older systems often used dedicated control devices for each function of the chiller. Modern chiller systems typically use a microprocessor control center that can handle many control functions at once and can combine several control points into a single sensor. Some or all of the following safety algorithms or cutouts may be provided in a liquid-chilling package to stop compressor(s) automatically. Cutouts may be manual or automatic reset.

- **High condenser pressure.** This pressure switch opens if the compressor discharge pressure exceeds the allowable limit. It is usually a dedicated pressure switch that interrupts the chiller main run circuit to ensure a positive shutdown in an overpressure situation.
- **Low refrigerant pressure (or temperature).** This device opens when evaporator pressure (or temperature) reaches a minimum safe limit.
- **High lubricant temperature.** This device protects the compressor if loss of lubricant cooling occurs or if a bearing failure causes excessive heat generation.
- **High motor temperature.** If loss of motor cooling or overloading because of a failure of a control occurs, this device shuts down the machine. It may consist of direct-operating bimetallic thermostats, thermistors, or other sensors embedded in the stator windings; it may be located in the discharge gas stream of the compressor.
- **Motor overload.** Some small, reciprocating-compressor hermetic motors may use a directly operated overload in the power wiring to the motor. Some larger motors use pilot-operated overloads. Centrifugal and screw-compressor motors generally use starter overloads or current-limiting devices to protect against overcurrent.
- **Low lubricant sump temperature.** This switch is used either to protect against lubricant heater failure or to prevent starting after prolonged shutdown before lubricant heaters have had time to drive off refrigerant dissolved in the lubricant.
- **Low lubricant pressure.** To protect against clogged lubricant filters, blocked lubricant passageways, loss of lubricant, or a lubricant pump failure, a switch shuts down the compressor when lubricant pressure drops below a minimum safe value or if sufficient lubricant pressure is not developed shortly after the compressor starts.
- **Chilled-liquid flow interlock.** This device may not be furnished with the liquid-chilling package, but it is needed in external piping to protect against cooler freeze-up in case the liquid stops flowing. An electrical interlock is typically installed either in the factory or in the field. Most chiller control panels include a terminal for field-connecting a flow switch.
- **Condenser water flow interlock.** This device, similar to the chilled-liquid flow interlock, is sometimes used in external piping.
- **Low chilled-liquid temperature.** Sometimes called **freeze protection**, this cutout operates at a minimum safe value of leaving chilled-liquid temperature to prevent cooler freeze-up in the case of an operating control malfunction.
- **Relief valves.** In accordance with ASHRAE *Standard* 15, relief valves, rupture disks, or both, set to relieve at shell design working pressure, must be provided on most pressure vessels or on piping connected to the vessels. Fusible plugs may also be used in some locations. Pressure relief devices should be vented outdoors or to the low-pressure side, in accordance with regulations or the standard.

1.5 STANDARDS AND TESTING

AHRI *Standard* 550/590 provides guidelines for rating and testing liquid-chilling machines. Design and construction of refrigerant pressure vessels are governed by ASME *Boiler and Pressure Vessel Code*, Section VIII, except when design working pressure is 15 psig or less (as is usually the case for R-123 liquid-chilling machines). Water-side design and construction of a condenser or evaporator are not within the scope of the ASME code unless design pressure is greater than 300 psi or design temperature is greater than 210°F.

ASHRAE *Standard* 15 applies to all liquid chillers and new refrigerants on the market. Requirements for equipment rooms are included. Methods for measuring unit sound levels are described in AHRI *Standard* 575.

1.6 GENERAL MAINTENANCE

The following maintenance specifications apply to reciprocating, centrifugal, and screw chillers. Equipment should be neither overmaintained nor neglected. Establish a preventive maintenance schedule; items covered can vary with the nature of the application. The list is intended as a guide; in all cases, the manufacturer's specific recommendation should be followed.

Continual Monitoring

- Condenser water treatment: treatment is determined specifically for the condenser water used.
- Operating conditions: daily log sheets should be kept (either manually or automatically) to indicate trends and provide advance notice of deteriorating chillers.
- Brine quality for concentration and corrosion inhibitor levels.

Periodic Checks

- Leak check
- Purge operation

- System dryness
- Lubricant level
- Lubricant filter pressure drop
- Refrigerant quantity or level
- System pressures and temperatures
- Water flows
- Expansion valves operation

Regularly Scheduled Maintenance

- Condenser and lubricant cooler cleaning
- Evaporator cleaning on open systems
- Calibrating pressure, temperature, and flow controls
- Tightening wires and power connections
- Inspection of starter contacts and action
- Safety interlocks
- Dielectric checking of hermetic and open motors
- Tightness of hot gas valve
- Lubricant filter and drier change
- Analysis of lubricant and refrigerant
- Seal inspection
- Partial or complete valve or bearing inspection, as per manufacturer's recommendations
- Vibration levels

Extended Maintenance Checks

- Compressor guide vanes and linkage operation and wear
- Eddy current inspection of heat exchanger tubes
- Compressor teardown and inspection of rotating components
- Other components as recommended by manufacturer

2. RECIPROCATING LIQUID CHILLERS

2.1 EQUIPMENT

Components and Their Functions

The reciprocating compressor described in Chapter 38 is a positive-displacement machine that maintains fairly constant-volume flow rate over a wide range of pressure ratios. The following types of compressors are commonly used in liquid-chilling machines:

- Welded hermetic, to about 25 tons chiller capacity
- Semihermetic, to about 200 tons chiller capacity
- Direct-drive open, to about 450 tons chiller capacity

Open motor-driven liquid chillers are usually more expensive than hermetically sealed units, but can be more efficient. Hermetic motors are generally suction-gas-cooled; the rotor is mounted on the compressor crankshaft.

Condensers may be evaporative, air, or water cooled. Water-cooled versions may be tube-in-tube, shell-and-coil, shell-and-tube, or plate heat exchangers. Most shell-and-tube condensers can be repaired; others must be replaced if a refrigerant-side leak occurs.

Air-cooled condensers are much more common than evaporative condensers. Less maintenance is needed for air-cooled heat exchangers than for the evaporative type. Remote condensers can be applied with condenserless packages. (Information on condensers can be found in Chapter 39.)

Coolers are usually direct expansion, in which refrigerant evaporates while flowing inside tubes and liquid is cooled as it is guided several times over the outside of the tubes by shell-side baffles. Flooded coolers are sometimes used on industrial chillers. Flooded coolers maintain a level of refrigerant liquid on the shell side of the cooler, while liquid to be cooled flows through tubes inside the cooler. Tube-in-tube coolers are sometimes used with small machines; they offer low cost when repairability and installation space are not important criteria. Chapter 42 describes coolers in more detail.

The **thermal expansion** valve, capillary, or other device modulates refrigerant flow from the condenser to the cooler to maintain enough suction superheat to prevent any unevaporated refrigerant liquid from reaching the compressor. Excessively high values of superheat are avoided so that unit capacity is not reduced. (For additional information, see Chapter 11 in the 2014 *ASHRAE Handbook—Refrigeration*.)

Lubricant cooling is not usually required for air conditioning. However, if it is necessary, a refrigerant-cooled coil in the crankcase or a water-cooled cooler may be used. Lubricant coolers are often used in applications that have a low suction temperature or high pressure ratio when extra lubricant cooling is needed.

Capacities and Types Available

Available capacities range from about 2 to 450 tons. Multiple reciprocating compressor units are popular for the following reasons:

- The number of capacity increments is greater, resulting in closer liquid temperature control, lower power consumption, less current in-rush during starting, and extra standby capacity.
- Multiple refrigerant circuits are used, resulting in the potential for limited servicing or maintenance of some components while maintaining cooling.

Selection of Refrigerant

R-12 and R-22 have been the primary refrigerants used in chiller applications. CFC-12 has been replaced with HFC-134a, which has similar properties. However, R-134a requires synthetic lubricants because it is not miscible with mineral oils. R-134a is suitable for both open and hermetic compressors.

R-22 provides greater capacity than R-134a for a given compressor displacement. R-22 is used for most open and hermetic compressors, but as an HCFC, it is scheduled for phaseout (see Chapter 29 of the 2013 *ASHRAE Handbook—Fundamentals* and the section in this chapter on Selection of Refrigerant under the Centrifugal Liquid Chillers section for more information on refrigerants and phaseout schedules). R-717 (ammonia) has similar capacity characteristics to R-22, but, because of odor and toxicity, R-717 use in public or populated areas is restricted. However, R-717 chillers are becoming more popular because of bans on CFC and HCFC refrigerants. R-717 units are open-drive compressors and are piped with steel because copper cannot be used in ammonia systems.

2.2 PERFORMANCE CHARACTERISTICS AND OPERATING PROBLEMS

A distinguishing characteristic of the reciprocating compressor is its pressure rise versus capacity. Pressure rise has only a slight influence on the volume flow rate of the compressor, and, therefore, a reciprocating liquid chiller retains nearly full cooling capacity, even on above-design-wet-bulb days. It is well suited for air-cooled condenser operation and low-temperature refrigeration. Typical performance is shown in Figure 6 and compared with centrifugal and screw compressors. Capacity control methods include the following:

- Unloading compressor cylinders (one at a time or in pairs)
- On/off cycling of compressors
- Hot-gas bypass
- Compressor speed control
- Combination of the previous methods

Figure 7 shows the relationship between system demand and performance of a compressor with three steps of unloading. As cooling load drops to the left of fully loaded compressor line A, compressor capacity is reduced to that shown by line B, which produces the required refrigerant flow. Because cooling load varies continuously whereas machine capacity is available in fixed increments, some compressor on/off cycling or successive loading and unloading of cylinders is required to maintain fairly constant liquid temperature. In practice, a good control system minimizes load/unload or on/off cycling frequency while maintaining satisfactory temperature control.

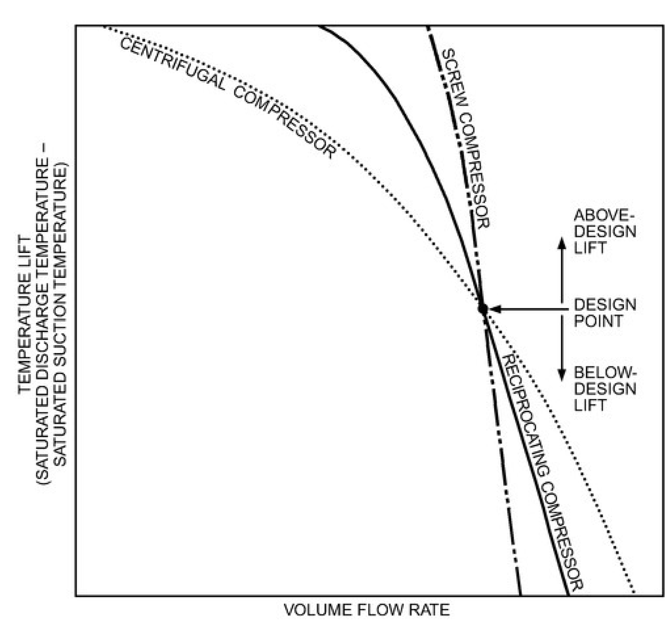

Figure 6. Comparison of Single-Stage Centrifugal, Reciprocating, and Screw Compressor Performance

2.3 METHOD OF SELECTION

Ratings

Two types of ratings are published. The first, for a packaged liquid chiller, lists values of capacity and power consumption for many combinations of leaving condenser water and chilled-water temperatures (ambient dry-bulb temperatures for air-cooled models). The second type of rating shows capacity and power consumption for different condensing and chilled-water temperatures. This type of rating allows selection with a remote condenser that can be evaporative, water, or air cooled. Sometimes the required rate of heat rejection is also listed to aid in selecting a separate condenser.

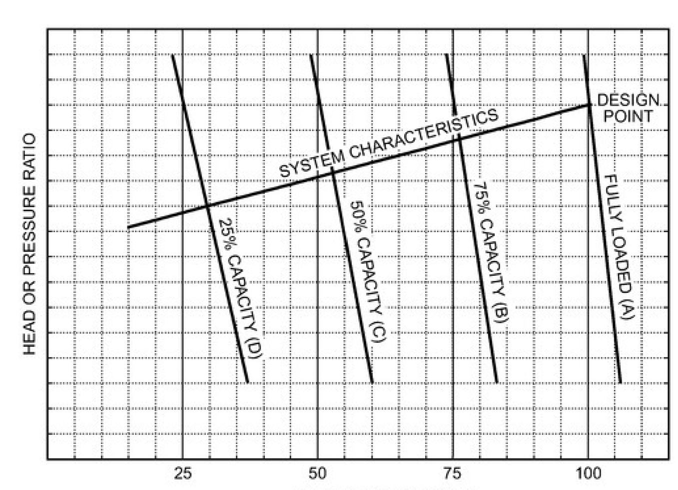

Figure 7. Reciprocating Liquid Chiller Performance with Three Equal Steps of Unloading

Power Consumption

With all liquid-chilling systems, power consumption increases as condensing temperature rises. Therefore, the smallest package, with the lowest ratio of input to cooling capacity, can be used when condenser water temperature is low, the remote air-cooled condenser is relatively large, or when leaving chilled-water temperature is high. The cost of the total system, however, may not be low when liquid chiller cost is minimized. Increases in cooling tower or fan-coil cost will reduce or offset the benefits of reduced compression ratio. Life-cycle costs (initial cost plus operating expenses) should be evaluated.

Fouling

A fouling allowance of 0.00025 $ft^2 \cdot °F \cdot h/Btu$ is included in manufacturers' ratings in accordance with AHRI *Standard* 550/590. However, fouling factors greater than 0.00025 should be considered if water conditions are not ideal.

2.4 CONTROL CONSIDERATIONS

A reciprocating chiller is distinguished from centrifugal and screw compressor-operated chillers by its use of increments of capacity reduction rather than continuous modulation. Therefore, special arrangements must be used to establish precise chilled-liquid temperature control while maintaining stable operation free from excessive on/off cycling of compressors or unnecessary loading and unloading of cylinders.

To help provide good temperature control, return chilled-liquid temperature sensing is normally used by units with steps of capacity control. The resulting flywheel effect in the chilled-liquid circuit damps out excessive cycling. Leaving chilled-liquid temperature sensing prevents excessively low leaving chilled-liquid temperatures if chilled-liquid flow falls significantly below the design value. It may not provide stable operation, however, if rapid load changes are encountered.

An example of a basic control circuit for a single-compressor packaged reciprocating chiller with three steps of unloading is shown in Figure 8. The on/off switch controls start-up and starts the programmed timer. Assuming that the flow switch, field interlocks, and chiller safety devices are closed, pressing the momentarily closed reset button energizes control relay C1, locking in the safety circuit and the motor-starting circuit. When the timer completes its program, timer switch 1 closes and timer switch 2 opens. Timer relay TR energizes, stopping the timer motor. When timer switch 1 closes, the motor-starting circuit is completed and the motor contactor holding coil is energized, starting the compressor.

The four-stage thermostat controls the compressor capacity in response to demand. Cylinders are loaded and unloaded by deenergizing and energizing the unloader solenoids. If load is reduced so that return water temperature drops to a predetermined setting, the unit shuts down until demand for cooling increases.

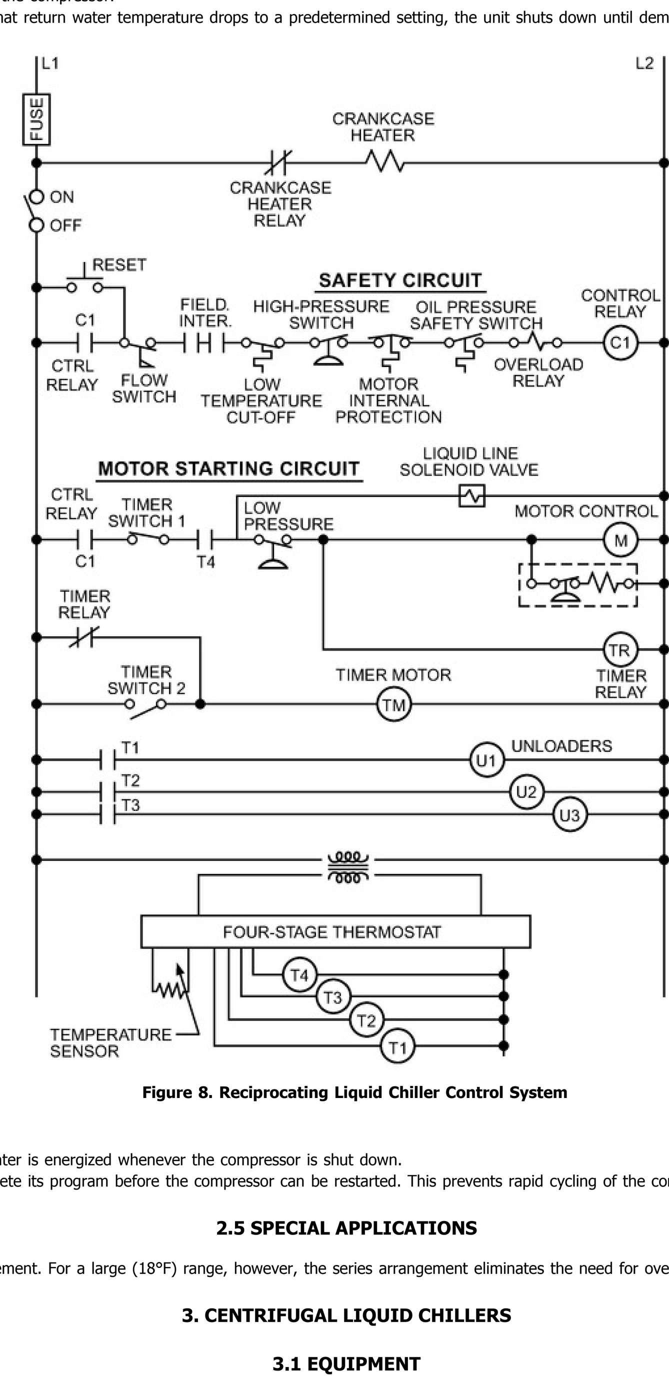

Figure 8. Reciprocating Liquid Chiller Control System

Opening a device in the safety circuit deenergizes control relay C1 and shuts down the compressor. The liquid line solenoid is also deenergized. Manual reset is required to restart. The crankcase heater is energized whenever the compressor is shut down.

If the automatic reset, low-pressure cutout opens, the compressor shuts down, but the liquid line solenoid remains energized. The timer relay TR is deenergized, causing the timer to start and complete its program before the compressor can be restarted. This prevents rapid cycling of the compressor under low-pressure conditions. A time delay low-pressure switch can also be used for this purpose with the proper circuitry.

2.5 SPECIAL APPLICATIONS

For multiple-chiller applications and a 10°F chilled-liquid temperature range, a parallel chilled-liquid arrangement is common because of the high cooler pressure drop resulting from the series arrangement. For a large (18°F) range, however, the series arrangement eliminates the need for overcooling when only one unit is operating. Special coolers with low water-pressure drop may also be used to reduce total chilled-water pressure drop in the series arrangement.

3. CENTRIFUGAL LIQUID CHILLERS

3.1 EQUIPMENT

Components and Their Function

Chapter 38 describes centrifugal compressors. Because they are not positive displacement, they offer a wide range of capacities continuously modulated over a limited range of pressure ratios. By altering built-in design items (e.g., number of stages, compressor speed, impeller diameters, choice of refrigerant), they can be used in liquid chillers having a wide range of design chilled-liquid temperatures and design condensing fluid temperatures. The ability to vary capacity continuously to match a wide range of load conditions with nearly proportional changes in power consumption makes a centrifugal compressor desirable for both close temperature control and energy conservation. Its ability to operate at greatly reduced capacity allows it to run most of the time with infrequent starting.

The centrifugal compressor has a minimum of bearing and other contacting surfaces that can wear; wear is also minimized by providing forced lubrication to those surfaces before start-up and during shutdown. Bearing wear usually depends more on the number of start-ups than the actual hours of operation. Thus, reducing the number of start-ups extends system life and reduces maintenance costs.

Compressors may be open or hermetic. Open compressors may be driven by steam or gas turbines or engines, or electric motors, with or without speed-increasing gears. (Engine and turbine drives are covered in Chapter 7, and electric motor drives in Chapter 45.)

Packaged electric-drive chillers may be open or hermetic and use two-pole, 50 or 60 Hz polyphase electric motors, with or without speed-increasing gears, which may be installed in a separate gearbox from the compressor. Several types of starters are commonly used with water-cooled chillers; starter selection depends on many variables, including cost, electrical system characteristics, voltage, and power company regulations at the installation. The electric drive motor can also be started with a variable-frequency drive (VFD), which provides a reduced-power start and can provide significant efficiency improvement at less than full load.

For larger chillers, starters or VFDs may be unit-mounted or remote-mounted from the chiller. The vast majority of units have unit mounting, which saves space, reduces installation costs, and increases the reliability of the chiller system. Unit-mounted starters or VFDs are predominant on centrifugal chillers because the entire chiller's electrical requirement is supplied with power through a single-point connection. Several electrical connections are required for remote-mounted starters or VFDs, and separate electrical feeds are required for the compressor, oil pump, and unit controls. These separate wiring connections must be field installed between the remote starter and the chiller.

Flooded coolers are commonly used, although direct-expansion coolers can also be used. The typical flooded cooler uses copper or copper alloy tubes that are mechanically expanded into the tube sheets, and, in some cases, into intermediate tube supports.

Because liquid refrigerant that flows into the compressor increases power consumption and may cause internal damage, mist eliminators or baffles are often used in flooded coolers to minimize refrigerant liquid entrainment in the suction gas. (Additional information on coolers for liquid chillers is found in Chapter 41.)

The condenser is generally water cooled, with refrigerant condensing on the outside of copper tubes. Large condensers may have refrigerant drain baffles, which direct refrigerant condensate from within the tube bundle directly to liquid drains, reducing the liquid film thickness on the lower tubes.

Air-cooled condensers can be used with units that use higher-pressure refrigerants, but with considerable increase in unit energy consumption at design conditions. Compare operating costs (including costs for cooling towers and condenser water pumps) for air-cooled and water-cooled condensing.

System modifications, including subcooling and economizing (described under Principles of Operation), are often used to conserve energy by enhancing the refrigeration cycle efficiency. Some units combine the condenser, cooler, and refrigerant flow control in one vessel; a subcooler may also be incorporated. (Additional information about thermodynamic cycles is in Chapter 2 of the 2013 *ASHRAE Handbook—Fundamentals*. Chapter 39 in this volume has information on condensers and subcoolers.)

Capacities and Types Available

Centrifugal packages are available from about 80 to 4000 tons at nominal conditions of 44°F leaving chilled-water temperature and 95°F leaving condenser water temperature, but these limits are continually changing. Field-assembled machines extend to about 10,000 tons. Single- and two-stage internally geared machines and two- and three-stage direct-drive machines are commonly used in packaged units. Electric motor-driven machines constitute the majority of units sold.

Selection of Refrigerant

All refrigerants have advantages and disadvantages that must be carefully considered when choosing a refrigerant and chiller. Legislative phaseout requirements also differ, based on environmental properties [e.g., ozone depletion potential (ODP)] and direct and indirect contributions to global warming as quantified by various metrics [e.g., global warming potential (GWP), total equivalent warming impact (TEWI), life-cycle climate performance (LCCP)]. Table 1 gives some properties of example refrigerants; for details, see Chapters 29 and 30 of the 2013 *ASHRAE Handbook—Fundamentals*.

All refrigerants have advantages and disadvantages, which must be carefully considered when choosing a refrigerant and a liquid-chilling system. Legislative phaseout requirements also differ, based on environmental properties such as ozone depletion potential (ODP), direct global warming potential (DGWP), and indirect global warming potential (IGWP). Table 1 summarizes these values for various refrigerants.

Global warming is a major global environmental concern. Refrigerants contribute to the greenhouse effect both directly (e.g., from leakage into the atmosphere during operation, maintenance, or at end of life) and indirectly (from energy used to operate air-conditioning equipment). The total warming effect of a chiller should take into account both these effects.

Direct contribution to global warming is evaluated by the refrigerant's GWP and the amount of refrigerant released in the atmosphere during the life of the equipment. Indirect contribution to global warming is related to chiller efficiency: a less efficient chiller requires more power to be generated at the local power plant, and thus has a greater indirect contribution to global warming. TEWI and LCCP are two metrics used to evaluate the combined effect of direct and indirect global warming contributions.

Whereas ozone-depleting substances are addressed by the Montreal Protocol, there are no global-warming-based phaseouts currently in effect for air-conditioning refrigerants in stationary applications. However, with the increasing attention on greenhouse gases, the industry is likely moving toward refrigerants with reduced GWP values.

Safety is also an important consideration. Regardless of the refrigerant selected, refrigerant leak detectors, alarms, and emergency ventilation are now required by code in many applications. Safety classifications of refrigerants are categorized by a code, with a letter designating toxicity levels [A = occupational exposure limit (OEL) of ≥400 ppm; B = OEL of <400 ppm] and a numeral indicating flammability ranking (1 to 3, with lower numbers indicating lower flammability). For example, R-123 has a B1 classification, and R-22 and R-134a have A1 classifications, as described in ASHRAE *Standard* 34. With proper safety procedures, R-123, R-22, and R-134a are all allowed under most North American codes.

Chiller operating pressure also affects pressure vessel requirements, emissive potential, and ancillary equipment:

- Any chiller with components operating below atmospheric pressure [e.g., R-123, R-1233zd(E)] must have a purge device to remove noncondensable gases, which may leak into the machine.
- Chillers with all components operating above atmospheric pressure (e.g., R-134a, R-22) do not require a purge device.
- A pressure vessel code may be required, depending on design working pressure.
- A chiller's refrigerant leak potential is related to the selected refrigerant's molecular weight and saturation pressure range, coupled with the machine's hermetic integrity and installation, maintenance, and service practices. In general, all chillers have the potential for extremely low emissions. ASHRAE *Standard* 147 provides methods for design, manufacturing and operational practices to achieve low leakage rates. Typical refrigerant leakage rates vary between 0.5 to 2.0% per year.

Refrigerant stability and **material compatibility** are also important considerations in chiller design; ways to control typical contaminants must be considered, as well. Various contaminants and their control are discussed in Chapter 7 of the 2014 *ASHRAE Handbook—Refrigeration*. Selecting elastomers and electrical insulating materials requires special attention because many of these materials are affected by refrigerants. Additional information on material selection can be found in Chapter 6 of the 2014 *ASHRAE Handbook—Refrigeration*, and information on testing methods can be found in ASHRAE *Standard* 97.

Table 1. Properties of Various Refrigerants

Refrigerant	ODP	GWP	Atmospheric Life, years	ASHRAE Classification	COP*	Evap. Pressure, psia	Cond. Pressure, psia
R-22	0.04	1760	12	A1	6.33	84.7	196.5
R-134a	0.00	1300	9.7	A1	6.32	50.7	128.6
R-1234yf	0.00	<1	0.027	A2L	6.08	54.1	129.8
R-1234ze(E)	0.00	<1	0.045	A2L	6.30	37.6	96.8
R-123	0.01	79	1.3	B1	6.68	5.92	18.9
R-1233zd(E)	0.0003	1	0.071	A1	6.62	8.66	26.6

* Cycle COP and pressures evaluated at 41/95°F saturation temperatures with zero subcooling and 80% isentropic compression efficiency.

Energy efficiency is a factor when selecting a refrigerant and chiller system. Each refrigerant discussed in this section has a different theoretical or baseline energy performance, according to its thermodynamic and thermophysical properties. At temperatures and pressures commonly applied in commercial comfort air-conditioning applications, R-123, R-134a, and R-22 are listed from highest to lowest theoretical COP. From that baseline, chiller manufacturers enhance their designs to optimize refrigerant properties. Furthermore, some chillers are more efficient at peak load, whereas others perform better at off-peak conditions, so an accurate load model is necessary to make a fully informed choice. Chiller performances at peak and off-peak operating conditions are a function of specific chiller and compressor design, not refrigerant type. More thorough data on refrigerant properties are available in Chapters 29 and 30 of the 2013 *ASHRAE Handbook—Fundamentals*.

For additional information on properties of refrigerants and their applications, see ASHRAE *Standards* 15 and 34.

3.2 PERFORMANCE AND OPERATING CHARACTERISTICS

Figure 9 shows a compressor's performance at constant speed with various inlet guide vane settings. Figure 10 shows a compressor's performance at various speeds in combination with inlet guide vanes. Capacity is modulated at constant speed by automatic adjustment of prerotation vanes that swirl the refrigerant gas at the impeller eye. This effect matches demand by shifting the compressor performance curve downward and to the left (as shown in Figure 9). Compressor efficiency, when unloaded in this manner, is superior to suction throttling. Some manufacturers automatically reduce diffuser width or throttle the impeller outlet with decreasing load.

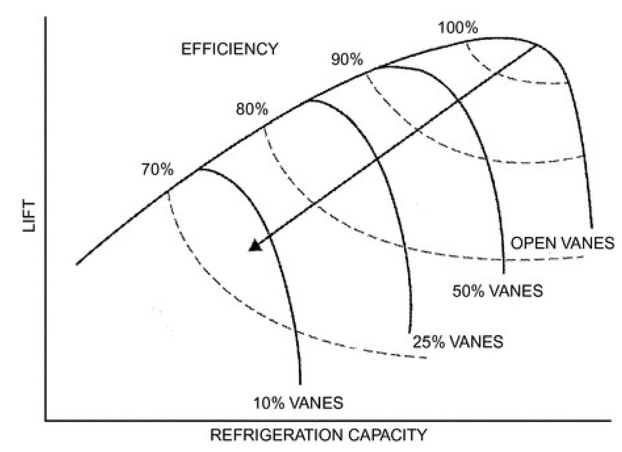

Figure 9. Typical Centrifugal Compressor Performance at Constant Speed
(Carrier 2004)

Speed control for a centrifugal compressor offers even lower power consumption. Variable-frequency drive (VFD) control continuously reduces the compressor's capacity, keeping operation in the maximum efficiency region over a much broader range of operation. Essentially, the VFD adjusts the compressor's speed to keep the inlet guide vanes (IGVs) as open as possible to meet the system lift requirements, with the lowest power consumption. Combined with the drop in condenser water temperature that occurs naturally in an air-conditioning system, the variable-speed centrifugal compressor more efficiently meets the flow and lift condition or state point required by the system.

Although capacity is directly related to a change in speed, the lift produced is proportional to the square of the change in speed.

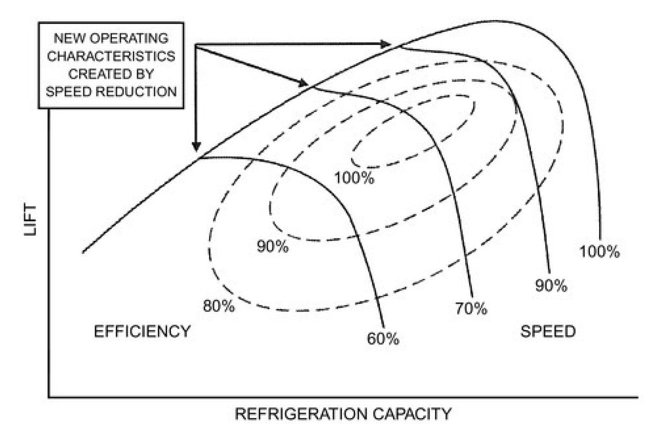

Figure 10. Typical Variable-Speed Centrifugal Compressor Performance
(Carrier 2004)

Hot-gas bypass allows the compressor to operate down to zero load. This feature is a particular advantage for intermittent industrial applications such as cooling quenching tanks. Bypass vapor maintains power consumption at the same level attained just before starting bypass, regardless of load reductions.

Figure 11 shows how **temperature lift** varies with load. A typical reduction in entering condenser water temperature of 10°F helps to reduce temperature lift at low load. Other factors producing lower lift at reduced loads include the following:

- Reduced condenser cooling water range (difference between entering and leaving temperatures, resulting from decreasing heat rejection)
- Decreased temperature difference between condensing refrigerant and leaving condenser water
- Similar decrease between evaporating refrigerant and leaving chilled-liquid temperature

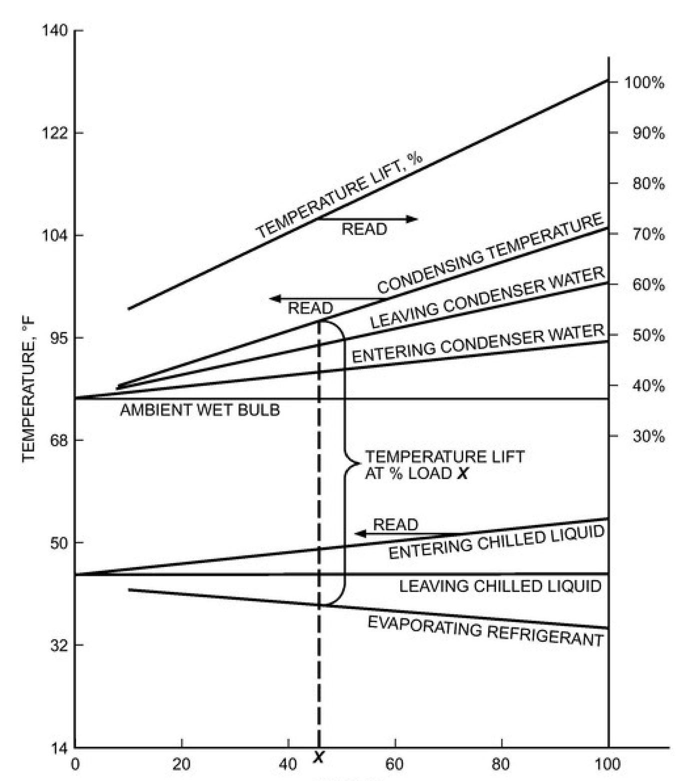

Figure 11. Temperature Relations in a Typical Centrifugal Liquid Chiller

In many cases, the actual reduction in temperature lift is even greater because the wet-bulb temperature usually drops with cooling load, producing a greater decrease in entering condenser water temperature.

Power consumption is reduced when the coldest possible condenser water is used, consistent with the chiller manufacturer's recommended minimum condenser water temperature. In cooling tower applications, minimum water temperatures should be controlled by a cooling tower bypass and/or by cooling tower fan control, not by reducing water flow through the condenser. Maintaining a high flow rate at lower temperatures minimizes fouling and the increase in power requirements caused by fouling.

Surging occurs when the system-specific work becomes greater than the compressor-developed specific work or above the surge line indicated in Figures 9 and 10. Excessively high temperature lift and corresponding specific work commonly originate from

- Excessive condenser or evaporator water-side fouling beyond the specified allowance
- Inadequate cooling tower performance and higher-than-design condenser water temperature
- Noncondensable gases in the condenser, which increase condenser pressure
- Condenser flow less than design

3.3 SELECTION

Ratings

A centrifugal chiller with specified details is typically selected using a manufacturer's computer-generated selection program, many of which are AHRI certified. Capacity, efficiency requirements, stability requirements, number of passes, water-side pressure drop in each of the heat exchangers, and desired electrical characteristics are input to select the chiller.

Stability is important in evaluating the part-load operating condition for a centrifugal chiller. If head pressure during part-load operation is higher than the chiller was selected for, the impeller may not be able to overcome the lift, and the chiller may begin unstable operation, causing the compressor to surge. For humid regions, typical stability is chosen at approximately 50% of full load at design entering condenser water, to guard against surge conditions.

Centrifugal chillers are typically selected for full- and/or part-load coefficient of performance (COP) targets. Then they are checked for part-load stability using software provided by the chiller manufacturer. A typical part-load stability check may involve running the chiller at part-load points at entering condenser water temperatures that follow a relief profile representative of the project geography.

Most manufacturers offer variations of evaporators, condensers, tube counts, tube types, compressor gears, impellers, etc. All of these permutations create an enormous product offering that is much too difficult to fit into a tabular format. For this reason, computer programs are the norm for chiller selections and ratings because they can analyze hundreds of combinations in a very short time.

Fouling

In accordance with AHRI *Standard* 550/590, manufacturers' ratings include a condenser fouling allowance of 0.00025 $ft^2 \cdot °F \cdot h/Btu$. (Chapter 39 has further information about fouling factors.) To reduce fouling, a minimum water velocity of about 3.3 ft/s is recommended in condensers. Maximum water velocities exceeding 11 ft/s are not recommended because of potential erosion problems with copper tubes.

Proper water treatment and regular tube cleaning are recommended for all liquid chillers to reduce power consumption and operating problems. Chapter 49 of the 2015 *ASHRAE Handbook—HVAC Applications* has water treatment information.

Continuous or daily monitoring of the quality of the condenser water is desirable. Checking the quality of the chilled liquid is also desirable. Intervals between checks become greater as the possibilities for fouling contamination become less (e.g., an annual check should be sufficient for closed-loop water-circulating systems for air conditioning). Corrective treatment is required, and periodic, usually annual, cleaning of the condenser tubes usually keeps fouling within the specified allowance. In applications where more frequent cleaning is desirable, an online cleaning system may be economical.

Noise and Vibration

Follow the chiller manufacturer's mounting recommendations to prevent transmission or amplification of vibration to adjacent equipment or structures. Auxiliary pumps, if not connected with flexible fittings, can induce vibration of the centrifugal unit, especially if the rotational speed of the pump is nearly the same as either the compressor prime mover or the compressor. Flexible tubing becomes less flexible when it is filled with liquid under pressure and some vibration can still be transmitted. General information on noise measurement and control may be found in Chapter 8 of the 2013 *ASHRAE Handbook—Fundamentals*, Chapter 48 of the 2015 *ASHRAE Handbook—HVAC Applications*, and AHRI *Standard* 575.

3.4 CONTROL CONSIDERATIONS

In centrifugal systems, the **chilled-liquid temperature sensor** is usually placed in thermal contact with the leaving chilled water. In electrical control systems, the electrical signal is transmitted to an electronic control module, which controls the operation of an electric motor(s) positioning the capacity-controlling inlet guide vanes. A current limiter is usually included on machines with electric motors. An electrical signal from a current transformer in the compressor motor controller is sent to the electronic control module. The module receives indications of both leaving chilled-water temperature and compressor motor current. The part of the electronic control module responsive to motor current is called the current limiter. It overrides the demands of the temperature sensor.

Inlet guide vanes, independent of demands for cooling, do not open more than the position that results in the present setting of the current limiter. The chilled-liquid temperature sensor provides a signal. The controlling module receives both that signal and the motor current electrical signal and controls the positioning of the inlet guide vanes.

The **current limiter** on most machines can limit current draw during periods of high electrical demand charges. This control can be set from about 40 to 100% of full-load current. When power consumption is limited, cooling capacity is correspondingly reduced. If cooling load only requires 50% of the rated load, the current (or demand) limiter can be set at 50% without loss of cooling. By setting the limiter at 50% of full current draw, any subsequent high demand charges are prevented during pulldown after start-up. Even during periods of high cooling load, it may be desirable to limit electrical demand if a small increase in chiller liquid temperature is acceptable. If temperature continues to decrease after capacity control reaches its minimum position, a low-temperature control stops the compressor and restarts it when a rise in temperature indicates the need for cooling. Manual controls may also be provided to bypass temperature control. Capacity control is at its minimum position when the compressor starts, to provide an unloaded starting condition.

Additional operating controls are needed for appropriate operation of lubricant pumps, lubricant heaters, purge units, and refrigerant transfer units. An **antirecycle timer** should also be included to prevent frequent motor starts. Multiple-unit applications require additional controls for capacity modulation and proper unit sequencing. (See the section on Multiple-Chiller Systems.)

Safety controls protect the unit under abnormal conditions. Safety cutouts may be required for high condenser pressure, low evaporator refrigerant temperature or pressure, low lubricant pressure, high lubricant temperature, high motor temperature, and high discharge temperature. Auxiliary safety circuits are usually provided on packaged chillers. At installation, the circuits are field-wired to field-installed safety devices, including auxiliary contacts on the pump motor controllers and flow switches in the chilled-water and condenser water circuits. Safety controls are usually provided in a lockout circuit, which trips out the compressor motor controller and prevents automatic restart. The controls reset automatically, but the circuit cannot be completed until a manual reset switch is operated and the safety controls return to their safe positions.

3.5 AUXILIARIES

Purge units may be required for centrifugal liquid-chilling machines to maintain system hermetic chemistry integrity and efficiency. ASHRAE *Standard* 147 requires purge units for liquid-chilling machines using refrigerants with working pressures below atmospheric pressure (e.g., R-11, R-113, R-123, R-245fa). If a purge unit were not used, air and moisture would accumulate in the refrigerant side. Noncondensable gases collect in the condenser during operation, reducing the heat-transfer coefficient and increasing condenser pressure as a result of both their insulating effect and their partial pressure. Compressor power consumption increases, capacity decreases, and surging may occur.

Free moisture may build up once the refrigerant becomes saturated. Acids produced by a reaction between free moisture and the refrigerant then cause internal corrosion. A purge unit prevents accumulation of noncondensable gases and ensures internal cleanliness of the chiller. However, a purge unit does not reduce the need to check for and repair leaks, which is required maintenance for any liquid chiller. Purge units may be manual or automatic, compressor operated, or compressorless. To reduce the potential for air leaks when chillers are off, chillers may be heated externally to pressurize them to atmospheric pressure.

ASHRAE *Standard* 15 requires most purge units and rupture disks to be vented outdoors. Because of environmental concerns and the increasing cost of refrigerants, high-efficiency (air-to-refrigerant) purges are available that reduce refrigerant losses during normal purging.

Lubricant coolers may be water cooled, using condenser water when the quality is satisfactory, or chilled water when a small loss in net cooling capacity is acceptable. These coolers may also be refrigerant or air cooled, eliminating the need for water piping to the cooler.

A **refrigerant transfer unit** may be provided for maintenance of centrifugal liquid chillers. The unit consists of a small reciprocating compressor with electric motor drive, a condenser (air or water cooled), a lubricant reservoir and separator, valves, and interconnecting piping. Refrigerant transfers in three steps:

1. **Gravity drain.** When the receiver is at the same level as or below the cooler, some liquid refrigerant may be transferred to the receiver by opening valves in the interconnecting piping.
2. **Pressure transfer.** By resetting valves and operating the compressor, refrigerant gas is pulled from the receiver to pressurize the cooler, forcing refrigerant liquid from the cooler to the storage receiver. If the chilled-liquid and condenser water pumps can be operated to establish a temperature difference, refrigerant migration from the warmer vessel to the colder vessel can also be used to help transfer refrigerant.
3. **Pump-out.** After the liquid refrigerant has been transferred, valve positions are changed and the compressor is operated to pump refrigerant gas from the cooler to the transfer unit condenser, which sends condensed liquid to the storage receiver. If any chilled liquid (water, brine, etc.) remains in the cooler tubes, pump-out must be stopped before cooler pressure drops below the saturation condition corresponding to the chilled liquid's freezing point.

If the saturation temperature corresponding to cooler pressure is below the chilled-liquid freezing point when recharging, refrigerant gas from the storage receiver must be introduced until cooler pressure is above this condition. The compressor can then be operated to pressurize the receiver and move refrigerant liquid into the cooler without danger of freezing.

Water-cooled transfer unit condensers provide fast refrigerant transfer. Air-cooled condensers eliminate the need for water, but they are slower and more expensive.

3.6 SPECIAL APPLICATIONS

Free Cooling

Cooling without operating the compressor of a centrifugal liquid chiller is called free cooling. When a supply of condenser water is available at a temperature below the needed chilled-water temperature, some chillers can operate as a thermal siphon. Low-temperature condenser water condenses refrigerant, which is either drained by gravity or pumped into the evaporator. Higher-temperature chilled water causes the refrigerant to evaporate, and vapor flows back to the condenser because of the pressure difference between the evaporator and the condenser. This free-cooling accessory is limited to a fraction of the chiller design capacity, and this option is not available from all manufacturers. Free-cooling capacity depends on chiller design and the temperature difference between the desired chilled-water temperature and the condenser water temperature. Free cooling is also available external to the chiller using either direct or indirect methods, as described in Chapter 40.

Heat Recovery Systems

Any building or plant requiring simultaneous operation of heat-producing and cooling equipment has the potential for a heat recovery installation.

Heat recovery systems extract heat from liquid being chilled and reject some of that heat, plus the energy of compression, to a warm-water circuit for reheat or heating. Air-conditioned spaces thus furnish heating for other spaces in the same building. During the full-cooling season, all heat must be rejected outdoors, usually by a cooling tower. During spring or fall, some heat is required indoors, while some heat extracted from air-conditioned spaces must be rejected outdoors.

Heat recovery offers a low heating cost and reduces space requirements for equipment. The control system must, however, be designed carefully to take the greatest advantage of recovered heat and to maintain proper temperature and humidity in all parts of the building. Chapter 9 covers balanced heat recovery systems.

Because cooling tower water is not satisfactory for heating coils, a separate, closed warm-water circuit with another condenser bundle or auxiliary condenser, in addition to the main water chiller condenser, must be provided. In some cases, it is economically feasible to use a standard condenser and a closed-circuit heat exchanger.

Instead of rejecting all heat extracted from the chilled liquid to a cooling tower, a separate, closed condenser cooling water circuit is heated by the condensing refrigerant for comfort heating, preheating, or reheating. Some factory packages include an extra condenser water circuit, either a double-bundle condenser or an auxiliary condenser.

A centrifugal heat recovery package is controlled as follows:

Chilled-liquid temperature is controlled by a sensor in the leaving chilled-water line signaling the capacity control device.

Hot-water temperature is controlled by a sensor in the hot-water line that modulates a cooling tower bypass valve. As the heating requirement increases, hot-water temperature drops, opening the tower bypass slightly. Less heat is rejected to the tower, condensing temperature increases, and hot-water temperature is restored as more heat is rejected to the hot-water circuit.

The hot-water temperature selected affects the installed cost of the heat recovery package, as well as on the power consumption while heating. Lower hot-water temperatures of 95 to 105°F result in a less expensive machine that uses less power. Higher temperatures require greater compressor motor output, perhaps higher-pressure condenser shells, sometimes extra compression stages, or a cascade arrangement. Installed cost of the centrifugal heat recovery machine increases as a result.

Another concern in design of a central chilled-water plant with heat recovery compressors is the relative size of cooling and heating loads. These loads should be equalized on each machine so that the compressor may operate at optimum efficiency during both full cooling and full heating seasons. When the heating requirement is considerably smaller than the cooling requirement, multiple chillers lower operating costs and allow less-expensive standard centrifugal packages to be used for the rest of the cooling requirement. In multiple packages, only one unit is designed for heat recovery and carries the full heating load.

Another consideration for heat recovery chiller systems is the potential for higher cooling energy use. A standard commercial building water chiller operates with condenser water temperatures at or below 100°F. For heat recovery to be of practical use, the condenser water may need to operate at higher temperatures, thereby increasing the chiller's energy consumption. The design engineer must examine the trade-off between higher cooling energy use versus lower heating energy use; the heat recovery chiller system may not necessarily be advantageous.

Air-Cooled System

Two types of air-cooled centrifugal systems are used. One consists of a water-cooled centrifugal package with a closed-loop condenser water circuit. Condenser water is cooled in a water/air heat exchanger. This arrangement results in higher condensing temperature and increased power consumption. In addition, winter operation requires using glycol in the condenser water circuit, which reduces the heat transfer coefficient of the unit.

The other type of unit is directly air-cooled, which eliminates the intermediate heat exchanger and condenser water pumps, resulting in lower power requirements. However, condenser and refrigerant piping must be leak free.

Because a centrifugal machine will surge if it is subjected to a pressure appreciably higher than design, the air-cooled condenser must be designed to reject the required heat. In common practice, selection of a reciprocating air-cooled machine is based on an outdoor dry-bulb temperature that will be exceeded 5% of the time. A centrifugal chiller may be unable to operate during such times because of surging, unless the chilled-water temperature is raised proportionately. Thus, the compressor impeller(s) and/or speed should be selected for the maximum dry-bulb temperature to ensure that the desired chilled-water temperature is maintained at all times. In addition, the condenser coil must be kept clean.

An air-cooled centrifugal chiller should allow the condensing temperature to fall naturally to about 70°F during colder weather. The resulting decrease in compressor power consumption is greater than that for reciprocating systems controlled by thermal expansion valves.

During winter shutdown, precautions must be taken to prevent cooler liquid freezing caused by a free cooling effect from the air-cooled condenser. A thermostatically controlled heater in the cooler, in conjunction with a low-refrigerant-pressure switch to start the chilled-liquid pumps, will protect the system.

Other Coolants

Centrifugal liquid-chilling units are most frequently used for water-chilling applications, but they are also used with secondary coolants such as calcium chloride, methylene chloride, ethylene glycol, and propylene glycol. (Chapter 31 of the 2013 *ASHRAE Handbook—Fundamentals* describes properties of secondary coolants.) Coolant properties must be considered in calculating heat transfer performance and pressure drop. Because of the greater temperature rise, higher compressor speeds and possibly more stages may be required for cooling these coolants. Compound and/or cascade systems are required for low-temperature applications.

Vapor Condensing

Many process applications condense vapors such as ammonia, chlorine, or hydrogen fluoride. Centrifugal liquid-chilling units are used for these applications.

3.7 OPERATION AND MAINTENANCE

Proper operation and maintenance are essential for reliability, longevity, and safety. Chapter 39 of the 2015 *ASHRAE Handbook—HVAC Applications* includes general information on principles, procedures, and programs for effective maintenance. The manufacturer's operation and maintenance instructions should also be consulted for specific procedures. In the United States, Environmental Protection Agency (EPA) regulations require (1) certification of service technicians, (2) a statement of minimum pressures necessary during system evacuation, and (3) definition of when a refrigerant charge must be removed before opening a system for service. All service technicians or operators maintaining systems must be familiar with these regulations.

Normal operation conditions should be established and recorded at initial start-up. Changes from these conditions can be used to signal the need for maintenance. One of the most important items is to maintain a leak-free unit.

Leaks on units operating at subatmospheric pressures allow air and moisture to enter the unit, which increases condenser pressure. Although the purge unit can remove noncondensable gases sufficiently to prevent an increase in condenser pressure, continuous entry of air and attendant moisture into the system promotes refrigerant and lubricant breakdown and corrosion. Leaks from units that operate above atmospheric pressure may release environmentally harmful refrigerants. Regulations require that annual leakage not exceed a percentage of the refrigerant charge. It is good practice, however, to find and repair all leaks.

Periodic analysis of the lubricant and refrigerant charge can also identify system contamination problems. High condenser pressure or frequent purge unit operation indicate leaks that should be corrected as soon as possible. With positive operating pressures, leaks result in loss of refrigerant and operating problems such as low evaporator pressure. A leak check should also be included in preparation for a long-term shutdown. (Chapter 7 in the 2014 *ASHRAE Handbook—Refrigeration* discusses the harmful effects of air and moisture.)

Normal maintenance should include periodic lubricant and refrigerant filter changes as recommended by the manufacturer. All safety controls should be checked periodically to ensure that the unit is protected properly.

Cleaning inside tube surfaces may be required at various intervals, depending on water condition. Condenser tubes may only need annual cleaning if proper water treatment is maintained. Cooler tubes need less frequent cleaning if the chilled-water circuit is a closed loop.

If the refrigerant charge must be removed and the unit opened for service, the unit should be leak-checked, dehydrated, and evacuated properly before recharging. Chapter 8 of the 2014 *ASHRAE Handbook—Refrigeration* has information on dehydrating, charging, and testing.

4. SCREW LIQUID CHILLERS

4.1 EQUIPMENT

Components and Their Function

Single- and twin-screw compressors are positive-displacement machines with nearly constant flow performance. Compressors for liquid chillers can be both lubricant-injected and lubricant-injection-free. (Chapter 38 describes screw compressors in detail.)

The cooler may be flooded or direct expansion. Neither design has a cost advantage over the other. The flooded cooler is more sensitive to freezing, requires more refrigerant, and requires closer evaporator pressure control, but its performance is easier to predict and it can be cleaned. The DX cooler requires closer mass flow control, is less likely to freeze, and returns lubricant to the lubricant system rapidly. The decision to use one or the other is based on the relative importance of these factors on a given application.

Screw coolers have the following characteristics: (1) high maximum working pressure, (2) continuous lubricant scavenging, (3) no mist eliminators (flooded coolers), and (4) distributors designed for high turndown ratios (direct-expansion coolers). A suction-gas, high-pressure liquid-refrigerant heat exchanger is sometimes incorporated into the system to provide subcooling for increased thermal expansion valve flow and reduced power consumption. (For further information on coolers, see Chapter 42.)

Flooded coolers were once used in units with a capacity larger than about 400 tons. DX coolers are also used in larger units up to 800 tons with a servo-operated expansion valve having an electronic controller that measures evaporating pressure, leaving secondary coolant temperature, and suction gas superheat.

The condenser may be included as part of the liquid-chilling package when water cooled, or it may be remote. Air-cooled liquid chilling packages are also available. When remote air-cooled or evaporative condensers are applied to liquid-chilling packages, a liquid receiver generally replaces the water-cooled condenser on the package structure. Water-cooled condensers are the cleanable shell-and-tube type (see Chapter 39).

Lubricant cooler loads vary widely, depending on the refrigerant and application, but they are substantial because lubricant injected into the compressor absorbs part of the heat of compression. Lubricant is cooled by one of the following methods:

- Water-cooled using condenser water, evaporative condenser sump water, chilled water, or a separate water- or glycol-to-air cooling loop
- Air-cooled using a lubricant-to-air heat exchanger
- Refrigerant-cooled (where lubricant cooling load is low)
- Liquid injection into the compressor
- Condensed refrigerant liquid thermal recirculation (thermosiphon), where appropriate compressor head pressure is available

The latter two methods are the most economical both in first cost and overall operating cost because cooler maintenance and special water treatment are eliminated.

Efficient lubricant separators are required. The types and efficiencies of these separators vary according to refrigerant and application. Field-built systems require better separation than complete factory-built systems. Ammonia applications are most stringent because no appreciable lubricant returns with suction gas from the flooded coolers normally used in ammonia applications. However, separators are available for ammonia packages, which do not require the periodic addition of lubricant customary on other ammonia systems. The types of separators used are centrifugal, demister, gravity, coalescer, and combinations of these.

Hermetic compressor units may use a centrifugal separator as an integral part of the hermetic motor while cooling the motor with discharge gas and lubricant simultaneously. A schematic of a typical refrigeration system is shown in Figure 12.

Capacities and Types Available

Screw compressor liquid chillers are available as factory-packaged units from about 30 to 1250 tons. Both open and hermetic styles are manufactured. Packages without water-cooled condensers, with receivers, are made for use with air-cooled or evaporative condensers. Most factory-assembled liquid chilling packages use R-134a.

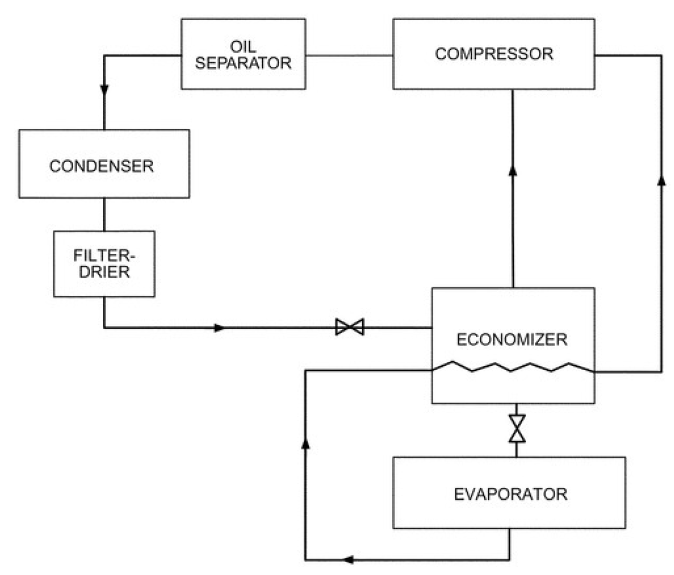

Figure 12. Refrigeration System Schematic

Additionally, compressor units, comprised of a compressor, hermetic or open motor, and lubricant separator and system, are available from 20 to 2000 tons. These are used with remote evaporators and condensers for low-, medium-, and high-evaporating-temperature applications. Condensing units, similar to compressor units in range and capacity but with water-cooled condensers, are also built. Similar open motor-drive units are available for ammonia, as are booster units.

Selection of Refrigerant

The refrigerants most commonly used with screw compressors on liquid chiller applications are R-134a and R-717. Active use of R-12, R-22, and R-500 has been discontinued for new equipment.

4.2 PERFORMANCE AND OPERATING CHARACTERISTICS

Figure 6 compares screw compressor operating characteristics with those for reciprocating and centrifugal compressors. Because the screw compressor is a positive-displacement compressor, it does not surge. Additionally, because it has no clearance volume in the compression chamber, it pumps high-volumetric flows at high pressure. Consequently, screw compressor chillers suffer the least capacity reduction at high condensing temperatures.

The screw compressor provides stable operation over the whole working range because it is a positive-displacement machine. The working range is wide because discharge temperature is kept low and is not a limiting factor because of lubricant injection into the compression chamber. Consequently, the compressor is able to operate single-stage at high pressure ratios.

An economizer can be installed to improve capacity and lower power consumption at full-load operation. An example is shown in Figure 12, where the main refrigerant liquid flow is subcooled in a heat exchanger connected to the intermediate-pressure port in the compressor. The evaporating pressure in this heat exchanger is higher than the suction pressure of the compressor.

Lubricant separators must be sized for the compressor size, type of system (factory assembled or field connected), refrigerant, and type of cooler. Direct-expansion coolers have less stringent separation requirements than do flooded coolers. In a direct-expansion system, refrigerant evaporates in the tubes, which means that velocity is kept so high that lubricant rapidly returns to the compressor. In a flooded evaporator, the refrigerant is outside the tubes, and an external lubricant-return device must be used to minimize the concentration of lubricant in the cooler. Suction or discharge check valves are used to minimize backflow and lubricant loss during shutdown.

Because the lubricant is exposed to the high-pressure side of the unit, precautions must be taken to prevent lubricant dilution. Dilution can also be caused by excessive floodback through the suction or intermediate ports; unless properly monitored, it may go unnoticed until serious operating or mechanical problems are experienced.

4.3 SELECTION

Ratings

Screw liquid chiller ratings are generally presented similarly to those for centrifugal chiller ratings. Tabular values include capacity and power consumption at various chilled-water and condenser water temperatures. In addition, ratings are given for packages without the condenser that list capacity and power versus chilled-water temperature and condensing temperature. Ratings for compressors alone are also common, showing capacity and power consumption versus suction temperature and condensing temperature for a given refrigerant.

Power Consumption

Typical part-load power consumption is shown in Figure 13. Power consumption of screw chillers benefits from reducing condensing water temperature as the load decreases, as well as operating at the lowest practical pressure at full load. However, because direct-expansion systems require a pressure differential, the power consumption saving is not as great at part load, as shown.

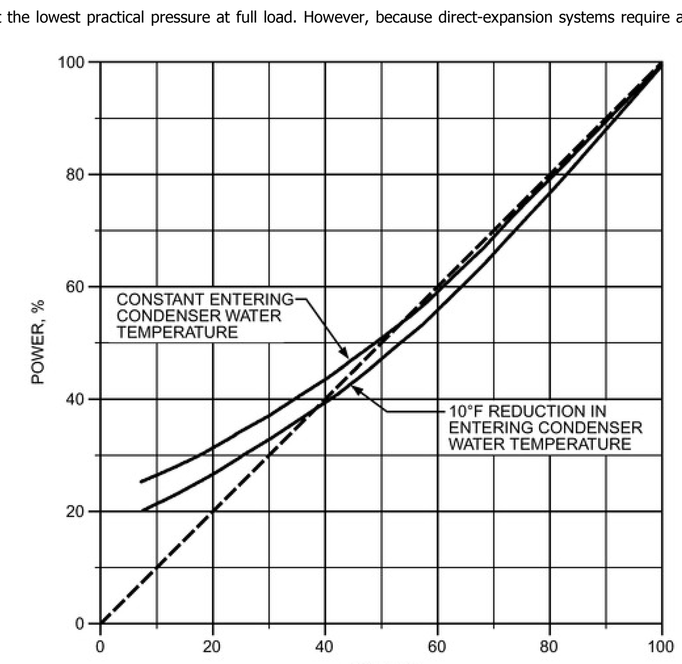

Figure 13. Typical Screw Compressor Chiller Part-Load Power Consumption

Fouling

A fouling allowance of 0.00025 $ft^2 \cdot °F \cdot h/Btu$ is incorporated in screw compressor chiller ratings. Excessive fouling (above design value) increases power consumption and reduces capacity. Fouling water-cooled lubricant coolers results in higher than desirable lubricant temperatures.

4.4 CONTROL CONSIDERATIONS

Screw chillers provide continuous capacity modulation, from 100% capacity down to 10% or less. The leaving chilled-liquid temperature is sensed for capacity control. Safety controls commonly required are (1) lubricant failure switch, (2) high-discharge-pressure cutout, (3) low-suction-pressure switch, (4) cooler flow switch, (5) high-lubricant- and discharge-temperature cutout, (6) hermetic motor inherent protection, (7) lubricant pump and compressor motor overloads, and (8) low-lubricant-temperature (floodback/dilution) protection. The compressor is unloaded automatically (slide valve driven to minimum position) before starting. Once it starts operating, the slide valve is controlled hydraulically by a temperature-load controller that energizes the load and unloads solenoid valves.

The current limit relay protects against motor overload from higher than normal condensing temperatures or low voltage, and also allows a demand limit to be set. An antirecycle timer is used to prevent overly frequent recycling. Lubricant sump heaters are energized during the off cycle. A hot-gas-capacity control is optionally available and prevents automatic recycling at no-load conditions such as is often required in process liquid chilling. A suction-to-discharge starting bypass sometimes aids starting and allows use of standard starting torque motors.

Some units are equipped with electronic regulators specially developed for screw compressor characteristics. These regulators include proportional-integrating (PI) control of leaving brine temperature and functions such as automatic/manual control, capacity indication, time circuits to prevent frequent recycling and to bypass the lubricant pressure cutout during start-up, switch for unloaded starting, etc. (Typical external connections are shown in Figure 14.)

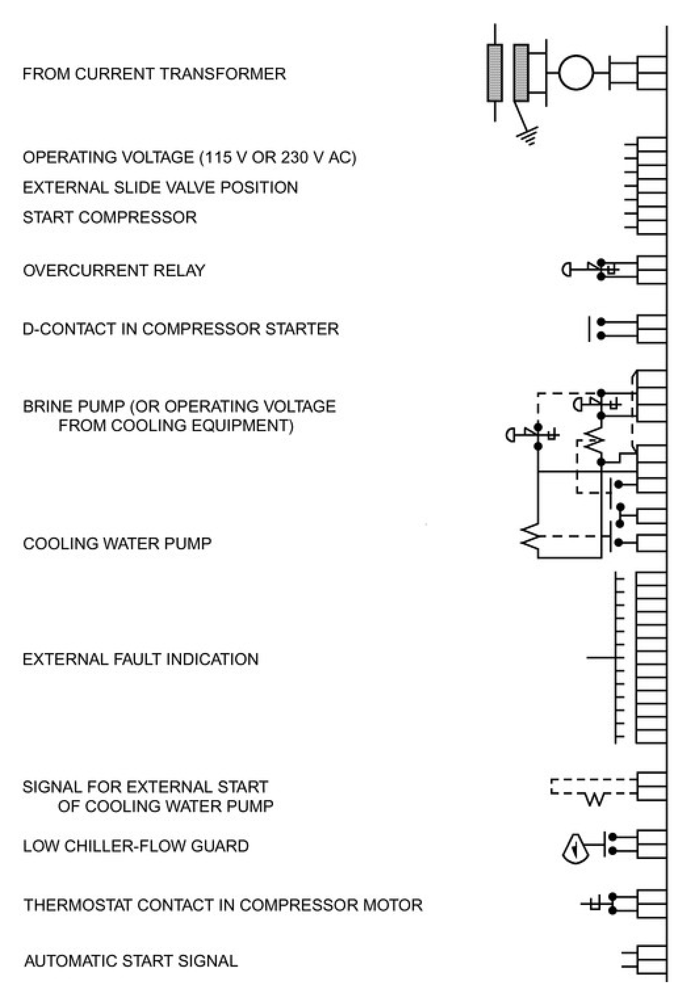

Figure 14. Typical External Connections for Screw Compressor Chiller

4.5 AUXILIARIES

A **refrigerant transfer unit** is similar to the unit described in the section on Auxiliaries under Centrifugal Liquid Chillers, and is designed for an appropriate operating pressure. Its flexibility is increased by including a reversible liquid pump on the unit. It is available as a portable unit or mounted on a storage receiver.

A **lubricant-charging pump** is useful for adding lubricant to the pressurized lubricant sump. Two types are used: a manual pump and an electric motor-driven positive-displacement pump.

Acoustical enclosures are available for installations that require low noise levels.

4.6 SPECIAL APPLICATIONS

Because of the screw compressor's positive-displacement characteristic and lubricant-injected cooling, its use for high-pressure-differential applications is limited only by power considerations and maximum design working pressures. Therefore, it is used for many special applications because of reasonable compressor cost and no surge characteristic. Some of the fastest-growing areas include the following:

- Heat recovery installations
- Air-cooled split packages with field-installed interconnecting piping, and factory-built rooftop packages
- Low-temperature brine chillers for process cooling
- Ice rink chillers
- Power transmission line lubricant cooling

High-temperature compressor and condensing units are used increasingly for air conditioning because of the higher efficiency of direct air-to-refrigerant heat exchange resulting in higher evaporating temperatures. Many of these installations have air-cooled condensers.

4.7 MAINTENANCE

Manufacturer's maintenance instructions should be followed, especially because some items differ substantially from reciprocating or centrifugal units. Water-cooled condensers must be cleaned of scale periodically (see the section on General Maintenance). If condenser water is also used for the lubricant cooler, this should be considered in the treatment program. Lubricant coolers operate at higher temperatures and lower flows than condensers, so it is possible that the lubricant cooler may have to be serviced more often than the condenser.

Because large lubricant flows are a part of the screw compressor system, monitor the lubricant filter pressure drop carefully and change the elements periodically. This is particularly important in the first month or so after start-up of any factory-built package, and is essential on field-erected systems. Because the lubricant and refrigeration systems merge at the compressor, loose dirt and fine contaminants in the system eventually find their way to the lubricant sump, where they are removed by the lubricant filter. Similarly, monitor the filter-drier cartridges for pressure drop and moisture during initial start and regularly thereafter. Generally, if a system reaches acceptable dryness, it stays that way unless it is opened.

It is good practice to check the lubricant for acidity periodically, using commercially available acid test kits. Lubricant does not need to be changed unless it is contaminated by water, acid, or metallic particles. Also, a refrigerant sample should be analyzed yearly to determine its condition.

Yearly or during a regularly scheduled shutdown, (1) check and calibrate all operation and safety controls, (2) tighten all electrical connections, (3) inspect power contacts in starters, (4) dielectrically check hermetic and open motors, and (5) check the alignment of open motors.

Regularly perform leak testing of the unit. A water-cooled package used for summer cooling should be leak tested annually. A flooded unit with proportionately more refrigerant in it, used for year-round cooling, should be tested every four to six months. A process air-cooled chiller designed for year-round operation 24 h per day should be checked every one to three months.

Based on 6000 operating hours per year and depending on the preceding considerations, a typical inspection or replacement timetable is as follows:

Shaft seals	1.5 to 4 yr	Inspect
Hydraulic cylinder seals	1.5 to 4 yr	Replace
Thrust bearings	4 to 6 yr	Check preload via shaft end play every 6 months and replace as required
Shaft bearings	7 to 10 yr	Inspect

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ONLINE RESOURCE

Ozone Secretariat, U.N. Environment Programme. ozone.unep.org.

The preparation of this chapter is assigned to TC 8.1, Positive Displacement Compressors, and TC 8.2, Centrifugal Machines.