Reference Note 32

Compression Cooling

The great majority of cooling equipment worldwide operates by compression. This Note is an overview of compression cooling systems, emphasizing the aspects of design and equipment selection that affect system efficiency.

In principle, you could select a system with the highest efficiency simply by using manufacturers' efficiency quotations. However, this is not a prudent approach. The efficiency of a cooling system is determined by a variety of factors involving cost, safety, space requirements, maintenance, and other issues. You need to consider all of these to achieve a good system.

There is fierce competition among manufacturers with different designs, and each touts its own advantages while being silent about its own disadvantages. This Note will help you to navigate through the competing claims by understanding the principles of compression cooling. It will enable you to ask the right questions when selecting new equipment, and it will give you a solid foundation for making efficiency improvements to existing cooling systems.

How Compression Cooling Works

All contemporary space cooling and process cooling equipment exploits the fact that a liquid absorbs heat when it evaporates. (There are a few exceptions, which are limited to unusual applications.) A liquid used for cooling is called a "refrigerant." The energy absorbed by the refrigerant in changing from a liquid to a vapor is called its "latent heat." When this heat is drawn from a body, the body is cooled. For a good demonstration of this, swab some alcohol on your arm. The wet spot will chill your skin until it all evaporates.

You can create cooling without any machinery if you have enough liquid to evaporate. Water has been used for cooling since before the dawn of humanity. However, it is not very satisfactory as a coolant under ambient conditions because it evaporates too slowly. There are many liquids that provide a large evaporative cooling effect, but they are not cheap enough to be used on a once-through basis.

Mechanical cooling can use more effective refrigerants and recycle them indefinitely. The process of doing this is called a "cooling cycle." The outer shell or casing of the cooling equipment serves as a pressure vessel, isolating the refrigerant from air and atmospheric pressure. This allows the cooling cycle to operate under conditions that provide the greatest cooling capacity and efficiency from the refrigerant.

The most common kind of cooling equipment uses a compression cooling cycle. After the refrigerant has been evaporated by heat from the cooling load, the vapor is compressed. This raises the temperature of the gas well above ambient temperature, so that the heat in the gas can be removed by cooling it with air or water at ambient temperature. Removing the heat causes the compressed gas to condense back to a warm liquid.

The warm refrigerant liquid from the condenser is metered into the cooling area (evaporator) by a flow control device of some kind. The pressure in the evaporator is determined by the suction of the compressor and by the rate of evaporation. Because the evaporator pressure is lower than the condenser pressure, a small portion of the liquid refrigerant "flashes" into vapor when it passes through the control device. This flashing cools the remaining liquid to the temperature of the evaporator. The liquid refrigerant is now ready to absorb heat from the cooling load, repeating the cycle.

Refrigerants

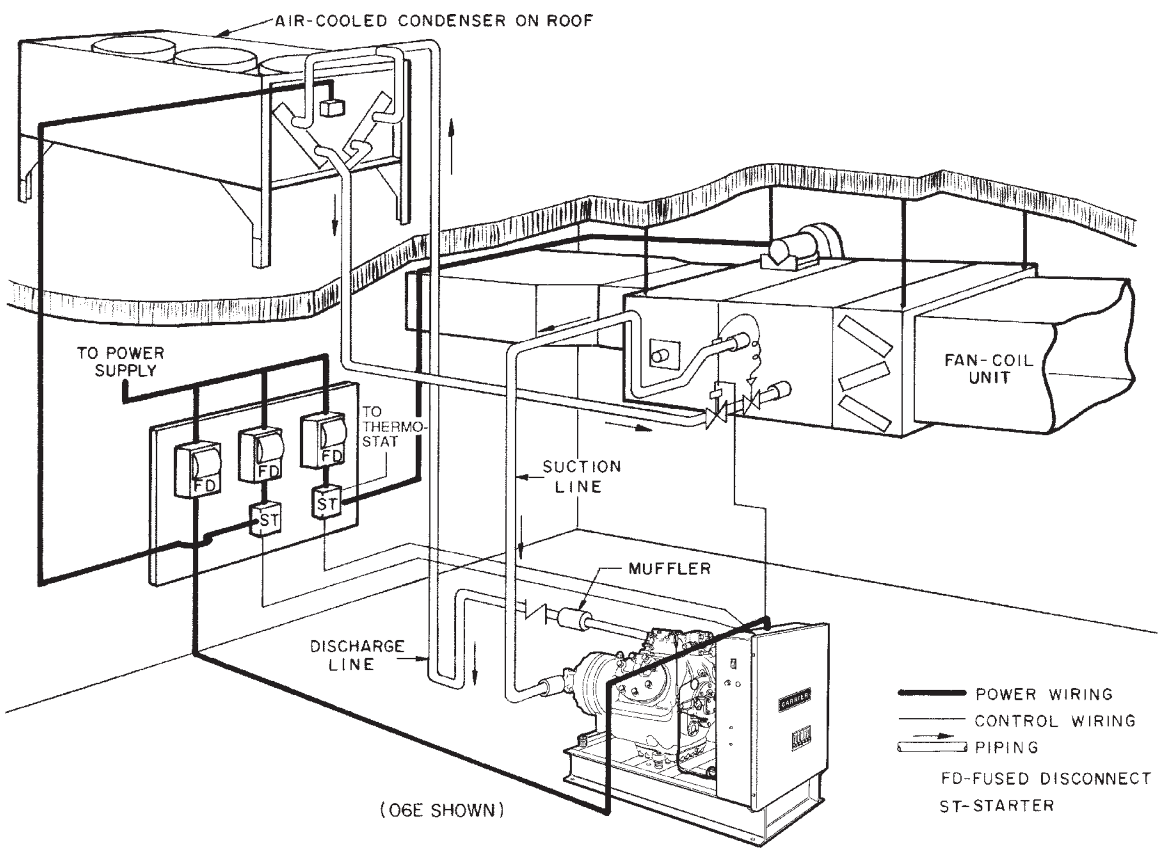
Nowadays, selecting the refrigerant may be the first choice you make in selecting or designing a cooling system. The choice of refrigerant limits the system's efficiency and affects the design of all the system hardware. Safety concerns with some refrigerants dictate where the equipment can be located, and how the surrounding space must be designed. Refrigerant selection has recently become more important and complex because of environmental concerns. To learn more about refrigerants and how to select them, see Reference Note 34, Refrigerants.

The Components of a Compression Cooling System

All compression cooling systems have five basic elements. As illustrated by the typical system in Figure 1, they are:

- the ***compressor.*** On its discharge side, the compressor increases the pressure of the evaporated refrigerant vapor to raise its temperature. On the suction side, the compressor lowers the pressure of the liquid refrigerant, causing the refrigerant to evaporate more rapidly, and at a lower temperature.

  In most systems, cooling capacity is regulated by varying the output of the compressor. There are several major types of compressors, discussed below.
- the ***evaporator,*** which is a heat exchanger on the suction side of the compressor. This is where the liquid refrigerant evaporates to do its work. If the machine is designed to cool air directly, as in Figure 1, the evaporator is an air coil. If the machine is designed to cool liquid, the evaporator typically is a tube-and-shell heat exchanger. (A cooling machine that is designed to deliver cooling by means of a liquid is commonly called a "liquid chiller," or simply a "chiller.")
- the ***condenser,*** which is a heat exchanger on the discharge side of the compressor. The high-pressure refrigerant gas from the compressor is cooled in the condenser so that it returns to a liquid state. If



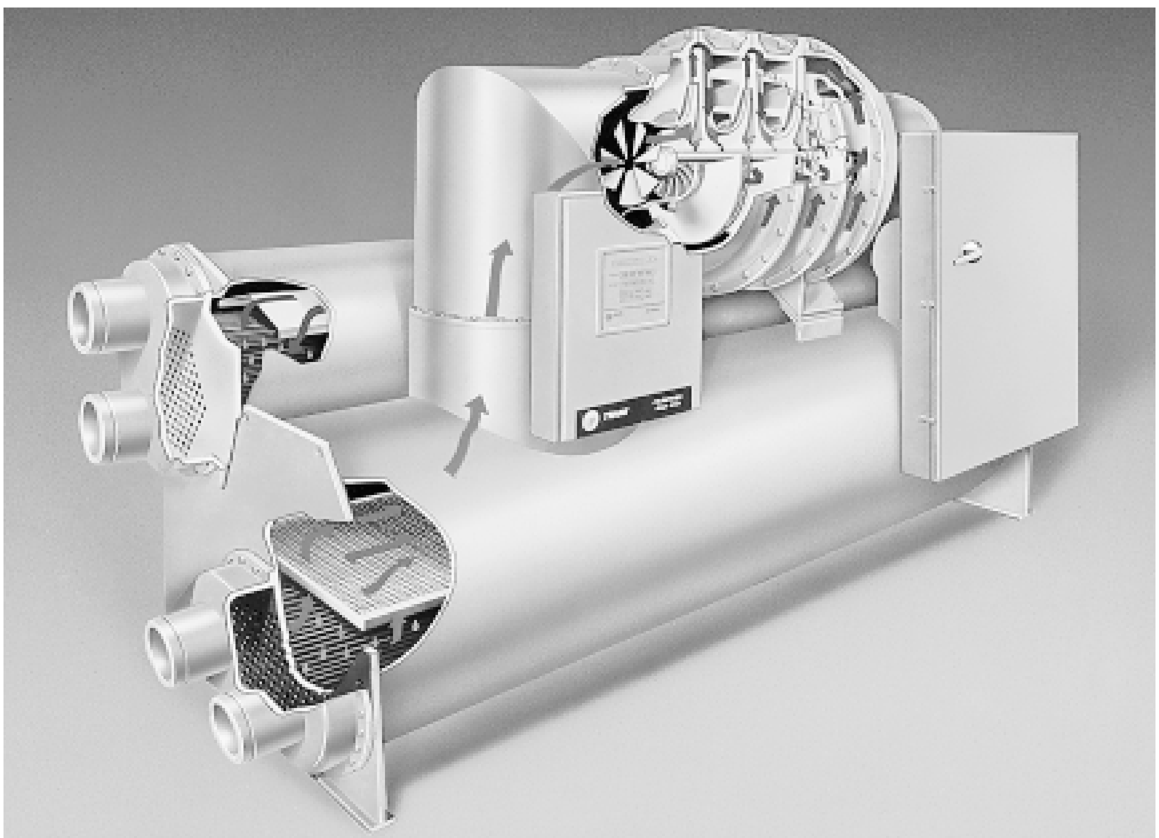
Carrier Corporation

Fig. 1 The elements of a compression cooling system In this system, the evaporator is the coil in the fan-coil unit. An expansion valve, installed on the side of the fan-coil unit, serves as a refrigerant metering device. The condenser is an air coil on the outside of the building. The system does not have a distinct refrigerant accumulator, but the bottom of the condenser coil and the refrigerant liquid pipe serve this function.

the cooling medium is air, the condenser is an air coil. If the cooling medium is water, the condenser is usually a tube-and-shell heat exchanger, or sometimes a coaxial tube heat exchanger.

- an ***accumulator*** or ***receiver,*** which is a reservoir that holds the liquid refrigerant until it is needed. Many cooling systems do not have a separate accumulator, instead depending on the volume of the condenser, evaporator, and/or refrigerant lines to hold the liquid refrigerant. For example, packaged water chillers typically use the evaporator shell as the liquid storage vessel. In Figure 1, the bottom of the condenser coil and the liquid discharge line act as the accumulator.
- a device or combination of devices for ***separating the high-pressure side of the system (condenser) from the low-pressure side (evaporator)*** and, in some systems, for ***metering the flow of refrigerant into the evaporator***. The device keeps the hot refrigerant gas from blasting through the condenser coil, and it maintains the discharge pressure that is necessary for condensing the refrigerant. In most liquid chillers, a simple ***orifice*** or ***float valve*** between the condenser and the evaporator serves this purpose. If the evaporator is partially wetted, rather than flooded, the flow of refrigerant into the evaporator is controlled by a metering device called an ***expansion valve***. Most air coils and some water-cooled evaporators use expansion valves. A recent development is the use of a small ***turbine*** to act as a metering device. This design recovers energy from the pressure difference that exists between the condenser and evaporator.

A compression cooling system may also have accessory devices or specialized features, such as crankcase heaters, purge units, hot gas bypass circuits, valves for controlling the flow of refrigerant to different parts of a coil, etc. Most of these accessories are specific to particular types, models, or system designs.



Trane Company

Fig. 2 Packaged water chiller The machine packages all the primary elements of a cooling system together. This model has a three-stage centrifugal compressor. The cooling output of the machine is controlled by throttling the flow of gas into the compressor with an inlet vortex damper. The evaporator, at bottom, is flooded with refrigerant. Tubes for chilling water are immersed in the refrigerant. The refrigerant evaporates under the reduced pressure of the compressor suction, chilling the water. The vapor is compressed to a hot gas by the compressor, and is discharged to the condenser in the rear. Cool water from a cooling tower flows through the tubes in the condenser, absorbing heat from the hot gas and condensing it. The warm refrigerant liquid drops down into the evaporator through an orifice. Upon exposure to the lower pressure in the evaporator, a portion of the warm refrigerant liquid evaporates, cooling the remaining liquid to the saturation temperature that corresponds to the evaporator pressure. The cycle continues as long as the compressor runs.

System Layouts

The five elements of a compression cooling system can be grouped in a variety of ways. You can find virtually all possible combinations in practice.

For example, Figure 1 shows a common arrangement where the compressor is located in the basement, an air-cooled condenser and accumulator is installed on the roof, and air coils with their expansion valves are installed on each floor.

In the popular "split system," the compressor is packaged with the condenser outside the building, and liquid refrigerant is piped to air coils or to a water chilling evaporator inside the building. This keeps the noisiest equipment outside the building.

Large water chillers generally include all their components in a compact package that is assembled at the factory. Figure 2 shows a typical packaged water chiller. Such packaging is becoming increasingly common in smaller systems as well. On the other hand, a cooling system may distribute its components throughout the facility.

If a system distributes its cooling by means of chilled water, this is called "hydronic" distribution. If liquid refrigerant is evaporated inside an air cooling coil, this is called "direct expansion" or "DX."

Larger systems generally use water for condenser cooling, because this allows the condensing temperature to be reduced by evaporative cooling of the water in a cooling tower. Smaller systems, and systems used in locations where the supply of water is limited, may reject heat directly to the outside air through an air coil that is called an "air-cooled condenser." A compressor that is packaged with an air-cooled condenser is called an "air-cooled condensing unit." An intermediate approach is spraying water over a condensing coil that is cooled by air flow. This arrangement is called an "evaporative condenser."

The Effect of Operating Temperatures on COP

The amount of power needed by the compressor depends on the difference in pressure between the compressor inlet (from the evaporator) and outlet (to the condenser). You know from basic chemistry that the temperature of a gas is proportional to its pressure. Therefore, we can express the power needed to compress the refrigerant vapor in terms of the difference between the evaporator and condenser temperatures.

This is a useful way of looking at compressor power, because the evaporator and condenser temperatures are determined largely by factors that are under the control of the equipment manufacturer, the system designer, and the plant operator. These factors are discussed below. But first, we need to understand the relationship between system temperatures and COP. If you need an explanation of COP, see Reference Note 31, How Cooling Efficiency is Expressed.

■ Maximum Theoretical COP

In 1824, the French engineer Sadi Carnot developed an analysis of compression cycles that allows their theoretical maximum efficiency to be expressed in terms of temperature alone. Carnot found that the maximum possible COP of a compression cooling machine is determined by this remarkably simple formula:

$$\text{Ideal COP} = \frac{\text{lowest temperature}}{(\text{highest temperature}) - (\text{lowest temperature})}$$

In this formula, the temperatures are absolute. You can use any system of absolute temperature units in this formula because the units cancel. (The Rankine absolute scale equals Fahrenheit plus 460°F. The Kelvin absolute scale equals Celsius plus 273°C.)

The lowest temperature in the system occurs at the compressor inlet. The highest temperature occurs at the compressor discharge. These temperatures are not fixed by the compressor. Instead, they are imposed on the compressor by the cooling application, by the

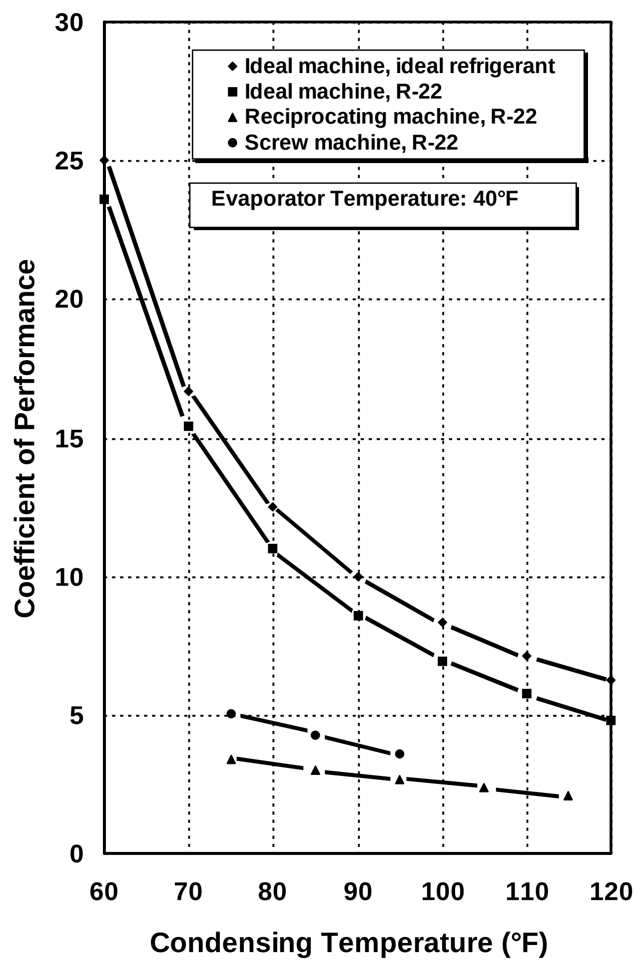


Fig. 3 The effect of system temperatures on COP The top curve shows the theoretical maximum COP that is possible, which is determined solely by the system temperatures. The second curve shows the efficiency loss related to a highly efficient real refrigerant. The bottom two curves show the COP's of real cooling machines with the same refrigerant.

temperature of the environment to which the heat is rejected, and by many system design factors.

This formula reveals the crucial role of the evaporator-to-condenser temperature differential in system efficiency. Cooling equipment moves heat from one place to another. The energy input to a cooling system is needed to overcome the "resistance" of the temperature differential. This viewpoint is evoked by the term "heat pump," which is used when a cooling machine is turned around to make it a heating device rather than a cooling device.

In Figure 3, the top curve shows the maximum theoretical COP's that can be achieved with an ideal cooling machine and an ideal refrigerant. This curve is calculated using Carnot's formula, assuming a cooling temperature of 40°F and a typical range of condensing temperatures.

■ The COP of an Ideal Machine with Real Refrigerants

In Figure 3, the second curve shows the COP's that would be achieved by an ideal cooling machine using HCFC-22 as a refrigerant. The curve assumes a cooling temperature of 40°F and a typical range of condensing temperatures. HCFC-22 (originally called Freon-22) is the most common refrigerant at present, and it is one of the most efficient.

This curve shows that some real refrigerants can approach the theoretical maximum COP. However, there is wide variation in efficiency among different refrigerants. The theoretical COP's of the most popular refrigerants are tabulated in Reference Note 34, Refrigerants.

■ The COP of Real Systems with Real Refrigerants

In Figure 3, the bottom two curves shows the manufacturer's COP ratings for two typical chillers, both using HCFC-22 refrigerant. As with the other curves, the cooling temperature is 40°F.

These two curves show that the COP's of real machines are considerably lower than the theoretical maximum, even accounting for limitations in the refrigerants. The losses are caused by mechanical inefficiencies in the compressor, by inefficiencies in the compression process, by energy waste in the expansion of refrigerant when it returns to the evaporator, and by heat transfer losses within the system. There is potential for improvement in all these areas.

The two curves also show that there is a considerable difference in COP between screw compressor machines and reciprocating machines. The COP of a good centrifugal machine would be somewhat higher than the COP of the screw machine.

Condensing temperatures below 75°F are not shown for the two real machines, because various design features keep them from operating with lower condensing temperatures.

The System Temperature Differential is Much Larger than the Cooling Load Temperature Differential

The temperature differential between evaporator and condenser is generally much higher than the temperature differential of the actual cooling load. This is a matter of great concern, because the temperature differential is the underlying theoretical factor that limits COP. As a realistic example of how the temperature differential builds up, consider the example of an air-cooled water chiller used for air conditioning. The temperatures throughout the system are depicted in Figure 4.

An air-cooled system was selected for this example to avoid the complications of temperature changes in cooling towers, which are really supplementary cooling systems. Other thermal complications, especially evaporator superheat, condensate subcooling, and interstage heat exchange, are discussed below. The illustration ignores small losses, such as the rise in chilled water temperature in the distribution system.

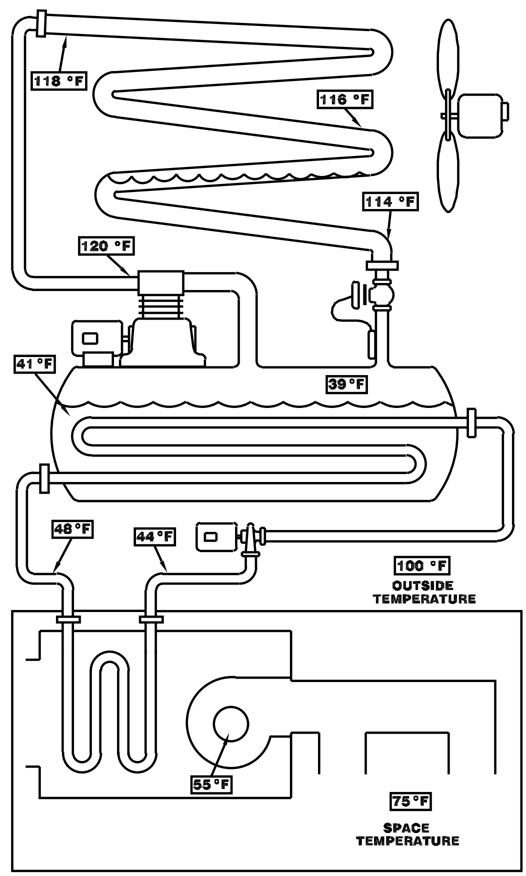


Fig. 4 The compressor temperature differential is much higher than the cooling load temperature differential In this example, the outside-to-inside temperature differential is only 25 degrees. Yet, the temperature differential on the compressor, which determines the system energy requirement, is 81 degrees! Of the excess, the evaporator side, including hydronics, accounts for 9 degrees; the condenser side accounts for 20 degrees; and, the air distribution system accounts for 27 degrees.

In this example, the original 25°F temperature differential created by the weather becomes an 81°F differential at the compressor! This has the effect of reducing the theoretical COP from 21.4 to 6.2, an enormous loss of efficiency. The COP of the actual chiller is reduced by roughly the same ratio.

Figure 4 shows that the compressor discharge temperature is determined primarily by the outside air temperature. However, the compressor suction temperature is much lower than the inside air temperature. This is mostly because of heat transfer losses in the cooling system and in the air handling system. Indeed, most of the temperature loss in this example occurs in the air handling systems.

This example illustrates an important point, namely, that *cooling system efficiency is determined largely by factors outside the design of the cooling equipment. Much of the waste in a typical cooling system occurs because the compressor must operate at a higher temperature (or pressure) differential than necessary.* The struggle to achieve better cooling efficiency is largely a war against temperature differential that is fought in many parts of the system.

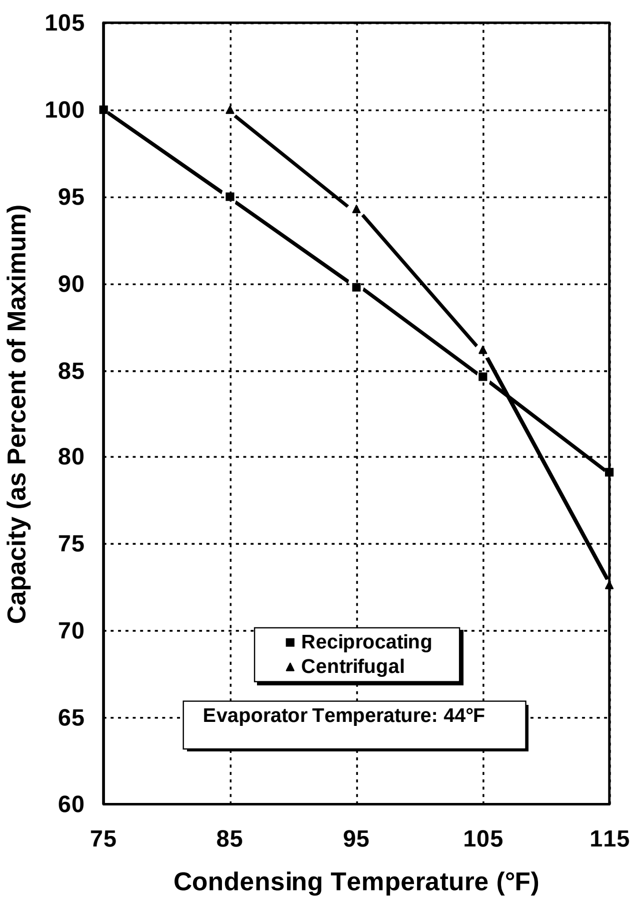


Fig. 5 The effect of system temperatures on capacity Increasing the temperature differential across a cooling machine reduces its capacity. The effect is important in typical applications. It varies with the type of compressor.

Reducing the temperature differential in air handling systems is accomplished by various Measures in Section 4. Increasing chilled water temperature and lowering condenser temperature is accomplished in Subsection 2.2. Reducing the temperature differentials inside the cooling system itself is a matter of selecting the best design options, which are explained below.

The greatest potential for reducing the system temperature differentials occurs during off-peak periods, when the system temperature differentials may be much larger than needed to satisfy the load.

The Effect of Operating Temperatures on System Capacity

The cooling system must overcome a temperature differential that resists the flow of heat. Reducing the temperature differential increases the cooling capacity of the system. This effect is dramatic. Figure 5 shows the loss of capacity for two typical machines, one with a reciprocating compressor and the other with a centrifugal compressor.

Conversely, by reducing the system temperature differentials that occur under peak load conditions, you can reduce the nominal capacity of the equipment that you need to buy for new installations. You do this by spending more money for larger heat exchangers, and by designing air distribution systems for more efficient flow. This extra cost is partially offset because the increased efficiency allows smaller compressors to satisfy the load.

The change in cooling capacity with temperature differential varies substantially among different types of compressors. Centrifugal compressors suffer more capacity loss than other types. This is because the gas is driven through the compressor only by its own centrifugal force. As the condenser temperature increases, this force is counteracted by the greater pressure in the condenser.

In contrast, positive displacement compressors push the gas through the machine without regard to the temperature differential. The cooling capacity of compressors with a fixed compression ratio, such as screw compressors, is affected least. This is because the refrigerant gas is isolated from the discharge pressure during the compression process.

The Compressor and System Efficiency

In a compression cooling machine, most of the input energy goes to compressing the refrigerant gas to make it liquify. Therefore, the design of the compressor and other aspects of the compression process play a large role in the system's efficiency. The following are the major factors that determine the efficiency of the compression process.

■ The Refrigerant

Until about 1990, it was possible to read a cooling equipment catalog without finding any mention of the refrigerant used by the equipment. That situation has reversed because of environmental concerns about refrigerants, so that the choice of refrigerant may be the first consideration in selecting a compressor. As discussed previously, the choice of refrigerant limits the potential system efficiency.

With respect to the system hardware, the refrigerant affects the system pressures, the types of metals that can be used, the handling of lubricants inside and outside the compressor, safety features, and other equipment selection considerations. See Reference Note 34 for more about these issues.

■ Efficiency of Gas Flow in the Compressor

Refrigerant vapor has mass, so it has kinetic energy. If the flow through the compressor is turbulent, a portion of this energy is wasted by converting it to heat energy. Reciprocating compressors unavoidably generate a large amount of turbulence as a result of the oscillating piston motion. In contrast, the other major types of compressors have smoother gas flow.

In order to achieve ideal thermodynamic efficiency, a compressor would have to provide the minimum power at each incremental stage of compression. No type of compressor is perfect in this regard. For example, efficient compression is achieved in a centrifugal compressor by careful attention to the shape of the impeller and diffuser, but this shape achieves maximum efficiency only at one refrigerant flow rate.

Any leakage within a compressor wastes compressor energy by allowing compressed gas to re-expand uselessly. Leakage occurs around the piston rings of a reciprocating compressor, around the impeller of a centrifugal compressor, between the scrolls of a scroll compressor, and between the rotors and casing of a screw compressor. Minimizing leakage is a challenge in all types of compressors.

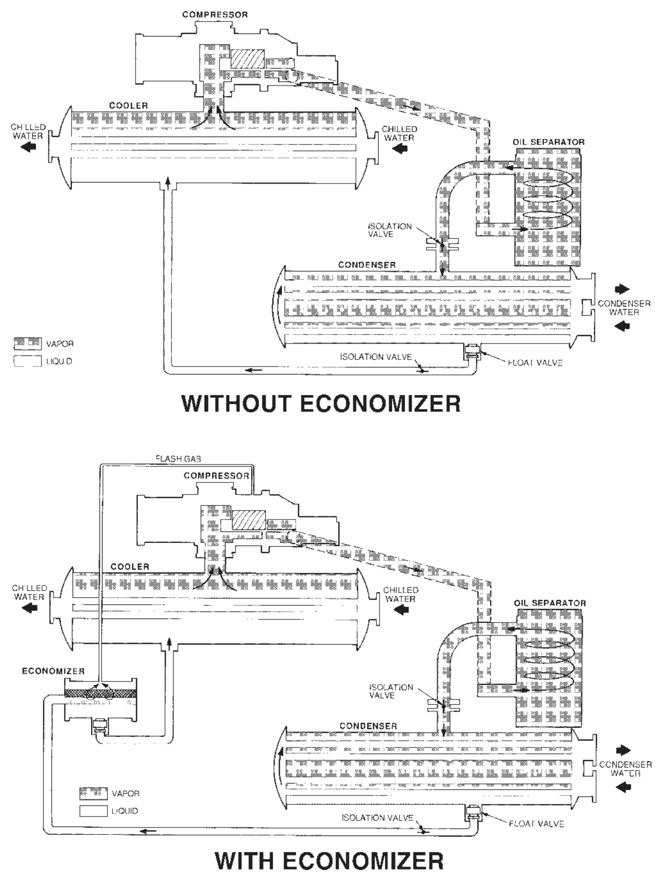
All types of positive-displacement compressors suffer re-expansion as a result of "clearance volume", which is the volume of gas left to re-expand at the end of the compression process. This problem is most severe with reciprocating compressors, which leave a significant amount of compressed gas in the cylinder at the top of the piston stroke. After the exhaust valve closes, the remaining gas expands in the first part of the suction stroke. The energy consumed to compress this gas is wasted.

■ Interstage Heat Transfer

When a gas is compressed, the heat of compression creates an expansion force that opposes the compression and increases compressor power. In an ideal compressor, the heat of compression would be removed as the gas is compressed. (If you are interested in the theory, this corresponds to the isothermal compression phase of the Carnot cycle.) Unfortunately, no conventional compressor design allows the gas to be cooled continuously during compression.

If the compressor has more than one stage, heat can be removed between the stages. Unfortunately, the interstage cooling cannot be done with ambient air or domestic water, because the heat exchange process occurs at low temperature. The compression process starts with a cold refrigerant gas and never gets very hot. The cooling is usually done by taking some liquid refrigerant from the condenser at high pressure, flashing it at a reduced pressure to get cool vapor, and injecting this vapor into the compressor between the stages. The mass of the added refrigerant also increases the cooling capacity.

The general technique of lowering gas temperature and/or increasing mass flow between stages is called an "economizer." (The same name is given to efficiency measures in other types of equipment, including absorption chillers, boilers, and air handling units). The



Carrier Corporation

Fig. 6 Interstage heat transfer in a screw compressor system A portion of the liquid refrigerant from the condenser is flashed into gas, which is introduced part way through the compression process. This lowers the average temperature rise in relation to the mass of gas that is compressed, which lowers the average work of compression.

specific technique of using refrigerant flash gas for this purpose is called “flash intercooling.”

With compressors that convey an isolated volume of gas through the compression process, as occurs in screw and scroll compressors, ports can be built into the compressor to inject gas for flash intercooling. Figure 6 shows how an economizer operates with a screw compressor chiller.

Interstage heat transfer produces a significant efficiency gain only if the compressor has a fairly high compression ratio. In this case, the heat of compression adds substantially to the gas pressure, increasing the work required from the compressor.

■ Fixed or Variable Compression Ratio

If the compressor discharge is open to the condenser as the compression is taking place, then the discharge pressure never exceeds the pressure needed to condense the refrigerant (except for a small expansion loss between the compressor and condenser). The leading examples of such compressors are the centrifugal and reciprocating types. In such compressors, the compression ratio adjusts itself to the needs of the system.

On the other hand, some compressors work by trapping a volume of gas and then compressing this amount independently of the condenser pressure. The gas is released to the condenser only near the end of the compression process. This is true of some screw compressors and most scroll compressors, and of some other types, such as vane compressors.

If the compressor discharge pressure exceeds the condenser pressure, then a fraction of the compression energy is wasted in compressing the gas more than necessary. On the other hand, if the compressor discharge pressure is lower than the desired condenser pressure, the condenser is not able to condense the gas at higher coolant temperatures. Therefore, systems using compressors with fixed compression ratios always err on the side of excess discharge pressure, which wastes energy at reduced loads.

The compression ratio corresponds to a ratio of temperatures between the evaporator and the condenser. Therefore, energy conservation measures that attempt to improve efficiency by raising the evaporator temperature or lowering the condenser temperature are less effective with compressors having fixed compression ratios.

■ Efficiency of Output Modulation

In all common types of cooling machines, the method used to throttle output is an integral part of the compressor, and may account for much of its efficiency limitations. Some compressors that are efficient at high load become inefficient at low loads. Some compressors cannot operate at all below some minimum load.

In typical applications, cooling systems operate over a wide range of loads, with full-load operation being an exception that occurs mostly on start-up. Many older cooling plants were designed at a time when manufacturers did not stress part-load efficiency, and these commonly provide major opportunities for improving efficiency by substituting machines that respond more efficiently to partial loads.

Losses in throttling output are most severe in centrifugal compressors. In the past, economies of scale led to decisions to cool a facility with one or two large centrifugal machines, but this configuration is wasteful at low loads. To increase part-load efficiency, you need to use a larger number of smaller machines, or to use different types of compressors, perhaps in combination with centrifugal machines. Improving part-load efficiency in an existing plant may require installing an additional, smaller machine to serve low loads. (Measure 2.8.1 recommends this technique.)

Reciprocating compressors retain their efficiency fairly well at lower loads, although part-load efficiency varies among different models. Smaller reciprocating compressors usually operate in an on-off mode, so they suffer efficiency loss only during the start of each cycle, while refrigerant flow in the system is stabilizing.

Scroll compressors usually operate in an on-off mode, so the efficiency of capacity reduction is not a factor. Other methods of modulation are being developed for scroll compressors, as discussed below. The efficiency performance of modulating scroll compressors is not yet well documented.

■ Limitations in Reducing Condenser Temperature

The previous discussion emphasized the importance of keeping condenser temperature as low as possible. With some compressors, the condensing temperature must be kept above a certain level. In such cases, the condenser temperature is kept artificially high by choking off the air or water that cools the condenser. This wastes energy in applications where the system may operate during cooler weather.

There are several reasons why a system may require an elevated condenser temperature. In some cases, the compressor is the limiting factor, because high condensing temperature may be needed to prevent migration of lubricants away from the compressor. More commonly, high condensing temperature may be needed for reasons not related to the compressor, such as maintaining adequate pressure for operation of an expansion valve or capillary refrigerant distributors. Other reasons are given in Measure 2.2.2.

Types of Compressors and Throttling Methods

The following are the efficiency characteristics of the most common types of cooling compressors. One of the most important efficiency characteristics is the method used by the compressor to reduce its output.

■ Centrifugal Compressors

Centrifugal compressors are the most efficient type when they are operating near full load. Their efficiency advantage is greatest in large sizes, and they offer considerable economy of scale, so they dominate the market for large chillers. They are able to use a wide range of refrigerants efficiently, so they will probably continue to be the dominant type in large sizes. The peak efficiency of centrifugal compressors has improved dramatically and progressively since about 1980, and several major improvements to part-load efficiency have been made in that time.

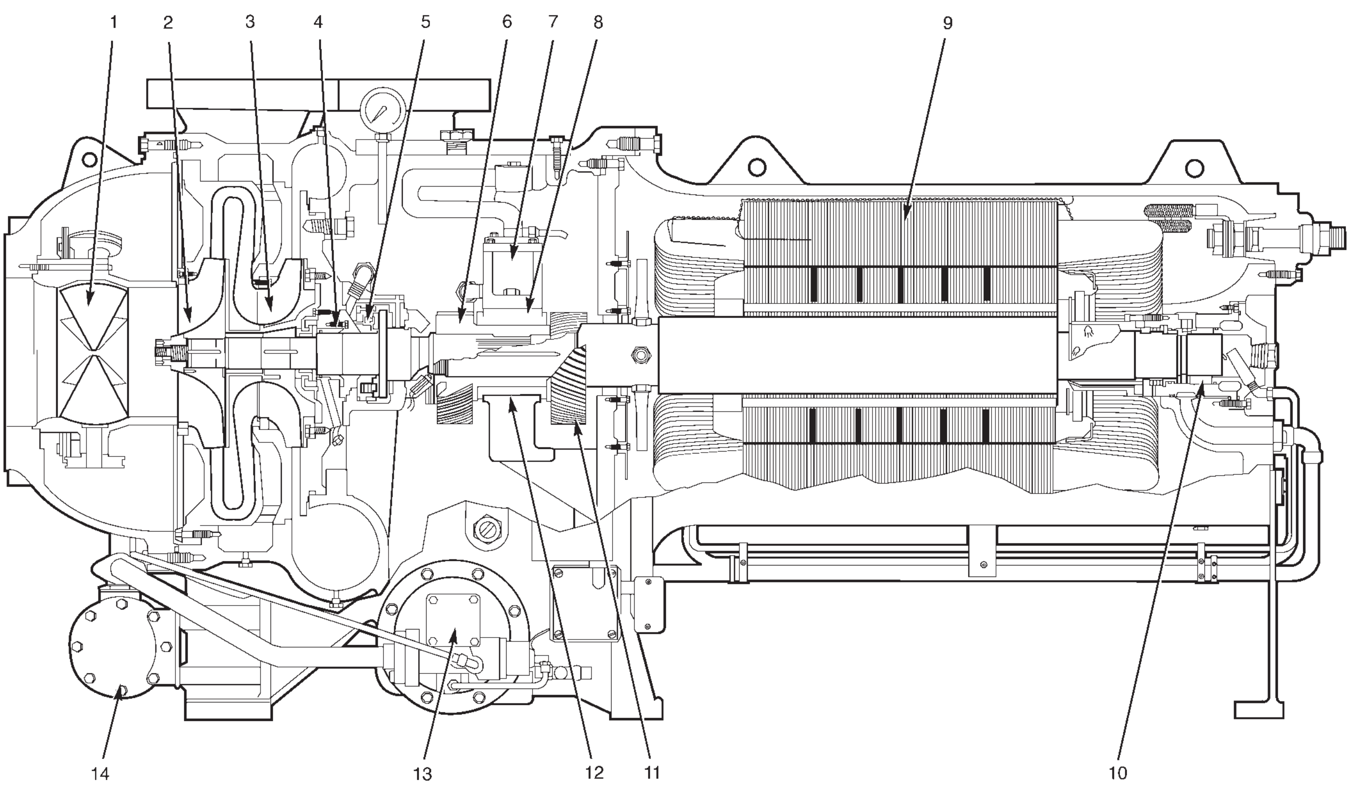
Centrifugal compressors have a single major moving part, an impeller that compresses the refrigerant gas by centrifugal force. The gas is given kinetic energy as it flows through the impeller. This kinetic energy is not useful in itself, so it must be converted to pressure energy. This is done by allowing the gas to slow down smoothly in a stationary diffuser surrounding the impeller.

Figure 7 is a detailed drawing of a centrifugal compressor that has two impellers on the same shaft, for two stages of compression. The impeller speed is increased by using a gear train between the motor and the impellers.

Figure 2 shows a centrifugal compressor that has three impellers, for three stages of compression. The impellers are driven directly by an electric motor, which limits the rotation speed. Three stages are needed to achieve the needed condensing pressure with the particular refrigerant that is used in this machine. Using a large impeller diameter also compensates for the low rotation speed.

Figure 8 shows a centrifugal chiller in which the compressor has only a single, relatively small impeller. The motor speed is limited by the line frequency, so this machine uses gears to increase the impeller speed.

High energy efficiency in a centrifugal compressor requires efficient gas flow through the impeller and the diffuser. Unfortunately, the design of the impeller and



LEGEND

1 — Variable Inlet Guide Vanes
2 — First-Stage Impeller
3 — Second-Stage Impeller
4 — Impeller Shaft Journal Bearing
5 — Thrust Bearing Assembly
6 — High-Speed Pinion
7 — Coastdown Reservoir
8 — Impeller Shaft Journal Bearing
9 — Motor
10 — Motor-End Journal Bearing
11 — Low Speed Bull Gear
12 — Motor Shaft Journal Bearing
13 — Oil Pump
14 — Oil Cooler

Carrier Corporation

Fig. 7 Centrifugal compressor with internal motor This model has two impellers on a common shaft, providing two stages of compression. To further increase compression, the impeller speed is increased by gears. Typical of most centrifugal compressors, the output of the machine is adjusted by throttling the flow of gas into the first stage using pre-rotation inlet vanes.

diffuser can be optimized for only one gas flow rate. To minimize efficiency loss at reduced loads, centrifugal compressors typically throttle output with pre-rotation vanes (inlet guide vanes) located at the inlet to the impeller(s). This method is efficient down to about half load, but the efficiency of this method decays rapidly below half load.

Older centrifugal machines are not able to reduce load much below 50%. This is because of “surge” in the impeller. As the flow through the impeller is choked off, the gas does not acquire enough energy to overcome the discharge pressure. Flow drops abruptly at this point, and an oscillation begins as the gas flutters back and forth in the impeller. Efficiency drops abruptly, and the resulting vibration can damage the machine.

Many older centrifugal machines deal with low loads by creating a false load on the system, such as by using hot gas bypass. This wastes the portion of the cooling output that is not required.

To improve both turndown range and low-load efficiency, some machines use two separate centrifugal compressors. The two compressors share a common condenser shell and a common evaporator shell. Figure 9 shows this approach used with a large chiller.

Another approach is to use variable-speed drives in combination with inlet guide vanes. This may allow the compressor to throttle down to about 20% of full load, or less, without false loading. Changing the impeller speed causes a departure from optimum performance, so efficiency still declines badly at low loads.

A compressor that uses a variable-speed drive reduces its output in the range between full load and approximately half load by slowing the impeller speed. At lower loads, the impeller cannot be slowed further, because the discharge pressure would become too low to condense the refrigerant. Below the minimum load provided by the variable-speed drive, inlet guide vanes are used to provide further capacity reduction.

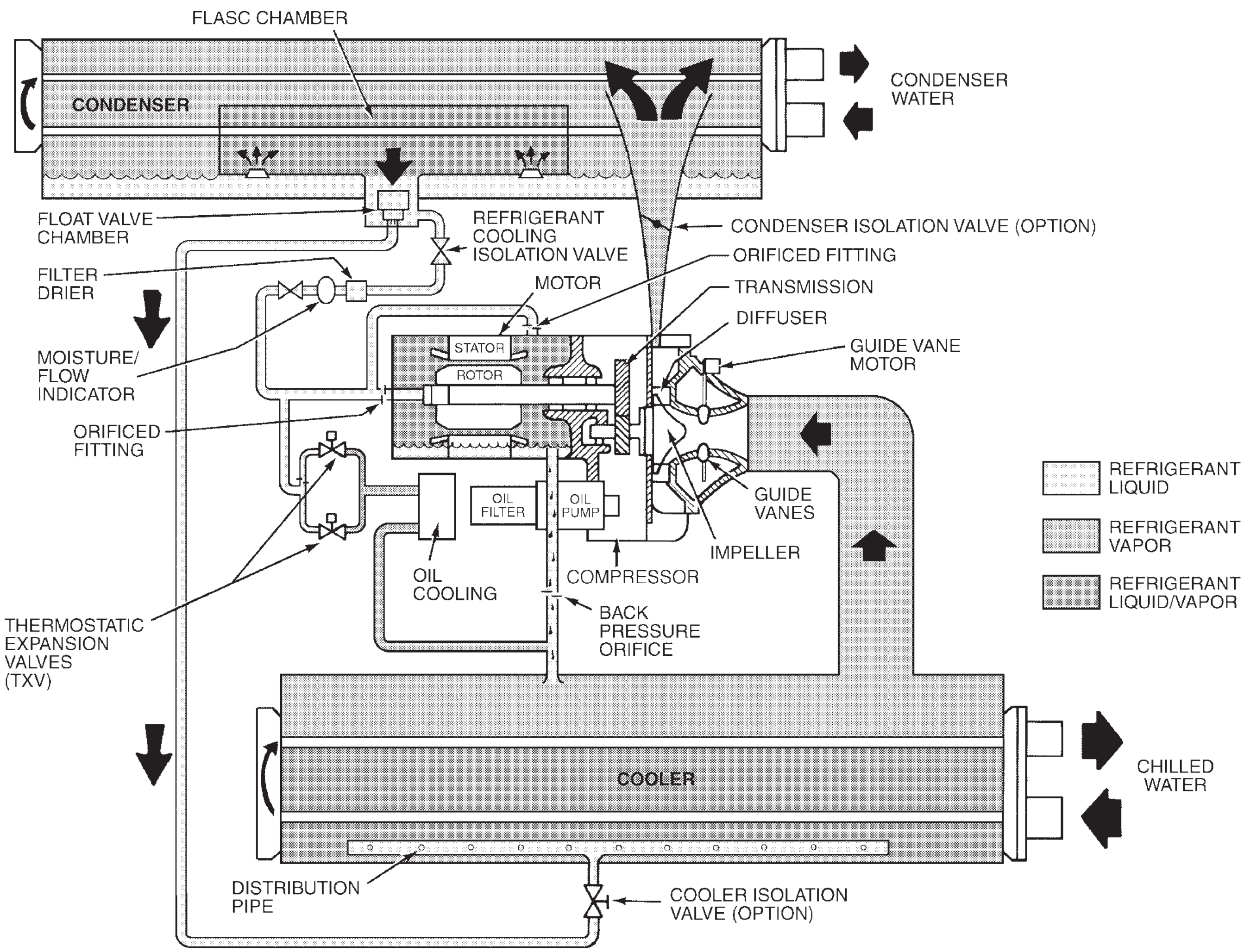


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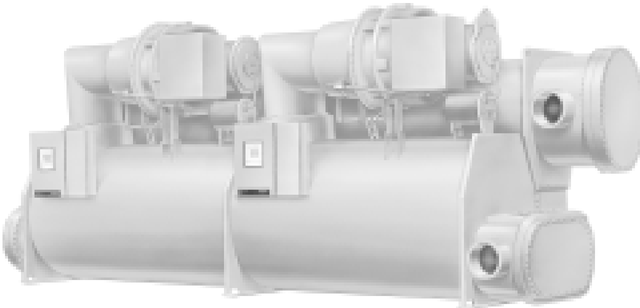
Fig. 8 Packaged centrifugal water chiller Details and accessories vary from one model to another, and from one manufacturer to another. Here, the flash chamber provides cool gas for motor cooling and oil cooling. This compressor has only a single stage, so an economizer is not possible.



Trane Company

Fig. 9 A large water chiller with two centrifugal compressors This is one way of maintaining efficiency at reduced cooling loads.

Unlike positive-displacement compressors, which are not subject to surge, the minimum load of a centrifugal compressor is sensitive to the evaporator and condensing temperatures. Raising the evaporator temperature and lowering the condenser temperature reduce the tendency to surge, and hence reduce the minimum load. The minimum load of an individual centrifugal machine varies widely, depending on these temperatures.

It is not advisable to turn a centrifugal compressor on and off to deal with low loads. Most centrifugal compressors use journal bearings, which are not positively lubricated until the shaft reaches a certain speed. Refrigerant flow within the machine may require several minutes to stabilize after each start-up. The types of motors used to drive centrifugal machines are more likely to overheat with frequent start cycles. And, the gears in gear-driven compressors are subjected to high stress on start-up.

The pressure output of a centrifugal compressor depends on the diameter and speed of the impeller(s). Refrigerants that have low condensing pressures can be compressed with a centrifugal machine that is driven directly from a 50 Hz or 60 Hz motor. Gases that require higher pressures require the compressor to have speed increasing gears, or several stages of compression (several impellers), or both.

For a given refrigerant, the equipment designer can choose to increase the number of stages of compression, while reducing the impeller speed and diameter. Using several stages allows an economizer (described previously) to be used between each stage. The theoretical efficiency improvement becomes smaller with each additional stage, and flow losses accumulate at the inlet and outlet of each impeller, so there is an optimum number of stages for each refrigerant. Increasing the number of stages increases cost and complexity.

Increasing the impeller speed by using gears incurs losses in the gears and in the additional bearings. It also eliminates the opportunity of exploiting interstage heat transfer.

■ Reciprocating Compressors

Reciprocating compressors are the oldest type, and they continue to be the dominant type in the small and medium size range. Figure 10 shows a typical unit.

In principle, reciprocating compressors can be designed for virtually any refrigerant. In practice, they are most economical for refrigerants that operate at medium and high pressures, because the higher gas densities provide more refrigeration effect for a machine of a given size.

The maximum efficiency of reciprocating compressors is lower than that of centrifugal and screw compressors. Efficiency is reduced by clearance volume (the compressed gas volume that is left at the top of the piston stroke), throttling losses at the intake and discharge valves, abrupt changes in gas flow, and friction. Also, reciprocating compressors tend to be used with systems having expansion valves, which are somewhat less efficient than the fluid metering methods used in larger systems. Lower efficiency also results from the smaller sizes of reciprocating units, because motor losses and friction account for a larger fraction of energy input in smaller systems.

For most air conditioning applications, reciprocating compressors can easily compress the refrigerant gas in a single stage, so there is no opportunity for improving the theoretical efficiency of compression by using an economizer (described previously). However, multiple stages of compression are commonly used in low-temperature refrigeration, and compression efficiency can be improved by using economizers in those applications.

Reciprocating compressors suffer less efficiency loss at partial loads than other types, and they may actually have a higher absolute efficiency at low loads

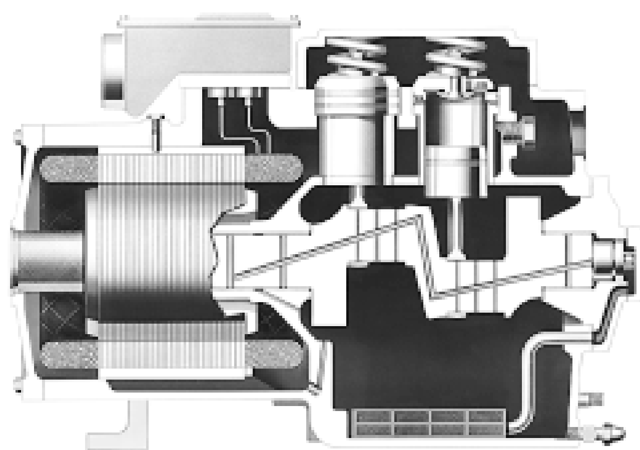


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Fig. 10 Reciprocating compressor Capacity is controlled by disabling individual cylinders, which can be done in several ways, or by varying the speed. The large springs allow the cylinder heads to lift if liquid refrigerant enters the cylinders, avoiding destruction. This type of enclosure, with an internal motor and bolted access plates, is called “semi-hermetic.”

than the other types. Smaller reciprocating compressors control output by turning on and off. This eliminates all part-load losses, except for a short period of inefficient operation when the machine starts.

Larger multi-cylinder reciprocating compressors commonly reduce output by disabling ("unloading") individual cylinders. When the load falls to the point that even one cylinder provides too much capacity, the machine turns off.

Several methods of cylinder unloading are used, and they differ in efficiency. The most common is holding open the intake valves of the unloaded cylinders. This eliminates most of the work of compression, but a small amount of power is still wasted in pumping refrigerant gas to-and-fro through the unloaded cylinders. Another method is blocking gas flow to the unloaded cylinders, which is called "suction cutoff."

If a multi-cylinder reciprocating compressor can reduce its capacity by more than 50%, a significant amount of additional complication is required to provide stable refrigerant flow through expansion valves, to avoid coil frosting, to achieve proper return of lubricating oil to the compressor, etc. For this reason, the trend in larger reciprocating systems is to use multiple compressors with independent refrigerant circuits, with each compressor unloading no more than 50% (i.e., in two steps of capacity).

Variable-speed drives can be used with reciprocating compressors, eliminating the complications of cylinder unloading. This method has not become popular yet, probably because the attention of designers is now focussed on newer types of compressors. Automotive air conditioning compressors, which are driven directly by the engine, operate successfully over a wide range of speeds.

■ Screw Compressors

Screw compressors, sometimes called "helical rotary" compressors, compress refrigerant by trapping it in the "threads" of a rotating screw-shaped rotor. There are two types of screw compressors, twin-screw and single-screw. At present, the twin-screw version is the most common.

In the twin-screw compressor, the refrigerant is pinched between the lobes (raised portions) and flutes (recessed portions) of two parallel mating screw rotors. Figure 11 is a cutaway drawing of a typical twin-screw compressor.

Figure 12 is a cutaway drawing of a chiller that uses a twin-screw compressor.

In single-screw compressors, the refrigerant is pinched between the threads of a single helical rotor and one or two star-shaped rotors (called "gaterotors") that rotate at right angles to the main rotor and mesh

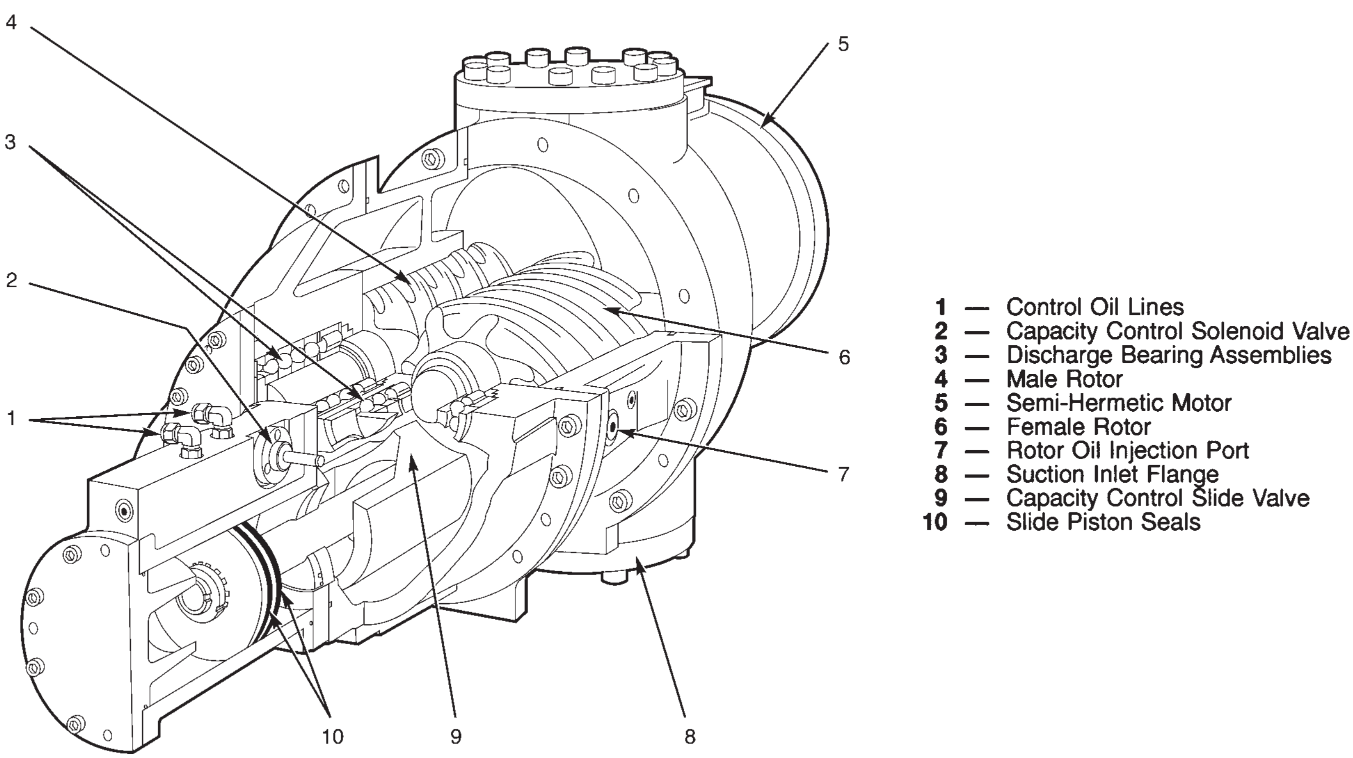

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Fig. 11 Twin-screw compressor The two helical rotors mesh, squeezing gas from the rear toward the front. The capacity control slide valve, 9, is a movable part of the housing that surrounds the rotors. By sliding away from the rest of the housing, it creates a gap of variable size that disables the adjacent portion of the rotors.

with the helix, like pinions being driven by a worm gear. The only purpose of the gaterotors is to block flow through the threads. They are idlers, and play no part in moving the gas.

Screw compressors have been used for a long time as low-pressure air compressors and engine superchargers, but leakage between the screws has made these units too inefficient for refrigeration work until the 1980's. At that time, improved machining technology made it possible to achieve the close tolerances that are necessary for good efficiency, and improved designs reduced other efficiency losses. Now, the best screw compressors are significantly more efficient than reciprocating compressors at all loads, and they may be more efficient than centrifugal compressors at low loads.

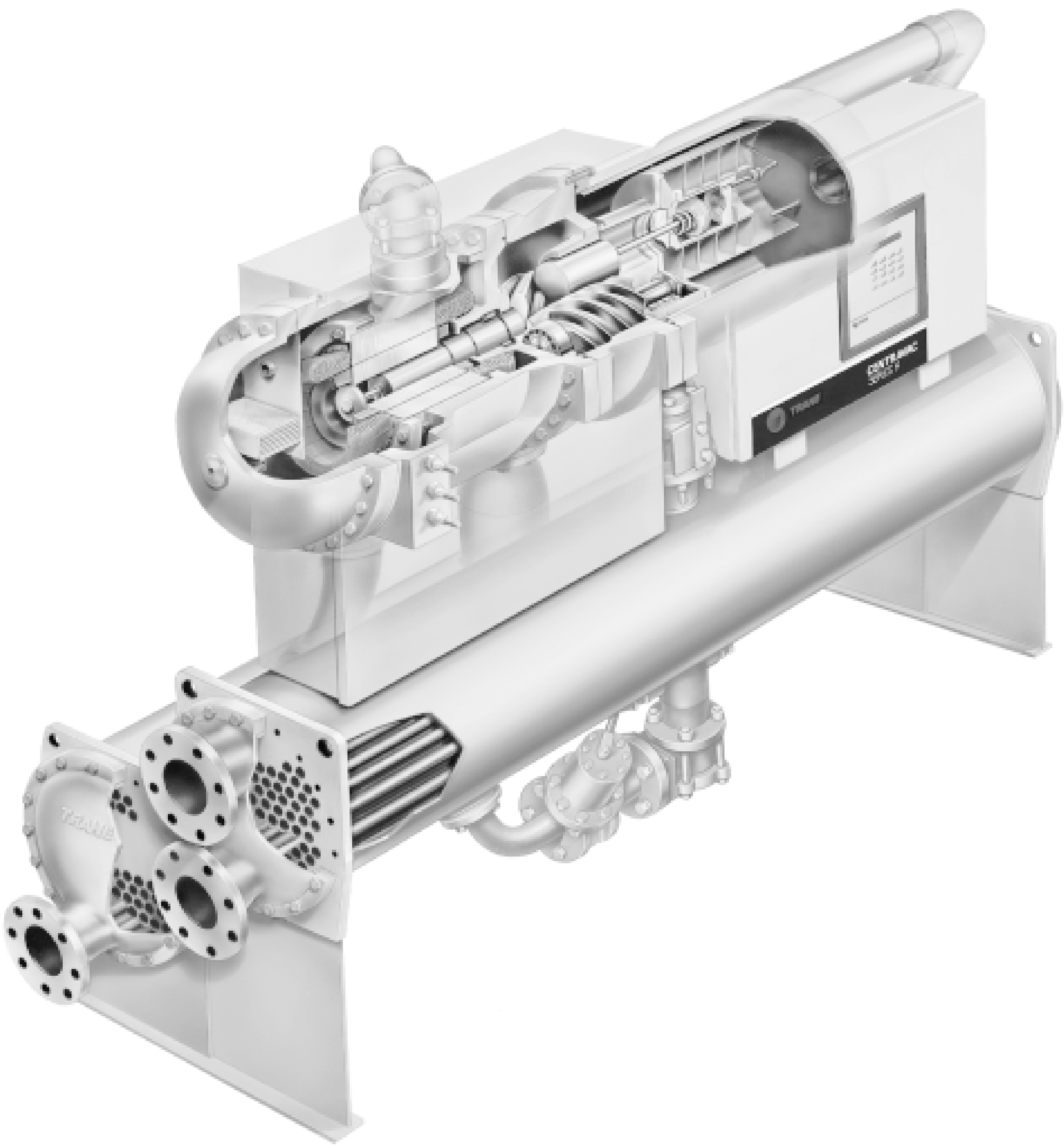

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Fig. 12 Chiller with twin-screw compressor Refrigerant gas enters the near end of the screw from the evaporator, in the lower rear. After a short passage through the rotors, the compressed gas is discharged into the condenser. The valves under the condenser flash liquid refrigerant for motor cooling, and perhaps, for an economizer.

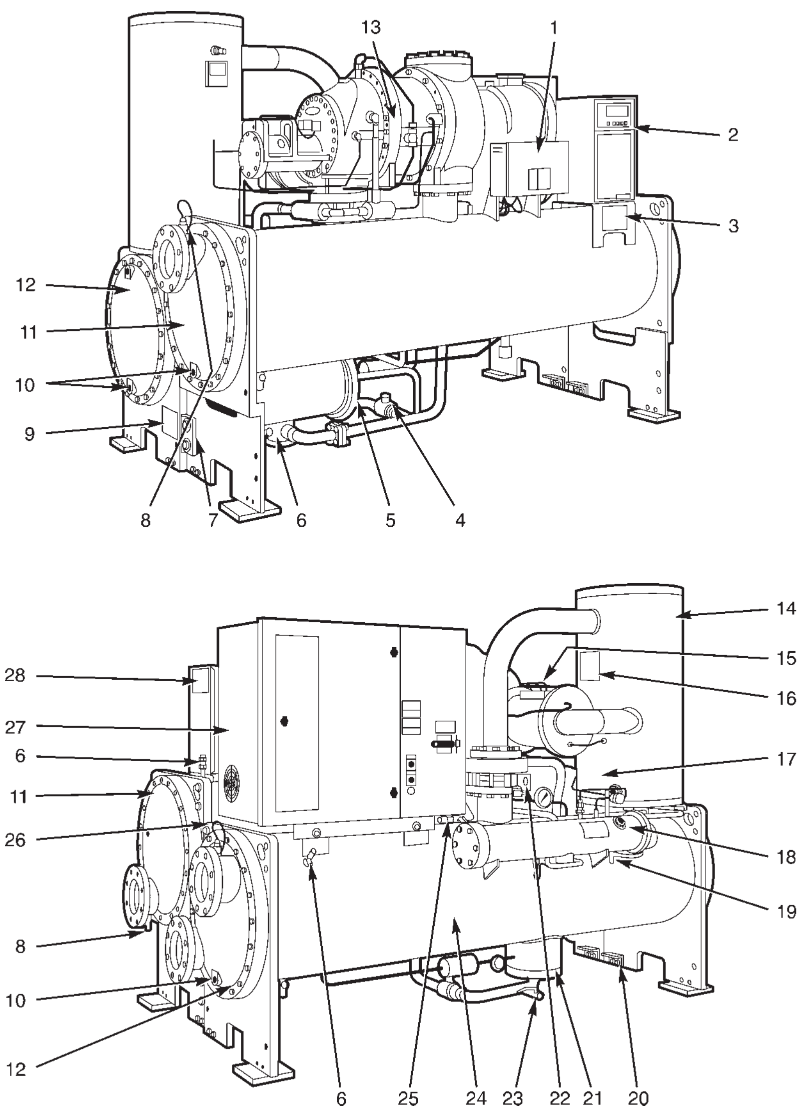
Screw compressors have increasingly taken over from reciprocating compressors of medium sizes and large sizes, and they have even entered the size domain of centrifugal machines.

Screw compressors are applicable to refrigerants that have higher condensing pressures, such as HCFC-22 and ammonia. They are especially compact. The practical upper limit of screw compressor size is determined by competition from centrifugal machines, which offer greater efficiency in larger sizes. However, it may turn out that screw compressors are better able to exploit the efficiency potential of their refrigerants, especially in applications with high temperature differentials (such as making ice), so screw compressors may prove to have no economical upper size limit. The lower limit of size is determined by price competition from reciprocating compressors and other types.

A major distinction between screw compressors is whether the unit operates with or without oil injection into the rotors. Oil is used to cool the refrigerant as it is compressed, reducing the work of compression and improving cycle efficiency. It also seals the leakage paths, allowing the compressor to operate efficiently at lower speeds. The oil typically takes up less than one percent of the compression volume.

In twin-screw compressors, the oil serves as a lubricant between the rotors, allowing one rotor to drive the other by direct contact. Rotor wear is small in this drive arrangement because the shape of the rotors is designed to mesh them with a rolling contact.

The oil is cooled in an oil cooler to get rid of the heat of compression. Cooling may be provided by any available cooling medium, including condenser water,



1 — Power Panel
2 — Local Interface Display (LID) Control Center
3 — ASME (American Society of Mechanical Engineers) Nameplate, Cooler
4 — Cooler Refrigerant Isolation Valve
5 — ASME Nameplate, Economizer (Hidden)
6 — Service Valve
7 — Take-Apart Rabbet Fit Connector (Lower)
8 — Cooler Temperature Sensor
9 — ASME Nameplate, Condenser
10 — Typical Waterbox Drain Port
11 — Cooler Supply/Return End Waterbox Cover
12 — Condenser Supply/Return End Waterbox Cover
13 — Compressor Nameplate

14 — Oil Separator
15 — ASME Nameplate, Muffler (Hidden)
16 — ASME Nameplate, Oil Separator
17 — Cooler Relief Valves (Hidden)
18 — Oil Sump Filter Assembly
19 — Oil Charging Valve
20 — Vessel Separation Feet
21 — Float Chamber
22 — Condenser Isolation Valve (Option)
23 — Refrigerant Charging Valve
24 — Condenser
25 — Condenser Relief Valves (Hidden)
26 — Take-Apart Rabbet Fit Connector (Upper)
27 — Unit Mounted Starter (Option)
28 — Machine Identification Nameplate

Carrier Corporation

Fig. 13 What is all that stuff? Screw compressor cooling machines have some large accessories. Note the size of the oil separator, 14. Other models have equally large suction filters to protect the narrow clearances of the rotors from debris in the refrigerant system.

ambient air, refrigerant, or chilled water. Cooling the oil with refrigerant or chilled water reduces the overall system efficiency, so avoid these methods of oil cooling.

Oil-injected compressors also require an oil separator to remove oil from refrigerant after it leaves the compressor. The oil separator presents some resistance to the flow of refrigerant gas on the discharge side, so it adds an efficiency penalty. Also, it typically is larger than the compressor itself. Figure 13 shows a screw compressor chiller with all its accessories, including the large oil separator.

Some screw compressors have another large accessory, a suction filter. This protects the compressor, which has very close tolerances, from any debris that travels through the refrigerant system, such as pieces of solder, motor insulation, etc.

In twin-screw compressors without oil injection, clearance between the two rotors is maintained by driving them through meshed gears. This increases cost, size, and maintenance requirements. Dry compressors must operate at high speed to minimize leakage of gas between the rotors, which increases noise. Since there is no oil to seal the gaps, more elaborate mechanical seals are required. On the positive side, no oil separator or oil cooler is needed.

Single-screw compressors may also operate with or without oil injection. In machines that do not inject oil, liquid refrigerant may be injected into the rotor, achieving both sealing and improved mass flow. These compressors can operate with minimal lubrication because the gaterotors are made of a compliant plastic material that provides tight sealing against the main rotor.

A variety of methods are used to control the output of screw compressors. There are major efficiency differences among the different methods. The most common is a slide valve that forms a portion of the housing that surrounds the screws. When the valve slides away from the rest of the housing, it creates a gap that deactivates the adjacent portion of the rotors.

Using a variable-speed drive is another method of capacity control. It is limited to oil-injected compressors, because slowing the speed of a dry compressor would allow excessive internal leakage.

There are other methods of reducing capacity, such as suction throttling, that are inherently less efficient than the previous two.

Screw compressors can achieve a much better turndown ratio than centrifugal compressors, typically down to about 10% of full load. Screw machines tolerate frequent on-off cycling for low-load operation, as with reciprocating machines. This avoids the temptation to create false loads to keep the machine running.

The basic screw compressor has a fixed compression ratio, which has efficiency limitations discussed previously. To minimize this problem, some screw compressors have a variable compression ratio. This is achieved with a variable discharge port that taps the compressed gas from different areas near the discharge end of the rotor(s). The most common form is a slide valve. The mechanism for this slide valve is sometimes combined with the inlet slide valve that controls compressor capacity.

The efficiency of single-screw and twin-screw compressors can be improved by flashing some liquid refrigerant and injecting the cool refrigerant gas into the rotor at a point downstream of the primary suction port. This feature is called an "economizer," and it is described above.

Don't confuse the economizer process with injecting liquid refrigerant into oil-injected compressors to cool the oil. The latter function has an efficiency penalty, because the oil heat adds to the cooling load.

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Fig. 14 Scroll compressor The compressor itself occupies the upper third of the case. The rest is the motor.

■ Scroll Compressors

The scroll compressor is an old invention that has finally come to market. Figure 14 shows a typical unit.

The gas is compressed between two scroll-shaped vanes, shown in Figure 15. One of the vanes is fixed, and the other moves within it. The moving vane does not rotate, but its center revolves with respect to the center of the fixed vane, as shown in Figure 16. This motion squeezes the refrigerant gas along a spiral path, from the outside of the vanes toward the center, where the discharge port is located. The compressor has only two moving parts, the moving vane and a shaft with an off-center crank to drive the moving vane.

Scroll compressors have only recently become practical, because close machining tolerances are needed to prevent leakage between the vanes, and between the vanes and the casing. A variety of designs are used to achieve good sealing, including oil flooding and pressure-loaded sliding contacts between the scrolls.

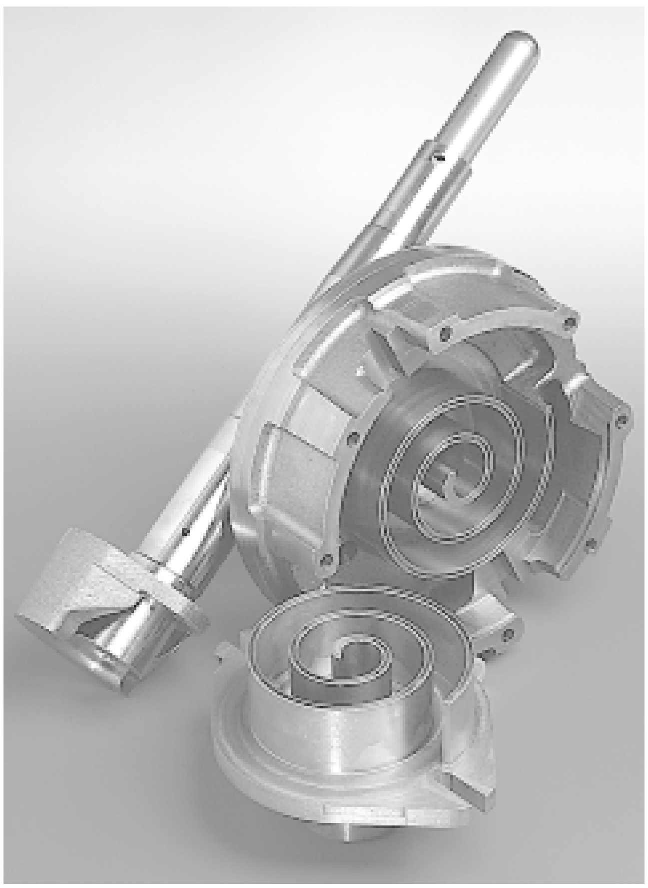

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Fig. 15 The parts of a scroll compressor The top scroll is fixed. The bottom scroll moves within the fixed scroll. It does not rotate, but moves with an eccentric motion that squeezes the refrigerant gas from the outside of the spiral toward the center, as shown in Figure 16. The slot on the side of the lower scroll engages a fixed pin that keeps it from rotating. In back is the drive shaft for the moving scroll, with a counterbalanced eccentric drive at the bottom. The performance of the compressor is dependent on very accurate machining of the scrolls.

Scroll compressors promise good efficiency because of their smooth gas flow. Unlike the gas flow in a reciprocating compressor, the gas moves through a screw compressor in only one direction, from the inlet port toward the outlet port. The absence of reversing gas flow greatly reduces the variation of motor torque during the compression cycle, as shown in Figure 17. This promises reduced vibration and noise.

Scroll compressors have a fixed compression ratio, which has efficiency limitations discussed previously. If they prove to be satisfactory, they seem likely to become prominent at the low end of the system size range.

Like other small compressors, scroll compressors usually control output by turning on and off. Variable capacity can be achieved by using several compressors. Electronic variable-speed drives have been used on some scroll compressors, but this method of capacity control is expensive in small sizes. Another method is to open ports that bleed gas from the early (outer) portion of the compression cycle, but this method wastes some energy.

■ Other Compressor Types

Mankind has devoted a great deal of ingenuity to finding ways of compressing gases, resulting in many compressor designs. The most efficient types approach the maximum achievable efficiency, but still leave room for significant improvement. Greater efficiency, reduced cost, reduced maintenance, and lower noise are all factors that may cause a new type of compressor to burst on the scene.

At present, there are no major contenders to displace the previous types, but this could change quickly, as witness the rapid commercialization of screw compressors and scroll compressors after years of dormancy. The best advice is to check the latest developments before selecting a compressor, but make sure that a model is well proven before buying it. The potential advantages of novel types are too small to justify reliability risks.

Vane compressors and trochoid compressors are types that have been used in various smaller refrigeration applications, such as residential refrigerators and air conditioners, but not yet in larger cooling systems. They are appealing because of their apparent simplicity, their compactness, and their ability to operate quietly. The major practical problem with both has been sealing.

Vane compressors use a rotor that is located eccentrically in a chamber. Sliding vanes in the rotor create spaces between the rotor and the chamber wall. The volume of these spaces changes as the rotor rotates. Refrigerant gas is drawn into the spaces in the half of the rotation where the size of the spaces is increasing. The gas is compressed as the rotor turns, and is discharged at the point where the spaces are smallest.

Trochoidal compressors are a general type in which a rotor rolls along the inside of a chamber, compressing the gas into pockets formed between the rotor and the chamber wall. ("Trochoid" is the name of a curve that is traced by the perimeter of a rolling circle.) The best known example of a trochoidal device is the Wankel rotary engine, a variant of which has been made into a commercial compressor.

Compressor Drivers

All the energy input to a compression cooling system goes into the compressor driver. This may be an electric motor, a reciprocating engine, a gas turbine, or other machine. Your selection of the compressor driver is a critical factor in efficiency and operation. The following are the most common choices to be made.

■ Internal vs. External Motors

If the compressor is driven by an electric motor that is located outside the compressor housing, a shaft must penetrate the compressor housing. This type of installation is called an "open drive." Figure 18 shows a typical open drive.

The motor may also be installed inside the compressor casing, along with all the other moving parts.

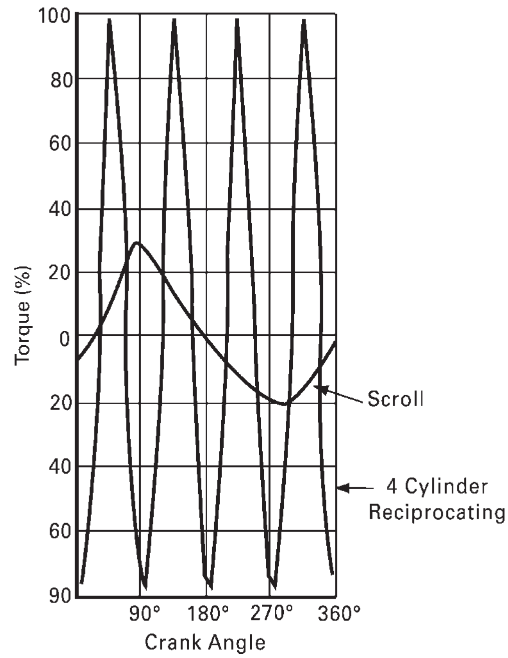

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Fig. 17 Torque characteristics of scroll and reciprocating compressors The scroll compressor has less torque vibration, largely because the gas does not have to reverse direction in going through compression.

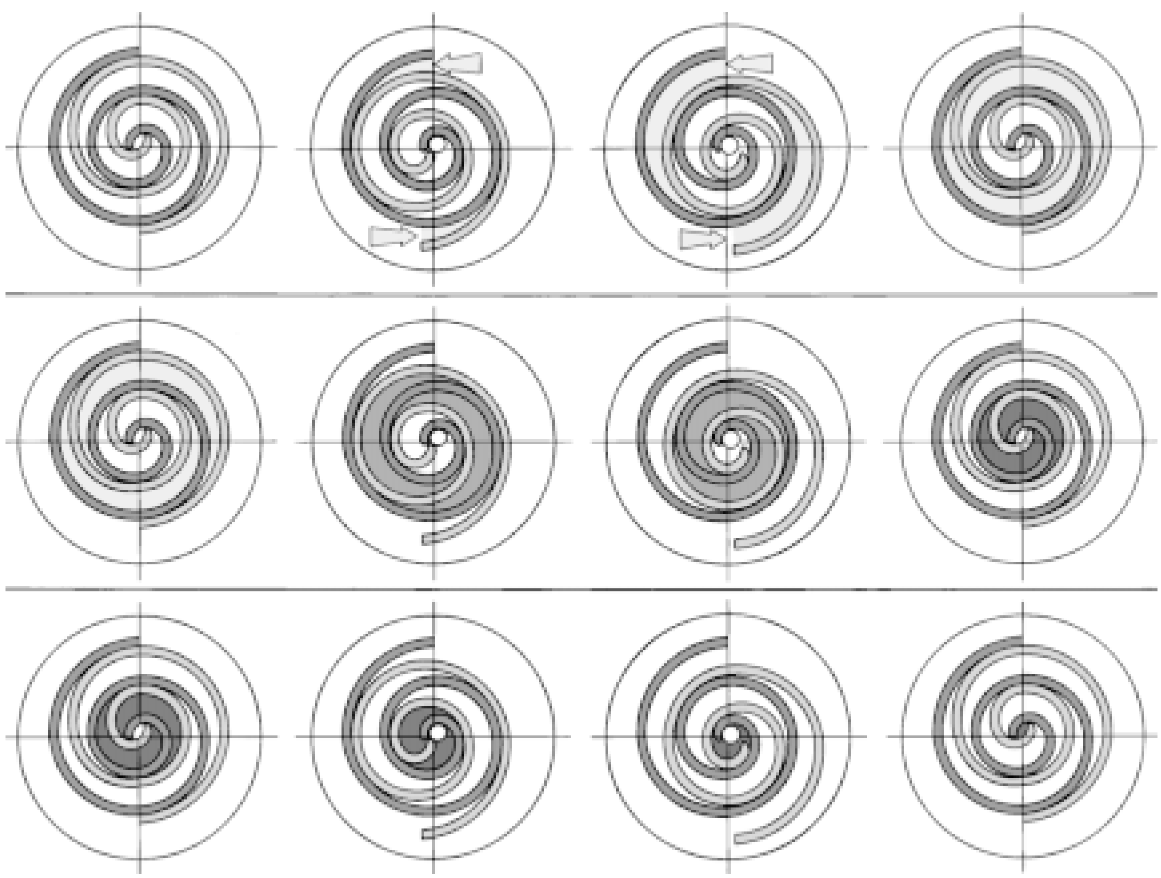

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Fig. 16 How a scroll compressor moves The dark scroll is fixed. The light scroll moves within it. The moving scroll does not rotate, but its center moves in a small circle. The effect is to squeeze gas from the outside toward the inside along a spiral path.

If the compressor and motor is totally encapsulated within a welded housing, the compressor is called "hermetic." True hermetic compressors are found only in smaller sizes. Figure 19 shows a typical example.

If the motor or other components are accessible through bolted access plates, the compressor is properly called "semi-hermetic," although it is common to call such compressors "hermetic" also. The compressor shown in Figure 10 is semi-hermetic.

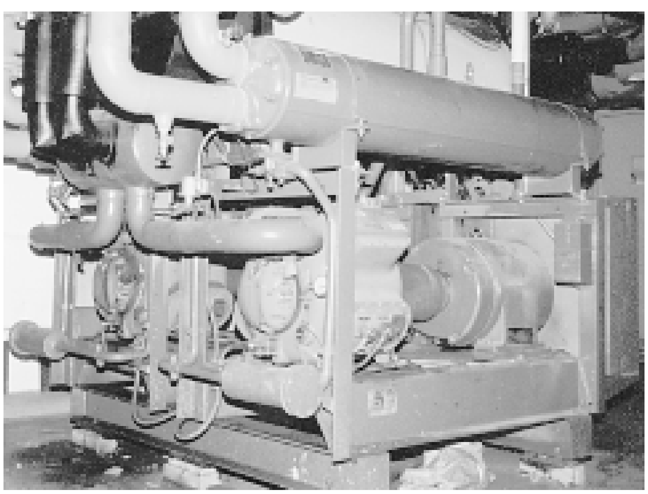
Are open or hermetic compressors better? There is no definite answer. Both types work well within their appropriate applications. However, increasing concern about the environmental hazard of certain refrigerants has shifted the balance toward hermetic machines, at least for machines that use harmful refrigerants. The advantages of hermetic systems are:

- ***reduced refrigerant leakage.*** Installing the motor inside the compressor housing eliminates the shaft penetration, which is the main source of refrigerant loss with open drive compressors. Low leakage is an important advantage if the refrigerant has objectionable environmental properties.
- ***motor longevity.*** Refrigerant cooling promises long motor life because temperatures are lower, and the coolant is clean. However, all compression refrigerants have some solvent behavior, and they tend to be absorbed by the organic materials used for motor insulation. This may create unexpected problems with newer refrigerants.

Hermetic motors have these disadvantages:

- ***reduced cycle efficiency and/or increased condenser size.*** The motor of a hermetic compressor may be cooled by cold suction gas from the evaporator, or by liquid refrigerant from the condenser. In both cases, the motor heat goes into the compression cycle.

  For example, the efficiency of the large motors used with centrifugal chillers ranges from 92% to 96%. The remaining percentage becomes motor heat, which reduces the COP of the chiller by about one or two percent.
- ***difficult access to the motor for maintenance.*** Getting to the motor requires pumping the refrigerant out of the system, and removing the access covers.
- ***need to clean out the entire refrigerant system in the event of a motor burnout.*** The electric arcing that occurs in an insulation burnout creates corrosive materials from most refrigerants. This requires cleaning out the entire refrigerant side of the cooling system.
- ***possible inability to retrofit variable-speed drives.*** If a hermetic compressor was originally designed to operate at a constant speed, it may not be possible to retrofit an electronic variable-speed motor drive. This is because the full motor speed may be needed for proper bearing lubrication and motor cooling.



WESINC

Fig. 18 Compressor with open drive An important disadvantage of this arrangement is leakage of refrigerant around the drive shaft. On the other hand, the arrangement has several advantages.

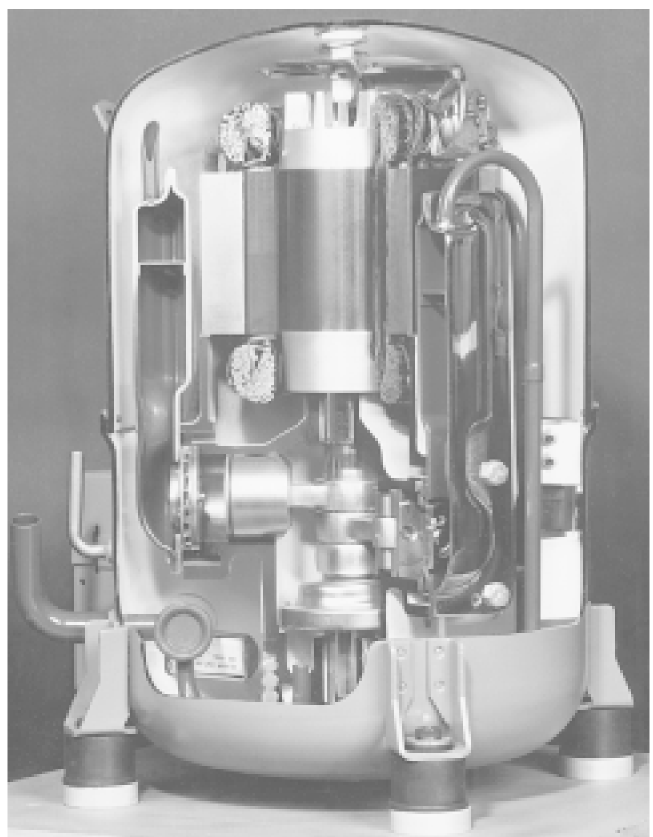


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Fig. 19 Hermetic compressor This arrangement virtually eliminates refrigerant leakage. However, it is not practical to repair this type of unit at the site.

Motor Efficiency

Motor efficiency is generally not an optional factor with hermetic compressors, where the motors are custom made for the machine. Motors of higher efficiency may be an option with open-drive compressors.

Controlling the compressor output with an electronic variable-frequency motor drive keeps the motor operating more efficiently at partial loads, although there is a small efficiency penalty at high loads. For more about this, see Reference Note 36, Variable-Speed Motors and Drives.

Other Types of Drivers

The great majority of compression cooling machines are driven by electric motors, but there are circumstances in which a different source of shaft power may be appropriate. The first refrigeration compressors were driven by reciprocating steam engines. Modern compressors are sometimes driven by diesel engines, natural gas reciprocating engines, gas turbines, and steam turbines.

A decision whether to choose such a drive requires detailed knowledge of the engineering, operating practices, and economics of the drive in question. There may be a temptation to use non-motor drives for "obvious" but illogical reasons. For example, a large urban hospital uses a condensing steam turbine to drive a chiller, apparently because the facility was designed with a high-pressure steam supply for other reasons. The steam turbine drive in this facility is much more expensive to operate than an electric motor would have been.

In general, electric motors combined with variable-frequency drives provide better part-load performance than other types of drives, along with lowest first cost and minimal maintenance requirements. If you are interested in a reciprocating engine drive, you have to find out whether the compressor is vulnerable to the torsional vibrations of the engine drive. This requires a sophisticated analysis of the rotating components by the compressor manufacturer.

Packaged engine-driven cooling machines are available. These are sold primarily as a means of reducing electrical demand during peak load periods.

Evaporators

The design of the evaporator can have a significant effect on system efficiency. We will cover the most common types of evaporators. Then, we will discuss evaporator superheat, which is the most important factor in evaporator efficiency.

Flooded Evaporators

Flooded evaporators are used in a large fraction of packaged water chillers, as shown in Figure 2. Chilled water is cooled in tubes that are completely submerged in liquid refrigerant. This provides complete utilization of the tube surface. The large free surface of the liquid refrigerant is directly exposed to the compressor suction so there is virtually no pressure loss between the evaporation area and the compressor suction.

This arrangement is simple as well as efficient. Liquid refrigerant from the condenser is simply drained back to the evaporator, typically using an orifice or float valve to isolate the evaporator from the pressure of the condenser.

The only significant disadvantage of flooded evaporators is that they require a larger quantity of refrigerant than evaporators where the refrigerant evaporates inside the tubes.

Liquid Overfeed Evaporators

In liquid overfeed systems, refrigerant is continuously pumped, or flows by gravity, through any number of evaporators. The evaporators can take any form needed by the application, such as an air coil or a plate ice maker. The name "liquid overfeed" derives from the fact that more liquid refrigerant is fed to each evaporator than evaporates, the excess liquid flowing back to a receiver. The receiver is open to the compressor suction, so the refrigerant liquid is kept at the temperature corresponding to the compressor suction pressure. Thus, each evaporator behaves almost like a flooded evaporator.

The system is flexible, in that it can serve any number and variety of evaporators. The only limitation is that all evaporators must operate at the same pressure, and hence, at the same temperature. Liquid overfeed has generally the same efficiency advantages as a flooded evaporator, except for a minimal energy loss in refrigerant pumping and piping pressure loss. There is no pressure difference between the evaporator receivers and the evaporators, except for any gravity head that may exist as a result of differences between the heights of the evaporators. As a result, the pumping power is minimal.

In addition to the low-pressure receiver for each evaporator, the system generally has a single high-pressure accumulator to allow for fluctuations in the quantity of refrigerant in the evaporators.

Since each evaporator in a liquid overfeed system is kept flooded with refrigerant, there is no way of controlling the evaporating temperature individually. To control the cooling output of each evaporator, it is necessary to throttle the flow of the cooled medium through the evaporator, or to bypass a portion of the cooled medium around the evaporator.

If only a single evaporator is needed, as in a central chiller system, liquid overfeed offers no significant advantage over a flooded evaporator, and it would be unnecessarily complex.

■ Evaporators with Expansion Valves

An expansion valve is an automatic valve for metering the flow of refrigerant into the evaporator. Figure 1 shows where an expansion valve is installed in the system.

Unlike flooded evaporators and liquid overfeed evaporators, the flow of refrigerant into evaporators that use expansion valves is restricted.

The name "expansion valve" is a misnomer. An expansion valve is actually a liquid refrigerant metering device. The only expansion that occurs at the valve itself is a relatively small fraction of the refrigerant that flashes because of the drop in pressure upon entering the evaporator. Most of refrigerant evaporates as a result of absorbing heat inside the evaporator.

Most air coil (DX) evaporators use expansion valves. Many smaller water chilling evaporators use them. Expansion valves limit the amount of refrigerant used in the evaporator to the minimum needed to satisfy the cooling load. This reduces the evaporator size and the refrigerant charge. Expansion valves are the most economical way of serving multiple evaporators in a single system. Compared to liquid overfeed, the piping is smaller and simpler. The main disadvantage of expansion valves is that they reduce the system COP, for reasons discussed below.

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Fig. 20 An "electronic" expansion valve This expansion valve minimizes superheat under all load conditions by changing its throttling behavior. The valve receives input signals from a microcomputer that senses system conditions.

Until recently, virtually all expansion valves were set to maintain a constant difference between the temperature of the vapor leaving the evaporator and the temperature of the liquid entering the evaporator. This temperature difference is called "superheat" because it represents sensible heating of the vapor above its saturation temperature after all the liquid is evaporated. Typical superheat ranges from 5°F to 10°F. Using an expansion valve forces the vapor outlet end of the coil to be dry, so this portion of the coil provides only minimal cooling capacity.

Direct-expansion heat exchangers, such as air coils, are commonly divided into many separate refrigerant circuits to increase the effective cooling area. In order to use all the surface most effectively, the refrigerant must be distributed evenly to all the circuits. To do this, thin distributor tubes are installed between the expansion valve and the individual circuits. The distributor tubes all have the same resistance to flow, so refrigerant is distributed uniformly.

An important energy conservation principle is keeping the condenser temperature as low as possible. Unfortunately, using an expansion valve limits this technique during cooler weather, when it is most valuable. The reason is that the condenser pressure must be kept high enough to drive refrigerant through the expansion valve and distributor tubes.

In small cooling equipment, the function of the expansion valve may be performed solely by the distributor tubes, in which case the internal diameter of the distributor tubes is carefully selected so that they provide the proper amount of resistance to isolate the evaporator from the condenser pressure. In such applications, the distributor tubes are called "capillary tubes." This method cannot accurately control superheat, or prevent liquid refrigerant from getting all the way through the evaporator. Therefore, it may require additional features to protect against liquid entering the compressor, such as using an accumulator at the compressor suction.

"Electronic" expansion valves are an improvement that became widespread during the 1990's. An electronic expansion valve adapts to changing load conditions, minimizing the superheat at all times. Figure 20 shows an electronic expansion valve.

■ How Evaporator Superheat Reduces COP

In an ideal cooling machine, the liquid refrigerant in the evaporator would be cooled down to the compressor suction temperature. This condition is nearly met in flooded evaporators and in liquid overfeed evaporators. This is because the liquid refrigerant is exposed directly to the compressor suction.

However, if an expansion valve is used to control the flow of refrigerant through an evaporator, all the refrigerant must evaporate before it leaves the evaporator. To ensure that this happens, the evaporator is oversized in relation to the refrigerant flow. As the refrigerant continues to travel through the evaporator after it has evaporated, it picks up sensible heat, increasing its temperature. The rise in vapor temperature above the evaporation (saturation) temperature is called "superheat."

Superheat reduces the system COP. To understand this, consider the example of a direct-expansion air coil evaporator that is operating with a constant cooling load. Assume that the superheat is adjustable. Initially, the superheat is set at zero, so the coil is completely filled with evaporating refrigerant. Then, increase the superheat setting. The immediate effect of this is to restrict the flow of refrigerant into the coil. Since the quantity of refrigerant must be constant to satisfy the cooling load, there is a rise in the air temperature. The system controls sense the rise in temperature, and increases the compressor power input to compensate. The greater compressor suction restores the flow of refrigerant through the expansion valve to its former value (less a small amount that accounts for the sensible cooling of the air by the superheated refrigerant vapor).

The increase in compressor power can be expressed in terms of the temperature difference across the compressor. In the previous example, the compressor power increased as the suction pressure dropped, requiring evaporation to occur at a lower temperature. As we discussed earlier, the COP of a cooling system suffers if the temperature differential between the evaporator and the condenser increases.

It is a common belief that superheat improves the efficiency of the machine because the absorption of sensible heat by the refrigerant provides additional cooling effect. This is not true. The sensible cooling is minor in relation to the increased compressor power required by the lower suction pressure.

Energy Recovery from Refrigerant Expansion

The refrigerant in the condenser is at high pressure and the refrigerant in the evaporator is at low pressure. When refrigerant is released into the evaporator, the reduction of pressure causes a fraction of the refrigerant to flash into vapor. In most large cooling machines, flow from the condenser to the evaporator is regulated by a float valve, a simple orifice, or an expansion valve. With any of these devices, refrigerant flashing is a free expansion process.

Free expansion wastes most of the energy that was required to compress the flashed refrigerant initially, because the expansion does no useful work. The flow of liquid refrigerant across the pressure difference also comprises a waste of energy, but this is a minor factor because the volume of the liquid is small.

Some new chiller designs recover this lost energy. The most direct approach is to pass the refrigerant from condenser to evaporator through a turbine. Figure 21 shows a machine that uses this approach.

The liquid refrigerant enters the turbine from the condenser. Inside the turbine, the liquid tends to flash into vapor, but it also tends to re-condense because it is losing energy. The turbine is designed to minimize the energy left in the refrigerant. The turbine, which is driven by the pressure differential and the expansion of the flash gas, helps to run the compressor.

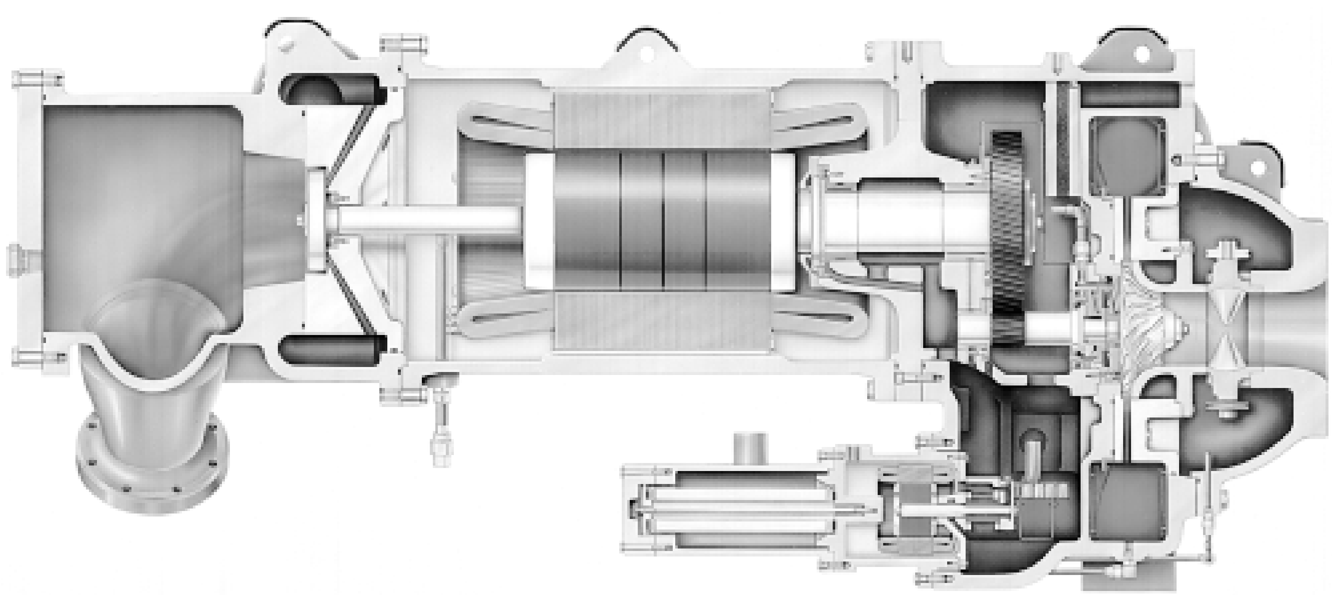

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Fig. 21 Energy recovery from refrigerant expansion The condenser is at much higher pressure than the evaporator. Energy is recovered by passing refrigerant through a turbine on its way from the condenser to the evaporator. The turbine helps the motor to drive the compressor. In this machine, the turbine wheel is on the left end of the motor shaft, and the compressor is on the right. The turbine refrigerant flow is entirely independent of the compressor flow.

(A similar idea is used in steam plants, where pressure reducing turbines are used in place of pressure reducing valves to get useful work.)

Since energy has been removed from the refrigerant before it enters the evaporator, it has more ability to absorb heat from the load. It also has less superheat, which reduces the power needed by the compressor to compress the gas.

This method can be used with flooded evaporators and liquid overfeed systems. It has little or no potential with expansion valve systems and with air coils that use capillary tubes or other types of flow restrictors to distribute refrigerant within the coils. This is because these devices require a significant pressure differential to operate properly.

Evaporator and Condenser Heat Transfer

Temperature differentials that occur in the evaporator and the condenser are important factors in the amount of work that the compressor must do, because these temperature differentials translate to an increased pressure difference across the compressor. Typical evaporator and condenser temperature drops are shown in Figure 4. The temperature differential is proportional to three factors: the heat transfer coefficient of the surfaces, the area of the heat transfer surfaces, and the rate of heat flow, or cooling load.

The evaporator and condenser temperature differentials are determined largely when the cooling machine is selected. They are a compromise between efficiency and first cost that the engineer makes in the selection process. Larger heat exchangers improve heat transfer, but heat exchangers are a major part of the system cost. The efficiency benefit is subject to a severe limitation of diminishing returns as the temperature differentials become small. For example, reducing the temperature differential from 4°F to 2°F requires doubling the heat transfer surface. This makes it very expensive to reduce the last few degrees of temperature differential.

Heat transfer is not limited primarily by the conductivity of the metal, but by heat transfer at the interfaces between the metal, liquid, and gas. The refrigerant side of evaporators involves two heat transfer processes, from the gas to the liquid film on the tube surface, and from the liquid film to the metal. Where water is used in evaporators and condensers, heat transfer is reduced by fouling from the water. This is especially severe with open cooling towers.

With refrigerant-to-water evaporators and condensers, minimum water flow rates are required to maintain adequate turbulence for good heat transfer. In variable-flow systems designed to reduce pump power, a separate loop must be provided to maintain a minimum water velocity through the heat exchanger.

Major improvements in the heat transfer coefficients of evaporators and condensers have been made since the 1970's. These improvements are achieved primarily by giving the tube surfaces a texture that increases turbulence, enhancing contact between the different mediums.

Heat transfer in air coils involves air velocity, fin spacing, number of rows of coils, and refrigerant circuiting. Air-cooled (DX) evaporators may require separate coil sections to allow operation at partial loads. Distribution of refrigerant within a DX evaporator requires elaborate distributors, and is difficult to optimize.

Heat transfer efficiency improves at partial loads because the heat transfer surface is then larger in relation to the amount of heat to be transferred.

■ Fouling Factor

When a system uses water for heat transfer in either the evaporator or condenser, a "fouling factor" is used in the rating conditions to account for fouling of the tube surfaces by dirt in the water. The fouling factor is a measure of thermal resistance, like the R-value used to rate insulation. The units are the same, for example, square feet-°F-hour per BTU in U.S. practice.

In the U.S., a fouling factor of 0.00025 is commonly assumed in rating large cooling machines. Experience has shown that this figure is appropriate for both evaporators and condensers. It is assumed that the fouling factor is kept from rising above this value by the scrubbing action of the water flow. For this assumption to be valid, the equipment must be designed with appropriate water velocities to maintain turbulent flow at the tube surfaces. Also, if the condenser uses water from an open cooling tower, you need to maintain an appropriate water treatment program for the tower water. The rating also assumes that tube surfaces are cleaned at appropriate intervals.

When comparing cooling equipment specifications, be careful to check the fouling factor that is actually being quoted by the manufacturer in its efficiency and capacity ratings. Although a fouling factor of 0.00025 is a standard value, a manufacturer may fudge comparisons with competing equipment by using different fouling factors.

The refrigerant sides of evaporators and condensers are kept clean by the solvent and detergent properties of the refrigerant materials. (Halocarbon refrigerants were widely used for cleaning purposes, before they were banned for environmental reasons. Ammonia is still a common cleaning agent.) Therefore, no fouling factor is needed for the refrigerant sides.

Parallel and Series Evaporator Circuits

In most facilities that have multiple water chillers, the evaporators are piped in parallel. This allows the chillers to be operated in any combination. However, it is possible to improve efficiency at high loads, at least in principle, by connecting the evaporators so that the chilled water flows through them in series.

To understand this, let's look at an example. Consider a facility that has two chillers of equal capacity, each operating at full load on a peak-load day. There is a large spread between the chilled water supply and return temperatures, for example, supply at 40°F and return at 52°F. If the chillers were operating in parallel, each would have to chill the water to 40°F. However, if the evaporators are connected in series, one of the machines can operate with a higher evaporator temperature. In this example, all the return chilled water is cooled in the first machine from 52°F to 46°F, and in the second machine from 46°F to 40°F. The COP of the first machine is increased substantially, while the COP of the second machine is reduced by a small amount. The average COP of the two machines might be increased by perhaps five percent under full load.

The efficiency advantage disappears below about half load, because one of the chillers is turned off in either the parallel or series arrangement. In most comfort cooling applications, the cooling load is less than half the peak design load for a majority of the time. Thus, the opportunity of exploiting a series connection is limited. However, if there are more than two chillers in the plant, the number of efficient operating hours may be extended by combining series and parallel connections.

The efficiency advantage of a series connection also drops rapidly below full load because the evaporator temperature of the chillers in a parallel connection can be raised to follow the load.

The main disadvantage of a series connection is that the chilled water must always flow through the evaporators of both chillers, even if one chiller is turned off. This wastes pump power. To minimize the pump power, the evaporators of series-connected chillers are usually designed for lower resistance, which wastes some efficiency and capacity in the individual chillers. For a given plant cost, these factors may eliminate any efficiency advantage that the series connection offers.

In principle, any number of chillers could be connected in series, but practical considerations limit the number to two.

Series-connected chillers should be similar in size, because the temperature drop across the evaporator of each machine will be proportional to its relative capacity. Some simple mathematics shows that the efficiency advantage diminishes if the temperature drops across the chillers are not divided almost equally.

To maximize the benefit of this configuration, the chillers should be controlled so that they share the load while both are running, and that one of the chillers is turned off at the appropriate load, typically at half of the cooling load or somewhat less. Inefficient load sharing between series-connected chillers wastes more energy than inefficient load sharing among parallel-connected chillers, which is another reason to be cautious about this configuration.

Condensate Subcooling

In an ideal cooling machine, the liquid refrigerant in the condenser would fall to the same temperature as the cooling water or air. Because heat transfer is imperfect, the condensed refrigerant is actually somewhat warmer than the cooling medium. This reduces efficiency by holding the compressor discharge temperature higher, increasing compressor power.

A condenser may cool the refrigerant below the temperature at which it condenses on the condenser surface. This is called "condenser subcooling." It is a cheaper alternative to more efficient condenser heat exchanger design. Subcooling provides some additional sensible cooling of the refrigerant, but sensible cooling is a minor part of the cooling potential of the refrigerant. Note that condenser subcooling does not significantly reduce the compressor discharge pressure.

Subcooling can be done in several ways. Most commonly, the refrigerant is routed through the coldest part of the condenser on the way out to the evaporator. Most condensers are tube-and-shell units, with the cooling water running in the tubes. To achieve subcooling of the condensed refrigerant, the water is brought into the condenser through the bottom tubes, and the condensate is allowed to pool around these lower tubes before flowing out of the condenser.

Condensate subcooling can be combined with an economizer. To do this, a portion of the condensate is routed through a separate vessel that is intermediate in pressure between the condenser and the evaporator. A portion of the condensate is flashed into vapor, cooling the condensate, and the cool vapor is injected into an intermediate stage of the compressor, as described previously.

The term "condensate subcooling" is also used for methods of improving the overall cycle efficiency of multi-stage compressors. This involves more theory than we need to discuss here.