

must be considered in the selection of refrigerants for centrifugal compression cycles:

1. *The pressure ratio required between condenser pressure and evaporator pressure.* It is preferable to maintain the lowest possible pressure ratio, in order to achieve the highest possible compressor efficiency, and to obtain the greatest possible useful range from the compressor. Normal practice in the refrigeration industry has been to use pressure ratios up to 2.5 per stage for multi-stage machines, and up to 4.5 for single-stage machines.

2. *The sonic velocity of the refrigerant.* The peripheral velocity necessary at the impeller tip to obtain the required pressure ratio is related to the speed of sound in the refrigerant. This relationship (U/a) is known as the impeller tip peripheral Mach number (also known as the rotational Mach number). Sonic velocities of the common refrigerants are relatively low, and the peripheral speeds for these applications are usually dictated by Mach number considerations. With gases such as air and helium, where sonic velocities are much higher, limits on peripheral speed are often established by the mechanical strength considerations of the impeller. If rotational speed is fixed, a relatively high sonic velocity will require a larger impeller diameter, and this will result in a larger overall machine size.

3. *The ratio of specific volume of the suction vapor to the refrigerant.* Together, items 1 and 2 establish the relationship between rotational speed and diameter, in order to obtain the required pressure ratio. This item establishes the limits of diameter and rotational speed for which there will be reasonable compressor efficiency at a given refrigeration load. When rotational speed is also fixed, as it is in 3600 rpm (2 pole) direct-drive hermetic compressors, the first two items establish the impeller tip diameter and item 3 establishes the capacity range for a given refrigerant.

In the early development of centrifugal compressors for refrigeration, the preceding factors led to the use of methylene chloride as a refrigerant. However, a wide variety of refrigerants became available with the development of other halo-carbon compounds. These make possible the selection of a refrigerant having suitable properties for virtually any specific use or type of equipment. Included in this group are the more common refrigerants: 11, 12, 22, 113, and 114. Of these, Refrigerant 11 has been used most extensively to date for air conditioning with centrifugal refrigeration. Besides having properties well suited to centrifugal compressors, it has a low operating pressure, high basic efficiency, and low cost. Refrigerants 12, 13, 500, and 22 have been used in high tonnage and low temperature applications. Refrigerant 114 has been utilized in intermediate capacity applications. During recent years, the advent of direct-drive hermetic machines created a requirement for refrigerants with high specific volume in order to obtain lower capacity ratings at the fixed rotational speed of 3600 rpm. Direct-drive, 60-cycle hermetics, therefore, employ Refrigerant 113 to obtain lower capacities than those which could be efficiently obtained with Refrigerant 11. Currently, however, this same load range is being covered by higher speed single-stage Refrigerant 11 compressors.

In the industrial and chemical fields, ammonia, methylene chloride, isobutane, methyl chloride, ethylene, butane, propane, sulfur dioxide, dichloroethylene, and water vapor have all been used as refrigerants in centrifugal refrigeration systems.

COMPRESSOR TYPES

The centrifugal compressor has been used extensively in compression cycle refrigeration, because of its simplicity, its early development, and the fact that its optimum size falls within the useful capacity range. The centrifugal compressor is a relatively high speed machine, in which a continuous stream of gas is compressed by a combination of centrifugal force and the conversion of kinetic energy into pressure by diffusion. Since the motion is one of pure rotation, it is possible to obtain smooth vibration-free mechanical operation.

Open Type Compressors

All early centrifugal machines were of the open type. The success of these machines is dependent upon the shaft seal.

The seal design for centrifugal machines is particularly critical because it must perform several functions:

1. Seal against leakage of air into the system when the compressor is operating below atmospheric pressure.
2. Seal against outward leakage of refrigerant when the compressor is operating above atmospheric pressure.
3. Seal against oil entering the system.
4. Perform the above functions, both during operation and when the machine is shut down.

A variety of seals have been developed to meet these requirements. While individual designs vary, there are several points common to all centrifugal compressors used for refrigeration:

1. A rotating seal ring is fixed to the shaft and rotates at compressor speed. This ring has a highly polished surface in a plane perpendicular to the shaft.
2. A stationary seal ring is fixed to the compressor casing and does not rotate. It is free to move along the axis of the compressor shaft when displaced, due to thrust forces. It has a highly polished surface which contacts the rotating seal ring. This is the point at which the rotating element is sealed from the stationary structure of the compressor.
3. The seal surfaces are lubricated and cooled by oil.
4. Oil which may leak into the compressor past the seal members is then returned directly to the oil reservoir, usually by gravity drainage.
5. Oil leaking outward past the seal is collected in an oil return chamber and returned either manually or automatically to the oil reservoir.

Variations in seal design involve the physical structure and arrangement of the stationary and rotating rings, lubrication and cooling provisions, and the method of seal oil return.

One seal used for low pressure refrigerants uses polished metal contact surfaces on rotating and stationary seal rings. These surfaces are separated when running, and the seal is maintained by a stream of oil flowing between the seal faces. During shutdowns, the sealing faces are held together by spring pressure.

Another type of seal employs one or more additional seal members between stationary and rotating rings. One or more carbon rings are held between the rotating and stationary seal rings by spring pressure, oil pressure, or a combination of the two. The seal faces and carbon ring are lubricated and cooled by oil, and are held in a fixed relationship to each other while operating and when shut down. The carbon ring is free to rotate between the rotating and stationary seal rings.

Many additional seal arrangements are in use that are as effective as those described. Those listed are merely intended to show the diversified designs available to meet the basic requirements for centrifugal compression duty.

Open type machines may be provided with either an inboard or outboard bearing design. With the inboard design, the bearing chambers are vented to the refrigerant passages and a single shaft seal is employed. With the outboard design, the bearing chambers and oil reservoir are vented to atmosphere, and shaft seals are provided on both ends of the shaft, between the gas passages and the bearings. With the latter design, oil leakage outward drains directly to the oil reservoir. Inward oil leakage may have provisions for automatic return to the reservoir, or may be limited to such minute amounts that oil return is not deemed necessary.

Open type machines have been built with from one to two stages (for water chilling applications) to nine stages (for use with ammonia). Three and four stages are often used for low temperature applications requiring a high pressure ratio.

Compressors

Special drive-through compressor arrangements with as many as twelve stages have been built, for very high compression ratios. While hermetic compressors are now used for most standard electrically driven water chilling applications, the open type compressor is still used with steam turbine drives and other suitable prime movers for special, industrial, and chemical applications. Some open type machines use variable inlet guide vanes as a capacity control, but many use variable speed or suction throttling, or both. Most open type compressor casings are made of a high grade cast iron and are horizontally split for easy assembly, inspection, and service. Impellers are either fabricated of carbon steel (which is often lead coated for corrosion protection), manufactured of stainless material, or are precision cast of aluminum. Braze steel and braze forged aluminum are also used.

Barrel-type casing designs are used with high pressure refrigerants. The internal design is similar to that of the horizontally split casing machines, but the entire unit is wrapped in a fabricated steel or forged steel barrel with end-flange type construction. The bearings and seals are mounted on the end flanges. This design offers considerable reduction in casing or shell thickness, and hence reduces machine size and weight.

Hermetic Compressors

The hermetic compressor is basically similar to the open type, except for the inclusion of the motor within the refrigerant space, which eliminates the shaft seal. However, certain limitations and innovations have characterized the hermetic machines. They have been limited to either one or two stages, utilizing variable inlet guide vanes for capacity control. The two-stage models use the guide vanes on either one stage or on both stages. Hermetic compressors have either shrouded or unshrouded impellers. They are generally single-purpose machines used for water chilling applications. Some two-stage models consist of two single-stages mounted on opposite ends of the motor, with a connecting crossover pipe between the first stage volute and the second stage inlet. Other models have two stages mounted axially on the same end of the motor, with a conventional crossover between the stages. The two-stage machines are normally directly connected to the motor shaft, and are driven by 2-pole motors.

Single-stage units which utilize smaller diameter impellers, driven at higher rotational speeds are now available. Most of these designs utilize speed increasing gears for 50/60-cycle electrical power. However, they are also available as direct-driven units, with high frequency power supplied by special motor-generator sets.

The early hermetic designs were in the low tonnage range (100 to 400 tons) employing Refrigerant 113 or Refrigerant 11. These were followed by units employing Refrigerant 11, up to a capacity of 1500 tons, and Refrigerant 114, to as high as 2000 tons. The present trend is toward the use of higher pressure refrigerants to reduce compressor size to a minimum. With the smaller compressor casings, it is possible to mount the compressors on the heat exchangers to give a completely preassembled cooling package. This minimizes installation costs and space requirements.

Motor cooling on hermetic centrifugal compressors has been accomplished by:

1. *Water cooling.* Circulating chilled water or condenser water through a jacket or cooled passages in the motor stator.
2. *Gas cooling.* Drawing suction, intercooler, or condenser gas through the motor passages.
3. *Liquid cooling.* Injection of high pressure liquid refrigerant into the motor, at either normal condensing temperature or sub-cooled to a point below condensing temperature, where it is expanded to suction pressure.

SYSTEM COMPONENTS

Evaporators and Condensers

Evaporators and condensers for centrifugal refrigeration systems are of the horizontal shell-and-tube type. (See Chapters 42 and 43.) The most common versions have a steel shell and copper tubes of the integral rolled-fin type, with water inside the tubes and refrigerant in the shell, and with two or more support sheets to support the tubes. Some have fabricated or cast-iron separable water boxes and others have integral welded water boxes. All have separate end plates (some containing the water nozzles) which can be removed so that the tubes can be cleaned by mechanical means from either or both ends.

The tubes fill the lower part of the shell in the evaporator, in such a manner that a number of different pass arrangements can be obtained on the water side. Liquid refrigerant, plus the expansion-flashed gas, flows in at the bottom of the partially flooded evaporator. The boiling action serves to splash liquid over the full tube surface area. The space used for separating the liquid splashed up by the boiling action is directly above the tubes. Some designs have sufficient space for gravity separation, and others have eliminators with gas space above, through which the dry vapor flows to the evaporator discharge pipe.

The tubes fill the major part of the shell in the condenser, leaving only enough extra space to distribute the gas throughout the shell. Just as in the evaporator, the tubes are laid out to permit a number of different pass arrangements. There are normally no segmented baffles to control crossflow, but there is often a plate directly in front of the condenser inlet to deflect the flow from the compressor to either side, thus avoiding direct impingement of the high velocity compressor discharge gas on the tubes. There may also be a longitudinal baffle to assist in isolating noncondensables in selected areas for efficient removal. The load on the condenser of a system consists of the evaporator load plus the work of compression. See Chapters 42 and 43 for heat transfer and other details of evaporators and condensers.

To obtain a more compact design, it is possible to combine the evaporator and condenser in a single shell. Several recent designs have been offered on this basis. The evaporator and condenser sections are separated by a longitudinal baffle which acts to seal the high side (condenser) tube bundle from the low side (evaporator) bundle.

Other Components

Another major part of every refrigeration system is the refrigerant flow control device. In centrifugal refrigeration the most common refrigerant flow control device in use is the float valve, which is especially suited for use with flooded type heat exchangers, and which automatically regulates the flow of refrigerant from the condenser to the evaporator. The float is usually placed on the high pressure side of the valve, thereby maintaining the condenser essentially free of liquid.

Many standard centrifugal refrigeration machines today have a lubricating system that is vented to the refrigerant. Some machines have an integral pump, driven directly, or by gearing, from the compressor shaft. Others use a separate motor-driven gear pump, immersed in the oil sump which is usually contained in the compressor base. Journal bearings and collar, or Kingsbury type, thrust bearings, are used almost exclusively; one exception is the special high-speed aircraft refrigeration compressor which uses ball bearings.

Centrifugal refrigeration systems, especially those operating with refrigerants having pressures below atmospheric, require