UNIT 3 REFRIGERATION EQUIPMENT

Structure

3.1 INTRODUCTION

Refrigeration system consists of several equipments like compressor, condenser, evaporator, expansion devices etc. A refrigerant compressor is a machine used to compress the refrigerant from the evaporator and to raise its pressure so that the corresponding temperature is higher than that of the cooling medium. The condenser is an important device used in the high pressure side of a refrigeration system. Its function is to remove heat of the hot vapour refrigerant discharged from the compressor. The evaporator is used in the low pressure side of a refrigeration system. The liquid refrigerant from the expansion device enters into the evaporator where it boils and changes into vapour. The function of an evaporator is to absorb heat from the surrounding location or medium which is to be cooled, by means of a refrigerant. The temperature of the boiling refrigerant in the evaporator must always be less than that of the surrounding medium so that the heat flows to the refrigerant. The expansion device which is also known as throttling device, divides the high pressure side and the low pressure side of a refrigeration system. It is connected between the receiver and the evaporator.

Objectives

After studying this unit, you should be able to

- describe various types of compressor,
- describe various types of condenser,
- describe various types of evaporator, and
- describe various types of expansion device.

Refrigeration system consists of different equipments. Individual knowledge of the equipments is required to understand the refrigeration system. The basic principle of the refrigerant equipments and the classification of those equipments are discussed here.

3.2 COMPRESSORS

3.2.1 Types of Compressor

There are different types of compressors that generally used in industry are,

(a) Reciprocating compressor
(b) Centrifugal compressor
(c) Rotary compressor
(d) Screw compressor
(e) Scroll compressor

The reciprocating and screw compressors are best suited for use with refrigerants which require a relatively small displacement and condense at relatively high pressure, such as R-12, R-22, Ammonia, etc.

The centrifugal compressors are suitable for handling refrigerants that require large displacement and operate at low condensing pressure, such as R-11, R-113, etc.

The rotary compressor is most suited for pumping refrigerants having moderate or low condensing pressures, such as R-21 and R-114; this is mainly used in domestic refrigerators.

Reciprocating Compressor

The compressors in which the vapour refrigerant is compressed by the reciprocating (i.e. back and forth) motion of the piston, called reciprocating compressors. These compressors are used for refrigerants which have comparatively low volume per kg and a large differential pressure, such as ammonia, R-12, R-22, etc.

Basic Cycle for Reciprocating Compressor

The p-v diagram of a reciprocating compressor is shown in the Figure 3.1 along with the skeleton diagram of the cylinder and piston mechanism.

When the piston is in the extreme left position of the inner dead centre (IDC), the volume occupied by the gas is $V_c = V_3$ called clearance volume, i.e. the volume between the piston and cylinder head. As the piston moves outward, the clearance gas expands to 4, when the pressure inside the cylinder is equal to the pressure at the suction flange of the compressor. As the piston moves further, the suction valve S opens and the vapour from the evaporator is sucked in till the extreme right position of the outer dead centre (ODC) is reached. At this position the volume occupied by the gas is V_1. The stroke or swept volume or piston displacement is

$$V_p = (V_1 - V_3) = \frac{\pi D^2}{4} L \qquad \ldots (3.1)$$

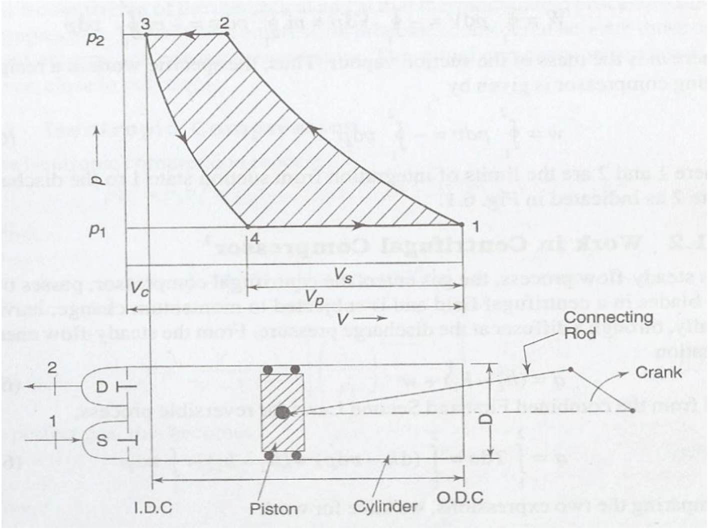


Figure 3.1 : Cylinder and Piston Mechanism and P-V Diagram of a Reciprocating Compressor

Where D is the bore or diameter and L is the stroke, i.e. the distance traveled by the piston between IDC and ODC of the cylinder. At 1, the suction valve closes as the piston moves inwards and the compression begins. At 2, the pressure in the cylinder is equal to the pressure at the discharge flange of the compressor. A further movement of the piston inward results in the pressure in the cylinder exceeding the condenser pressure. This opens the discharge valve D and the vapour from the cylinder flows into the condenser till the piston reaches again the IDC position. Gas equal to the clearance volume V_c remains in the cylinder and the cycle is operated.

The work done for compression is given by the cyclic integral of pdV.

Hence,
$$W = \oint pdV = \int_1^2 pdV + \int_2^3 pdV + \int_3^4 pdV + \int_4^1 pdV$$

$$= \int_1^2 pdV + p_2(V_3 - V_2) + \int_3^4 pdV + p_1(V_1 - V_4)$$

= Area 1-2-3-4

It will be seen that this area is also expressed by the term $-\oint Vdp$. Hence

$$W = \oint pdV = -\oint Vdp = -m\oint vdp$$

where, m is the mass of the suction vapour. Thus, the specific work in a reciprocating compressor is given by

$$w = -\int vdp$$

Volumetric Efficiency of Reciprocating Compressor

Volumetric efficiency is the term defined in the case of positive displacement compressors to account for the difference in the displacement in-built in the compressor V_p and actual volume V_s, of the suction vapour sucked and pumped. It is expressed by the ratio

$$\eta_v = \frac{V_s}{V_p} \qquad \dots 3.2$$

Clearance Volumetric Efficiency

The clearance or gap between the I.D.C. position of the piston and cylinder head is necessary in reciprocating compressors to provide for thermal expansion and machining tolerances. A clearance of (0.005L+0.5) mm is normally provided. This space together with the volume of the dead space between the cylinder head and valves, forms the clearance volume. The ratio of the clearance volume V_c to the swept volume V_b is called the clearance factor C, i.e.,

$$C = \frac{V_c}{V_p} \qquad \ldots 3.3$$

This factor is normally ≤ 5 per cent.

The effect of clearance in reciprocating compressors is to reduce the volume of the sucked vapour, as can be seen from Figure 3.1. The gas trapped in the clearance space expands from the discharge pressure to the suction pressure and thus fills a part of the cylinder space before suction begins. Considering only the effect of clearance on volumetric efficiency, we have from Figure 3.1 , for clearance volumetric efficiency

$$\eta_{cv} = \frac{V_1 - V_4}{V_p} = \frac{\left(V_p\ V_c\right) - V_4}{V_p} \qquad \ldots 3.4$$

The volume occupied by the expanded clearance gases before suction begins is

$$V_4 = \left(\frac{p_2}{p_1}\right)^{\frac{1}{\gamma}} V_c = \left(\frac{p_2}{p_1}\right)^{\frac{1}{\gamma}} VC_p \qquad \ldots 3.5$$

so that

$$\eta_{cv} = \frac{V_p + CV_p - CV_p\left(\frac{p_2}{p_1}\right)^{\frac{1}{\gamma}}}{V_p}$$

$$= 1 + C - C\left(\frac{p_2}{p_1}\right)^{\frac{1}{\gamma}} \qquad \ldots 3.6$$

Variation of Volumetric Efficiency with Suction Pressure

As shown in Figure 3.2 the nature of variation of the p-V diagram of a reciprocating compressor with suction pressure for constant discharge pressure. It is seen that with decreasing suction pressure, or increasing pressure ratio, the suction volume V and hence volumetric efficiency decrease until both become zero at a certain low pressure p'. Thus the refrigerating capacity of a reciprocating compressor tends to zero with decreasing evaporator pressure.

It can be seen from equation 3.6 that the clearance volumetric efficiency will be zero for a pressure ratio given by

$$\frac{p_2}{p_1} = \left(\frac{1}{C} + 1\right)^{\gamma} \qquad \ldots 3.7$$

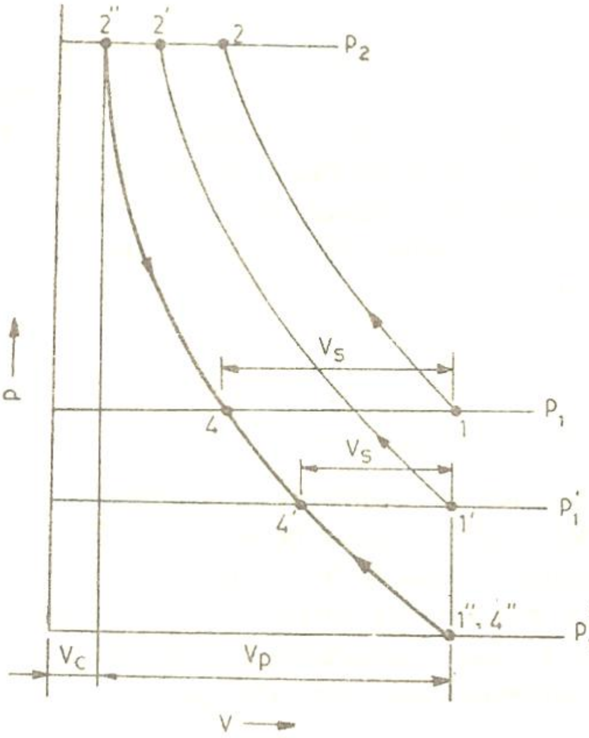


Figure 3.2: Decrease in Suction Volume in a Reciprocating Compressor with Decreasing Evaporator Pressure

Effect of Valve Pressure Drops

For the flow of any fluid, the pressure must drop in the direction of flow. Both suction and discharge valves will open only when there is a pressure drop across them. The effect of these pressure drops on the indicator diagram of the compressor is shown in Figure 3.3 It is seen that as a result of throttling or pressure drop on the suction side the pressure inside the cylinder at the end of the suction stroke is Ps while the pressure at the suction flange is $P_{1.}$ The pressure in the cylinder rises to the suction flange pressure P_t only after the piston has travelled a certain distance inward during which the volume of the fluid has decreased from $(V_p + V_c)$ to V_1.

Assuming the compression index to be n instead of γ, as the compression process is also polytropic due to heat exchange with cylinder walls and friction, we have

$$V_1 = (V_p + V_c)\left(\frac{p_s}{p_1}\right)^{\frac{1}{n}} \qquad \ldots 3.8$$

The expression for volumetric efficiency becomes

$$\eta_{cv} = \frac{V_1 - V_4}{V_p} = \frac{(V_p - V_c)\left(\frac{p_s}{p_1}\right)^{\frac{1}{n}} - V_c\left(\frac{p_2}{p_1}\right)^{\frac{1}{m}}}{V_p}$$

$$= (1 + C)\left(\frac{p_s}{p_1}\right)^{\frac{1}{n}} - C\left(\frac{p_2}{p_1}\right)^{\frac{1}{m}} \qquad \ldots 3.9$$

Considering the effect of pressure drop at the discharge valve as well, it can be shown that the expression for volumetric efficiency is

$$\eta_{cv} = (1 + C)\left(\frac{p_s}{p_1}\right)^{\frac{1}{n}} - C\left(\frac{p_d}{p_1}\right)^{\frac{1}{m}} \qquad \ldots 3.10$$

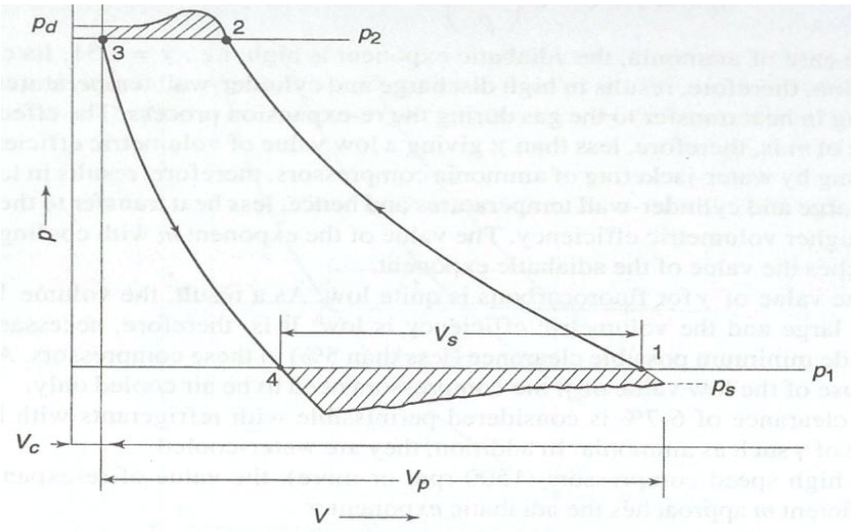


Figure 3.3: Effect of Valve Pressure Drops

Overall Volumetric Efficiency

Considering the effect of wire-drawing at the valves, polytropic compression, re expansion, and leakage, we may write the expression for the overall or total volumetric efficiency as follows

$$\eta_v = (1 + C)\left(\frac{p_2}{p_1}\right)^{\frac{1}{n}} - C\left(\frac{p_d}{p_1}\right)^{\frac{1}{m}} - 0.01r \qquad \ldots 3.11$$

The methods of improving the volumetric efficiency include the following:

(a) Providing clearance as small as possible,

(b) Maintaining low pressure ratio,

(c) Cooling during compression,

(d) Reducing pressure drops at the valves by designing a light-weight valve mechanism, minimizing valve overlaps and choosing suitable lubricating oils.

Effect of Clearance on Work

The effect of the clearance volume on the work of compression is mainly due to the different values of the exponents of the compression and expansion processes. If the exponents are different, the net work is given by

$$W = -\int_1^2 V dp + \int_4^3 V dp$$

$$= -\frac{n}{n-1} p_1 V_1 \left[\left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}} - 1\right] + \frac{m}{m-1} p_1 V_4 \left[\left(\frac{p_2}{p_1}\right)^{\frac{m-1}{m}} - 1\right] \qquad \ldots 3.12$$

When the two exponents are equal, i.e. m= n

$$W = \frac{n}{n-1} p_1 V_s \left[\left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}} - 1\right] \qquad \ldots 3.13$$

where $V_s = V_1 - V_4$ volume of the vapour sucked. Thus the work is only proportional to the suction volume. The clearance gas merely acts like a spring, alternately expanding and contracting. In practice, however, a large clearance volume results in a low volumetric efficiency and hence large cylinder dimensions, increased contact area between the piston and cylinder and so, increased friction and work.

3.2.2 Centrifugal Compressor

A single-stage centrifugal compressor mainly consists of the following four components as shown in Figure 3.4.

(a) An inlet casing to accelerate the fluid to the impeller inlet.

(b) An impeller to transfer energy to the fluid in the form of increase in static pressure and kinetic energy.

(c) A diffuser to convert the kinetic energy at the impeller outlet into pressure energy (static enthalpy).

(d) A volute casing to collect the fluid and to further convert the kinetic energy into pressure energy (static enthalpy).

Besides these, there are intercoolers, generally integrated with the casing, in a multistage compressor. The casing is usually made of cast iron and the impeller, of alloy (chrome-nickel) steels. The maximum stress is developed at the root of the blades.

The diffuser is normally vaneless type as it permits more efficient part load operation which is quite usual in any air-conditioning plant. A vaned diffuser will certainly cause shock losses if the compressor is run at reduced capacity and flow.

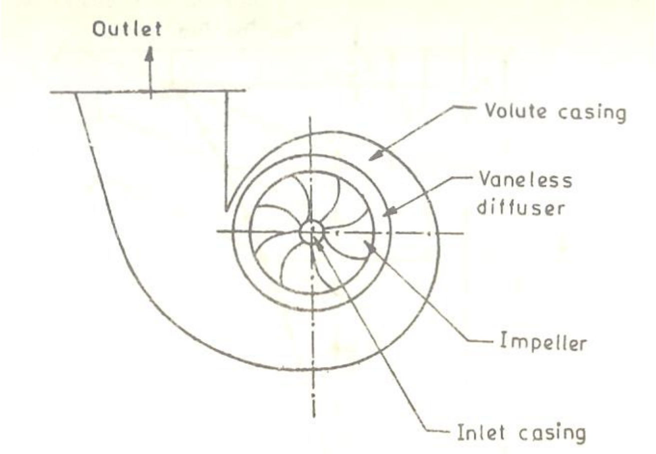


Figure 3.4: Elements of a Centrifugal Compressor

Performance Characteristics

The principal performance curve of a centrifugal machine is the head-flow characteristic.

With γ_2 = radius of impeller

β_2 = angle of exit at impeller tip

C = velocity with suffix *r* for radial, *u* for tangential and 2 for exit

ω = angular speed of impeller in rad/s

u = velocity of impeller tip

we may write for the tangential velocity at the exit

$$C_{u2} = u_2 - C_{r2} \cot \beta_2 \qquad \ldots 3.14$$

We know that head developed with no pre-whirl is given by,

$$w = C_{u2} u_2 \qquad \ldots 3.15$$

form the above two equations we get,

$$w = u_2 \left(u_2 - C_{r2} \cot \beta_2 \right)$$

$$= u_2^2 - u_2 C_{r2} \cot \beta_2$$

$$= (\omega r_2)^2 - (\omega r_2) C_{r2} \cot \beta_2 \qquad \ldots 3.16$$

Thus we find that for a given compressor, for which γ_2 and β_2 are fixed, and a rotating with certain speed, the head developed is a straight line function of the radial velocity C_{r2}. The flow rate a, in turn, is proportional to C_{r2}, The limiting head is u_2^2 which is developed at, $C_{r2}=0$, i.e., at zero flow rate. This occurs when the impeller is simply rotating in a mass of the fluid with the delivery valve closed.

It is seen that the nature of the characteristic depends on the outlet blade angle β_2 as follows:

Three types of blades are identified. They are backward-curved, radial and forward curved.

(a) For backward-curved blades, $\beta_2 < 90°$ head decreases with flow and hence with Q

(b) For radial blades, $\beta_2 = 90°$ head = u_2^2 = const.

(c) For forward-curved blades, $\beta_2 > 90°$, head increases with flow

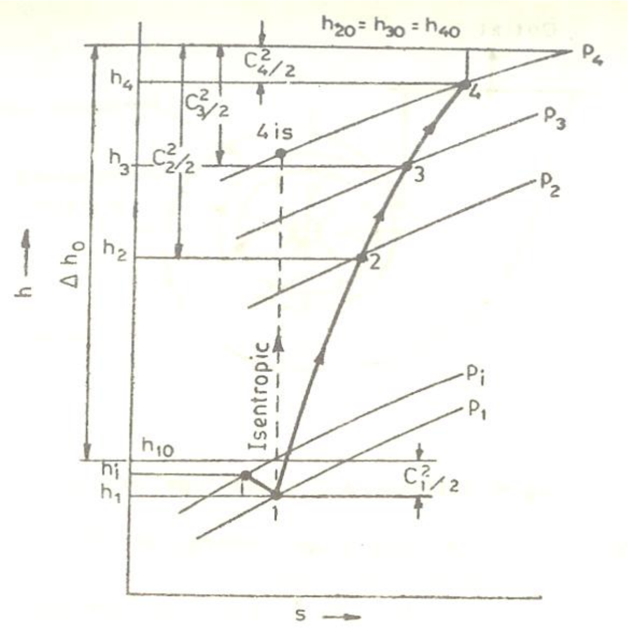


Figure 3.5: Mollier Diagram of Centrifugal Stage

From the point of view of optimal design, an outlet blade angle of 32° is normally preferred. A simple design will, however, have radial blades.

Figure 3.6 shows the theoretical head-flow characteristic for the three cases of angle β_2. For the case of backward-curved blades, it is a drooping characteristic.

The actual characteristic can, however, be obtained by considering the following losses as shown in Figure 3.6

(a) Leakage loss L_1 proportional to the head.

(b) Friction loss L_2 proportional to $\frac{C_{rel}^2}{2}$ and hence Q^2

(c) Entrance loss L_3 due to turning of the fluid to enter the impeller, being zero at the design point, which also corresponds to maximum efficiency.

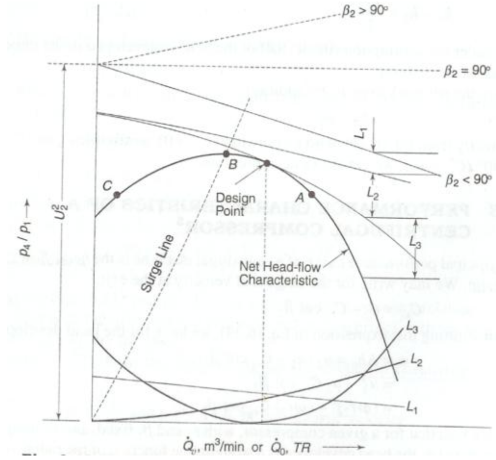


Figure 3.6: Performance Characteristic and Losses of a Centrifugal Compressor

Surging

Consider A as the point of operation at full load. When the refrigeration load decreases, the point of operation shifts to the left until point B of maximum head is reached. If the load continues to decrease to the left of B, say to C, the pressure ratio developed by the compressor becomes less than the ratio required between the condenser and evaporator pressure. viz.,

$$\frac{p_4}{p_1} < \frac{p_k}{p_0}$$

Hence some gas flows back from the condenser to the evaporator, thus increasing the evaporator pressure and decreasing $\frac{p_k}{p_0}$ .The point of operation suddenly shifts to A. As the refrigeration load is still less, the cycle will repeat itself. This phenomenon of reversal of flow in centrifugal compressors is called surging. It occurs when the load decreases to below 35 per cent of the rated capacity and causes severe stress conditions in the compressor as a result of hunting.

Capacity Control of Centrifugal Compressors

Centrifugal compressors require high tip speeds to develop the necessary pressure ratio. The high tip speed is achieved by employing either a large diameter impeller or high rpm or both. Because of large u_2, the velocities in general including the flow velocity C are high. Also, there must he a reasonable width of the shrouds to minimize friction and achieve high efficiency. Thus, because of the sufficiently large flow area (diameter D and width of shrouds b) required and large flow velocity, the satisfactory volume that can be handled by a centrifugal compressor is about 30-60 cubic metres per minute. A single centrifugal compressor, therefore, can be designed for a minimum capacity approximately of the order of 250 TR with R 11 and 150 TR with R 113 for the purpose of air conditioning.

One of the methods to control the capacity of the compressors is by varying the compressor speed through a speed-reduction gear. The decrease in speed results in an operation on a lower head-flow characteristic giving a lower volume flow rate corresponding to the same pressure ratio.

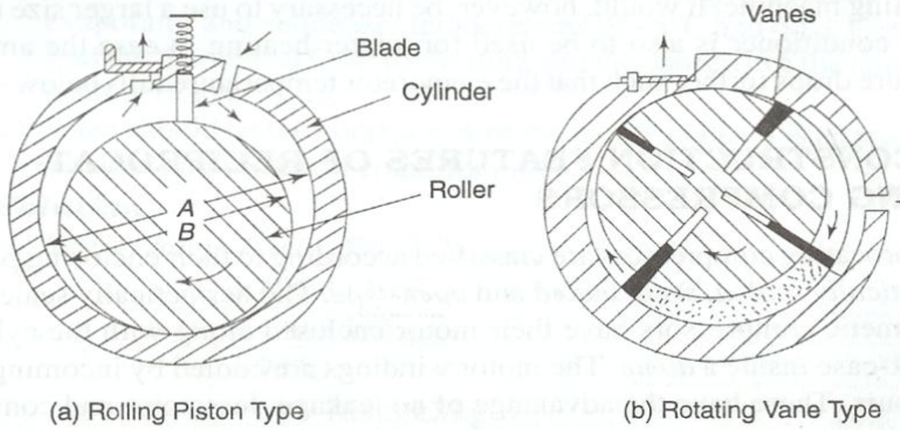
Capacity can be controlled by the use of variable inlet whirl vanes that are frequently employed with a constant speed drive. The capacity is varied by changing the angle at which the gas enters the impeller. The gas then enters with pre-rotation and this result in a decrease in flow.

3.2.3 Rotary Compressor

Rotary compressors are positive displacement, direct-drive machines. There are essentially two designs of this compressor:

(a) Rolling piston type

(b) Rotating vane type



(a) Rolling Piston Type (b) Rotating Vane Type

Figure 3.7: Rotary Compressor

In the rolling piston type, shown in Figure 3.7(a) the roller is mounted on an eccentric shaft with a single blade, which is always in contact with the roller by means of a spring. The theoretical piston displacement is

$$V_p = \frac{H\,(A^2 - B^2)}{4} \qquad \ldots 3.17$$

where A and B are respectively the diameters of the cylinder and rolling piston and H the lenght of the cylinder.

In the rotating vane type, as shown in Figure 3.7(b) with four vanes, the rotor is concentric with the shaft. The vanes slide within the rotor but keep contact with the cylinder. The assembly of rotor and the vanes is off-centre with respect to the cylinder.

In both designs, the whole assembly is enclosed in a housing (not shown in the figures), filled with oil and remains submerged in oil. An oil film forms the seal between the high-pressure and the low-pressure sides. When the compressor stops, this seal is lost and the pressure equalizes.

Rotary compressors have high volumetric efficiencies due to negligible clearance. They are normally used in a single stage up to a capacity of 5 TR with R-114. Large rotary compressors are used in low-temperature fields, such as in chemical and industrial processing, cold storages and freezing, as high displacement. low-stage or booster compressors at -90 to -l00°C evaporator temperature with R-12, R-22 and ammonia. They are available in l0 to 600 hp sizes with 2 to 120 cubic metres per minute displacement in one unit.

3.2.4 Screw Compressor

Rotary screw compressors also belong to the category of positive displacement compressors machine a rotary compressor essentially consists of two helically-grooved rotors as illustrated in Figure 3.8 which rotate in a housing.

The male rotor consists of lobes and is normally the driving rotor. The female rotor has gullies and is normally the driven rotor. A four-lobe male rotor will drive a six-gully female rotor at two-thirds of its speed. At 3600 rpm the number of compressed gas discharges of a four-lobe rotor will he 4 × 3600 = 14,400 per minute.

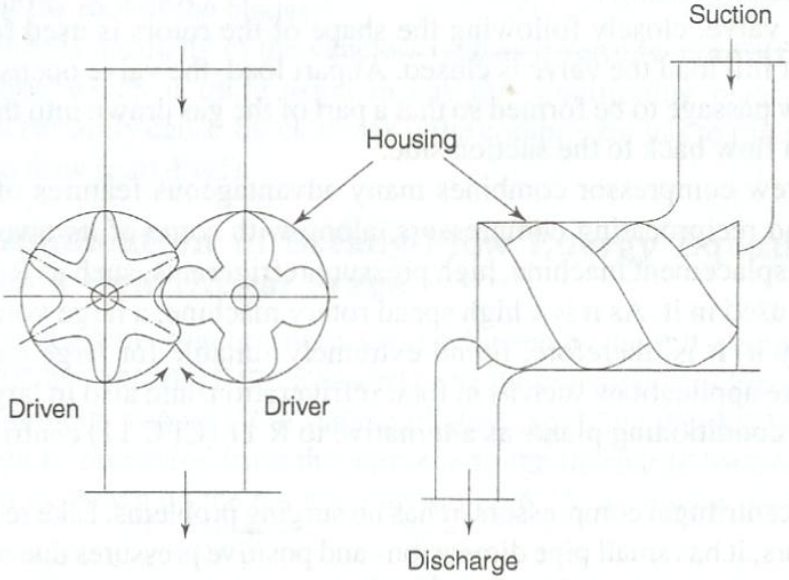


Figure 3.8: Sectional and Side Views of a Screw Compressor

As in the case of other positive displacement machines, there are three basic continuous phases of the working cycle, viz., suction, compression and discharge. When the male rotor turns clockwise, an interlobe space between a pair and housing nearest to the suction end opens and is filled with the gas. There are four such pairs to be filled during one revolution in a four-lobe rotor and the suction periods overlap one another.

When remeshing starts, the volume decreases and the pressure rises. The charge is moved helically and compressed until the trapped volume reaches the discharge end. The compression ratio is thus fixed.

Further rotation simply empties the rotors of the high pressure gas until the last traces of the gas are squeezed out, irrespective of the pressure in the condenser.

On completion of the discharge phase, there is no residual gas remaining in the rotors. As a result, there is no expansion of clearance gases. The compressor has no suction and discharge valves.

There are leakage paths in a screw compressor mainly across the line of mesh between the rotors and across the clearance between the rotors and the housing. To eliminate leakage, oil is injected in a number of small jets directed towards the mesh. Oil injection also serves the purpose of cooling and lubricating along with that of sealing the leakage paths.

A slide valve, closely following the shape of the rotors is used for capacity control. At full load the valve is closed. At part load, the valve opens enabling a return flow passage to be formed so that a part of the gas drawn into the interlobe spaces can flow back to the suction side.

The screw compressor combines many advantageous features of both centrifugal and compressors, along with some of its own. As it is a positive displacement machine, high pressure refrigerants, such as R-22 and ammonia are used in it. As it is a high speed rotary machine, a large volume can be handled by it. It is, therefore, found extremely suit able for large capacity low temperature applications such as in food refrigeration.

Like reciprocating compressors, it has no surging problems. It has small pipe dimensions and positive pressures due to the use of high pressure refrigerants. Like centrifugal compressors, it has high compression efficiency, continuous capacity control, unloaded starting and no balancing problems. Also, the compressor is suitable for large capacity installations.

3.3 CONDENSERS

The functions of the condenser are to desuperheat the high pressure gas, condense it and also sub- cool the liquid.

Heat from the hot refrigerant gas is rejected in the condenser to the condensing medium-air or water. Air and water are chosen because they are naturally available. Their normal temperature range is satisfactory for condensing refrigerants.

Like the evaporator, the condenser is also heat-exchange equipment.

3.3.1 Types of Condenser

There are three types of condensers, viz.

(a) Air- cooled,

(b) Water-cooled and

(c) Evaporative.

As their names imply, air-cooled condensers use air as the cooling medium, water-cooled condensers use water as the medium and the evaporative condenser is a combination of the above, i.e. uses both water and air.

3.3.2 Air-Cooled Condensers

There are two types under this category, viz. (a) natural convection and (b) forced-air type.

Natural Convection Condenser

Air movement over the surface of condenser tubes is by natural convection. As air comes in contact with the warm-condenser tubes, it absorbs heat from the refrigerant and thus the temperature of the air increases. Warm air being lighter, rises up and in its place cooler air from below rises to take away the heat from the condenser. This cycle goes on. Since air moves very slowly by natural convection, the rate of flow of heat from the refrigerant to air will be small. Thus a natural convection condenser is not capable of rejecting heat rapidly. Therefore a relatively large surface area of the condenser is required. Hence the use of this type of condenser is limited to very small units such as domestic refrigerators. It, however, requires very little maintenance.

In the small units, the condenser is fixed at the rear of the refrigerator cabinets. Generally, steel tubes are used, steel being cheaper than copper. To increase the heat-transfer area, wires are welded to the condenser tubes. These wires provide mechanical strength to the coil as well. In certain designs, widely-spaced fins are used. It is necessary to space the fins quite widely to avoid resistance to free (natural convection) air movement over the condenser.

Still another design is the plate-type. The condenser coil is fastened to a plate. The plate being in contact with the condenser tubes, the surface area of the condenser is increased. The plate-type condenser is mounted on the back of the refrigerator cabinet with a small gap between the cabinet and the plate. This gap gives an air- flue effect and facilitates better natural convection air currents.

It is obvious that while locating refrigerators or deep-freezes cabinets with a natural convection condenser fixed on the cabinet, sufficient care should be taken to allow free air movement. Also they should not be near an oven or any warm location.

Forced-air Circulation Condenser

This type employs a fan or blower to move air over the condenser coil at a certain velocity. The condenser coil is of the finned type. Fins in such coils are closely spaced (ranging between 8 and 17 fins per inch). The space between the fins gets choked with dirt and lint. Therefore to obtain optimum capacity, the fins should be kept clean. For circulating air over the condenser, fans are mounted on the shaft/pulley of the compressor motor. For bigger-capacity plants a separate motor is used to drive the fan or blower as also for hermetic-compressor units.

3.3.3 Water Cooled Condensers

There are three types of condensers which fall under this category:

(a) tube-in-tube or double pipe,

(b) shell-and-coil, and

(c) shell-and-tube.

Tube-in-Tube or Double Pipe Condenser

In this type, a smaller diameter pipe inserted inside a bigger diameter pipe is bent to the desired form. Water flows through the inner tube and the refrigerant through the annular space between the two tubes; the flow of refrigerant and water being arranged in opposite direction to get the maximum benefit of heat-transfer. Due to the impurities present in water, scale can form on the water-side of the tube which can impede the heat transfer; also muck can settle on the surface. Therefore it becomes necessary to periodically clean the water tube. But in the tube-in-tube system, cleaning is not easy, unless a removable header is provided to connect all the tubes.

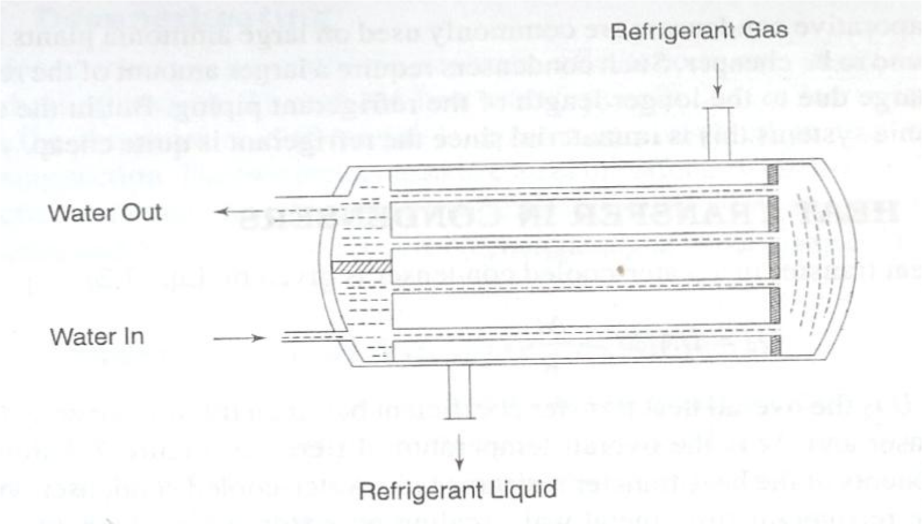


Figure 3.9: Schematic Representation of a Two-Pass Water-Cooled Shell and Tube Condenser

Shell-and-Coil Condenser

It consists of a welded-steel shell containing a coil of finned tubing. Water flows in the coil, the refrigerant being in the shell. Since the tube bundle is in the form of a coil, the water-side of the tube cannot be brushed but can only be cleaned chemically.

Shell-and-Tube Condenser

Figure 3.9 shows a typical shell-and-tube condenser. This is similar in construction to the flooded chiller. A number of straight tubes with integral fins are stacked inside a cylindrical shell, the tube ends expanded into tube sheets which are welded to the shell at both the ends. Intermediate tube supports are provided in the shell to avoid sagging and rattling of the tubes. Since it is very easy to clean the water-side and also, it can be easily repaired, this type of water-cooled condenser is very popular. Since ammonia affects copper, steel tubes are used for ammonia condensers. Water flows through the condenser water tubes while the refrigerant remains in the shell.

Since copper has a high thermal expansion and contraction rate, the tube tends to move back and forth in the tube sheets due to the variations in temperature.

To prevent the tubes from getting loose at the rolled ends due to this action, the holes in the tube sheets have small grooves. They are only a few hundredths of mm deep. When the tube ends are rolled or expanded in the tube-sheet holes, the copper tubes also expand into the grooves, thereby effectively anchoring the tube ends to the tube sheets and preventing movement of the tubes at the ends. However the expansion forces can cause the tubes to bow.

Removable water boxes are provided at the ends of the condenser to facilitate brushing of the water tubes.

Hot (superheated) refrigerant gas enters at the top of the shell and gets cooled (desuperheated) and condensed as it comes in contact with the water tubes. The condensed liquid drains off to the bottom of the shell. In some condensers extra rows of water tubes are provided at the lower end of the condenser for sub-cooling the liquid below the condensing temperature.

Often the bottom portion of the condenser also serves as the receiver, thereby eliminating the necessity of a separate receiver. However, if the maximum storage capacity (for the refrigerant) of the condenser is less than the total charge of the system, a receiver of adequate capacity has to be added in case the pump down facility is to be provided-such as in ice-plants, cold-storage jobs, etc.

Care should be taken not to overcharge the system with the refrigerant. This is because an excessive accumulation of liquid in the condenser tends to cover too much of the water tubes and reduce the heat-transfer surface available for condensing the high-pressure gas. This result in increasing the head pressure and condensing temperature, and excessive overcharge can create hydraulic pressures.

A fusible plug or safety pressure relief valve is fixed on the shell of the condenser to protect the high side of the refrigeration system against excessive pressures.

3.3.4 Evaporative Condenser

These condensers (Figure 3.10) have some features of both air-and water-cooled types. Both air and water are employed as a condensing medium. Water is pumped from the sump of the evaporative condenser to a spray header and sprayed over the condenser coil. At the same time a fan thaws air from the bottom-side of the condenser and discharges it out at the top of the condenser. An eliminator is provided above the spray header to stop particles of water from escaping along with the discharge air. The spray water coming in contact with the condenser tube surface evaporates into the air stream. The source of heat for vaporizing the water is taken from the refrigerant, thereby condensing the gas.

The evaporative condenser combines the functions of the water-cooled condenser and the cooling tower and hence occupies less space. Moreover, it needs less power than a water-cooled condenser. But the most troublesome point about the evaporative condenser is the difficulty in keeping the surface of the condenser coil clean. The condenser coil being both hot and wet in operation, the dirt carried along with the air stream forms a hard layer on the condenser. Scale also forms a hard layer if hard water is used. Once these hard layers are allowed to form, it is never possible to effectively clean the coil. So the capacity of the condenser gets substantially affected. Because of this maintenance problem, evaporative condensers are not much in favour.

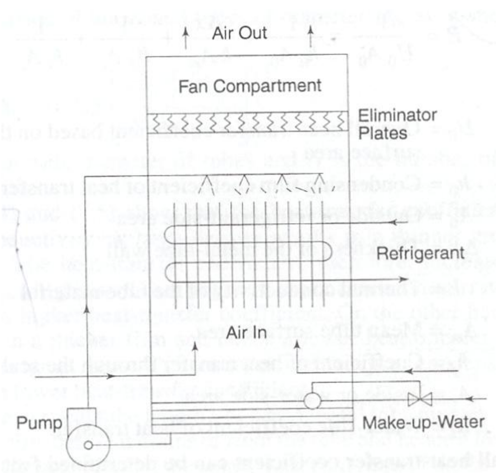


Figure 3.10: Evaporative Condenser

3.3.5 Heat Transfer in Condensers

The heat transfer in a water-cooled condenser is described by the Equation given below

$$\dot{Q} = UA\Delta t = \frac{\Delta t}{R} \qquad \ldots 3.18$$

where U is the overall heat transfer coefficient based on the surface area A of the condenser and Δt is the overall temperature difference. Figure 3.11 shows the components of the heat-transfer resistance in a water-cooled condenser, viz., the outside refrigerant film, metal wall, scaling on water-side surface and inside-water film. The overall resistance is obtained by adding all the resistances which are in series.

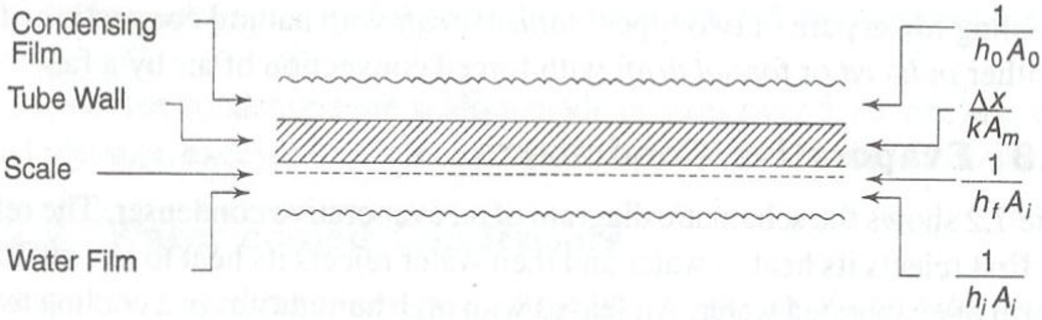


Figure 3.11: Thermal Resistance in Water-Cooled Condenser

$$R = \frac{1}{U_0 A_0} = \frac{1}{h_0 A_0} + \frac{\Delta x}{k A_m} + \frac{1}{h_f A_f} + \frac{1}{h_i A_i} \qquad \ldots 3.19$$

where

U_0 = Overall heat-transfer coefficient based on the outside surface area

h_0= Condensing film coefficient of heat transfer

A_0 = Outside or refrigerant-side area

k = Thermal conductivity of the tube material

A_m = Mean tube surface area

h_f = Coefficient of heat transfer through the scale

A_i = Inside or water-side area

h_i= Water-side coefficient of heat transfer.

Thus the overall heat-transfer coefficient can be determined from the above Equation 3.19 after estimating the individual resistances.

3.4 EVAPORATORS

The process of heat removal from the substance to be cooled or refrigerated is done in the evaporator. The liquid refrigerant is vaporized inside the evaporator (coil or shell) in order to remove heat from a fluid such as air, water etc.

Evaporators are manufactured in different shapes, types and designs to suit a diverse nature of cooling requirements. Thus, we have a variety of types of evaporators, such as prime surface types, finned tube or extended surface type, shell and tube liquid chillers, etc.

3.4.1 Types of Evaporator

Evaporators are classified into two general categories-the ‘dry expansion’ evaporator and ‘flooded’ evaporator.

Dry Expansion Evaporator

In the dry-expansion evaporator, the liquid refrigerant is generally fed by an expansion valve. The expansion valve controls the rate of flow of refrigerant to the evaporator in such a way that all the liquid is vaporized and the vapour is also superheated to a limited extent by the time it reaches the outlet end. At the inlet of the evaporator, the refrigerant is predominantly in the liquid form with a small amount of vapour formed as a result of flashing at the expansion valve. As the refrigerant passes through the evaporator, more and more liquid is vaporized by the load. The refrigerant, by the time it reaches the end of the evaporator, is purely in the vapour state and that too superheated. Thus the evaporator in its length is filled with a varying proportion of liquid and vapour. The amount of liquid in the evaporator will vary with the load on the evaporator. The inside of the evaporator is far from ‘dry’ but wetted with liquid. All the same, this type is called the ‘dry-expansion’ system to distinguish it from the ‘flooded’ system and also probably because by the time the refrigerant reaches the evaporator outlet it is no more wet (no liquid) but dry (superheated) vapour.

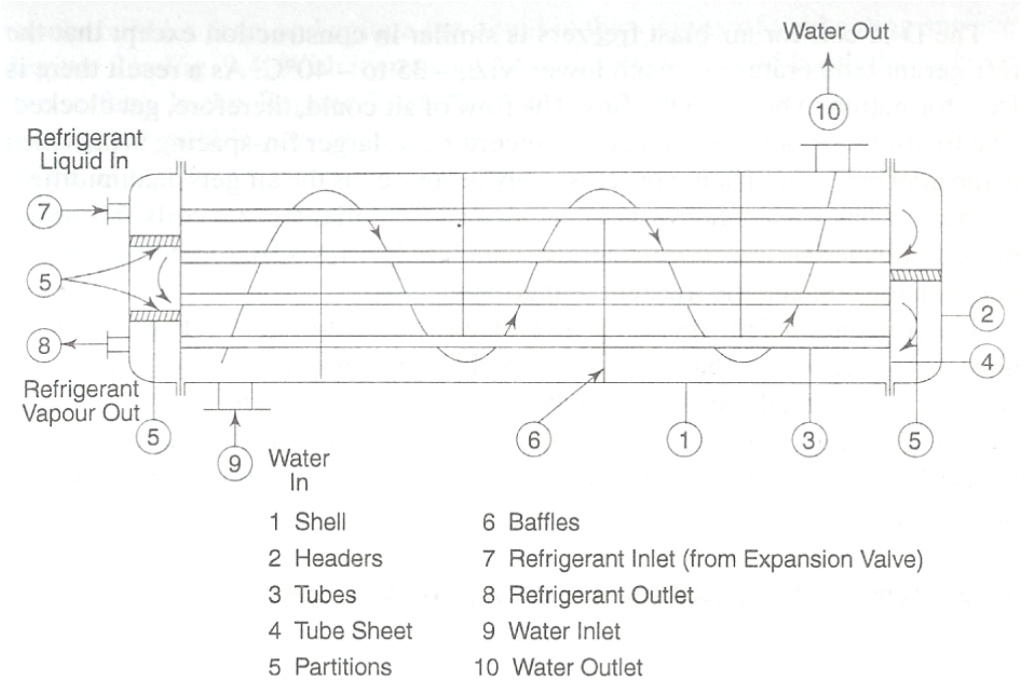


Figure 3.12: Direct Expansion Evaporator

Flooded Evaporator

In a flooded-type evaporator a constant refrigerant liquid level is maintained. A float valve is used as the throttling device which maintains a constant liquid level in the evaporator. Due to the heat supplied by the substance to be cooled, the liquid refrigerant vaporizes and so the liquid level falls. The float valve opens to admit more liquid and thus maintains a constant liquid level. As a result, the evaporator is always filled with liquid to a level as determined by the float adjustment and the inside surface is wetted with liquid. Thus this type is called the flooded evaporator. The heat-transfer efficiency increases because the entire surface is in contact with the liquid refrigerant and, therefore, the flooded evaporator is more efficient. But the refrigerant charge is relatively large as compared to the dry-expansion type. As the evaporator is filled with liquid, it is obvious that the vapour from the evaporator will not be superheated but will be at saturation. To prevent liquid carry over to the compressor, accumulators' are generally used in conjunction with flooded evaporators. The accumulator also serves as the chamber for the liquid level float valve. The evaporator coil is connected to the accumulator and the liquid flow from the accumulator to the evaporator coil is generally by gravity. The vapour formed by the vaporization of the liquid in the coil being lighter, rises up and passes on to the top of the accumulator from where it enters the suction line as shown in Figure 3.13. In some cases, liquid eliminators are provided in the accumulator top to prevent the possible carry-over of liquid particles from the accumulator to the suction line. Further, a liquid-suction heat exchanger is used on the suction line to superheat the suction vapour. For some applications, a refrigerant liquid pump is employed for circulating the liquid from the accumulator to the evaporator coil and such a system is called a 'liquid-overfeed system'.

While the terms 'dry expansion' and 'flooded' indicate the manner in which the liquid refrigerant is fed into the evaporator and circulated, the terms 'natural convection' and 'forced convection' describe the way in which the fluid (air or liquid) is cooled/circulated around the evaporator.

Natural convection relies on the movement in a fluid, where the colder layer at the top being heavier falls down and the warmer layer rises up. By keeping an evaporator in the topmost portion of an insulated cabin, the air inside the cabin gets cooled by natural convection. A domestic refrigerator is a typical example. In 'forced-convection' types, the fluid is 'forced' over the evaporator by means of a fan or a liquid pump. In a room air conditioner, a fan continuously circulates the room air over the cooling coil and thus cools the room air. In a chilled-water system, a water pump or brine pump circulates the fluid through the chiller and cooling coils. For a 'coil-in-tank' arrangement, such as in an ice plant, an agitator is used to move the brine over the cooling coil with a certain amount of velocity.

3.4.2 Heat Transfer in Evaporators

The three heat-transfer resistances in evaporators are:

(a) Refrigerant side for the transfer of heat from solid surface to the liquid refrigerant.

(b) Metal wall.

(c) Cooled-medium side which could be due to air, water, brine or any other fluid or a wetted surface on a cooling and dehumidifying coil.

The heat transfer from solid surface to the evaporating refrigerant is of primary interest here. However, the mechanism of boiling i so complex because of the influence of such factors as surface tension, saturation temperature, latent heat and nature of the solid surface, in addition to the usual transport properties, that it is very difficult to predict the heat-transfer coefficient analytically. Nevertheless, no attempt is made here to present correlations applicable to evaporating refrigerants which are available in the large amount of published information available on the subject.

In commercial equipment, the boiling process occurs in two types of situations: one, of pool boiling as in flooded evaporators with refrigerant boiling the shell-side and the other, of flow or forced convection boiling as in direct- expansion evaporators with refrigerant on the tube-side.

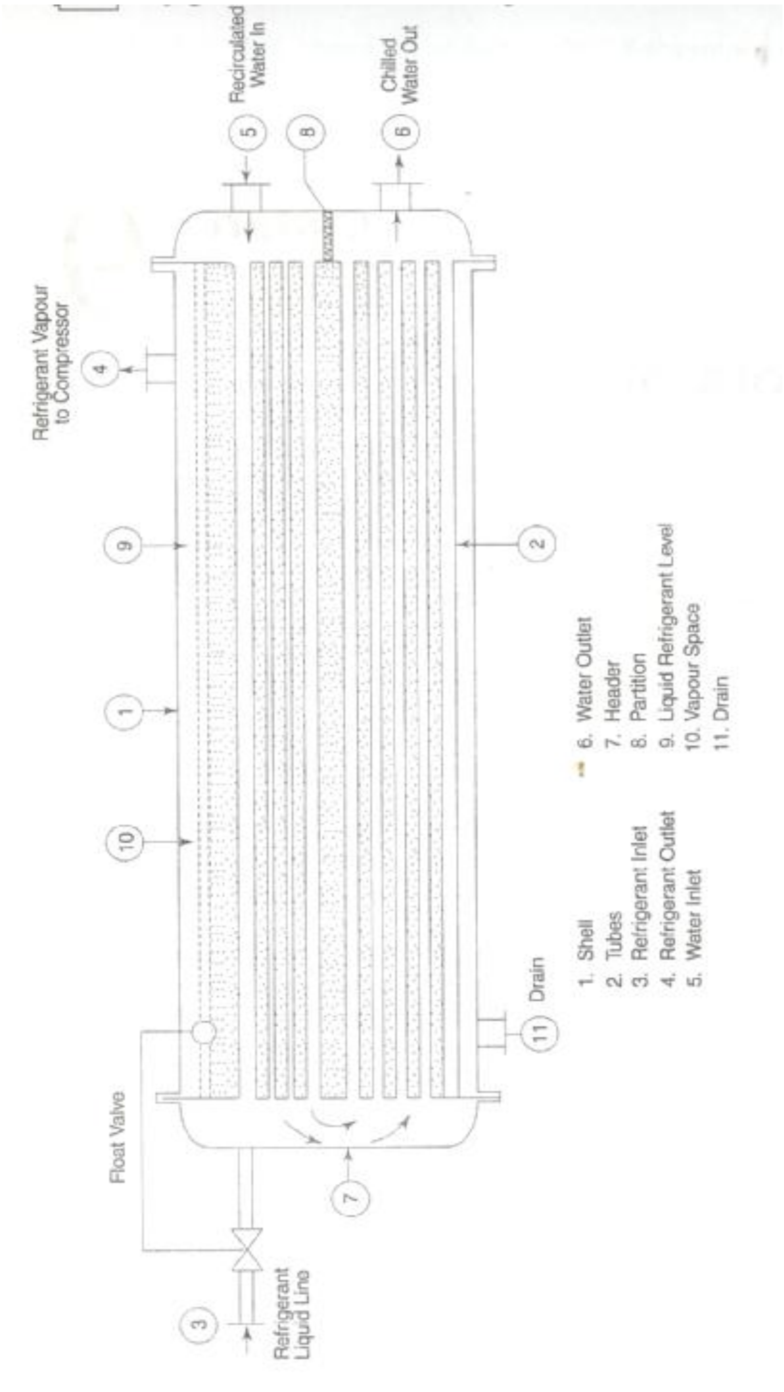


Figure 3.13: Flooded Evaporator

3.5 EXPANSION DEVICES

There are different types of expansion or throttling devices. The most commonly used are:

(a) Capillary tube,

(b) Float valves,

(c) Thermostatic expansion valve.

3.5.1 Capillary Tube

Instead of an orifice, a length of a small diameter tube can offer the same restrictive effect. A small diameter tubing is called ‘capillary tube’, meaning ‘hair-like’. The inside diameter of the capillary used in refrigeration is generally about 0.5 to 2.28 mm (0.020 to 0.090’). The longer the capillary tube and/or the smaller the inside diameter of the tube, greater is the pressure drop it can create in the refrigerant flow; or in other words, greater will be the pressure difference needed between the high side and low side to establish a given flow rate of the refrigerant.

The length of the capillary tube of a particular diameter required for an application is first roughly determined by empirical calculations. It is then further correctly established by experiments. The capillary tube is not self-adjusting. If the conditions change, such as an increase in the discharge/condenser pressure due to a rise in the ambient temperature, reduction in evaporator pressure, etc. the refrigerant flow-rate will also change. Therefore a capillary tube, selected for a particular set of conditions and load will operate somewhat less efficiently at other conditions. However if properly selected, the capillary tube can work satisfactorily over a reasonable range of conditions.

As soon as the plant stops, the high and low sides equalize through the capillary tube. For this reason, the refrigerant charge in a capillary tube system is critical and hence no receiver is used. If the refrigerant charge is more than the minimum needed for the system, the discharge pressure will go up while in operation. This can even lead to the overloading of the compressor motor. Further, during the off-cycle of the unit, the excess amount will enter the cooling coil and this can cause liquid flood back to the compressor at the time of starting. Therefore, the refrigerant charge of the capillary tube system is critical. For this reason, a refrigerant liquid receiver cannot be used. The charge should be exactly the quantity as indicated by the manufacturer of the refrigeration unit.

Since the capillary tube equalizes the high side with the low side during the off-cycle, the idle pressures at the discharge and suction of the compressor will be equal. Therefore at the time of starting, the compressor motor need not overcome the stress of the difference of pressure in the suction and the discharge sides. In other words the compressor is said to start unloaded. This is a great advantage as a low starting torque motor is sufficient for driving the compressor.

The capillary tube is quite a simple device and is also not costly. Its pressure equalization property allows the use of a low starting torque motor. The liquid receiver is also eliminated in a capillary tube system because of the need to limit the refrigerant charge. All these factors help to reduce the cost of manufacture of the systems employing a capillary tube as the throttling device.

The capillary tube is used in small hermetic units, such as domestic refrigerators, freezers and room air conditioners.

3.5.2 Float Valves

There are mainly two types of float valves- low side float valves and high side float valve.

Low-side Float Valve

This is similar to the float valves used for water tanks. In a water tank the float valve is fixed at the outlet of the water supply pipe to the tank. When the water level is low in the tank, the float ball hangs down by its own weight and the float arm keeps the valve fully open to allow water flow into the tank. As the water level rises, the float ball (which is hollow) floats on the water and gradually rises according to the water level, throttling the water through the valve. Ultimately when the tank is full, the float valve completely closes the water supply. As the water from the tank is used, the water level falls down; the float ball also lowers down, opening the valve according to the level of water in the tank.

The low-side float valve also acts in the same way in a refrigeration system. As the name implies the float valve is located in the low pressure side of the system. It is fixed in a chamber (float chamber) which is connected to the evaporator. The valve assembly consists of a hollow ball, a float arm, needle valve and seat. The needle valve-seat combination provides the throttling effect similar to the expansion valve needle and seat. The movement of the float ball is transmitted to the needle valve by the float arm. The float ball being hollow floats on the liquid refrigerant. The needle valve and seat are located at the inlet of the float chamber. As the liquid refrigerant vaporizes in the evaporator, its level falls down in the chamber. This causes the float ball to drop and pull the needle away from the seat, thereby allowing enough liquid refrigerant to flow into the chamber of the evaporator to make up for the amount of vaporization. When enough liquid enters, the float ball rises and ultimately closes the needle valve when the desired liquid level is reached. The rate of vaporization of liquid and consequent drop in the level of the liquid in the evaporator is dependent on the load. Thus the movement of the float ball and amount of opening of the float valve is according to the load on the evaporator. The float valve responds to liquid level changes only and acts to maintain a constant liquid level in the evaporator under any load without regard for the evaporator pressure and temperature.

Like in the expansion valve, the capacity of the low-side float valve depends on the pressure difference across the orifice as well as the size of the orifice.

Low-side float valves are used for evaporators of the flooded-type system. In bigger capacity plants a small low-side float valve is used to pilot a liquid feed (and throttling) valve. According to the liquid level in the evaporator, the float valve transmits pressure signals to the main liquid feed valve to increase or decrease the extent of its opening. Thus the low-side float valve in such a system is called a ‘pilot’ and the liquid-feed valve is known as the pilot-operated liquid-feed valve.

High-side Float Valve

The high-side valve like the low-pressure float valve, is a liquid level sensing device and maintains a constant liquid level in the chamber in which it is fixed. However it differs from the low-side float valve in the following respects.

(a) The high-side float valve and its chamber are located at the high-pressure side of the system, while the low-side float valve is located at the low-pressure side of the system.

(b) The needle and seat of the valve are at the outlet of the chamber as against the needle valve being at the inlet of the chamber in the low-side float.

(c) In the high-side float valve, the valve opens on a rise in the liquid level in the chamber, just the opposite action of the low-side float valve, which closes on a rise in liquid level in the chamber.

The high-side float chamber is located between the condenser and evaporator. The liquid condensed in the condenser flows down to the float chamber.

As the liquid level rises in the chamber, the float ball also rises, thereby opening the needle valve. As the liquid level falls in the chamber, the float valve tends to close the seat orifice. It is obvious that refrigerant vapour is condensed in the condenser at the same rate at which the liquid vaporizes in the evaporator; the float chamber receives and feeds liquid to the evaporator at the same rate. Since the rate of vaporization of the liquid in the evaporator is according to the load, the high-side float obviously works as per the load.

This type of float valve is generally used in centrifugal-refrigeration plants.

Refrigerant feed/throttling devices for flooded chillers are usually the low-side or high-side float valve. For example, in centrifugal plants, the chiller is of the flooded type and generally high-side float valves are used as throttling devices. In a flooded chiller working in conjunction with a reciprocating compressor, a low-side float valve is used as the throttling and refrigerant liquid flow control.

3.5.3 Thermo - static Expansion Valve

The name ‘thermostatic-expansion valve’ may give the impression that it is a temperature control device. It is not a temperature control device and it cannot be adjusted and used to vary evaporator temperature. Actually TEV is a throttling device which works automatically, maintaining proper and correct liquid flow as per the dictates of the load on the evaporator. Because of its adaptability to any type of dry expansion application, automatic operation, high efficiency and ability to prevent liquid flood backs, this valve is extensively used.

The functions of the thermostatic-expansion valve are:

(a) To reduce the pressure of the liquid from the condenser pressure to evaporator pressure,

(b) To keep the evaporator fully active and

(c) To modulate the flow of liquid to the evaporator according to the load requirements of the evaporator so as to prevent flood back of liquid refrigerant to the compressor.

It does the last two functions by maintaining a constant superheat of the refrigerant at the outlet of the evaporator. It would be more appropriate to call it a ‘constant superheat valve’.

The important parts of the valve are:

Power element with a feeler bulb, valve seat and needle, and a superheat adjustment spring.

3.6 SUMMARY

Compressor, condenser, evaporator, expansion devices are important equipments which are generally used in the refrigeration system. Compressor is used to compress the refrigerant from the evaporator and to raise its pressure so that the corresponding temperature is higher than that of the cooling medium. Since compressor virtually takes the heat at a low temperature from the evaporator and pumps it at the high temperature to the condenser, therefore it is often to as a heat pump. The condenser is used in the high pressure side of a refrigeration system. Its function is to remove heat of the hot vapour refrigerant discharged from the compressor. The hot vapour refrigerant consists of the heat absorbed by the evaporator and the heat of compression added by the mechanical energy of the compressor motor. The heat from the hot vapour refrigerant in a condenser is removed first by transferring it to the walls of the condenser tubes and then from the tubes to the condensing or cooling medium. The function of an evaporator is to absorb heat from the surrounding location or medium which is to be cooled, by means of a refrigerant. The evaporator cools by using the refrigerant’s latent heat of vaporization to absorb heat from the medium being cooled. The temperature of the boiling refrigerant in the evaporator must always be less than that of the surrounding medium so that the heat flows to the refrigerant. The expansion device reduces the high pressure liquid refrigerant to low pressure liquid refrigerant before being fed to the evaporator. It also maintains the desired pressure difference between the high and low pressure sides of the system, so that the liquid refrigerant vaporizes at the designed pressure in the evaporator.