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S. Y. B.Sc. Semester-4
Industrial chemistry/ IC (Vocational)
USO4CICV01/US04CICH02: Chemical Plant Utilities
UNIT – 3

Refrigerant Compressors

Introduction

A refrigerant compressor, as the name indicates, is a machine used to compress the vapour refrigerant from the evaporator and to raise its pressure so that die corresponding saturation temperature is higher than that of the cooling medium. It also continually circulates the refrigerant through the refrigerating system. Since the compression of refrigerant requires some work to be done on it, therefore, a compressor must be driven by some prime mover.

Since the 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 referred to as a heat pump.

Classification of Compressors

The compressors may be classified in many ways, but the following are important from the subject point of view:

1. According to the method of compression
    - (a) Reciprocating compressors
    - (b) Rotary compressors
    - (c) Centrifugal compressors
2. According to the number of working strokes
    - (a) Single acting compressors
    - (b) Double acting compressors.
3. According to the number of stages
    - (a) Single stage (or single cylinder) compressors
    - (b) Multi-stage (or multi-cylinder) compressors
4. According to the method of drive employed
    - (a) Direct drive compressors
    - (b) Belt drive compressors.
5. According to the location of the prime mover
    - (a) Semi-hermetic compressors (direct drive, motor and compressor in separate housings)
    - (b) Hermetic compressors (direct drive, motor and compressor in same housings)

Important Terms

The following important terms, which will be frequently used in this chapter, should be clearly understood at this stage

1. Suction pressure: It is the absolute pressure of refrigerant at the inlet of a compressor,

2. Discharge pressure: It is the absolute pressure of refrigerant at the outlet of compressor.

3. Compression ratio (or pressure ratio): It is the ratio of absolute discharge pressure to the absolute suction pressure. Since the absolute discharge pressure is always more than the absolute suction pressure, therefore, the value of compression ratio is more than unity.

The compression ratio may also be defined as the ratio of total cylinder volume to the clearance volume.

4. Suction volume: It is the volume of refrigerant sucked by the compressor during its suction stroke. It is usually denoted by V_s.

5. Piston displacement volume or stroke volume or swept volume: It is the volume swept by the piston when it moves from its top or inner dead position to bottom or outer dead centre position. Mathematically, piston displacement volume or stroke volume or swept volume,

$$Vp = \frac{\pi}{4} \times D^2 \times L$$

Where, D = diameter of cylinder
L = length of piston stroke

6. Clearance factor: It is the ratio of clearance volume(Vc) to the piston displacement volume (Vp). Mathematically, clearance factor,

$$C = \frac{Vc}{Vp}$$

7. Compressor capacity: It is the volume of the actual amount of refrigerant passing through the compressor in a unit time. It is equal to the suction volume (Vs). It is expressed in m^3 /s.

8. Volumetric efficiency: It is the ratio of the compressor capacity or the suction volume (Vs) to the piston displacement volume (Vp). Mathematically, volumetric efficiency,

$$\eta = \frac{Vs}{Vp}$$

A good compressor has a volumetric efficiency of 70 to 80 percent Refrigerant

Reciprocating Compressors

The compressors in which the vapour refrigerant is compressed by the reciprocating (i.e. back and forth) motion of the piston, are 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-717), R-12, R-22, and methyl chloride (R-40). The reciprocating compressors are available in sizes as small as 1/12 kW which are used in small domestic refrigerators and upto about 150 kW for large capacity installations.

The two types of reciprocating compressors in general use are single acting vertical compressors and double acting horizontal compressors. The single acting compressors usually have their cylinders arranged vertically, radially or in a V or W form. The double acting compressors usually have their cylinders arranged horizontally.

Fig. 9.1 shows a single stage single acting reciprocating compressor in its simplest form. The principle of operation of the compression cycle is as discussed below:

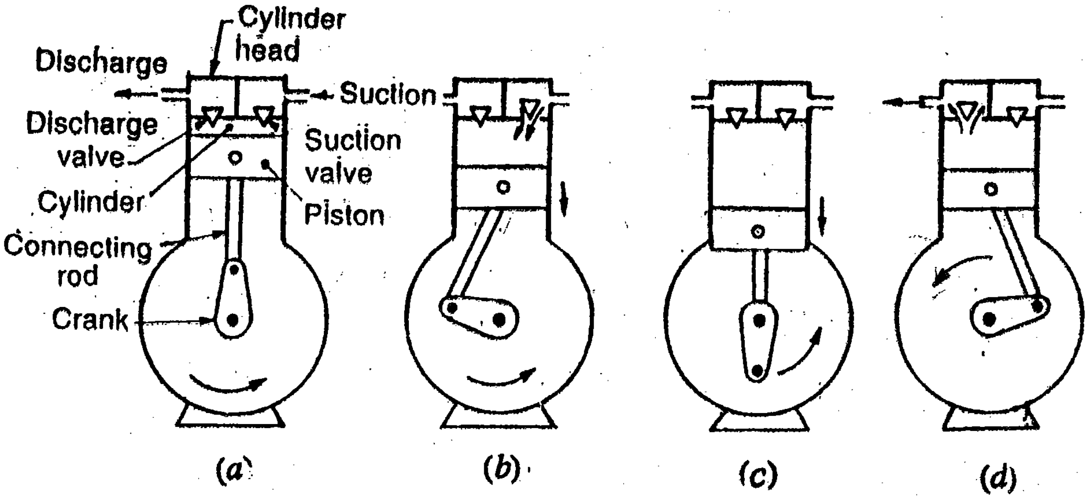

Figure:1 Principle of operation of single stage, single acting reciprocating compressor

Let us consider that the piston is at the top of its stroke as shown in Figure: 1(a). This is called top dead centre position of the piston. In this position, the suction valve is held closed because of the pressure in the clearance space between the top of the piston and the cylinder head. The discharge valve is also held closed because of the cylinder head pressure acting on the top of it.

When the piston moves downward (i.e. during suction stroke) as shown in Figure: 1 (b) the refrigerant left in the clearance space expands. Thus the volume of the cylinder (above the piston) increases and the pressure inside the cylinder decreases. When the pressure becomes slightly less than the suction pressure or atmospheric pressure, the suction valve gets opened and the vapour refrigerant flows into the cylinder. This flow continues until the piston reaches the bottom of its stroke (i.e. bottom dead centre). At the bottom of the stroke, as shown in Figure: 1 (c), the suction valve closes because of spring action. Now when the piston moves upward (i.e. during compression stroke) as shown in Figure: 1 (d), the volume of the cylinder decreases and the pressure inside the cylinder increases. When the pressure inside the cylinder becomes greater than that on the top of the discharge valve, the discharge valve gets opened and the vapour refrigerant is discharged into the condenser and the cycle is repeated.

It may be noted that in a single acting reciprocating compressor, the suction, compression and discharge of refrigerant takes place in two strokes of the piston or in one revolution of the crankshaft.

1. In a double acting reciprocating compressor, the suction and compression takes place on both sides of the piston. It is thus obvious, that such a compressor will supply double the volume of refrigerant than a single acting reciprocating compressor (neglecting volume of piston rod).

2. There must be a certain distance between the top of the piston and the cylinder head when the piston is on the top dead centre so that the piston does not strike the cylinder head. This distance is called clearance space and the volume therein is called the clearance volume. The refrigerant left in this space is at discharge pressure and its pressure must be reduced below that of suction pressure (atmospheric pressure) before any vapour refrigerant flows into the cylinder. The clearance space should be a minimum.

3. The low capacity compressors are air cooled. The cylinders of these compressors usually have fins to provide better air cooling. The high capacity compressors are cooled by providing water jackets around the cylinder.

Work Done by a Single Stage Reciprocating Compressor

We have already discussed that in a reciprocating compressor; the vapour refrigerant is first sucked, compressed and then discharged. So there are three different operations of the compressor. Thus we see that work is done on the piston during the suction of refrigerant. Similarly, work is done by the piston during compression as well as discharge of the refrigerant. A little consideration will show that the work done by a reciprocating compressor is mathematically equal to the work done by the compressor during compression as well as discharge minus the work done on the compressor during suction.

Here we shall discuss the following two important cases of work done:

1. When there is no clearance volume in the cylinder, and
2. When there is some clearance volume

Work done by a Single Stage, Single Acting Reciprocating Compressor without Clearance Volume:

Consider a single stage, single acting reciprocating compressor without clearance as shown by the p-v and T-s diagrams in Figure: 2.

Let P_1=suction pressure of the refrigerant(before compression)
V_1= suction volume of the refrigerent(before compression)
T_1 = suction temperature of the refrigerent(before compression)
P_2,V_2 and T_2 = corresponding values for the refregerant at the discharge point i.e. after compression and
r = compression ratio or pressure ratio, P_2/P_1

As a matter of fact, the compression of refrigerant may be isothermal, polytropic, or isentropic (reversible adiabatic). Now we shall find out the amount of work done in compressing the refrigerant in all the above mentioned three cases.

1. Work done during isothermal compression:

We have already discussed that when the piston moves from the top dead centre (point A), the refrigerant is admitted into the compressor cylinder and it continues till the piston reaches at its bottom dead centre (point B). Thus the line A B represents suction stroke and the area below this line (i.e. area AB B' A') represents the work done during suction stroke. From the figure, we find that work done during suction stroke,

W_1=Area ABB'A' = P_1V_1

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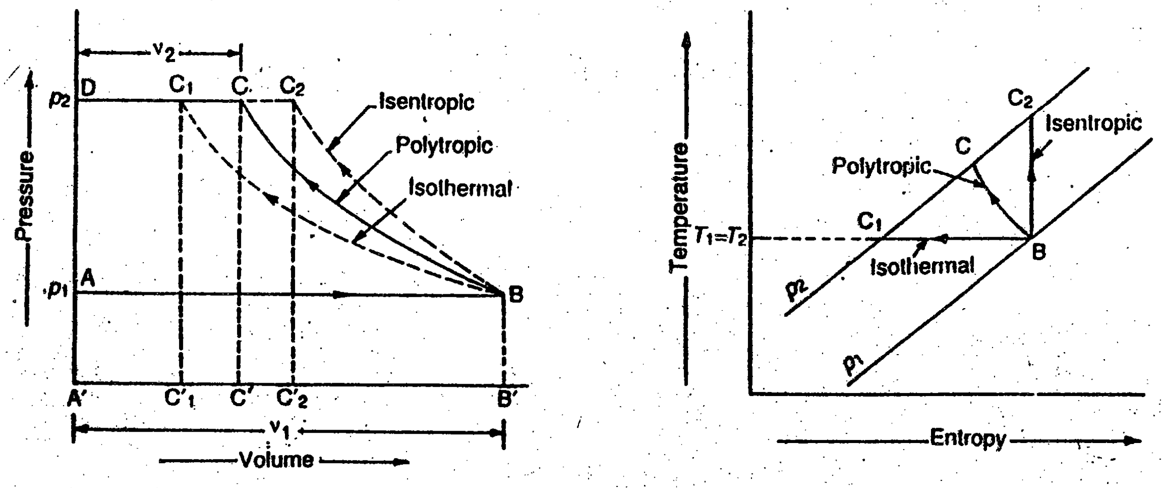
The refrigerant is compressed during the return stroke (or compression stroke BC_1) of the piston at constant temperature. The compression continues till die pressure (p_2) in the cylinder is sufficient to force open the discharge valve at C_1. After that no compression takes place with the inward movement of the piston. Now during the remaining part of the compression stroke, the compressed refrigerant is discharged to condenser till the piston reaches its top dead centre.



(a) p-v diagram.

(b) T-s diagram.

Figure : 2 p-v and T-s diagrams for a single stage reciprocating compressor

From the figure, we find that

Work done during compression,

W_2 = Area B C_1 C_1' B' = $P_1V_1 \log_e\left(\frac{V_1}{V_2}\right)$

and work done during discharge,

W_3 = Area C_1 d A' C_1' = P_2V_2

Work done by the compressor per cycle,

W = Area ABC_1D

= Area C_1 D A' C_1' + Area BC_1C_1' B' - Area ABB' A'

= $W_3 + W_2 - W_1$

$= P_2V_2 + P_1V_1 \log_e \left(\frac{V_1}{V_2}\right) - P_1V_1 = P_1V_1 \log_e\left(\frac{V_1}{V_2}\right)$ .....($P_1V_1 = P_2V_2$)

$= 2.3\ P_1V_1 \log\left(\frac{V_1}{V_2}\right) = 2.3\ P_1V_1 \log r$ .... $\left(\frac{V_1}{V_2} = \frac{P_2}{P_1} = r\right)$

$= 2.3\ m\ R\ T_1 \log r$ ....($P_1V_1 = mRT_1$)

2. Work done during polytropic compression: (PV^n = Constant)

The polyfiropic compression is shown by the curve BC in Fig 2. Now CD represents the volume of refrigerant delivered (i.e. V_2). We know that work done during suction,

$$W_1 = \text{Area ABB' A'} = P_1V_1$$

Work done during polytropic compression,

$$W_2 = \text{Area BCC' B'} = \frac{P2V2-P1V1}{n-1}$$

and work done during discharge,

$$W_3 = \text{Area CDA'C'} = P_2V_2$$

Work done by the compressor per cycle,

$$W = \text{Area ABCD}$$
$$= \text{Area CDA'C'} = \text{Area BCC' B'}- \text{Area ABB'A'}$$
$$= W_3 + W_2 - W_1$$
$$= P_2V_2 + \frac{P2V2-P1V1}{n-1} - P_1V_1$$
$$= \frac{(n-1)P_2V_2 + P_2V_2 - (n-1)P_1V_1}{(n-1)}$$
$$= \frac{n}{n-1} * (P_2V_2 - P_1V_1) \quad .....(i)$$
$$= \frac{n}{n-1} * P1V1\left(\frac{P_2V_2}{P_1V_1} - 1\right) \quad .....(ii)$$

We Know that polytropic compression,

$$P_1V_1^n = P_2V_2^n$$
$$\left(\frac{V_1}{V_2}\right) = \left(\frac{P_2}{P_1}\right)^{\frac{1}{n}} or \left(\frac{V_2}{V_1}\right) = \left(\frac{P_1}{P_2}\right)^{\frac{1}{n}}$$

Substituting the value of V2/V1 in equation (ii)

$$W = \frac{n}{n-1} * P_1V_1\left[\frac{P_2}{P_1}\left(\frac{P_1}{P_2}\right)^{\frac{1}{n}} - 1\right]$$
$$= \frac{n}{n-1} * P_1V_1\left[\frac{P_2}{P_1}\left(\frac{P_2}{P_1}\right)^{\frac{-1}{n}} - 1\right]$$
$$= \frac{n}{n-1} * P_1V_1\left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 1\right]$$
$$= \frac{n}{n-1} * mRT_1\left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 1\right]$$
$$= \frac{n}{n-1} * mRT_1\left[\left(\frac{T_2}{T_1}\right) - 1\right] \quad .... \left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} = \frac{T_2}{T_1}\right]$$
$$= \frac{n}{n-1} * mR(T_2 - T_1)$$

3. Work done during isentropic compression:

The isentropic compression is shown by the curve BC_2 in Fig 2. fo this case, the volume of refrigerant delivered (i.e. V_2) is represented by the line C_2D.

The work done by the compressor per cycle during compression may be worked out in the similar way as polytropic compression. The polytropic index n is changed to isentropic index γ in the previous results.

Work done by the compressor per cycle

$$W = \frac{\gamma}{\gamma - 1} * P_1 V_1 \left[\left(\frac{P_2}{P_1} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right]$$

$$= \frac{\gamma}{\gamma - 1} * mRT_1 \left[\left(\frac{P_2}{P_1} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right] = \frac{\gamma}{\gamma - 1} * mR(T_2 - T_1)$$

We know that ratio of specific heats,

$$\frac{Cp}{Cv} = \gamma \; ; \quad \text{and} \quad c_p - c_v = R$$

or

$$R = c_p\left(1 - \frac{1}{\gamma}\right) = c_p\left(\frac{\gamma - 1}{\gamma}\right)$$

Substituting the value of R in the above expression, the work done by the compressor per cycle,

$$W = \frac{\gamma - 1}{\gamma} * mc_p \left(\frac{\gamma - 1}{\gamma}\right)(T_2 - T_1) = mc_p(T_2 - T_1)$$

This shows that the work done by the compressor per cycle during isentropic compression is equal to the heat required to raise the temperature of refrigerant from T_1 to T_2 at constant pressure.

Power Required to Drive a Single Stage Reciprocating Compressor

We have already obtained, in the previous article, the expressions for the work done (W) per cycle during isothermal, polytropic and isentropic compression. The power required to drive the compressor may be obtained from the usual relation,

$$P = \frac{W(In\ N{-}m/min)}{60}\ watts$$

$$= \frac{W(In\ N{-}m) * Nw}{60}\ watts$$

If N is the speed of the compressor in r.p.m., then number of working strokes per minute,

Nw = N ...(For single acting compressor)
= 2N ...(For doubling acting compressor)

Since the compression takes place in three different ways, therefore, the power obtained from different works done will be different. In general, following are the three values of power obtained:

1. Isothermal power = $\frac{W\ (in\ isothermal\ compression) Nw}{60}\ watts$
2. Indicated power = $\frac{W\ (in\ polytropic\ compression) Nw}{60}\ watts$
3. Isentropic power = $\frac{W\ (in\ isentropic\ compression) Nw}{60}\ watts$

Example:. A single stage reciprocating compressor is required to compress 1.5 m^3/min of vapour refrigerant from 1 bar to 8 bar. Find the power required to drive the compressor, if the compression of refrigerant is 1 . isothermal ; 2, poly tropic with polytropic index as 1.12 ; and 3. isentropic with isentropic index as 1 .31.

Solution: Given : V_1= 1.5 m_3/min, P_1 = 1 bar = $1*10^5$ N/m^2, P_2 = 8 bar = $8*10^5$ N/m^2, n=1.12, $\gamma = 1.31$

1. Isothermal compression

We know that work done by the compressor,

$$= 2.3P_1V_1\log\left(\frac{P_2}{P_1}\right) = 2.3*1*10^5*1.5 \log\left(\frac{8}{1}\right) N-m/\min$$

$= 3.45*10^5*0.9031 = 3.12*10^5$ N-m/min

Power required to drive the compressor

$= 3.12*10^5/60 = 5200$ W = 5.2 kW Ans.

2. Polytropic compression

We know that work done by the compressor

$$= \frac{n}{n-1} * P_1V_1\left[\left(\frac{P_2}{P_1}\right)^{\frac{n}{n-1}} - 1\right]$$

$$= \frac{1.12}{1.12-1} *1*10^5*1.5 \left[\left(\frac{8}{1}\right)^{\frac{1.12}{1.12-1}} - 1\right] N-m/\min$$

$=14*10^5(1.25-1) = 3.5*10^5$ N-m/min

Power required to drive the compressor

$= 3.5*10^5/60 = 5833$ W = 5.833 kW

3. Isentropic compression

We know that work done by the compressor,

$$= \frac{\gamma}{\gamma-1} * P_1V_1\left[\left(\frac{P_2}{P_1}\right)^{\frac{\gamma}{\gamma-1}} - 1\right]$$

$$= \frac{1.31}{1.31-1} *1*10^5*1.5 \left[\left(\frac{8}{1}\right)^{\frac{1.31-1}{1.31}} - 1\right] N-m/\min$$

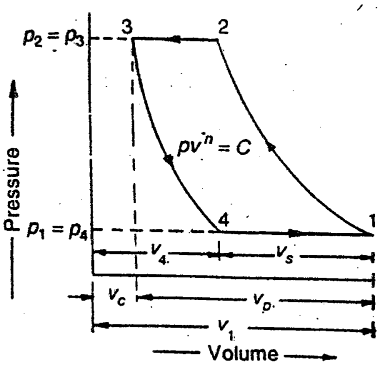
$= 6.34*10^5(1.63-1) = 4*10^5$ N-m/min

Power required to drive the compressor

$= 4*10^5(1.63-1) = 4*10^5$ N-m/min

Work Done by Reciprocating Compressor with Clearance Volume

In the previous articles, we have assumed that there is no clearance volume in tibe compressor cylinder. In other words, the entire volume of the refrigerant, in the compressor cylinder, is compressed by the inward stroke of the piston. But in actual practice, it is not possible



Thep-v diagram of a reciprocating compressor with clearance volume is shown in Fig. 3

Since the refrigerant gases are expanded and compressed in every cycle, therefore, the curve 3-4 is called re-expansion curve. Applying pv^n — C to points 3 and 4.

Figure 3 *p-v* diagram with clearance volume.

$$P_3V_3^n = P_4V_4^n$$

or

$$P_2V_C^n = P_1V_4^n$$

$$V_4 = Vc\left(\frac{P_2}{P_1}\right)^{\frac{1}{n}}$$

Substituting the value of v_4 in equation (i)

$$\eta_v = \frac{V_1 - Vc\left(\frac{P_2}{P_1}\right)^{\frac{1}{n}}}{V_1 - Vc}$$

$$= \frac{V_1 + Vc - V_1 - Vc\left(\frac{P_2}{P_1}\right)^{\frac{1}{n}}}{V_1 - Vc} = \frac{V_1 - Vc}{V_1 - Vc} + \frac{Vc}{V_1 - Vc} - \frac{Vc\left(\frac{P_2}{P_1}\right)^{\frac{1}{n}}}{V_1 - Vc}$$

$$= 1 + C - C\left(\frac{P_2}{P_1}\right)^{\frac{1}{n}}$$

Where, C= Clearance factor $\frac{Vc}{V1 - Vc}$

Example . A single stage, single acting reciprocating compressor has a bore of 200 mm and a stroke of 300 mm. It receives vapour refrigerant at 1 bar and delivers it at 5.5 bar. If the compression and expansion follows the law $pv^{1.3}$ = Constant and the clearance volume is 5 percent of the stroke volume, determine : 1. The power required to drive the compressor, if it runs at 500 r.p.m. ; and 2. The volumetric efficiency of the compressor.

Solution: Given: D = 200 mm = 0.2m ; L = 300 mm = 0.3 m ; P_1 = 1 bar = $1*10^5$ N/m^2 ;

P_2 = 5.5 bar = $5.5*10^5$ N/m^2 ; n = 1.3 ; v_c = 5% v_s ; N = 500 r.p.m.

We know that the stroke volume.

$V_S = \frac{\pi}{4}*D^2*L = \frac{\pi}{4}(0.2)^2*0.3 = 0.0094 m^3$

Clearance volume,

$V_C = 5\%V_s = 0.05\ V_s = 0.05*0.0094 = 0.00047\ m^3$

Total cylinder volume,

$V1 = V_C + V_s = 0.00047 + 0.0094 = 0.00987\ m^3$

Multi-stage Compression

In the previous articles, we have taken into consideration the compression of vapour refrigerant in a single stage (i.e. single cylinder) compressor. In other words, the vapour refrigerant is compressed in a single cylinder and then delivered at a high pressure. But sometimes, the vapour refrigerant is required to be delivered at a very high pressure as in the case of low temperature refrigerating systems. In such cases, either we should compress the vapour refrigerant by employing a single stage compressor with a very high pressure ratio or compress it in two or more compressors placed in series. It has been experienced that if we employ a single stage compressor for producing very high pressure refrigerant, it suffers the following draw backs:

- The size of the cylinder will be too large.
- Due to compression, there is a rise in temperature of the refrigerant. It is difficult to reject heat from the refrigerant in the small time available for compression.

- Sometimes, the temperature of refrigerant at the end of compression is too high. It may heat up the cylinder head or burn the lubricating oil.
- The friction losses and running cost are high.
- The volumetric efficiency is low.

In order to overcome the above mentioned difficulties, the vapour refrigerant is compressed in two or more cylinders in series with intercooling arrangement between them. Such an arrangement is known as compound or multi-stage compression.

Advantages of Multi-stage Compression

Following are the main advantages of multi-stage compression over single stage compression

- The work done per kg of refrigerant is reduced in multi-stage compression with intercooler as compared to single stage compression for the same delivery pressure.
- It improves the volumetric efficiency for the given pressure ratio.
- The sizes of the two cylinders (i.e. high pressure and low pressure cylinders) may be adjusted to suit the volume and pressure of refrigerant).
- It reduces the leakage loss considerably.
- It gives more uniform torque, and hence a smaller size flywheel is required.
- It provides effective lubrication because of lower temperature range.
- It reduces the cost of compressor.

Two Stage Reciprocating Compressor with Intercooler:

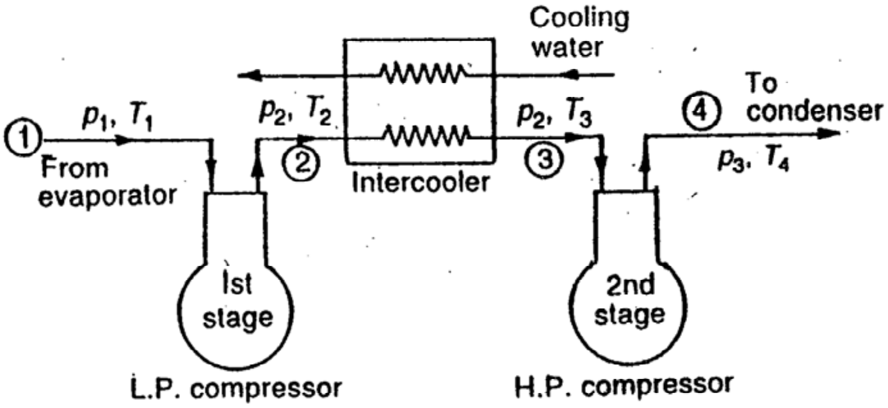


Figure 4 Two stage reciprocating compressor with intercooler

The schematic arrangement for a two stage reciprocating compressor with water intercooler is shown in Figure 4.

First of all, the vapour refrigerant from the evaporator at pressure P_1 and temperature T_1 is sucked by the low pressure (L.P.) compressor at point 1 during its suction stroke. The refrigerant after compression in the L.P.compressor (first stage compressor) is delivered at point 2 to the intercooler at pressure p_2 and temperature T_2. In the intercooler, the compressed refrigerant is cooled from temperature T_2 to T_3 at constant pressure p_2. This cooled refrigerant is now sucked by the high pressure (H.P.) compressor at point 3 during its suction stroke. Finally, the refrigerant after compression in the H.P. compressor (second stage compressor) is delivered at point 4 to a condenser at pressure $p_3$and temperature T_4.