Lesson
20
Rotary, Positive Displacement Type Compressors

The specific objectives of this lecture are to:

1. Discuss working principle and characteristics of a fixed vane, rolling piston type compressor (*Section 20.1*)
2. Discuss working principle and characteristics of a multiple vane, rotary compressor (*Section 20.2, 20.3*)
3. Discuss working principle and characteristics of a twin-screw type compressor (*Section 20.4.1*)
4. Discuss working principle and characteristics of a single-screw type compressor (*Section 20.4.2*)
5. Discuss working principle, characteristics and specific advantages of a scroll compressor (*Section 20.5*)

At the end of the lecture, the student should be able to

1. Explain with schematics the working principles of rotary fixed and multiple vane type compressors, single- and twin-screw type compressors and scroll compressors.
2. Explain the performance characteristics, advantages and applications of rotary, positive displacement type compressors.

20.1. Rolling piston (fixed vane) type compressors:

Rolling piston or fixed vane type compressors are used in small refrigeration systems (upto 2 kW capacity) such as domestic refrigerators or air conditioners. These compressors belong to the class of positive displacement type as compression is achieved by reducing the volume of the refrigerant. In this type of compressors, the rotating shaft of the roller has its axis of rotation that matches with the centerline of the cylinder, however, it is eccentric with respect to the roller (Figure 20.1). This eccentricity of the shaft with respect to the roller creates suction and compression of the refrigerant as shown in Fig.20.1. A single vane or blade is positioned in the non-rotating cylindrical block. The rotating motion of the roller causes a reciprocating motion of the single vane.

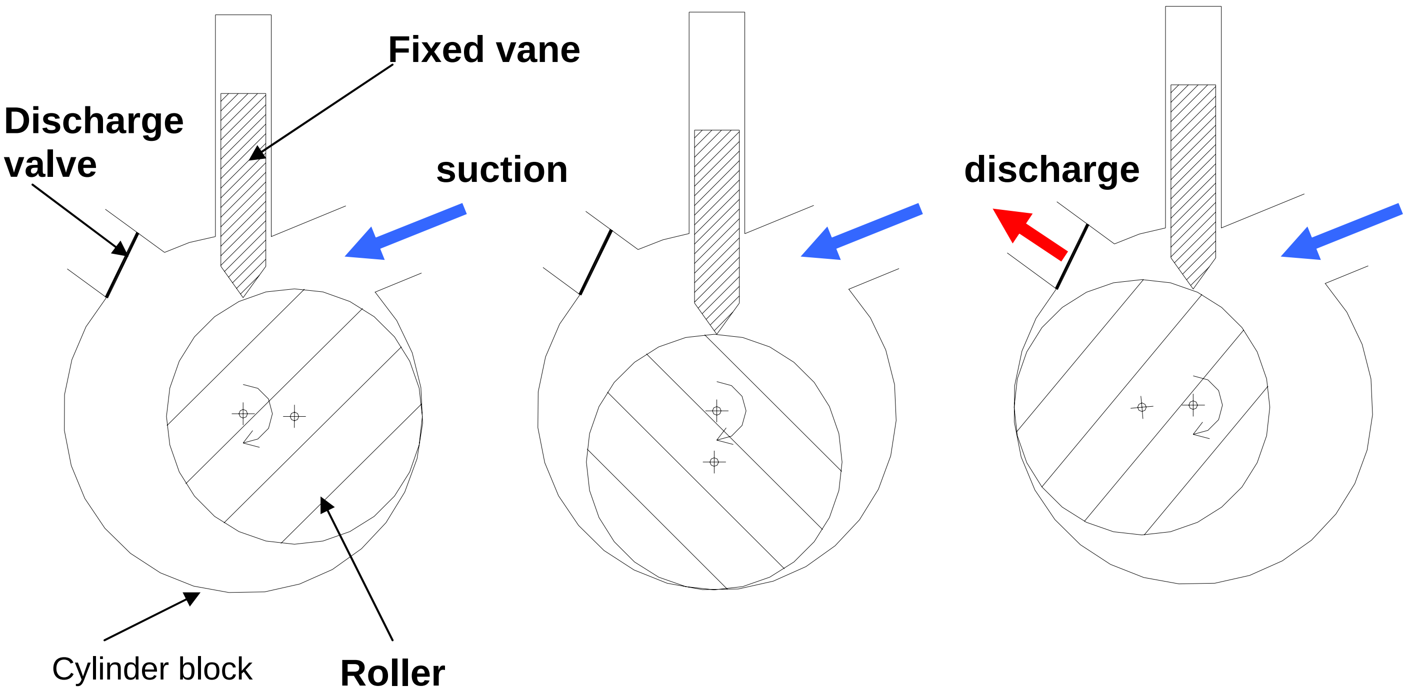


***Fig.20.1**: Working principle of a rolling piston type compressor*

As shown in Fig.20.1, this type of compressor does not require a suction valve but requires a discharge valve. The sealing between the high and low pressure sides has to be provided:

- Along the line of contact between roller and cylinder block
- Along the line of contact between vane and roller, and
- between the roller and end-pates

The leakage is controlled through hydrodynamic sealing and matching between the mating components. The effectiveness of the sealing depends on the clearance, compressor speed, surface finish and oil viscosity. Close tolerances and good surface finishing is required to minimize internal leakage.

Unlike in reciprocating compressors, the small clearance volume filled with high-pressure refrigerant does not expand, but simply mixes with the suction refrigerant in the suction space. As a result, the volumetric efficiency does not reduce drastically with increasing pressure ratio, indicating small re-expansion losses. The compressor runs smoothly and is relatively quiet as the refrigerant flow is continuous.

The mass flow rate of refrigerant through the compressor is given by:

$$\dot{m} = \eta_V \left(\frac{\dot{V}_{SW}}{v_e} \right) = \left(\frac{\eta_V}{v_e} \right) \left(\frac{\pi}{4} \right) \left(\frac{N}{60} \right) (A^2 - B^2) L \qquad (20.1)$$

where A = Inner diameter of the cylinder
B = Diameter of the roller
L = Length of the cylinder block
N = Rotation speed, RPM
η_V = Volumetric efficiency
v_e = specific volume of refrigerant at suction

20.2. Multiple vane type compressors:

As shown in Fig.20.2, in multiple vane type compressor, the axis of rotation coincides with the center of the roller (**O**), however, it is eccentric with respect to the center of the cylinder (**O'**). The rotor consists of a number of slots with sliding vanes. During the running of the compressor, the sliding vanes, which are normally made of non-metallic materials, are held against the cylinder due to centrifugal forces. The number of compression strokes produced in one revolution of the rotor is equal to the number of sliding vanes, thus a 4-vane compressor produces 4 compression strokes in one rotation.

In these compressors, sealing is required between the vanes and cylinder, between the vanes and the slots on the rotor and between the rotor and the end plate. However, since pressure difference across each slot is only a fraction of the total pressure difference, the sealing is not as critical as in fixed vane type compressor.

This type of compressor does not require suction or discharge valves, however, as shown in Fig.20.3, check valves are used on discharge side to prevent reverse rotation during off-time due to pressure difference. Since there are no discharge valves, the compressed refrigerant is opened to the discharge port when it has been compressed through a fixed volume ratio, depending upon the geometry. This implies that these compressors have a fixed built-in volume ratio. The built-in volume ratio is defined as "the ratio of a cell as it is closed off from the suction port to its volume before it opens to the discharge port". Since the volume ratio is fixed, the pressure ratio, r_p is given by:

$$r_p = \left(\frac{P_d}{P_s} \right) = V_b^{\,k} \qquad (20.2)$$

where P_d and P_s are the discharge and suction pressures, V_b is the built-in volume ratio and k is the index of compression.

Since no centrifugal force is present when the compressor is off, the multiple vanes will not be pressed against the cylinder walls during the off-period. As a result,

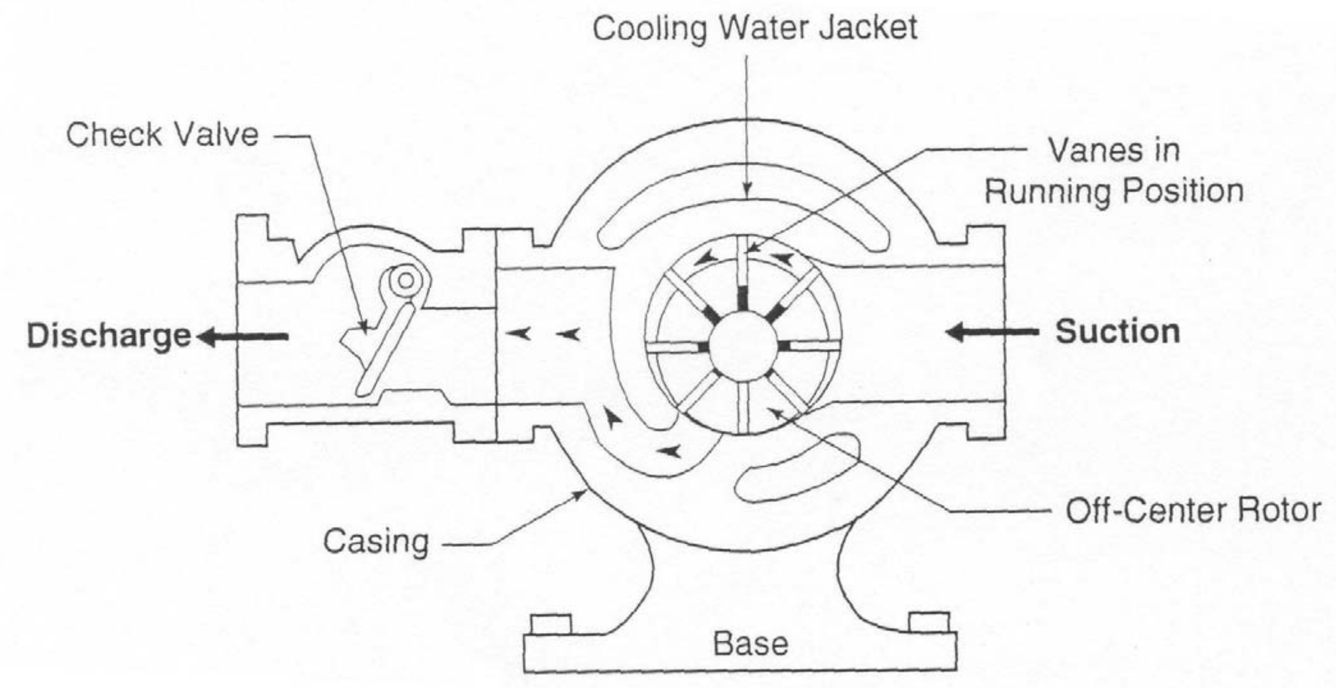


***Fig.20.3**: Sectional view of a multiple vane, rotary compressor*

high pressure refrigerant from the discharge side can flow back into the side and pressure equalization between high and low pressure sides take place. This is beneficial from the compressor motor point-of-view as it reduces the required starting torque. However, this introduces cycling loss due to the entry of high pressure and hot refrigerant liquid into the evaporator. Hence, normally a non-return check valve is used on the discharge side which prevents the entry of refrigerant liquid from high pressure side into evaporator through the compressor during off-time, at the same time there will be pressure equalization across the vanes of the compressor.

20.3. Characteristics of rotary, vane type compressors:

Rotary vane type compressors have low mass-to-displacement ratio, which in combination with compact size makes them ideal for transport applications. The

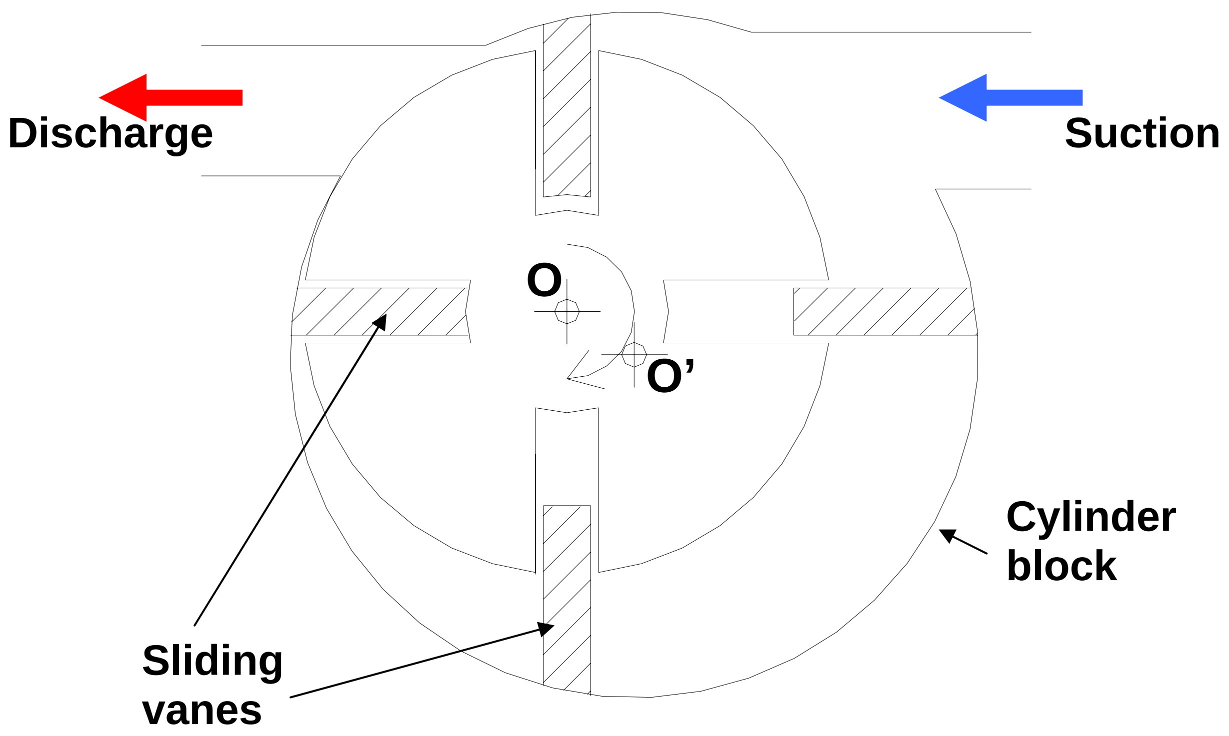


***Fig.20.2**: Working principle of a multiple vane, rotary compressor*

compressors are normally oil-flooded type, hence, oil separators are required. Both single-stage (upto –40^{o}C evaporator temperature and 60^{o}C condensing temperature) and two-stage (upto –50^{o}C evaporator temperature) compressors with the cooling capacity in the range of 2 to 40 kW are available commercially. The cooling capacity is normally controlled either by compressor speed regulation or suction gas throttling. Currently, these compressors are available for a wide range of refrigerants such as R 22, ammonia, R 404a etc.

20.4. Rotary, screw compressors:

The rotary screw compressors can be either twin-screw type or single-screw type.

20.4.1. Twin-screw compressor:

The twin-screw type compressor consists of two mating helically grooved rotors, one male and the other female. Generally the male rotor drives the female rotor. The male rotor has lobes, while the female rotor has flutes or gullies. The frequently used lobe-gully combinations are [4,6], [5,6] and [5,7]. Figure 20.4 shows the [4,6] combination. For this [4,6] combination, when the male rotor rotates at 3600 RPM, the female rotor rotates at 2400 RPM.

As shown in Fig.20.5, the flow is mainly in the axial direction. Suction and compression take place as the rotors unmesh and mesh. When one lobe-gully combination begins to unmesh the opposite lobe-gully combination begins to mesh. With 4 male lobes rotating at 3600 RPM, 4 interlobe volumes are per revolution, thus giving 4 X 3600 = 14400 discharges per minute.

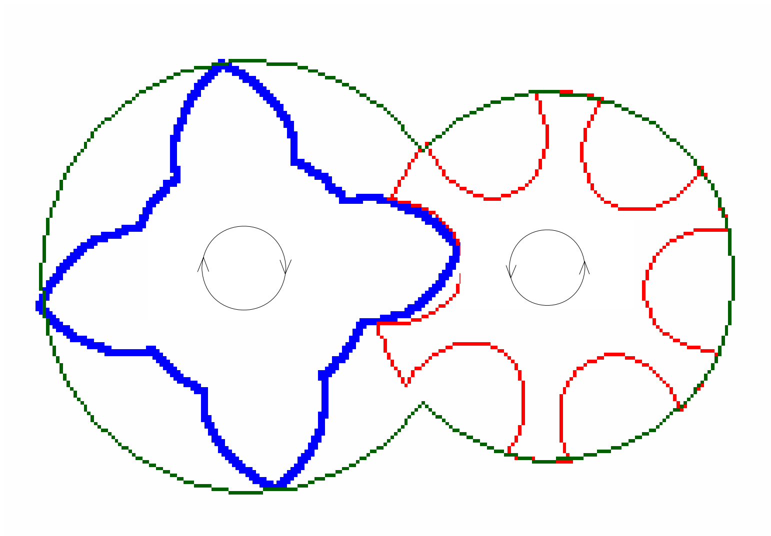


***Fig.20.4**: Twin-screw compressor with 4 male lobes and 6 female gullies*

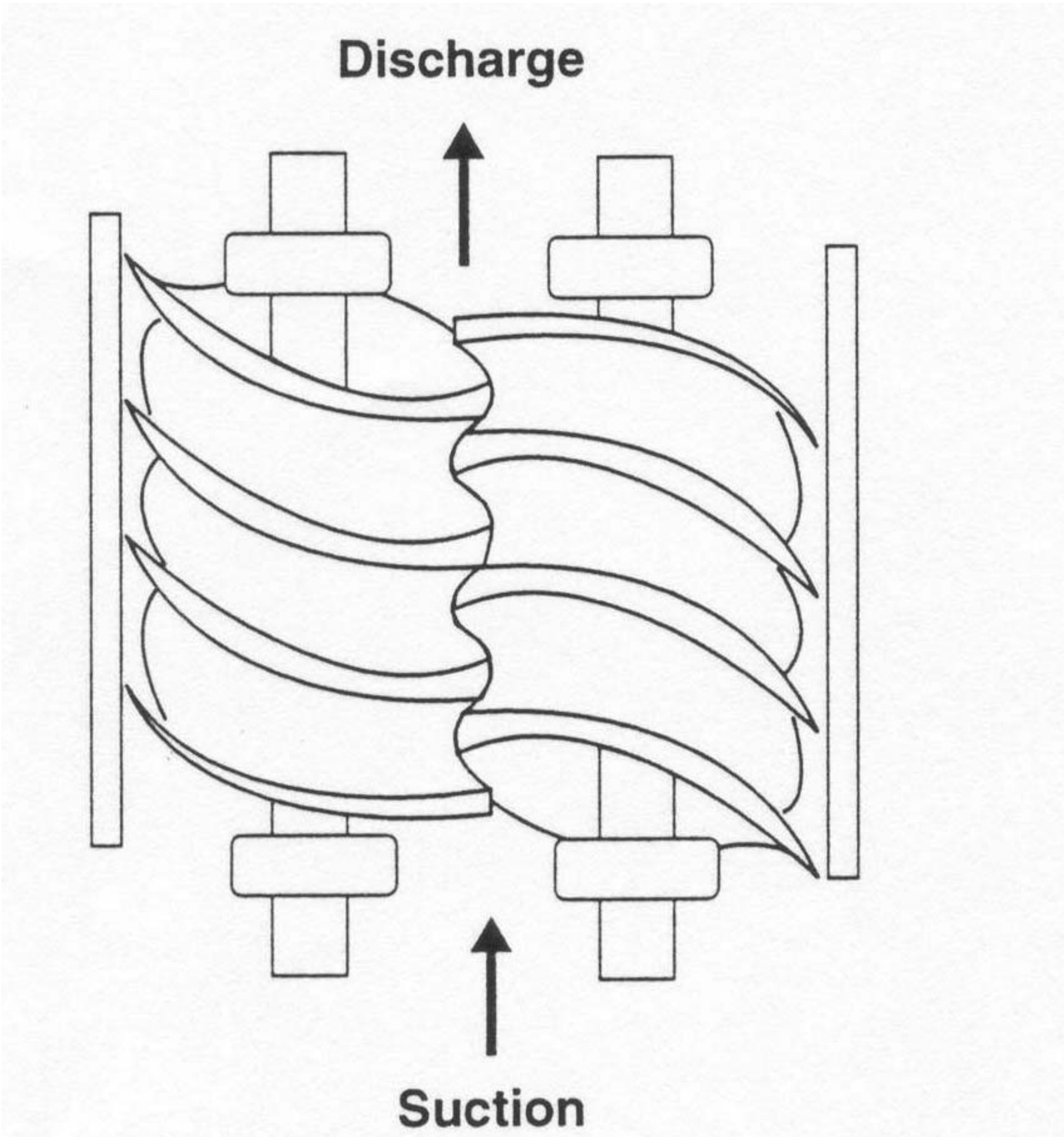


***Fig.20.5**: Direction of refrigerant flow in a twin-screw compressor*

Discharge takes place at a point decided by the designed built-in volume ratio, which depends entirely on the location of the delivery port and geometry of the compressor. Since the built-in volume ratio is fixed by the geometry, a particular compressor is designed for a particular built-in pressure ratio. However, different built-in ratios can be obtained by changing the position of the discharge port. The built-in pressure ratio, r_p given by:

$$\mathbf{r_p} = \left(\frac{\mathbf{P_d}}{\mathbf{P_s}}\right) = \mathbf{V_b}^{\mathbf{k}} \qquad (20.3)$$

Where P_d and P_s are the discharge and suction pressures, V_b is the built-in volume ratio and k is the index of compression.

If the built-in pressure at the end of compression is less than the condensing pressure, high pressure refrigerant from discharge manifold flows back into the interlobe space when the discharge port is uncovered. This is called as under-compression. On the other hand, if the built-in pressure at the end of compression is higher than the condensing pressure, then the compressed refrigerant rushes out in an unrestrained expansion as soon as the port is uncovered (over-compression). Both under-compression and over-compression are undesirable as they lead to loss in efficiency.

Lubrication and sealing between the rotors is obtained by injecting lubricating oil between the rotors. The oil also helps in cooling the compressor, as a result very high pressure ratios (upto 20:1) are possible without overheating the compressor.

The capacity of the screw compressor is normally controlled with the help of a slide valve. As the slide valve is opened, some amount of suction refrigerant escapes to the suction side without being compressed. This yields a smooth capacity control from 100 percent down to 10 percent of full load. It is observed that the power input is approximately proportional to refrigeration capacity upto about 30 percent, however, the efficiency decreases rapidly, there after.

Figure 20.6 shows the compression efficiency of a twin-screw compressor as a function of pressure ratio and built-in volume ratio. It can be seen that for a given built-in volume ratio, the efficiency reaches a peak at a particular optimum pressure ratio. The value of this optimum pressure ratio increases with built-in volume ratio as shown in the figure. If the design condition corresponds to the optimum pressure ratio, then the compression efficiency drops as the system operates at off-design conditions. However, when operated at the optimum pressure ratio, the efficiency is much higher than other types of compressors.

As the rotor normally rotates at high speeds, screw compressors can handle fairly large amounts of refrigerant flow rates compared to other positive displacement type compressors. Screw compressors are available in the capacity range of 70 to 4600 kW. They generally compete with high capacity reciprocating compressors and low capacity centrifugal compressors. They are available for a wide variety of refrigerants and applications. Compared to reciprocating compressors, screw compressors are balanced and hence do not suffer from vibration problems.

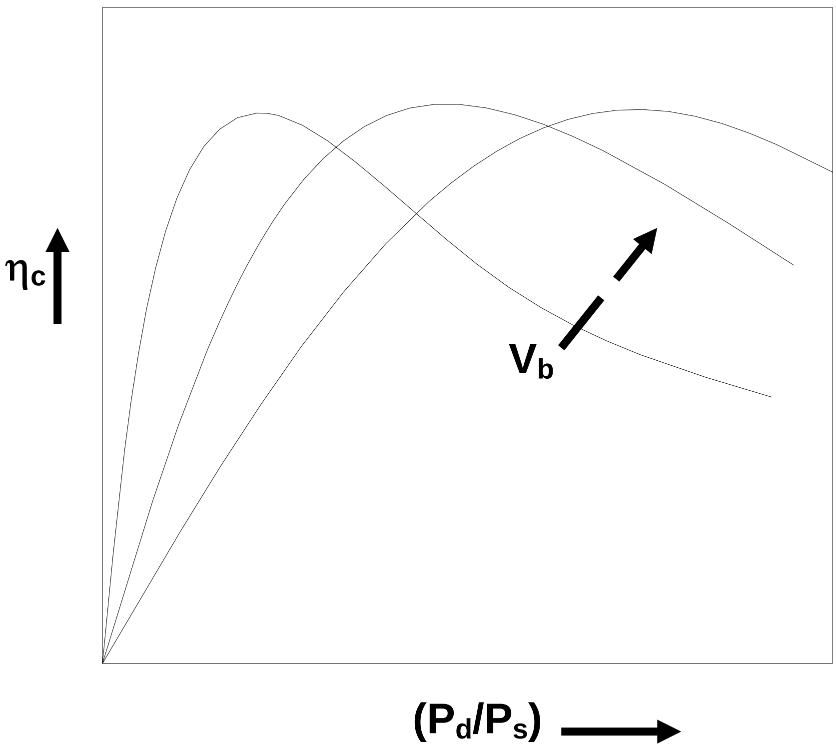


***Fig.20.6**: Variation of compression efficiency of a twin-screw compressor with pressure ratio and built-in volume ratio*

Twin-screw compressors are rugged and are shown to be more reliable than reciprocating compressors; they are shown to run for 30000 – 40000 hours between major overhauls. They are compact compared to reciprocating compressors in the high capacity range.

20.4.2. Single-screw compressors:

As the name implies, single screw compressors consist of a single helical screw and two planet wheels or gate rotors. The helical screw is housed in a cylindrical casing with suction port at one end and discharge port at the other end as shown in Fig. 20.7. Suction and compression are obtained as the screw and gate rotors unmesh and mesh. The high and low pressure regions in the cylinder casing are separated by the gate rotors.

The single screw is normally driven by an electric motor. The gate rotors are normally made of plastic materials. Very small power is required to rotate the gate rotors as the frictional losses between the metallic screw and the plastic gate rotors is very small. It is also possible to design the compressors with a single gate rotor. Similar to twin-screw, lubrication, sealing and compressor cooling is achieved by injecting lubricating oil into the compressor. An oil separator, oil cooler and pump are required to circulate the lubricating oil. It is also possible to achieve this by injecting liquid refrigerant, in which case there is no need for an oil separator.

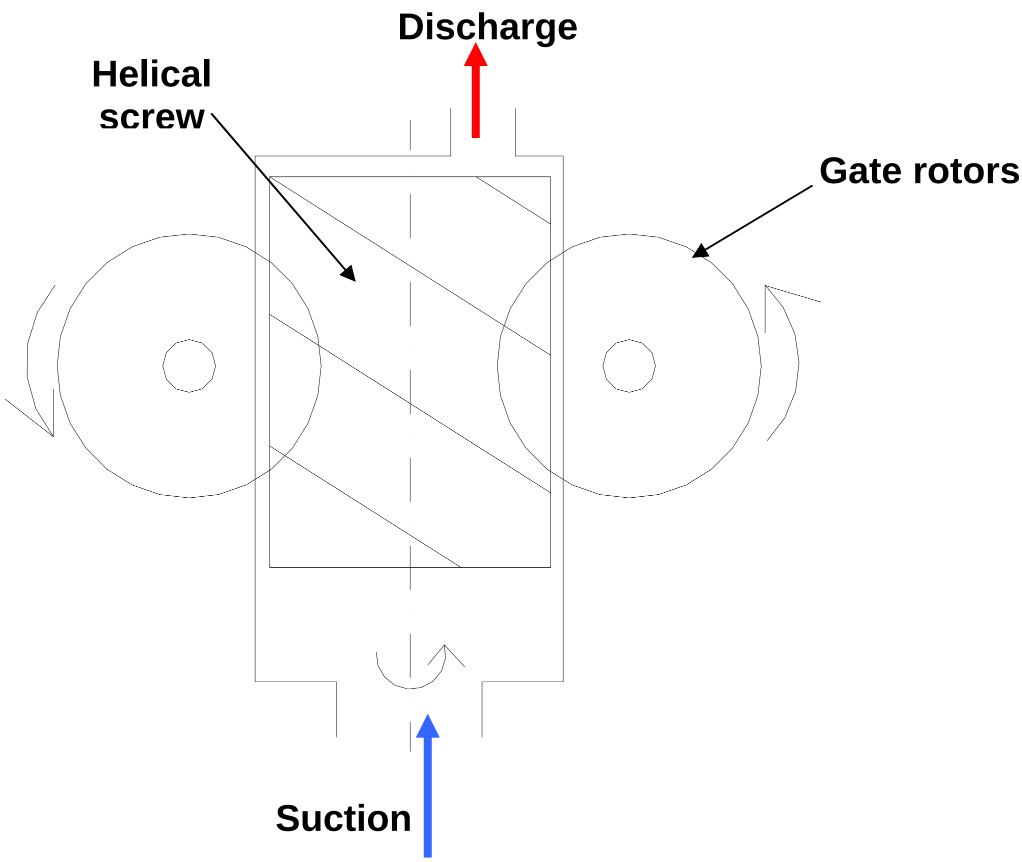


Fig.20.7: *Working principle of a single-screw compressor*

20.5. Scroll compressors:

Scroll compressors are orbital motion, positive displacement type compressors, in which suction and compression is obtained by using two mating, spiral shaped, scroll members, one fixed and the other orbiting. Figure 20.8 shows the working principle of scroll compressors. Figures 20.9 and 20.10 show the constructional details of scroll compressors. As shown in Fig.20.8, the compression process involves three orbits of the orbiting scroll. In the first orbit, the scrolls ingest and trap two pockets of suction gas. During the second orbit, the two pockets of gas are compressed to an intermediate pressure. In the final orbit, the two pockets reach discharge pressure and are simultaneously opened to the discharge port. This simultaneous process of suction, intermediate compression, and discharge leads to the smooth continuous compression process of the scroll compressor. One part that is not shown in this diagram but is essential to the operation of the scroll is the anti-rotation coupling. This device maintains a fixed angular relation of 180 degrees between the fixed and orbiting scrolls. This fixed angular relation, coupled with the movement of the orbiting scroll, is the basis for the formation of gas compression pockets.

As shown in Figs.20.9 and 20.10, each scroll member is open at one end and bound by a base plate at the other end. They are fitted to form pockets of refrigerant between their respective base plates and various lines of contacts between the scroll walls. Compressor capacity is normally controlled by variable speed inverter drives.

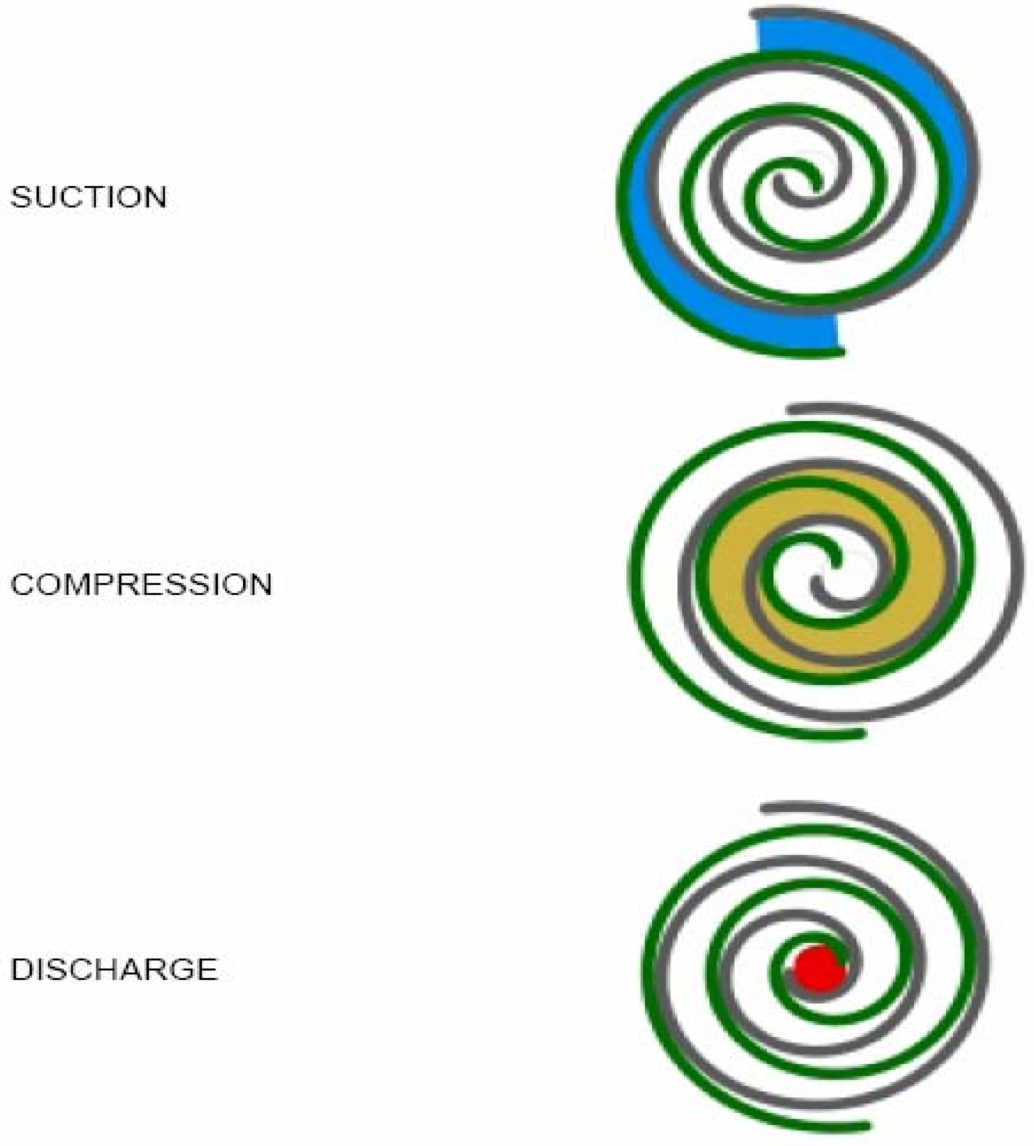


Fig.20.8*: Working principle of a scroll compressor*

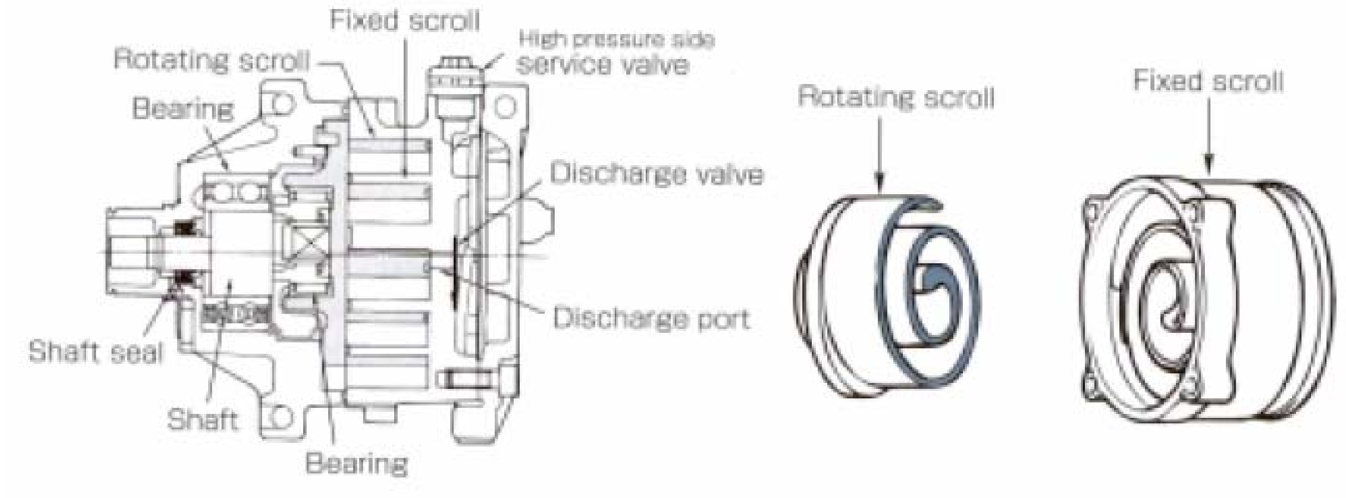
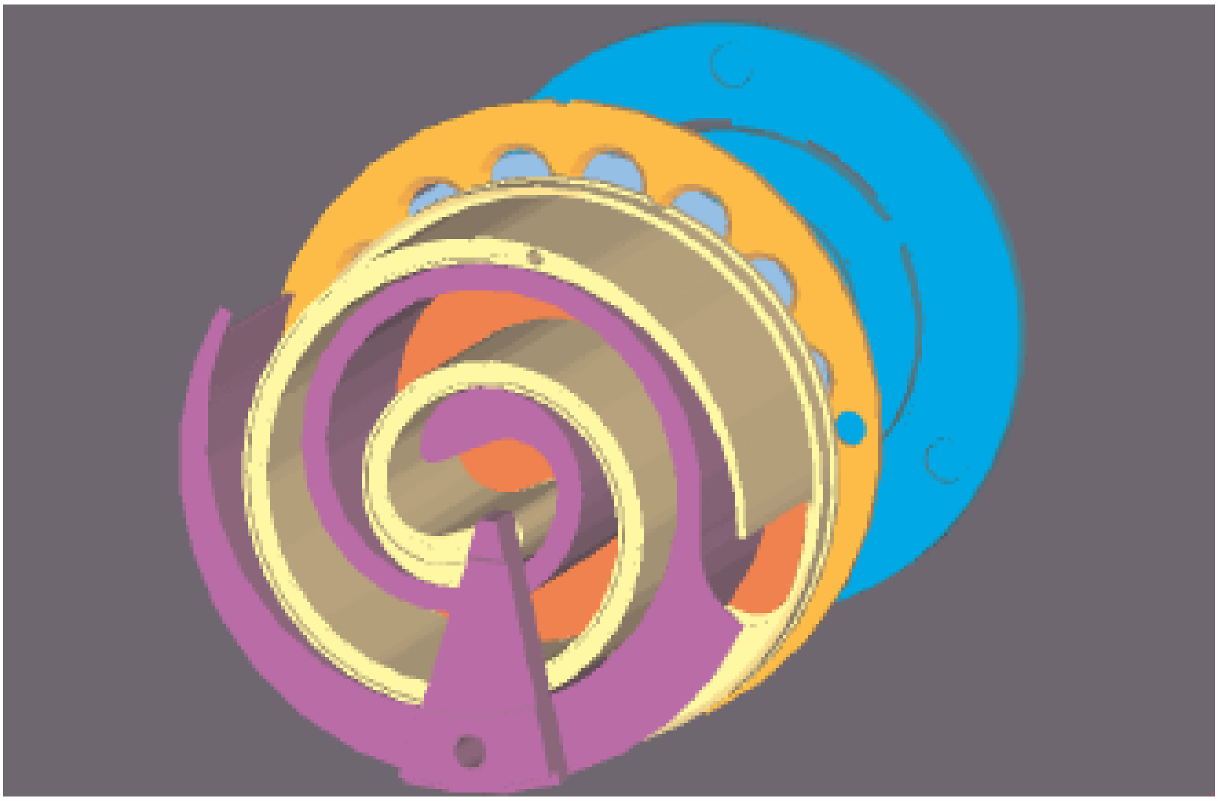
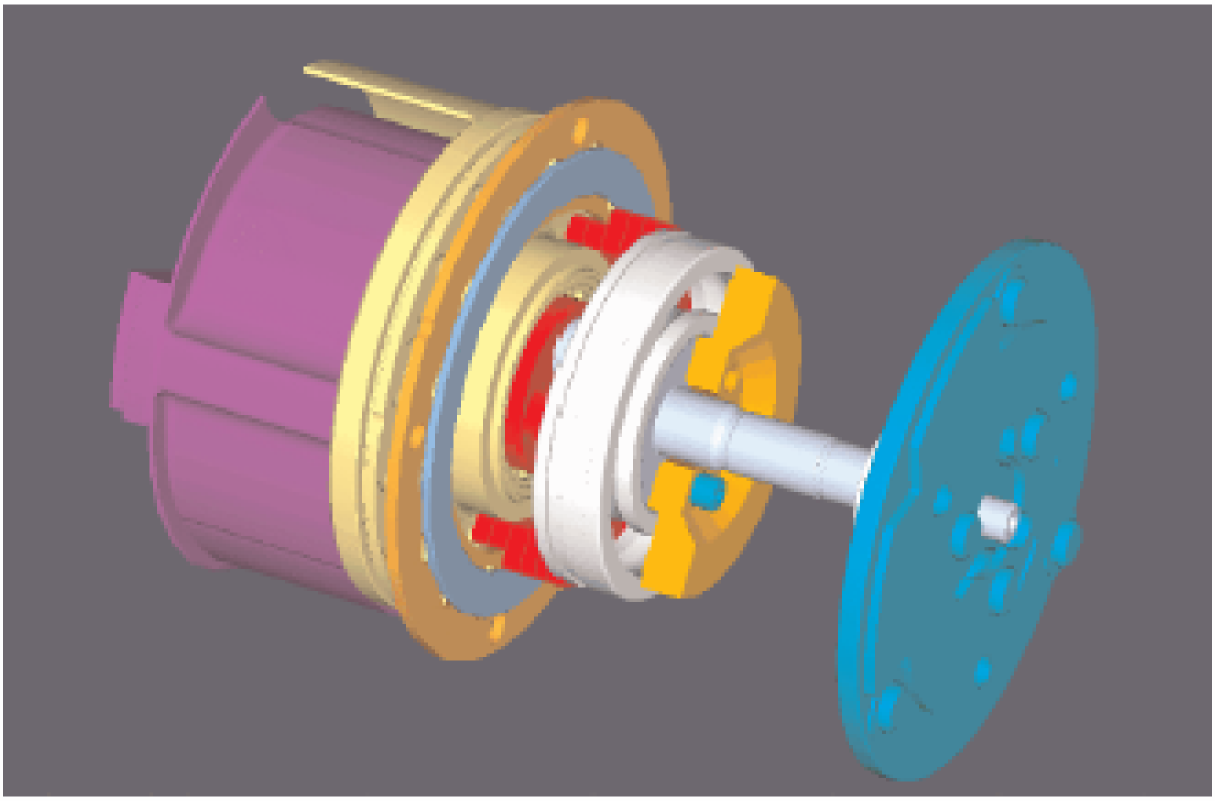


Fig.20.9*: Main parts of a scroll compressor*



This graphic shows the two spiral-shaped intermeshing scrolls.



The graphic shown above shows a side view of the interior components of the scroll compressor.

***Fig.20.10**: Different views of a scroll compressor*

Currently, the scroll compressors are used in small capacity (3 to 50 kW) refrigeration, air conditioning and heat pump applications. They are normally of hermetic type. Scroll compressors offer several advantages such as:

1. Large suction and discharge ports reduce pressure losses during suction and discharge

2. Physical separation of suction and compression reduce heat transfer to suction gas, leading to high volumetric efficiency

3. Volumetric efficiency is also high due to very low re-expansion losses and continuous flow over a wide range of operating conditions

4. Flatter capacity versus outdoor temperature curves

5. High compression efficiency, low noise and vibration compared to reciprocating compressors

6. Compact with minimum number of moving parts

Questions and Answers:

1. Which of the following statements concerning fixed vane, rotary compressors are true?

a) These compressors are used in small capacity systems (less than 2 kW)
b) They require suction valve, but do not require discharge valve
c) Refrigerant leakage is minimized by hydrodynamic lubrication
d) Compared to reciprocating compressors, the re-expansion losses are high in rotary vane compressor

Ans.: a) and c)

2. Which of the following statements concerning multiple vane, rotary compressors are true?

a) Compared to fixed vane compressors, the leakage losses are less in multiple vane compressors
b) Multiple vane compressors do not require suction and discharge valves
c) A non-return, check valve is used on suction side of the compressor to minimize cycling losses
d) All of the above

Ans.: d)

3. Which of the following statements concerning rotary vane type compressors are not true?

a) They are compact due to high volumetric efficiency
b) They are ideal for transport applications due to low mass-to-capacity ratio
c) They are easier to manufacture compared to reciprocating compressors
d) They are better balanced, and hence, offer lower noise levels

Ans.: c)

4. For a twin-screw type compressors with 5 male lobes and a rotational speed of 3000 RPM, the number of discharges per minute are:

a) 600
b) 15000
c) 1200
d) 3000

Ans.: b)

5. Twin-screw compressors can be operated at high pressure ratios because:

a) These compressors are designed to withstand high discharge temperatures
b) Lubricating oil, which also acts as a coolant is injected between the rotors
c) The cold suction gas cools the rotors during suction stroke
d) All of the above

Ans.: b)

6. Which of the following statements concerning screw compressors are true?

a) Compared to reciprocating compressors, screw compressors are rugged and are more reliable
b) Screw compressors are easier to manufacture and are cheaper compared to reciprocating compressors
c) The compression efficiency of a screw compressor increases with built-in volume ratio
d) Screw compressors are available in refrigeration capacity ranging from fractional kilowatts to megawatts

Ans.: a)

7. Which of the following statements concerning screw compressors are true?

a) The capacity of a screw compressor can be varied over a large range by using the slide valve
b) Compared to reciprocating compressors, screw compressors are compact for small capacities and bulky for large capacities
c) An oil separator and an oil cooler are required in a screw compressor irrespective of the type of refrigerant used
d) Vibration is one of the practical problems in operating screw compressors

Ans.: a) and c)

8. Which of the following statements concerning scroll compressors are true:

a) Currently available scroll compressors are of open type
b) Currently scroll compressors are available for large capacities only
c) The possibility of suction gas heating is less in scroll compressors
d) Scroll compressors are easier to manufacture

Ans.: c)

9. The advantages of scroll compressors are:

a) High volumetric efficiency
b) Capacity is less sensitive to outdoor conditions
c) Compactness
d) Low noise and vibration
e) All of the above

Ans.: e)