Compressors

Selection of gas compressors: part 2

In this multipart series, Eduardo Larralde and Rafael Ocampo aim to provide a comprehensive survey of the current state of the art concerning gas compressors. Following the elucidation of the basic concepts and theory in the opening article, the series continues with the classification of different compressor types.

Before attempting to select a compressor for an industrial application it is a vital requirement to recall the basics concerning the classification, physical structure and technical features of these machines.

Regarding compressor types, the compressors currently applied in industry can be classified according to the synoptic chart presented in Box 2.1.

Considering design and construction characteristics, the most commonly used reciprocating and centrifugal types of compressors can be further classified according to the following subdivisions.

Reciprocating compressors

According to the number of compression stages:

- Single stage
- Multiple stages

According to the action of the cylinders:

- Simple acting (gas is compressed by only one side of the piston)
- Double acting (gas is compressed by both sides of the piston)

According to the number of cylinders working in parallel:

- Simplex (only one cylinder)
- Duplex/triplex (two/three cylinders working in parallel), and so on

According to the capacity:

- Small capacity (up to approximately 600 m^3/h)
- Medium capacity (between 600 m^3/h and 1,800 m^3/h)
- Large capacity (more than 1,800 m^3/h)

According to the discharge pressure:

- Low (up to 1 MPa)
- Medium (between 1 MPa and 8 MPa)
- High (8 MPa to 100 MPa)
- Very high (more than 100 MPa) (hypercompressors)

According to the arrangement of the cylinders:

- Horizontal, vertical, V arrangement, W arrangement, L arrangement, M arrangement (boxer type)

According to the chemical composition of the gas being handled:

- Air, freon, nitrogen, ammonia, hydrogen, oxygen, carbon dioxide, etc.

Centrifugal compressors

According to the number of casings:

- One, two, three casings, etc.

According to the number of impellers on one rotor:

- One, two, three impellers, etc.

According to the design of the casing:

- Horizontally split
- Vertically split (barrel, pipeline and overhung)

Box 2.1. Synoptic chart showing the main compressor types

Compressors	Positive displacement	Reciprocating	Piston
			Diaphragm
		Rotary	Screw
			Lobe
			Sliding vane
			Liquid ring
			Scroll
	Rotodynamic	Centrifugal	
		Axial	

 0262 1762/11

According to the flow direction:

- In-line
- In-line with side streams
- In-line with intercooling
- Double flow
- Back to back with or without intercooling

According to the type of drive:

- Steam turbine
- Gas turbine
- Electric motor
- Combustion engine
- Expansion turbine

According to the coupling to the drive:

- Direct coupling
- With speed reducers
- With speed multipliers
- Integrally geared
- Integrated motor compressor

Other different ways of classifying compressors can be used but because they are very specific they are not mentioned in this article.

Operating principles

Reciprocating compressors

This type of machine achieves the compression of the gas by reducing the volume of the space where the gas is confined. Figure 2.1 presents a sectional view of a piston compressor with a horizontal arrangement.

Successive steps take place as the piston moves inside the cylinder, namely intake, compression and discharge of the gas. This ideal cycle occurs as shown in Figure 2.2, assuming that there is no gas pressure drop through the suction and discharge valves, that intake and discharge are constant pressure processes, and that no gas is left inside the cylinder at the end of the discharge step.

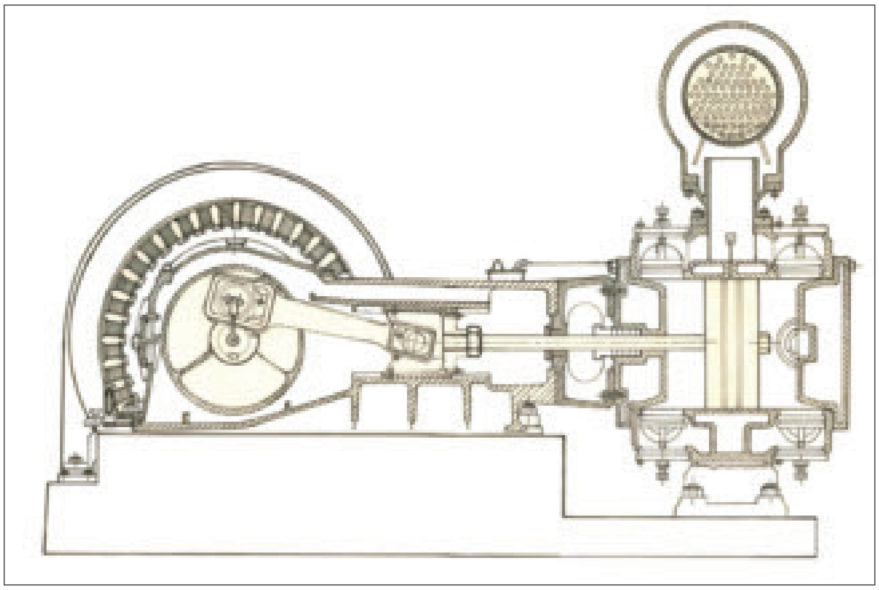

Figure 2.1. Piston compressor with horizontal cylinder arrangement.

Figure 2.3 shows a p-V diagram corresponding to a compressor with clearance. Note that the main difference from Figure 2.2 is that some gas is left inside the cylinder at the end of the discharge step and this gas expands during the beginning of the intake stroke, preventing the ingress of new gas from the system until the pressure inside the cylinder becomes slightly lower than the pressure in the suction pipe. The space where the gas is retained is referred to as the clearance. Its existence is unavoidable because of the need for a certain gap between the piston head and the cylinder and also because of the space required to place the valves.

The volumetric efficiency of the compressor (η_v) depends on the ratio (c) between the clearance volume (v_c) and the piston displacement (v_d), on the ratio of pressures (p_2/p_1) and on the polytropic exponent (n), as can be seen in the following equation determined from the conventional diagram with clearance:

$$\eta_v = 1 + c - c(p_2/p_1)^{1/n} \qquad (2.1)$$

Usually the value for the clearance ratio (c) varies between 0.06 and 0.14 depending on the compressor size. In large multistage machines it can be as low as 0.025.

When the compressibility factor (Z) is not constant during the compression process, the following correction to Equation 2.1 should be introduced:

$$\eta_v = 1 + c - (Z_1/Z_2)\cdot c(p_2/p_1)^{1/n} \qquad (2.2)$$

As stated earlier in Part 1 of this series[1], the volumetric efficiency is defined as the ratio of the actual compressor capacity (Q) and its displaced volume (v_d):

$$\eta_v = Q/v_d \qquad (1.22)$$

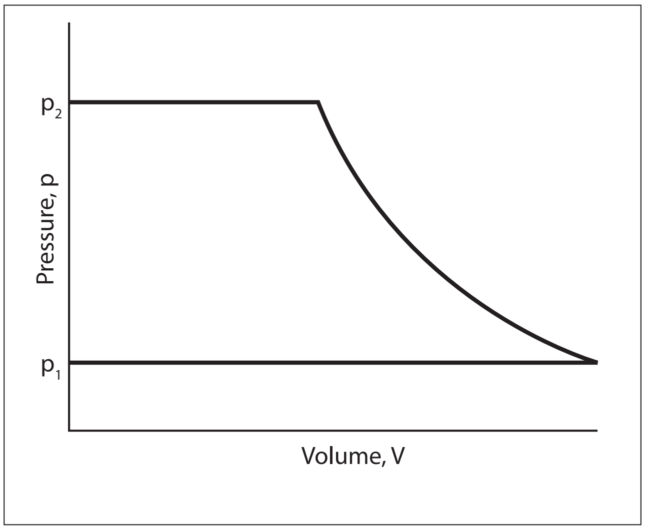

Figure 2.2. p-V diagram for an ideal compressor.

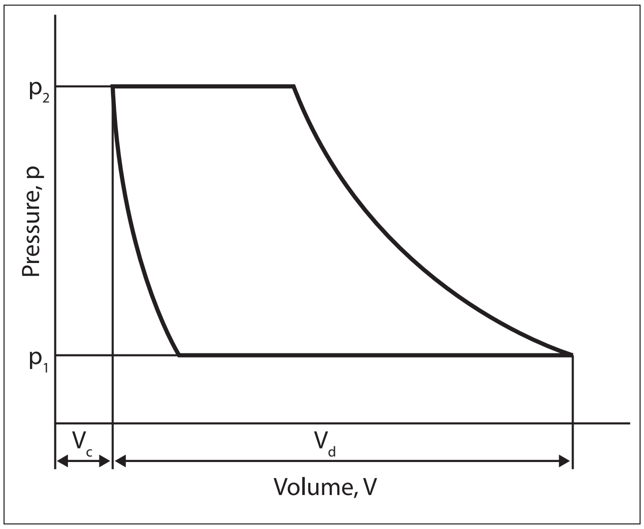

Figure 2.3. p-V diagram with clearance.

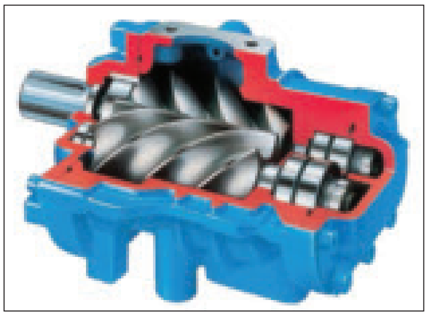

Figure 2.4. Screw compressor (image courtesy of Boge Compressors).

For a given compressor, as the clearance increases both the volumetric efficiency and the capacity decrease. This feature can be used to control the gas flow rate for a piston compressor.

The real value for volumetric efficiency, which varies between 65% and 90%, can be obtained through testing. Clearance size, the magnitude of gas leaks through packings, valves and piston rings, as well as the heating of the gas inside the cylinder are all factors influencing the value of the real volumetric efficiency. That is why Equation 2.2 is modified to include empirical data that better express the real volumetric performance of piston compressors[2]:

$$\eta_v = 0.97 + c - (Z_1/Z_2)\cdot c(p_2/p_1)^{1/n} - GL \qquad (2.3)$$

where GL is 0.02–0.06 for lubricated compressors, and 0.07–0.10 for non-lubricated compressors.

However, volumetric efficiency is not a reliable indicator by which to evaluate the quality of a compressor. Instead, the power consumption for the desired capacity should be assessed.

Rotary compressors

This type of machine applies the same operating principle as reciprocating compressors but in rotary compressors the decrease in volume is achieved through the gradual reduction of the space between the rotor and the casing obtained while the rotor rotates inside the casing.

Nowadays screw compressors (Figure 2.4) stand out among positive displacement rotary-type machines. Figure 2.5 shows a typical p-V diagram for a screw compressor working under different conditions. Compression is achieved by the intermeshing of a male and a female rotor. As the rotors turn, the location of the intermeshing of the rotor lobes moves from the suction port to the discharge port; correspondingly, the gas in the rotor pockets – contained by the intermeshing – is compressed and expelled. Oil-free rotary screw compressors rely on tightly controlled rotor-to-rotor and rotor-to-casing clearances to prevent internal recirculation of the compressed gas from discharge to suction. Timing gears synchronize rotation of the male and female rotors, preventing metal-to-metal contact and eliminating the need for oil injection.

Screw compressors allow liquid injection – normally oil – which enables operation at slow speeds and fulfils three functions:

- Reducing and even eliminating inter-lobe space tolerances.
- Refrigerating gas during compression.
- Lubricating the rotors, thus avoiding the need to use timing gears.

Oil injection can flush gas streams contaminated with different substances such as polymers. When screw compressors operate under off-design conditions (Figure 2.5), efficiency drops, especially if they have a fixed volume ratio. That is why variable volume ratio machines are preferred because of their self-adjusting ability for peak off-design efficiency.

Centrifugals (turbocompressors)

In centrifugal compressors, the compression is achieved by firstly increasing the kinetic energy of the gas by using the principle of centrifugal force and then converting the kinetic energy to pressure energy.

Rotation of the impeller creates a depression at its inlet side (Figure 2.6), allowing the continuous inflow of gas from the suction pipe to the impeller vanes. Inside the impeller, centrifugal force pushes the gas from the inlet side to the periphery, increasing the gas velocity and density between the impeller vanes. The gas then moves to the casing or diaphragm, both of which have the form of a diffuser, where the high velocity of the gas is transformed into pressure. In multistage machines, the gas emerging from the first-stage diffuser is fed to the second-stage impeller by the guiding vanes, which are also located on the diffuser (Figure 2.7). Finally, the compressed gas reaches the volute and then the discharge pipe. In those compressors with interstage cooling, the gas goes through heat exchangers after each compression stage or group of stages.

Interstage cooling is the most commonly used method of cooling because it yields the closest process to the isothermal and it is therefore the most economic from the energy standpoint. There is another cooling method, which consists of circulating cooling water through channels bored into the diaphragms, but this solution makes the casing design and manufacture more difficult.

The effective quantity of energy supplied by the driver to compress the gas is actually greater than that required for isentropic compression because of the additional

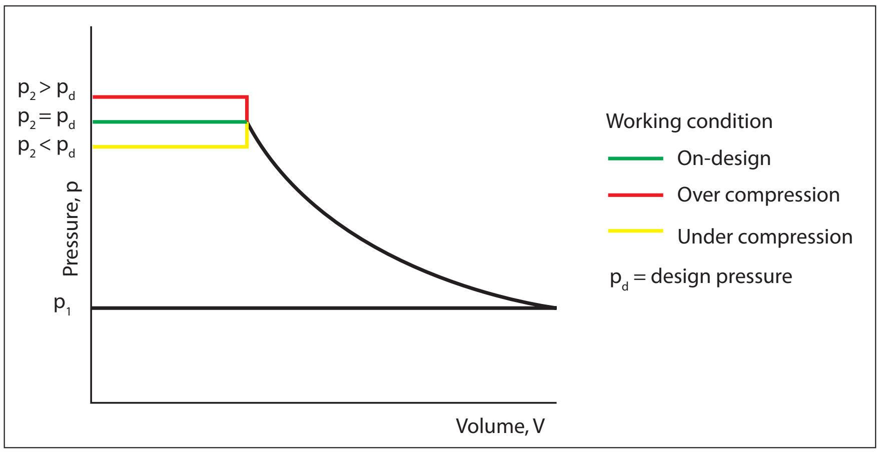

Figure 2.5. p-V diagram for a screw compressor.

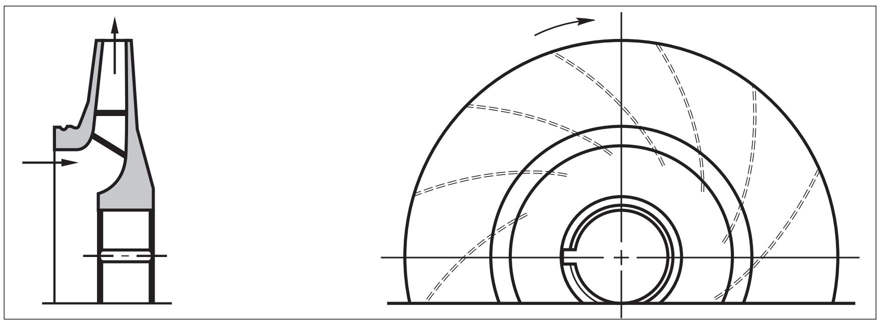

Figure 2.6. Gas movement in a centrifugal compressor impeller.

energy used to overcome the friction of the gas against the impeller channels, diffuser channels and the casing, and also the fluid friction of the impeller immersed in the compressed gas. All the extra energy supplied is converted into heat.

Axial compressors

In this type of rotodynamic machine, the pressure increase is obtained by the combined effect of the increase in the gas velocity and the simultaneous increase of area occurring during the passage of the gas through the blades as the rotor rotates.

The gas enters the compressor (Figure 2.8) in a direction parallel to the compressor shaft. After reaching the rotor blades the gas rotates with them and also moves axially from one blade row to the next.

There are fixed blade rows in the casing in between the rotor blade rows. The functions of the fixed blades are to remove the turbulence of the gas caused by the movement of the mobile blades and to direct the gas flow to the next row of mobile blades. Normally, the blades on the first stator row are adjustable by external devices for better performance control and for broader operational flexibility.

Main features

There follows a summary of the main features, advantages and disadvantages for each type of compressor. These points need to be taken into account during the selection of the appropriate compressor for a given service.

Piston compressors

- Low speed (nowadays 'high speed' reciprocating compressors are also available, ranging from 22 kW to 6,700 kW direct-coupled to prime movers operating at 720 rpm to 1,800 rpm).
- High discharge pressure.
- Best for high pressure increase in one stage or at low capacity.
- Wide pressure range.
- Very small change in capacity for gas pressure variations when running at a fixed speed.
- Suitable for portable use.
- Larger footprint than centrifugal or rotary compressors.
- High vibrations and pulsating gas flow.
- Cylinder cooling and lubrication are required. Non-lubricated compressors require the use of self-lubricating materials.
- Sensitive to low gas densities.
- High maintenance requirements. Prone to service failures.

Diaphragm compressors

- Usually the working speed is lower than 580 rpm.
- Suitable for applications where leaks or product contamination are not allowed.
- Smaller capacities than piston compressors.
- High pressure rates.
- Low efficiency.
- Diaphragm set as a whole should be carefully designed in order to attain an acceptable lifespan.

Screw compressors

- High operating speed (lower than centrifugals but higher than reciprocating compressors).
- Wide range of operating speed.
- Pressure ratio up to 20 depending on type and size. Overall pressure ratios of more than 25 are possible with multistage compressor frames.
- Efficiency between 60% and 70%.
- Lower efficiency for operation at off-design conditions particularly on fixed internal volume machines.
- Oil-free gas discharged.
- Some sensitivity to low gas densities.
- Presence of liquid and non-abrasive dirt in the gas being handled is allowed.
- High gas discharge temperature.

Lobe compressors

- Medium capacities.
- Normal compression rates not higher than 2.2. Dry high-pressure machines can reach values up to 4.5.
- Smooth and oil-free gas delivery.
- Almost constant capacity for a given speed regardless of the gas pressure and temperature.
- Pressure self-adjustment without power loss.
- Can handle any gas.
- Presence of liquid in the gas being handled is allowed.
- Can operate with efficiency at any pressure in the design range.
- Small losses.

Sliding vane compressors

- Medium capacities. Compression rate not higher than 2.7.
- High rotating speed.
- Smooth flow.
- Valves are not required.
- Small footprint.
- Usually water cooling is required.
- Positive lubrication required.

Liquid ring compressors

- Medium pressure and capacity machines.
- Especially well suited to handling explosive or highly corrosive gases.
- Smooth discharge flow.
- Cold and clean discharged gas.
- No friction parts and no lubrication required.
- Large power demand.
- Low efficiency. Maximum value around 48%.
- Water (or another liquid) supply required.
- Good construction materials required.

Figure 2.7. Multistage centrifugal compressor (image courtesy of Elliot Group, Jeannette, PA, USA).

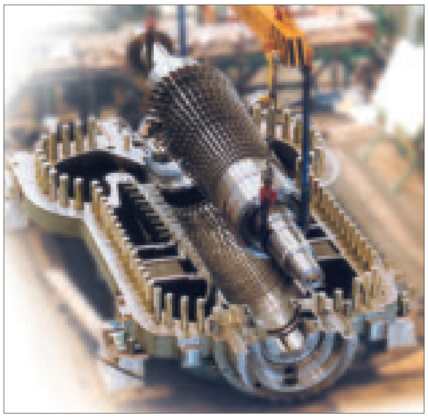

Figure 2.8. Axial compressor (image courtesy of Nuovo Pignone Spa – © All rights reserved).

Scroll compressors

- Low pressures and capacities.
- No valves needed. A dynamic discharge valve is used in some applications.
- Small torque fluctuation.
- Very low noise and vibration.
- Higher volumetric efficiency than piston compressors.
- Small-sized scroll compressors are more efficient.

Centrifugal compressors

- High operating speed.
- Low starting torque required, as with rotary compressors.
- High capacity. Low limit between 1,000 m^3/h and 3,000 m^3/h.
- Operate satisfactorily over a wide range of capacity and pressure.
- Discharge pressure very limited for a single impeller. Almost all applications require several compression stages.
- Low, medium and high discharge pressures (35 MPa and over), although smaller discharge pressures than piston compressors.
- Smooth discharge flow.
- Oil-free gas discharged.
- High efficiency even when handling dirty gases. Liquid injection allowed.
- Low level of vibrations, allowing light and cheap foundations.
- High operating reliability.
- Low maintenance cost.
- Behaviour extremely sensitive to inlet gas pressure, temperature and molecular weight.
- Substantial change in capacity for pressure variations.
- Unstable operation (surging) at limited flows.

Axial compressors

- Low pressure ratio (up to 10) and very large flow (100,000 m^3/h to 900,000 m^3/h inlet capacity).
- Limited compression rate mainly because of the difficulty of installing interstage cooling.
- Characteristics very similar to centrifugal compressors. Better efficiency for capacities greater than 100,000 m^3/h and discharge pressure not greater than 1.0 MPa. Smaller footprint and weight.
- Not suitable for portable applications (as with centrifugals).

The values given above for each type of compressor correspond to standard designs. For specific applications, parameters outside those limits can be found.

Part 3 of this series will explain the physical structure of piston compressors. ■

References

[1] E. Larralde and R. Ocampo, 'Selection of gas compressors: part 1', *World Pumps*, No. 536, pp. 24–28, (May 2011).

[2] Compressed Air and Gas Institute, *Compressed Air and Gas Handbook*, Third Edition, New York, NY, USA, (1961).

Contact

Eduardo Larralde
Email: larralde@quimica.minbas.cu
Rafael Ocampo
Email: rocampod@gmail.com