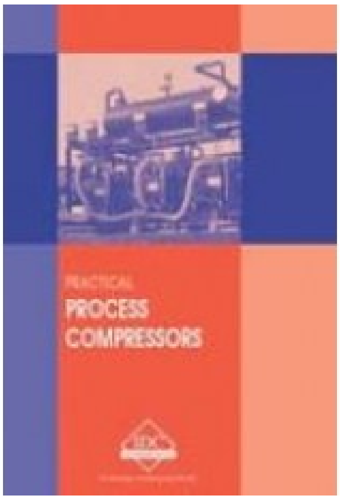
CO-E - Practical Process Compressors



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Short Description

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First Chapter

Practical Process Compressors - Basics

1 Compressor basics

This chapter lays down the basic principles of a compressor and defines the characteristics of various types of compressors. A list of terms related to compressors is also given in this chapter.

Learning objectives

- Compressor basics
- Compressor types and their characteristics
- Definitions related to compressors

1.1 What is a compressor?

In our bouquet of childhood memories, there lies one of using the bicycle pump for the first time. Few can forget the trickling sweat and the satisfactory feel of the hard cycle tier. For many, that was probably the first experience of operating a compressor.

From inflating footballs to spray painting, from vacuum cleaners to refrigerators, from ventilators to air conditioners, from the dentist's whining drill to the deafening pneumatic hammers on construction sites, there are few aspects in our present day lifestyles that remain untouched by the need of air or gas at higher pressures.

These and countless more requirements have evolved and sustained the demand for machines that capture a volume of gas and raise its pressure. These machines are called fans, blowers or compressors.

Compressors are devices that transfer energy to a gaseous fluid for the purpose of raising the pressure of the gas. It can also be considered the engine driving gas from one part of the process to another.

Pressure is often expressed in units of bar, atmospheres, kg/cm^2 or psi (pounds per square inch). Fans, blowers or compressors are distinguished by their ability to raise the pressure of the gas they handle.

If suction of atmospheric air (0 kg/cm^2-g) is considered, then devices that can develop pressure to 0.1 kg/cm^2-g are called fans. Blowers are a bit stronger and can build a pressure to 0.9 kg/cm^2-g. Above this range, pressurizing devices are called compressors.

Compressors can basically be divided into two types:

- Positive displacement compressors
- Dynamic compressors

Positive displacement compressors

The old bicycle pump (a misnomer) remains the most well known positive displacement compressor. It comprises a piston that moves to and fro in a metal cylinder. As the piston is pulled up, it sucks in a certain volume of air. During the “push” or the downward stroke of the piston, the air that is entrapped between the moving piston and the cylinder is compressed into a smaller volume. This compression causes the increase in pressure. As soon as the air pressure inside the cylinder exceeds that in the cycle tier, air is forced into the tier tube.

Positive displacement compressors entrap a volume of gas in a confined space. The volume of this space is reduced leading to a reduction in the volume of the gas. This raises the pressure of the gas. After the pressure of the gas has been raised, it is pushed out of the confined space.

Positive displacement compressors for a given speed are typically constant flow, variable pressure ratio (ratio of the discharge pressure to the suction pressure) machines. The volume of gas compressed is directly proportional to the speed of the compressor.

The above can be understood by keeping the example of the bicycle pump in mind. It is quite easy to imagine that the volume of air being delivered during every stroke of the pump would remain the same as long as the travel of the piston or the stroke remained the same. If the number of strokes per minute increased, the total volume of delivered air would also increase proportionately.

In the initial stages when the tier is flat, the pressure inside the tier is less; so the pump builds less pressure to push the air inside. However as the tier gets filled up, the discharge pressure of the pumps rises to match the tier pressure. We thus observe that this device can vary its discharge pressure to match the system requirement. Hence these are variable pressure ratio machines.

Such compressors normally handle smaller volumes of gas.

The various types of positive displacement compressors are:

Reciprocating compressors

In reciprocating compressors, successive volumes of gas are confined within a closed space and elevated to a higher pressure by forcing the mass of gas into a smaller volume.

It usually comprises a circular piston, which traverses back and forth along a linear path inside a cylinder. It has valves on the suction and discharge ends. With every suction stroke of the piston the gas is taken into the cylinder. In the forward stroke, the gas is trapped as both the suction and discharge valves are closed. Midway during the forward stroke, when the pressure of the gas in the cylinder becomes higher than the system into which it has to deliver, the discharge valve opens. Subsequently, the compressed gas is then pushed into the system at its pressure.

The reciprocating mechanism is hundreds of years old but the modern design of the reciprocating compressor has invariably been developed from the steam engine.

This slider-crank mechanism adopted in the above machines comprises a rotating crankshaft. This rotary motion is converted to a linear motion of the piston by a connecting rod. This connecting rod has an oscillatory motion. In a steam engine, the steam pushes the piston and a rotary motion is derived from the crankshaft whereas in a compressor the rotary motion of the crankshaft is used to reciprocate the piston so as to entrap and compress the gas.

Therefore, although they may have similar mechanisms, thermodynamically they are opposite in nature. One has the gas doing the work and in the other, work is done on the gas. One is a prime mover and the other is a driven machine.

Thomas Newcomen in the eighteenth century designed a reciprocating steam engine that used a true piston and piston rod assembly. It was James Watt who built a piston using brass rings in the late 1700's. In 1769 Watt patented his single acting steam engine and in 1782, he patented his double acting steam engine.

The invention of the reciprocating compressor is vague; many countries had been using steam engines and the technology produced reciprocating compressors.

Screw compressors

Screw compressors also belong to the family of positive displacement compressors. In fact they are often termed ‘rotary piston compressors’.

A screw compressor comprises two intermeshing lobes; one male and another female. Each has a helical form. A volume space is formed by the helical profiles of the two lobes and the casing. The gas from the inlet is trapped within this space. As the lobes rotate this volume that entraps the gas reduces and also moves in a forward direction. This reduction in volume compresses the gas and transfers it from the inlet or the suction to the discharge vessel.

Figure 1.1

Screw compressor

The principle of the screw compressor was first patented by Heinrich Krigar in Germany in 1878. He modified and improved his designs and lodged a second patent a few months later in the same year.

Heinrich Krigar lived in Hannover. The illustrations of his compressor clearly show a two lobe rotor assembly, each rotor having the same profile as the other. The rotor configuration was similar to the lobe design, exhibited in Europe during 1867, with the exception that the rotors in the Krigar screw compressor twisted through an angle of 180° along their length of the lobe.

At that time it was difficult to progress any further due to the lack of manufacturing technology.

Almost fifty years later, a Swedish steam turbine manufacturer called Ljungstroms Angturbin AB appointed a new Chief Engineer, Alf Lysholm.

He played a pivotal role in the development of the modern screw compressor. At that time, Lysholm was interested in developing a light weight compressor for gas and steam turbine applications.

By this time the original patent rights had expired.

Lysholm developed the profile of the screw compressor and tested various configurations and rotor lobe combinations. He not only designed the rotor configurations but also evolved a methodology to machine them accurately. This he patented. This patent in 1935 probably signaled the arrival of the modern screw compressor.

Ljungstroms Angturbin AB later changed its name to Svenska Rotor Maskiner AB in 1951. This company is well known throughout the world as SRM.

Several other compressor manufacturers have since invested in their own R&D programs to produce new 'in-house' profiles, all based upon an initial concept now over 120 years old.

Screw compressor design involves rotating components that do not have physical contact. This greatly enhances their availability as compared to the reciprocating compressors. The gas flow has lower pressure pulsations and its gas handling capacity is higher than the reciprocating machines.

Vane compressors

This is a rotary positive displacement machine in which axial vanes slide rapidly in a rotor that is eccentrically mounted in a cylindrical casing.

Figure 1.2

Vane compressor

The vanes are thrown outwards by centrifugal force when the compressor is running and the vanes move in and out of the slot because the rotor is eccentric to the casing. The vanes sweep the cylinder. Gas trapped between consecutive vanes is compressed and displaced.

Rotary vane compressors use either carbon vanes for low-pressure oil-free duties, or asbestos/steel vanes for lubricated duties. The present day vanes though are made of advanced thermoplastics called ‘polyamide imides’. Various asbestos (and similar performance asbestos free) compounds are also widely used for low-pressure applications. When the discharge pressure is higher than 3 bar-g, the vanes are made of steel or cast iron. Higher pressure differentials cause excessive bending forces on the vanes when the machine is running.

One of the first vane type machines was the Lemielle exhauster, invented in France during the early 1800s, and widely used in Belgium to provide ventilation for collieries.

In this large machine, hinged vanes were mounted on the surface of a rotating drum. This drum was mounted eccentrically within a casing.

The vane travel was limited to ensure semi-contact with the outer casing. It did not take long to graduate to the present design of sliding vanes.

The principle of the modern sliding vane compressor dates back to the early 1900s when an American by the name of Robert Blackmer invented the first rotary vane pump.

An Italian manufacturer called Pneumofore SPA in the late 1920s first produced the oil injected sliding vane compressor. In the UK, towards the end of the 1940s, Major P.C. Bird patented a new type of lubricated vane compressor under the trade name 'Oilvane'. Alfred Bullows acquired an exclusive license from Major Bird, and after a period of development the first Hydrovane compressors followed.

Lobe blowers

Lobe blowers also belong to the rotary group. In this type two straight mating lobes trap the gas between the lobe profile and casing. Their rotation displaces the gas from suction to discharge with no internal compression.

Figure 1.3

Lobe compressor

Compression is caused because the induced gas is forced into a closed conduit, thereby causing the gas to become pressurized after it has left the lobe compressor.

The Roots brothers discovered the principle of the lobe blower in the mid 1800s. They were Philander and Francis Roots and joint owners of a woolen mill in Connersville, Indiana. This positive displacement blower was named after them and the original Roots Blower Company was formed. The name Roots blower has almost become synonymous to describe this generic type of compressor/blower.

The Roots blower was exhibited in Paris during 1867 and was seen as a possible answer to the then difficult problems of deep mine ventilation.

About forty years later a rival blower manufacturer was formed in the same city, called Connersville Blowers. The companies competed with each other until

1931, when they were both bought out by a third party and merged.

These are typically used to produce low pressure compressed air. It has many applications and one of the main uses is in pneumatic conveying of powders. In this application, the powder flows in the same way as a liquid. Pneumatic conveying is usually carried out at fairly low pressures from 0.4 bars to 1 bar depending upon the nature of the material being conveyed.

Liquid ring/piston compressors

These are rotary positive displacement machines in which a liquid (mostly water) is used as a piston to compress and displace the gas.

Figure 1.4

Liquid ring compressors/vacuum pump

The Nash Engineering Company in 1905 was the originator of the liquid ring vacuum pump. Serving a growing customer base from a small facility in Norwalk, Connecticut, early applications of this new technology included vacuum steam heating and vacuum sewage collection systems for cities throughout the United States. This provided a technology base that allowed them to develop major innovations in various types of industries such as pulp and paper, chemical processing, mining, food and many others.

The same principle is adopted to use the machine as a compressor.

It operates on the rotary liquid piston principle; the shaft and the impellers are the only moving parts.

The shaft and impeller assembly is mounted eccentrically with respect to the pump casing. As the impeller rotates, the service liquid (this is in constant circulation) is forced outwards by centrifugal force to form a revolving liquid ring, which is concentric to the casing.

Because of the eccentric position of the impeller, the liquid ring moves towards and away from the shaft, resulting in a liquid piston action. This displaces the air or gases between the spaces of the impeller blades.

As the impeller rotates, the liquid is thrown out by centrifugal force and air or gas is drawn in through the suction port.

After the suction port is passed, the service liquid is forced back into the spaces between the impeller blades, gradually compressing the air or gases.

When the spaces between the impeller blades reach the discharge point, the liquid ring forces the compressed gas or air between the blades into the discharge port.

Diaphragm compressors

The principle of operation of a diaphragm compressor is very similar to a reciprocating compressor. In this case, the piston is replaced by a flexible diaphragm (typically metallic). The flexible diaphragm is clamped between two washers or plates. The bottom washer derives its reciprocating motion from the connecting rod, which in turn is connected to a rotating eccentric.

Figure 1.5

Diaphragm compressor

As the diaphragm flexes inwards, a low pressure is created above the diaphragm. The gas is drawn into the chamber. When the diaphragm flexes outwards, the gas is expelled into the discharge header.

A Howden Group Company, Burton Corblin, invented the diaphragm compressor and pioneered the dry lubricated process piston compressor. The main application is in non-contaminating compression.

Dynamic compressors

In dynamic compressors, the mechanical motion of the compressor rotor transfers the kinetic energy to the gas. A large portion of the velocity head is then converted into a pressure head in the impeller as well as in the increasing area sections called diffusers or diaphragms. In such compressors, there is no entrapment of gas as in positive displacement compressors; hence the flow is continuous and there are no valves.

Dynamic compressors can have a variable flow and fairly fixed pressure ratios. These vary with the speed but the range is limited.

These compressors are used in applications when large volumes of gas have to be compressed.

The various types of dynamic compressors are:

- Centrifugal compressor

These are rotary continuous flow machines. Here the rapidly rotating impellers, usually shrouded on both sides, accelerate the gas as it passes through it. The conversion of the velocity head to pressure is done partially in the rotor and the rest in stationary diffusers or blades. Main gas flow discharge is radial or orthogonal to the shaft axis.

- Axial flow compressors

These are also dynamic machines in which gas acceleration is obtained by the action of the bladed rotor. Main gas flow is axial and parallel to the shaft axis. The conversion of velocity head to pressure is done both in the rotating and the stationary blades. These can handle higher flows than the centrifugal compressor but is limited by the pressure ratio per stage. Relatively the pressure ratio per stage capability of an axial compressor is half to that of a centrifugal compressor. Hence axial flow compressors are almost always multistage compressors.

Figure 1.6

Axial compressor

- Mixed flow compressors

In these dynamic machines, the impeller form combines characteristics of both the centrifugal and axial types. The flow and head capabilities are also in-between the two types.

The first turbo compressors were manufactured at the turn of the 1900s. They were originally developed by steam turbine manufacturers and were widely used for ventilation purposes in deep shaft mining, particularly in the coal industry. At that time, the method of producing an impeller depended on fabrication process.

It was some decades later when the technology evolved to produce highly efficient turbo compressors.

Typically, some blades were riveted on to a hub and the resulting impellers were then balanced as best as possible. The typical pressure ratios across early riveted impellers were to the order of 1.2:1.

It wasn't until the early 1950s that sufficient money was invested in technology, to allow the production of efficient high speed compressors and that created the market for such compressors.

Regarding the axial flow compressor, it is believed that in **1872** *a man by the name of* **Stolze***designed the first true gas turbine. His engine incorporated a multistage turbine section and a multistage axial flow compressor. He tested working models in the early* **1900s***.*

1.2 Compressor definitions

Gauge pressure

This is pressure measured in bar-g, kg/cm^2-g or psig (pounds per square inch-gauge) above the atmospheric pressure. It is the pressure read on a pressure indicator or a pressure gauge.

Absolute pressure

This is the summation of the gauge pressure and the local atmospheric pressure or barometric pressure.

At sea level the atmospheric pressure is 1.033 kg/cm^2 (14.7 psia)

Thus absolute pressure is 1.033 kg/cm^2-a or (14.7 psia)

The above equals 1 atmosphere.

1 atmosphere equals 1.01325 bar.

At 5000 feet (1524 m) elevation, the absolute pressure can drop to 0.86 kg/cm^2-a (12.2 psia).

Absolute temperature

This is obtained by adding the actual measured temperature in °C + 273.16. This unit for this temperature value is in °K (Kelvin).

°K = °C + 273.16

When the measured temperature is in °F, the absolute temperature is obtained by adding 460 to the measured reading. The unit for the absolute temperature in this case is °R (Rankine).

°R = °F + 460

Pressure ratio

Pressure ratio is the ratio of the discharge pressure to the suction pressure considered in **absolute values**.

If the suction and discharge pressure gauges indicate 1.6 kg/cm^2 and 6.5 kg/cm^2, then the pressure ratio is

PR = (6.5 + 1.033) / (1.6 + 1.033) = 2.861

Capacity

Compressors are volumetric machines. This implies that for any gas handled, the volume of gas derived is the same. The volume of gas handled by the compressor in a unit of time is known as the capacity of the compressor.

However the problem is that volume at different inlet conditions can be different and hence there is a need to specify the inlet conditions when capacity of a compressor is referred to.

There are three conditions at which compressor capacity can be described;

- Normal (Sea Level, 0 ºC)
- Standard
    - [Compressed Air Institute – 1.033 kg/cm^2-a (14.7 psia), 15.5 ºC, (60 ºF)]
    - [ASME - 1.033 kg/cm^2-a (14.7 psia), 20 ºC (68 ºF), RH – 36%]
    - [Natural Gas Pipeline Industry – 1.012 kg/cm^2-a (14.2 psia), Gas suction temperature]

- Inlet (Compressor Suction conditions)

The i*nlet* condition is mostly specified and it is common to come across ICFM (Inlet Cubic feet per minute) or ACFM (Actual Cubic feet per minute).

CFM in metric units is meter cube per hour (m^3/hr).

Also, when none is specified it can be assumed that *inlet* conditions are being considered.

Stages

In many cases an application may require gas to be raised to a high pressure ratio. This may be beyond the design capability of the compressor to do in one step. As a result compression is split into two or more steps called ‘stages’.

As the gas is compressed its temperature rises. So in multistage compressor after every stage, gas is cooled in a heat exchanger and then led to the inlet of the next stage. This method of intercooling the gas reduces the energy required to compress the gas.

Basic criteria for compressor selection:

Prior to selecting the type of compressor, various factors need to be taken into consideration. Some of these include:

- Gas and its nature
- Capacity
- Pressure ratio
- Power supply characteristics
- Size and weight of compressor
- Type of foundation required
- Type of controls
- Maintenance costs
- Availability

Figure 1.7

Typical range of different types of compressors

The above figure is only an approximate range of the different types of compressors. Every year the demand for higher pressure ratios and flow requirements are pushing the envelopes of each type of compressor to higher numbers. These would be revisited during the discussion of individual types of compressors.

The prime factors of *capacity* and *pressure ratio* are the first to be used to choose between positive displacement and dynamic compressors. The further selection between the two broad types is an engineering decision based on many additional factors like life cycle costing and the process involved.

Among the dynamic compressors, the application ranges of the additional types are represented in the table below.

Table 1.1

Application ranges of compressors

Compressor types		**Q – m^3/hr**	**Discharge pressure bar**
Turbo blowers - single stage		1150 180000	1.3 2.4
4-stage geared compressor		3600 216000	4.8 11
Turbo-compressor radial design	A	1000 216000	2.6 20
	B	720 396000	20 50
Turbo-compressor axial design		36000 1152000	2 10
Turbo-compressor radial barrel design	A	540 39600	10 52
	B	540	52

	39600	180
C	360	180
	10800	600

Some of the features of the various types of compressors are tabulated below:

Table 1.2

Compressor Features

Type	**Advantages**	**Disadvantages**
Centrifugal	Wide operating range	Unstable at low flow
	Low maintenance	Moderate efficiency
	High reliability	
Axial	High efficiency	Low pressure ratio per stage
	Hi-speed capability	Narrow flow range
	Higher flow for a given size	Fragile and expensive bladi
Positive displacement	Pressure ratio capability not affected by gas properties	Limited capacity
		High weight to capacity ratio
	Good efficiencies at low specific speed	

Exercises

1.0 Fans, blowers and compressors are differentiated on the basis of their;

1. Flow rate
2. Inlet temperature
3. Pressure ratio
4. Gas handled

2.0 The flow rate handled by dynamic compressors as compared to positive displacement compressors is

1. Higher
2. Lower
3. Almost the same

3.0 Screw compressors belong to the family of

1. Centrifugal compressors
2. Rotary positive displacement compressors
3. Rotary dynamic compressors
4. Lobe blowers

4.0 In a reciprocating positive displacement compressor

1. Gas volume is trapped, compressed and displaced to a higher pressure system
2. Pressure is increased by sliding vanes
3. A high speed rotor imparts energy to gas which is converted to pressure head
4. Rotating screws trap a gas volume, compress and discharge it to a higher pressure line

5.0 The figures below describe which compressor

1. Axial compressor
2. Vane compressor
3. Liquid ring compressor
4. Centrifugal compressor

6.0 Pressure gauges installed on the suction and discharge lines of a compressor are indicating 1 bar and 5 bar respectively. The pressure ratio of the compressor is

1. 2
2. 5

3. 3
4. 4

7.0 Inlet volumetric capacity of a compressor is given 3500 i-m^3/hr. This implies that the inlet temperature is

1. 0 ºC
2. 5ºC
3. Gas temperature at compressor inlet
4. Gas temperature at normal conditions

8.0 Multistage compressor is required when

1. Flow rate is high
2. Pressure ratio is high
3. Discharge pressure is high
4. Outlet temperature is high

9.0 One among the following factors is usually not considered during compressor selection

1. Pressure ratio
2. Gas to be compressed
3. Availability
4. Piping

Answers:

1.0	c)	2.0	a)	3.0	b)	4.0	a)
5.0	d)	6.0	c)	7.0	c)	8.0	b)
9.0	d)						