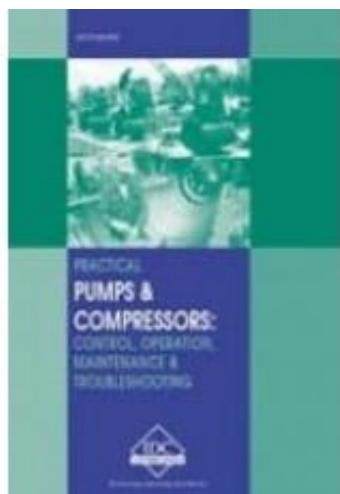


CM-E - Pumps and Compressors Control, Operation, Maintenance and Troubleshooting



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Short Description

This manual focuses on the fundamentals of centrifugal pumps and compressors. It discusses pump/compressor construction, design-applications, operations, maintenance and management issues provides you with the most up-to-date information and best practice in dealing with the subject. This is not an advanced manual but one focusing on the fundamentals and therefore will not be suitable for you if you are a pump or compressor "guru"!

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Table of Contents

Download Chapter List

[Table of Contents](#)

First Chapter

Compressors - Practical Pumps and Compressors: Control, Operation, Maintenance and Troubleshooting

1 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 satisfactory feel of the hard bicycle tyre. 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 life that remain untouched by the need of air or some gas at higher pressures.

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

Compressors transfer energy to a gaseous fluid for raising the pressure of a gas. It can also be regarded as an engine driving a gas from one part of the process to another.

Pressure is often expressed in the units of kg/cm² 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 the atmospheric air (0 kg/cm²-g) is considered, devices that can develop pressure to 0.1 kg/cm²-g are called fans. Blowers are stronger and can build a pressure to 0.9 kg/cm²-g. Pressurizing devices above this range are called compressors.

There are basically two types of compressors:

- Positive displacement compressors
- Dynamic compressors

1.1.1 Positive displacement compressors

The old bicycle pump (a misnomer) remains the most well known positive displacement compressor. It comprises of 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 trapped between the moving piston and the cylinder is compressed into a smaller volume. This compression causes an increase in pressure. At the instant when the air pressure inside the cylinder exceeds that in the cycle tyre, air is forced into the tyre 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 using the example of the bicycle pump. It is 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 tyre is flat, the pressure inside the tyre is less. The pump builds lesser pressure to push the air inside. However, as the tyre becomes filled, the discharge pressure of the pump rises to match the tyre pressure. We 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:

1.1.2 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 of 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 gas pressure inside the cylinder becomes higher than the system into which it has to deliver, the discharge valve opens. Subsequently, the compressed gas is pushed into the system at its pressure.

The reciprocating mechanism is hundreds of years old, but the modern design of the reciprocating compressor is believed to have been derived from the steam engine.

This slider-crank mechanism adopted in the above machines comprises of a rotating crankshaft. This rotary motion is converted to a linear motion of the piston by a connecting rod. This 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 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 designed a reciprocating steam engine in the eighteenth century that used a true piston and piston rod assembly. James Watt built a piston using brass rings in the late 1700s. He patented his single-acting steam engine in 1769 and patented his double-acting steam engine in 1782.

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

1.1.3 Screw compressors

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

A screw compressor comprises of two intermeshing lobes: one male and the other female. Each one 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 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

A Screw Compressor

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

He lived in Hannover. The illustrations of his compressor clearly show a two-lobe rotor assembly, with each rotor having similar profiles. In fact, the rotor configuration resembles the lobe design initially exhibited in Europe in 1867, with the exception that the rotors in the Krigar screw compressor twisted through an angle of 180° along their length of the lobe.

It was not possible to develop the idea any further at that time due to the lack of manufacturing technology. Almost 50 years later, Ljungstroms Angturbin AB, a Swedish steam turbine manufacturer, appointed a new Chief Engineer, named Alf Lysholm.

He played a pivotal role in the development of the modern screw compressor. At that time, Lysholm was interested in developing a lightweight 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. He eventually had it patented. This patent in 1935 probably signalled the arrival of the modern screw compressor.

The company 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 on an initial concept which is now over 120 years old.

Screw compressor design involves rotating components that do not have any physical contact. This greatly enhances their availability when compared to the reciprocating compressors. The gas flow does not have pressure pulses and usually, the capacity is higher than the reciprocating machines.

1.1.4 Vane compressors

These are rotary positive displacement machines in which axial vanes slide rapidly in rotor eccentrically mounted in a cylindrical casing.

Figure 1.2

A Vane Compressor

The vanes are thrown outward by centrifugal force when the compressor is running. The vanes move in and out of the slot as 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 are made of advanced thermoplastics called polyamide imides. Various asbestos (and similar performance asbestos free) compounds are also widely used for low-pressure applications. Over and above the pressure of 3 bar-g, the vanes are steel or cast iron, due to excessive bending forces that act on the vanes when the machine is running.

The Lemielle exhauster was one of the first vane type machines 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 a 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 Robert Blackmer, an American, invented the first rotary vane pump.

Pneumofore SPA, an Italian manufacturer first produced the oil-injected sliding vane compressor in the late 1920s. Toward the end of the 1940s, Major P.C. Bird patented a new type of lubricated vane compressor in the UK 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.

1.1.5 Lobe compressors

Lobe compressors are of a rotary type also. Two straight mating lobes trap the gas between the lobe profile and the casing. Their rotation displaces the gas from the suction to discharge with no internal compression.

Figure 1.3

A Lobe Compressor

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

Philander and Francis, the Roots brothers, discovered the principle of the lobes blower in the mid 1800s. They were 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 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 40 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.

Lobe compressors are typically used to produce low-pressure compressed air. They have 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, between 5 psig and 15 psig depending on the nature of the material being conveyed.

1.1.6 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

A Liquid ring/piston compressor

The Nash Engineering Company was the originator of the liquid ring vacuum pump in 1905. 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 the impeller assembly are mounted eccentrically with respect to the pump casing. As the impeller rotates, the service liquid (this is in constant circulation) is forced outward by centrifugal force to form a revolving liquid ring, which is concentric to the casing.

Owing to the eccentric position of the impeller, the liquid ring moves toward 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 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.

1.1.7 Diaphragm compressors

The operating principle 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 in 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.

1.1.8 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 pressure head in the impeller as well as in the increasing area sections known as diffusers or diaphragms. In such compressors, there is no entrapment of gas as in positive displacement compressors and therefore, 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, though the range is limited.

These compressors are normally used in applications where large volumes of gas need to be compressed.

The various types of dynamic compressors are:

- **Centrifugal compressors**

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 remainder in stationary diffusers or blades. The main gas flow is radial or

orthogonal to the shaft axis.

- **Axial flow compressors**

These are dynamic machines where gas acceleration is obtained by the action of the bladed rotor. Main gas flow is axial along the shaft axis.

Figure 1.6

Axial Compressor

- **Mixed flow compressors**

These are dynamic machines with an impeller form combining some characteristics of both the centrifugal and axial types.

The first turbo compressors were manufactured at the turn of the 1900s. They were originally developed by steam turbine manufacturers and 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 the 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 the early riveted impellers were 1.2:1. It wasn't until the early 1950s that sufficient money was invested into technology which allowed for the production of efficient, high-speed compressors; this created the market for such compressors.

*With regard to the axial flow compressor, it is believed that a person named **Stolze** designed the first true gas turbine in **1872**. 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

1.2.1 Gauge pressure

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

or a pressure gauge.

1.2.2 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/cm² (14.7 psia).

Thus, absolute pressure is 1.033 kg/cm²-a or (14.7 psia). At an elevation of 5,000 feet (1,524 m), the absolute pressure can drop to 0.86 kg/cm²-a (12.2 psia).

1.2.3 Absolute temperature

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

$$^{\circ}\text{K} = ^{\circ}\text{C} + 273.16$$

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

$$^{\circ}\text{R} = ^{\circ}\text{F} + 460$$

1.2.4 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/cm² and 6.5 kg/cm², then the pressure ratio is:

$$\text{PR} = (6.5 + 1.033) / (1.6 + 1.033) = 2.861$$

1.2.5 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 is known as the capacity of the compressor.

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

There are three conditions at which compressor capacity can be stated:

- Normal (sea level, 0°C)
 - Standard
- o [Compressed Air Institute – 1.033 kg/cm²-a (14.7 psia), 15.5°C, (60°F)]
 - o [ASME - 1.033 kg/cm²-a (14.7 psia), 20°C (68°F), RH – 36%]
 - o [Natural Gas Pipeline Industry – 1.012 kg/cm²-a (14.2 psia), Suction temperature]
 - Inlet (compressor suction conditions)

The *Inlet* 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 (m³/hr). Also, when no conditions are specified, it can be assumed that inlet conditions are being considered.

1.2.6 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 accomplish with one step. As a result, compression is split into two or more steps, known as stages.

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

1.2.7 Basic criteria for compressor selection

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

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

- Availability and cost of cooling water

The prime factors of *capacity* and *pressure ratio* are the first to be used to choose between positive displacement and dynamic compressors. A further selection between the two broad types is an engineering decision based on many additional factors such as lifecycle, cost and the process involved.

The above is an approximate application range for the different types of compressors.

Here, the numbers on the X-Y axes are powers of 10 for actual cubic feet per minute (ACFM) and discharge pressure in pounds per square inch (psi).

**1 CFM = 1.7 m³/hr, and
1 psi = 0.07 kg/cm².**

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

Compressor Types		Q – m³/hr	Discharge Pressure kg/cm²
Turbo Blowers - Single Stage		1150	1.3
		180000	2.4
Four-stage Geared Compressor		3600	4.8
		216000	11
Turbo-compressor Radial Design	A	1000	2.6
		216000	20
	B	720	20
		396000	50
Turbo-compressor Axial Design		36000	2
		1152000	10
Turbo-compressor Radial Barrel Design	A	540	10
		39600	52

B	540	52
	39600	180
C	360	180
	10800	600

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

Type	Advantages	Disadvantages
Centrifugal	<ul style="list-style-type: none"> Wide operating range Low maintenance 	<ul style="list-style-type: none"> Unstable at low flow Moderate efficiency
Axial	<ul style="list-style-type: none"> High reliability High efficiency Hi-speed capability Higher flow for a given size 	<ul style="list-style-type: none"> Low pressure ratio per stage Narrow flow range Fragile and expensive blading
Positive displacement	<ul style="list-style-type: none"> Pressure ratio capability not affected by gas properties Good efficiencies at low specific speed 	<ul style="list-style-type: none"> Limited capacity High weight to capacity ratio