Abu Dhabi Gas Liquefaction Company Ltd

Job Training

Mechanical Technician Course

Module 9

Compressors

ADGAS Personnel & Training Division

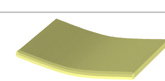
Contents

Contents

Pre-Requisite	Completion of A.T.I. Maintenance Programme, ADGAS Induction Course and Basic Maintenance Technician Course.
Course Objectives	The Job Training Mechanical Technician Course is the second phase of the development programme. It is intended specifically for Mechanical Maintenance Developees. On completion of the Course the developee will have acquired an awareness of some of the equipment, terminology, and procedures related to mechanical maintenance of ADGAS LNG plant. Appropriate safety procedures will continue to be stressed at all times.
Module Objectives	On completion of this module, the developee will be able to correctly : • identify types of compressors • identify compressor parts and state their functions • describe compressor principles • identify compressors used on the plant, their types and configurations • describe, in simple terms, compressor surge and its consequences • identify P&ID and PFD symbols for compressors and their auxiliaries
Methodology	The above will be achieved through the following: • pre-test • classroom instruction • audio visual support • site visit • tasks & exercises • post-test

Abbreviations and Terminology

BOG	Boil-off gas
C_3	Propane
HP	High pressure
LNG	Liquefied natural gas (methane and ethane)
LP	Low pressure
LPG	Liquefied petroleum gas (propane and butane)
MCR	Mixed component refrigerant
MP	Medium pressure
VRU	Vapour recovery unit

Aerofoil section	Shape of an aircraft wing section. 
After-cooling	Gas cooling after final stage of compression.
Baffle	Plate used to stop flow in a straight line.
Barrel	Cylinder that can be closed at both ends—traditionally a wooden container for liquids.
Boil-off-gas	Vapour from LNG held in tanks.
Bundle	A collection of items packaged together.
Compressor process stage	Section of a compressor between two external feeds or discharges.
Compressor stage	Section of a compressor that increases pressure: can be a cylinder or an impeller. (See also compressor *process stage.*)
Conduction	Method of heat travel through a solid.
Convection	Method of heat travel in a liquid or gas.
Cryogenic	Describing extremely low temperatures.
Differential (pressure)	The difference (of pressure) between two points.
Downstream	Located after something, in the direction of flow.
Feed gas	Gas being processed in the LNG Plant. (See also *process gas*.)
Fuel gas	Gas used as fuel for boilers, gas turbines, etc.
Header	Item dividing one flow into many, or combining many flows into one.
Inter-cooling	Gas cooling between stages of compression.
Inter-stage	Between stages.
Leaf spring	Spring made from a flat or slightly curved strip of metal. 
Process gas	Gas being processed in the LNG Plant. (See also *feed gas*.)
Side-stream	Gas entering or leaving a compressor between stages.
Upstream	Located before something, against the direction of flow.
Vapour recovery	Removal and re-liquefaction of vapour from LPG held in tanks.

1 Introduction

The main purpose of a compressor is to increase the pressure of a gas.

ADGAS uses compressors:

- to supply compressed air for use throughout the plant
- to raise the pressure of *process gas* (or *feed gas*) received from the ADMA gas-oil separation plant going to Trains I and II for liquefaction
- in refrigeration processes that cool gas to liquefy it
- to re-compress *boil-off-gas* (LNG) and *vapour recovery* (LPG) in the STOREX area
- in gas turbines, to increase the pressure if air entering the turbine

Compressors are also needed where gas has to be moved through long pipelines. As gas flows along a pipeline, some of its pressure energy changes to heat energy because of fluid friction. This results in a loss of pressure. Compressors are located at points along the pipeline to *boost* the pressure.

To ***boost*** something is to increase it.

You can think of compressors as 'gas pumps'. They do a similar job to a pump, have similar components and can often look like pumps.

Most of the compressors on the ADGAS plant are centrifugal compressors. They have the same principal of operation as a centrifugal pump but run at much higher speeds than a pump. They are often driven directly by turbines. If they are driven by electric motors, a gearbox may be needed to increase the drive speed to the compressor.

Reciprocating compressors are used mainly in the STOREX area.

The only axial-flow compressor on the plant is located in the gas turbine drive for an electrical generator.

Other common types of compressors are described in this module to give you an awareness of the full range available.

2 Compressor Basics

The principle of operation of a compressor is the same as that for a pump. The compressor driver supplies kinetic energy that the compressor converts to pressure energy. Some energy is wasted because of fluid friction; this turns kinetic energy to heat energy. Like all other machines, compressors efficiency is always less than 100%.

2.1 Pressure Units

The units used to measure gas pressure are the same as those used for liquids. The basic SI unit is the newton/metre squared (N/m^2), or, to use its other name, the pascal (Pa). The most common unit of gas pressure used on the ADGAS plant is the bar but the pound/square inch (psi) is also still used.

$$1\text{bar} = 100000 \text{ or } 10^5 \text{ Pa (or } 10^5\text{N/m}^2\text{)}$$

$$1\text{bar} = 14.5038\text{psi}$$

The only pressure unit not commonly used for gas is *metres of head*. Head is only used for liquids because it is convenient to describe pressure by the height the liquid is pumped through.

Gas pressure may be given as

- absolute pressure (bara and psia)—pressure measured above that of a perfect vacuum and used mainly for pressure calculations
- gauge pressure (barg and psig)—pressure measured above atmospheric pressure; the unit shown on most pressure gauges on the plant
- a pressure difference or pressure *differential* (bar and psi) measured as the change in pressure between to parts of a process

2.2 Effects of Pressure on a Gas

The main difference between liquids and gases is that:

- liquids are *incompressible*—pressure has almost no effect on a liquid's volume
- gases are *compressible*—pressure has a great effect on the volume of a gas

There is a law that describes how a change of pressure changes the volume of a gas. You met this law in the *Physics* module in the *Basic Course*. It is called *Boyle's Law* and it says something very simple: as long as the temperature of the gas does not change, increasing the pressure on a gas always decreases its volume. This is probably obvious: a gas is squashed by pressure.

If you **reduce** the pressure on a gas the opposite happens. **Figure 2.1** shows these changes.

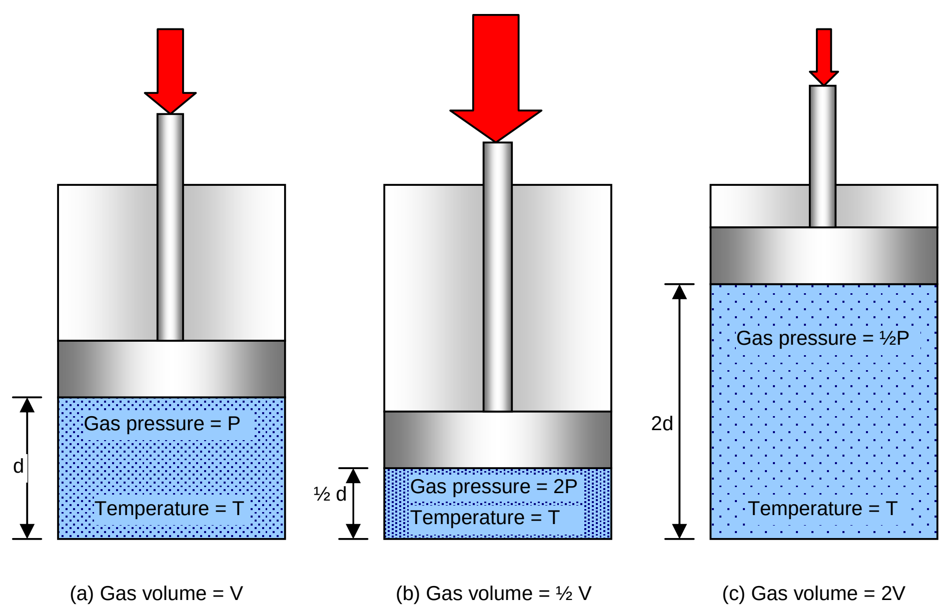


Figure 2.1: Boyles Law

- if you double the pressure, the volume is halved (**Fig. 2.1(a)** to **(b)**)
- if you halve the pressure, the volume doubles (**Fig. 2.1(a)** to **(c)**)

Normally, pressure also has an effect on the temperature of a gas. As you increase the pressure on a gas its temperature also increases.

To give the exact relationship between pressure and volume described by Boyle's Law—doubling pressure halves volume—you have to cool the gas to stop its temperature increasing. In **Figure 2.1**, the gas has to be cooled to get from (a) to (b).

Decreasing pressure has the opposite effect—as the pressure decreases its temperature also decreases. To get from (a) to (c) in the **Figure 2.1** the gas has to be heated.

When gas pressure is increased in a compressor, it can not be kept at the same temperature. As the gas is compressed, its temperature rises. **Figure 2.2** shows how the temperature change affects the volume of a gas. The pressure changes here are the same as those shown in **Figure 2.1**.

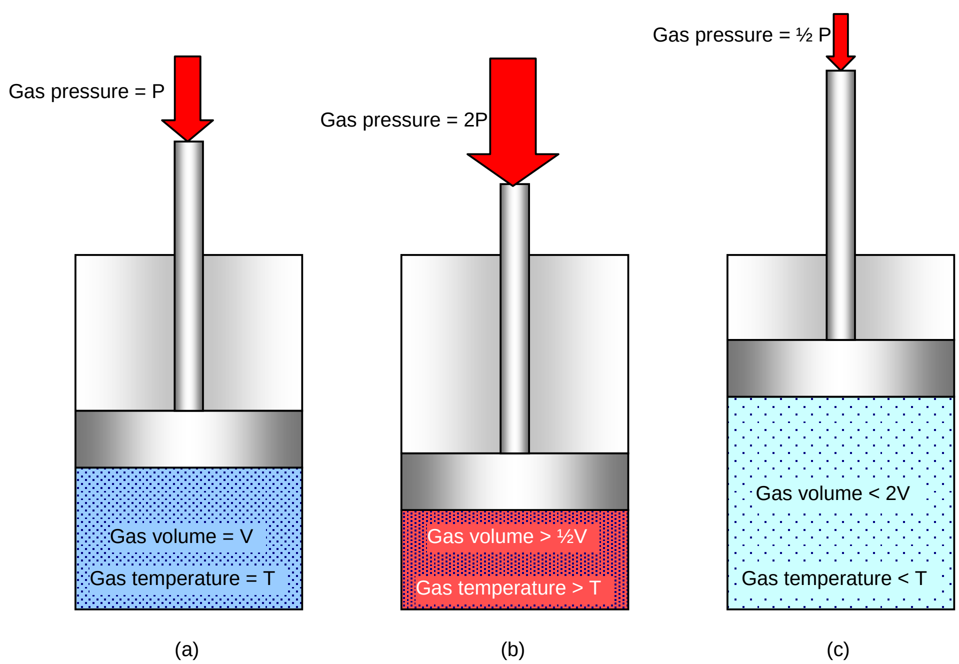


Figure 2.2: Effect of Pressure on Gas Temperature and Volume

In **Figure 2.2(a)** to **(b)**, when the pressure of the gas is doubled, the gas gets hotter (>T) and tries to expand. The volume of the gas is more than it would be if the gas temperature remained constant (>½V).

Decreasing the pressure has the opposite effect. **Figure 2.2 (a)** to **(c)** shows that when the pressure of the gas is halved, the gas gets cooler (<T) and tries to contract. The volume of the gas is less than it would be if the gas temperature remained constant (<2V).

This increase of the gas temperature can be a problem. It can cause a compressor to overheat. Overheating decreases lubricant viscosity and can result in the breakdown of lubricant films in bearings. It also causes expansion of components that may result in damage to bearings, seals, etc.

To liquefy a gas, it is compressed and cooled. The heating effect of compression is a disadvantage in the liquefaction process— the gas needs even more cooling.

2.3 Compression Ratio

The *compression ratio* of a compressor tells us how much the pressure of a gas increase as it travels from the suction to the discharge of the compressor.

$$\text{Compression ratio} = \frac{\text{discharge pressure}}{\text{suction pressure}}$$

2.4 Capacity

The capacity of a compressor is the volume flow rate of gas through the compressor.

This is similar to pump capacity, which is volume flow rate of liquid through a pump. Pump capacity has the SI units of litres/second (l/s)

Compressor capacity is usually given in the SI units of metres cubed/hour (m^3/h).

$$1m^3 = 1000\text{litre}$$

Because gas volume changes as its pressure and temperature change, the volume flow rate must be given for the gas at a fixed pressure and temperature. If not, you would get different capacity values at suction and discharge of the same compressor. ADGAS uses the *standard flow rate* measured in *normal metres cubed/hour* (Nm^3/h) to measure compressor capacity. *Normal* means that the flow rate is calculated after converting the gas volume to what it would be if it was at atmospheric pressure (1.1013bara) and at a temperature of 15^oC.

2.5 Parallel and Series Connections

Compressors can be connected in two ways: parallel and series, just like pumps.

Parallel connection increases the capacity because the gas flowing through each compressor is added together.

Two identical compressors connected in parallel:

- give the same pressure increase as a single compressor
- give double the flow rate (capacity) of a single compressor

Figure 2.3 shows two compressors in parallel.

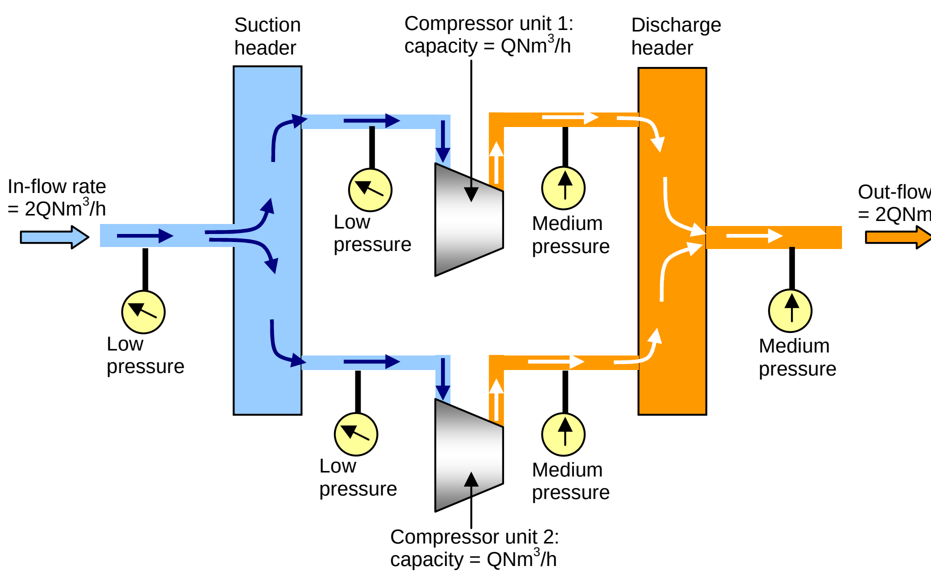


Figure 2.3: Parallel Compressors—Total Capacity 2Q

Notice the symbol used for a compressor. It gets smaller in the direction of flow. This is because the gas volume gets smaller as it passes through the compressor.

The suction ports of compressors in parallel are connected to a *suction header*. Discharge ports are connected to the *discharge header*. These headers may be replaced by *snubbers* (see **Section 4.1.2**) or *knockout drums* (see **Section 6.2**)

Series connection increases the pressure because all the gas is compressed by the first unit, then compressed again by the second.

Two compressors connected in series:

- give a greater pressure increase than a single compressor
- give the same flow rate (capacity) as a single compressor

Figure 2.4 shows two compressors in series.

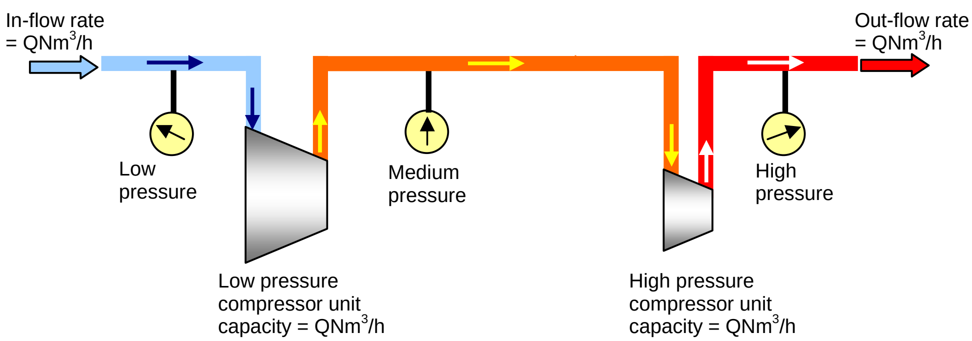


Figure 2.4: Series Compressors—Total Capacity Q

Notice that the high pressure (HP) compressor unit is smaller than the low pressure (LP) unit. This is because the volume of the gas entering the second unit is smaller than that entering the first—it has been compressed.

The compressor units shown in **Figures 2.3** and **2.4** may be separate machines or they may be combined in the same casing.

Compressor units connected in series, as in **Figure 2.4**, are called *stages*. Each compressor stage increases the gas pressure.

When compressors are connected in parallel, it is possible to stop one of them and maintain flow through the others. This is useful if full capacity is not always wanted, if one compressor unit develops a fault or when routine maintenance is needed.

When compressors are connected in series, all flow stops as soon as any one compressor stops.

3 Classification of Compressors

Compressors are classified in the same way as pumps. The chart in **Figure 3.1** shows the most common types. Compressors that are not used on the ADGAS plant are shaded in grey.

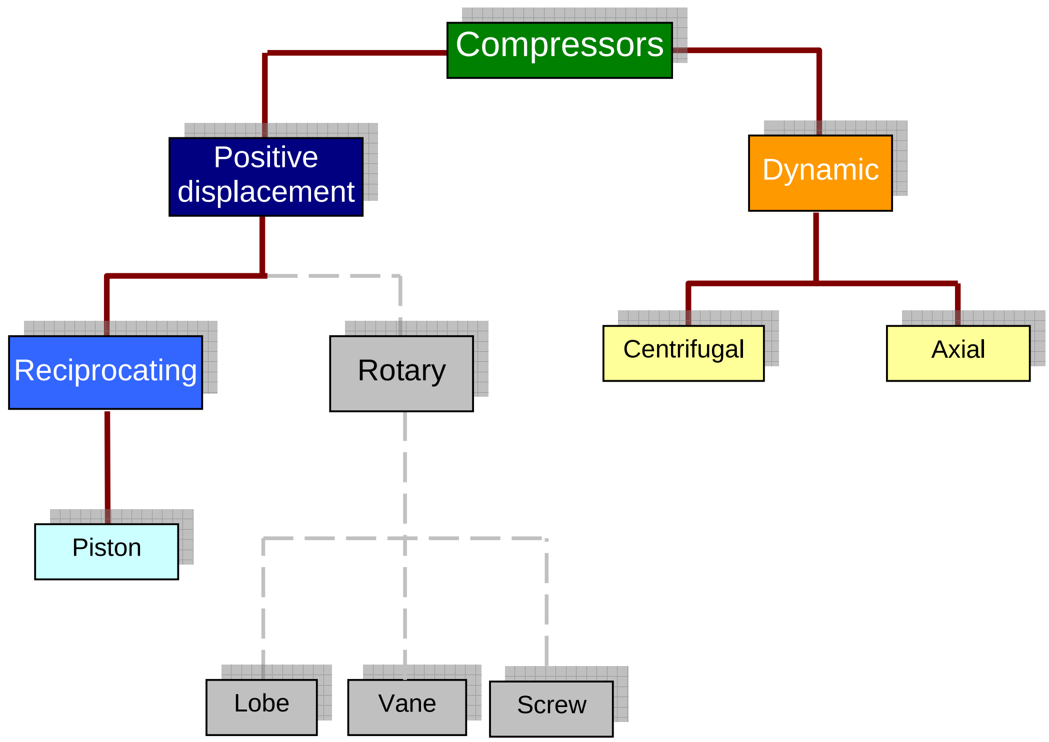


Figure 3.1: Compressor Classification Chart

The same two main groups are used for compressors as for pumps:

- positive displacement
- dynamic

ADGAS does not use rotary compressors on the plant and axial compressors are only found in the gas turbine used for electrical power generation.

Now try **Exercise 1**

4 Positive Displacement Compressors

Positive displacement compressors include those shown in that part of the classification chart repeated in **Figure 4.1**.

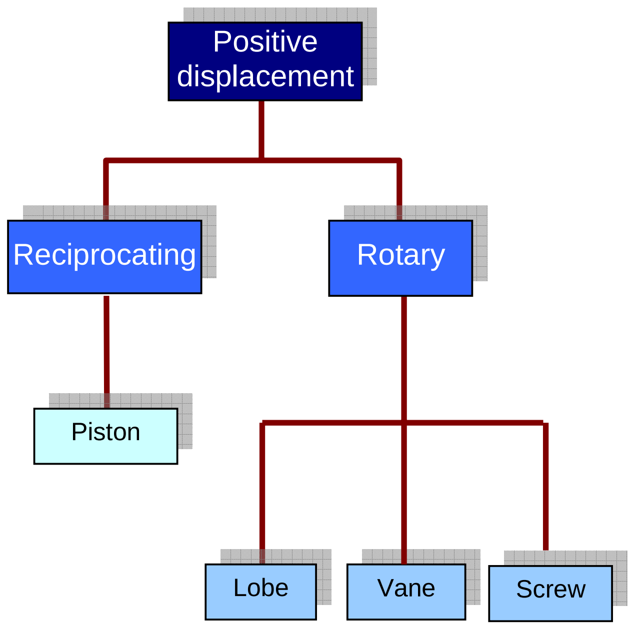


Figure 4.1: Positive Displacement Compressors

All positive displacement compressors draw in a volume of gas that depends on the size of the *fluid chamber*. They trap this gas in a space formed between the *compressing element*, a piston or rotor, and the compressor casing. The gas volume is reduced and its pressure increased. It is then displaced by the compressing element as it is pushed out of the discharge port.

Although the volume of gas discharged is less than the volume entering from the suction port, because the capacity is measured *as if the pressure and temperature were fixed at 1.1013bara and 15^{o}C*, the capacity of these compressors depends only on their size and speed.

Positive displacement compressors do not give a steady discharge of gas.

They are usually driven by electric motors, directly or through a gearbox.

4.1 Reciprocating Compressors

Most reciprocating compressors are piston-type. Piston compressors are very similar to piston pumps in their basic design.

ADGAS uses piston reciprocating compressors to:

- supply instrument and service air for the Sulphur STOREX area
- supply emergency instrument air for all other plant
- compress vapour that evaporates off the liquefied gas held in storage tanks in the STOREX area

Vapour from the LNG tanks is called *boil-off gas* (BOG). This is compressed in one of the two *BOG compressors* and used as *fuel gas* on the plant.

Vapour from the C_3 (propane) LPG tanks is compressed in the *vapour recovery unit* (VRU) compressor before cooling and converting back to liquid.

Figure 4.2 shows one of the two air compressors in the Sulphur STOREX area.

Figure 4.2: STOREX Air Compressor (Tag# 28-K-70)

4.1.1 Single- and Double-acting Compressors

Reciprocating compressors can have single- or double-acting cylinders. The principle of operation of these two arrangements is exactly the same as for pumps. **Figure 4.3** shows a single-acting compressor with the main components labelled.

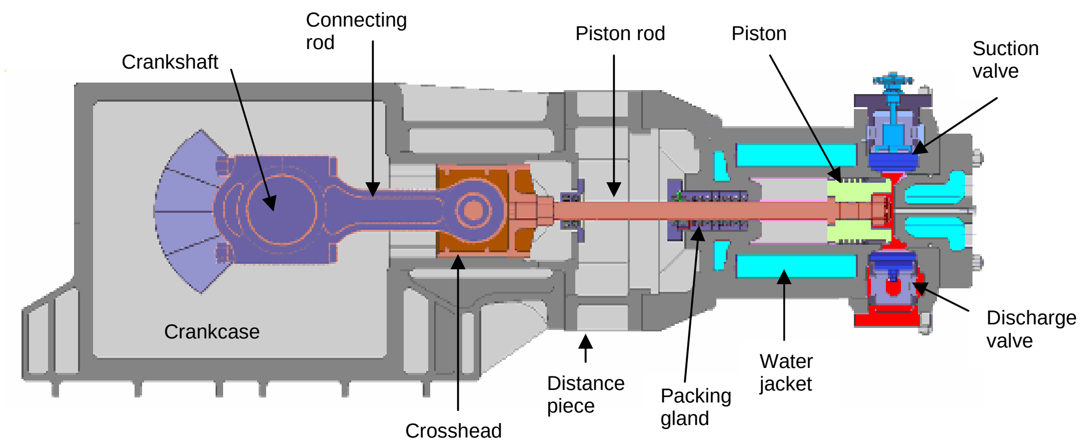


Figure 4.3: Single-acting Reciprocating Compressor

The single-acting compressor discharges gas on every second stroke, as the piston moves away from the crankshaft. This gives a pulsating flow.

The section drawing in **Figure 4.3** shows the piston at top-dead-centre—the piston is as far to the right as it can go. The compressor shown is a horizontal unit with the cylinder axis horizontal. It is also cooled by water and the cylinder has a water jacket around it.

The main components of a piston compressor are very similar to those of a piston pump.

Figure 4.4 shows a similar compressor but this one is double-acting.

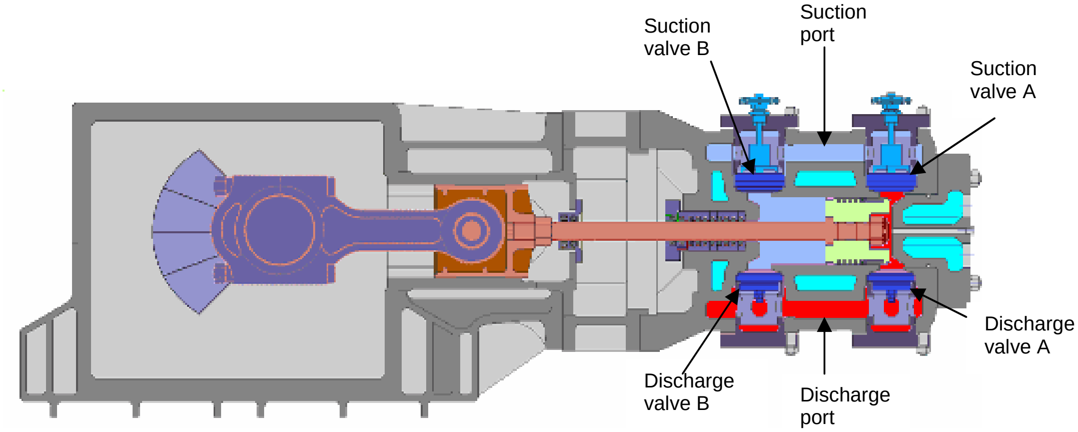


Figure 4.4: Double-acting Reciprocating Compressor

The double-acting compressor discharges gas on every stroke:

- As the piston moves away from the crankshaft (to the right in the figure) gas discharges from discharge valve A.
- As the piston moves towards the crankshaft (to the left in the figure) gas discharges from discharge valve B.

This still gives a pulsating flow but it is smoother than the discharge from a single-acting machine.

4.1.2 Snubbers

To reduce pulsations and to provide a more continuous flow from the discharge, pulsation dampeners or *snubbers* are fitted in the discharge and suction lines. These are large drums that do the same job as the pulsation dampener and suction stabiliser used with reciprocating pumps. **Figure 4.5** shows the suction and discharge snubbers on a large reciprocating compressor.

Figure 4.5: Suction and Discharge Snubbers—Two Cylinders in Parallel

Where more than one cylinder is connected in parallel, the snubber can also act as a header as shown in **Figure 4.5**.

4.1.3 Cylinder Arrangements

The simplest reciprocating pump has a single cylinder. This may have its axis horizontal, as shown in **Figures 4.3** and **4.4** or vertical, as shown in **Figure 4.6**.

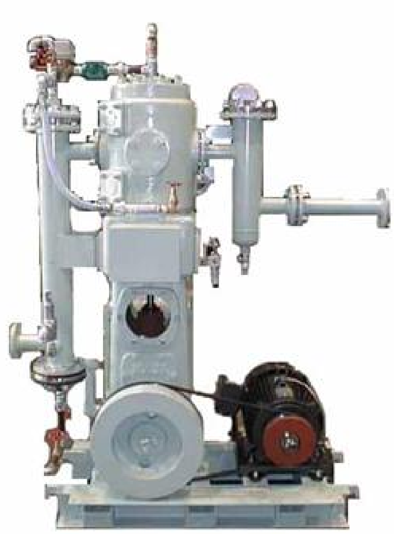


Figure 4.6: Small Vertical Compressor

Multi-cylinder compressors have more than one cylinder. Each cylinder has its own piston, piston rod, crosshead, connecting rod and valves, just like a single-cylinder compressor. These moving parts are operated by the same crankshaft. The cylinders may be arranged in a number of different ways:

- in-line (vertical or horizontal)
- balanced-opposed
- L-type (or angle-type)
- V-type
- W-type

In-line compressors have two or more cylinders mounted side-by-side. All cylinders are located on the same side of the crankshaft. These can be designed to operate vertically or horizontally. **Figure 4.7** shows a small two-cylinder, in-line compressor with pistons driven directly from the connecting rods (without crossheads).

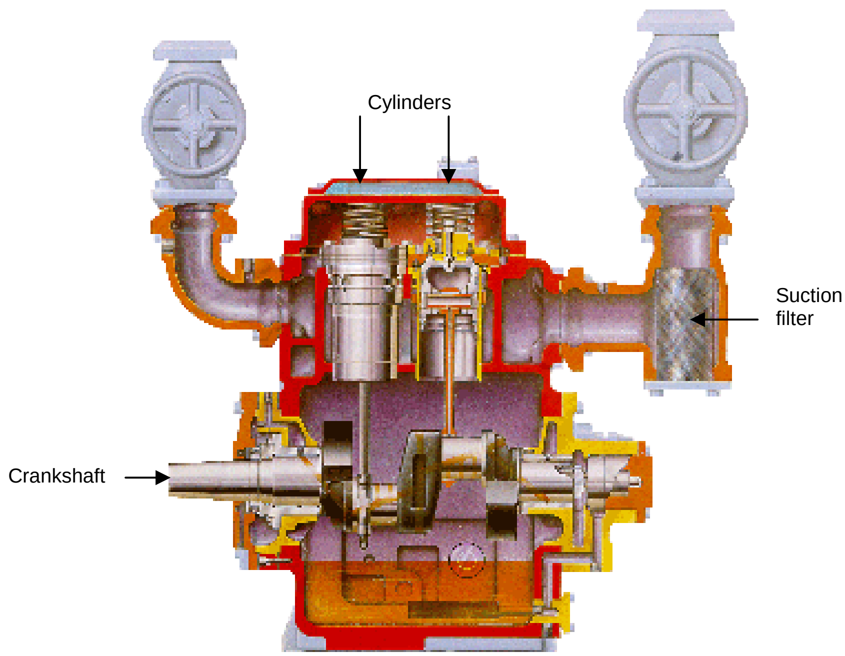


Figure 4.7: Two-cylinder, In-line Vertical Compressor

Balanced-opposed compressors have horizontal cylinders located on opposite sides of the crankshaft as shown in **Figure 4.8**.

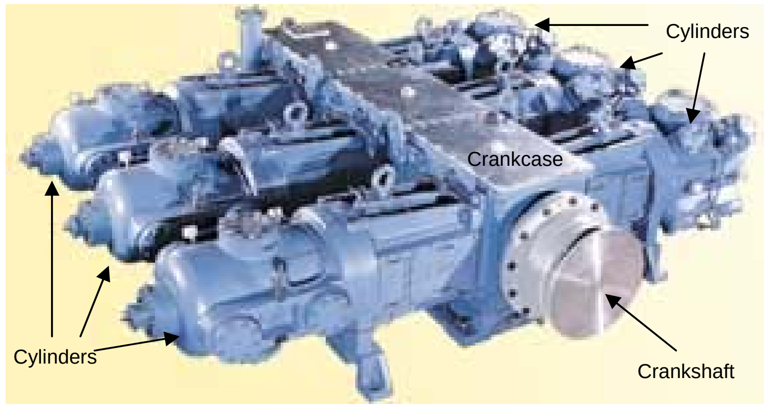
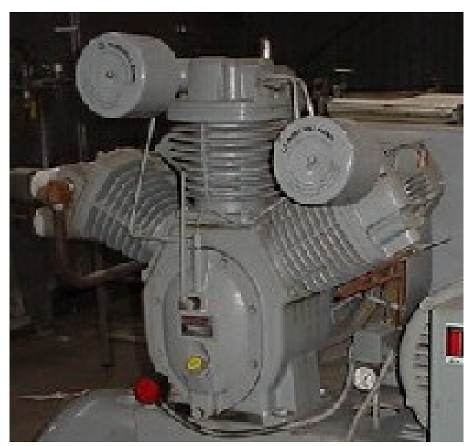


Figure 4.8: Six-cylinder, Balanced-opposed Compressor

With pistons moving in opposite directions there is less vibration and the compressor is better balanced. There are always an equal number of cylinders on each side of the crankshaft. Most ADGAS reciprocating compressors are balanced-opposed.

Figure 4.9 shows two of the other cylinder arrangements listed. An L-type or angle compressor is shown in **Figure 4.12** in the next section.

(a) V-type Two Cylinder



(b) W-type Three Cylinder

Figure 4.9: Compressor Cylinder Arrangements

The compressors shown in **Figure 4.9** are cooled by air flowing around fins on the cylinders. This method of cooling is often used for small compressors.

Cylinders of the same size can be connected in parallel, to increase capacity.

4.1.4 Multi-staging

Compressor cylinders connected in series increase pressure in stages. The size of each cylinder must be different. The lower pressure cylinders are bigger than higher pressure cylinders. This is because the same quantity of gas has a bigger volume at low pressure and a smaller volume at high pressure. **Figure 4.10** shows the change of volume of a gas as it passes through a two-stage compressor.

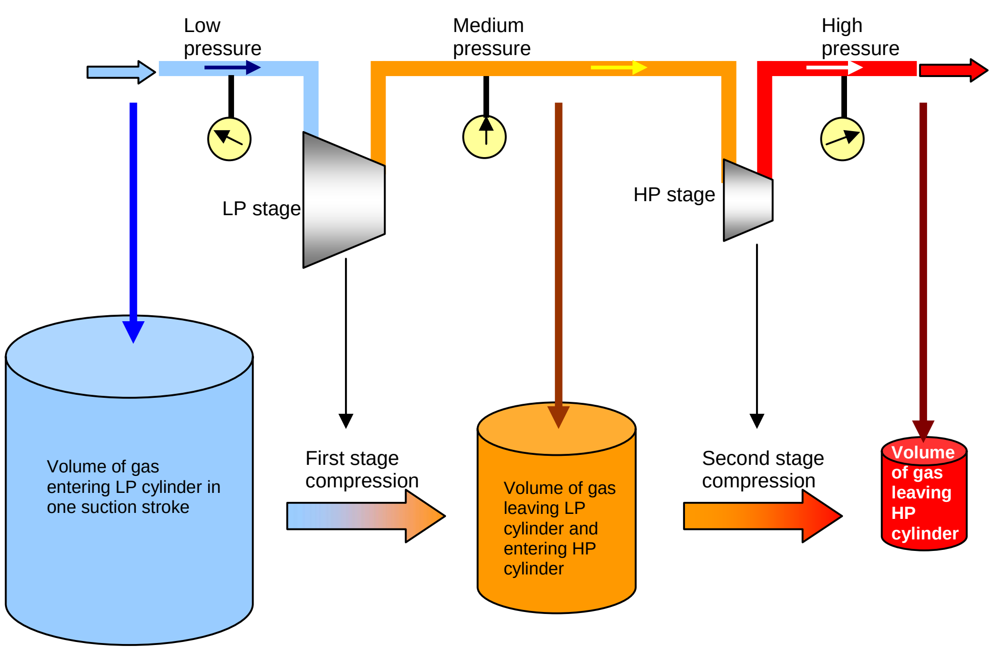


Figure 4.10: Changes of Gas Volume during Two-stage Compression

You can tell if the cylinders of a compressor are acting in parallel, to give extra capacity, or in series, to give low- and high-pressure stages by:

- tracing the gas path to see how they are connected
- looking at the cylinder size to see if there are big LP, or smaller HP stages

Figure 4.11 shows a section through a two-cylinder, two-stage, in-line reciprocating compressor.

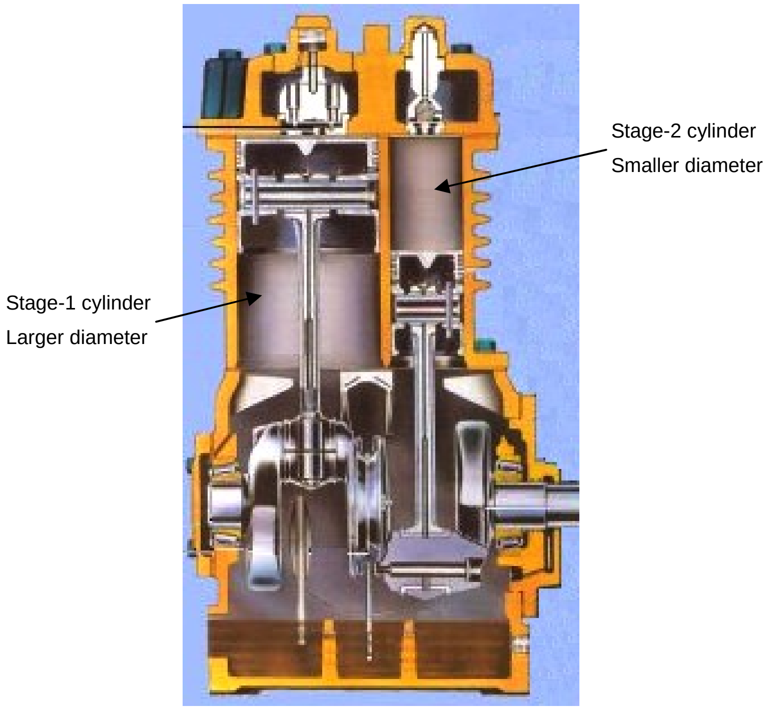


Figure 4.11: Two-stage In-line Compressor

In **Figure 4.12** you can see a two-stage angle, or L-type compressor. Notice the connection from the first-stage cylinder to the second and the sizes of the two cylinders.

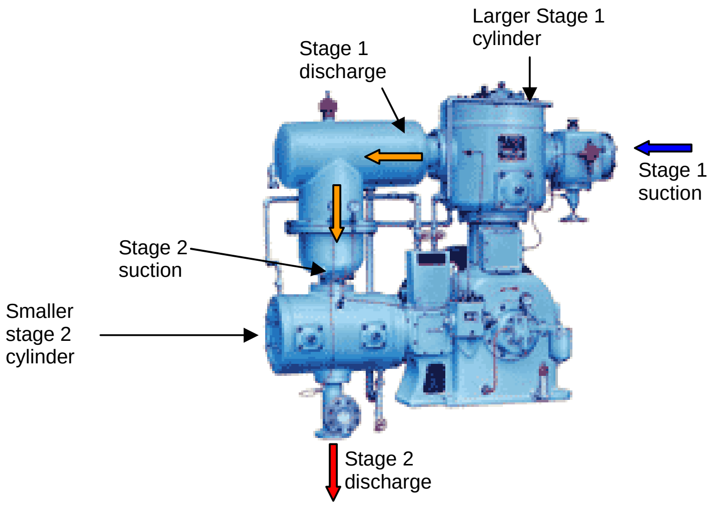


Figure 4.12: Two-stage L- or Angle-type Compressor

Some multi-cylinder compressors have some cylinders connected in parallel and some in series. In **Figure 4.13** you can see a large two-stage balanced-opposed compressor. The two cylinders on one side of the crankshaft are connected in parallel by a snubber to form the first stage. The gas then passes to the two cylinders on the opposite side of the crankshaft—a series connection. These two cylinders, also connected together in parallel by a discharge snubber, are the second stage.

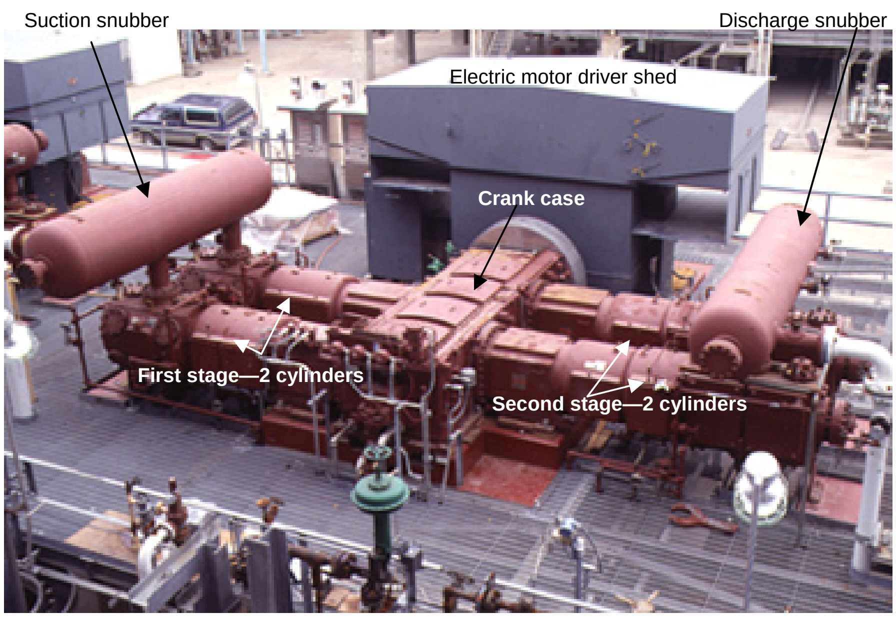


Figure 4.13: Balanced-opposed, Two-stage, Four-cylinder Compressor

The cylinders of large, multi-cylinder compressors are often separate units attached to a common crank case. You can see the four separate cylinder casings in **Figure 4.13**. This compressor may be described as having four *casings* instead of four cylinders. The balanced-opposed compressor shown has two first-stage casings and two second-stage casings.

The compressor shown in **Figure 4.12** has two casings: one low-pressure first stage and one high pressure second stage.

4.1.5 ADGAS Reciprocating Compressors

Most of the reciprocating compressors on the ADGAS plant are double-acting, multi-stage units.

Instrument and service air for the Sulphur STOREX area is supplied by two compressors.

These compressors are:

- balanced-opposed
- two-stage
- two-cylinder (two casings)
- double-acting

The two cylinders are connected in series as shown in **Figure 4.14**.

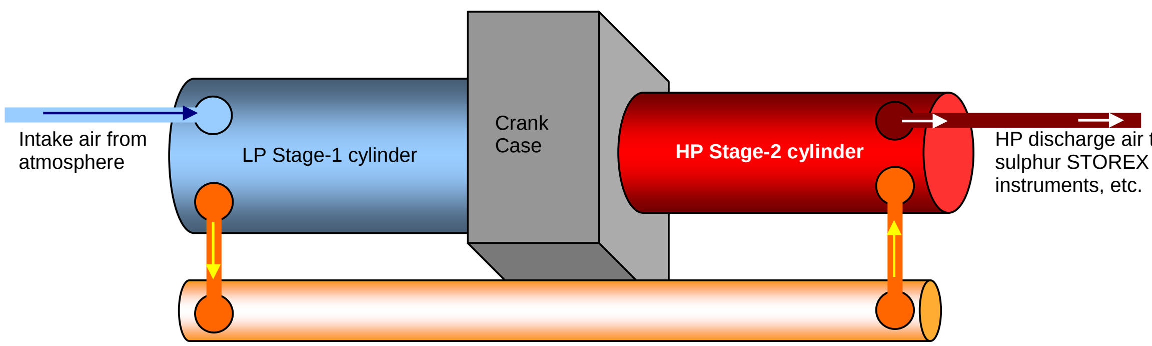


Figure 4.14: Cylinder Configuration of Sulphur STOREX Air Compressors

In **Figure 4.15** you can see one of these compressors at the front of the picture. The other identical compressor is at the back of the picture. These compressors are driven by electric motors.

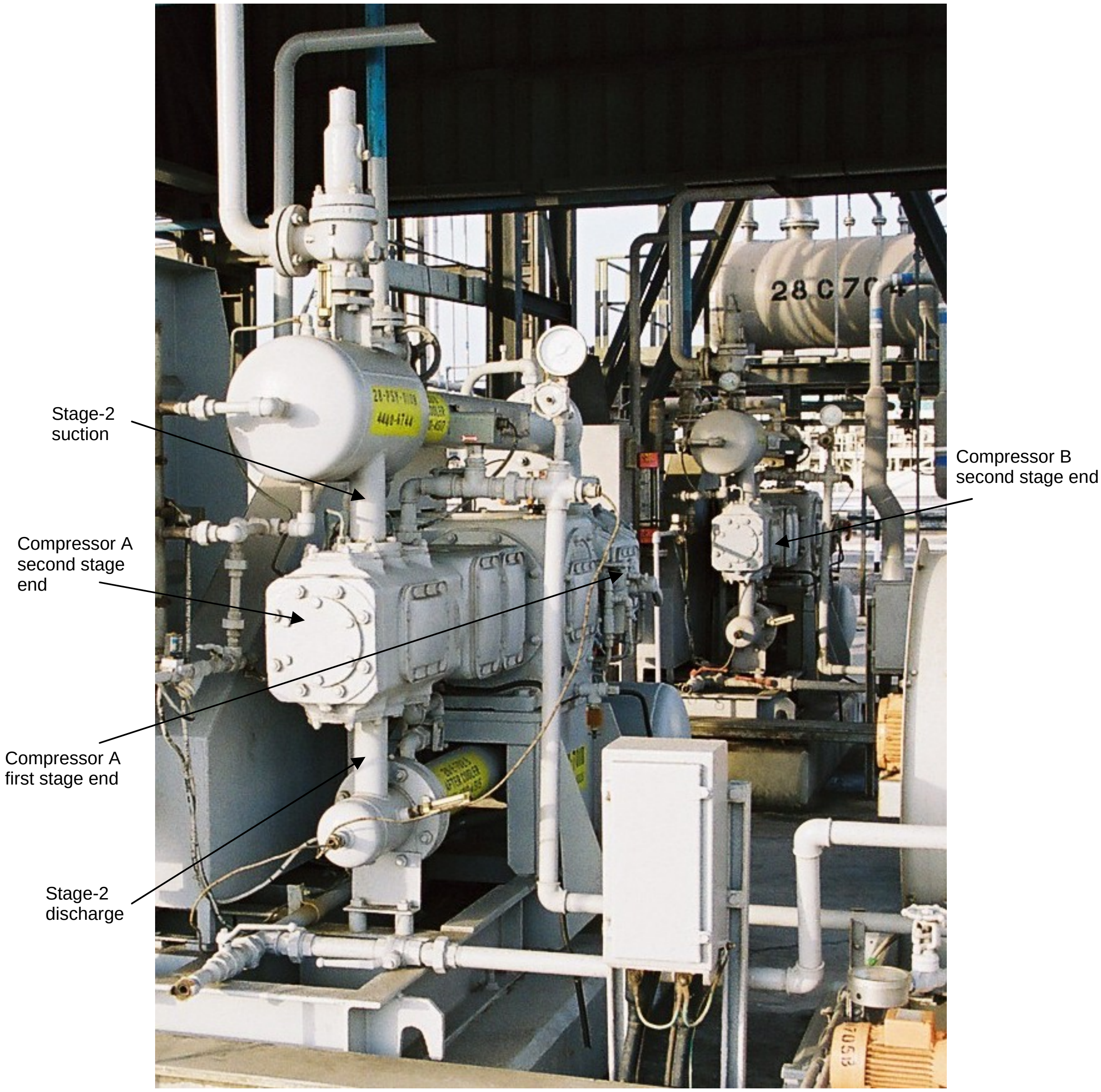
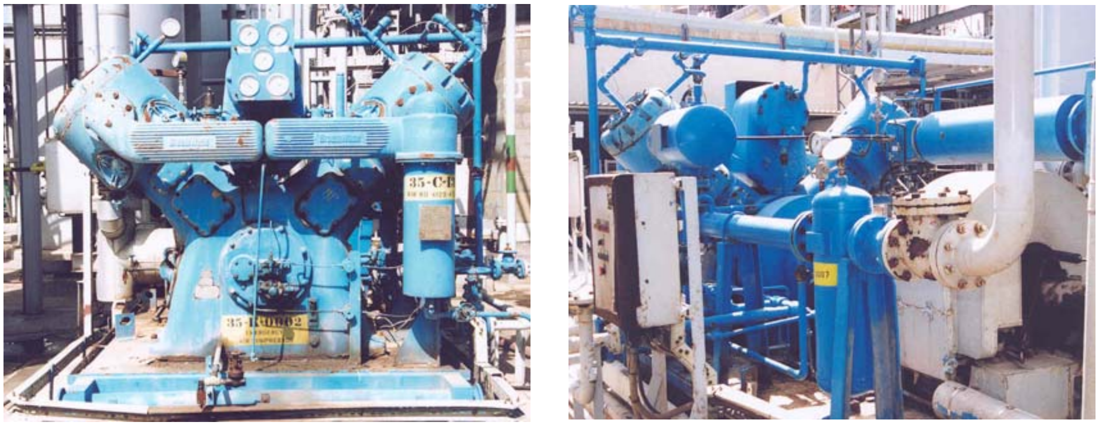


Figure 4.15: Sulphur STOREX Instrument Air Compressors (Tag# 28-K-701 A and B)

Emergency instrument air for all other plant is supplied by a two-cylinder, two-stage V-type compressor. This compressor is part of the Utilities Air Plant and is driven by a steam turbine. **Figure 4.16** shows two views of this compressor.



(a) V-type Reciprocating Compressor—Front View

(b) V-type Reciprocating Compressor—Rear View

Figure 4.16: Emergency Air Compressor (Tag# 35-K-2)

There are other small V-type compressors in the Nitrogen and Firewater Plants. **Figure 4.17**: Shows the compressor used for diesel engine start-up in the Firewater Plant.

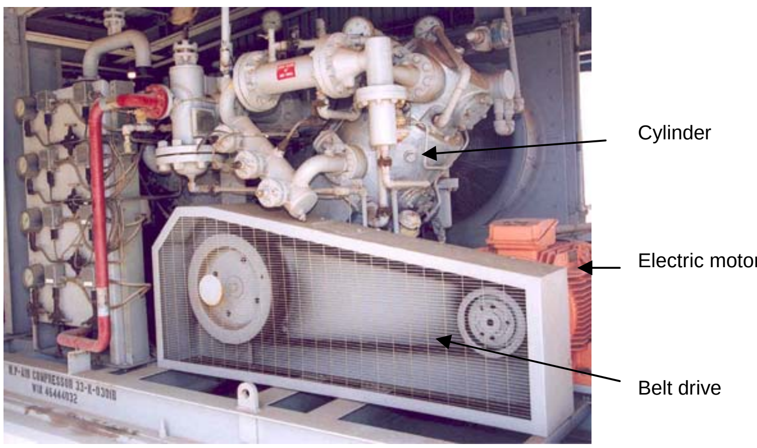


Figure 4.17: Air Compressor for Diesel Start-up (Tag# 33-K 301B)

Boil-off gas (BOG) compressors in the STOREX area take vapour from the top of the LNG tanks. This vapour (gas) is removed to help maintain the correct operating pressure inside the tanks during filling and emptying operations. Before the BOG compressors were installed the boil-off gas was all sent to flare. The BOG compressors help to save money by using this gas. They also reduce pollution by reducing the amount of gas going to flare.

There are two BOG compressors, known as the 'Old' BOG (Tag# 27-K-103) and the 'New' BOG (Tag# 48-K-301). Both are driven by electric motors.

Gas from the New BOG compressors is used as fuel gas in Train III boilers and gas from the Old BOG goes to fuel heaters in Trains I and II regeneration equipment.

The Old BOG compressor is:

- in-line vertical
- three-stage
- four-cylinder (four casings)
- double-acting

There is one crankshaft housed in a single crank case. This crankshaft operates all four pistons. The four cylinders are housed in four separate casings and are connected so that:

- two stage-1 cylinders are connected in parallel
- stage-2 and stage-3 cylinders are connected in series with the stage-1 cylinders

This arrangement is shown in **Figure 4.18**.

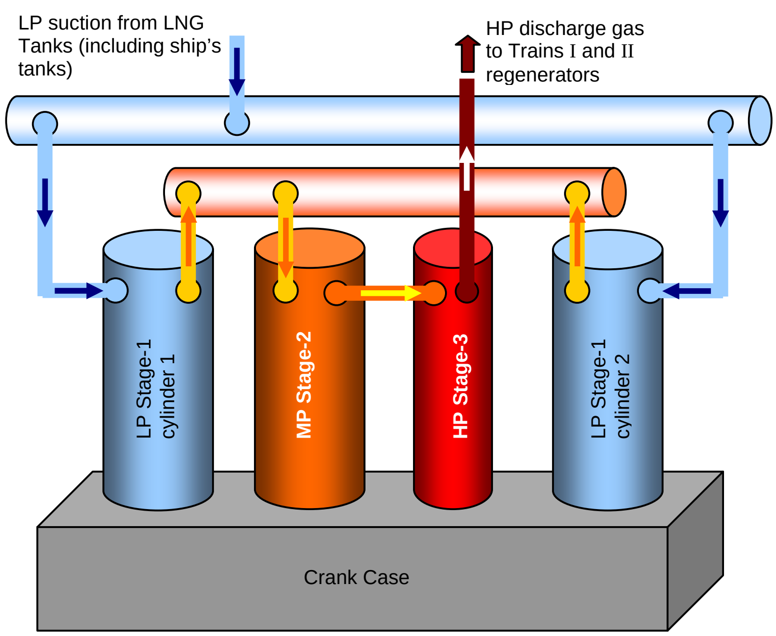


Figure 4.18: Cylinder Configuration of Old BOG Compressor

The New BOG compressor is:

- balanced-opposed
- two-stage
- six-cylinder (six casings)
- double-acting

There is one crankshaft housed in a single crank case. This crankshaft operates all six pistons. The six cylinders are housed in six separate casings:

- three stage-1 cylinders are connected in parallel
- three stage-2 cylinders are connected in parallel
- stage-1 cylinders are connected in series with stage-2 cylinders

This arrangement is shown in **Figure 4.19**.

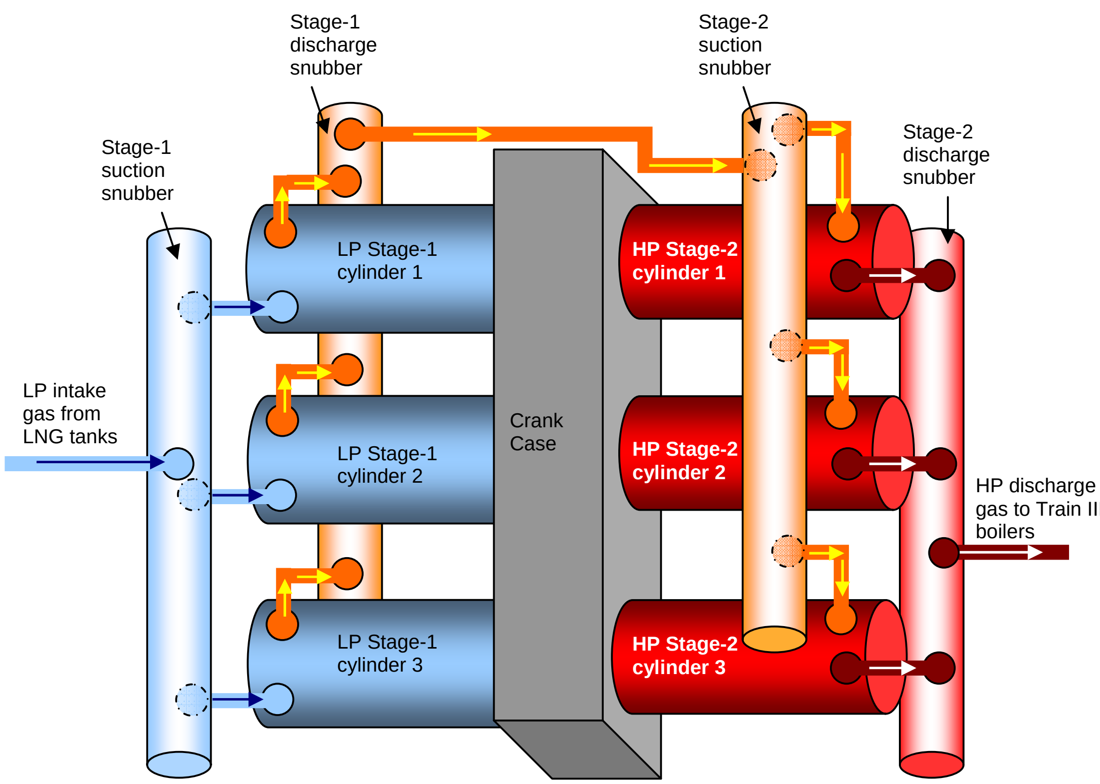
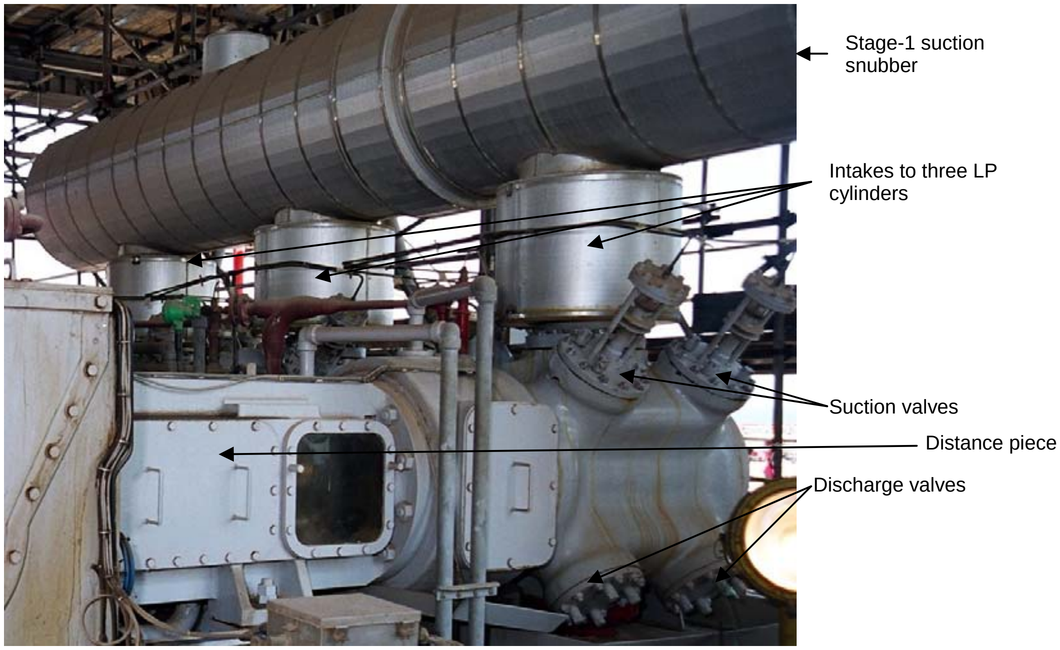
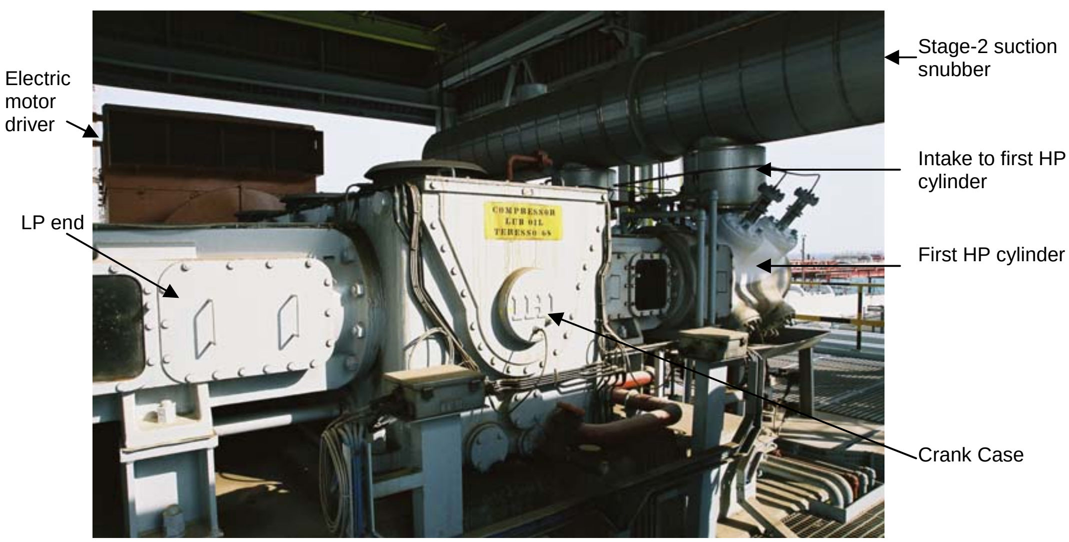


Figure 4.19: Cylinder Configuration of New BOG Compressor

Figure 4.20(a) shows stage 1 and **Figure 4.20(b)** shows stage 2 of the New BOG compressor.



(a) First-stage End Showing Intakes to Three LP Cylinders



(b) Second-stage, HP end

Figure 4.20: New BOG Compressor
(Tag# 48-K-301)

Vapour recovery unit (VRU) compressors in the STOREX area take vapour from the top of the propane tanks. They help maintain the correct pressure inside the propane tanks during filling and emptying operations. They also reduce the wastage of gas and pollution, like the BOG compressors.

There are two identical VRU compressors. They are:

- balanced-opposed
- three-stage
- four-cylinder (four casings)
- double-acting

The four cylinders are connected so that:

- two stage-1 cylinders are connected in parallel
- stage-2 and stage-3 cylinders are connected in series with the stage-1 cylinders

This arrangement is shown in **Figure 4.21.**

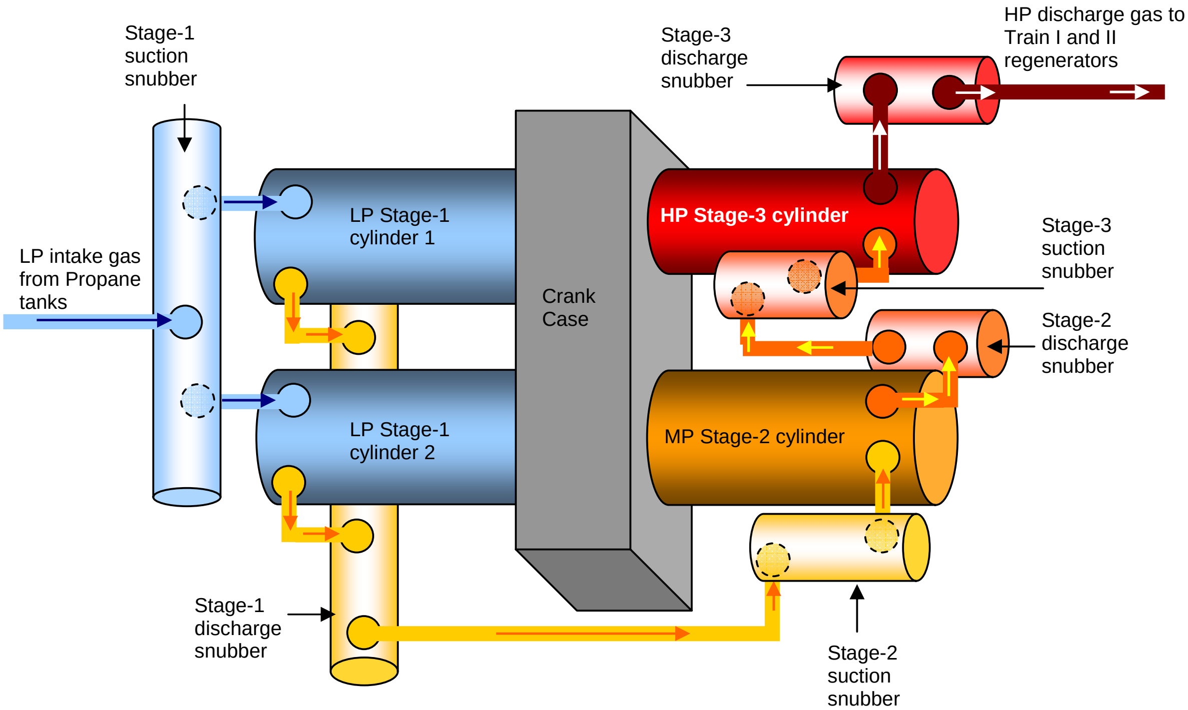


Figure 4.21: Cylinder Configuration of VRU Compressors

Figure 4.22 shows one of the VRU compressors.

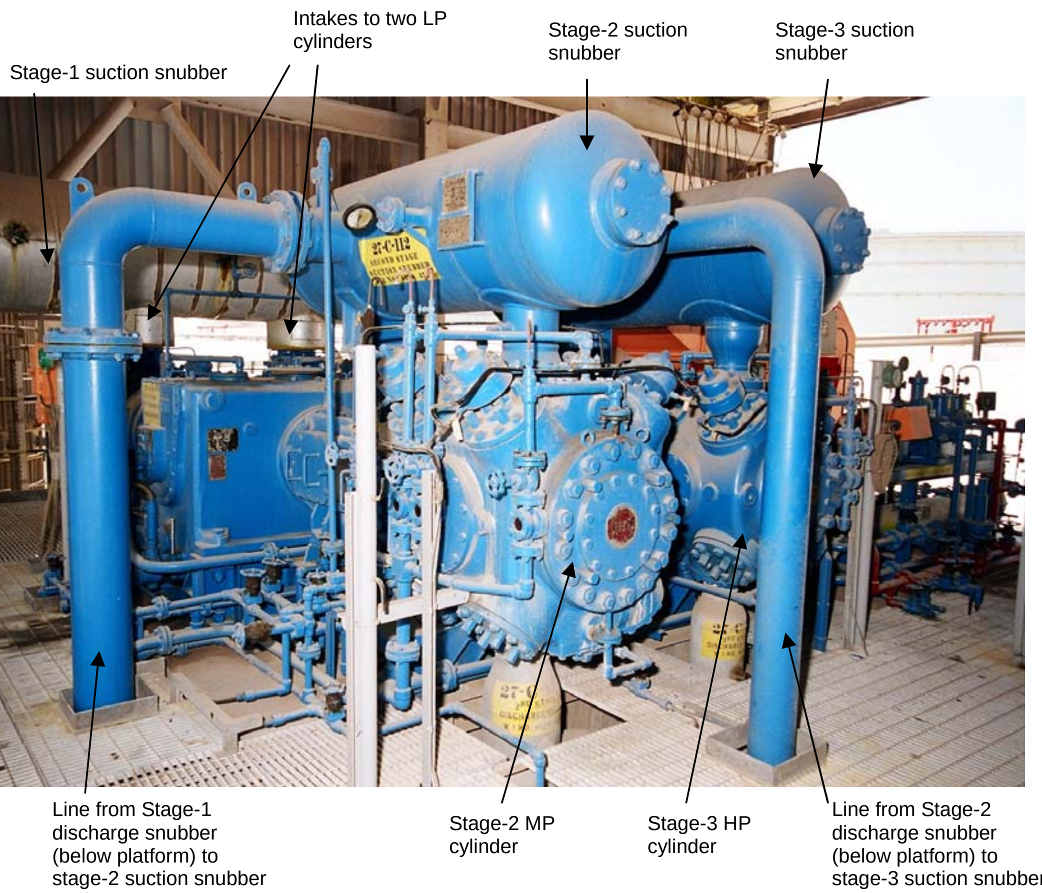


Figure 4.22: VRU Compressor
Tag# 27-K-101

Of the reciprocating compressors described in this section, only the emergency instrument air compressor (Tag# 35-K-0002) is driven by a steam turbine. All the others are driven by electric motors.

Now try **Exercise 2**

4.1.6 Valves

Compressor valves control the flow of gas into and out of the compressor cylinder. They are check-valves as they allow flow in one direction only.

There are three main types:

- poppet valves
- disc valves
- channel valves

Springs hold the moveable parts (poppets, discs or channels) closed against valve seats. The pressure difference that causes gas to flow into or out of the cylinder opens the valve by pushing against the springs.

The greater the valve *lift*, the lower the friction loss as gas flows through the valve and the more efficient the valve is.

The smaller the valve lift, the more reliable and the less maintenance needed.

Poppet valves are the most expensive but the most efficient valves. They are often used for high-capacity applications.

The closing elements are small circular plugs (poppets). They are held normally-closed by coil springs as shown in **Figure 4.23**.

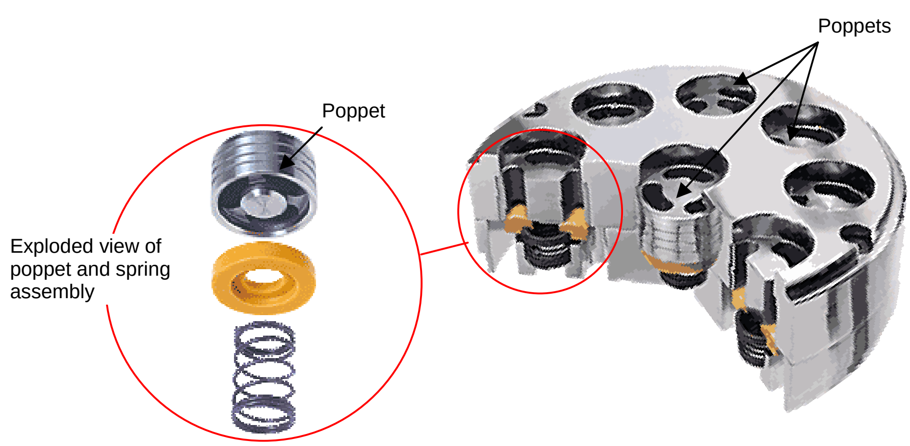


Figure 4.23: Poppet Valve

Gas pressure pushes on both sides of the valve. It pushes on the poppets with a force given by: force = pressure x area

Figure 4.24 shows the forces acting on a compressor valve.

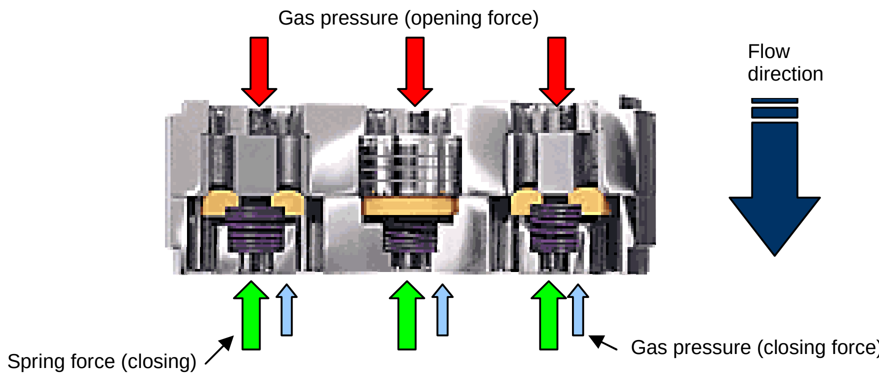
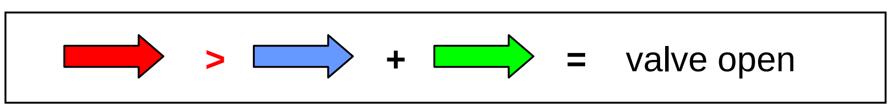
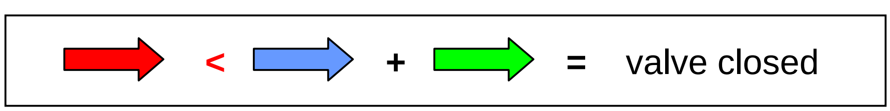


Figure 4.24: Forces Acting on a Valve

When the gas force on the opening side is greater than the gas force on the closing side, plus the spring force, the valve opens.



When the gas force on the opening side is less than the gas force on the closing side, plus the spring force, the valve closes.

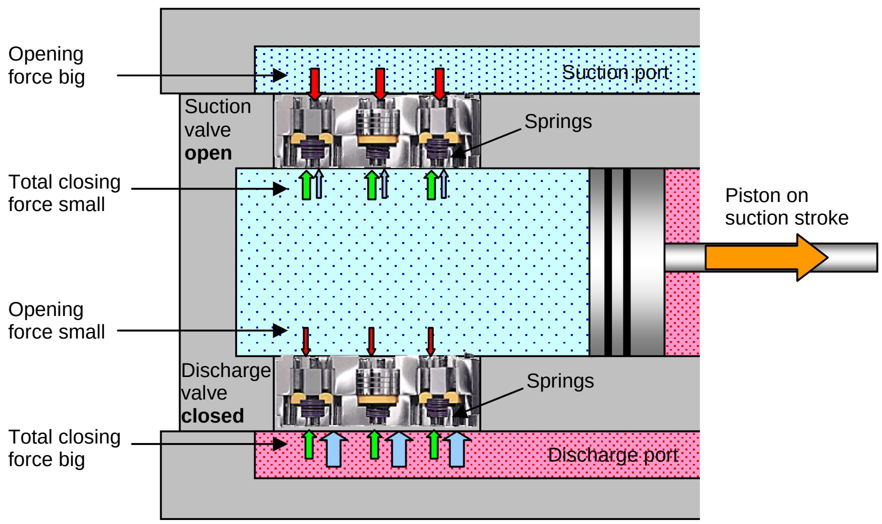


Flow through the valve is always in the direction that pushes the valve open against the springs.

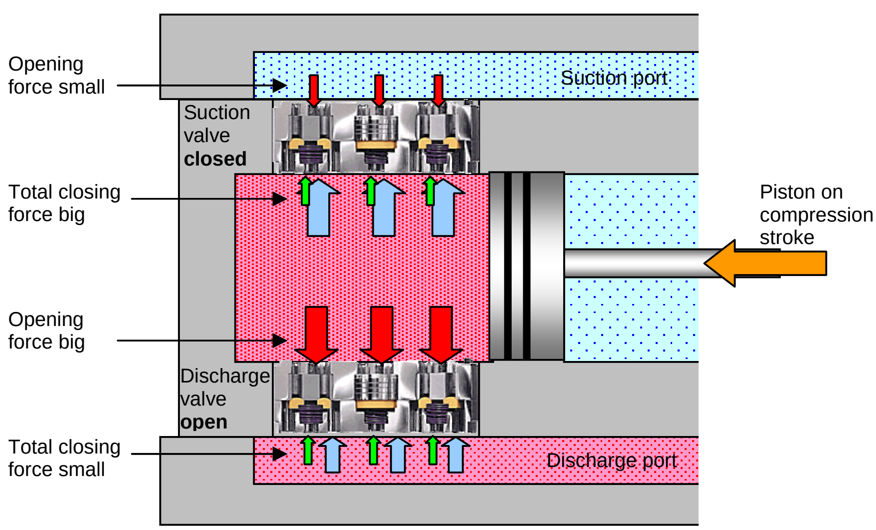
- The suction valve allows flow into the cylinder when the springs compress.
- The discharge valve allows flow out of the cylinder when the springs compress

The suction valve opens when gas force in the suction port is greater than the gas force in the cylinder plus the spring force. This happens when the piston is on the suction stroke—when suction port pressure exceeds cylinder pressure.

The discharge valve opens when gas force in the cylinder is greater than the gas force in the discharge port plus the spring force. This happens when the piston is on the compression stroke—when cylinder pressure exceeds discharge port and suction port pressure. **Figure 4.25** shows forces on the valves during the suction and compression stroke.



(a) Suction stroke—Gas enters cylinder through open suction valve



(b) Compression stroke—Gas leaves cylinder through open discharge valve

Figure 4.25: Valve Operation

Plate, disc or ring valves are used for high-pressure applications. They work in a similar way to poppet valves but the closing elements are circular rings (the 'discs'). They open when the gas pressure difference provides a force greater than the spring force as shown in **Figure 4.26**.

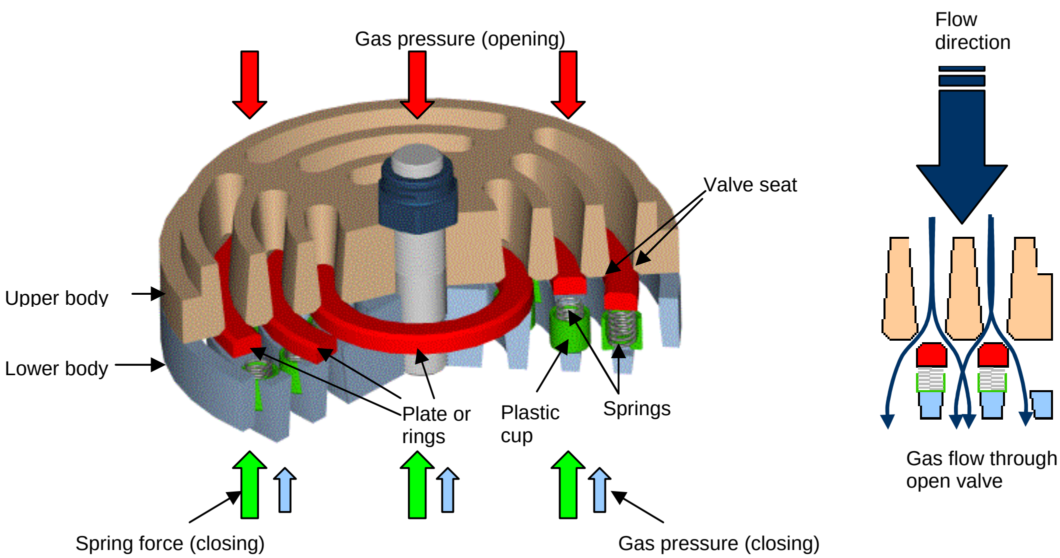


Figure 4.26: Disc Valve

Gas entering through the upper body forces the valve discs down against springs. The gas then passes between the valve discs and the valve seats and out through the lower valve body, as shown to the right of **Figure 4.26**.

The springs are located in plastic cups. This stops any pieces of broken spring entering the cylinder if the spring breaks.

The rings may be joined together, as shown in **Figure 4.27(a)** or separate, as shown in **Figure 4.27(b)**.

(a) Joined Rings

(b) Separate Rings

Figure 4.27: Valve Rings

Strip or channel valves are the cheapest and most common for standard applications. The closing elements are *channel-section* strips that are held normally-closed by *leaf springs*. **Figure 4.28** shows an exploded view of a channel valve.

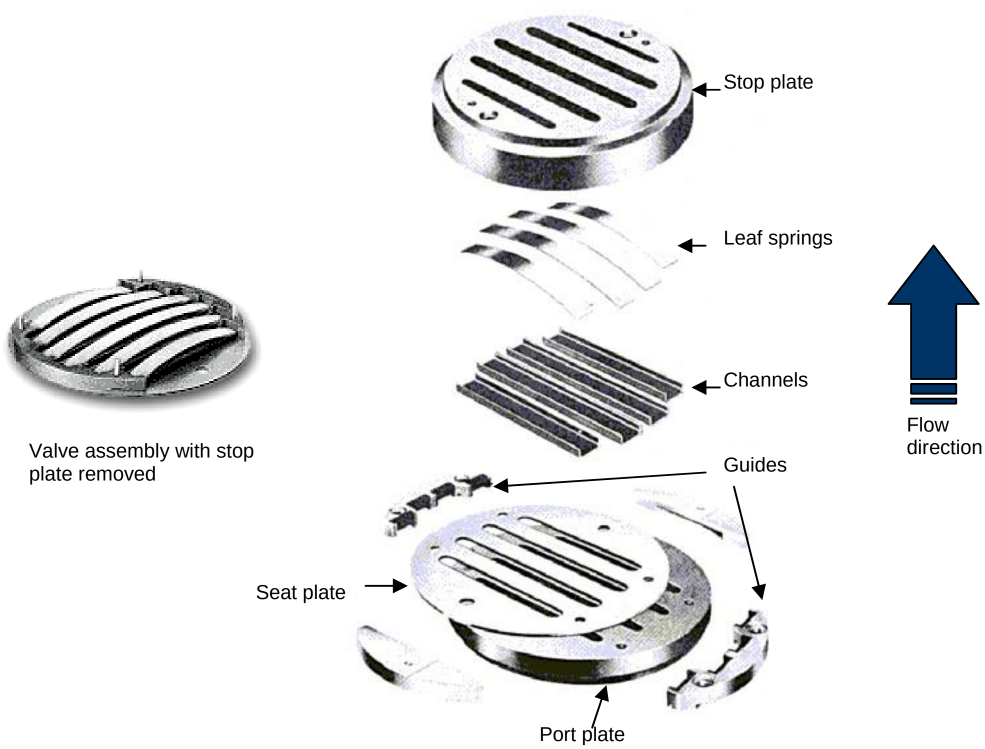


Figure 4.28: Channel Valve

The port plate and the seat plate fit together with their openings lined up. The channels fit over these openings and are held down against the seat plate by the leaf springs. The springs fit inside the channels and are held in place by the stop plate.

Gas enters through the port plate and pushes the channels up off the seat plate against the springs. It then passes out through the openings in the stop plate. Strips of self-lubricating material in the channels stop metal-to-metal contact between the channels and the valve springs.

4.1.7 Unloading Mechanisms

Reciprocating compressors can have very high compression ratios. They can continue to discharge gas until the pressure is high enough to stop the driver or until something breaks. Pressure safety valves (PSVs) are fitted to protect equipment on the discharge side from overpressure and possible damage.

PSVs are not meant to control discharge pressure during normal operating conditions.

Changing the speed of the compressor driver changes the compressor output. But all compressor drivers on the ADGAS plant are designed to operate at constant speed.

Unloaders control the discharge pressure to meet the operating requirements of the plant. They do this by holding one or more of the suction valves open. The gas at suction pressure then passes freely in and out of the cylinder through the open suction valve. No gas is compressed in that cylinder. This has two effects:

- reduces the capacity of the compressor so that it discharges less gas into the system, maintaining normal operating pressure
- reduces the load on the compressor driver

The second effect is useful during compressor start-up. One or more valve unloaders hold suction valves open to reduce the load on the driver until it reaches full speed. **Figure 4.29** shows unloaders on one of the New BOG compressors.

Figure 4.29: Unloaders on New BOG Compressor

Some unloaders are manually operated.

Automatically controlled unloaders are pneumatically operated. Sensors monitor discharge pressure and activate one or more unloaders as soon as it exceeds the set point. Control air acts on a diaphragm that operates a rod. A set of fingers on the end of the rod push the valve against its spring pressure, holding it open. **Figure 4.30** shows a pneumatically controlled unloader.

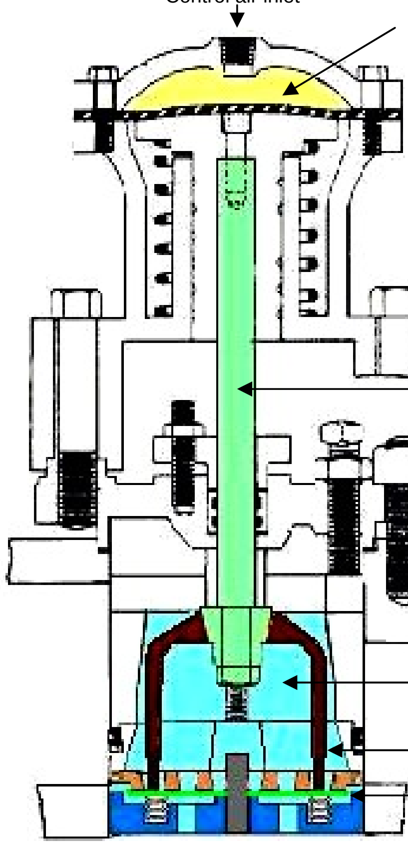


Figure 4.30: Pneumatically-activated Compressor Unloader

Now try **Exercise 3**

4.2 Rotary Compressors and Blowers

At the time of writing this module there are no rotary compressors in the ADGAS plant. They are described briefly here as they are quite common in other places.

Rotary compressors with low compression ratios are often called *blowers*.

The three most common rotary compressors are in that part of the classification chart repeated in **Figure 4.31**.

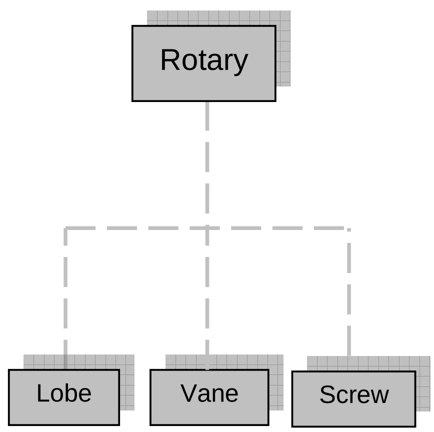


Figure 4.31: Common Rotary Compressors

They are all very similar in appearance and operation to the pumps that have the same name.

4.2.1 Lobe Compressors

Lobe compressors are also called *Roots blowers*. Two or more lobes rotate inside a housing. There are very small clearances between the lobes, and between lobes and housing. **Figure 4.32** shows a two-lobe blower with the rotor directions indicated.

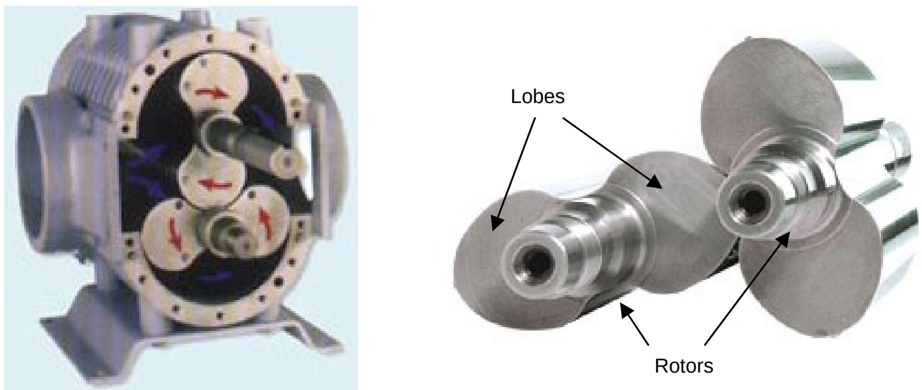


Figure 4.32: Two-lobe Roots Blower

The spaces between lobes and housing get bigger as they pass the suction port. This reduces the pressure inside and gas flows in. As the gas is carried around to the discharge port, the spaces get smaller, the gas pressure rises and it flows out.

One rotor is turned by the drive motor. This rotor drives the other through *synchronising gears* that keep both rotors turning together, maintaining minimum clearance between them. You can see this gear drive in **Figure 4.33**.

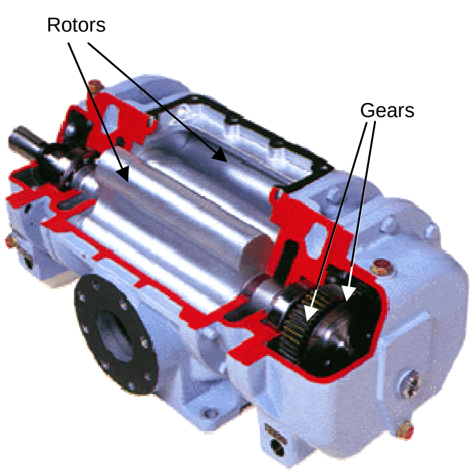


Figure 4.33: Lobe Blower Synchronising Gears

4.2.2 Sliding-vane Compressors

Vane compressors have a single rotor. Vanes slide freely in slots in the rotor and are held against the casing by centrifugal force. The housing is shaped so the spaces between rotor, vanes and housing change as the rotor turns. The spaces change in the same way as those described for the lobe compressor: they get bigger as they pass the suction port and smaller as the pass the discharge port. The vane compressor in **Figure 4.34** has two suction and two discharge ports.

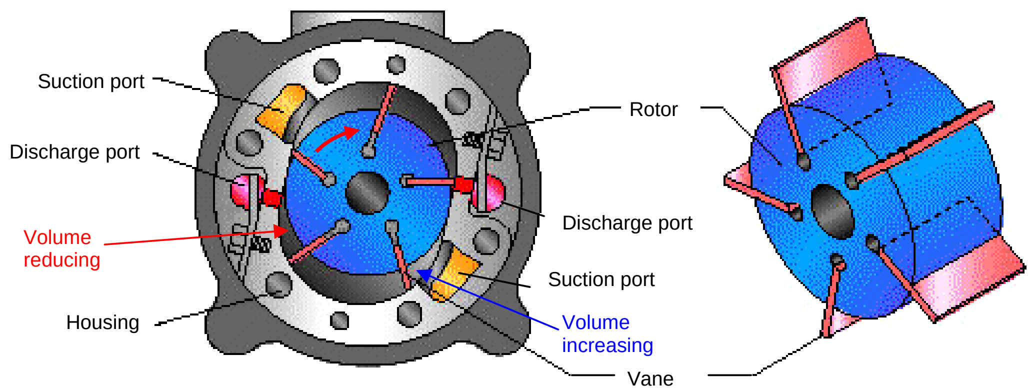


Figure 4.34: Five-vane Compressor

The rotor is turning clockwise. Gas entering the left-hand suction port is carried around the top to the right-hand discharge port. Gas entering the right-hand suction port is carried around the bottom to the left-hand discharge port. You can see how the volume of the gas space changes as it travels from suction to inlet ports. **Figure 4.34** shows a vane compressor with part if its casing cut away to show the rotor and vanes.

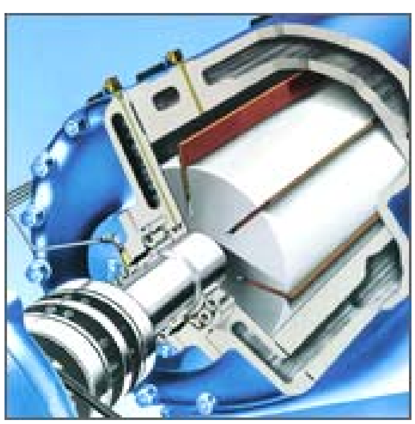


Figure 4.35: Vane Compressor Cutaway

4.2.3 Screw Compressors

Most screw compressors have two meshing helical screw rotors. They may be single-flow, with gas entering at one end and leaving from the other, or double-flow, with gas entering at both ends and leaving at the centre. These are the same arrangements as for screw pumps. **Figure 4.36** shows an axially split, single-flow screw compressor with the top casing-half removed.

Figure 4.36: Screw Compressor

Gas is compressed as it is 'screwed' along the lengths of the rotors and forced out of the discharge.

Wet screw compressors are lubricated by oil sprayed into the gas as it enters. These can operate without synchronising gears. One of the screw rotors then becomes an idler and is turned by the drive rotor. If the gas must be oil-free, non-lubricated *dry* compressors are used. These need synchronising gears to avoid metal-to-metal contact between the screws.

5 Dynamic Compressors

The most common types of dynamic compressor are shown in that part of the classification chart repeated in **Figure 5.1**.

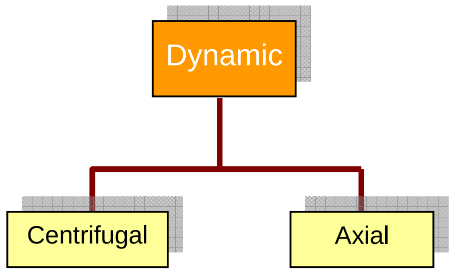


Figure 5.1: Dynamic Compressors

This group of compressors uses *impellers* to give kinetic energy directly to the gas. The kinetic energy is then converted to pressure energy as the gas travels to the compressor discharge.

The compression ratio and capacity of a dynamic compressor depend on the operating conditions, as well as its speed and design.

As pressure in the gas receiving vessel increases, the compressor's discharge pressure increases and it discharges less gas—its capacity becomes less. The same happens if the supply to the suction is reduced, causing low suction pressure

Dynamic compressors give continuous discharge with no pulsing.

They may be driven by electric motors, either directly or through a gearbox, or by gas or steam turbines.

Now try **Exercise 4**

5.1 Centrifugal Compressors

ADGAS uses centrifugal compressors in the Utilities area to supply compressed air for:

- instrumentation and the operation of pneumatic actuators
- workshop services—air lines, pneumatic tools, etc.
- raw material for the production of nitrogen in the Nitrogen Plant

In the Process area there are centrifugal compressors in Trains I and II. These raise the pressure of feed gas received from ADMA gas/oil separation plant at four different (low) pressures. Some also comes directly from the gas field at high pressure (52barg/780psig). All the feed gas must be raised to the same pressure (52barg/780psig) before the liquefaction process begins. **Figure 5.2** shows the low-pressure booster compressors that take in gas at atmospheric pressure.

Figure 5.2: Booster Compressor Platform, Trains I and II

Centrifugal compressors are also used in Trains I, II and III to compress propane and MCR (mixed component refrigerant). These are used in the refrigeration process for liquefying gas in the *cryogenic* exchanger.

The principle of operation and construction of centrifugal compressors is similar to that of centrifugal pumps. The drawing of the basic construction shown in **Figure 5.3** is exactly the same as for a pump.

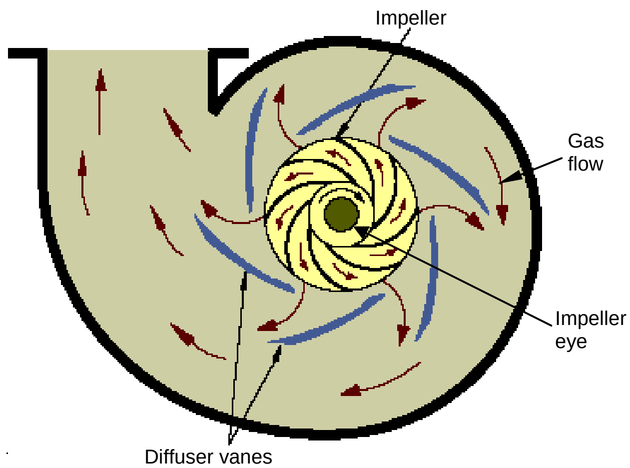


Figure 5.3: Basic Centrifugal Compressor

Gas enters the low-pressure area at the eye of the impeller. As the impeller rotates, the gas moves outwards by centrifugal action and its pressure starts to increase. It then passes between the vanes of the diffuser, where pressure increases more. Finally it travels around the volute, the pressure continuing to increase as it makes its way to the discharge. **Figure 5.4** shows a medium-sized, single-stage centrifugal compressor.

Figure 5.4: Single-stage Centripetal Compressor

5.1.1 Impellers

Centrifugal compressor impellers work in exactly the same way as a pump impeller but they are a little different in design. Impellers may be:

- open—with no shrouds
- semi-closed—with a shroud on one side
- closed—with shrouds on both sides

These three types of impeller are shown in **Figure 5.5**.

(a) Open

(b) Semi-closed

(c) Closed

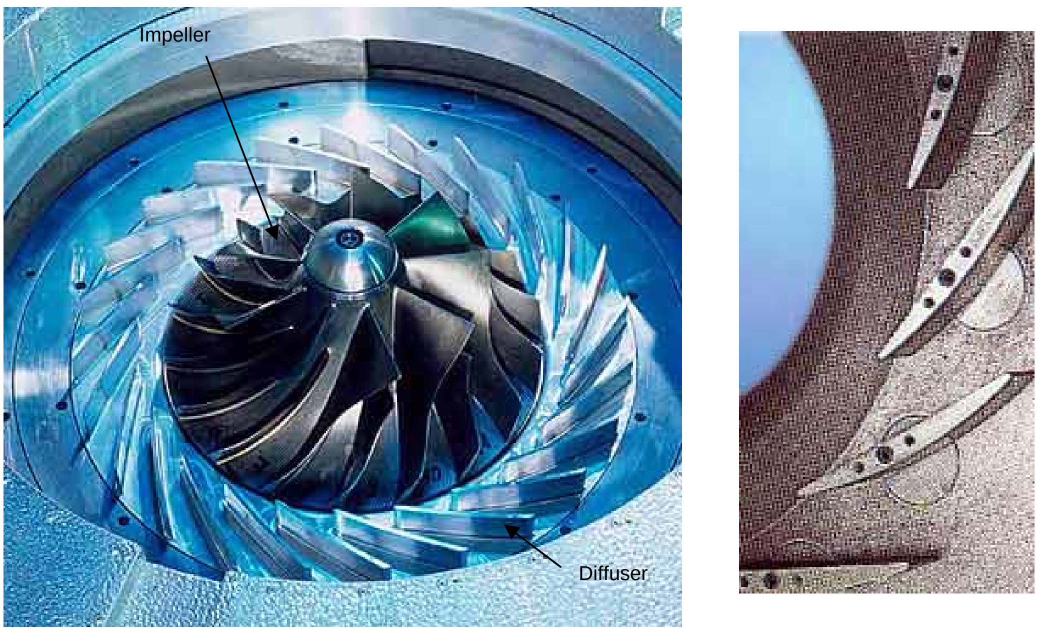
Figure 5.5: Centrifugal Compressor Impellers

Most centrifugal compressors use semi-closed or closed impellers. Multi-stage compressors may have an open-impeller first stage, with closed impellers for the other stages. The vanes at the impeller eye are often more steeply angled to give a smoother entry path for the gas, as shown in **Figure 5.5(b)**.

5.1.2 Diffuser and Volute

The purpose of the diffuser and volute is to increase gas pressure by reducing its speed of flow. These opposite changes of energy keep the total energy of the gas constant—if kinetic energy reduces, pressure energy increases.

The diffuser does not rotate; it is fixed in the compressor casing. The spaces between diffuser vanes increase as they get further from the impeller. This allows a wider flow path for the gas and it slows down. You can see the increase of these spaces in **Figure 5.6**.



(a) Impeller and Diffuser Assembled in Casing

(b) Diffuser Vanes

Figure 5.6: Diffuser

The vane angle on some compressors is adjustable to change the performance of the compressor.

The gas enters the volute after passing through the diffuser. The flow path around the volute gets bigger as the gas gets closer to the discharge. This allows the gas to slow even more, and its pressure continues to increase. **Figure 5.7** shows the gas flow path through the volute casing of an electric-motor driven compressor.

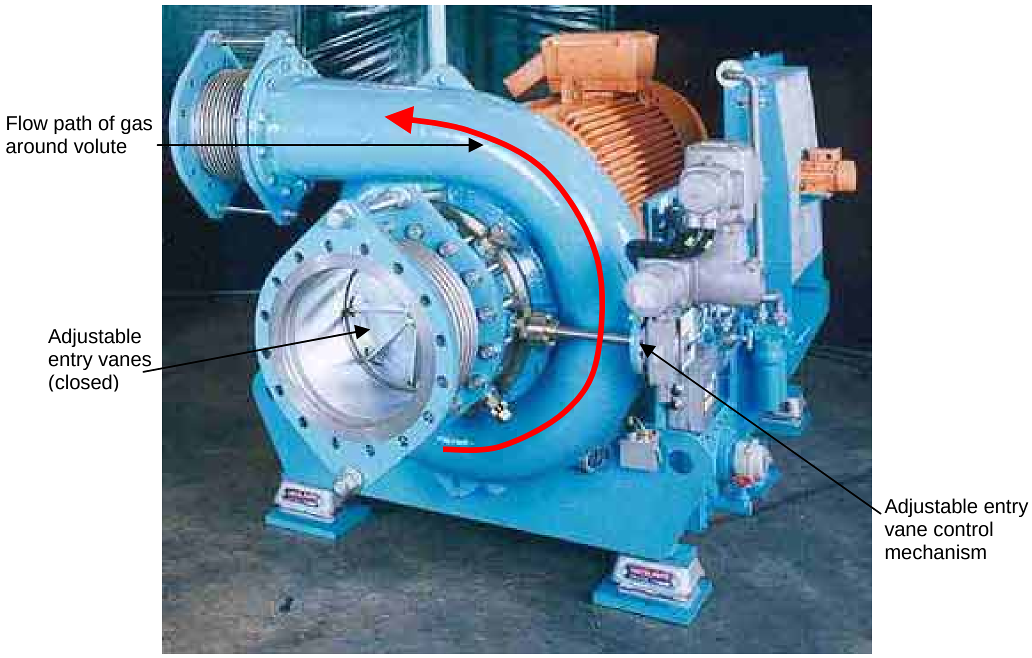


Figure 5.7: Volute Casing with Adjustable Entry Vanes

Some centrifugal compressors have additional vanes at the compressor inlet. These can be opened or closed to control capacity.

5.1.3 Multi-stage Compressors

There is a limit to the compression ratio of a single-impeller compressor. This is not enough for the pressures needed for most applications on the plant. One way to increase the discharge pressure is to connect more than one unit in series. Multi-stage compressors have a series of impellers and volutes contained in one or more casings.

There is a difference between the way that process operators and mechanical technicians use the term *multi-stage* which can cause confusion.

For process personnel on the plant, a compression *stage* is any part of a compressor between points where a gas stream enters or leaves the casing. Whether there is a single impeller or many between those points makes no difference to them. They are not interested in how many impellers are inside the compressor casing. The gas may pass through *several* impellers before leaving the compressor for cooling or to be joined by another, higher-pressure feed. That is still called a *single stage* on the plant.

Several is a number more than two but not very large.

For a mechanical engineer, each impeller in the casing means another stage. There can be *inter-stage* cooling, or gas streams (*side streams)* can enter or leave at different points but this does not change the number of impellers, and therefore the number of stages of the compressor.

For reciprocating compressors, each stage has a separate cylinder and piston. The gas always leaves one cylinder casing before entering the next so there is no confusion.

Although, as mechanical technicians, you may call each impeller a stage, you must understand that this may not be the meaning of stage used on the plant.

In this module, the mechanical meaning of a compressor stage is used. The number of compressor stages is the same as the number of impellers in the casing.

Each section between a gas inlet and a gas outlet will be called a compressor *process stage*.

Figure 5.8 shows a section through a nine-stage centrifugal compressor. The cut surfaces of the sectioned impellers are shown in red. The path of the gas through the compressor is shown in green.

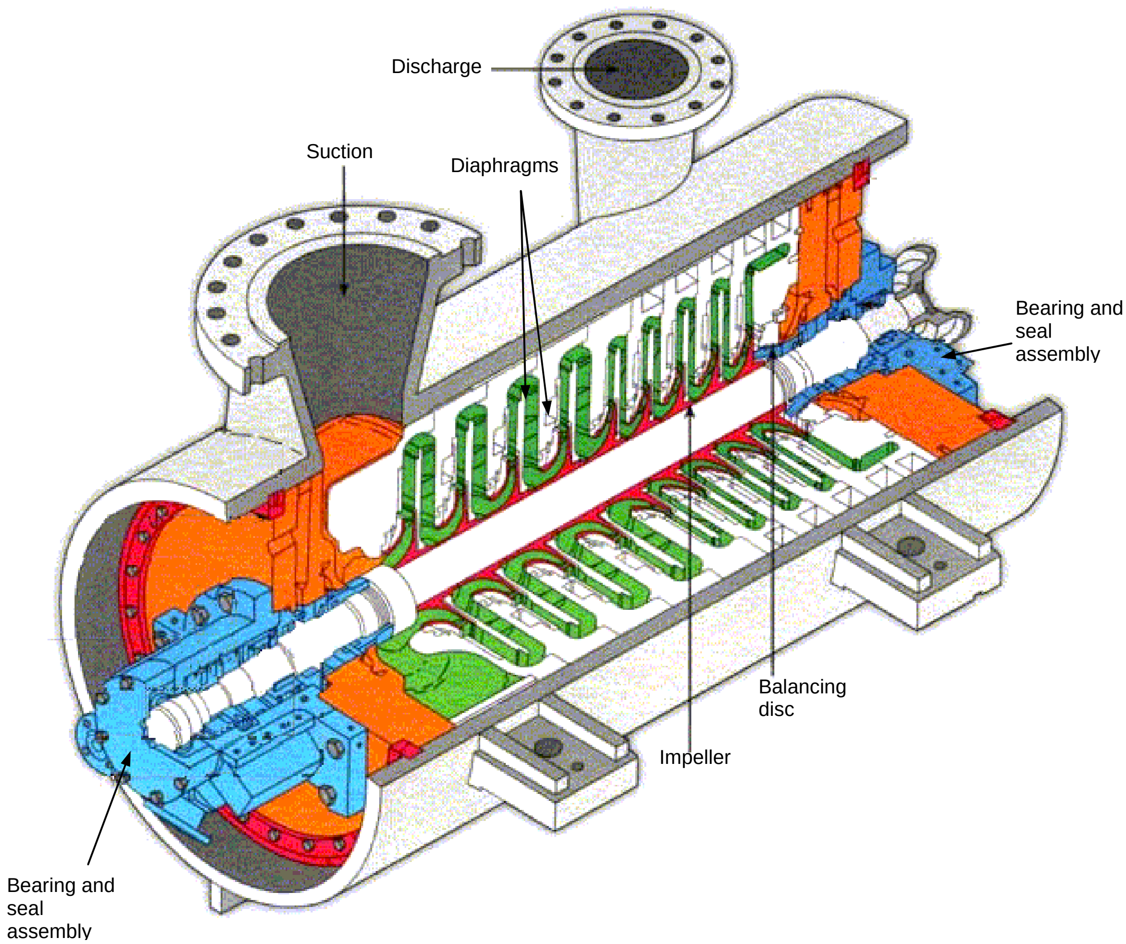


Figure 5.8: Multi-stage Compressor

Gas flows through passages from the discharge of one impeller to the suction eye of the next. Diffusers are located in that part of the passage leading away from the outside of the impeller. A return passage then takes the gas back to the eye of the next impeller.

These passages are formed by *diaphragms* that are held in the casing and do not rotate.

The difference of pressure acting on suction and discharge sides of the impellers cause a thrust that pushes from the discharge end towards the suction end. This is the same axial force that was described for multi-stage centrifugal pumps in the *Pumps* module. Some compressors have back-to-back impellers to avoid this problem, as shown in **Figure 5.9**.

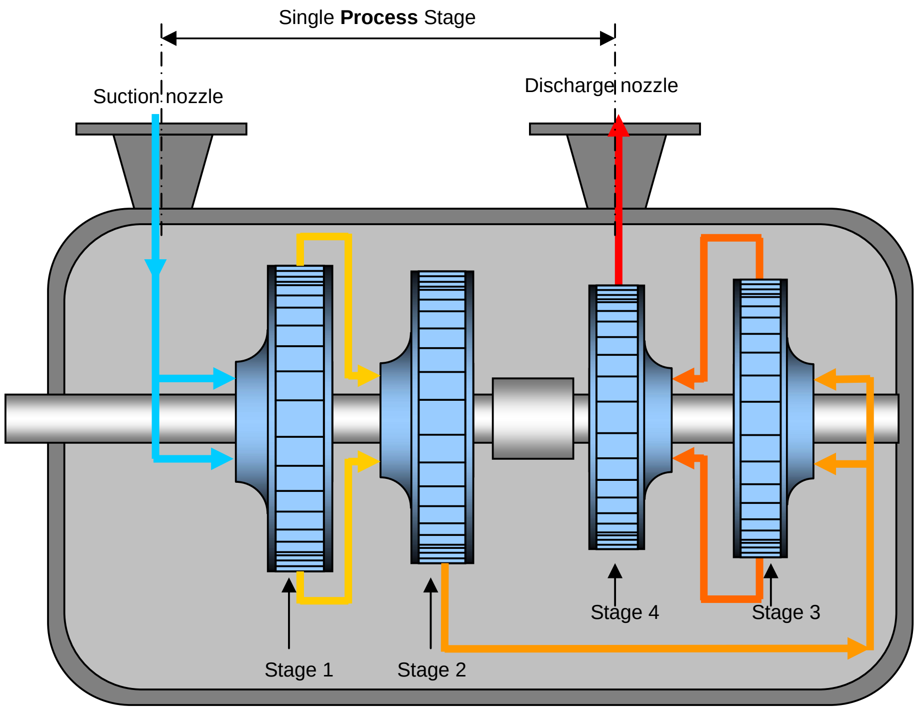


Figure 5.9: Back-to-back Impellers

Notice three things about the compressor in **Figure 5.9**:

- the impellers get smaller as the gas pressure increases and its volume is compressed, just like the cylinders of reciprocating compressors
- this compressor has four impellers so a **mechanical engineer** would describe it as a four-stage compressor
- the gas only enters the casing at one point and leaves the casing at one point so a **process engineer** would call it a single-stage compressor

If impellers are all facing the same way, balancing drums or balancing discs are fitted to reduce this out-of-balance force. They are located at the discharge end of the impeller shaft as was shown in **Figure 5.8**. Gas at final discharge pressure pushes back against the impeller thrust to reduce the load on thrust bearings.

If some gas is needed at a pressure lower than the final discharge pressure it can be taken out of the compressor between stages. Also, if some of the feed gas is at a pressure higher than the main feed it can enter the compressor between stages, as shown in **Figure 5.10**.

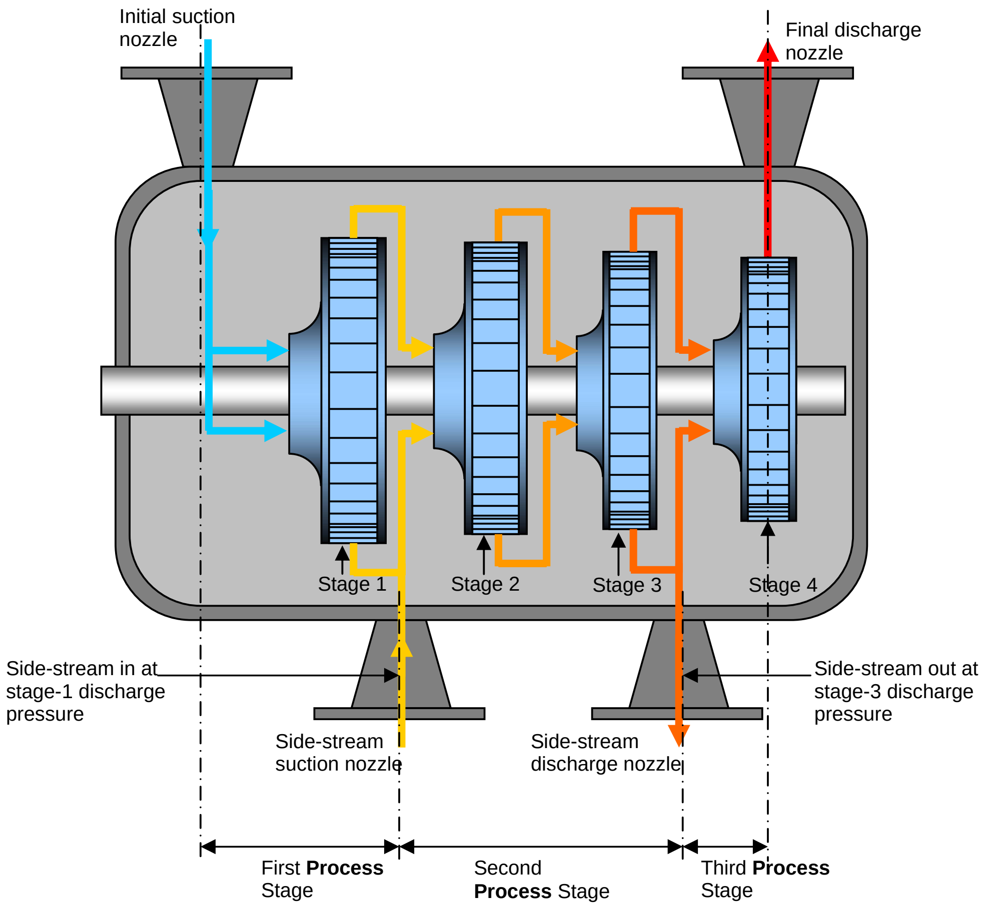


Figure 5.10: Inter-stage Side Streams

This is called a four-stage compressor by mechanical engineers and a three stage compressor by process engineers.

5.1.4 Casing Splits

Centrifugal compressor casings may be split:

- axially (horizontally)—compressors are usually installed with the rotor axis horizontal
- radially (vertically)—with barrel-type casing for higher pressures

Horizontally-split compressors allow the internal parts to be reached easily without *disturbing* them too much. **Figure 5.11** shows an exploded drawing of a horizontally-split compressor. The impeller shaft assembly (the rotor) can be removed in one piece for inspection or dismantling.

You ***disturb*** something by moving it in a way that might affect its normal operation.

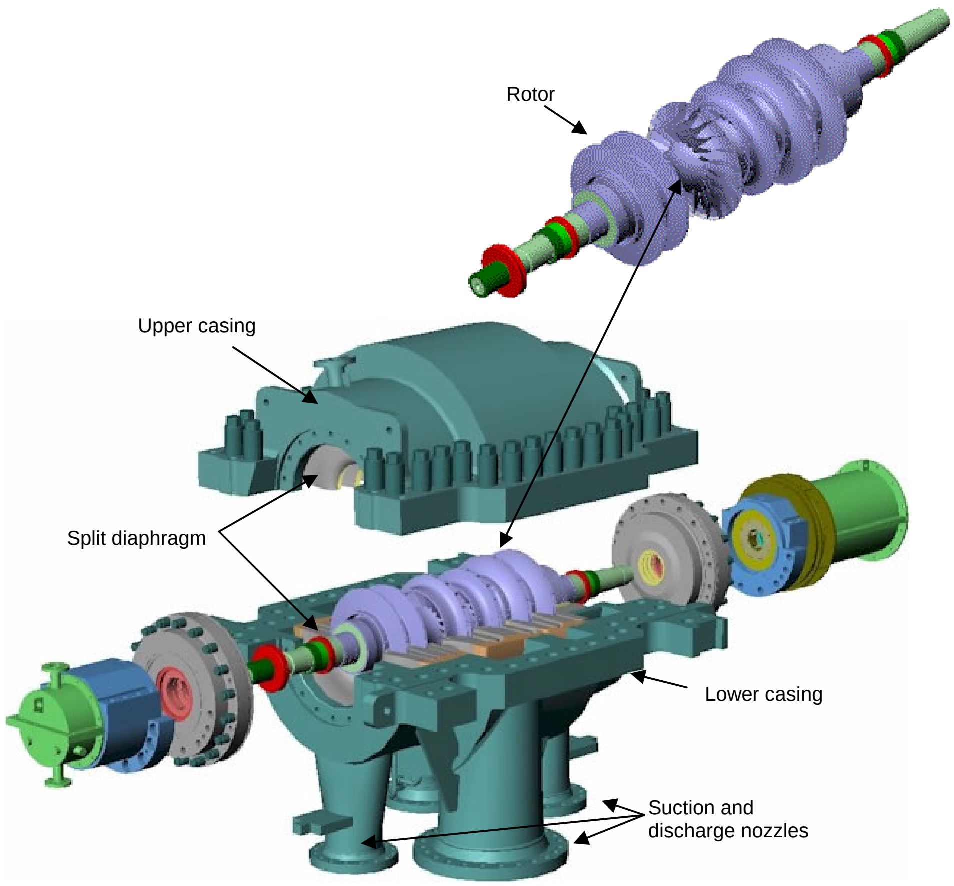


Figure 5.11: Horizontally (or Axially) Split Casing

Split bearings and split diaphragms can be used in a horizontally-split casing. Also it is easier to check running clearances with the upper casing removed and the rotor in place. **Figure 5.12** shows the rotor sitting in the lower casing. You can see the many large-diameter studs that keep the casing halves together.

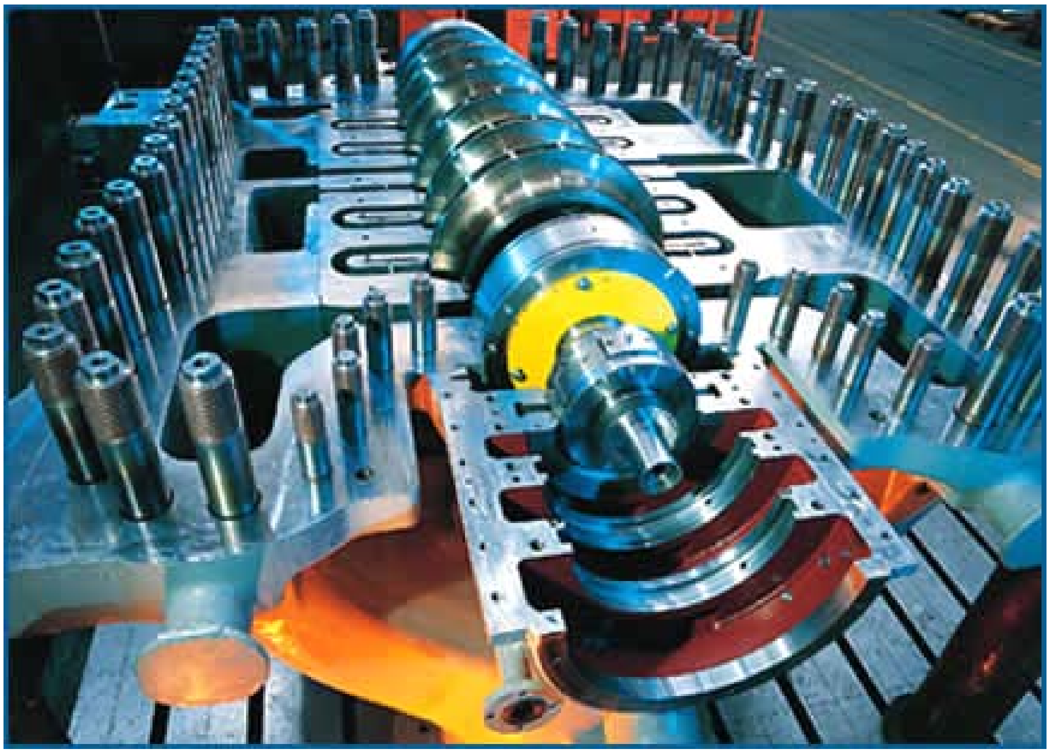


Figure 5.12: Horizontally-split Compressor with Upper Casing Removed

Most centrifugal compressors on the ADGAS plant are horizontally split.

A horizontal split limits the maximum pressure inside the compressor. The gas pressure acting radially outwards pushes the two casing halves apart and this can cause pressure leaks at the joint. Vertically-split *barrel* casings can take higher internal pressures.

A barrel casing is cylindrical, like an oil barrel, with end covers. It has no joint that can be forced apart by radial pressure. Axial pressure acts on the end covers but the axial force is not as great because the area of an end-cover is quite small.

The barrel contains the rotor and diaphragms, which together are sometimes called the *bundle*. An exploded drawing of a barrel-type compressor is shown in **Figure 5.13**.

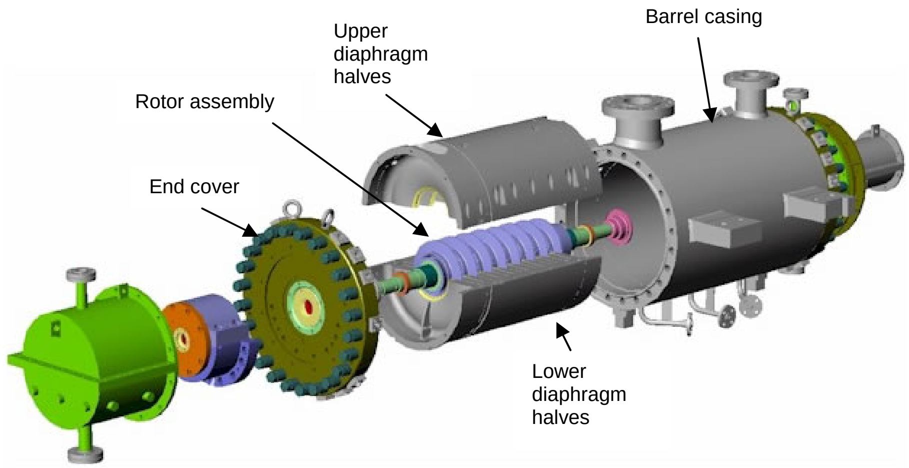


Figure 5.13: Vertically-split Barrel Casing

The compressor shown in **Figure 5.8** is a barrel-type with separate diaphragm sections for each stage. **Figure 5.14** shows lower diaphragm halves with diffuser vanes.

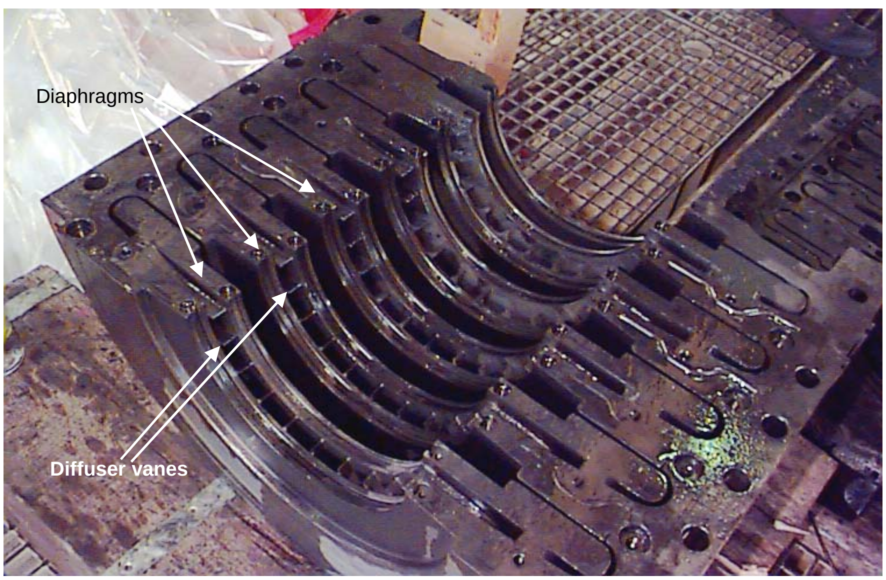


Figure 5.14: Lower Diaphragm Halves

5.1.5 ADGAS Centrifugal Compressors

ADGAS uses centrifugal compressors to:

- raise low-pressure feed gas to 780psig/52barg for the liquefaction process in Trains I and II
- compress refrigerants (MCR, propane, etc.) as part of the gas liquefaction cooling process
- supply air for process, instruments and service to all areas except Sulphur STOREX

Feed Gas Compressors

Train III receives only high-pressure gas (780psg/52barg) directly from the gas fields. This does not need to be compressed before starting the liquefaction process.

Trains I and II receive feed gas either at high pressure (780psg/52barg), direct from the gas fields or at lower pressures from ADMA gas-oil separation plant. Gas comes from different stages of the ADMA gas-oil separation process at pressures of 0psig (atmospheric), 35psig, 75psig and 230psig. All these have to be compressed to the same high pressure (780psg/52barg) before starting the liquefaction process.

Two *booster compressors* connected in parallel take gas coming from ADMA at atmospheric pressure. They raise this gas pressure from 0psig to 35psig. This gas then goes to Train I and Train II. Each train has a *feed gas compressor* that increases the pressure in three compressor *process stages* to a final pressure of 780psg/52barg.

Note: ADGAS uses barg units for pressures in the liquefaction process; psig units are used for feed gas entering the system from ADMA.

The feed gas compressor *process stages* also take gas directly from ADMA gas-oil separation plant at 35psig, 75psig and 230psig. These enter the compressors as side streams. The feed gas compression process is shown in **Figure 5.15**.

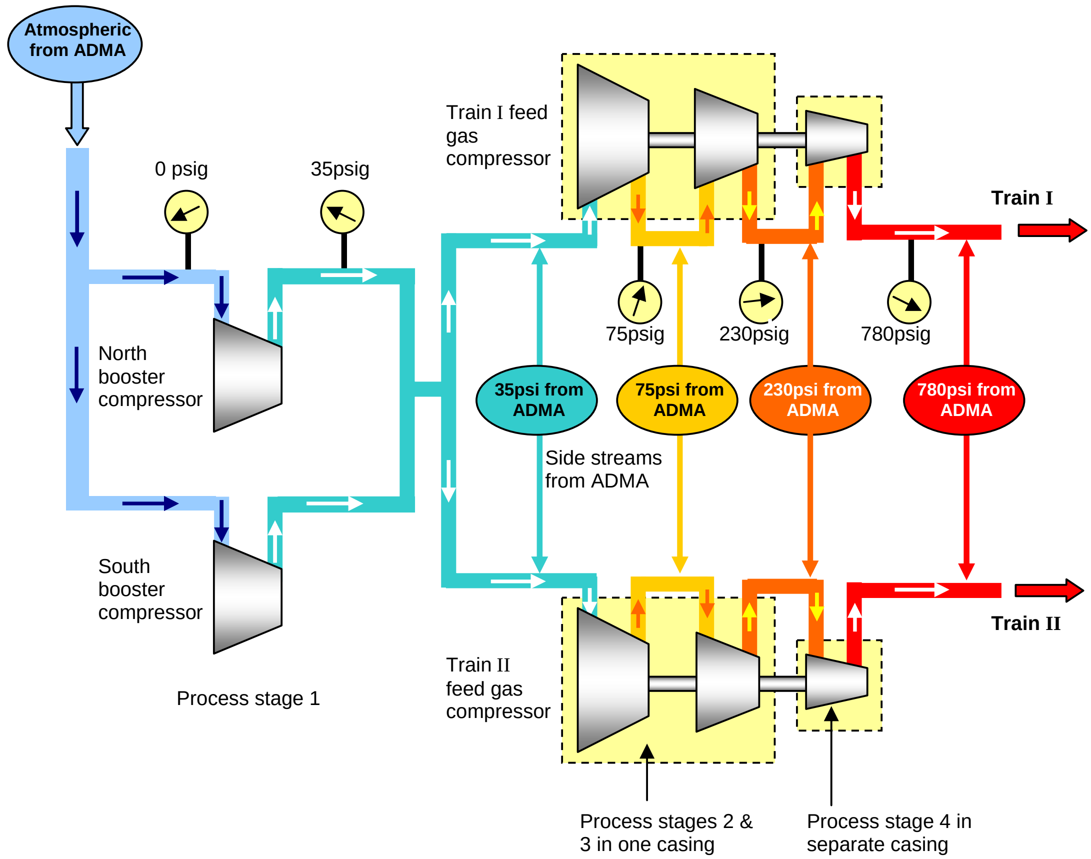


Figure 5.15: Booster and Feed-gas Compressor Layout

The two booster compressors are known as the North and South Booster Compressors—they are both the same.

Because they have only one suction and one discharge they are called single-stage compressors by process personnel—they have a single compressor *process stage*. Mechanically they are multi-stage compressors as they have more than one impeller. The impellers are mounted back-to-back with a central volute and discharge. Casings are horizontally-split. They are driven by steam turbines.

Figure 5.16 shows one of the booster compressors.

Figure 5.16: Booster Compressor (Tag# 26-K-101 and 201)

Figure 5.17 shows the steam turbine driver for the booster compressor.

Figure 5.17: Steam Turbine Driver (Tag# 26-KT-101 and 201)

Similar **feed-gas compressors** are located in Trains I and II. They are called three-stage compressors by process personnel because they have one main intake and two side-stream intakes.

On the plant, compression of the feed gas is described as going through a total of four stages:

- stage one in the booster compressor
- stages two, three and four in the feed-gas compressor

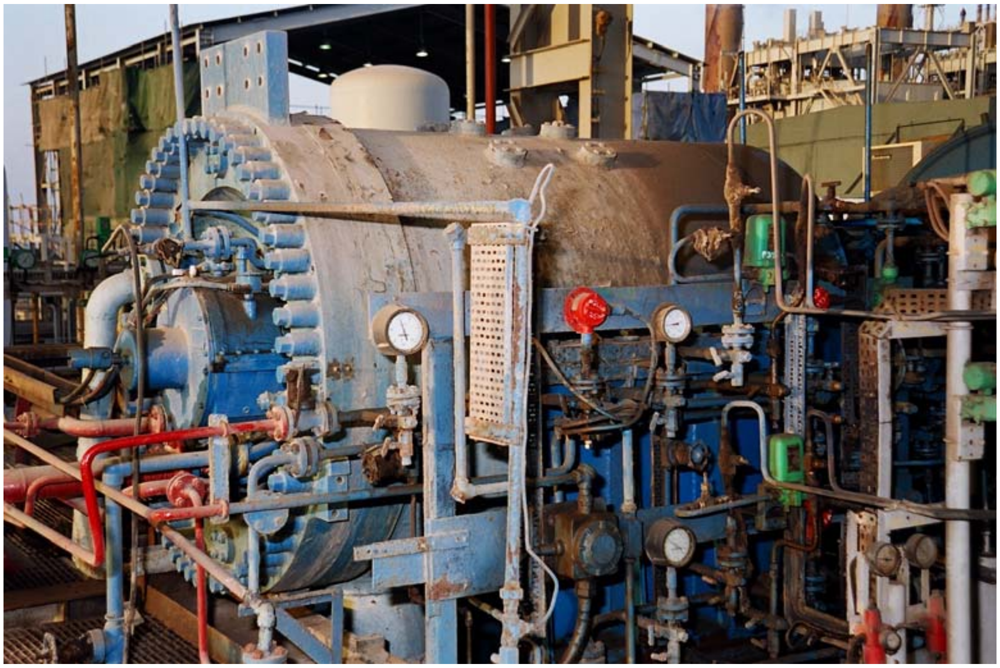
Each feed-gas compressor has two casings. The first two compressor *process stages* are housed in a horizontally-split, low-pressure casing. Impellers are mounted back-to-back, similar to the booster compressors. The third stage is housed in a vertically-split, high-pressure barrel casing. Impellers for all stages are mounted on the same shaft and driven by the same steam turbine.

Figure 5.18 shows one of the feed-gas compressors.

Figure 5.18: Feed-gas Compressor (Tag# 1-K-101 and 201)

Figure 5.19 shows the two casings on each feed gas compressor more clearly.

(a) Horizontally-split *Process Stages* 2 and 3



(b) Vertically-split *Process Stage* 4

Figure 5.19: Feed-gas Compressor Casings

Refrigerant Compressors

To liquefy the feed gas it must be compressed and then cooled.

Cooling is done in heat exchangers. Initial cooling of the feed gas is done in exchangers called *chillers*. The final temperature reduction (and liquefaction) is done in the *cryogenic exchanger*.

In these exchangers, the feed gas being cooled flows close to a colder fluid. This colder fluid is called the *refrigerant*. Heat passes from the higher temperature feed gas to the lower temperature refrigerant. Heat exchangers are described in a later module in this course.

As heat from the feed gas enters the refrigerant, the refrigerant temperature increases and some of it changes to vapour. Before it can be used again, the refrigerant vapour must be turned back to liquid. This is done by compressing and cooling it: a process similar to, but much simpler than, gas liquefaction.

Refrigerant compressors increase the refrigerant pressure before cooling and returning it to the chillers or the cryogenic exchanger.

The refrigerants used in the LNG production process are:

- propane (C_3)—for initial feed gas cooling (to -34^{o}C) in *propane chillers*
- MCR (mixed component refrigerant)—in the cryogenic exchanger (to -164^{o}C)

Each gas liquefaction train has a propane compressor and an MCR compressor.

The propane compressor has a single, horizontally-split casing. It has three compressor *process stages* that receive propane vapour at high, medium and low pressures from different chillers. It compresses this vapour before it is cooled and returned to the chillers. **Figure 5.20** shows the compressor arrangement.

Note 1: In Train III the propane chillers are all located in the *cold box*. In Trains I and II they are at different locations in the plant.

The propane compressors are driven by steam turbines.

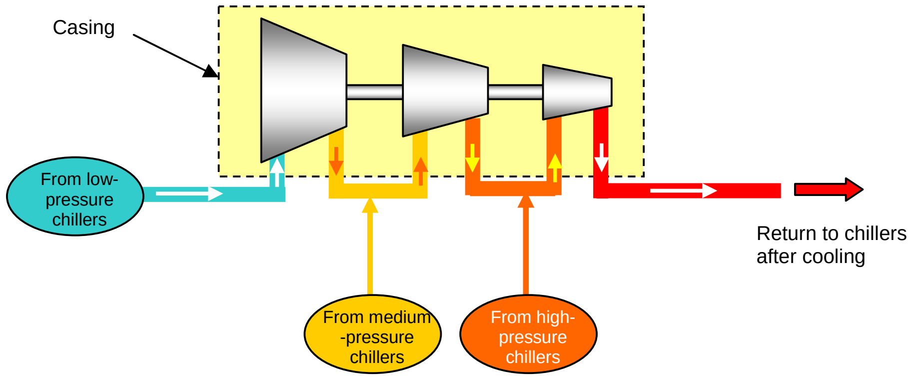


Figure 5.20: Propane Compressor

Note 2: Propane chillers are also used to cool MCR after compression, as well as other products from the plant.

Each MCR compressor has a single, horizontally-split casing. It receives MCR vapour from the cryogenic exchanger. It compresses the vapour before it is cooled and returned to the cryogenic exchanger. Each compressor has two compressor *process stages* to allow the MCR to be cooled between stages as shown in **Figure 5.21**. It is driven by a steam turbine.

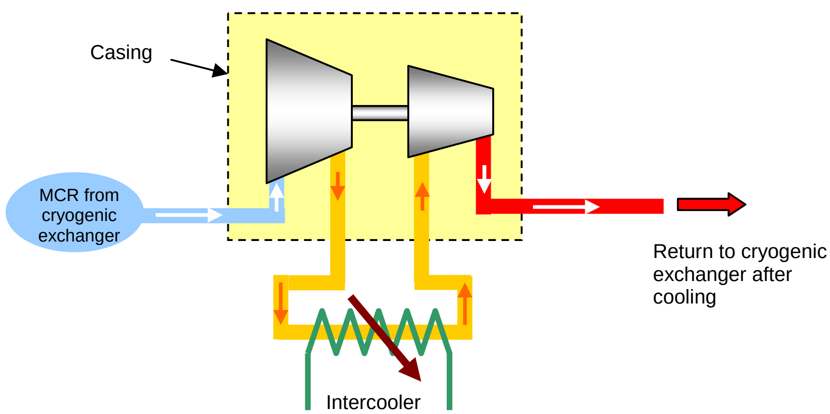


Figure 5.21: MCR Compressor

Note 3: All compressors on the plant have intercoolers. These have not been shown on earlier compressor diagrams for simplicity. They are described in **Section 6.1** of this module.

Note 4: There are other small refrigeration compressors in the Utilities Nitrogen Plant.

Air Compressors

These are located in the Utilities areas of the plant. They supply air to all areas except the Sulphur STOREX area.

Air from Utilities is used for:

- process—Trains I, II and III
- instrumentation—pneumatically controlled valves, etc.
- service—air hoses in workshops, etc.
- Nitrogen Plant

Centrifugal compressors provide a continuous supply of air for normal operation. There is one reciprocating air compressor in the Utilities area that is used for emergency instrument air. This was described in **Section 4.1.5**.

Trains I and II are supplied by three centrifugal air compressors:

- two of them are four-stage compressors each with a single, vertically-split barrel casing,: one steam-turbine driven and the other electric-motor driven
- one is a three-stage compressor driven by an electric-motor

Figure 5.22 shows examples of these compressors.

(a) Electric-Motor Driven Four-stage Compressor (B) (b) Electric-Motor Driven Three-stage Compressor (C)

Figure 5.22: Train I and II Air Compressors (Tag#s 35-K-1 B and C)

Train III is supplied by three, three-stage centrifugal compressors. Each of these has two horizontally-split casings: one houses the first two (single impeller) stages on a single shaft (or *pinion*) and the other houses stage three (also single impeller) on a separate shaft.

A gear train connects the two shafts to increase the speed of the third-stage rotor. This arrangement is shown in **Figure 5.23**.

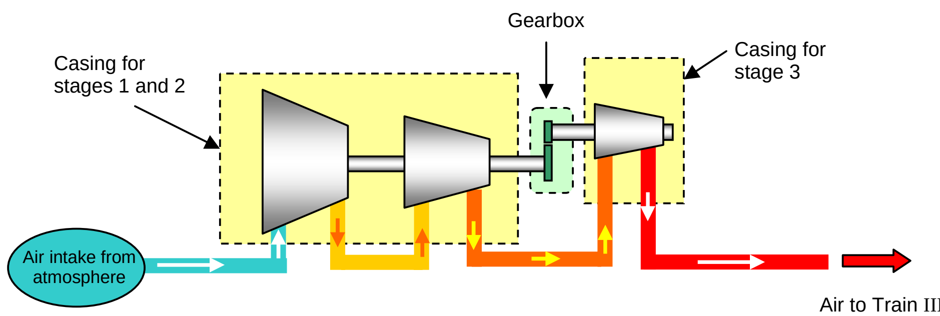


Figure 5.23: Train III Air Compressor

Two of these compressors run all the time. They are driven by steam-turbines.

One compressor only cuts in when air pressure drops below the normal supply value of 8barg. This compressor is electric-motor driven.

Electric motors can start and stop quickly and are suitable for stand-by operation. Steam turbines take a long time to warm up before starting and to cool down again afterwards, before they can be re-started. They should not be used for stand-by operation.

Now try **Exercise 5**

5.1.6 Compressor Seals

There must always be clearance between the stationary and rotating parts in a machine. In a centrifugal compressor it is very important to stop, or at least reduce to a minimum, the leakage of gas from high to low pressure through these clearances. Different types of seals are used wherever leakage of gas is possible. They are located between:

- impellers and diaphragms
- rotor shaft and casing

These locations are shown in red in **Figure 5.24**. This figure does not show bearings.

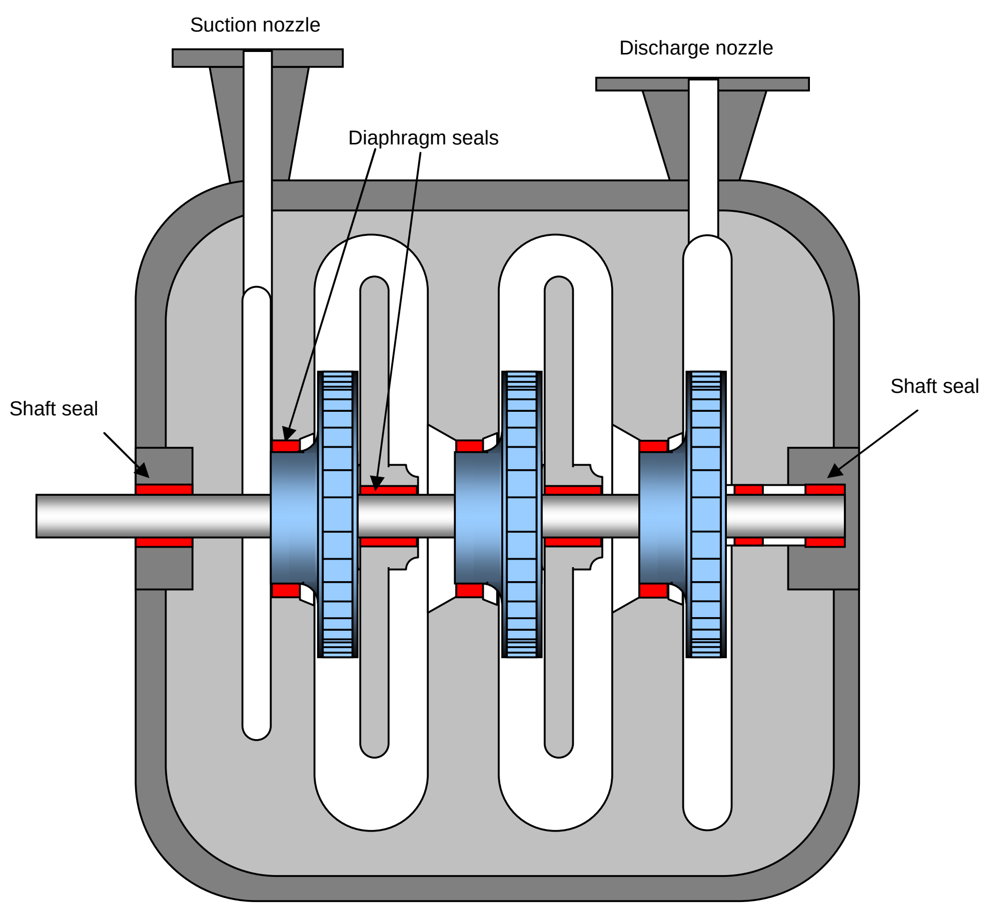


Figure 5.24: Seal Locations

The four main types of compressor seals are:

- labyrinth
- carbon ring
- mechanical
- liquid film

Labyrinth seals are the most common type used for sealing diaphragms. A labyrinth seal is shown in **Figure 5.25**.

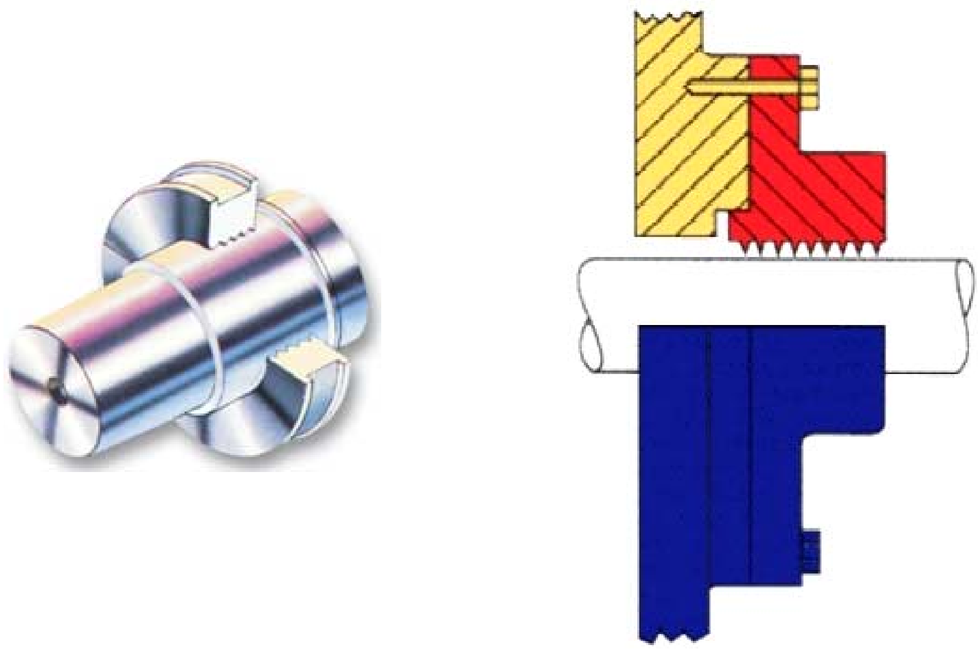


Figure 5.25: Labyrinth Seal

These seals leave a large number of very small gaps for the gas to pass through. There is a lot of fluid friction as the gas squeezes through each gap. This friction loss results in a pressure loss. By the time the gas reaches the outside its pressure has dropped so much that it is no higher than the outside pressure and it can not flow out.

Carbon ring seals are seperate carbon rings located in spacers. They are in sections, held together by a spring. When the compressor is operating, gas pressure pushes the rings against the spacers, forming a seal as shown in **Figure 5.26**.

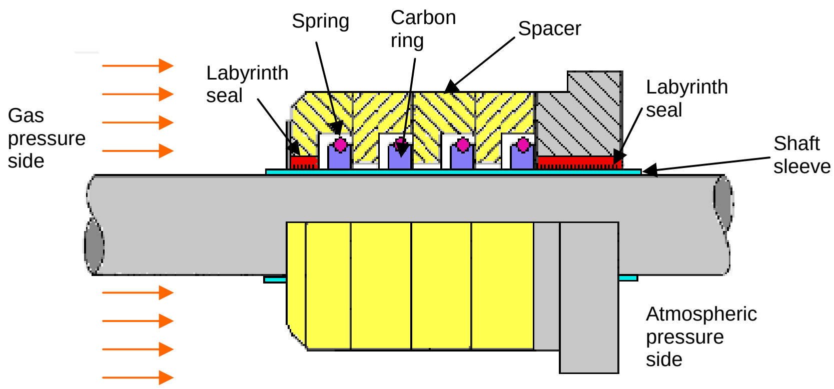


Figure 5.26: Carbon Ring Seal

Carbon is a solid material with natural lubricating properties. Labyrinth seals may also be used to help make a good seal. A sleeve on the shaft prevents any contact wear on the shaft.

Liquid film seals use oil pumped into the seal to stop gas leakage. The oil is at a pressure higher than the compressed gas pressure so no gas can flow into the seal. **Figure 5.27** shows a liquid film seal.

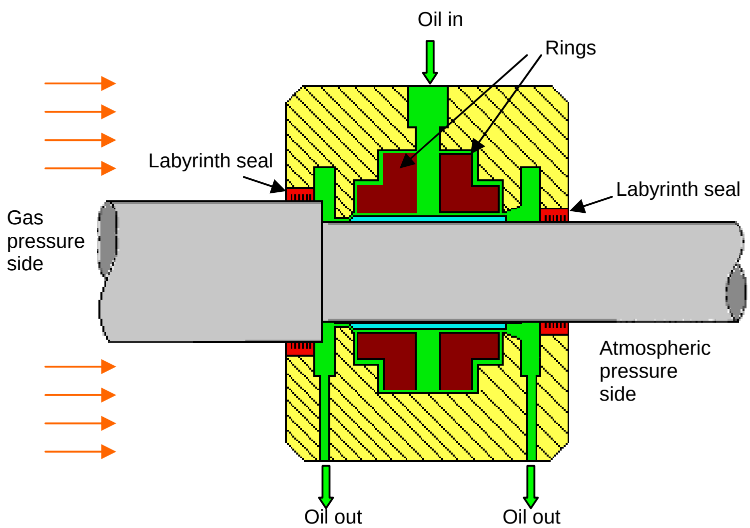


Figure 5.27: Liquid Film Seal

Labyrinth seals are also used to help stop the seal oil from flowing into the gas stream.

Mechanical seals can come in many different designs. They can be supplied with high-pressure liquid or gas to help keep the compressed gas from escaping. A basic mechanical seal was described in the module on *Pumps* in this course. Another example of a simple mechanical seal is shown in **Figure 5.28.**

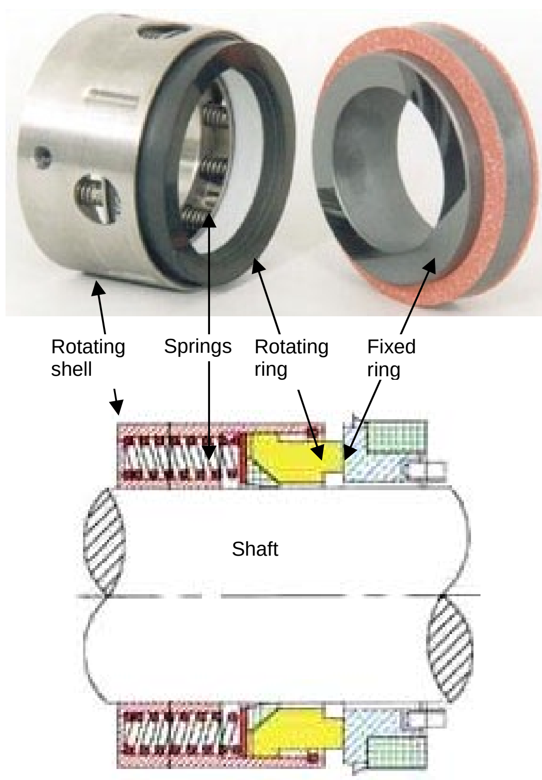


Figure 5.28: Mechanical Seal

A seal is made between the faces of the fixed and rotating rings.

All of these seals are described in more detail in the *Seals* module.

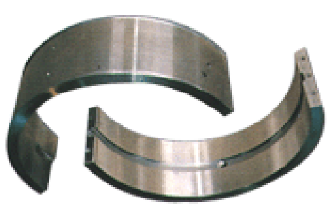
5.1.7 Compressor Bearings

Centrifugal compressor bearings must support:

- radial load—from the weight of shaft and impellers and any out-of-balance forces
- thrust—from pressure differences on opposite sides of impellers

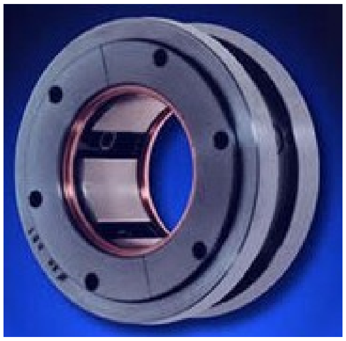
Radial loads are supported by:

- plain radial bearings (**Fig. 5.29(a)**)
- anti-friction radial bearings (**Fig. 5.29(b)**)
- tilting-pad radial bearings (**Fig. 5.29(c)**)



(a) Plain Bearing—Split Shells

(b) Anti-friction Ball Bearing



(c) Tilting-pad Bearing

Figure 5.29: Radial Bearings

Thrust loads are supported by:

- plain thrust bearings (**Fig. 5.30(a)**)
- anti-friction thrust bearings (**Fig. 5.30(b)**)
- tilting-pad thrust bearings (**Fig. 5.30(c)**)

(a) Plain Bearing—Thrust Pads

(b) Anti-friction Ball Thrust Bearing

(c) Tilting-pad Bearing

Figure 5.30: Thrust Bearings

These bearings, and others designed to take both radial and thrust loads, are fully described in the *Bearings* module.

5.2 Axial Compressors

The only axial compressor used on the ADGAS plant forms part of the gas turbine-driven electrical generator. This supplies some of the electrical power for the plant.

All gas turbines use axial compressors to increase the pressure, and energy, of the air entering them.

The principle of operation of axial compressors is similar to that of axial pumps but the construction is quite different. The simplest type of axial 'compressor' is the electric fan used to cool a room, as shown in **Figure 5.31**.

Figure 5.31: Room Cooling Fan

This fan moves air in a direction parallel to the shaft of the fan by turning a propeller-shaped rotor. Fans are used to move air, not to increase its pressure. Fin fans used for cooling equipment on the plant are similar to this.

The pressure increase from a single fan is quite small. Axial gas compressors use the same principle but have a number of stages to produce higher pressures.

Axial compressors move gas parallel to the rotor axis. Each stage of the rotor has a set of blades. **Figure 5.32** shows the rotor of an axial compressor.

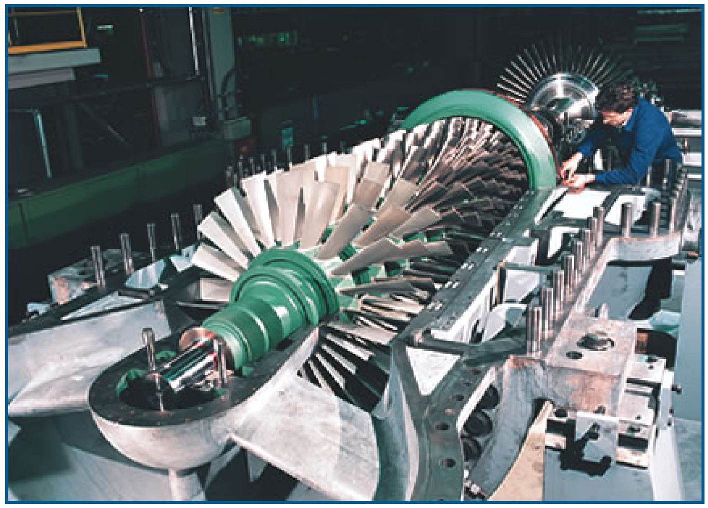


Figure 5.32: Axial Compressor Rotor

Between one set of *rotor* blades and the next is a set of *stator* blades. These do the same job as diaphragms in centrifugal compressors. They change the direction of the gas leaving one stage so that it enters the next stage at the correct angle. **Figure 5.33** shows a diagram of stator and rotor blades and the gas flow through them..

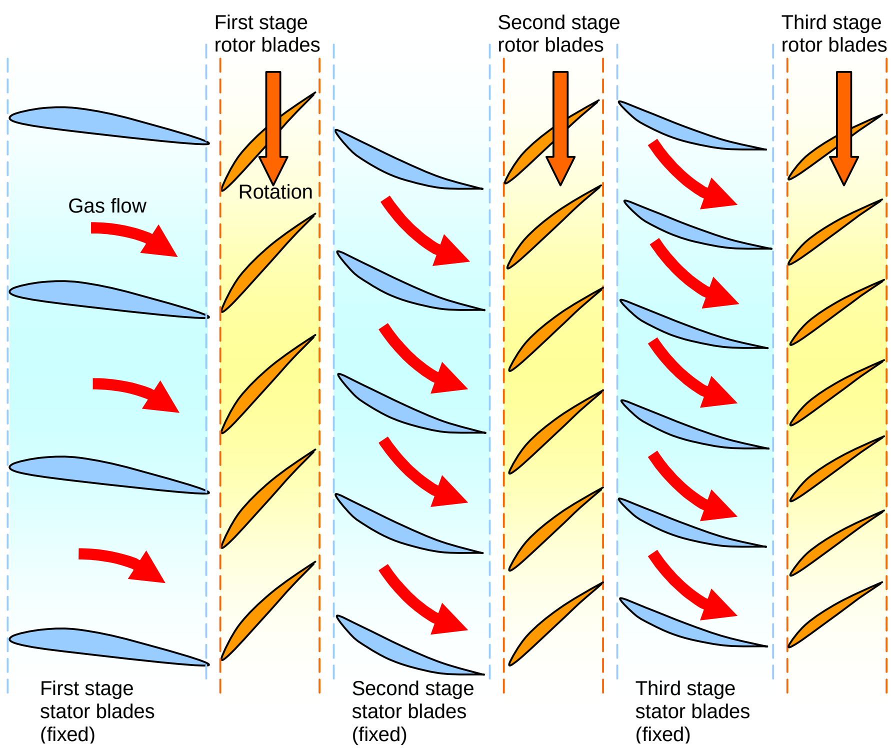
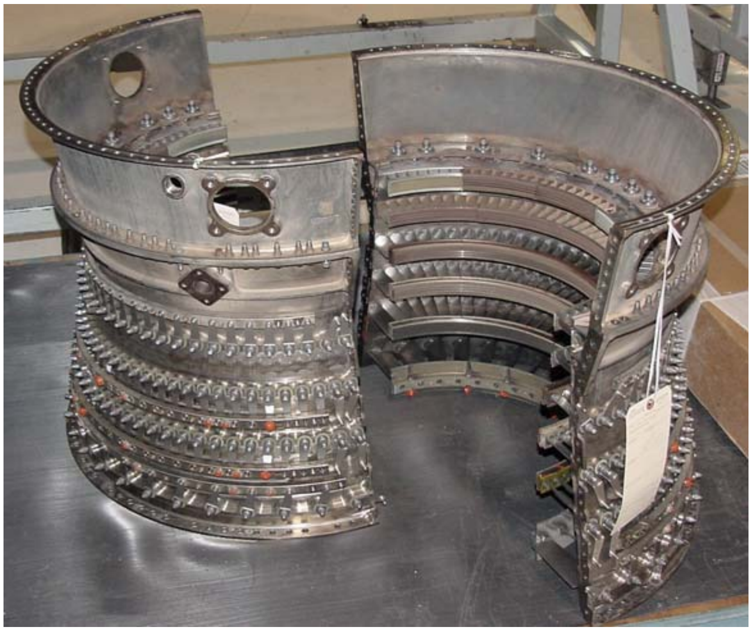


Figure 5.33: Flow through Axial Compressor Blading

Blades have an *aerofoil section*, like the wing of an aircraft, as shown in **Figure 5.33**. Their length and the spaces between them get smaller as gas is compressed from one stage to the next. Rotor blades are fixed to rotor discs or a drum that turns with the compressor shaft. Stator blades are fixed to the inside of the compressor casing. The casing is axially, or horizontally, split to allow assembly of the stators between rotor stages. A rotor and stator-halves are shown in **Figure 5.34**.

(a) Rotor



(b) Axially Split casing with Stator Blades

Figure 5.34: Rotor and Stator Blading

5.3 Compressor Surge

Compressor *surge* affects centrifugal and axial compressors. It is a repeated change in the direction of flow from the compressor discharge.

A ***surge*** is a sudden movement in one direction.

A compressor will surge when there is not enough gas flowing through it. This can happen when:

- the *upstream* supply of gas to the compressor suction is *restricted*
- there is a build-up of pressure in the discharge line *downstream* from the compressor.

Something is ***restricted*** when its quantity or size is limited.

Either of these can cause the downstream pressure to become higher than the discharge pressure at the impeller. When this happens, the flow can reverse back to the compressor discharge.

Gas returning to the impeller discharge tries to turn the impeller in the opposite direction.

Forces trying to reverse the impeller rotation:

- increase the twisting (*torsion*) load on the impeller shaft
- set up *severe* vibrations that can damage bearings and seals and can even damage blading and the rotor shaft
- reduce the compressor speed

Something very great, and strong in a bad way, is ***severe***.

As soon as the compressor speed reduces, the driver tries to return it to its normal operating speed. This corrects the flow direction but only for a very short time. If the original problem still exists, the same thing happens again, and gas flow reverses again. This keeps happening, causing vibrations that get worse and worse.

To avoid surge, the flow through the compressor can be increased by re-cycling some of the discharge gas back to the suction intake.

All dynamic compressors on the ADGAS plant have surge control systems. Sensors monitor the flow rate and pressure difference across each compressor *process stage* and automatically open a re-cycle valve before surge starts. **Figure 5.35** shows a two-stage compressor with anti-surge recycle lines.

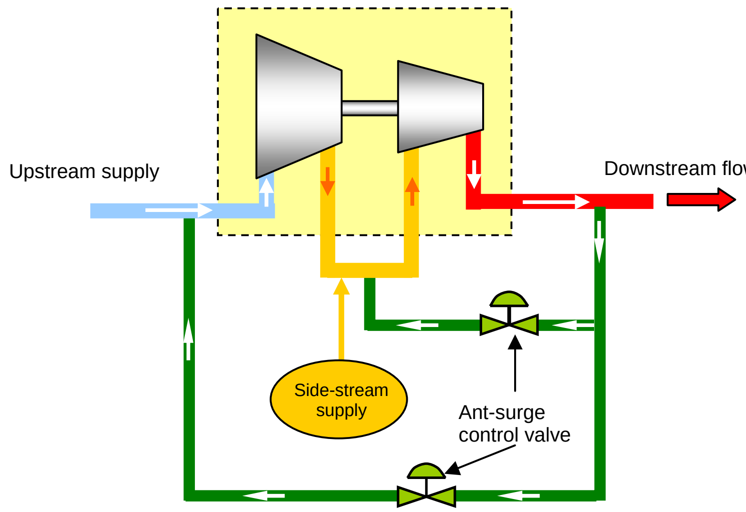


Figure 5.35: Anti-surge Control

When the anti-surge control valve opens, the recycled gas joins the other gas flowing through the compressor *process stage*. This increases the total gas flow through that stage and any following stages.

Air compressors can prevent surge by opening a valve in the discharge line that vents to atmosphere. This increases flow through the compressor. Because it is only air that escapes back into the atmosphere there is no danger and no pollution hazard. In this case the anti-surge control valve is often called a *blowoff* valve.

Now try **Exercise 6**

6 Compressor Auxiliaries

Compressors usually have additional equipment to help them to work efficiently and to reduce the chance of damage. Snubbers have already been described for reciprocating compressors. They are pulsation dampeners that smooth the flow of gas entering and leaving the compressor cylinder on each discharge stroke of the piston. Snubbers are items of *auxiliary* equipment for reciprocating compressors.

Something that is ***auxiliary*** gives additional help.

Other auxiliary equipment:

- helps to cool the gas during and after compression
- removes liquid droplets and solid particles from the gas stream
- supplies lubricating oil to the compressor
- supplies sealing liquid to shaft seals

6.1 Gas Cooling

Increasing the pressure of a gas reduces its volume, but it also raises its temperature. When gas gets hotter it tries to expand, increasing its volume again. This reduces the capacity of the compressor as the gas becomes less dense

Remember what was said about compressor capacity in **Section 2.4** of this module. The capacity, or volume flow rate, is measured as if the gas was at atmospheric pressure (1.1013bara) and at a temperature of 15°C. A compressor may be discharging a vary large volume of gas every hour but if its temperature is high, that volume would be a lot less at 15°C and the capacity may be quite low. Gas at high temperature reduces the efficiency of a compressor.

Gas must be compressed and cooled to change it to liquid. If the compression is part of a gas liquefaction process, cooling during compression increases the efficiency of the process.

The gas is cooled between compressor *process stages* and after final discharge.

A cooler connected between *process stages* of a compressor is called an *intercooler*. Cooling between compression stages:

- reduces the gas volume (increases its density) before compression in the next stage
- saves power—intercooling between stages of compression reduces the power needed from the driver
- liquefies any vapours in the gas that might condense during compression—liquid droplets can damage a compressor
- makes lubrication more effective by keeping lubricants cooler
- reduces the chance of damage from overheating the compressor

Gas leaving the final discharge of a compressor is cooled by passing it through an *aftercooler*.

Intercoolers and aftercoolers are types of heat exchanger. In a heat exchanger the hot fluid flows past a cooler fluid. Heat passes from the hotter to the cooler fluid. The cooler fluid may be air, water or a cooler process fluid.

The liquid-cooled type has a drum (the shell) with tubes passing through it. One fluid passes through the tubes while the other flows into and out of the shell, surrounding the tubes as it flows. Heat exchangers are described more fully in a later module in this course. **Figure 6.1** shows a simplified shell and tube cooler.

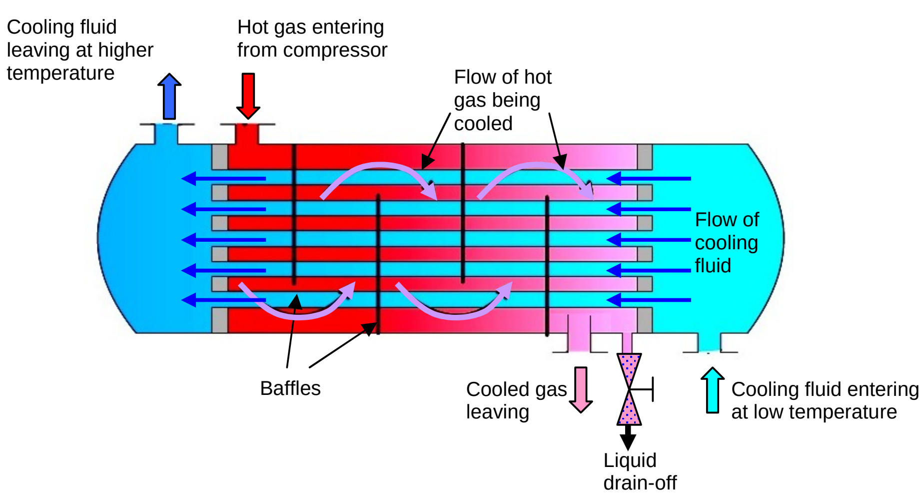


Figure 6.1: Shell and Tube Cooler

The cooling fluid enters one end of the shell. It passes through tubes, where it takes heat from the hot gas, and leaves at the other end of the shell. The hot compressed gas enters the main part of the shell. As it passes through the shell, *baffles* make it flow around the tubes. It loses some of its heat to the cooling fluid by *conduction* through the tube walls. The two fluids flow in opposite directions and do not mix.

Cooled gas leaving an intercooler returns to the compressor for the next compression stage. Any liquid formed drains from the bottom of the intercooler. The cooled gas that leaves an aftercooler passes to a discharge *knock-out drum* (see next section).

Intercoolers have a safety valve, pressure gauge and thermometer on the compressed gas side, and a thermometer on the cooling water side.

Aftercoolers have a pressure gauge and thermometer. If there is a shutoff valve between the aftercooler and the receiver, the aftercooler must also be fitted with a safety valve.

Figure 6.2 shows the water-cooled intercooler and aftercooler on one of the Sulphur STOREX air compressors.

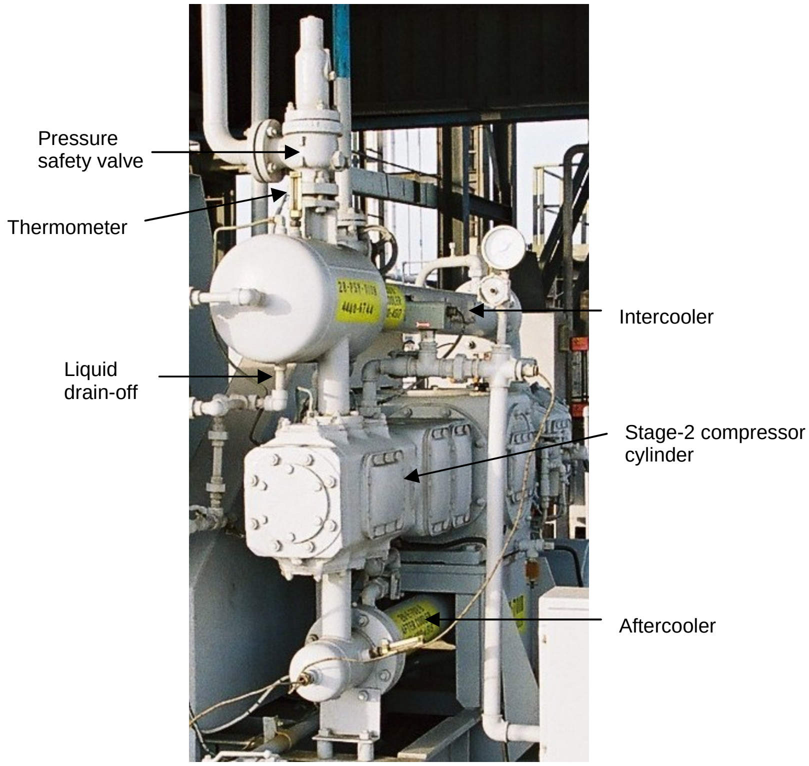


Figure 6.2: Water-cooled Intercooler and Aftercooler for Small Air Compressor

Air-cooled intercoolers and aftercoolers pass the gas through a finned tube. Heat passes through the tube by *conduction* and is lost from the tube surface by *convection*. The fins increase the surface area of the tube. This gives more area for the heat to escape from. Heat is carried away by the surrounding air. Fin fans move this air over the tube fins, helping to remove heat by increasing the convection effect.

Figure 6.3 shows an air-cooled aftercooler for the Vapour Recovery Unit compressors.

Figure 6.3: Air-cooled Aftercooler for VRU Compressor

6.2 Removal of Solids and Liquids

Solid particles entering a compressor can increase wear between sliding surfaces in bearings, etc. They can also affect the operation of valves in reciprocating compressors.

In dynamic compressors, rotational speeds can be very high. Any solid that enters with the gas stream can cause erosion damage to impellers.

Liquid droplets can have a similar effect to solid particles when they hit fast moving impeller vanes.

A knockout drum, often with a filter, located close to the compressor's intake removes solid particles and liquid droplets from the gas entering the compressor. A knockout drum is a long cylindrical drum through which the gas passes. The drum contains baffles to make the gas change direction as it passes through. Solid particles and liquid droplets are heavier (more dense) than the gas. They can not change direction so easily. When the gas flows around a baffle, any liquids or solids hit it and fall to the bottom of the drum. These can then be drained off. Mist extractors remove very small liquid droplets from the air leaving the drum.

Knockout drums may be positioned horizontally or vertically as shown in **Figure 6.4**.

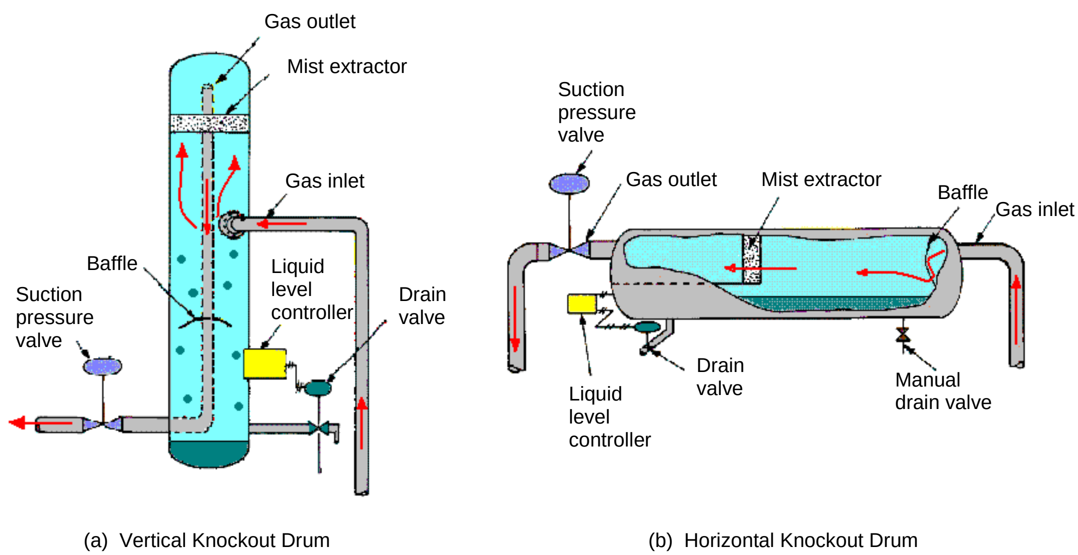


Figure 6.4: Knockout Drums

Knockout drums are not only used at the compressor intake. Gas (or vapour) is turned into liquid by first increasing its pressure and then cooling it. We do not want the gas to start to liquefy while it is in the compressor as this can damage the compressor.

Some gases need less cooling and lower pressures to change them to liquid than others. If the gas being compressed is a mixture of gases, those that liquefy more easily may start to change inside the compressor. To avoid this, the gas may also pass through knockout drums between compressor *process stages*. It also passes through a discharge knockout drum after the final stage. This makes sure that gas entering the next stage of the process contains no liquid droplets.

Figure 6.5 shows the suction and discharge knockout drums for the New Boil-off Gas Compressor.

(a) Suction Knockout Drum

(b) Discharge Knockout Drum

Figure 6.5: Knockout Drums for New BOG Compressor

Knockout drums are sometimes called *scrubbers* or *separators*.

6.3 Compressor Lubrication

Most large compressors have an external lubricating-oil (*lube-oil*) system to supply lubricant under pressure to bearings etc. The main parts of an external lube-oil system are:

- oil reservoir—a tank to hold oil not being circulated
- strainers and filters—to remove solid particles from the oil
- pumps—to pressurise and circulate the oil
- coolers—to reduce the oil temperature and increase its viscosity

A strainer in the pump suction line removes larger solid particles before the oil enters the pump. Oil is pumped from the reservoir, through the strainer to coolers and filters before reaching the bearings. It then flows back to the reservoir by gravity.

Because lubrication is so important, there is usually a second, back-up pump in case the main pump fails. Two filters are fitted so that lubrication can continue while one filter is being replaced. There are controls to monitor pressures, temperatures and levels of lubricant in the system. **Figure 6.6** shows a P&ID for a typical centrifugal compressor lubrication-oil system.

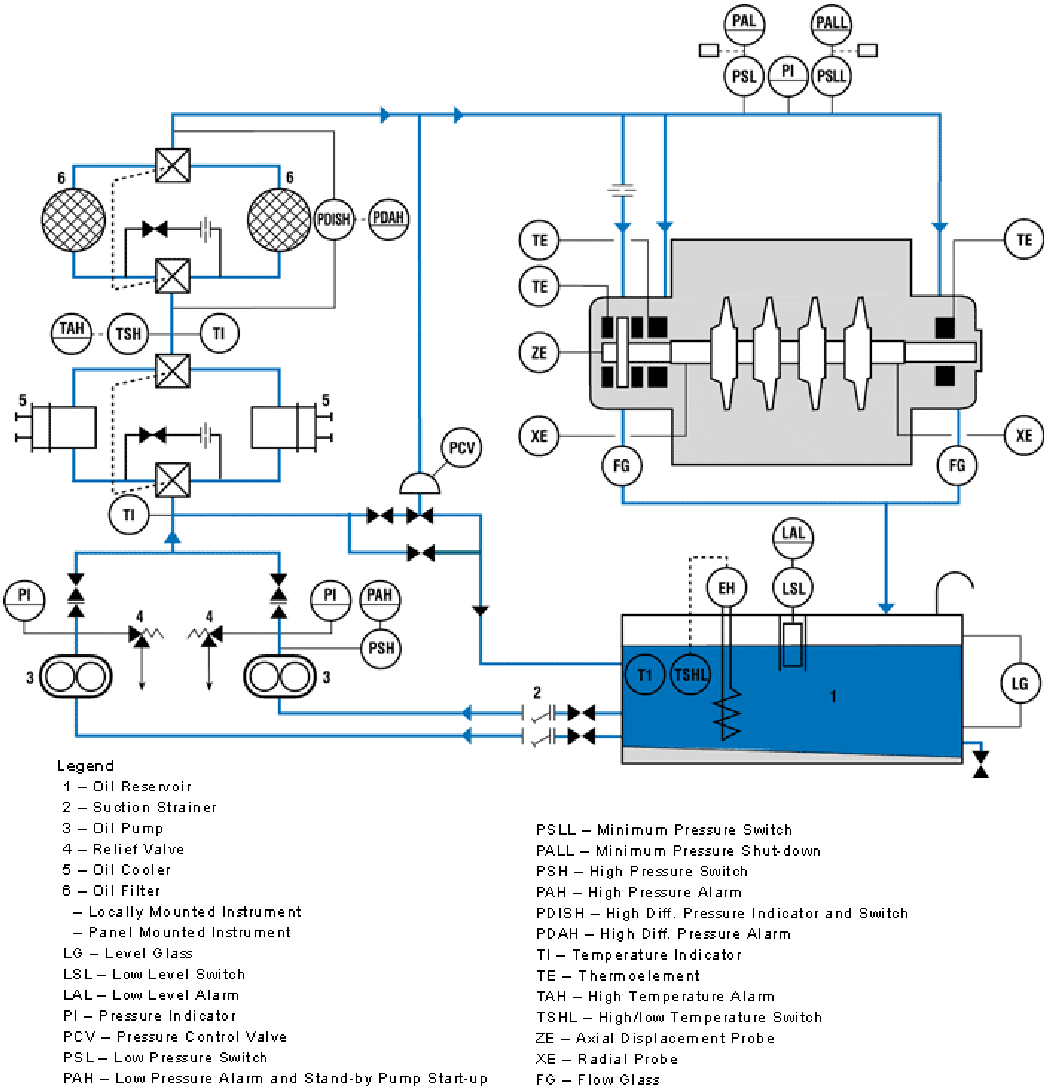


Figure 6.6: Compressor Lube-oil P&ID

Some systems include a *dump tank* that feeds oil to the bearings by gravity from a small reservoir. The dump tank valve opens automatically if the main system fails.

Figure 6.7 shows the lube-oil systems for two of the reciprocating compressors on the ADGAS plant.

(a) Lube-oil Supply for VRU Compressor

(b) Lube-oil Supply for New BOG Compressor

Figure 6.7: External Lube-oil Supply Systems

Now try **Exercise 7**

7 Compressor Maintenance

Because of the similarity between compressors and pumps, most of what was said about maintenance in the *Pumps* module also applies to compressors. Most of the items that you should check for damage and items that can be repaired or replaced are the same.

Reciprocating compressor valve construction is different. The sealing surfaces are usually formed between very flat plates. Valve lapping is done on a rotating lapping table shown in **Figure 7.1**.

Figure 7.1: Valve-lapping Table

Centrifugal compressors make more use of labyrinth seals and these are used in place of the wear rings used in pumps.

Mechanical seals used in compressors can be more complicated than those used in pumps. They often use gas at high pressure instead of, or as well as liquid to stop product gas from escaping. These are described in the *Seals* module in this course.

8 P&ID and PFD Symbols for Compressors and Auxiliaries

Most ADGAS PFDs and P&IDs use one symbol for all types of compressors. Intercoolers and aftercoolers are both types of heat exchanger. No special symbols are used for these.

Snubbers and knockout drums are shown as vessels or drums.

Table 8.1 shows these symbols.

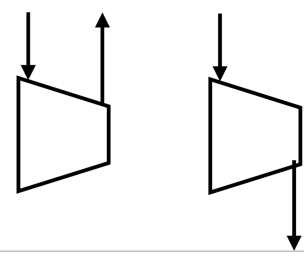
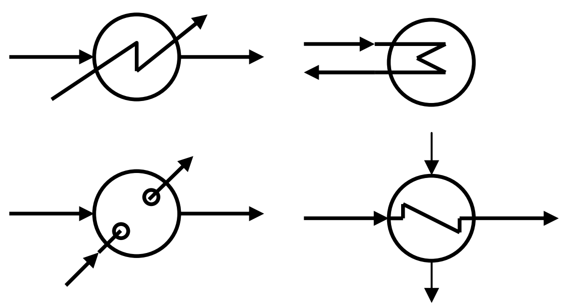
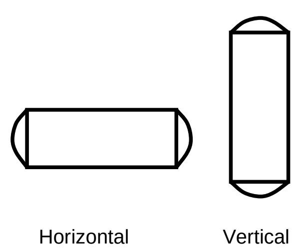
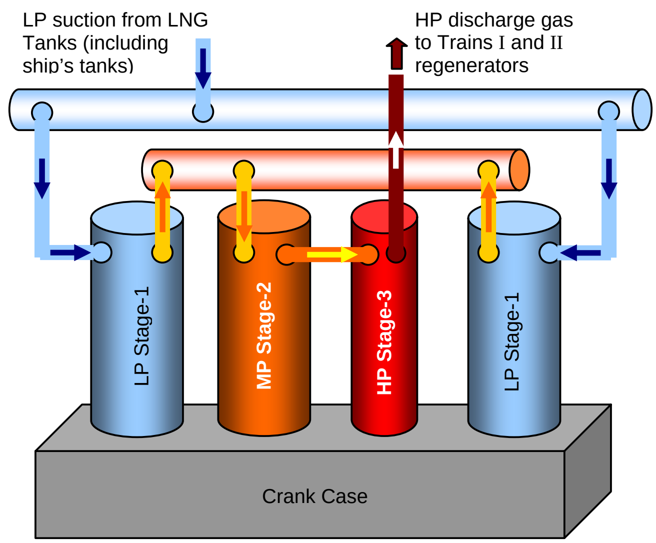
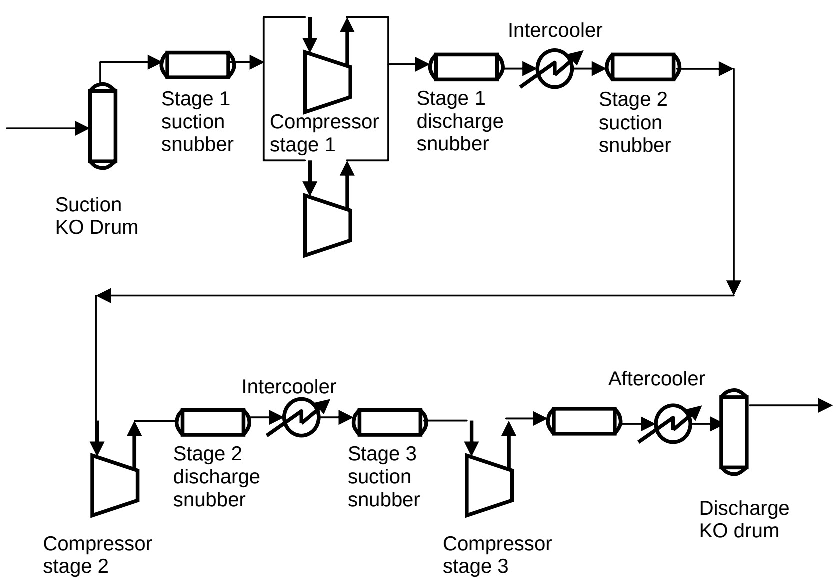
Equipment	Symbol
Compressor (Note that flow enters at the larger end and leaves at the smaller end to show compression of the gas)	
Intercooler Aftercooler (Heat exchanger symbols)	
Snubber Knockout drum; scrubber; separator; suction and discharge drums (Drum or vessel symbols)	

Table 8.1: Compressor and Auxiliary Equipment Symbols

Figure 8.1(a) shows the drawing of the Old BOG compressor arrangement you saw in **Section 4.1.5**. In **Figure 8.1(b)** you can see the diagrammatic version of the same compressor with knockout drums, snubbers and coolers added.



(a) Old BOG Compressor—Simplified Drawing



(b) Old BOG Compressor—PFD showing Auxiliary Equipment

Figure 8.1: Comparison between Simplified Drawing and PFD of Old BOG Compressor

Now try **Exercise 8**

9 Summary

In this module you have looked at the different designs of compressors that are available.

You have looked in more detail at the main reciprocating and centrifugal compressors used on the ADGAS plant and you should now have seen these on site visits.

You should be able to identify most of the compressors on the plant and know how each one functions. You should be able to describe how casings are connected for different stages of compression and the purposes of compressor auxiliary equipment.

From the information in this module and from that in the *Pumps* module you should know where to look for wear and damage when you are maintaining a compressor. You should also know what is meant by compressor surge.

More detailed information about seals and heat exchangers is given in other modules in this course.

10 Glossary

Here are some words used in this module that might be new to you. You will find these words in *coloured italics* in the notes. There is a short definition in a box near the word in the notes.

Word	First Used on Page:	Part of Speech	Meaning	Example of Use
Auxiliary	76	adjective	Additional	ADGAS Utilities provide auxiliary services for the Production Trains.
Boost	6	verb	To increase or raise.	The company is always trying to think of ways to boost production.
Disturb	53	verb	To interfere with the normal arrangement or function of something	It is difficult to work when you keep being disturbed by telephone calls.
Restricted	74	adjective	Reduced or limited.	Access to Das Island is restricted for security reasons.
Several	49	quantifier	More than two but not a great number.	There were several people at the meeting that I had not met before.
Severe	74	adjective	Strong or great, but in a bad sense.	There should be more severe penalties for driving dangerously.
Surge	74	noun/verb	To suddenly move forward.	There was a surge from the crowd as the president stepped off the plane.

Exercises