Pneumatics

1. Principles

A pneumatic system is a fluid power system which uses the energy of a prime mover (electric or diesel motor) in order to drive a compressor and produce air at a pressure higher than atmospheric pressure. Potential energy is stored within the compressed air, which is confined in the storage and distribution systems. When the air is used to operate a machine or tool, it will expand and release its energy. The power obtained from the tool is related to the pneumatic system's operating pressure and the air-flow rate.

The reason for using pneumatics, or any other type of energy transmission on a machine, is to perform work. The accomplishment of work requires the application of kinetic energy to a resisting object, resulting in the object moving through a distance. In a pneumatic system, energy is stored in a potential state in the form of compressed air. Working energy (kinetic energy and pressure) results in a pneumatic system when the compressed air is allowed to expand. For example, a tank is charged to 100 PSIA with compressed air. When the valve at the tank outlet is opened, the air inside the tank expands until the pressure inside the tank equals the atmospheric pressure. Air expansion takes the form of airflow.

1.1. Pneumatic circuit

Pneumatic control systems can be designed in the form of pneumatic circuits. A pneumatic circuit is formed by various pneumatic components, such as cylinders, directional control valves, flow control valves, etc. Pneumatic circuits have the following functions:

- To control the injection and release of compressed air in the cylinders.
- To use one valve to control another valve.

1.2. Main pneumatic components

Pneumatic components can be divided into two categories:

- Components that produce and transport compressed air.
- Components that consume compressed air.

All main pneumatic components can be represented by simple pneumatic symbols. Each symbol shows only the function of the component it represents, but not its structure. Pneumatic symbols can be combined to form pneumatic diagrams. A pneumatic diagram describes the relations between each pneumatic component, that is, the design of the system.

1.3. The production and transportation of compressed air

Examples of components that produce and transport compressed air include compressors and pressure-regulating components.

Compressor

A compressor can compress air to the required pressures. It can convert the mechanical energy from motors and engines into the potential energy in compressed air. A single central compressor can supply various pneumatic components with compressed air, which is transported through pipes from the cylinder to the pneumatic components. Compressors can be divided into two classes: reciprocatory and rotary.

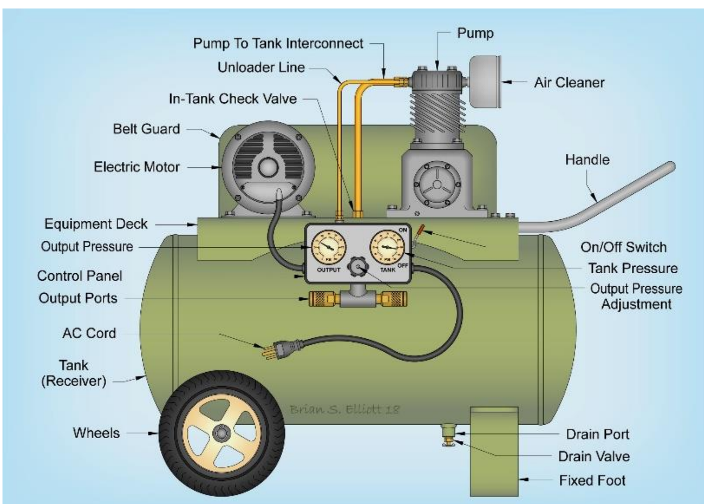

Figure 12. Air compressor

Pressure-regulating component

Pressure-regulating components are formed by various components, each of which have their own pneumatic symbol:

- Filter – can remove impurities from compressed air before it is fed to the pneumatic components.
- Pressure regulator – to stabilize the pressure and regulate the operation of pneumatic components
- Lubricator – to provide lubrication for pneumatic components.

2. Air supply system

The pneumatic system carries power by employing compressed gas (generally air) as a fluid for transmitting the energy from an energy-generating source to an energy – requiring point to accomplish useful work.

Functions of components

- Pneumatic actuator converts the fluid power into mechanical power to do useful work
- The compressor is used to compress the fresh air drawn from the atmosphere.
- The storage reservoir is used to store a given volume of compressed air.
- Valves are used to control the direction, flow rate, and pressure of compressed air.
- An external power supply (Motor) is used to drive the compressor.
- The piping system carries the pressurized air from one location to another.

3. Seals

3.1. Introduction

Excessive leakage in a pneumatic circuit reduces efficiency and results in power loss or creates a housekeeping problem or both. Here you will be introduced to the main types of seal and their applications. You will be required to identify, inspect, and change seals in your practical tasks on compressors, actuators, pressure valves, and directional control valves. From your reading, you will have learned that pneumatic seals prevent leakage by closing off air passageways; they seal gaps to prevent fluid loss. Seals have two general types of application, static and dynamic, as illustrated below.

3.2. Static Seals

A static seal is one that is compressed between two rigidly-connected parts to seal the fluid passage, having a compression of approximately 25 percent.

3.3. Dynamic Seals

A dynamic seal is one that is installed between two parts which move relative to one another, for example on a rotating shaft or a sliding piston. The sealing principle requires the seal to be compressed slightly (approximately 10 percent) during installation. The seal is allowed to flex in the sealing chamber and a mechanical or fluid pressure forces the seal to distort and block the passageway. These seals require lubrication during movement or sealing.

4. Piping, joints, and fittings

The main types of pipe and other fluid conductors used in pneumatic systems are as follows.

- **Steel pipe** – Inexpensive steel pipes are often used for pipe over 13 millimeters in diameter (half-inch) in fixed installations where the air is conducted along straight paths and use can be made of welding fittings. Small-diameter pipes are connected with threaded joints, whereas large-diameter pipes are connected with flange joints.
- **Copper and brass pipes** – These are often used when corrosion resistance, heat resistance, and high rigidity are required. Annealed copper pipes have good formability for bending. Brass pipes have higher strength than copper pipes but cannot be worked as easily because of their high strain-hardening nature. Stainless steel pipes have poor formability and are primarily used in cases when very large diameter pipes and straight pipes are necessary.
- **Nylon tube** – This is suitable where small-diameter pneumatic tubing is necessary. This is because of its good corrosive resistance, high strength, and medium hardness, despite its poor heat resistance. However, it cannot be used where it would undergo shock, since it is easily deformed by a strong force. Because its rigidity is very low, it cannot support a filter without additional support. There are metric and imperial diameter dimensions available, so combinations of tubing and joints must be examined carefully. In addition, soft polyurethane tube is usually used for tubing which is under six millimeters in diameter.
- **Rubber hose** – Since rubber hose has good elasticity, it is the most suitable where an operator, using air-actuated tools, needs to pull the hose to different positions.
- **Screw-type joints** – There are external threads on the ends of pipes and internal threads in the joint fittings. These are connected by screwing the pipe into the fitting. Generally, a tapered thread is used for piping, which makes the joint seal itself sufficiently. Even though high-precision tapered threads can achieve a good seal, sealing cement or sealing tape is used for a much better connection.
- **Flange joints** – A flange is formed or welded at the end of a pipe and is then connected to the flat surface of another flange. Flanges are usually welded to piping but sometimes brazing or bolts are used. Since flange joints can be easily connected or disconnected and sealed with a gasket, they are commonly used for piping around compressors and very large diameter pipes.

Figure 13. Various pipe fittings

5. Valves

5.1. Directional control valve

Directional control valves ensure the flow of air between air ports by opening, closing and switching their internal connections. Their classification is determined by the number of ports, the number of switching positions, the normal position of the valve and its method of operation. Common types of directional control valves include 2/2, 3/2, 5/2, etc. The first number represents the number of ports; the second number represents the number of positions.

Directional air control valves are the building blocks of pneumatic control. Symbols representing these valves provide a wealth of information about the valve it represents. Symbols show the methods of actuation, the number of positions, the flow paths, and the number of ports.

5.1.1 Two-Way Directional Valve:

A two-way directional valve consists of two ports connected to each other with passages which are connected and disconnected. In one extreme spool position, port A is open to port B; the flow path through the valve is open. At the other extreme, the large diameter of the spool closes the path between A and B; the flow path is blocked. A two-way directional valve provides an on-off function.

5.1.2. Three-Way Directional Valve

A three-way directional valve consists of three ports connected through passages within a valve body that are shown here as port A, port P, and port Ex. If port A is connected to an actuator, port P to a source of pressure and port Ex is open to exhaust, the valve will control the flow of air to (and exhaust from) Port A. The function of this valve is to pressurize and exhaust one actuator port. When the spool of a three-way valve is in one extreme position, the pressure passage is connected with the actuator passage. When in the other extreme position, the spool connects the actuator passage with the exhaust passage.

5.1.3. Four-Way Directional Valve

Perhaps the most common directional valve in simple pneumatic systems consists of a pressure port, two actuator ports, and one or more exhaust ports. These valves are known as “four-way valves” since they have four distinct flow paths or "ways" within the valve body.

A common application of the four-ported four-way directional valve is to cause reversible motion of a cylinder or motor. To perform this function, the spool connects the pressure port with one actuator port. At the same time, the spool connects the other actuator port with the exhaust port. This is a four-ported four-way valve.

5.1.4. Five-Port / Four-Way Directional Valve

Four-way valves are also available with five external ports, one pressure port, two actuator ports, and two exhaust ports. Such valves provide the same basic control of flow paths as the four-ported version but have individual exhaust ports. In the fluid power field, this is referred to as a "five-ported, four-way valve." This type of valve brings all flow paths to individual external ports. The pressure port is connected to system pressure after a regulator. Actuator ports are connected to inlet and outlet ports of a cylinder or motor. Each exhaust port serves an actuator port.

5.1.5. 2/2 Directional control valve:

The structure of a 2/2 directional control valve is very simple. It uses the thrust from the spring to open and close the valve, stopping compressed air from flowing towards working tube ‘A’ from air inlet ‘P’. When a force is applied to the control axis, the valve will be pushed open, connecting ‘P’ with ‘A’. The force applied to the control axis has to overcome both air pressure and the repulsive force of the spring. The control valve can be driven manually or mechanically, and can be restored to its original position by the spring.

5.1.6. 3/2 Directional control valve

A 3/2 directional control valve can be used to control a single acting cylinder. The open valves in the middle will close until ‘P’ and ‘A’ are connected together. Then another valve will open the sealed base between ‘A’ and ‘R’ (exhaust). The valves can be driven manually, mechanically, electrically or pneumatically. 3/2 directional control valves can further be divided into two classes: Normally open type (N.O.) and normally closed type (N.C.)

5.1.7. 5/2 Directional control valve

When a pressure pulse is put into the pressure control port 'P', the spool will move to the left, connecting inlet 'P' and work passage 'B'. Work passage 'A' will then release air through 'R1' and 'R2'. The directional valves will remain in this operational position until signals of the contrary are received. Therefore, this type of directional control valves is said to have the function of 'memory'.

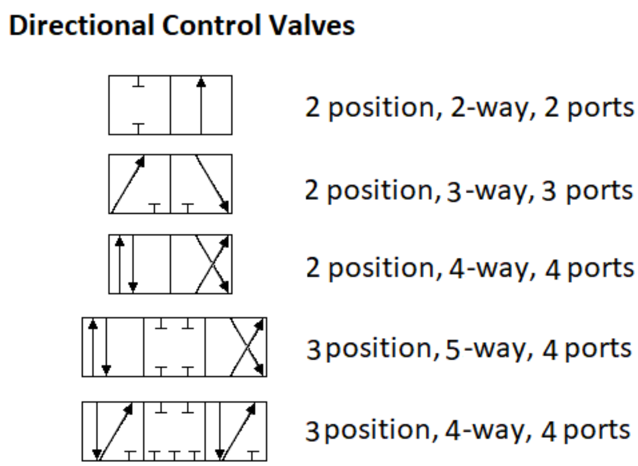

Figure 14. Common directional control valves

5.2. Control valve

A control valve is a valve that controls the flow of air. Examples include non-return valves, flow control valves, shuttle valves, etc.

5.2.1. Non-return valve

A non-return valve allows air to flow in one direction only. When air flows in the opposite direction, the valve will close.

5.2.2. Flow control valve

A flow control valve is formed by a non-return valve and a variable throttle

5.2.3. Shuttle valve

Shuttle valves are also known as double control or single control non-return valves. A shuttle valve has two air inlets 'P1' and 'P2' and one air outlet 'A'. When compressed air enters through 'P1', the sphere will seal and block the other inlet 'P2'. Air can then flow from ‘P1’ to ‘A’. When the contrary happens, the sphere will block inlet ‘P1’, allowing air to flow from ‘P2’ to ‘A’ only.

6. Cylinders

6.1. Sizing a Cylinder

To determine the size of the cylinder that is needed for a particular system, certain parameters must be known. First of all, a total evaluation of the load must be made. This total load is not only the basic load that must be moved but also includes any friction and the force necessary to accelerate the load. Also included must be the force needed to exhaust the air from the other end of the cylinder through the attached lines, control valves, etc. Any other force that must be overcome must also be considered as part of the total load. Once the load and required force characteristics are determined, a working pressure should be assumed. This working pressure that is selected MUST be the pressure seen at the cylinder's piston when motion is taking place. It is obvious that the cylinder's working pressure is less than the actual system pressure due to the flow losses in lines and valves.

With the total load (including friction) and working pressure determined, the cylinder size may be calculated using Pascal's Law. Force is equal to pressure being applied to a particular area. The formula describing this action is:

Force = Pressure * Area

Force is proportional to pressure and area. When a cylinder is used to clamp or press, its output force can be computed as follows**:**

F = P * A

P = pressure (PSI (Bar) (Pascal's))

F = force (pounds (Newtons))

A = area (square inches (square meters))

These pressure, force and area relationships are sometimes illustrated as shown below to aid in remembering the equations.

Force

Force is an effort capable of causing a load to move or to stop it from moving. The unit of measurement is the *Newton*, a force which can be best appreciated by placing a mass of one kilogram in your hands, as illustrated below. The sensation you experience by supporting the weight is caused by a force of approximately 10 Newtons, which your hands must provide in order to prevent the one-kilogram mass from falling due to gravity (at an acceleration rate of 9.81 meters per second).

A force of one Newton is that which, if applied to a mass of one kilogram, would give it an acceleration rate of one meter per second.

Area

In the context of pneumatics, the area is the surface over which the force is applied. Its unit of measurement is the *square meter*. The example below shows how to calculate the surface area of a pneumatic piston with a diameter (d) of 100 mm (or 0.1 m).

Note: We must convert millimeters to meters and thus divide by 1000. The value of π is approximately 3.14.

$$\text{Area} = \frac{\pi \times d^2}{4}$$

$$\text{Area} = \frac{\pi \times 0.1^2}{6}$$

$$\text{Area} = \frac{\pi \times 0.01}{4}$$

$$\text{Area} = \frac{0.0314}{4}$$

$$\underline{\textbf{Area} = \textbf{0.00785 m}^2}$$

Pressure

Pressure is produced when a force is applied over an area. The unit of measurement is the *Pascal*, which is equivalent to the force of one Newton applied over an area of one square meter.

Fluids have no shape of their own, they will take the shape of the container and, in a contained fluid, the pressure is transmitted equally in all directions. We can use these principles to transmit power and multiply a force.

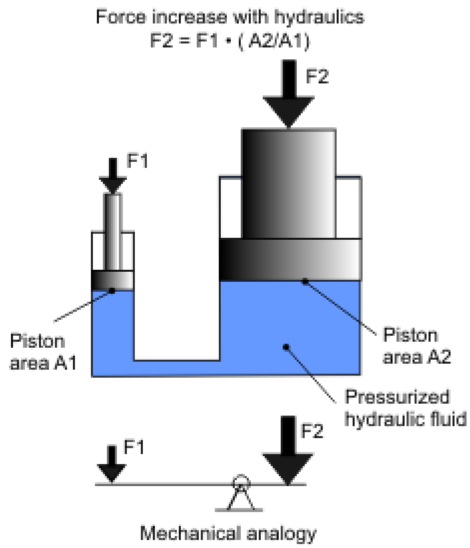

Figure 15. Force multiplication using hydrostatic pressure

For example, as illustrated above, if a 1000 Newton force is applied to a piston with a surface area of one square meter, it will produce a pressure of 1000 Pascals, as demonstrated by the following calculation.

Pascal's laws of fluid pressures state that this same pressure is transmitted to all points of the container – that is, it acts equally in all directions and at right angles to any surface in contact with the fluid. Therefore, this pressure is also applied to the five-square-meter piston, achieving a five-fold multiplication of the original force, as shown in the calculation below.

$$\text{Pressure} = \frac{\text{force}}{\text{area}} = \frac{1000\text{ N}}{1\text{m}^2} = 1000\text{ Pa}$$

$$\text{Force} = \text{pressure} \times \text{area} = 1000\text{ Pa} \times 5\text{ m}^2 = 5000\text{ N}$$

6.2. Laws governing compressed air

Atmospheric pressure

The Earth's atmosphere is a sea of air which contains approximately 78 percent nitrogen, 20 percent oxygen, 4 percent water vapor and numerous smaller quantities of a number of other gases such as argon, carbon dioxide, neon, helium etc. This envelope of gas exerts a pressure on everything about us and its value is dependent upon its position above or below sea level. For example, at sea level, the average atmospheric pressure is 101.3 kilopascals. However, on top of a mountain 1500 meters high, the pressure is 84 kilopascals and in Death Valley (America), which is 85 meters below sea level, the pressure is 105 kilopascals. Therefore, the term ‘atmospheric pressure’ refers to the gravity force exerted per unit area by the mass of air above us. As we ascend, the pressure decreases because the mass of air above us decreases.

Gauge pressure

The term ‘gauge pressure’ refers to the pressure reading on gauges used to measure the pressure of gases in vessels such as oxygen cylinders and air receivers etc. These gauges are calibrated to show pressures above or below atmospheric pressure. A gauge reading of 300 kPa indicates that the pressure of a gas is really 300 kPa above normal atmospheric pressure.

Absolute pressure

Absolute pressure is the sum of atmospheric pressure and gauge pressure. In other words, absolute pressure is the total pressure above a perfect vacuum. Gauges that read absolute pressures usually have the letter ‘A’ inscribed on their face.

6.3. Cylinder types

Single acting cylinder - a cylinder in which air pressure is applied to the movable element (piston) in only one direction.

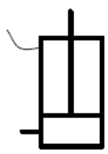

Figure 16. Single acting cylinder

Spring return cylinder - a cylinder in which a spring returns the piston assembly.

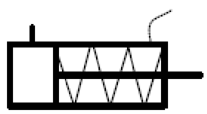

Figure 17. Single acting cylinder with a spring return

Ram cylinder - a cylinder in which the movable element is the piston rod.

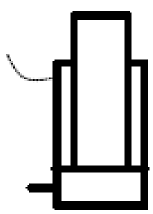

Figure 18. Ram cylinder

Double acting cylinder - a cylinder in which air pressure may be alternately applied to the piston to drive it in either direction.

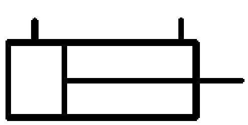

Figure 19. Double acting cylinder

***Double acting – double rod cylinder* -** Double acting cylinder with a piston rod extending from each end. The piston rods are connected to the same piston. Double rod cylinders provide equal force and speed in both directions.

Figure 20. Double acting – double rod cylinder

6.4. Direct control

A difference between a single acting cylinder and a double acting cylinder is that a double acting cylinder uses a 5/2 directional control valve instead of a 3/2 directional control valve. Usually, when a double acting cylinder is not operated, outlet 'B' and inlet 'P' will be connected. In this circuit, whenever the operation button is pushed manually, the double acting cylinder will move back and forth once. In order to control the speed in both directions, flow control valves are connected to the inlets on both sides of the cylinder. The direction of the flow control valve is opposite to that of the release of air by the flow control valve of the single acting cylinder. Compared to the throttle inlet, the flow control valve is tougher and more stable. Connecting the circuit in this way allows the input of sufficient air pressure and energy to drive the piston.

7. Air Motors

7.1. Introduction

A pneumatic motor converts potential energy stored in a fluid to continuous mechanical rotary motion and torque. The design and operation of pneumatic motors resemble, in many respects, those of pneumatic pumps. All pneumatic motors have several design features in common. For example, all must have a driving surface area subject to the pressure differential. In gear, vane and rotary abutment motors, this surface is rectangular. In radial and axial piston motors, the surface is circular. This surface area must be connected mechanically to an output shaft and there must be a way of timing the porting of the pressure fluid to the pressure surface in order to provide continuous rotation.

A rotary actuator, or fluid motor, may use either sliding vanes, gears or pistons to convert the pneumatic energy to a mechanical rotary movement. The circuit symbols shown below are for rotary actuators.

7.2. Air MotorsTypes

7.2.1. Vane motors

Vane motors consist of a rotor, ring, vanes and a port plate which has kidney-shaped ports to allow the fluid into and out of the motor. As a combined unit, the rotor, vanes, and ring are called a “cartridge”.

Vane motors are positive-displacement motors that produce torque from the pneumatic pressure acting upon their vanes. The vanes are held in place and are allowed to slide, by a rotor. The vanes are held against the cam ring by pneumatic pressure, as well as springs and centrifugal force. The rotor is attached to a splined driveshaft which drives the load, as illustrated below.

7.2.2. Gear motors

Gear motors are also positive displacement type, with rotation and torque being a result of the pneumatic pressure acting upon the gear teeth, as shown below. The main parts of an external gear motor are also illustrated. The gear motor consists of two spur gears and a housing or case. The drive gear is attached to the output shaft which provides the drive to the load.

7.2.3. Piston motors

Piston motors may be either axial or radial in configuration. Both types are positive-displacement motors. Radial piston motors are usually used where high torque at a relatively low speed is required. The main parts of an axial piston motor are illustrated below. The valve plate has kidney-shaped ports so as to allow air sufficient time to enter and discharge from the cylinder block. The cylinder block houses the pistons, which are allowed to slide axially inside the block. Attached to the pistons are the slippers. These ride on the swash plate and are held in place by a retention plate which is spring-loaded. Once the motor is running, pneumatic pressure also holds the slippers and pistons onto the swash plate.

When pressure is applied to the motor as illustrated above, the pistons push against the swash plate, which is at an inclined angle. This produces a tangential force, which causes the slippers to ride up the inclined surface. The pistons and cylinder block then begin to rotate and produce torque. To change the direction of rotation, the air flow to the motor is reversed. The cylinder block is splined to a drive shaft, the rotation of which can be used to drive a load.

Torque

Two terms commonly used in relation to motors are **running torque** and **start-up (breakaway) torque**. Running torque is the torque that is required by the motor to keep the load moving. Start-up torque is the torque required to overcome the inertia and internal friction of the motor and drive train to accelerate the load from a stationary position. Generally, start-up torque is much higher than the running torque. Torque is the force acting at a radial distance measured from the center of the driveshaft, and can be calculated by using the formula below.

$$\text{Motor torque (Nm)} = F \times R \times \eta_{HM}$$

where F = is the force applied (in Newtons)

R = is the radial distance measured from the centre of the motor shaft in metres

η_{HM} is the hydro-mechanical efficiency of the motor (expressed as a percentage).

8. Drying compressed air

All atmospheric air contains water vapor: more at high temperatures and less at lower temperatures. When the air is compressed, the water concentration increases. For example, a compressor with a working pressure of 7 bar and a capacity of 200 l/s that compresses air at 20˚C with a relative humidity of 80% will release 10 liters/hour of water in the compressed air line. To avoid problems and disturbances due to water precipitation in the pipes and connected equipment, the compressed air must be dried. This takes place using an after-cooler and additional drying equipment. The term "pressure dew point" (PDP) is used to describe the water content in the compressed air. It specifically refers to the temperature at which water vapor condenses into water at the current working pressure. Low PDP values indicate that small amounts of water vapor are present in the compressed air.

It is important to remember that the atmospheric dew point cannot be compared with PDP when comparing different dryers. For example, a PDP of +2˚C at 7 bar is equivalent to –23˚C at atmospheric pressure. To use a filter to remove moisture (lower the dew point) simply does not work. This is because further cooling leads to the continued precipitation of condensated water. You can select the main type of drying equipment based on the pressure dew point. When taking cost into account, the lower the dew point required, the higher the investment.

A compressor that delivers 200 liters/second of air also supplies approx. 10 liters/hour of water when compressing air at 20˚C. Problems due to water precipitation in the pipes and equipment are avoided by the use of after-cooler and drying equipment.

9. Air Compressor

An air compressor is a machine that takes in air at a low pressure (usually atmospheric) and compresses it to a higher pressure. The compressor converts the mechanical energy of a prime mover, such as an electric motor or an internal combustion engine, into the potential energy of compressed air. This is then used to operate a machine by activating a pneumatic cylinder or rotating a pneumatic motor.

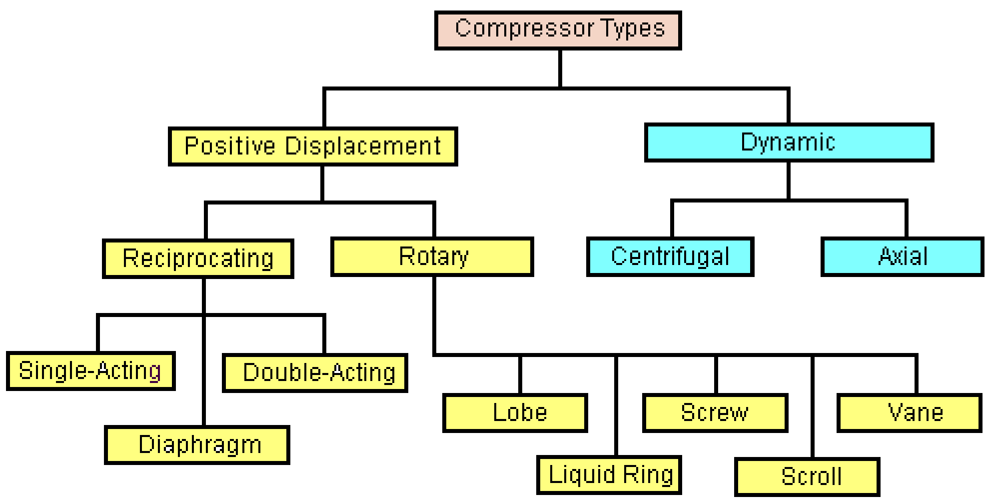

Figure 21. Types of compressors

9.1. Principles of operation

Positive-displacement compressors produce a pulsating flow but provide a positive internal seal against slippage – and the compressor's flow variation is negligible when compared with system pressure variation. If the compressor's discharge is fully restricted, the flow will still continue, so positive-displacement compressors must have some avenue for the fluid medium to return to the atmosphere. This is generally achieved by the installation of a relief valve on the compressor's discharge line or receiver. This valve opens if the compressor's discharge flow is halted or restricted, allowing the pressurized air flow access to the atmosphere and thus providing a safety release. Displacement compressors draw successive volumes of air into a confined space and compress the air by reducing its volume. This reduction in volume is accompanied by increases in pressure and temperature. Positive-displacement compressors are further classified as either rotary or reciprocating. Dynamic compressors compress air by using a high-speed rotating element to accelerate the air. This type of compressor draws in the air continuously and speeds it up, imparting high amounts of kinetic energy. Some of this energy is converted to pressure energy when the air slows down again, while the remainder is converted to heat. Dynamic compressors are further classified as radial flow or axial flow. Compressors are made up of one or more basic elements. Those with one element, or several elements working in parallel, are classified as single-stage compressors.

However, many applications for compressors involve conditions beyond the capabilities of single-stage compressors, because high compression ratios may cause excessive temperatures in discharged air, as well as other potential design problems.

During compression, air temperature increases with pressure. As the temperature rises, the work required to keep compressing the air increases. To overcome this problem, air can be compressed in stages, with the heat of compression being reduced between each stage. Cooling the air between stages reduces its volume and temperature before it enters

the next stage. This improves the volumetric efficiency, which reduces the cost of air compression.

Each stage is a basic compressor within itself and is sized to operate in series with one or more other elements. Although they are individual units, they are generally driven from a single power source.

9.2. Positive-displacement compressors

Positive-displacement compressors are divided into two main groups – reciprocating (including piston and diaphragm compressors) and rotary (including vane and screw compressors and roots blowers).

<u>9.2.1. Reciprocating compressors</u>

These machines are designed to cover a wide range of operating pressures. The operating cycle is that air is drawn through the suction valve at low pressure, compressed in the cylinder (or cylinders) to the desired pressure and then discharged to an air receiver. An essential feature of a well-designed reciprocating compressor is that the clearance between the piston and cylinder cover at top dead centre is kept to the smallest practical limit, because when the piston starts its suction stroke, all the air trapped in the clearance space has to ‘re-expand’ to atmospheric pressure before any new air can be admitted to the cylinder. A large clearance would seriously affect efficiency because air admission could not start until the piston had traveled a considerable distance of its stroke. Another essential feature is that the piston should be airtight, meaning that the piston rings need very careful fitting. Otherwise, leakage past the rings will occur with a resultant loss of efficiency. Pistons are usually fitted with ground, centrifugally cast rings. These rings have bedding with equal pressure at all points in the ground and honed cast-iron cylinders, thereby reducing frictional losses to a minimum. Also fitted are large water jackets enveloping the cylinders, to help in heat reduction.

9.2.1.a. Reciprocating piston compressors

These are the oldest and, for small and medium power requirements, still the most common type of air compressor used in the industry. A reciprocating piston compressor is similar in construction to an internal combustion engine, the main difference being the construction of the inlet and delivery valves, as illustrated below. The reciprocating compressor uses automatic spring-loaded valves, which open only when a pressure differential exists across them. Inlet valves open when the pressure in the cylinder is slightly less than the intake pressure and delivery valves open when the pressure in the cylinder is slightly higher than the discharge pressure.

A two-stage piston compressor compresses air in two separate steps, using pistons with different diameters. The piston with the larger diameter performs the first stage of compression. The smaller piston compresses air in the second stage. As the crankshaft is turned by its prime mover, the large-diameter piston strokes downward. Air enters the chamber from the atmosphere through the open inlet valve. When the piston starts its upward movement, the inlet valve closes. Air is compressed (and heated) until a certain pressure is reached, at which point the outlet valve opens, discharging hot, compressed air. This air is then directed by means of a tube, called an intercooler, to the second-stage piston. The air is cooled by means of air blowing over the tube or water flowing across the tube. By the time it reaches the second-stage piston, a great portion of the heat from the first-stage compression has been dissipated.

The cooler air is now ready to be compressed a second time. With compressed air at its inlet, the smaller-diameter piston is pulled downward. Compressed air then fills the chamber and the inlet valve closes. The piston is stroked upward, compressing the air further. As it discharges from the compressor, the compressed air is at an elevated temperature. However, it is not nearly as much above ambient temperature as it would be if one stage were used for the same output. Two-stage compressors do not waste as much energy in compressing air as single-stage units.

9.2.1.b. Diaphragm compressors

This type of compressor belongs to the piston compressor group. The piston is separated from the suction chamber by a diaphragm – so the air does not come into contact with the reciprocating parts. Thus, the air is always kept free of oil. For this reason, its use is preferred in the foodstuffs, pharmaceutical, and chemical industries.

9.2.2. Rotary compressors

9.2.2.a. Vane or sliding vane

Rotary compressors employ an eccentrically mounted rotor which rotates in a cylindrical housing that has inlet and outlet slots. The advantages of this type of compressor are its compact dimensions, its quiet running, and its smooth, steady air delivery.

Sliding vanes are contained in slots in the rotor and form chambers with the cylindrical wall. When rotating, the centrifugal energy forces the vanes against the wall and, owing to the shape of the housing, the chambers are increased or reduced in size.

9.2.2.b. Screw compressors

These consist of two intermeshing rotors, one having a convex profile and the other a concave profile. There are fine tolerances both between the screws themselves and between them and the surrounding casing. The screws are usually kept from contacting each other by timing gears. Air enters one end of the casingcasings, is trapped between the screw flutes, and is forced out of the compressor outlet. These compressors typically operate at high revolutions-per-minute rates.

9.2.2.c. Roots blower

In a Roots blower type of compressor, the air is conveyed from one side to the other without any change in volume. It is trapped between two lobes and the compressor casing, being transported to the outlet. The rotating lobes are prevented from contacting each other by timing gears and the lobes' edges produce the necessary sealing on the pressure side.

9.3. Dynamic compressors

9.3.1. Radial flow compressors

This type of compressor is properly called a blower. It delivers large quantities of air at low pressure, with a stage pressure ratio of four being about the maximum feasible. The principle of operation is that, when the shaft is rotated, the effect of centrifugal force upon the air within the impeller causes its compression and, at the same time, induces it to flow through the impeller. Air enters the eye of the impeller and is accelerated radially by the rotating impeller. As the air leaves the impeller, it enters a divergent shaped duct prior to exiting the compressor. This decreases the air's velocity and further increases its pressure.

9.3.2. Axial flow compressors

This type of compressor is properly called a turbine. It delivers large quantities of air at high velocity. It can have many rotors to increase efficiency. The rotors have blades which accelerate the air along the axis of the compressor. These compressors can rotate at up to 100,000 rpm.

9.4. Compressor capacity

This unit of competency is concerned with displacement compressors only – in particular, reciprocating piston, sliding vane, and rotary screw types. In practice, the selection of a compressor is based on two major factors: free air delivery (FAD) and working pressure. The rating of an air compressor is determined by comparing its discharge flow rate to the rate at which air is drawn in from the atmosphere. This latter factor is called *free air delivery* (FAD) – it is the amount of air (at atmospheric condition) that can be drawn into the inlet of a compressor. It is a standardized measure which is used to express the capacity of air compressors.

To determine the free air delivery of a compressor, the following information is required:

- the atmospheric pressure at the inlet of the compressor (P1)
- the air temperature at the inlet side (T1)
- the compressor discharge pressure (P2)
- the discharge air temperature (T2)
- the volume of the air discharged (V2), from the compressor.

FAD can be obtained by working back from the discharge volume, relating its pressure and temperature to inlet conditions using the Combined or Ideal Gas Law, as shown below where V1 is the amount of FAD.

$$V_1 = \frac{V_2 P_2 T_1}{P_1 T_2}$$

9.5. Compressor accessories

9.5.1. Intercoolers

The most effective way of controlling air temperature between the stages of a multistage air compressor is found by using intercoolers. Intercooling is used to achieve the following effects:

- reduce the temperature of the air between stages
- reduce the volume of the air to be compressed in the succeeding stage
- condense water vapor, *and*
- reduce the power requirements of the prime mover.

An intercooler is a heat exchanger which generally employs the same cooling medium as the compressor which it serves. For example, water-cooled compressors use water-cooled intercoolers and air-cooled compressors use air-cooled intercoolers. Air-cooled intercoolers may have a small number of finned tubes through which the hot air passes under pressure, or they may be of the radiator type with many tubes. Cooling air is forced over the fins to dissipate the heat. Water-cooled intercoolers may consist of a nest of tubes enclosed in a shell or casing. The cooling water flows through the tubes as the hot air passes through the casing. In other types, the air flows through the tubes with the water outside. Whichever method is used, water flow is generally in the opposite direction to air flow. Perfect intercooling is attained when the temperature of the air leaving each stage is equal to the inlet air temperature. Intercoolers require periodic maintenance if one is to ensure that the cooling mechanism is operating efficiently. The fins of air-cooled intercoolers should be kept clean. Watercooled intercoolers should have clear water passages that are free of scale and other foreign materials that may reduce their efficiency. An example of a compressor with an intercooler is illustrated in Figure 22.

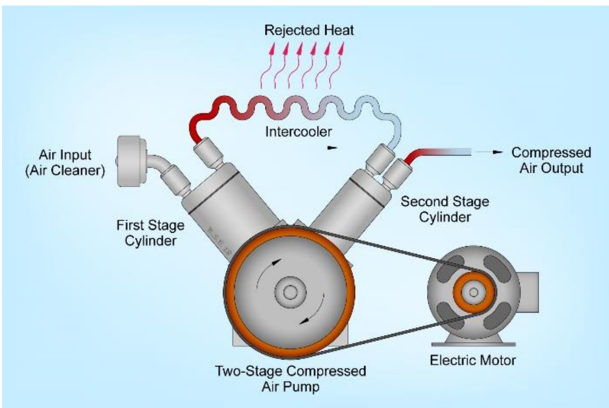

Figure 22. Intercooler and compressor

A pressure-relief valve must be fitted to an intercooler and should be manually operated regularly. Automatic drains should also be checked for correct operation.

9.5.2. Intake filters

To ensure reliable operation, a compressor should always be supplied with clean, cool and dry air at the intake. Without filtration, abrasive pollutants in the air would become suspended in the lubrication oil and cause wear on cylinders, piston rings, bearings etc. A good air filter should satisfy the following requirements:

- High separation efficiency – the filter should permit large quantities of pollutants to collect on the filter element without significantly reducing its other properties.
- Good accumulation capacity – this prolongs the intervals between filter cleaning.
- Low air resistance – the resistance exerted by a filter varies slightly with the type. Oil-bath filters have a pressure drop across the element of 15 millibars.

9.5.3. Control methods

The demand for air in most factories fluctuates throughout the day, so some type of control system is needed in order to match supply with demand. Where no air is sometimes required, or demand is small, an automatic stop-start system may be used.

Other methods of controlling compressors include:

- inlet throttling
- bypass control
- exhaust regulation
- variable speed control
- bypass/blow-off system

9.5.4. Aftercoolers

When air is compressed, the reduction in volume is accompanied by a substantial rise in temperature. Heat is an undesirable by-product of compression. If the hot air was delivered directly from the compressor, the discharge pipe would lengthen due to heat-related expansion. On shutdown, the pipe would contract as it cooled. The repeated cycle of expansion and contraction would result in leaking joints and inefficiency due to air loss. So, instead of passing hot air directly into an air receiver, the air is generally passed through an aftercooler.

An aftercooler is a heat exchanger and, as its name implies, it removes the heat of compression from the air after it leaves the final stage of the compressor. Aftercoolers may be air-cooled or water-cooled. The method of cooling generally depends on the type of cooling used for the compressor; for example, air-cooled aftercoolers are generally used with air-cooled compressors. The temperature of the compressed air leaving the aftercooler is usually about 100 ºC above that of the cooling water inlet – or 120–160 ºC above ambient temperature when an air-cooled aftercooler is used. Apart from removing excess heat from compressed air, cooling also reduces the moisture-carrying capacity of the air. Provided that they are correctly sized, aftercoolers can separate up to 90 percent of the water originally contained in the intake air. An aftercooler should be fitted with an efficient water separator, preferably with an automatic one. Air leaving an aftercooler is generally dry enough for most applications. However, some operations require dryer air, in which case air dryers are used. The three main types of air dryer are:

- refrigerant
- absorption
- adsorption

10. Air service units

Air service units (ASU) – or filter, regulator, lubricator units (FRL) – are used to perform the following system functions:

a. filter the air and remove condensate (water) prior to use and thus provide the pneumatic machine or tool with clean air
b. limit maximum system pressure in a pneumatic circuit and thus provide the pneumatic machine or tool with the correct working pressure
c. provide working elements with the correct amount of lubrication where required.

To summarize what you have covered in your readings, the main points are as follows.

- The ASU can consist of three units, which can be separate components or combined as a module to meet the needs of the system.
- Where oil-free air is required, the lubricator may not be used.
- The filtration unit is generally rated 40 to 60 microns, depending upon system requirements.
- The filter not only removes contaminants from the air but also separates condensate.
- Filters can have a manual or automatic drain to remove any condensate trapped in the filter bowl.
- Because filter bowls can be made of polycarbonates, care must be taken to ensure that these parts are not exposed to volatile chemicals such as acetone.

- Polycarbonate bowls should be cleaned with soapy water and should be thoroughly dried thereafter.
- The filter may be incorporated with a pressure regulator (pressure-reducing valve) in one modular unit.
- The pressure-reducing valve (regulator) is a normally-open valve that senses downstream pressure.
- The pressure regulator can be provided with a secondary relief function.
- Air-line lubricators work on a venturi principle and can be of the oil fog or mist type.
- The lubricator should be located as close as possible to the pneumatic machine to prevent the oil from coalescing (and returning to a liquid state) in the air lines.
- Only the correct type of lubricant (usually light mineral oil) and oil-feed rate should be used.
- Ideally, the air service unit should be located as close as possible to the machine.