Study Unit

Pneumatics, Part 1

Preview

Just about all physical processes in our society—from operating a computer to driving a car—involve a transfer of either information or energy from one place to another. In many cases, the information controls the transfer of energy. You may have already learned how a hydraulic pilot signal can open a valve to a cylinder, which then uses hydraulic pressure to lift a weight. In both cases, energy was used to accomplish some desired work, and some type of control information was used to determine when, how much, or where the energy was used to do the work.

Pneumatics is the use of gases to control or supply energy to a process. Pneumatic control signals can be used to control hydraulic, pneumatic, or electrical power sources. Also, electrical (or hydraulic) control signals can be used to control hydraulic, pneumatic, or electrical power sources. There are many possible combinations of control/power systems, each with advantages for specific applications. Because hydraulic and pneumatic systems both use fluids, you'll find many of the concepts and principles of pneumatics similar to those of hydraulics. The fundamental difference is that pneumatic systems use a fluid (a gas) that's compressible. Many of the basic concepts involving calculations of flows, forces, or power are the same. However, because of the unique properties of gases, especially air, other important factors in the design, installation, and maintenance of pneumatic systems must be considered.

When you complete this study unit, you'll be able to

- Understand the basic concepts of pneumatic systems and how they compare and contrast with hydraulic systems
- Describe the fundamental relationships among pressure, volume, and temperature that determine how pneumatic systems function
- Understand and describe some basic applications of pneumatic systems
- Calculate the forces produced by a pneumatic cylinder
- Understand, describe, and specify common components of pneumatic systems
- Recognize and use schematic symbols that represent pneumatic components

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Pneumatics, Part 1

FLUID POWER CONCEPTS

Characteristics of Pneumatic Systems

Pneumatic power is energy transmitted by means of a pressurized gas. The most common gas is air, and most of our discussions will focus on the use of pressurized air; however, other gases such as nitrogen are used for special applications. The simplest of pneumatic systems contains a compressor; a motor, actuator, or cylinder; some type of control device, such as a valve; and piping or tubing to conduct the compressed air from the compressor to the actuator. The *compressor* takes air from the surrounding environment and compresses it from atmospheric pressure to a higher working pressure. The *actuator* or *cylinder* uses the compressed air to force the movement of a metal rod or the rotation of a rotor. It changes the pressure and flow of the air into mechanical motion. The *piping* or *tubing* carries the compressed air from the compressor to the location where the work is to be done by the actuator, and the *valves* control when and how much air flows in the system.

Study the following summary of the function of these components while referring to Figure 1:

- *Compressor*—Converts electrical energy to mechanical energy, which is then converted into a form of potential energy stored in a compressed gas

- *Actuator* (or *motor/cylinder*)—Converts fluid power into mechanical work

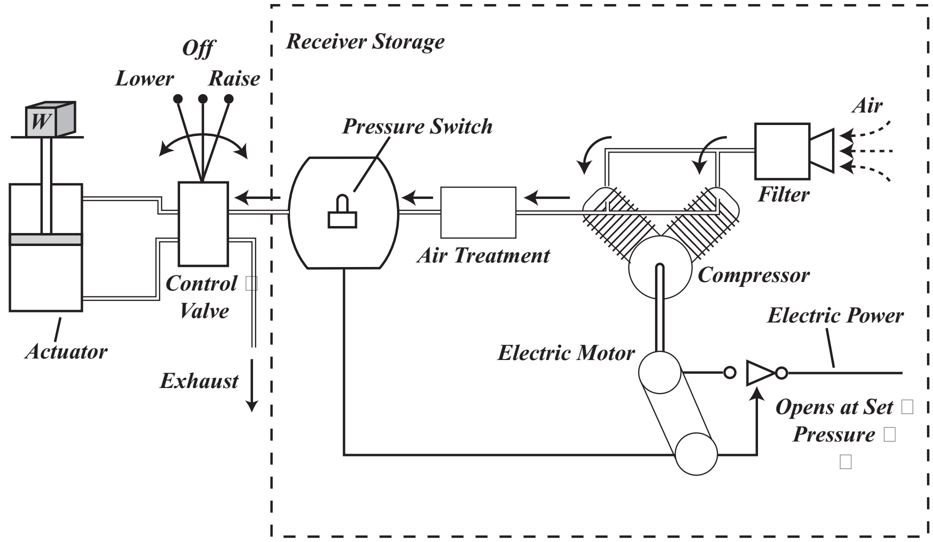


FIGURE 1—A basic pneumatic system contains a compressor with its electrical supply and input filter, a primary conditioning unit that cools and removes moisture, a receiver to store compressed air, a control valve to direct the compressed air, and a cylinder or actuator to do the required task.

- *Valves*—Control pressure, direction, and rate of flow of the gas
- *Conductors*—Provide a path for controlled movement of the gas from the compressor to the output device (a motor or cylinder). Conductors may be pipes, semirigid tubing, or flexible tubing.

These are the most basic components of a simple pneumatic system. However, other components are necessary to make the system function reliably and efficiently:

- *Filters, regulators, lubricators*—"Condition" the gas to make it work efficiently for a specific application. These three devices are often packaged together as one component.
- *Sealing components*—Seal the gas inside the system at joints or moving parts, such as cylinder rods
- *Receivers*—Store a reserve of gas to be used at a later time, and dampen pressure variations in the system due to uneven consumption of pneumatic power. Receivers are also used to supply emergency power in the event of electrical power failure.

- *Fittings, couplings, manifolds*—Used to assemble, disassemble, and distribute compressed air tubing systems for more complex pneumatic applications
- *Measuring devices*—Monitor the system's performance. Typical instruments include temperature sensors, pressure sensors and transducers, pressure switches, gauges, and flow meters.

We'll study all of these components of a typical pneumatic system and discuss important characteristics of each. You'll also learn how they interact with each other in a working application.

Pneumatic Gases

The word *pneumatic* is derived from the Greek word *pneuma,* which means air, or wind. The perfect gas for pneumatic applications would be one that's *inert*—that is, it doesn't react with other materials such as lubricants, other gases, or the materials used in the components. The gas should also be nonflammable, nontoxic, and free of impurities and particulates. An ideal gas would also be plentiful and inexpensive to obtain in large volumes. Since the gas is often used in equipment with moving internal parts, lubricants are often mixed with the gas to oil the moving parts. The two most common gases used in pneumatic applications are compressed air and nitrogen.

When you compress a gas, you're using one type of energy and converting it to another. Electrical energy, or perhaps chemical energy from gasoline, is used to make the mechanical energy of motion in a compressor. The compressor then takes air from the surrounding atmosphere and squeezes it within a tank, or what's called a receiver. You can look at the process this way: the energy of one type—electrical or chemical—is converted and stored as potential energy in compressed gas, much the same way energy is stored in a spring. When we want to use the potential energy at another time or another location, we direct it to the proper place and use the energy to power tools, move liquids and powders, lift weights, or perform other useful work.

The amount of potential energy is related to how much the gas is compressed; higher compression ratios represent more stored energy. We measure the amount of compression by the "psi" of the gas in the storage tank. The term *psi* means pounds per square inch. Psi measures pressure, which we'll discuss later. For now, just keep in mind that higher pressures mean more energy is available. A useful analogy is that the psi of a pneumatic receiver is like the voltage of a battery.

Compressed air. The air around us is composed of nitrogen (about 78%), oxygen (about 21%), and a small amount of other gases including argon (0.9%) and carbon dioxide (0.3%). Water vapor is also present, and the amount of water the air can hold is a function of the air temperature. Air is able to "dissolve" a certain amount of water vapor, depending on its temperature. As air is compressed and stored within a receiver tank, the relative humidity increases due to the decrease in volume. Moisture must be removed from the receiver by a drain as part of a periodic maintenance plan, or else with a timed automatic drain system.

The presence of this water greatly affects the design, operation, and maintenance of pneumatic systems. Changes in temperature within the equipment can cause the water vapor to condense inside the system. Also, the humidity in the air when it's first compressed will condense because of the change in volume and pressure. This condensation can damage the equipment by causing corrosion and dilution of lubricants. If the humidity freezes, blockages can occur. Because of this, dryers of various types are used in compressed air systems. You'll learn about these in later lessons. Air itself is inert, but the oxygen in air can react with flammable materials to cause intense fires. Compressed air systems are categorized by their operating pressures: high pressure (HP) 3000–5000 psi, medium pressure (MP) 150–1000 psi, or low pressure (LP) below 150 psi. Many factory systems use compressed air at about 90 psi.

Inert gases, such as Argon, are nonflammable and nontoxic. You'll learn more about them later in this study unit.

Nitrogen. Nitrogen gas consists of paired nitrogen atoms that form molecules. Nitrogen is nonflammable and inert, and doesn't promote combustion or corrosion. For many applications such as military aircraft and missile systems, nitrogen is a preferred pneumatic gas; however, the production of nitrogen is rather complex, making it somewhat expensive for many common systems.

Contamination of the gas is a leading cause of system failure. The principal contaminants are moisture and solid particles, and most systems are equipped with devices to remove both moisture and particulate contamination. You'll learn more about these devices later, but it's important to realize that the condition of the gas is important in the efficient, economical, and reliable operation of pneumatic systems. Proper installation, adjustment, and servicing of the conditioning components is an important part of the preventive maintenance program in any factory or business using pneumatic systems.

Comparison of Hydraulic and Pneumatic Systems

Pneumatic and hydraulic systems both work on the principle of a pressurized fluid transferring power from one location to another. Both systems use either a compressor or a pump to develop pressure within the fluid. Compressors and pumps operate in a similar way. In both systems, control valves and piping direct the fluid flow, and actuators, motors, or cylinders provide the mechanical output of the system. The types of components used in hydraulic and pneumatic systems are similar in their principles of operation. And in most instances, schematic symbols for components such as valves, accumulators, switches, and cylinders are the same or similar.

The main difference between hydraulic and pneumatic systems is, of course, the fluid used. Hydraulic systems use liquids, whose properties are vastly different from gases. Hydraulic fluids are virtually incompressible; when a force pressurizes a hydraulic system, the volume change of the fluid is minuscule. In a pneumatic system, an external force applied to a component such as a cylinder can cause the rod to retract if it's great enough, and yet the rod will return to its normal position after the force is removed. Because fluids cannot be compressed, hydraulic systems are rigid. If the temperature of a hydraulic fluid increases, the increase in fluid volume will translate into increased system pressure and/or movement of the components. An increase in the gas temperature will elevate the system pressure only a comparatively small amount. In terms of safety, hydraulic fluids are often flammable, toxic, and environmentally hazardous. Leaks from fittings can be extremely hazardous; high-pressure hydraulic fluids can be difficult to see, yet they can easily cut through the flesh of unsuspecting personnel.

Each system has advantages and disadvantages that a designer considers when a particular application arises. Because of the fluid requirements, hydraulic systems are often more complex than pneumatic systems. However, hydraulic systems are capable of delivering large amounts of power and generating tremendous forces for use in heavy-duty applications such as lifting, earth-moving vehicles, and material-handling equipment in factories. Pneumatic systems have less demanding fluid conditioning requirements, are easier to maintain, and can be made to accurately position and hold parts or tools very rapidly. These qualities make pneumatic systems suitable for many automated manufacturing applications. Many pneumatic systems are less expensive to implement for a specific mechanical function than an electromechanical system. Because of the ease of distributing the air through piping systems, compressed air is popular as a factory-wide power source for tools and equipment.

Hydraulic Systems	Pneumatic Systems
High forces available	Medium forces available
Fluids dangerous, flammable	Fluids nontoxic, nonflammable
Distribution system limited to local sites	Distribution system easy to construct and maintain
Medium operational costs, compared with electric-powered systems	Lower operating costs than electric- and hydraulic-powered systems

The Kinetic Theory of Gases

To understand how pneumatic systems function, you must understand how a gas behaves in a confined system. For many years before our modern scientific discoveries, people didn’t realize that we live at the bottom of an ocean of air.

This ocean is unconfined and mostly unnoticed except in times of weather events such as storms. However, to account for the observed behavior of gases, a scientist named Daniel Bernoulli (1700–1782) proposed what's now called the *kinetic theory of gases.* Bernoulli explained the behavior of gases by realizing that a gas is composed of a large number of individual particles called *molecules.* The molecules are extremely small and move rapidly in random directions. The properties of gases result from collisions of molecules with each other and with the walls of a container (Figure 2).

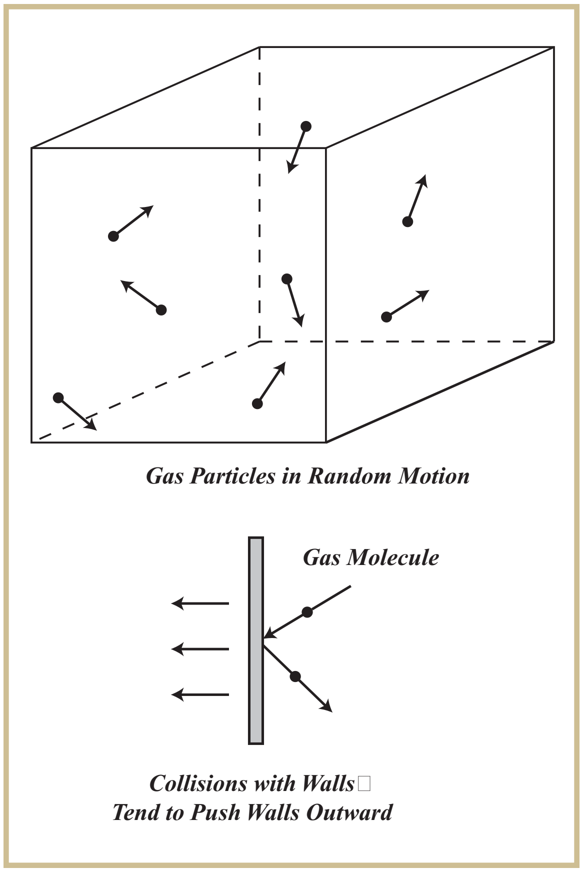


FIGURE 2—Rapidly moving molecules of gas exert a force on the walls of a container.

Think about a sealed box filled with a gas. The gas molecules have kinetic energy and are moving very fast. The individual molecules are moving in straight-line paths and change direction when they hit each other or the walls of the box. The molecules behave like billiard balls, in that when one molecule strikes another, each rebounds according to its momentum (mass multiplied by velocity). When a molecule strikes the wall, the molecule and the wall rebound from the collision. Since the mass of the wall is much greater than the molecule, the wall only moves very slightly. However, with millions of molecules striking each wall every instant, the wall is pushed back with a significant force. This is the explanation of what we call "pressure." For example, the air molecules in a car tire hit the walls of the tire and force them outward, supporting the wheel and the vehicle. We measure the pressure in a tire as a way of determining how much weight the tire can safely support.

Pressure

Even one molecule in a closed container will eventually hit the wall and cause a force that moves the wall away from the gas. If billions of molecules are present, considerable force can be generated. We measure the pressure of a gas inside a container by measuring the force it produces on an area of the wall. In the U.S. Customary System (USCS), the force is measured in pounds, and the area is measured in square inches. Thus, pressure is the number of pounds the gas generates on one square inch of wall area, or "pounds per square inch," abbreviated as psi (Figure 3).

$$\text{Pressure} = \frac{\text{Force}}{\text{Area}}$$

or

$$P = \frac{F}{A} \qquad \text{(Equation 1)}$$

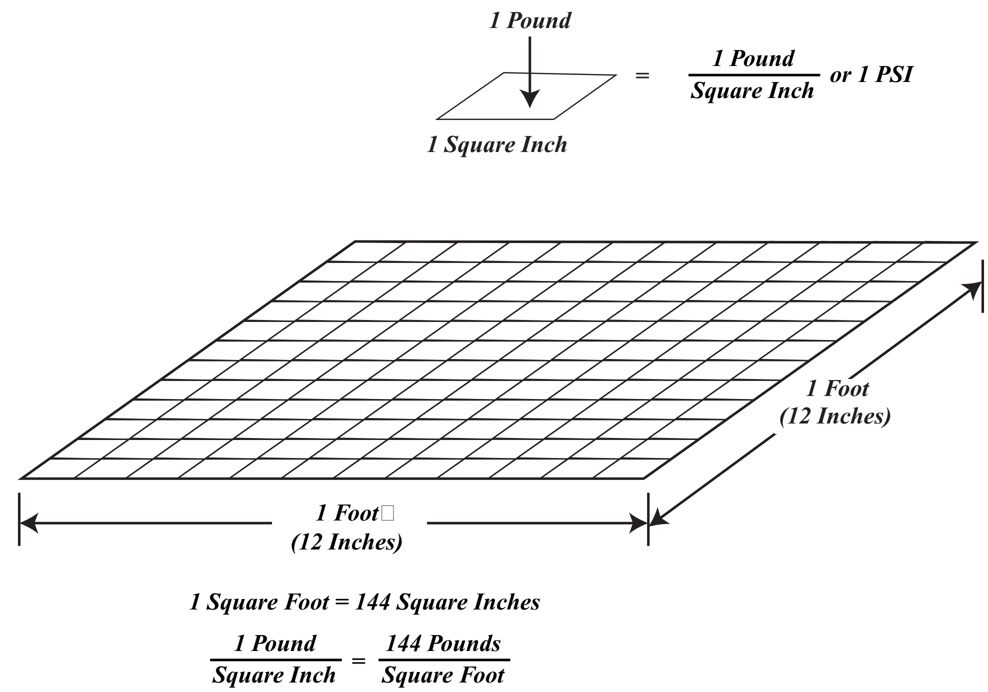


FIGURE 3—Pressure is defined as the amount of force exerted over an area. Most U.S. industries use the pound per square inch as the unit of pressure measurement. The metric unit of pressure is the Newton per square meter ($^N/_{m^2}$), or Pascal (Pa).

In the metric system (System Internationale, or SI), the units of force are Newtons and the units of area are square meters. In the metric system, a unit of pressure equal to one Newton per square meter (1 $^N/_{m^2}$) is given a special name called the *Pascal,* which is abbreviated as *Pa.* The Pascal is a relatively small unit, and normal pressures are often measured in *kilo-Pascals,* or *kPa.* One pound per square inch (psi) is equal to 6894.76 Pascals. And as you can see, the Pascal can be cumbersome to use at the pressures normally encountered in everyday applications.

Atmospheric Pressure

The air around us exerts a constant pressure on us at all times. We don't notice this force because the pressure on the outside of us is balanced equally by the pressure on the inside in our lungs and bloodstream. Atmospheric pressure varies as we move to higher elevations. We normally reference a given air pressure to sea level, which is taken as 14.7 psi, at a temperature of 70°F. The SI equivalent is 101,353 Pa, or 101.4 kPa. A container that's "pressurized" has more than 14.7 psi; a container with fewer than 14.7 psi is said to have a *vacuum.*

The bar is another unit of pressure that's sometimes used. One *bar* is defined as equal to $1.00 \times 10^5\ ^{N}/_{m^2}$, so a bar is slightly less than one atmosphere of pressure. Two bars would be about two atmospheres of pressure, three bars would be about three atmospheres, and so forth. Sometimes pressure units are given in millibars, or thousandths of a bar, especially when vacuums are involved. Millibars are a much smaller unit for situations that require a fine resolution of pressure. The bar unit is used often in meteorology and on weather maps.

Another unit of pressure, and also of vacuum, is the *torr.* When barometers were first invented, they were made from columns of mercury in a closed tube that measured the air pressure. Barometers indicate approaching weather changes when the atmospheric pressure rises and falls, and at the neutral position, the column was 760 millimeters tall, or 760 mm. The unit of torr was given in honor of Evangelista Torricelli (1608–1647), the inventor of the mercury barometer, and the torr is defined as 1 millimeter of mercury, or 1 mm-Hg. You'll see this unit when pressure measurements are made at pressures near one atmosphere or in low-vacuum conditions, because it's a relatively fine unit compared with the psi or the Pascal. For low-pressure applications, you may also see the *inches of water,* or *in-*H_2O*,* unit.

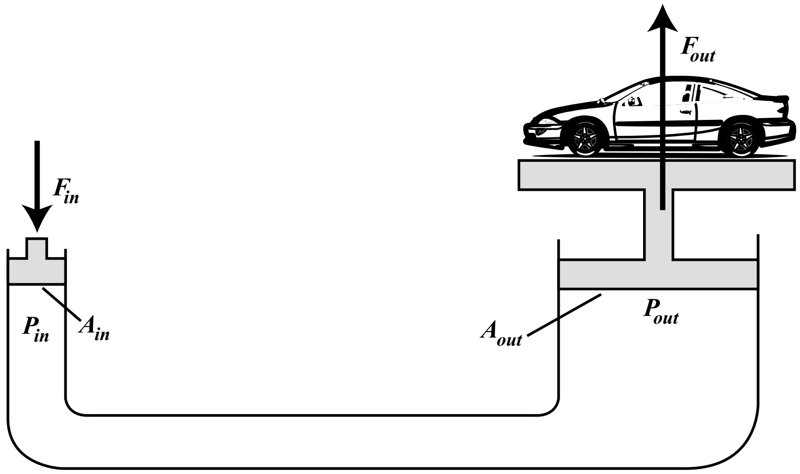
Some pressure conversions that may be useful:

1 atm = 1.015 $\times$ 10^5 M/m^2	1 atm = 760 torr
1 bar = 1.000 $\times 10^5$ M/m^2	1 atm = 1.013 bar
1 torr = 133 N/m^2	1 lb/in^2 = 6.9 $\times$ 10^3 N/m^2
1 atm = 14.7 lb/in^2	1 atm = 2.12 $\times$ 10^3 lb/ft^2

Pressure in Pneumatic Applications

Probably the most fundamental characteristic of a pressurized container, and the principle on which all hydraulic and pneumatic devices work, is that once a container is pressurized, that pressure exists at all points on the inside of the system, on every wall, and in every component attached to the system, no matter how small the connection. This is known as *Pascal's principle,* which states that pressure applied to a confined fluid increases the pressure throughout the entire system by the same amount. Two common applications that take advantage of this principle are the power brakes in your car and the hydraulic lift in the service station. In Figure 4, a force is applied to a small piston area of the system to generate pressure. Since the pressure will be the same throughout the system, the pressure acts on the large piston area to generate a large force, raising the automobile. The output force will be proportional to the area of the large piston, and the mechanical advantage of the system will be the ratio of the areas of the large and small pistons. You may think you get "something for nothing" when you see this characteristic, but even though you're able to generate large forces, you must supply the same amount of work no matter what: if you have a small force, you must move it a large distance. The large force moves a correspondingly small distance.

In a system that has a static pressure of 100 psi, there are 100 psi on the inside of the piping and tubing, in the cylinders and valves, and in the storage tanks that hold the gas. By manipulating this pressure, we can transfer energy from one point to another to let us do useful work.



$$P_{out} = P_{in}$$

$$P_{out} = \frac{F_{out}}{A_{out}} \qquad P_{in} = \frac{F_{in}}{A_{in}}$$

$$\frac{F_{out}}{A_{out}} = \frac{F_{in}}{A_{in}}$$

$$\text{Mechanical Advantage} = \frac{F_{out}}{F_{in}} = \frac{A_{out}}{A_{in}}$$

FIGURE 4—Pascal's principle, named for French scientist and Christian philosopher Blaise Pascal (1623–1662), is the reason we can generate very large forces with very small input forces. The pressure within every part of the system is the same.

You also must understand the difference between static pressure and dynamic pressure. Pressure alone doesn't allow us to do work with pneumatic (or any other) systems. For example, if you connect a garden hose with a closed nozzle to a faucet, open the faucet to allow the hose to be pressurized, and then close the faucet again, you'll have a hose under pressure. If you open the nozzle at the end, you'll see a short burst of water, and then the flow will stop. This shows another basic characteristic of fluid power systems: the fluid must flow from one point to another to allow us to do work with the components. A good analogy is that pressure in a pneumatic circuit is much like the voltage in an electrical circuit. The voltage represents a potential energy. As voltage is necessary to move electrical current through a wire, pressure is necessary to move fluid through tubes. Wires must be large enough to carry the needed volume of electrical current, and pneumatic conductors must be large enough to carry the volume of air at the required pressure.

When we cause fluids to flow from one point to another, we'll get a pressure drop as the energy of the moving fluid is used up during its travel. Sometimes this is done on purpose, as a method of changing a high pressure to a low pressure. Most times, however, a pressure drop is something to be avoided. Pressure drops occur as fluids travel through devices such as filters, regulators, tubing, or other components attached to the system (provided the fluid is traveling). Piping that's too small or that has an excessive number of bends will cause unacceptable pressure drops.

Absolute Pressure vs. Gauge Pressure

A container that's open to the atmosphere and then closed will still measure 14.7 psi of *absolute pressure*—that is, the pressure exerted by the molecules on the inside walls of the container. Since this is a condition of equilibrium with the outside pressure, we often put gauges on the system that measure only the pressure above normal atmospheric pressure. This is called *gauge pressure,* and the units marked on the gauge will indicate *psig.* It's important for you to understand that a gauge that measures psig will indicate "0 psig" when the pressure is the same as the outside pressure, even though there's still an absolute pressure of 14.7 psi. Gauges are available to measure absolute pressure, and they're marked *psia* on the face to indicate that they measure absolute pressure: when the system is open to the atmosphere, the gauge will
still indicate 14.7 psi. When you do calculations involving pressure, you'll most often use absolute pressure. You must make sure to convert gauge pressures to absolute pressures before doing any calculations.

$$P_{absolute} = P_{gauge} + P_{atmospheric} \text{ (14.7 psi)}$$

For example, if a bicycle tire is inflated to 30 psi, the absolute pressure is 30 psi + 14.7 psi = 44.7 psi.

Boyle's Law

Robert Boyle (1627–1691), an English scientist, was one of the first people to experiment with the relationship between the pressure and volume of an enclosed gas. He noticed that in experiments where he could change the volume of a container, such as a cylinder with a moveable piston, the pressure rose when he decreased the volume. When the volume increased, the pressure decreased. These experiments were done with the temperature of the gas kept constant, because, as we'll see, the temperature is also affected by the pressure and volume of a gas. The relationship that came to be known as *Boyle's Law* can be written mathematically as

$$V_1 \times P_1 = V_2 \times P_2 \quad \text{(Equation 2)}$$

or

$$\frac{V_1}{V_2} = \frac{P_2}{P_1} \quad \text{(Equation 3)}$$

In these equations V_1 and P_1 are the initial volume and pressure, and V_2 and P_2 are the final volume and pressure. These equations show the inverse mathematical relationship between pressure and volume. Boyle's Law is the first of the gas laws that you must study to understand pneumatic systems. Remember, when doing calculations, you must convert any gauge pressures to absolute pressures before calculating.

Example:

The air inside a tank with a volume of 4.5 ft^3 is pressurized to 125 psig. Another tank with a volume of 2.5 ft^3 is connected by a pipe through a valve. When the valve is opened, what's the final pressure after the tanks have equalized? Neglect the volume of the pipe and valve.

Solution:

1) Convert 125 psig to absolute pressure, psia:

   P_1 = $\underline{\text{125 psi + 14.7 psi =}}$ 139.7 psia

   Therefore, V_1 = 4.5 ft^3 and P_1 = 139.7 psia.

2) Calculate the final volume:

   V_2 = 4.5 ft^3 + 2.5 ft^3 = 7.0 ft^3

3) Use Equation 2 to solve for P_2:

$$P_2 = \frac{(V_1 \times P_1)}{V_2}$$

$$P_2 = \frac{4.5\ ft^3 \times 139.7\ psia}{7.0\ ft^3}$$

$$P_2 = 89.81\ psia$$

$$P_2 = 89.81\ psia - 14.7\ psia = 75.1\ psig$$

After the tanks have equalized, the new pressure in the system will be 75.1 psig.

Example:

A cylinder with a movable piston has an internal pressure of 90 psia applied to the inside of the cylinder, so that the rod extends upward. An external load is then applied to the rod so that the cylinder pressure is raised to 150 psia from the additional compression of the gas. If the volume of the cylinder with the piston in the original position is 110 in^3, what's the new volume after the piston is moved?

Solution:

Note that the pressures are given in psia, so there's no need to convert.

Use Equation 2 or 3 to solve for V_2.

$$V_1 \times P_1 = V_2 \times P_2$$

$$V_2 = \frac{(V_1 \times P_1)}{P_2}$$

$$V_2 = \frac{(110\ in^3 \times 90\ psia)}{150\ psia}$$

$$V_2 = 66\ in^3$$

The volume of the cylinder with the force applied to the piston is 66 in^3. If we knew the diameter of the cylinder, we could easily calculate the distance the rod has moved with the force applied.

Temperature

You may recall that our common temperature scales are based on the boiling and freezing points of water. In the Fahrenheit scale, the freezing point of water is 32°F, and the boiling point is 212°F. In the Celsius scale, the freezing and boiling points are 0°C and 100°C, respectively. The temperature of an object is a measure of the thermal energy, and the temperature of a gas is a measure of the kinetic energy of motion of the molecules. However, when the temperature of the gas measures 0 on either the Celsius or Fahrenheit scale, there's still a considerable amount of kinetic energy—and motion of the molecules—present within the gas. To truly represent the amount of kinetic energy of a gas by a temperature, it's necessary to use an absolute temperature scale. In an absolute scale, 0 degrees represents a point at which the kinetic energy of the molecules has reached a minimum value. This point is called *absolute zero.* Modern scientists have lowered temperatures of materials to within several thousandths of a degree, but a true absolute zero appears to be unachievable.

There are two absolute temperature scales, the Rankine scale and the Kelvin scale. The scale that uses the same size degrees as the Fahrenheit scale is the Rankine scale. On this scale, the point of zero energy has a temperature of zero, the freezing point of water (0°F) is 491.67°R, and the boiling point of water (212°F) is 671.67°R. The absolute temperature scale in the metric system is the *Kelvin scale.* Again, the temperatures start at absolute zero, but in this case the freezing point of water is 273.13 K and the boiling point of water is 373.13 K. Note that the degree symbol "°" isn't used in this scale. We say that the boiling point of water is "373.13 Kelvins," not "373.13 degrees Kelvin."

To convert Kelvins to Celsius degrees, subtract 273.15° from the number of Kelvins:

$$TC = TK - 273.13°$$

To convert Rankine degrees to Fahrenheit degrees, subtract 459.67°:

$$TF = TR - 459.67$$

To convert Fahrenheit degrees to Celsius degrees:

$$TC = \frac{5}{9} \times [TF - 32]$$

To convert Fahrenheit degrees to Celsius degrees:

$$TF = \frac{9}{5} \times TC + 32$$

Charles' Law

Jacques Charles (1746–1843) discovered many of the concepts that developed the kinetic theory of gases. Among other things, he discovered that as the temperature of a gas is increased, the speed of the molecules increases—an increase in the kinetic energy of the molecules. If the gas is enclosed in a sealed container, he found that the pressure of the gas increased when the temperature was increased. This means that the force against the wall has increased due to the increased velocity of the molecules and the increased forces generated by the impact of the molecules.

Through his experiments, Charles determined that there was a definite relationship between the volume that a gas occupies and its absolute temperature, if the pressure is held constant. If the temperature is increased, the volume the gas occupies increases; if the volume increases, the temperature must increase to maintain the same pressure. This relationship, known as *Charles' Law,* is the second major gas law you must be familiar with to understand pneumatic systems:

$$\left(\frac{V_1}{V_2}\right) = \left(\frac{T_1}{T_2}\right) \quad \text{(Equation 4)}$$

Also, he found that if the temperature of a gas is increased without a change in volume, the pressure must increase. This can be expressed as:

$$\frac{P_1}{T_1} = \frac{P_2}{T_2} \quad \text{(Equation 5)}$$

What do you think will happen to the pressure in a gas cylinder if it's left exposed in the sunlight, or stored in a hot vehicle? The temperature of the gas will increase, and the pressure will increase as a result. If the pressure rise is too great, the tank will burst. This is why most storage cylinders for compressed gases have an over-pressure relief valve.

Charles' Law explains a common phenomenon that we see when we let air out of a pressurized container, such as a tire. We notice that the air seems to be very cold. As the air expands exiting the nozzle, the pressure decreases rapidly, making the temperature drop quickly. It isn't unusual to see ice forming under some conditions where gases are expanding rapidly, due to moisture in the air condensing and freezing on a nearby surface.

Example:

A cylinder with a piston must expand in volume from 6.0 in^3 to 8.0 in^3, while maintaining a constant pressure. If the original temperature is 68°F, what must the final temperature be to maintain a constant pressure?

Solution:

First, convert the temperature to absolute value:

V_1 = 6.0 in^3 V_2 = 8.0 in^3

1) 0°F = 459.7°R Therefore, 68°F = 527.7°R.

2) Use Equation 4 to solve for the final temperature:

$$\left(\frac{V_1}{V_2}\right) = \left(\frac{T_1}{T_2}\right) \qquad T_2 = \frac{T_1 \times V_2}{V_1}$$

$$T_2 = \frac{527.7°R \times 8.0\ in^3}{6.0\ in^3}$$

T_2 = 703.6°R T = 703.6°R – 459.7 = 243.9°F

Example:

A cylinder of compressed CO_2 under a pressure of 1200 psi at 70°F is left in a hot car. If the temperature inside the car heats the gas to 130°F, what pressure does the gas inside the cylinder reach?

Solution:

1) Convert the temperatures to absolute temperatures:

T_1 = 70°F + 459.67° = 529.67°R

T_2 = 130°F + 459.67° = 589.67°R

2) Convert the pressure V_1 to absolute pressure:
V_1 = 1200 psig +14.7 psi = 1214.7 psia

3) Rearrange Equation 5 to solve for P_2:

$$P_2 = \frac{P_1 \times T_2}{T_1}$$

$$P_2 = \frac{1214.7\ psia \times 589.67°R}{529.67°}$$

P_2 = 1352.3 psia – 14.7 psi = 1337.6 psig

From the increase in temperature, the gauge pressure of the cylinder has increased from 1200 psi to 1338 psi.

General Gas Law

The individual laws that we've discussed can be combined into one general gas law that accounts for changes in temperature, pressure, and volume, going from one initial condition to a final condition. The *general gas law* says that for a gas in a sealed system, $P \times V \div T$ is equal to a constant, or

$$\frac{(P_1 \times V_1)}{T_1} = \text{constant} = \frac{(P_2 \times V_2)}{T_2} \qquad \text{(Equation 6)}$$

Proper Units

While the general gas law and other relationships given here are quite useful, it's critical that you use appropriate *absolute* units whenever called for.

Using this equation, you can find the results of any changes in the conditions for a gas in a sealed container. By knowing this relationship, you can predict the impact various changes will have on a system without doing calculations.

You're just about ready to start your study of fluid flow in pneumatic systems. Now take a few moments to review what you've just learned by completing *Self-Check 1*.

Self-Check 1

At the end of each section of *Pneumatics, Part 1*, you'll be asked to pause and check your understanding of what you've just read by completing a "Self-Check" exercise. Answering these questions will help you review what you've studied so far. Please complete *Self-Check 1* now.

1. Pneumatics is the transmission of power and energy by means of a/an _______.
2. Filters, regulators, and lubricators are said to _______ a pneumatic gas to make it suitable for use.
3. Compressed air held in a/an _______ is a way of storing potential energy for later use.
4. An ideal pneumatic gas should be _______, _______, and free of _______.
5. The two most common pneumatic gases are _______ and _______.
6. Most factory pneumatic air systems use air compressed to about _______.
7. The main difference in operating characteristics between a pneumatic and a hydraulic system is that hydraulic fluid is _______.
8. Pressure in a container is caused by _______ inside the container striking the walls and exerting an outward push.
9. Pressure is _______ divided by the _______, and the USCS units are _______.
10. The two most common temperature scales for measuring gas temperatures are the _______ and the _______.
11. If the gas in a closed container is heated, the pressure will _______.
12. A measurement of 25 psig is an absolute pressure of _______.
13. Moving air through conductors and equipment always results in a/an _______ due to disturbances in the airflow.
14. According to the general gas law, if the volume of a gas in a closed container is reduced while maintaining a constant temperature, the pressure will _______.
15. According to the general gas law, if the pressure of a gas in a closed container is reduced while maintaining a constant volume, the temperature will _______.

Check your answers with those on page 83.

FLUID FLOW IN PNEUMATIC SYSTEMS

Calculating Flow Rates

The flow rate or volume of a gas passing through a conductor such as a pipe or length of tubing is most often expressed as *standard cubic feet per minute,* abbreviated as *SCFM.* In the metric system, the flow rates are given as *normal liters per minute, nL/min.* The term standard cubic feet per minute refers to air at predefined standard conditions, which in the United States is most commonly defined as 14.696 psia, 60°F, and 0% relative humidity.

For example, if a gas is passing through a pipe with a 2-inch inside diameter at a velocity of 20 inches per second, we can calculate the flow rate in cubic feet per minute. Figure 5 shows a diagram of how this calculation is made. In general, the flow volume is calculated as the product of the area times the fluid velocity.

FIGURE 5—Flow volume can be calculated by knowing the flow velocity and the inside diameter of the pipe or tubing.

First, calculate the area of the inside of the pipe:

$$\text{Area} = \pi \times \frac{D^2}{4} = \frac{\pi \times 2.0^2}{4} = 3.14 \text{ in}^2$$

If the flow velocity is 20 inches per second, we can calculate the volume change in the pipe for every second:

$$\text{Flow Volume} = \frac{\text{Area} \times \text{Length}}{\text{Time}}$$ (or, Area × Velocity), where the length is the distance traveled by the gas in one second.

Flow Volume = 3.14 in^2 × 20 in = 62.80 in^3 every second

Since 1 cubic foot is equal to 1728 in^3, we can find the flow rate in one minute (60 seconds) by dividing the volume change by 1728 in^3 per ft^3.

$$\text{Flow rate, CFM} = \frac{\left[\dfrac{62.80\ in^3}{sec} \times \dfrac{60\ seconds}{minute}\right]}{\dfrac{1728\ in^3}{ft^3}}$$

$$\text{CFM} = \frac{2.16\ ft^3}{min}$$

This procedure works for any fluid flowing in a pipe. In the case of a pneumatic system, the air is compressed, and we must further account for the compression ration. We'll discuss that in a later lesson.

Example:

What's the minimum necessary diameter of a conductor that must pass 3.5 SCFM when the airflow velocity is 10 ft/sec?

1. Rearrange the above relationship:

   Area = Flow Volume/Velocity

2. Velocity = 10 ft/sec × 60 sec/min = 600 ft/min

3. Area = 3.5 ft^3/min/600 ft/min = 0.00583 ft^2

4. Convert area in square feet to square inches:

   0.00583 ft^2 × 144 in^2/ft^2 = 0.840 in^2

5. Solve for the diameter based on the area:

   Diameter = $\sqrt{(4 \times A/\pi)} = \sqrt{(4 \times 0.840\ in^2/\pi)}$ = 1.03 in

The next higher pipe size would be selected to be conservative, allowing for possible future expansion of the system.

Types of Flow

You learned earlier that for fluid power systems to do work, the fluid must be moved through the piping. We'll be talking about gases, but the same concepts apply to hydraulic applications. Pressure causes the gas to move from one part of a system to another, with the gas molecules moving from areas of high pressure to areas of lower pressure. As the molecules flow through the pipes and components, they'll bump into each other and the walls of the system. How they contact other molecules and the walls over time determines the type of flow within various parts of the system. As the molecules move from one point to another, some of their kinetic energy is lost, which causes a pressure drop through the system. If the pressure drop is too great, the work will be done inefficiently or else the system will have to start with a higher pressure to accomplish the work.

If the molecules flow in a straight line long enough, they'll eventually sort themselves out so that the faster molecules are in the center of the pipe and the slower molecules are near the wall. They'll continue to travel this way if the path is straight or nearly so. The paths traced out by molecules within the pipe are called *streamlines.* When these streamlines are relatively straight and don't cross each other, we say we have *laminar flow*—that is, the flow is straight and smooth. Laminar flow allows the molecules to move from one point to another in an orderly fashion, without disruption, and most important, with a minimum of pressure drop. Figure 6 shows examples of these types of flow.

When the molecules run into obstructions such as sharp corners, reduced diameters, or abrupt transitions, the molecules will bump into each other, reverse directions, slow down, or accelerate in a chaotic fashion. The streamlines cross each other, twist and turn, and otherwise follow complex paths. This is called *turbulent flow.* Turbulent flow always results when the geometry of the system causes abrupt changes in the paths and velocities of the molecules. This happens, for example, when a pipe makes a sharp turn, or when the molecules pass through a valve with a restricted diameter, or when the tube connects to a component such as a tank with a sudden change in the flow area. Figure 6 shows the effect of a sharp turn on the flow of air. Note how the streamlines cross and follow complex paths. The pressure will drop across this bend because energy is removed from the air due to velocity and direction changes. As air enters a straight pipe again, it will tend to revert to laminar flow once more if the path is straight enough.

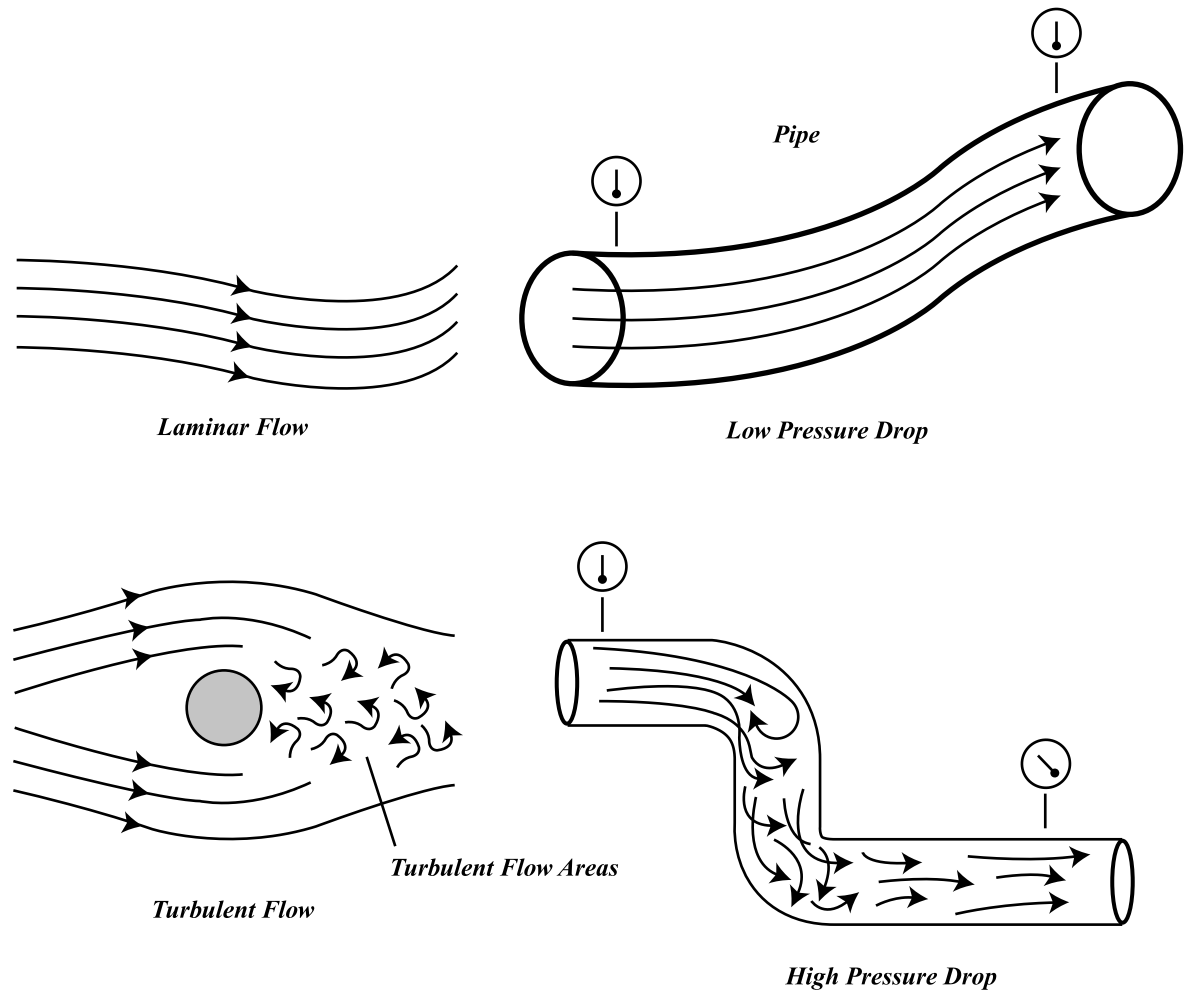


FIGURE 6—Although we usually don't see streamlines as fluids move, these diagrams show how the velocity of the fluid particles changes when obstructions are encountered. Any change of velocity, including a change in direction, requires energy, so pressure is lost as fluids travel in turbulent flow areas.

Pressure Drop

Pressure drop is defined as a difference in pressure between any two points in a system. In a static system, there will be no pressure drops because no work is being done, and no molecules are moving. When the devices are turned on with a task to accomplish, you can measure pressure differences with gauges at various points. For example, you might measure 90 psi on one side of a valve and 87 psi on the other side. Pressure can be measured with either mechanical or electrical sensors, and you'll learn more about them later in this unit.

As the gas molecules move through the piping and components, some of the kinetic energy is lost, and as a result the pressure drops through the system as the gas flows from the source of the pressure, such as the output of the compressor, to the place where the gas is used to do work, such as a cylinder or actuator. In areas where the molecules move smoothly in a laminar flow, the kinetic energy lost is minimal, and the pressure drops tend to be smaller.

In a section of tubing with turbulent flow, a large portion of the kinetic energy of the molecules is lost to friction and the pressure drop is greater. This affects the amount of remaining pressure available to move the molecules downstream from that point. For the most part, turbulent flow is undesirable, and designers and technicians should ensure that the flow is disrupted as little as possible. This means that tubing bends should be as large as possible, and there should be a minimum number of fittings and connections where practical. In areas of severe turbulent flow, the components often heat up. In hydraulic systems, the parts may be corroded internally from cavitation, where the liquid actually eats away the parts from the inside out. Turbulent flow areas are often marked by high noise levels as the gas molecules collide violently with the walls of the system.

Now take a few moments to review what you've just learned by completing *Self-Check 2.*

Self-Check 2

1. The usual unit for measuring airflow in pneumatic systems is ________.

2. The volumetric flow rate for fluids moving through a pipe can be calculated from the product of the ________ times the ________.

3. The type of flow characterized by smooth straight-line paths of air molecules is called ________.

4. Turbulent flow causes ________ to be removed from the gas due to changes in velocity, resulting in pressure drops.

5. Turbulent flow areas are often marked by ________ levels in the lines or components.

Check your answers with those on page 83.

PNEUMATIC COMPONENTS

In this section, we'll look at the individual components that are often present in pneumatic systems. As we said before, all pneumatic systems have at least a source of compressed gas; output devices such as cylinders, actuators, or motors; conductors such as tubing or piping through which the gas moves; and control devices such as valves. Depending on the application, some pneumatic systems will have additional components. You'll learn about how these components function and how they work with the other devices in the system. You'll find that many of the components you study in pneumatic systems are very similar, if not identical, to hydraulic components. Many components such as valves and regulators can be used in both types of systems. However, remember that hydraulic systems generally operate at significantly higher pressures than pneumatic systems and that safety, operating, and maintenance procedures will differ greatly for each type of application.

Fluid power refers to both hydraulic and pneumatic systems. That's because both liquids, like oil in a hydraulic system, and gases like air, are considered to be fluids.

Because hydraulic and pneumatic systems are similar, you'll find that many excellent resources at your nearby library, or the local component distributor, will be found under the general category of fluid power. Many Web sites are available that can direct you to catalog and technical information about pneumatic components and design information. Some of these include

- The National Fluid Power Association—http://www.nfpa.com/
- The Power Society—http://www.ifps.org/
- The American Society of Mechanical Engineers—http://www.asme.org/
- The Fluid Power Educational Foundation—http://www.fpef.org/
- GlobalSpec—http://www.globalspec.com/
- Society Manufacturing Engineers—http://www.sme.org/

Compressors and Auxiliary Equipment

The heart of a pneumatic system is the *air compressor,* which is responsible for compressing the ambient air and preparing it for delivery to the other components. Air compressors and equipment can be quite complex, and there's much you need to know about them to be a knowledgeable technician. Our discussion here will review some of the more important aspects of compressors and auxiliary equipment.

Types of Compressors

There are two broad categories of compressors, the positive-displacement types and the dynamic types. Positive-displacement types can be either reciprocating or rotary screw designs. A *positive displacement compressor* produces a fixed volume of compressed air for every cycle of the compressor movement. A *dynamic compressor* depends on the ability of a moving rotor with vanes to move the gas from low- to high-pressure areas by changing the gas's kinetic energy. Vanes on the impeller strike the molecules and force them to move toward the output side of the compressor. Figure 7 shows a schematic diagram of a simple impeller-type air compressor.

Reciprocating Compressors

Reciprocating compressors are positive-displacement machines that pressurize air by reducing its volume. Air is drawn into a cylinder through an intake valve by a reciprocating piston. When the cylinder is at the bottom of its stroke and the cylinder volume is at a maximum, the intake valve is closed and the piston moves upward to compress the air and move it into a receiver that holds the compressed air. The cycle is much like the compression cycle of an internal combustion engine, except that there's no ignition of a fuel/air mixture. Figure 8 shows a diagram of the compression cycle for a single-stage reciprocating air compressor.

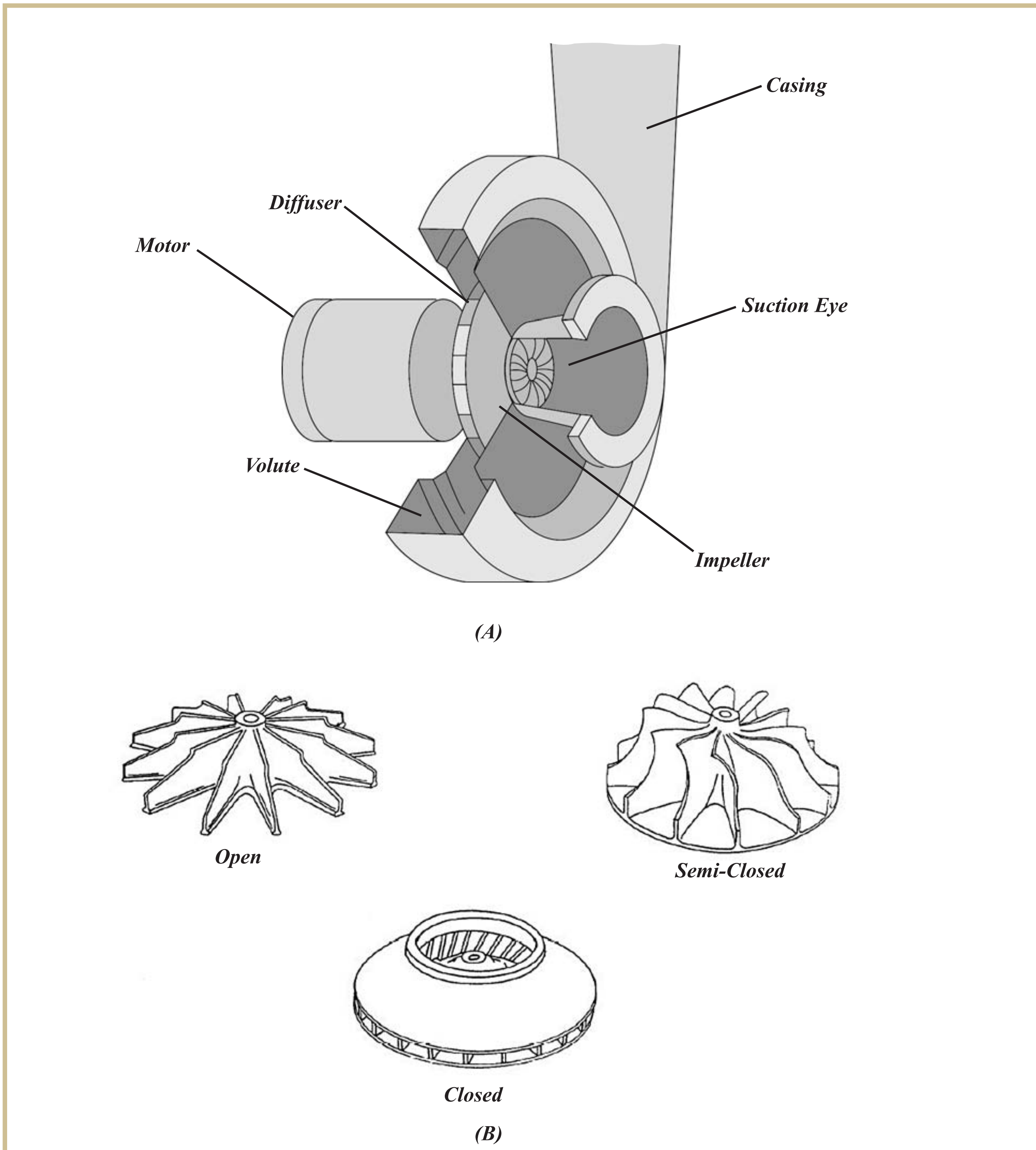


FIGURE 7—(A) The major parts of a simple single-stage centrifugal air compressor are shown here. (B) These are three different types of impellers used in the construction of centrifugal air compressors.

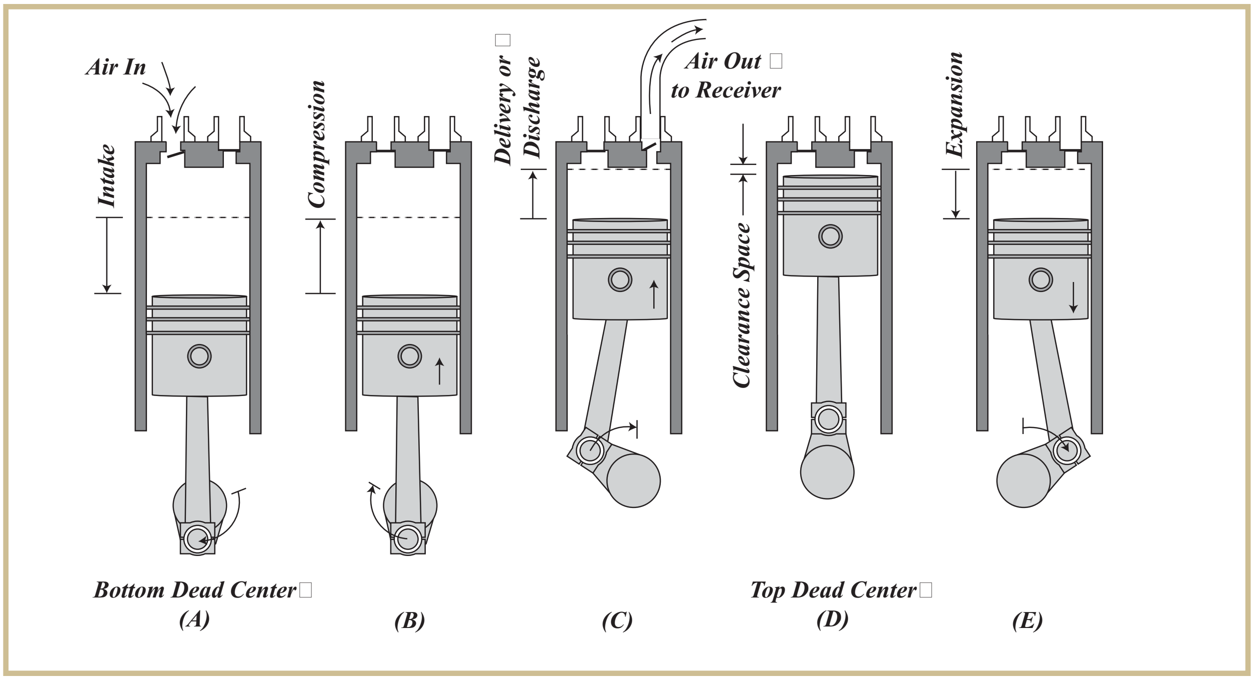


FIGURE 8—This represents the steps in a complete compression cycle in a reciprocating air compressor.

Single-stage and two-stage compressors are available, with two-stage types used for pressures in the range of 100–250 psi. They can also be single-acting or double-acting. A *single-acting compressor* uses only one side of the piston, whereas the *double-acting compressor* uses both sides of the piston for compression. Figure 9 shows the internal construction of a two-stage piston-type air compressor.

Load reduction, at times when there's little or no demand for compressed air by the system, is accomplished by bypassing individual cylinders or by throttling the inlet pressure of the cylinders. The capacity of reciprocating compressors can be changed by altering the speed of their drive motors.

Rotary Screw Compressors

Rotary screw compressors compress air by means of rotating screws that mesh with each other inside a sealed housing. The air inlet is at one end of the screws, and the rotation of the screws forces air to move along axially to the high-pressure outlet. There are no valves and the internal sealing is done with oil, which also functions as a coolant. Rotary

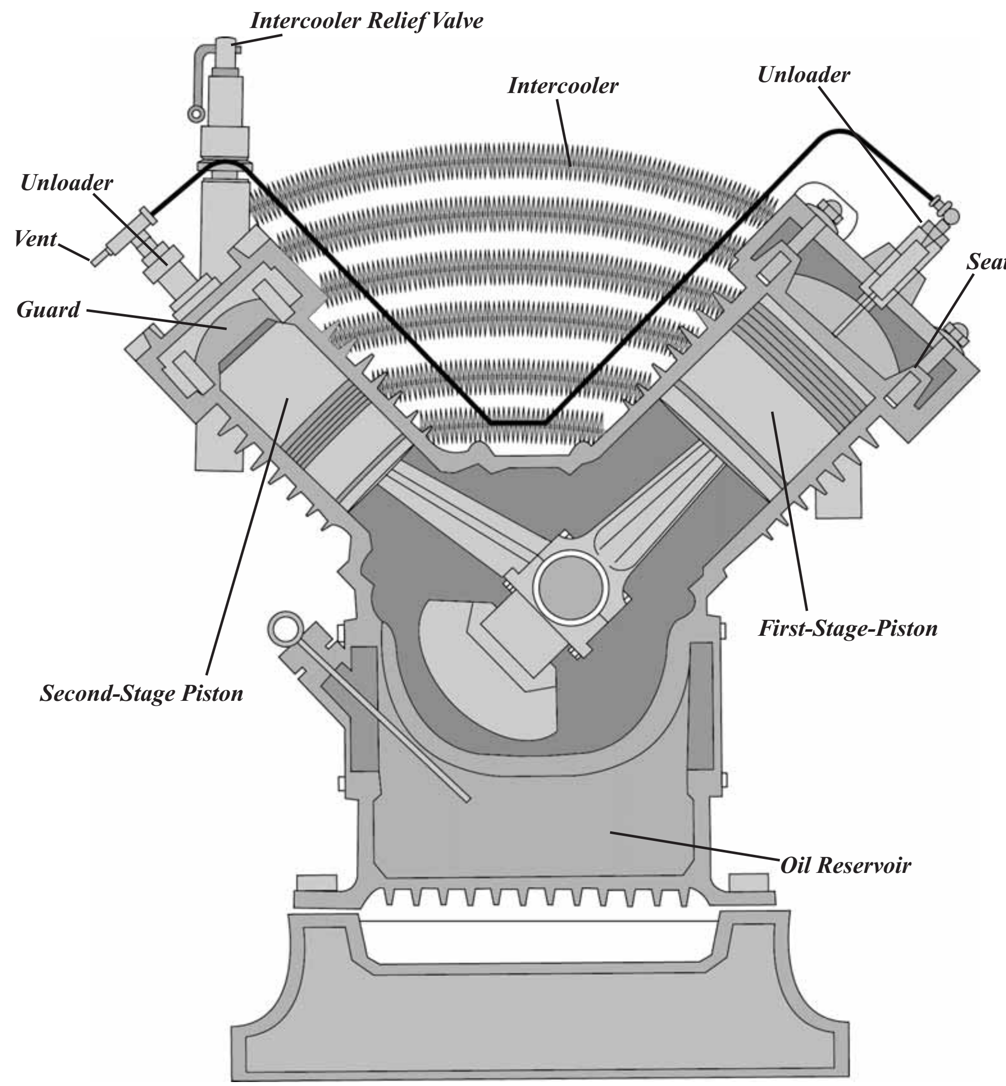


FIGURE 9—This diagram of a typical two-stage reciprocating air compressor shows the unloaders on both the first- and second-stage cylinders.

compressors are reliable and easy to maintain and operate. Capacity changes can be accomplished with either variable drive speeds or variable compressor displacement using internal sliding valves. Special designs are available that yield oil-free air if required.

Centrifugal Compressors

Centrifugal compressors are dynamic types that depend on the transfer of kinetic energy to the contained air from a moving impeller. Airflow to and from the impeller can be either axial or radial. For efficiency, these compressors must rotate at higher speeds and are suitable for high capacities because flow through the compressor is continuous. *Dynamic compressors,* sometimes called *blowers,* are used in applications that require large volumes at relatively low pressures, such as pneumatic conveying, air supply to furnaces or boilers, or even ventilation. Figure 10 shows the basic construction of centrifugal and axial-type dynamic compressors.

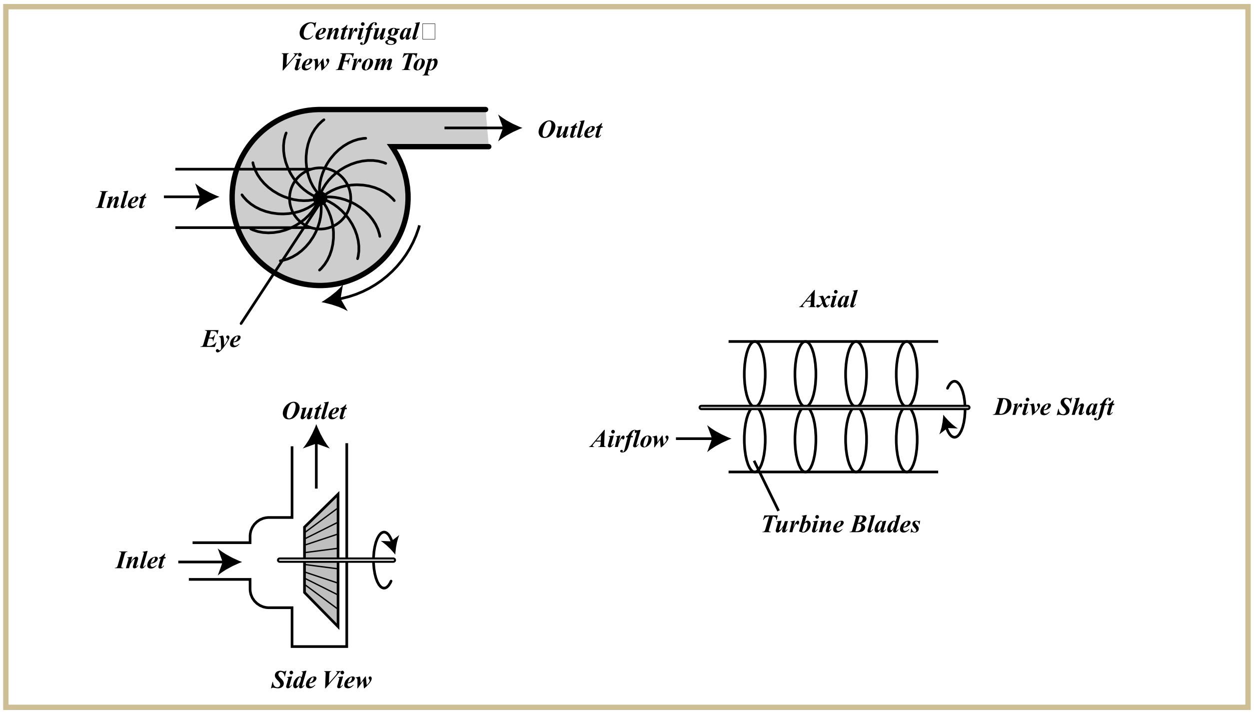


FIGURE 10—This diagram shows how dynamic compressors operate.

Adjusting inlet guide vanes and restricting input volumes and flows controls a dynamic compressor's capacity. The centrifugal compressor is inherently oil-free, since lubrication of the shaft is separate from the air pathway and there are no seals internal to the compressor. They're suitable for continuous service at very high volume outputs; however, they're sensitive to dirt in the air and are expensive compared with other types of compressors.

Auxiliary Equipment

Compressors cannot function without several important pieces of auxiliary equipment, and a compressor is most often purchased with these devices as a packaged self-contained unit. Figure 11 shows all of the major components of a pneumatic system. Controls aren't shown in this diagram, but all pneumatic systems will have these components to ensure proper operation of the pneumatic equipment.

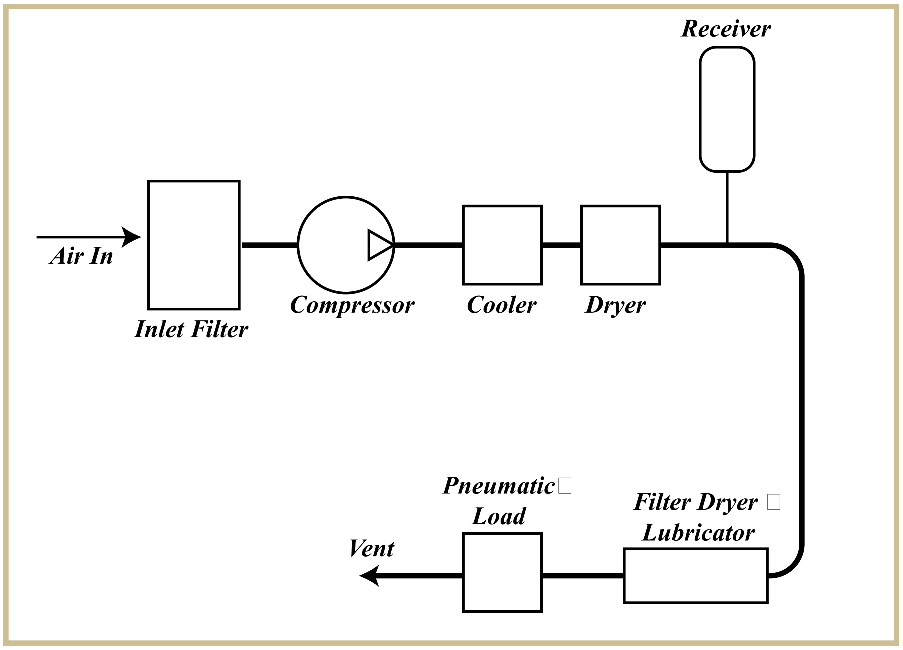


FIGURE 11—At a minimum, all industrial pneumatic systems will have these components. Note that there are two locations where air is treated for use: the primary treatment, which is often located at or around the compressor, and the secondary treatment, which is located just before the air is used at the load.

Inlet filters. Air drawn in from outside often contains dust and dirt particles that could injure internal parts of the compressors. Air filters are necessary to remove these particles but must not hinder airflow, especially for large-capacity compressors. There are many designs for filters that are classified as dry or wet filters, each with specific advantages. Some filters depend on certain air velocities for proper function. Filters must be cleaned and replaced at regular intervals. Air filters are unavoidable sources of pressure drops, and dirty filters will cause excessive pressure drops if not regularly maintained.

Intercoolers and aftercoolers. Air that's compressed becomes very hot, as you learned from your study of the gas laws. This heat must be removed before the air is passed onto subsequent compressor stages or to the system. The intercooler and aftercooler are optimized to carry heat away from the moving compressed air and can be designed with air or water as the cooling agent. Figure 9 shows an intercooler that cools compressed air between the first and second stages of a two-stage compressor. The intercoolers are typically made from a pipe with cooling fins brazed on the outside. These fins carry away the heat generated by the contained air.

Separators and traps. Moisture trapped in the compressed air must be removed before it's passed into the system. Water can plug nozzles and small conductors as well as corrode the internal parts of the system. Lubricants are often in the air as a result of compressor lubrication requirements, and excess oil must be removed to prevent contamination of the system or the process for which the air is used. There are several designs for these separators and traps, but all must have some way of draining fluids from the system after accumulation of moisture and lubricants. Some traps have manual drains; others are automatically controlled. A simple trap works on the principle of rapidly changing the airflow direction. Water molecules—larger and heavier than air molecules—can't change direction as quickly and are thus forced onto the walls of the bowl, as shown in Figure 12. The moisture drains to the bottom, where it can be removed.

Silencers. Compressor silencers are similar to automotive mufflers. They're usually tubes filled with sound-absorbing materials to reduce the compressor output noise to acceptable levels. Moisture in the air often condenses in the baffles of silencers, so a drain or drain system must be part of the silencer.

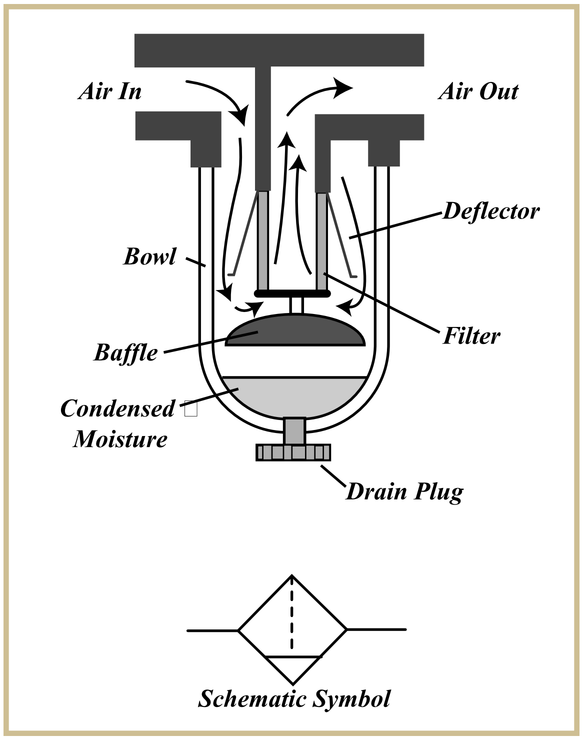


FIGURE 12—Water is removed from a pneumatic system by redirecting the airflow, forcing water molecules to hit the wall of the bowl. Drains must be periodically opened to remove collected moisture and oil.

Receivers. Compressed air delivered from the compressor is stored temporarily in an air receiver. This stored air functions as a reserve to meet occasional excess demands on the system. It also acts as a pulsation damper for reciprocal compressors that have a pulsed output. Receivers are usually mounted as vertical tanks and are equipped with drains and over-pressure relief valves. They're usually cylindrical, and the relatively large internal surface area helps to dissipate the heat that results from the change in volume.

Compressed air from the compressor is conducted to the receiver until a preset pressure is reached, at which point the unloader valve of the compressor discharges to the atmosphere. A pressure-activated switch can also cut off electrical power to the compressor motor. If the pressure in the receiver should rise higher than a preset safe level, a relief valve opens to prevent excess pressure in the system. Receivers may have pressure and temperature gauges, isolation valves, and an access cover for cleaning. Figure 13 shows a schematic diagram of a receiver outfitted with typical accessories for safe operation.

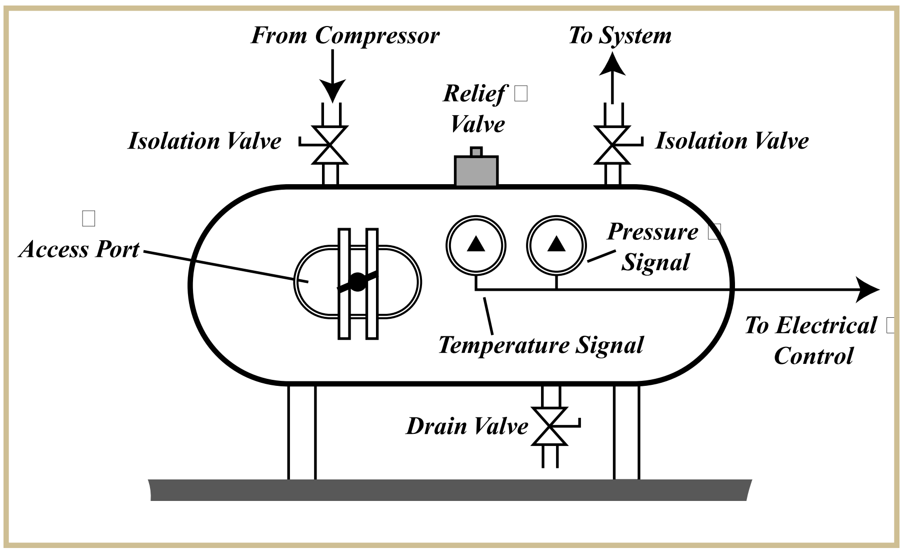


FIGURE 13—A receiver is an integral part of a pneumatic system. Most receivers have the accessories shown here.

Dryers. Air that's required to be moisture-free, such as air for painting or sandblasting or air that's in lines subject to freezing temperatures, must have the moisture removed completely by a drying process. Moisture accumulates in the receiver because the relative humidity rises rapidly as the air volume decreases through compression. Water droplets from condensation inside the system can cause rust. They can also mix with oil to form a sludge that can plug lines and damage tools and equipment connected to the system.

There are several designs for dryers, including adsorption, deliquescent, and refrigeration methods. You should research these methods of drying air to learn the advantages of each as well as typical costs and maintenance requirements.

Filters, Regulators, and Lubricators

Air that's brought in from the atmosphere to the compressor can't be used without filtering, which prevents dust and dirt from entering the compressor and causing damage. This is called *primary treatment.* After the air is compressed, delivered to the receiver, and cooled, it must be treated again before it's ready to be used by the system. This treatment consists of another filter, a regulator to drop the pressure to the required operating pressure, and a lubricator to put oil into the supply air to lubricate the other equipment attached to the lines. This function occurs so often that filters, regulators, and lubricators are often packaged together in one box and called *FRLs.* The National Fluid Power Association has published guidelines for the selection and use of FRLs in a document entitled "Recommended practice—Pneumatic fluid power—Filters, regulators, and lubricators—Application guidelines." This paper is an NFPA Recommended Practice (NFPA/T3.12.17 – 2002) and is available from their Web site at http://www.nfpa.org.

Filters

A popular filter design first has the incoming air directed against a set of baffle plates that cause the air to swirl around. This causes the larger particles of dirt, dust, and moisture droplets to separate from the air stream, where they're collected at the bottom of the bowl and removed through a drain either manually or automatically. The air is then passed through a solid filter made of fine mesh screens or solid material made from sintered metals, such as bronze or other porous materials.

This filter must be large enough to pass the amount of air required downstream from the filter. Filters are rated by the smallest size of the particle they'll pass, and typical filters for these applications are rated as 40, 20, or 5 microns. A micron is 10^{-6} meters, or a millionth of a meter. It's abbreviated as "μm." A 40 μm filter will stop all particles larger than 40 μm. Filters must be sized to allow enough air to pass through to the equipment without causing an unacceptable pressure drop.

Fine wire mesh is often used as a "pre-filter" to remove larger particles. The mesh size of the filter determines the size of the particles it can remove. A 325 mesh filter has wire spacing about 30 microns apart, a 550 mesh filter has wire spacing about 10 microns apart, and a 570 mesh filter has wire spacing about 6 microns apart. To give you an idea of filtering requirements, dust particles are 10 microns or larger, and smoke and oil particles are about 1 micron. Special microfilters can filter contaminants down to about 0.01 microns, which is about the limit of what a filter can remove.

Filters rated with higher numbers generally have higher flow rates. You should check with the manufacturer's rating of the filter to ensure that you've sized the filter for more airflow than is required by equipment attached to the line. Filters are offered in a wide variety of port sizes; filters should be sized by airflow requirements and not simply matched to existing air lines. A typical pressure drop across a filter may be on the order of 1 to 5 psig.

Regulators

Various types of pneumatic equipment require different operating pressures for maximum efficiency, and it's essential to supply enough compressed air at the proper pressure for all equipment connected to the air supply line. Often the compressor delivers air to a receiver at a much higher pressure than is required for any of the individual components connected to the lines. Airflow velocities in a pneumatic system can be very high, and pressure drops through fittings and lines can be very high. Because of this, regulators should be placed close to the equipment and adjusted with the equipment operating at normal flow requirements.

To deliver compressed air at the right pressure, a regulator lowers the pressure to the correct value at the location of the equipment. As equipment is turned off and on and as the demand for air varies throughout the system, the regulator maintains a constant pressure and airflow to the equipment connected to its downstream side. A filter is usually placed immediately upstream from the regulator to prevent damage to the regulator or the equipment.

The simplest type of regulator is a *relief valve*. These are used in places where an over-pressure can be dangerous to the system or personnel, such as the receiver. Figure 14 shows a simple relief valve, which is a spring-loaded ball that seats in a housing. Excess pressure lifts the ball against the spring, thus some of the following pressure to escape. The amount of airflow escaping this valve depends on the amount of excess pressure.

There are two general categories of regulators, relieving and nonrelieving. *Relieving regulators* vent excess pressure to the outside air by means of vents that release air. *Nonrelieving regulators* adjust the downstream pressure without allowing air to escape the system. The pressure drop across the regulator is a function of the airflow through the line. The greater the airflow, the lower the pressure drop; therefore, the pressure setting should be made under the equipment's regular flow conditions.

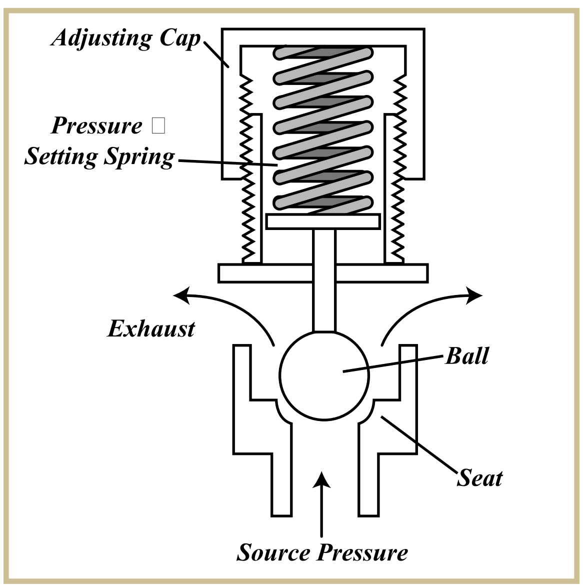


FIGURE 14—This simple relief valve is adjustable by controlling the spring force that holds the ball onto the valve seat.

A simple regulator uses a spring-loaded diaphragm to control a valve opening. How far the spring is compressed determines the downstream pressure. If the downstream pressure rises, the increased pressure helps the spring close the valve, causing the pressure to drop. If the downstream pressure drops, perhaps with an increased demand for air, the higher upstream pressure causes the spring to compress further and raise the pressure downstream. In many cases, the spring is adjustable so that the desired set pressure can be varied by turning a handle or screw.

Figure 15A shows a cross-section of a relieving pressure regulator, while Figure 15B shows a nonrelieving regulator.

In the relieving regulator shown in Figure 15A, the pressure setting is determined by the lower spring. The adjusting screw pushes the spring into the diaphragm, which has a vent located in the center. The poppet assembly has a small valve that seats in the vent. The adjustment spring lifts the upper poppet against the light spring, allowing air to flow. If the output pressure is too low, the diaphragm and vent seat raise the upper poppet to allow more air to flow. If the output pressure is too high, the diaphragm is pushed down, closing off the upper poppet while opening the vent.

More sophisticated regulators can vary the pressure with what's called a *pilot pressure* from another source, either air or hydraulic. These regulators use feedback from sensors to change the pilot pressure, which, in turn, changes the regulator set-point pressure.

Lubricators

Pneumatic equipment such as air tools, cylinders, and motors all have moving parts that require lubrication for efficiency and long life. Moving parts and seals demand lubrication to minimize friction and wear. Injecting an oil mist into the line downstream from the regulator allows proper lubrication to reach critical parts. The amount of lubrication is also critical. Too much oil can leak from the tool or equipment, causing contamination and cleanup problems, and too little oil can damage tools and equipment. Specifying the proper lubricator and ensuring its proper setting is crucial to system performance.

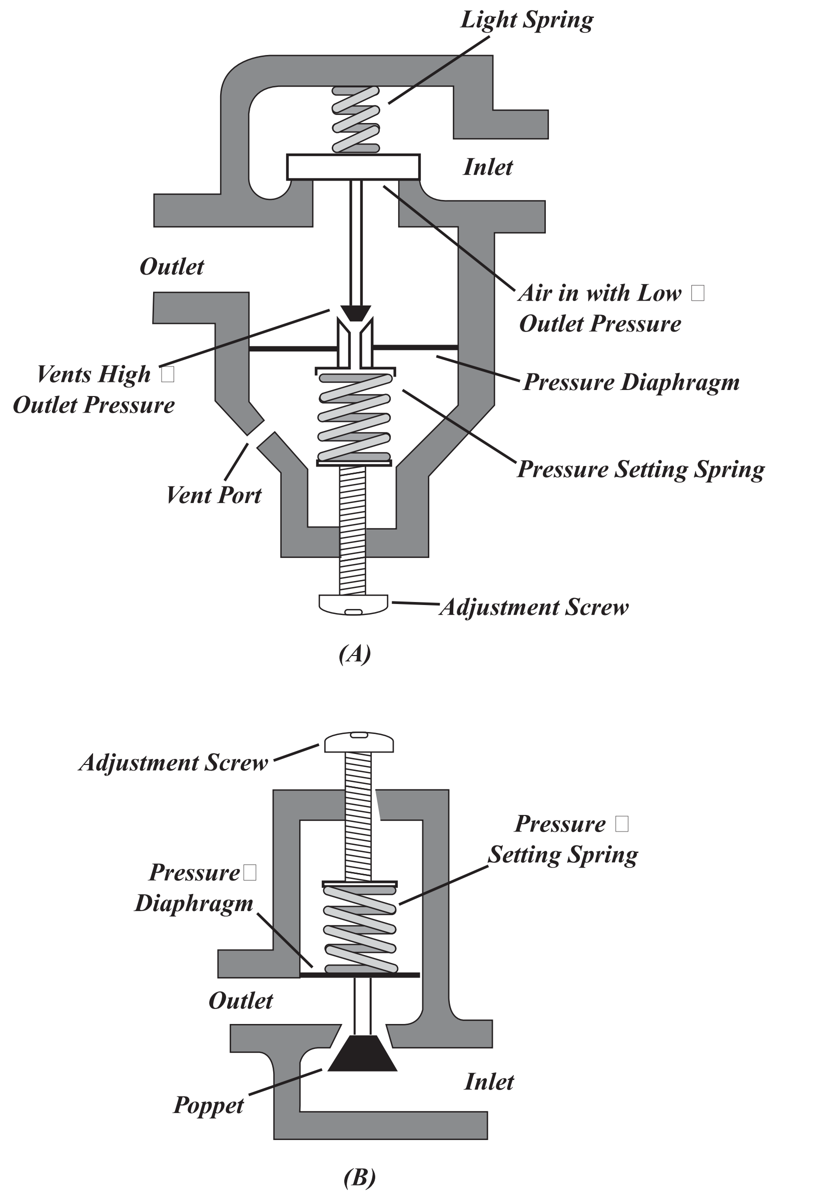
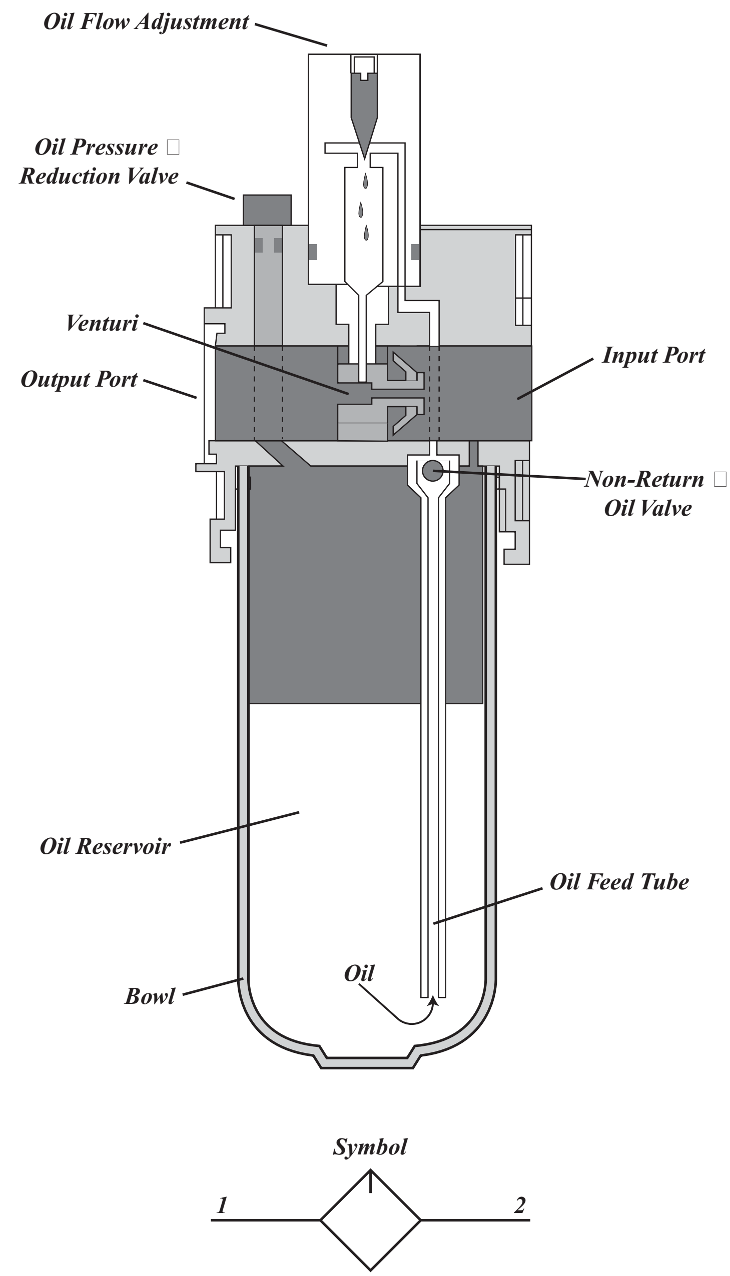


FIGURE 15—Relieving (A) and Nonrelieving (B) Pressure Regulators

Lubricators work on the principle of a venturi, similar to an automobile carburetor. A lubricator is constructed by placing an orifice in the section of line with the reduced diameter and connecting the orifice to an oil reservoir by means of a small tube. The low pressure at the orifice causes oil to be pulled from the reservoir. The moving air stream breaks the oil flow into small droplets, forming a mist or fog within the flowing air. This lubricant then flows downstream into the equipment. Figure 16 shows one example of how oil may be delivered to the airflow stream using these principles.

The *venturi* is a section of air line that's reduced in diameter. Air that flows through this reduced-diameter line speeds up. And as you know by Bernoulli's Principle, when the air velocity speeds up, the pressure goes down.

FIGURE 16—An oil mist lubricator works on the principle of a venturi, which uses a reduced diameter to increase the fluid velocity, thus lowering the pressure. The low pressure then draws oil from a reservoir into the air stream.



Since lubricators work from airflow, it's important to specify a lubricator based on expected airflow. In some lubricators, all of the air moves through the venturi at lower airflows; at higher flows, some of the air is diverted around the venturi and later joined to the lubricated air. Figure 17 shows part of a commercially available combination of relief valve and lubricator. Units that include filters, regulators, and lubricators are called *FRL assemblies.*

FIGURE 17—Filters, regulators, dryers, and lubricators are used so often that they're often packaged as combined assemblies.

Fittings and Conductors

While the more complex pneumatic components such as pumps, valves, and controls may be more interesting, the basic components used to conduct compressed air from one point to another are still very important to the successful operation of any pneumatic application. In general, these components are known as conductors, and a number of important factors must be considered when selecting and applying pneumatic fittings, pipe, hoses, or tubing. Important considerations include the size required, the maximum pressure, the maximum temperature at which the components operate, and the external environment.

General Classifications of Conductors

Conductors for both hydraulic and pneumatic systems are generally classified into three types: *rigid,* or *piping; semirigid,* or *tubing;* and *flexible,* or *hose* and *conduit.* The type of conductor used will be dictated by the application. Distribution lines in factories are often large-diameter pipes, while pneumatic tools and robots require flexible hoses. Common sizes for pipe and tubing run from $^{1}/_{8}$ inch to more than 36 inches (Table 1). Standards published by the American National Standards Institute (ANSI) govern pipe wall thicknesses for different pressure applications. The ANSI "schedule numbers" for pipe indicate the wall thickness.

Rigid pipe is available in a number of common sizes:

- Standard—Schedule 40
- Extra Strong—Schedule 80; for up to 1000 psi
- Schedule 160, for pressures up to 3000 psi
- Double extra strong, for pressures higher than 3000 psi

All of the fittings that connect to these pipes, such as elbows, tees, and unions, are available in the same sizes. The pipe sizes are specified by their nominal inside diameter. All pipes of the same size will have the same outside diameter, but the actual inside diameter will vary depending on the schedule: high-pressure pipe will have a greater wall thickness and smaller inside diameter than a lower-schedule pipe.

Table 1

PIPE TABLE—PHYSICAL DIMENSIONS AND PRESSURE RATINGS

Schedule 40 Pipe

Pipe Size	Outer Diameter	Inner Diameter	Wall Thickness	Inside Area	Working PSI	Burst PSI
1/8	.405	.269	.068	.0568	2238	13432
1/4	.540	.364	.088	.1040	2173	13037
3/8	.675	3493	.091	.1908	1797	10785
1/2	.840	.622	.109	.3037	1730	10380
3/4	1.050	.824	.113	.5330	1435	8609
1	1.315	1.049	.133	38649	1348	8091
1 1/4	1.660	1.380	.140	1.495	1124	6747
1 1/2	1.900	1.610	.145	2.035	1017	6105
2	2.375	2.067	.154	3.354	864	5187
2 1/2	2.875	2.469	.203	4.785	941	5648
3	3.500	3.068	.216	7.390	823	4937

Schedule 80 Pipe

Pipe Size	Outer Diameter	Inner Diameter	Wall Thickness	Inside Area	Working PSI	Burst PSI
1/8	.405	.215	.095	.0363	3128	18765
1/4	.540	.302	.119	.0716	2938	17630
3/8	.675	.423	.126	.1405	2489	14933
1/2	.840	.546	.147	.2340	2333	14000
3/4	1.050	.742	.154	.4320	1955	11733
1	1.315	.957	.179	.7190	1815	10890
1 1/4	1.660	1.278	.191	1.282	1534	9205
1 1/2	1.900	1.500	.200	1.766	1403	8421
2	2.375	1.939	.218	2.951	1224	7343
2 1/2	2.875	2.323	.276	4.236	1280	7680
3	3.500	2.900	.300	6.600	1143	6857

Schedule 160 Pipe

Pipe Size	Outer Diameter	Inner Diameter	Wall Thickness	Inside Area	Working PSI*	Burst PSI
1/2	.840	.464	.188	.1690	2984	17904
3/4	1.050	.612	.219	.2940	2781	16686
1	1.315	.815	.250	.5214	2535	15200
1 1/4	1.660	1.160	.250	1.056	2008	12048
1 1/2	1.900	1.338	.281	1.405	1972	11831
2	2.375	1.687	.344	2.234	1931	11587
2 1/2	2.875	2.125	.375	3.545	1739	10435
3	3.500	2.624	.438	5.405	1668	10011

*Working PSI at a safety factor of 6:1

Semirigid conductors are specified by their inside diameter and wall thickness (Table 2). The outside diameter is important, however, since the fittings must fit over the outside diameter of the tube. Fittings for tubing are generally of two kinds, flared and flareless. *Flared* fittings require the end of the tubing to be flared with a special flaring tool after the nut and ferrule are placed over the tube end. There are two flare angles that you may see in practice: 37° and 45°. Mating fittings must have the same flare angle.

Flexible tubing or hose is used where the conductors must flex or connect to tools that must move. Pneumatic tools such as hammers, drills, or wrenches must move around the work site while connected to the air supply. Flexible tubing can handle operating pressures that are quite high due to their construction. They're usually made with three separate layers. The tube is the inside lining, or the material that actually conducts the fluid. The next layer, the carcass, provides the strength of the hose. It's composed of material such as cotton, synthetic fiber, or even steel braid that's woven or wound around the tube for strength. The final layer, the cover, is a layer of protective material such as rubber that protects the carcass from corrosion or abrasion in service.

As a pneumatic system is installed or evaluated, it's important to remember there's always a pressure drop, or *loss,* as air flows through a conductor. The amount of loss typically depends on the size (diameter) and length of the conductor in relation to the amount of air flowing through it. Table 3 provides an estimate of the suitable conductor size required for typical manufacturing applications. The guidelines in the table recommend a pipe diameter that will result in a 1-psi loss, for every hundred feet of pipe length, at the flow rate listed in the left-hand column (assuming a pressure of 100 psig). For example, a system that required 120 SCFM of air flow at 100 psig with an approximate conductor length of 150 feet would call for a pipe diameter of $1^1/_2$ inches. You should realize that this is an estimate only and there are more exact methods of calculating a required diameter that you'll learn more about in later studies. The column on the right side of the table lists the approximate (two-stage) compressor horsepower it takes to produce the SCFM in the left column at 100 psig. In our example above we would need a 20 Hp compressor to deliver the required flow rate. Again, we'll discuss more exact methods of choosing a compressor, but the table can be used as a guideline to estimate system parameters.

Table 2						
CARBON STEEL TUBING DATA						
Tube O.D.	Wall Thickness	Tube I.D.	Inside Area	Burst PSI	Working PSI @6*	Working PSI @8**
1/8	.028	.069	.00373	24640	4107	3080
	.032	.061	.00292	28160	4693	3520
	.035	.055	.00237	30800	5133	3850
3/16	.032	.1235	.01197	18733	3130	2347
	.035	.1175	.01084	20533	3422	2567
1/4	.035	.180	.02543	15400	2567	1925
	.042	.166	.02163	18480	3080	2310
	.049	.152	.01814	21560	3593	2695
	.058	.134	.01410	25520	4253	3190
	.065	.120	.01130	28600	4767	3575
5/16	.035	.2425	.04616	12320	2053	1540
	.042	.2285	.04099	14784	2464	1848
	.049	.2145	.03612	17248	2875	2156
	.058	.1965.	.03031	20416	3403	2552
	.065	1825	.02615	22880	3813	2860
3/8	.035	.305	.07302	10267	1711	1283
	.042	.291	.06647	12320	2053	1540
	.049	.277	.06023	14373	2300	1797
	.058	.259	.05266	17013	2875	2127
	.065	.245	.04712	19067	3178	2383
1/2	.035	.430	.14515	7700	1283	963
	.042	.416	.13585	9240	1540	1155
	.049	.402	.12686	10780	1797	1348
	.058	.384	.11575	12760	2127	1595
	.065	.370	.10747	14300	2383	1788
	.072	.356	.09949	15840	2640	1980
	.083	.334	.08757	18260	3043	2283
5/8	.035	.555	.24180	6160	1027	770
	.042	.541	.22975	7392	1232	924
	.049	.527	.21802	8624	1437	1078
	.058	.509	.20338	10208	1701	1276
	.065	.495	.19234	11440	1907	1430
	.072	.481	.18162	12672	2112	1584
	.083	.459	.16538	14608	2435	1826
	.095	.435	.14854	16720	2787	2090
3/4	.049	.652	.33371	7187	1198	898
	.058	.634	.31554	8507	1418	1063
	.065	.620	.30175	9533	1589	1192
	.072	.606	.28128	10560	1760	1320
	.083	.584	.26773	12173	2029	1522
	.095	.560	.24618	13933	2322	1742
	.109	.532	.22217	15987	2664	1998
*(Safety factor of 6.) **(Safety factor of 8.)						

(Continued)

Table 2—Continued

CARBON STEEL TUBING DATA						
Tube O.D.	**Wall Thickness**	**Tube I.D.**	**Inside Area**	**Burst PSI**	**Working PSI @6***	**Working PSI @8****
7/8	.049	.777	.47393	6160	1027	770
	.058	.759	.45222	7291	1215	911
	.065	.745	.43569	8171	1362	1021
	.072	.731	.41947	9051	1509	1131
	.083	.709	.39460	10434	1739	1304
	.095	.685	.36834	11943	1990	1493
	.109	.657	.33884	13703	2284	1713
1	.049	.902	.63686	5390	898	674
	.058	.884	.61344	6380	1063	798
	.065	.870	.59417	7150	1192	894
	.072	.856	.57520	7920	1320	990
	.083	.834	.54601	9130	1522	1141
	.095	.810	.51504	10450	1742	1306
	.109	.782	.48005	11990	1998	1500
	.120	.760	.45342	13200	2200	1650
1 1/4	.049	1.152	1.0418	4312	719	539
	.058	1.134	1.0095	5104	851	638
	.065	1.020	.98470	5720	953	715
	.072	1.106	.96024	6336	1056	792
	.083	1.084	.92242	7304	1217	913
	.095	1.060	.88203	8360	1393	1045
	.109	1.032	.83604	9592	1600	1200
	.120	1.010	.80078	10560	1760	1320
1 1/2	.065	1.370	1.4734	4767	794	596
	.072	1.356	1.4434	5280	880	660
	.083	1.334	1.3970	6087	1014	761
	.095	1.310	1.3471	6967	1161	871
	.109	1.282	1.2902	7993	1332	1000
	.120	1.260	1.2463	8800	1467	1100
1 3/4	.065	1.620	2.0602	4086	681	511
	.072	1.606	2.0247	4526	754	566
	.083	1.584	1.9696	5217	870	652
	.095	1.560	1.9104	5971	995	746
	.109	1.532	1.8424	6851	1142	856
	.120	1.510	1.7899	7543	1257	943
	.134	1.482	1.7241	8423	1404	1053
2	.065	1.870	2.7451	3575	596	447
	.072	1.856	2.7041	3960	660	495
	.083	1.834	2.6404	4565	761	571
	.095	1.810	2.5717	5225	871	653
	.109	1.782	2.4928	5995	100	749
	.120	1.760	2.4316	6600	1100	825
	.134	1.732	2.3549	7370	1228	921

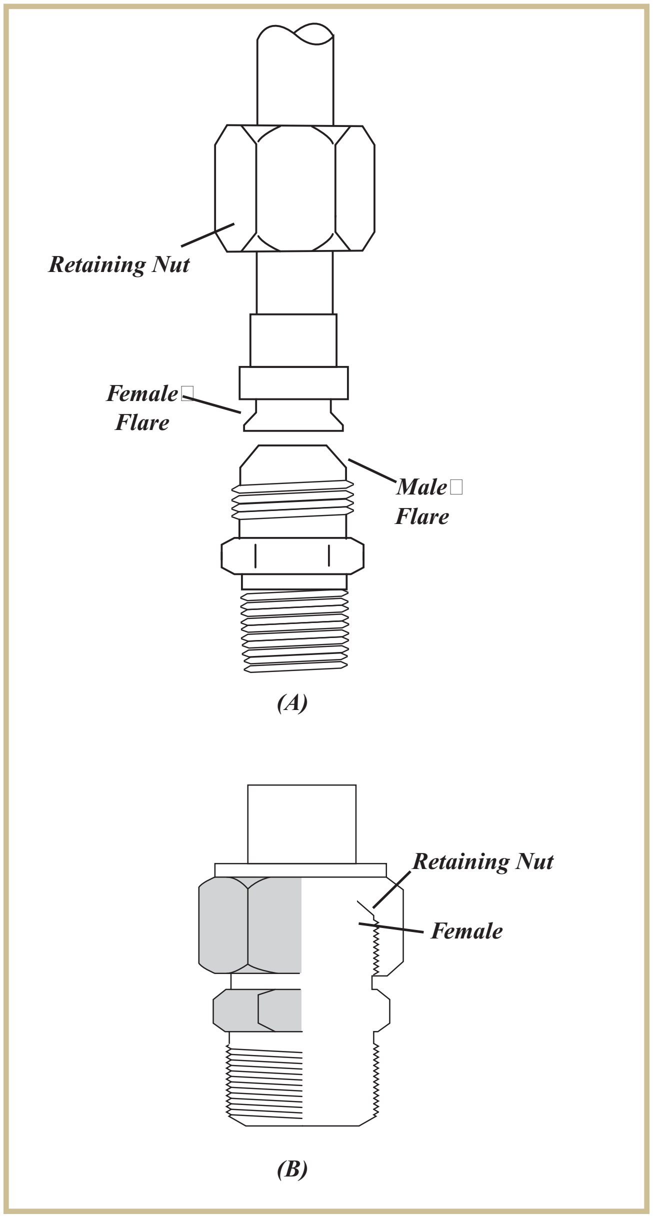


FIGURE 18—This diagram shows flare and flareless fittings.

Table 3										
AIR PIPE SIZE (inches)										
SCFM Flow	25′ Run	50′ Run	75′ Run	100′ Run	150′ Run	200′ Run	300′ Run	500′ Run	1000′ Run	Compressor Hp
6	½	½	½	½	½	½	½	¾	¾	1
18	½	½	½	¾	¾	¾	¾	1	1	3
30	¾	¾	¾	¾	1	1	1	1	1	5
45	¾	¾	1	1	1	1	1¼	1¼	1¼	7½
60	¾	1	1	1	1¼	1¼	1¼	1½	1½	10
90	1	1	1¼	1¼	1¼	1¼	1¼	1½	2	15
120	1	1¼	1¼	1¼	1½	1½	1½	2	2	20
150	1¼	1¼	1¼	1¼	1½	2	2	2	2½	25
180	1¼	1½	1½	1 ½	2	2	2	2½	2½	30
240	1¼	1½	1½	2	2	2	2½	2½	3	40
300	1½	2	2	2	2	2½	2½	3	3	50
360	1½	2	2	2	2½	2½	2½	3	3	60
450	2	2	2	2½	2½	3	3	3	3 ½	75
600	2	2 ½	2½	2½	3	3	3	3½	4	100
750	2	2 ½	2½	3	3	3	3½	3½	4	125

Quick-Connect Fittings

The ability to quickly disconnect a tool from an airline is often required for various pneumatic applications, such as factories, automotive shops, or machine shops. All quick-connect fittings use a male and female portion to make or break a connection. Depending on the application, the fitting may seal off the pressurized air in one direction only, both directions, or neither direction. The typical air tool for inflating tires will have a flexible hose with a female socket on the end that seals the air when a tool isn't connected. When a tool is plugged in, the male plug is captured and held fast by a mechanism such as a cam-lock, bayonet coupling, or ball lock. A popular pneumatic quick-connect fitting uses several spring-loaded balls in the socket that are forced into a groove in the plug to capture it securely (Figure 19). Inserting the plug opens a valve in the socket to allow air to flow through the fitting.

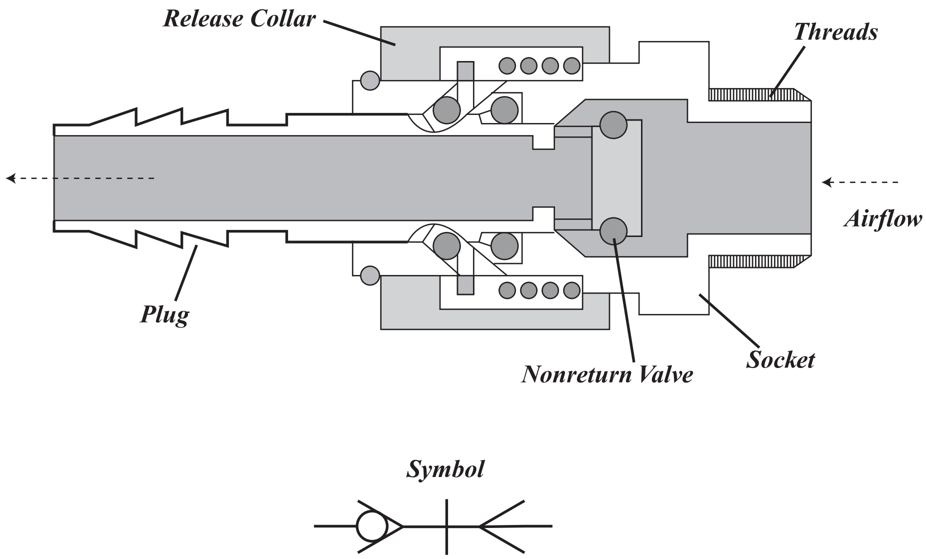


FIGURE 19—Quick-connect fittings allow rapid connection and disconnection of airlines and tools to pneumatic lines. The coupling elements incorporate non-return valves to seal air flow when the male plug is disconnected.

Materials

Common conductor materials that you'll see in pneumatic applications include steel, copper, stainless steel, plastic and polyvinyl chloride (PVC), aluminum, brass and bronze, rubber, and nylon. As you can see, a wide variety of materials is available "off the shelf" from suppliers. Special materials or processes such as part plating are available from manufacturers who supply custom applications.

The primary factor in determining the material is the environment in which the conductors operate. If the external environment has corrosive elements such as salts or other chemicals, the material must be chosen for its ability to operate successfully in a hostile environment. Stainless steel may be required for a corrosive environment, whereas a copper, brass, or bronze material may be specified for a saltwater environment. Air lines in factories are usually made of galvanized pipe so that moisture doesn't cause rust to form inside, which can flake off and damage other components.

Semirigid tubing is typically available in several common materials: seamless 1010 (carbon) steel, fully annealed; seamless 18-8 stainless steel, fully annealed; seamless aluminum; seamless fully annealed copper; and plastic.

Annealing is a heating process that softens a metal so that it can be bent and formed.

Many of the components that connect must have seals that maintain the pressure of the system. Components with moving parts such as cylinders and motors must have seals that prevent air loss, allow movement, and provide lubrication. The choice of seal materials depends on the environment, as some materials are more resistant to corrosive materials or extreme temperatures. Table 4 shows a list of common seal materials, with recommended applications and temperature ranges.

Table 4

SEAL MATERIALS FOR FLUID POWER

Seal Material	Recommended For:	Temperature Range
Leather, wax impreg.	Air, oil, water (limited temp.)	-65 to + 180°F
Leather, rubber impreg.	Air, oil, water (higher temp.)	-65 to + 250°F
Corfam	Air, oil, water	-65 to + 250°F
Natural rubber	Brake fluid, non-petroleum oils	-65 to + 250°F
Buna-S	Water, water/glycol	-40 to + 225°F
Buna-N, Hycar	Air, oil, water, water/gycol	-40 to + 250°F
Butyl	Water, water/glycol, phosphate ester	-65 to + 225°F
Silicone	Water, oil, phosphate ester	-120 to + 600°F
Neoprene	Water, water/glycol	-40 to + 250°F
Viton	Air, oil, water, water/glycol, phosphate ester	-40 to + 450°F
Polyurethane	Oil only	-20 to + 200°F
Teflon, Kel-F	Oil, water, phosphate ester, water/glycol	-320 to + 500°F

Manifolds

Where many controls are located in a relatively confined space, the use of a *manifold* reduces the complexity of the piping and potential sources of leaks. Valves and other controls can be mounted on flat plates with drilled or cast air passages. The flat surface provides an easily sealed surface where many components can be mounted in a compact space. The cost of manifolds is initially quite high, but they pay for themselves in ease of servicing, troubleshooting, ability to change components quickly, and reduction of air leaks.

Modern pneumatic components may stack against each other and mount on a support that can hold multiple valves or controls of the same external shape. Each component contains passageways that allow other connected components access to the air supply. Figure 20 shows an example of this type of island.

FIGURE 20—This example shows how modular pneumatic valves can be stacked for simplicity and a compact assembly. Stacked assemblies greatly simplify tube-installation and troubleshooting tasks. (Photo courtesy of Festo Corporation, Hauppauge, NY)

Controls and Valves

Compressors generate compressed air, and receivers collect it. *Secondary conditioners* filter, regulate, and lubricate the air so it's ready to be used by the equipment, and conductors direct the air to the point of use. The next step in understanding pneumatic systems is to learn about the components that allow people, computers, or other machines to direct and control the flow of air so that the system does what it was designed to do. In pneumatic systems, controls are necessary to direct airflow, regulate the speed of equipment operation, and limit the pressure at which the components are operated. In this section we'll look briefly at directional and flow control valves.

Directional Control Valves

Directional control valves are used to control the flow of pressurized air. These controlling actions include starting, stopping, and changing the direction of flow from one conductor to another. In schematics of pneumatic systems, directional control valves are drawn as square blocks, with the number of squares indicating the number of valve positions. Lines and arrows indicate the available connections between the ports, and a short line ending with another perpendicular line means the port is blocked. Figure 21 shows a typical control valve symbol with terminology and symbols. A solid arrow in schematics generally indicates a hydraulic component. While arrows that are "hollow" technically indicate pneumatic components, it's often the case that solid arrows represent both hydraulic and pneumatic components. The direction of the arrowhead shows the direction of fluid flow.

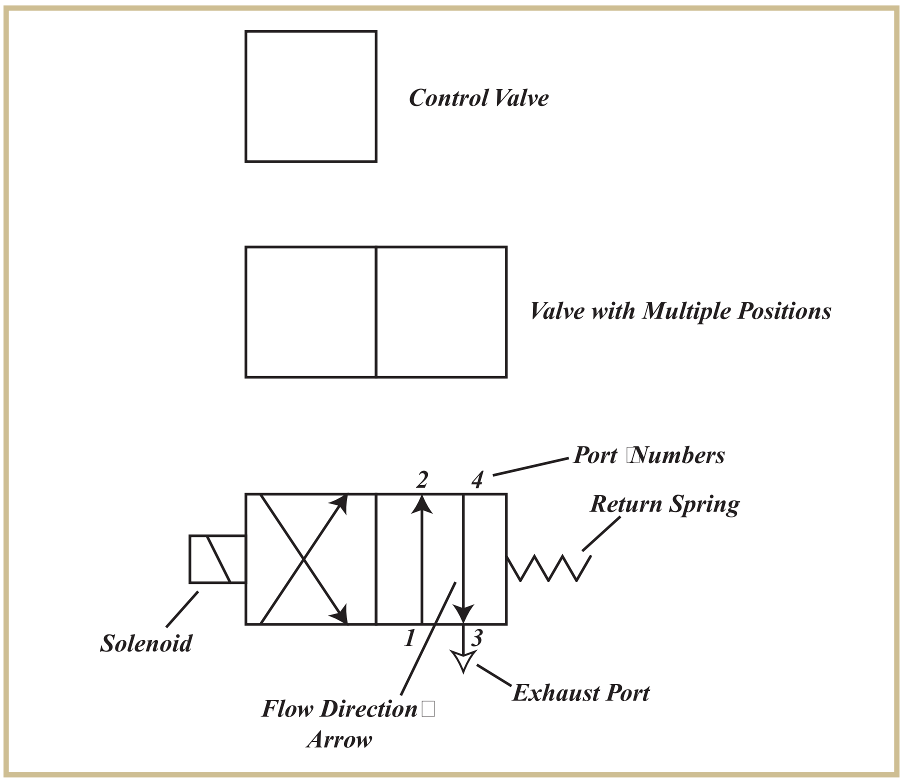


FIGURE 21—Control valves and other pneumatic equipment are drawn on schematics with standard symbols that tell technicians the function and location of the system components.

To visualize the operation of a valve shown in a schematic, picture the conductors remaining fixed in the diagram and imagine the "boxes" sliding back and forth so that the conductors line up with the directional arrows in each of the individual boxes of the valve. The method of valve operation is indicated by the symbol at the ends of the boxes, and springs are often used to return the valve to its starting position. Springs are indicated by zigzag lines at the ends of the boxes. There are manually operated valves, solenoid-operated valves, and pilot-operated valves. Appendix A shows examples of many—but not all—of the different types of valves you may run across. Notice the symbols of the different types of operational methods.

In general, valves that have fixed positions of operation (as opposed to variable valves that have adjustable positions to regulate flow) are designated by a *port/position* nomenclature. For example, a valve with three ports and two possible operating positions—indicated by two boxes in the schematic symbol—would be called a 3/2 valve. This indicates that the valve has three ports and two fixed positions of operation.

The ports used in control valves are designated by a letter or number depending on their function. Newer schematics use numbers, but you may encounter schematics that use letter designations. Table 5 shows the relationship between the port function and the number or letter.

Table 5

PORT FUNCTION WITH NUMBER OR LETTER DESIGNATION

Function	Number Designation	Letter Designation
Pressure port	1	P
Output port (to cylinder)	2, 4…	A, B …
Exhaust port	3, 5 …	R, S …
Control port	10, 12, 14 …	Z, Y, X …

Control valves are made in three configurations: poppet valves, spool valves, and rotary valves. In a *poppet valve,* a simple disc or ball is used with a valve seat to control the flow of air. The ball or disk is spring-loaded against the seat, and a plunger operated by a lever or solenoid pushes the ball

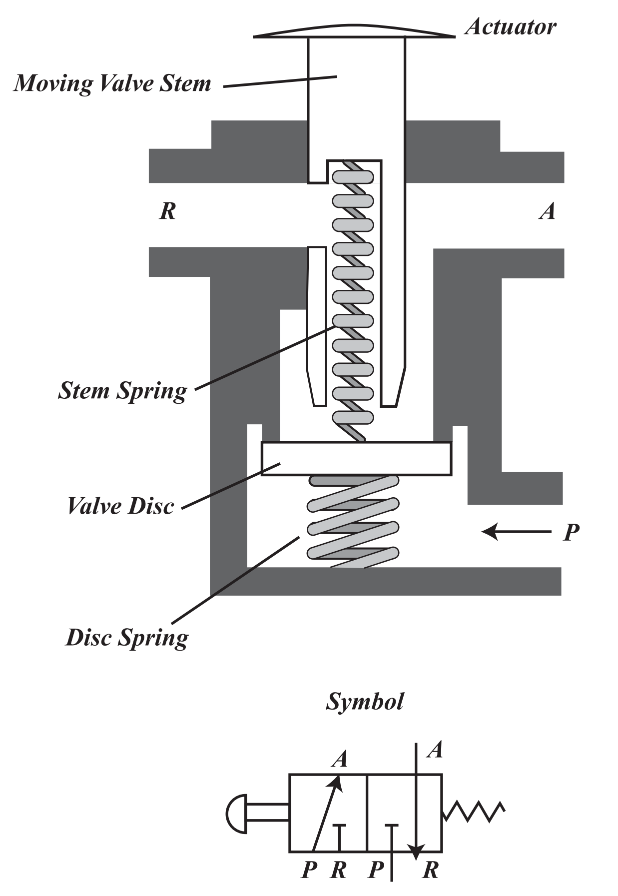


FIGURE 22—The internal construction details of a typical poppet valve are shown here, along with the schematic symbol. Note that schematic symbols don't indicate the valve type.

or disk off the seat to allow flow. When the plunger is released, the spring moves the ball or disk toward the seat, and the pressure forces the ball against the seat to seal the output port. Figure 22 shows the construction of a typical poppet-type valve that's equipped with a disk.

Spool valves operate similarly to hydraulic spool valves. A cylindrical spool moves back and forth within a housing, with cavities and passages that direct airflow. The spool has areas of smaller diameters such that when the relieved area lines up with a cavity, air is allowed to flow around the spool and through the cavity to the outlet port. The larger diameters of the spool have seals that prevent airflow between cavities. Spool valves are actuated easily because the pressure is nearly balanced on the inside faces of the spool. The actuating mechanism doesn't have to work against high pressure, as in the case of the poppet valves. Figure 23 shows the construction and schematic symbol of a spool valve. Note that the symbol doesn't tell you anything about the internal construction of the valve, only its function.

Rotary valves consist of a cylinder with drilled or cast passages, which is fitted into a sleeve with ports. As the cylinder is rotated, the passages line up with the various ports in the sleeve, allowing air to flow to the appropriate ports. Rotary valves also don't require an actuator to work against pressure and are thus easy to operate. Rotary valves are generally used in low-pressure systems, often for hand-operated mechanisms. A diagram of the internal construction of a rotary valve is shown in Figure 24.

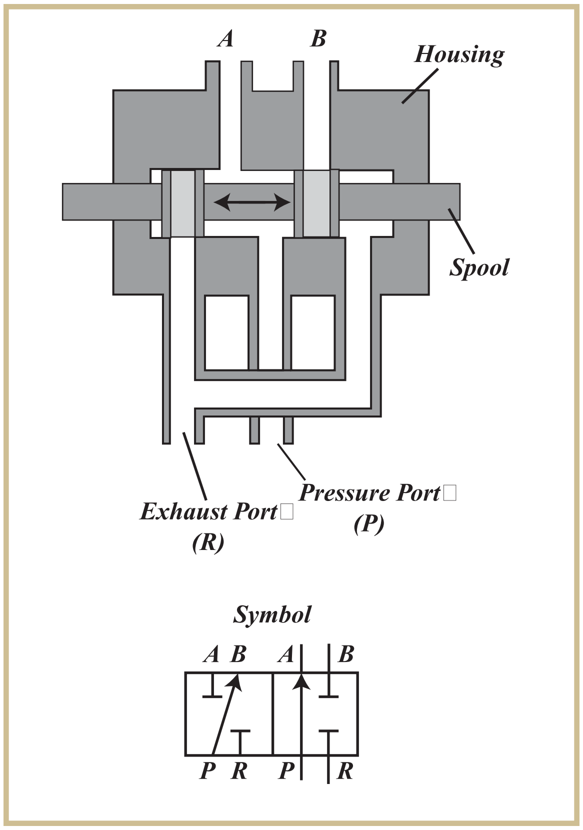


FIGURE 23—A spool valve has a cylindrical spool that slides back and forth within a housing, connecting ports internally. In its present position this valve allows air to flow in through port A and out through port P. Air flow through port B is blocked.

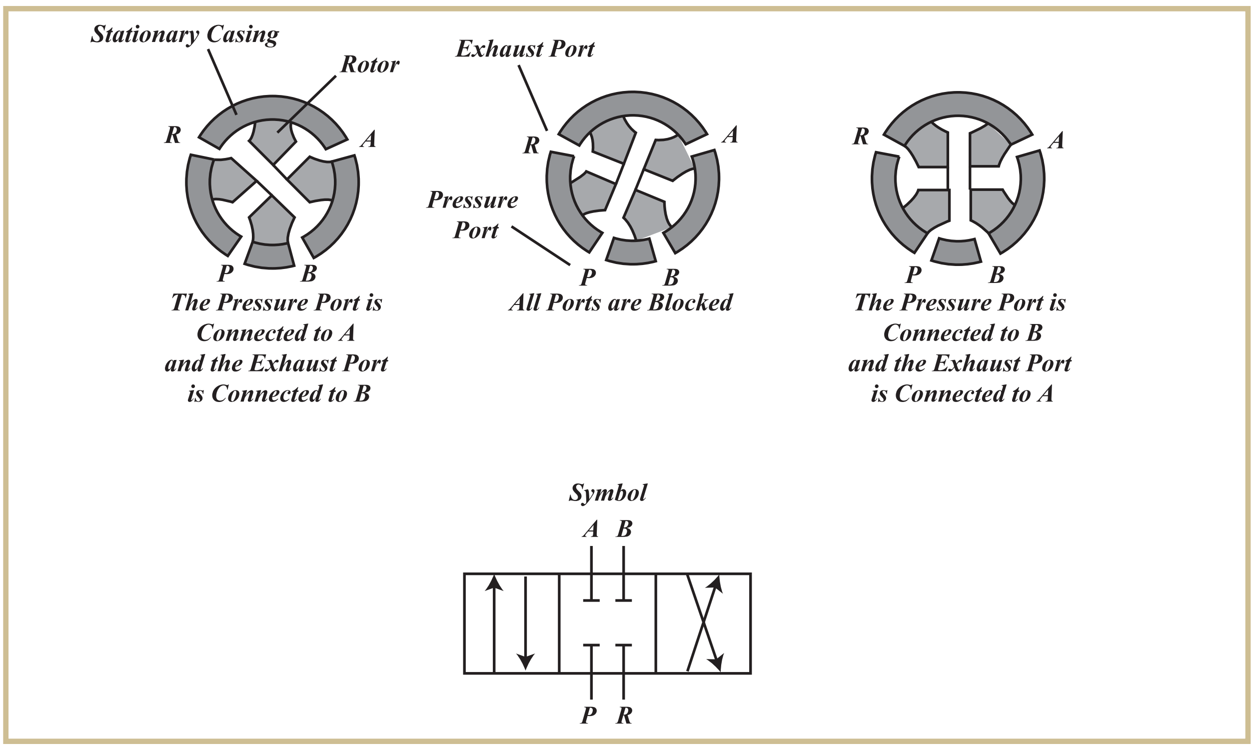


FIGURE 24—A rotary valve has the same function as a poppet or spool valve, but with a different internal construction. Rotary valves are used principally in low-pressure systems.

At a minimum, control valves have an inlet and an outlet; however, most control valves have three or more ports, and either two or three available positions. Actuation of the valve can be done mechanically, such as by a hand- or foot-operated lever, or it can be controlled by an electric solenoid or pilot air pressure. *Pilot air* is air that's available for control purposes, and not for doing work in motors or actuators. Flow requirements for pilot air are very low. If the inlet is normally connected to the outlet when the valve is in the de-energized position, we say it's a *normally open (NO) valve*. If the inlet port is blocked and the valve needs to be actuated to connect the inlet to the outlet, we say it's a *normally closed (NC) valve*. The two-way valve is the simplest of the control valves, with only two ports, and it's normally used to simply shut off airflow. The schematic in Figure 25 shows a solenoid-operated, spring return, 4/2 valve that serves as the pilot control for another 4/2 valve, which controls a cylinder. Study the symbols in Appendix A to learn the different types of valve configurations and operation methods.

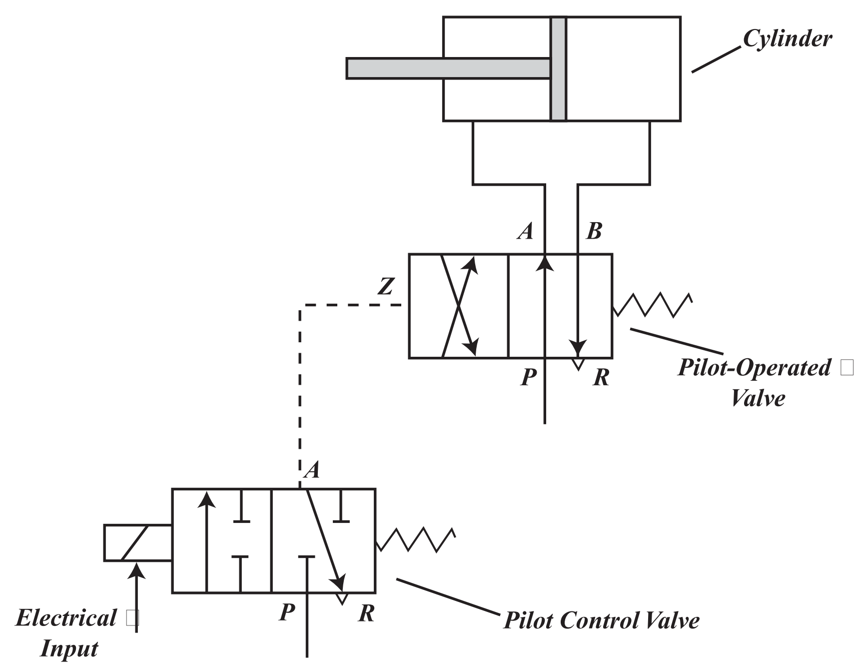


FIGURE 25—This schematic shows a pilot-operated valve. The valve is controlled by another valve that's operated by an electric signal to a solenoid. Note that while a pressure signal is sent to the pilot-operated valve, Z isn't counted as one of the valve's ports when identifying it as a 4/2 valve.

An example of a 4/3 valve that has an inlet, two outlet ports, and an exhaust port is shown in Figure 26. These controls are designed with three possible positions of operation. The exhaust port in a pneumatic system most often dumps "used" air into the atmosphere. In some cases, the air is discharged directly from the valve. In other cases, the exhaust port is fitted with a muffler, or silencer. An outward-pointing arrow drawn directly on the port indicates that air is discharged directly from the port, while a short line and then an outward-pointing arrow indicate that a fitting is connected to the port. An additional rectangle with three short internal lines is the symbol for a silencer.

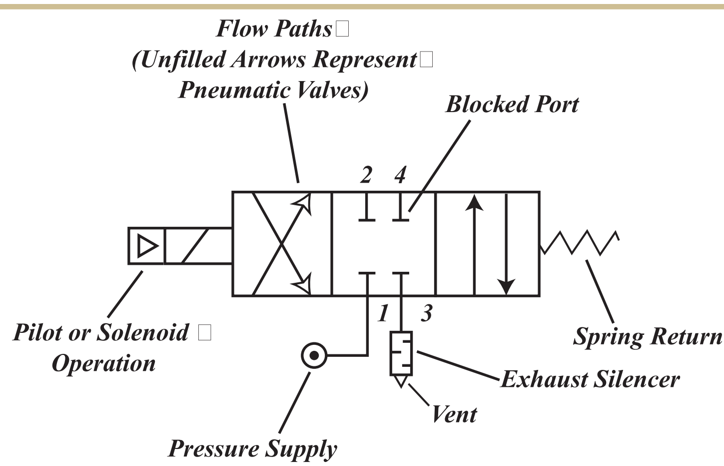
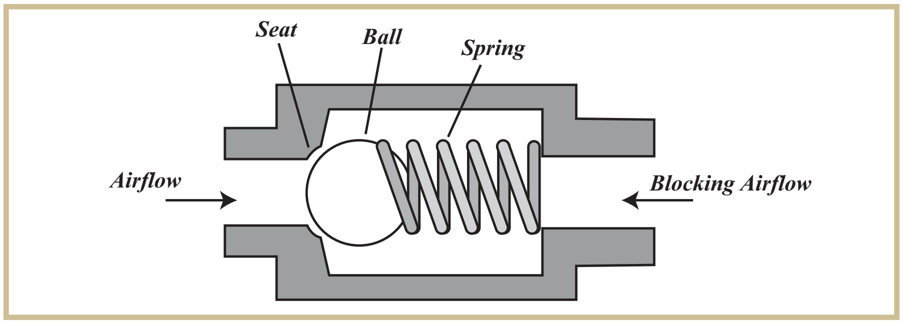


FIGURE 26—This diagram of a 4/3 valve shows symbols for operation, pressure supply source, spring return, and an exhaust silencer and vent.

A *check valve,* or *nonreturn valve,* is another directional control device, although it's usually independent of mechanical or electrical controls. A check valve allows airflow in only one direction. In a simple configuration, a ball is pushed into a seat by a lightly loaded spring. When pressure is applied in the proper direction, the ball is easily moved away from the seat, and air flows relatively freely. If pressure applied to the other port is greater than the pressure from the correct direction, the ball will be pushed back into the seat and flow will stop. Figure 27 shows a simplified version of a check valve equipped with a ball-type restriction.

Check valves can be made that allow air to flow in the reverse direction for special conditions by providing pilot operation. A pilot-operated piston pushes the ball or disc seal off the seat, even when pressure from the port tends to close the valve.

FIGURE 27—A check valve, or no-return valve, prevents flow in one direction while allowing free flow in the opposite direction. Nonreturn valves are also available in 90º configurations.



Check valves are used to stop loads from creeping. They're also often used with a flow control valve to meter airflow in the opposite direction, as opposed to stopping it completely.

Control valves may utilize different methods of flow control, including a tapered plug, a poppet or disk, or a sliding spool, similar to hydraulic valves. There are several types of valves that are used for either hydraulic or pneumatic applications, but you should consult manufacturers' catalogs for allowable applications.

Flow Controls

The check valve you just read about is a type of flow control valve, but its operation is very simple: it either allows flow to occur, or it stops it altogether. In some applications, it's necessary to control the speed of operation of a cylinder or motor. In many applications, the pressure is applied to the cylinder while the load's inertia determines the speed of operation and the amount of force or torque required from the actuator. Flow control valves are available with metered flow in one direction and free flow in the other, or metered flow in both directions. Restricting the amount of airflow will effectively limit the speed of operation of an actuator.

One method of limiting flow rates is to place a restriction check valve in the line before the actuator. This type of control valve allows free flow in one direction and metered flow in the reverse direction. Figure 28 shows the schematic diagram and symbol of a restriction check valve. These valves are often used to limit the airflow from a cylinder on the extension or retraction stroke.

Metered flow enters the valve in Figure 28 from the left. Air pressure and the weak spring hold a poppet against the

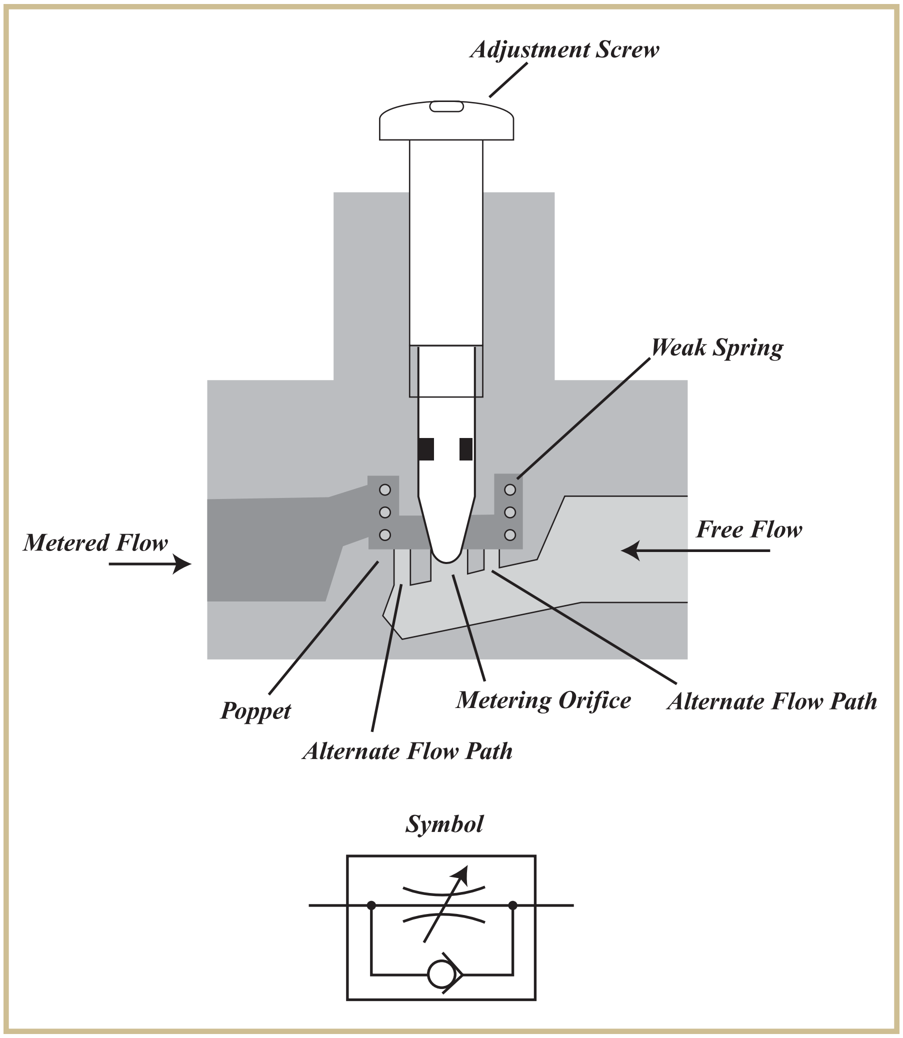


FIGURE 28—Nonreturn valves can be made with limited flow in the reverse direction, which can be adjustable. They're used to limit the speed of cylinders in either extend or retract direction.

alternative flow paths, ensuring all flow (from left to right) must move through the metering orifice area that's formed between the conical end of the adjustment screw and the seat on the inside diameter of the poppet. The adjustment screw is threaded in the valve body and adjusting the screw depth changes the metered flow area. When air flows from the right side of the valve to the left, the pressure will raise the poppet against the weak spring, opening the alternate flow paths and offering a much greater flow area and therefore greater flow volumes.

Another type of flow control valve is a simple orifice, which limits flow in both directions. The valve can be fixed, or it can be a variable type. The schematic symbol for both types is shown in Figure 29. These are also called *throttle valves,* and are used to adjust the airflow so that speed of equipment is limited. A throttle valve operates similar to a flow control

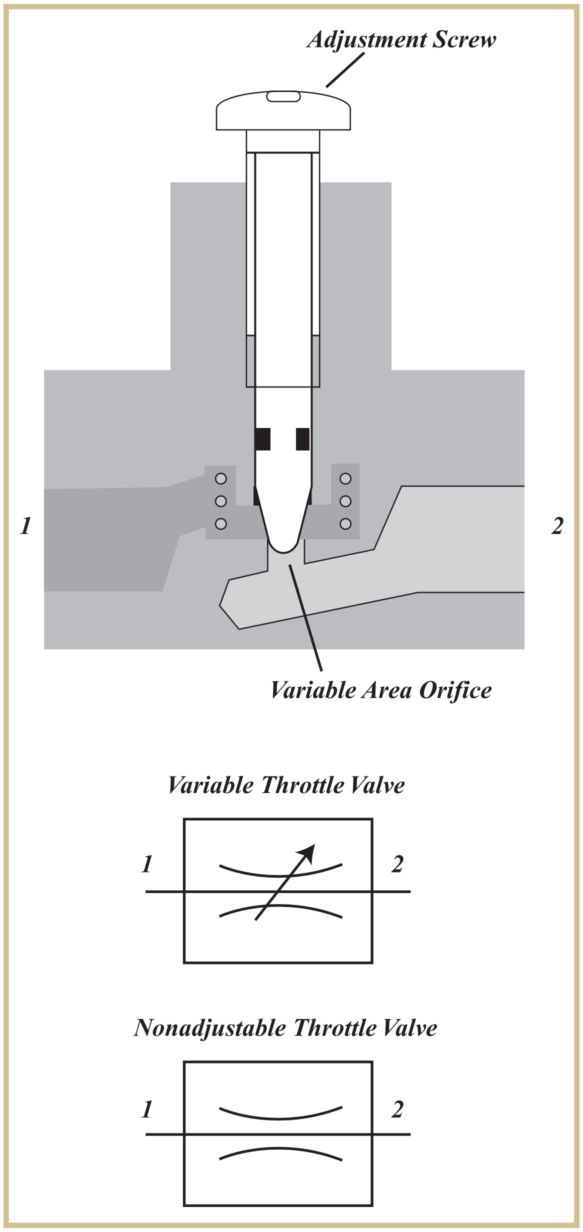


FIGURE 29—A throttle valve is used to limit the speed of equipment by restricting airflow in both directions.

valve except there is no check-valve feature to allow nearly free flow in one of the directions. Air flow entering either side of the valve must pass through the metering orifice, whose size is determined by the depth of the adjustment screw. Some applications require fixed orifice throttle valves that aren't adjusted by the operators or technicians. These may consist simply of fittings with reduced inside diameters through which air must flow.

You'll be exposed to several other common flow control valves as a technician. A *time-delay valve* (Figure 30) is used to provide a time delay from the time the valve is actuated until pressure increases at the output port. These valves allow movements of other equipment before the controlled equipment is allowed to move. The time is controlled by a reservoir chamber that's metered to prevent rapid pressure buildup. When the pressure in the reservoir reaches the correct level, the valve then actuates.

Figure 31 shows a quick exhaust valve and a shuttle valve. *Quick exhaust valves* are used to vent cylinders quickly instead of returning air through conductors. They're located close to the cylinders they vent. A *shuttle valve* is constructed from a ball or poppet that's free to move so that it will seat in either of two directions. This valve is used as an OR gate in pneumatic logic circuits. Shuttle valves and quick exhaust valves operate in similar fashions. In a shuttle valve, if either side is pressurized, the poppet will slide or move towards the opposite side of the valve, thus sealing the other port and allowing air to flow only from the pressurized port. Shuttle valves can also be configured as quick-exhaust valves, which allow a cylinder to be pressurized form one port (port 1 in Figure 31A) while blocking the exhaust (port 3). Removing pressure from port 1 allows the cylinder to return to its static position, which

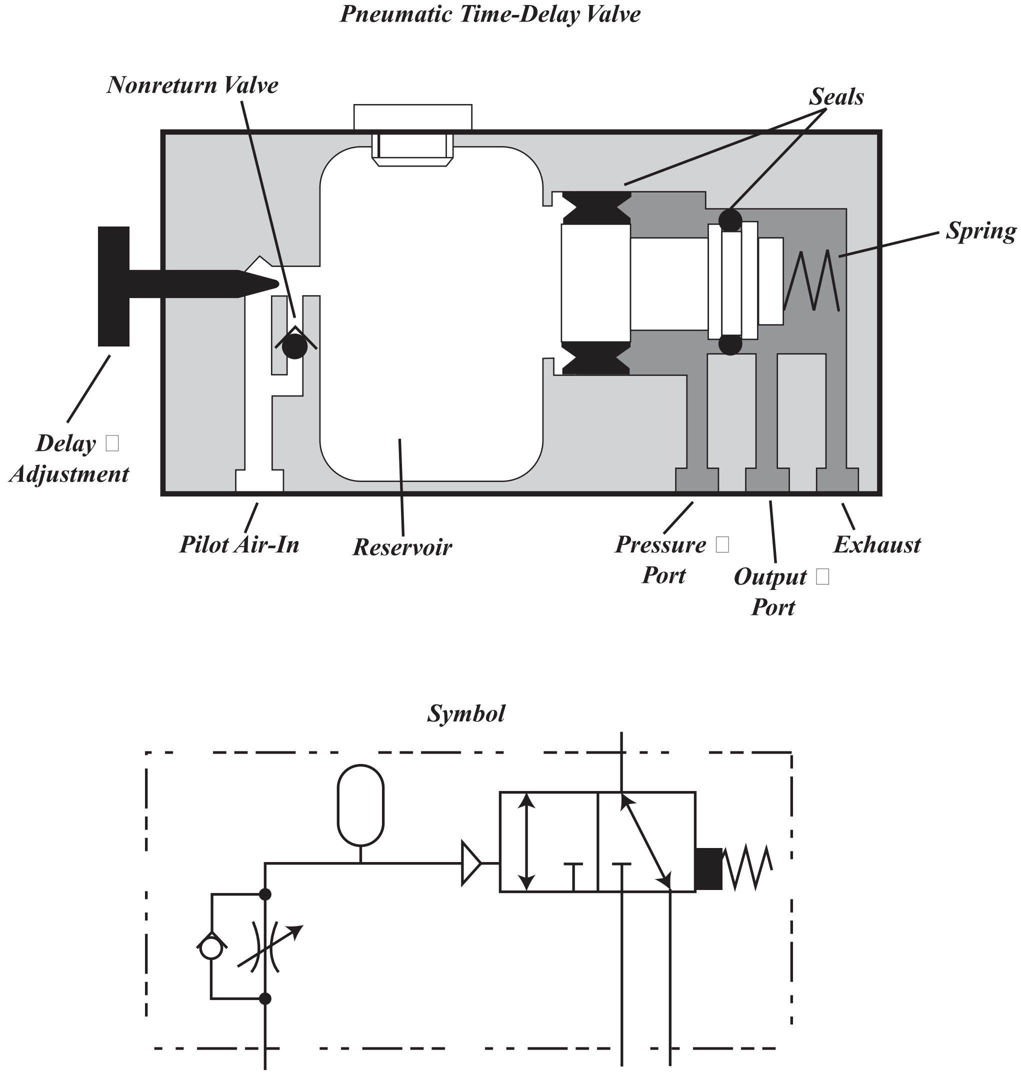
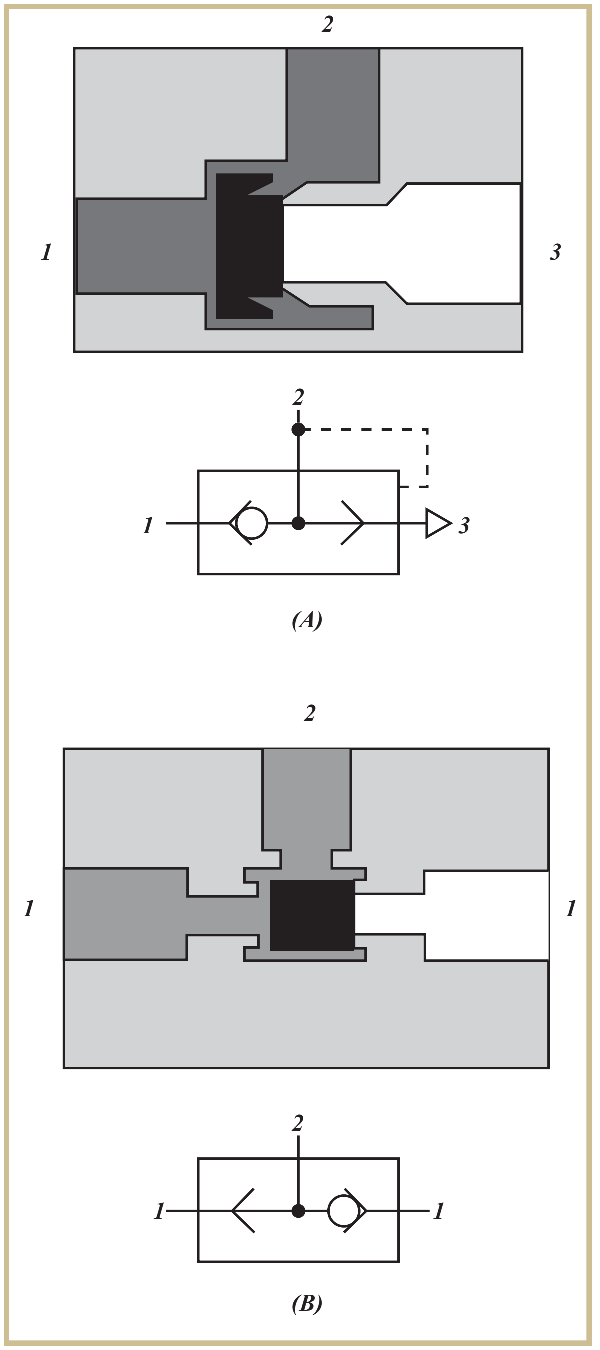


FIGURE 30—A pneumatic time delay can be made by metering a reservoir whose pressure operates a poppet or spool. The fill rate of the reservoir determines the time delay.

allows the air pressure trapped within the cylinder to push the poppet to the other side of the valve, dumping the contained air through port 3 to the environment. This allows the air to escape more quickly than if it were routed through additional valves and conductors, thus speeding op the cylinder's cycling rate. The dotted line in Figure 31A indicates that pilot pressure supplied from port 2 (from the cylinder) is used to actuate the valve. Figure 31B represents a more traditional shuttle-valve installation without the presence of a pilot signal.

FIGURE 31—Shuttle valves and quick exhaust valves perform special pneumatic functions.



There are more complex flow control devices that use both pneumatic and electric feedback to control process variables such as flow, pressure, temperature, weight, or position. These types of controls are often linked with computers in modern manufacturing facilities. Despite the advances in electronics and computer equipment, pneumatic systems linked by networks continue to remain at the forefront of modern manufacturing technology. We'll learn more about these specialized systems in a later unit.

Actuators and Motors

Actuators are the devices in a pneumatic system that turn the potential energy of the compressed gas into the mechanical energy used to perform work. Actuators are available in two broad categories called linear actuators or rotary actuators. As the name implies, *linear actuators* cause a motion in a straight line, and *rotary actuators* cause a rotary motion. While a linear actuator has a maximum stroke, a rotary actuator can either have a fixed angular motion or it can produce a continuous rotation, as in a motor.

Linear Actuators

The most basic linear actuator for use in pneumatic systems is the cylinder. A simple cylinder consists of a cylindrical sleeve with caps on each end that contain a piston inside, as shown in Figure 32. The piston has a rod in the center that protrudes through the end cap; the piston is the part usually connected to the load that's to be moved. Cylinders can have two rods, one on each side of the piston, for special applications. Each end of the cylinder has a port that can be connected to compressed air. When air is applied to the inside of either end of the cylinder, the air exerts a force upon all of the internal walls. The cylinder walls are fixed, of course, and cannot move. However, the air pressure exerts the same force upon the piston, which can move, and thus causes it to move inside and push the rod out of (or pull it into) the cylinder. As air flows into one side of the cylinder, it must be removed from the other.

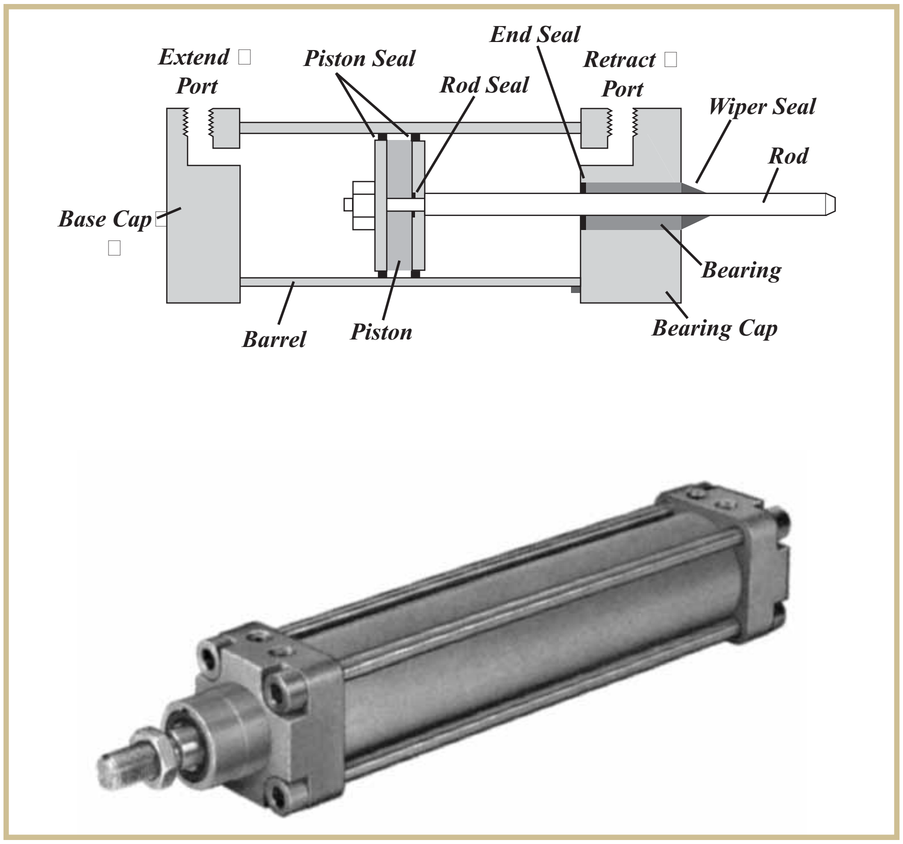


FIGURE 32—An air cylinder features simple construction and is available in a wide variety of configurations. Custom cylinders are also available from many vendors.

Calculating Cylinder Force

How much force can a cylinder generate? It depends on the diameter of the cylinder and the air pressure available. Remember that Pascal's Principle says that every surface on the inside of a pressurized container experiences the same pressure. The air pressure develops a force proportional to the area of the piston, which causes the piston and rod to move.

The magnitude of this force can be calculated from the following equation:

$$\text{Force (lbs)} = \text{Pressure (lbs/in}^2\text{)} \times \text{Area (in}^2\text{)}$$

For example, if an air cylinder has a bore diameter of 4 inches and a pressure of 90 psi is available from the system's air, what's the force developed by the cylinder?

$$\text{Area} = \pi \times \frac{D^2}{4} = \pi \times \frac{(4\ \text{in})^2}{4} = 12.57\ \text{in}^2$$

$$\text{Force} = 90\ \text{lb/in}^2 \times 12.57\ \text{in}^2 = 1131\ \text{lbs}$$

As you can see, a pneumatic actuator can produce a very high force. If the actuator is pressurized from the rod end, say to make the cylinder retract from the previous extension, the rod area must be subtracted from the piston area because no pressure is applied to this part of the piston in the direction of movement. A simplified equation for calculating the area of a piston with a rod is

$$\text{Area (in}^2\text{)} = \pi \times \frac{(\text{Piston diameter (in)}^2 - \text{Rod diameter (in)}^2)}{4}$$

For example, if the above 4-inch diameter piston has a 1.25-inch diameter rod, the area of the piston exposed to the air pressure and, therefore, producing the force would be:

$$\text{Area} = \pi \times \frac{(4.0^2 - 1.25^2)}{4} = 11.34 \text{ in}^2$$

The force would then be

$$\text{Force} = 90 \text{ lb/in}^2 \times 11.34 \text{ in}^2 = 1020.5 \text{ lbs}$$

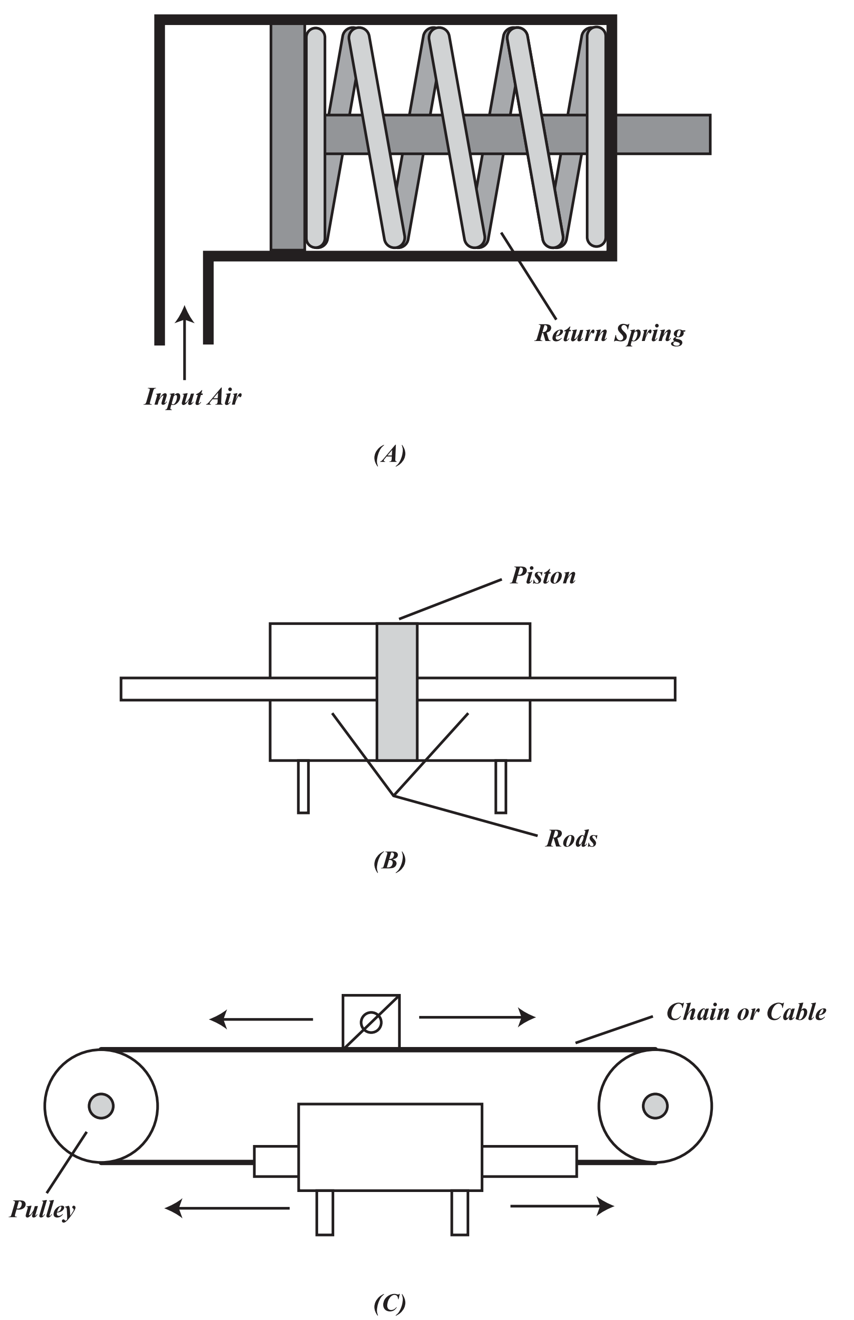
As you can see, when the same pressure is applied to the rod end of a cylinder, the available force to retract the rod is less. If the same force is required, the pressure would have to be greater. Double-rod cylinders with the same size rod on each end would generate the same force when a given pressure is applied to either side. Many pneumatic cylinders are required to operate many complete extensions and retractions, or *cycles*. To accomplish this, air is alternately directed at each port, extending and then retracting the rod.

Cylinder Construction

Cylinders are either single-acting or double-acting. The cylinders we've been discussing up to now have been *double-acting*—that is, they can be made to either extend or retract, by air pressure. A *single-acting* cylinder can be pressurized for one direction only, and the return stroke is accomplished with a force provided by either the load or an internal spring. Figure 33A shows the schematic of a single-acting cylinder. The disadvantage of the single-acting cylinder is that the cylinder must be physically longer for a given stroke to allow sufficient room for the spring.

Cylinders can be made with two rods, one on each end. The double-rod cylinder in Figure 33B has equal force in each direction because the available piston areas are the same. The double-rod cylinder is used to move loads in two directions at once. A common application is to connect the ends together with a cable or chain over a pulley system so that a load is positioned linearly by the movement of the rods, as shown in Figure 33C.

FIGURE 33—Cylinders are available in many configurations for specific applications.



Pneumatic cylinders are relatively simple in their construction. The basic parts are the cylinder, the end caps (with ports drilled and threaded), the piston, the rod(s), and the seals. Cylinders are easy to manufacture, and cylinders of various stroke lengths can be manufactured from the same or similar sets of parts. End caps can be welded to the cylinder, or they can be clamped to the ends of the cylinder with rods extending through the caps.

Cylinders require seals in several locations to prevent air leakage and contamination from dirt particles. A seal is required where the rod is connected to the piston. Seals are also required on the piston to maintain the pressure differential from one side of the cylinder to the other. If the end caps are welded, no seal is required; but if the cylinder is assembled with clamping rods, or if the caps are threaded on the cylinder, seals are required. A very important component of the cylinder is the seal around the rod where it protrudes from the cap. This seal is exposed to external dirt and contaminants, and also keeps compressed air from leaving the cylinder. This seal is usually accompanied by a wiper that scrapes dirt and other materials off the rod as it extends and retracts. Cylinders in very dirty environments can be covered with a flexible rubber boot that can cover the rod as it moves out of the end cap. Figure 34 shows some of the important seal locations and designs.

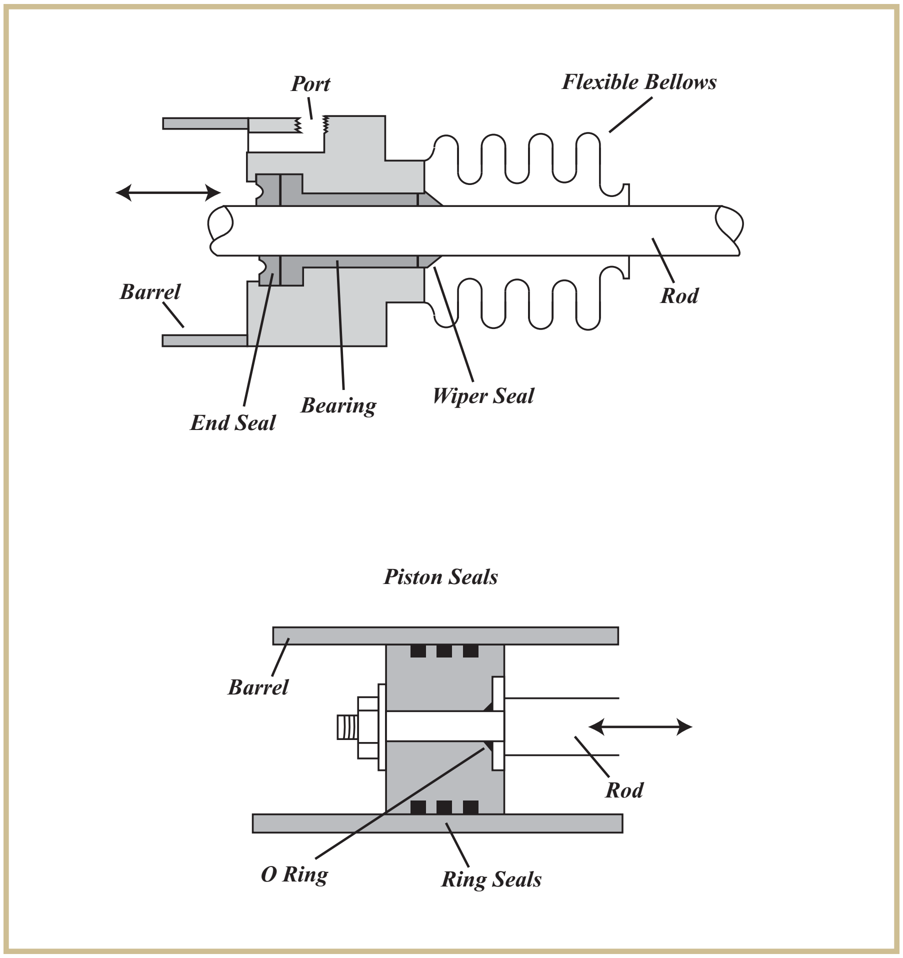


FIGURE 34—Seals protect a cylinder from external contamination, contain pressurized air, and protect the moving parts.

Rods are meant to push and pull, but they can often be exposed to side loads as they're operated. A bearing in the end cap supports the rod as it moves back and forth, to keep the rod straight and prevent friction or jamming of the translating rod. Bearings are typically made from a hardened bronze material, similar to other bearing applications.

Unless there are special environmental requirements, the cylinder is usually made from seamless steel tube, which has been machined and polished on the inside to make it very smooth. The piston is made from steel or cast iron, and may have a bearing material such as bronze on the outside diameter where it contacts the cylinder. Rods are usually made from a high-strength hardened steel alloy that's ground and polished to a smooth finish.

As the pressure moves the piston and rod from end to end, significant forces can cause damage if the piston is allowed to travel forcefully into the end cap. The piston must be decelerated as it approaches the end of its stroke to prevent damage to the parts. Some cylinders have simple rubber dampers that absorb the shock of the piston as it hits the cap. A more sophisticated design, and one that offers adjustable deceleration rates requires the use of cushioning valves, as shown in Figure 35. This design uses a plunger that momentarily seals the end of the cylinder as the piston approaches the end cap. Air is then forced through a more restricted path from the cylinder to the port. By putting a metering valve in this path, the deceleration rate can be controlled.

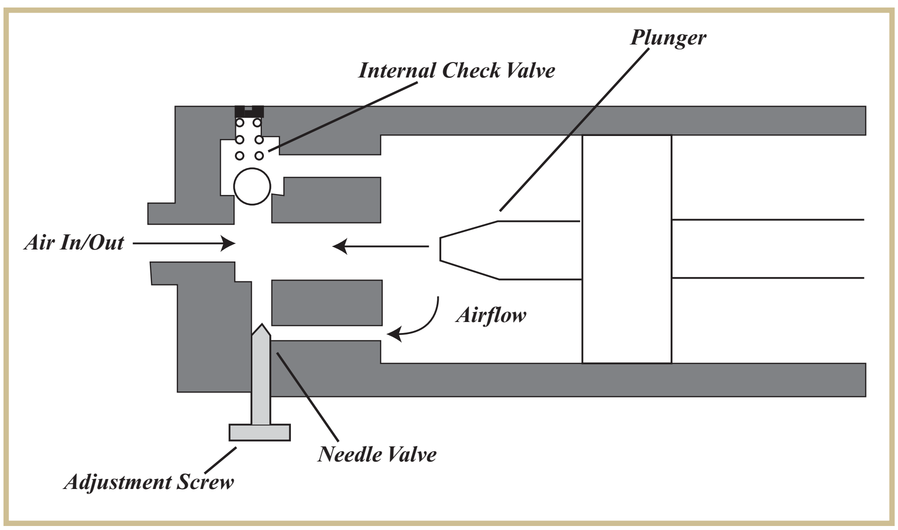


FIGURE 35—Cylinders can be decelerated as they approach the end of their travel by directing exhaust air pass through a valve.

Cylinder Mounting

There are thousands of applications for actuators, and therefore a wide variety of mounting methods are available. Manufacturers' catalogs are very helpful in determining the possible mounting configurations, and you should consult them when configuring new applications. Some of the basic types of cylinder include flange mounts or trunnion mounts. *Flange mounting* secures the cylinder to a mounting surface with clamping bolts on the front and/or rear flanges. The end caps can also incorporate feet with mounting holes. Front and rear flanges can also have male threads on them so that the cylinder can be threaded into a mounting plate. Figure 36 shows a variety of possible mounting configurations.

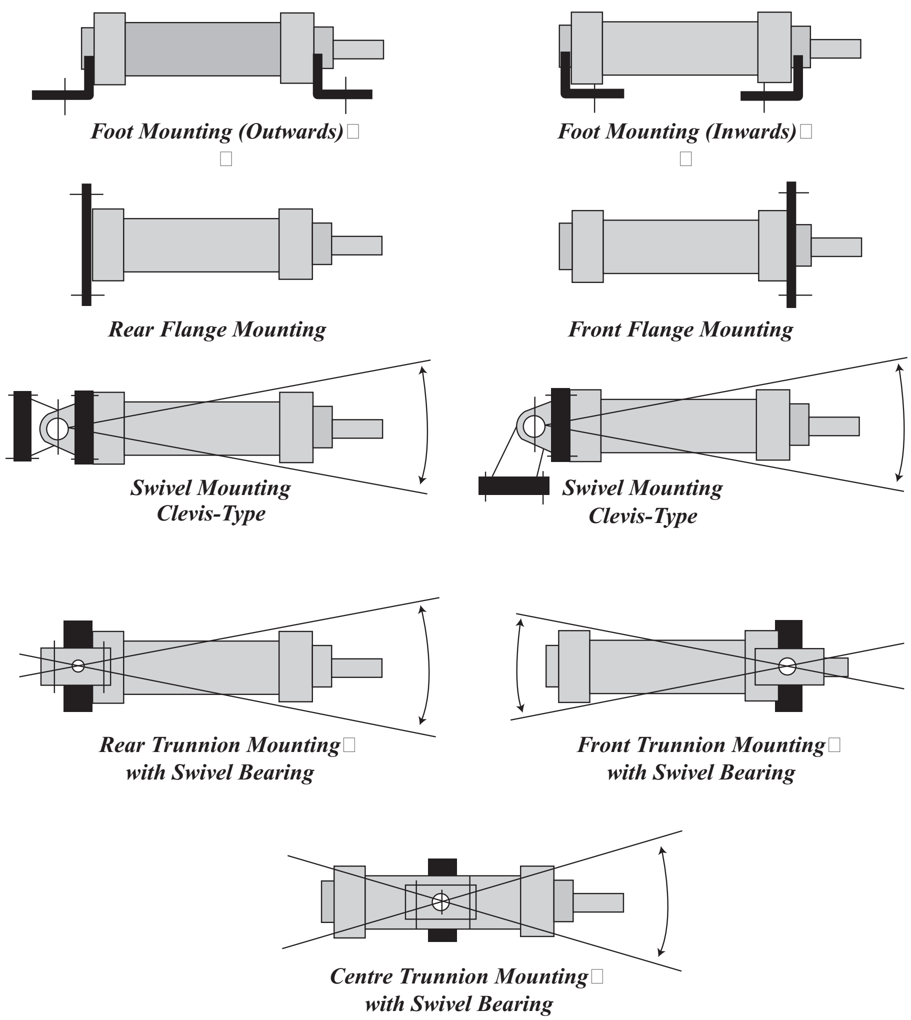


FIGURE 36—Cylinders are available in many mounting configurations.

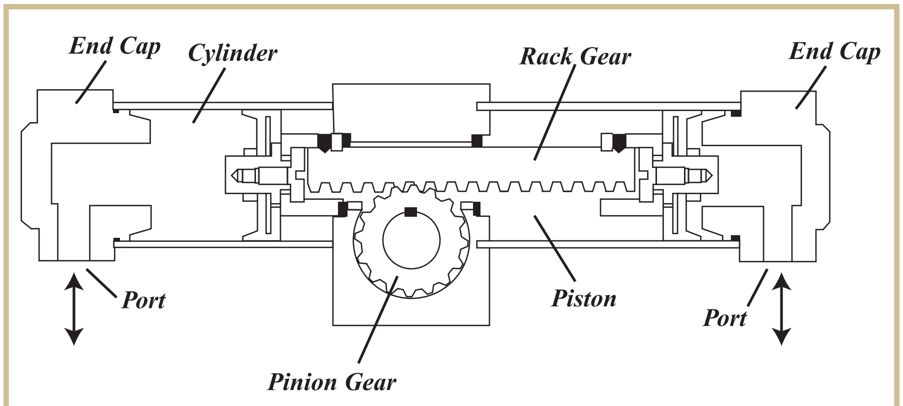
Trunnion mounts are mating flanges connected with a clevis pin that allows a cylinder to rotate around an axis as the rod extends or retracts. Trunnions can be mounted at the front or back of the cylinder, or in the middle. The trunnion mounts can incorporate clevis pins to allow rotation around one axis, or they can incorporate a swivel mount to allow limited rotation around more than one axis. The rod ends can have a variety of connection methods, such as threads, clevis joints, swivel joints, and flexible couplings.

Rotary Actuators

Rotary actuators rely on air pressure to power applications that require rotary motion, such as a motor, or a drive gear that requires limited rotation. Some applications, such as a motor, require constant rotary motion. However, other applications require 360° movements but only for several turns, or only for a limited number of degrees of rotation of an arm, such as in a clamping or lifting operation. Rotary actuators are used to produce high torques with limited ranges of rotation.

A rotary actuator is constructed similarly to a linear actuator, with a cylinder and internal piston that's moved back and forth by air pressure when alternate ports are pressurized and exhausted. However, instead of a rod, the piston is connected internally to a rack gear. This gear, in turn, drives a pinion gear. The pinion gear is mounted on a drive shaft that protrudes from the side(s) of the actuator. This drive shaft is connected to external loads by additional gears, pulleys, or keyed shafts.

FIGURE 37—This diagram shows the internal construction of a rotary actuator. Linear motion is converted to limited rotary motion by the use of a rack and pinion gear set.



The torque produced by a rotary actuator is the product of the force produced by the piston, in pounds, times the radius of the pinion gear. For example, a 2-inch diameter cylinder with a pinion diameter of 1 inch operating at 90 psi will have the following force:

$$F = 90\ \text{lb/in}^2 \times \pi \times \frac{(2.0\ \text{in}^2)}{4} = 283\ \text{lbs}$$

The torque produced will be

$$T = F \times r$$

$$T = 283\ \text{lb} \times 1.0\ \text{in} = 283\ \text{lb-in}$$

Air Motors

Air motors are the equivalent of the hydraulic motor or electric motor, and are usually characterized by the amount of torque they produce. A great advantage of air motors is that, unlike electric motors, they produce large amounts of torque even at zero speed without danger of overheating. In fact, air motors produce their largest torques when stalled. Another advantage is that they can be used in or near combustible gases because there's no danger of sparks causing explosions.

Torque is a product of force times the diameter of the rotor radius. The force produced in the motor is a function of the pressure differential between the input and output ports. The horsepower produced by a motor is described by the equation:

$$Hp = \frac{\text{Torque (lb-in)} \times \text{RPM}}{63025}$$

Air motors are specified by their torque rating, which is expressed as the amount of torque produced per psi:

$$\text{Torque rating} = \frac{\text{Torque}}{\text{Psi}}$$

The rotational speed can be controlled by the amount of air-flow through the motor. Figure 38 shows a torque vs. RPM chart. You can see that the torque is highest at zero speed and falls off rapidly as the speed increases. If the pressure is increased, the available torque increases but still follows the same shape curve. A graph of horsepower vs. RPM is shown in Figure 39. As expected, the horsepower produced by the motor rises from zero (even though maximum torque is produced at zero speed), reaches a maximum, and then falls off to low values again at high speeds. As you may expect, if the pressure is increased, the maximum horsepower also increases but follows the same shape curve.

FIGURE 38—The torque of an air motor is highest at stall and falls to zero as the RPM increases. Increasing the pressure increases the stall torque.

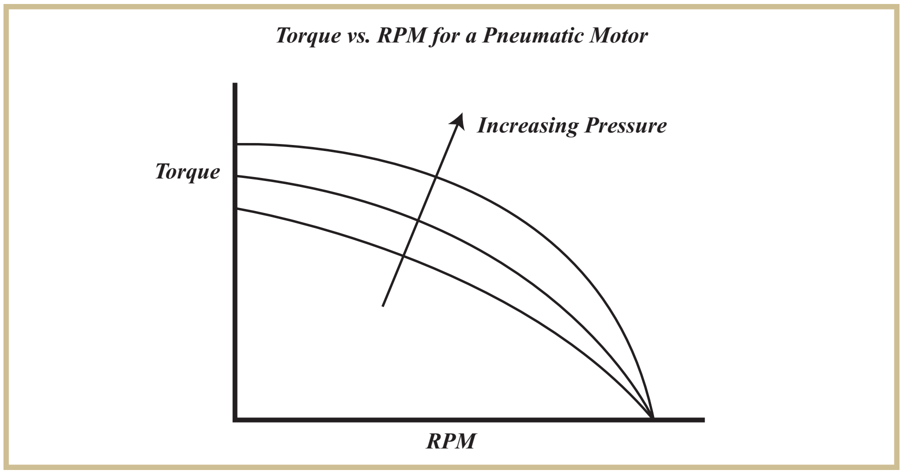
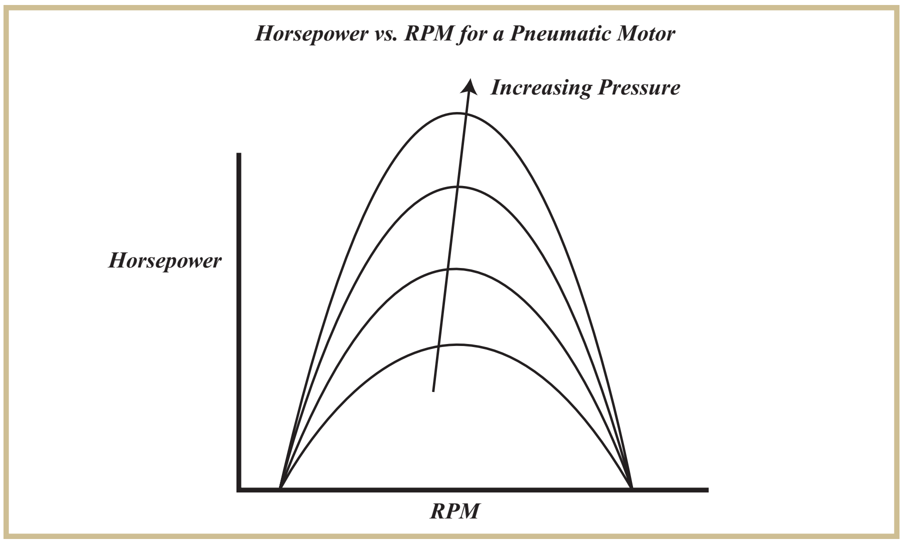


FIGURE 39—Horsepower is a function of torque and speed. As the pressure increases, maximum horsepower increases.



Example:

What is the torque output of an air motor rated for 1.5 horsepower at 250 RPM?

$$\text{Solution: Hp} = \frac{\text{Torque (lb-in)} \times \text{RPM}}{63025}$$

$$\text{Torque} = \text{Hp} \times 63025/\text{RPM}$$

$$\text{Torque} = 1.5\ \text{Hp} \times 63025/250\ \text{RPM} = 378\ \text{lb-in}$$

Gauges and Sensors

Technicians and operators must know how a pneumatic system is performing, and depend on information to troubleshoot problems when the system operates poorly. In many applications, the process itself requires measurements of parameters such as position, velocity, and acceleration of the equipment or loads. Computers may receive and process this information to make adjustments to the system or to perform process procedures such as moving, positioning, counting, or clamping. Gauges and sensors are the eyes and ears of the system and the people who operate and maintain the equipment.

In addition to the sensors we'll study here, many kinds of pneumatic sensors are available. Pneumatic sensors can be designed to measure position, proximity, count, and other functions in special applications. They're often used in conjunction with electronic sensors that connect to a computer or controller. We'll look at these pneumatic-electronic interfaces in a later unit when we discuss modern applications for pneumatic systems.

Temperature Gauges

Temperature gauges are used to measure the temperature of the air or equipment connected to the system. As you learned earlier, when air is compressed, its temperature increases dramatically. It's moved to a receiver, where it's cooled before use in the system. A temperature gauge in the receiver will tell the operator if the air has cooled sufficiently, or if there's a problem in the system that's generating excessive heat. Temperature gauges can be a simple thermometer—or more likely in industrial environments, mechanical bimetal or electrical thermocouple or resistance gauges.

A thermometer works on the principle of an expanding liquid or gas. As the temperature of a substance contained in the thermometer increases, it expands in volume. Temperatures can be read directly off a scale, as in the common mercury thermometer, or else the expansion can cause a mechanical deformation in a tube that engages a lever. The lever operates a needle that indicates the temperature. The fluid inside the reservoir chamber can be a liquid or gas, with gas types usually used for higher temperatures. A *bimetallic strip* is another temperature-measuring technique expanding material. The strip consists of two materials with different coefficients of expansion bonded together along their lengths and curled into a compact shape. One end of the coil is clamped for support and to prevent movement; the other end, the center of the coil, is connected to a mechanical linkage that causes a needle to move, indicating the temperature. These thermometers, as shown in Figure 40B, are rugged, easy to install and maintain, and relatively inexpensive. They're useful over a wide range of temperatures and for a wide variety of applications.

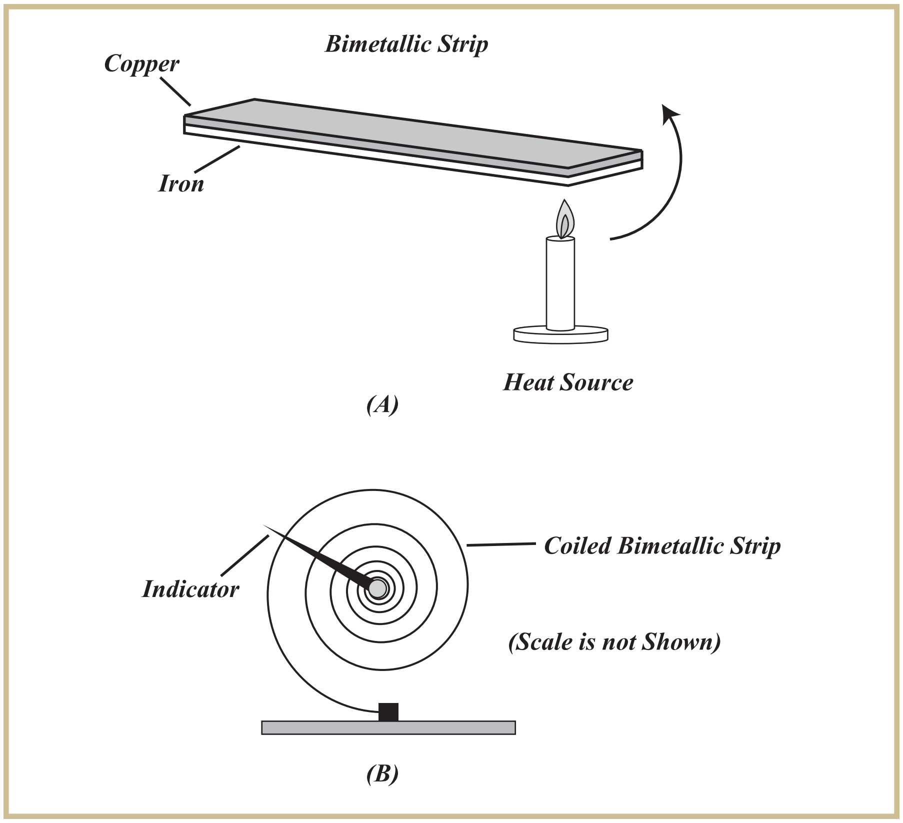


FIGURE 40—A bimetallic strip bends in one direction as the temperature is increased. A practical thermometer is made from a bimetallic strip shaped into a coil, with an indicator attached to the center.

Another method of temperature measurement utilizes the change in electrical resistance of materials as the temperature changes. The resistance of a conductor or semiconductor increases as the temperature increases. A *resistance thermometer* uses a constant voltage source to supply voltage to a sensor that consists of a length of resistive materials such as oxides of cobalt, manganese, nickel, or platinum.

This resistive element is located at or in the material to be measured. If the voltage is constant, changes in temperature cause changes in the resistance and therefore changes in the current through the sensing element. This change is measured by an electronic amplifier and compared with a reference source. The electronic circuit converts this signal to a temperature indicated on a display. The materials listed above are typically useful from –50°F to +300°F, while materials such as platinum can measure temperatures up to 1700°F.

Accurate temperature measurements can also be made with a device called a thermocouple. A *thermocouple sensor* consists of two dissimilar metal wires joined at the ends and insulated the rest of their length. The ends of the wires are connected to an electronic amplifier. In a junction of two dissimilar metals, a small voltage—several millivolts—is generated that can be amplified and calibrated to indicate temperature. Figure 41 shows the basic connection of a thermocouple. As the temperature increases, the voltage output of the junction increases, which can be used to accurately measure the temperature of the junction. The junctions of the wires themselves are very small and don't have much mass. These thermocouples respond very quickly to any changes in temperature, giving them a distinct advantage for many applications.

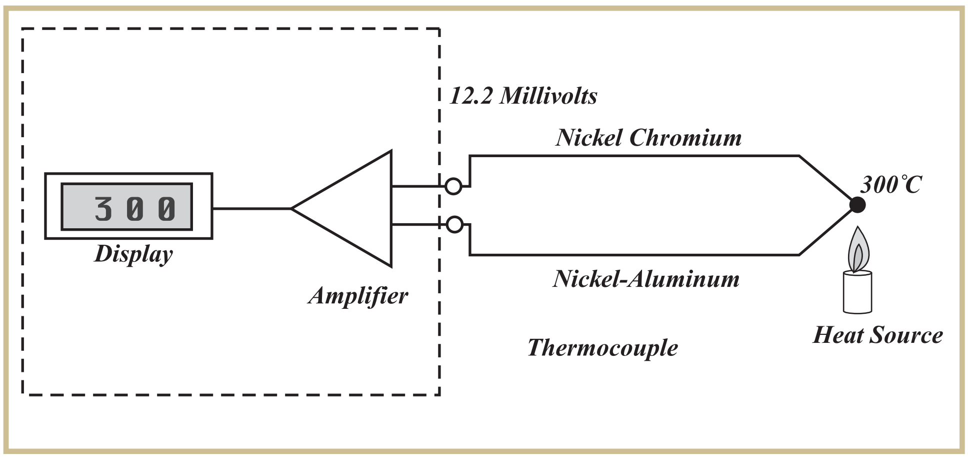


FIGURE 41—A thermocouple is an accurate way to measure temperatures in a wide variety of processes and environments. Many different types of thermocouples are available to cover different temperature ranges.

There are new, high-tech ways of measuring temperature that you may want to investigate. *Thermal imaging,* pictures taken with a special heat-sensitive film, can indicate hot spots in a room of equipment. While temperature isn't indicated

A *Pyrometer* is a device that indirectly measures temperature by determining the amount of light energy emitted by an object.

directly, good estimates can be made by comparing the image with known temperature ranges. Another newer method of temperature measurement relies on the principle that all materials above absolute zero radiate energy in the infrared region of the light spectrum, a region invisible to the human eye. The technique is complex electronically but easy to do in practice: the device resembles a gun that's pointed at the object to be measured, as shown in Figure 42. These infrared pyrometers are fairly accurate if calibrated properly and are very useful for reading temperatures of equipment that cannot be easily reached, such as overhead pipes. Many times an accurate reading of temperature isn't needed, but rather the technician needs the ability to compare the temperature at one location with another, or compare a temperature difference from one time to another.

FIGURE 42—Radiation pyrometry is a technique that uses the radiation from solid objects to measure their temperature. (Courtesy of Raytek Portable Products, Inc. Website www.raytek.com)

Pressure Gauges

Pressure gauges are of primary importance in a pneumatic system. These gauges will be located throughout the system from the compressor output to the equipment and tool tap-in points. The most common pressure gauge is based on the Bourdon tube (Figure 43), named for the French inventor Eugene Bourdon (1808–1884). The gauge consists of a hollow tube with an oval cross-section bent in the shape of a hook.

Gas is admitted to the open end of the tube, and the pressure tends to try to straighten the tube. The end of the tube is coupled with a geared lever linked to a gear-mounted needle. The needle rotates as the pressure increases, and the reading is indicated on a scale on the face of the gauge. Bourdon-tube gauges are very rugged and dependable and are still frequently used, even though they've been in existence for more than 100 years.

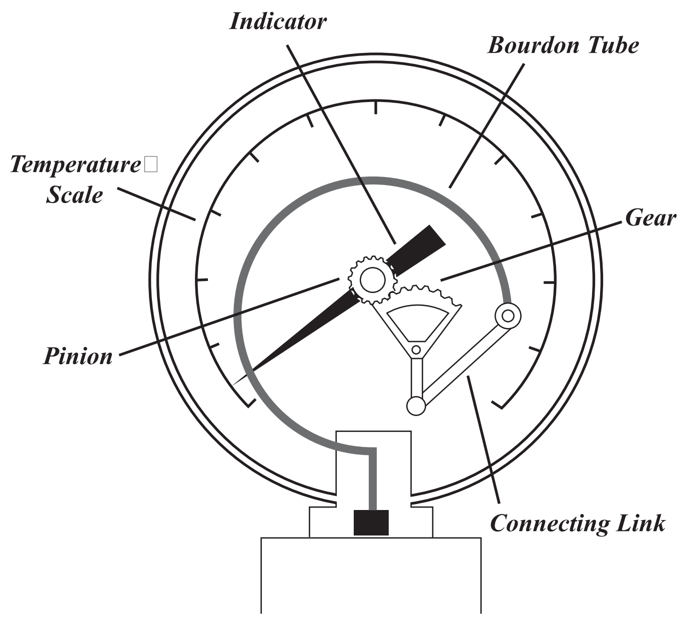


FIGURE 43—A Bourdon-tube device is a rugged, versatile pressure gauge.

Another simple mechanical pressure gauge is the *plunger-type* gauge. This design consists of a housing, movable plunger, spring, and an indicator and scale. The housing holds the plunger and is connected to the system air line. The plunger rides in a bore in the housing and moves when pressure is applied to the bottom. The plunger moves through a seal against a spring that's chosen to indicate the proper pressure range, and the distance the plunger moves is a function of the pressure in the line. A needle on the plunger moves against the scale to read actual pressure.

Other methods of pressure measurement use electronic sensors to measure small changes in the position of a diaphragm. Using a position sensor such as a *linear variable differential transformer (LVDT)* that's connected to an electronic amplifier, movements in a diaphragm are measured electronically and displayed as a pressure on a gauge, or a signal is sent to a controller or computer to indicate the status of a process. The advantage of this type of pressure sensor is the accuracy, precision, and repeatability of the measurements, the rapidity with which rapid changes in pressure can be relayed to controllers, and the isolation of the sensor from the system air by the diaphragm.

Flow Measurement

Some critical pneumatic applications require measurement of the amount of air flowing to equipment. Airflow rate can be used to indicate velocity of moving components, for example, or it can be used to make sure that an air stream is moving a material such as grain commonly encountered fast enough. Flow meters used to measure airflow use either mechanical or electrical means. Figure 44 shows two types of mechanical and electro-mechanical flow meters.

One method of measuring airflow is to insert a rotor in the airstream of a pipe. As air flows past the vanes of the rotor, it turns as shown in Figure 44A. This type of meter is similar to the anemometer that measures wind speed in your backyard. If the area of the inside of the pipe and the velocity of the air are known, you can calculate the volume of air that passes a certain point in the air line during a given time interval. The greater the air velocity, the greater the airflow will be. The RPM of the rotor is counted using either a mechanical or electrical tachometer, or perhaps a Hall Effect sensor, and a velocity is measured. This can be converted easily to CFM. The disadvantage of this type of flow measurement is the additional restriction and pressure drop caused by the moving rotor. The other flow meter shown in Figure 44B relies on the moving air's ability to support a weight in the air stream. The diameters of the tube and amount of weight are selected to match the quantity of airflow.

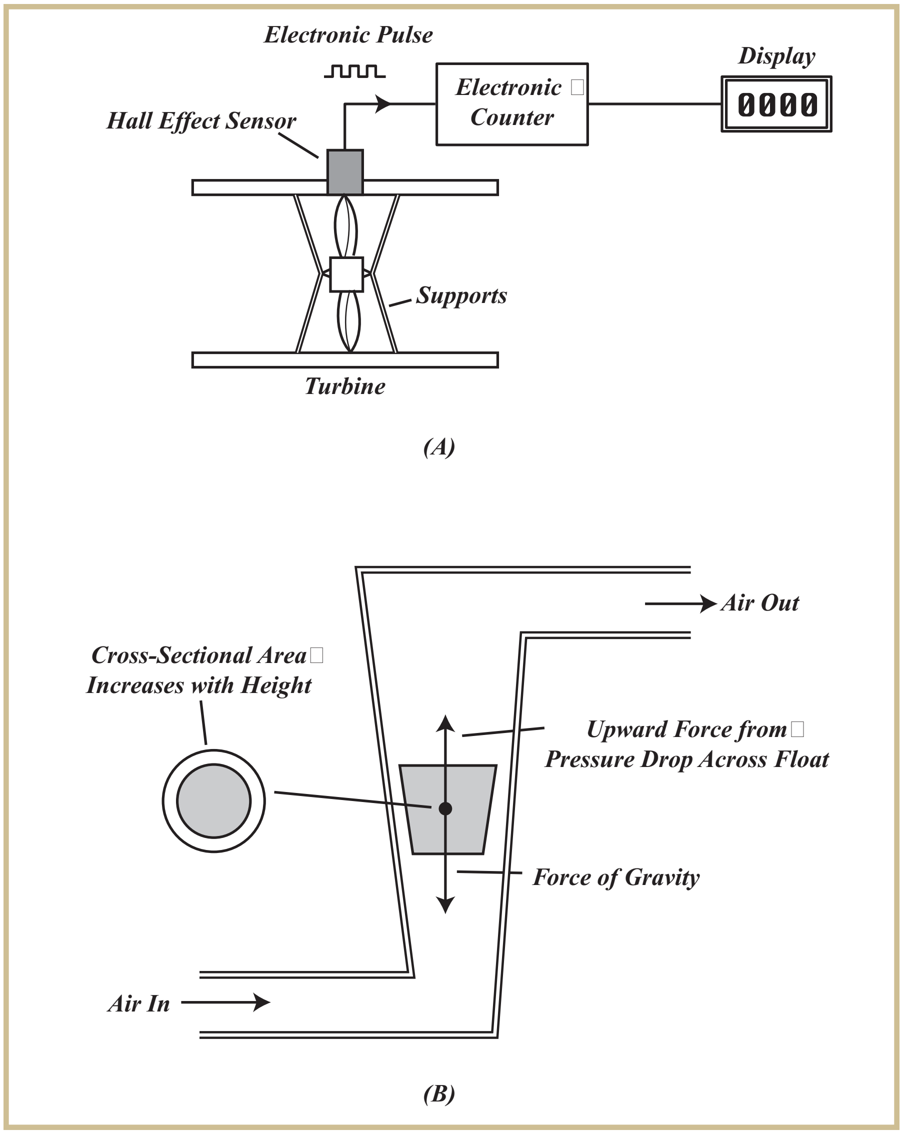


FIGURE 44—A wide variety of flow meters are available and have been used over the years for measuring airflow. A disadvantage of anything that disturbs the airflow is the resulting pressure drop caused by the meter itself. Newer electronic pressure gauges avoid these problems.

Another common method of measuring air velocity—and therefore air volume—is the use of a venturi tube. Figure 45 shows the basic construction of a venturi-type flow meter. As you learned earlier, when air speeds up, the pressure drops, in accordance with Bernoulli's Principle. A *venturi meter* is a section of pipe with a known inside diameter tapering to a section of reduced diameter. A pressure gauge at the beginning of the meter measures the static pressure inside the pipe. Another meter measures the static pressure at the reduced-diameter section, which will be lower because the air velocity is greater. The difference in the static pressures can be converted to a flow volume. Modern venturi meters use electronic pressure sensors that measure and convert automatically, instead of using manual pressure gauges and charts. The venturi meter has the advantage of having less impact on the moving air than a moving-vane type meter.

Another modern method of measuring airflow uses what's called a *hot-wire anemometer.* This is an electronic meter that measures the resistance of a special sensor wire inserted into the air stream. The wire is connected to a known constant voltage and heated to a fixed temperature. As the air flows past the heated wire, it tends to cool the wire by convective heat transfer. A given velocity will cool the wire a known amount, and the electronics in the meter convert the cooling effect into an air velocity. The volumetric airflow is then calculated using the known inside diameter of the sensor section of the pipe. This method is used in newer automobiles to optimize combustion and fuel mileage. The engine computer measures the amount of air coming into the motor and calculates the amount of gasoline needed for the most efficient combustion. This part on the car is known as the mass *airflow sensor,* or *MAF sensor.* These types of meters are rugged and reliable, relatively inexpensive, and easy to integrate into electronic controls of pneumatic systems.

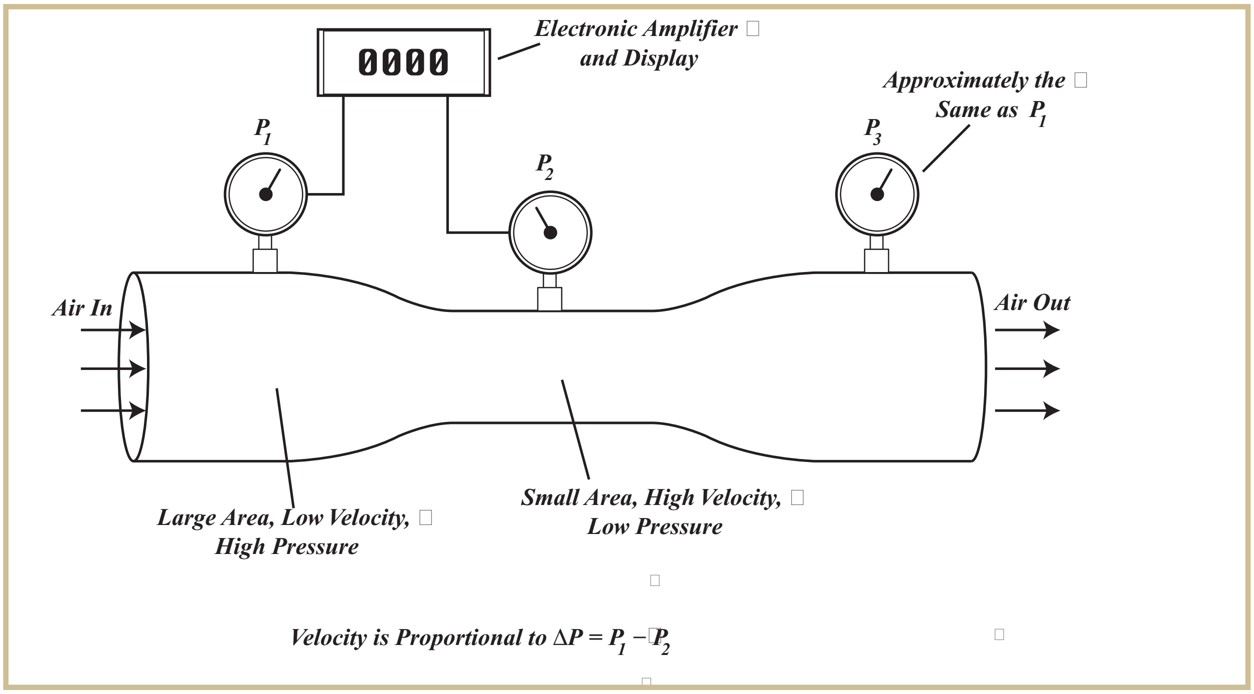


FIGURE 45—A venturi flow meter takes advantage of the pressure drop caused by increased velocity. Electronic amplifiers can measure the pressure differences and calculate the flow velocity and volume.

Now take a few moments to review what you've just learned by completing *Self-Check 3.*

Self-Check 3

1. Two general categories of air compressors are ________ and ________ compressors.

2. A compressor that resembles an internal combustion engine in its operation is a/an ________.

3. Air that's compressed is often cooled between stages by a/an ________.

4. The process of compressing air often introduces ________ into the system that needs to be removed by traps and dryers.

5. Secondary air treatment usually consists of ________, ________, and ________ the air before it's used by equipment in the system.

6. A combination package used for secondary air treatment is sometimes referred to as a/an ________.

7. Two general types of regulators are ________ and ________ regulators.

8. Three types of conductors used in pneumatic systems are ________, ________, and ________.

9. The American National Standards Institute designates a number called the ________ of a pipe that designates the wall thickness and suitability for a given pressure.

10. Equipment that must be frequently attached and removed from pneumatic systems is often attached using ________ fittings.

11. The pressure port on a pneumatic valve is labeled on the schematic by the number ________or the letter ________.

12. A control valve with four ports and two possible positions would be known as a/an ________.

13. Three design types of control valves include ________, ________, and ________.

(Continued)

Self-Check 3

14. The amount of force that a cylinder can generate depends on the _______ and the _______.

15. A rugged type of pressure gauge that uses a hollow metal tube connected to a lever and gear is the _______ pressure gauge.

Check your answers with those on page 83.

Self-Check 1

1. pressurized gas
2. condition
3. receiver
4. nonflammable, nontoxic, contamination
5. air, nitrogen
6. 90 psi
7. incompressible
8. molecules
9. force, area, pounds per square inch
10. Celsius, Fahrenheit
11. increase
12. 39.7 psi
13. pressure drop
14. increase
15. decrease

Self-Check 2

1. cubic feet per minute, CFM
2. area, flow velocity
3. laminar flow
4. kinetic energy
5. high noise

Self-Check 3

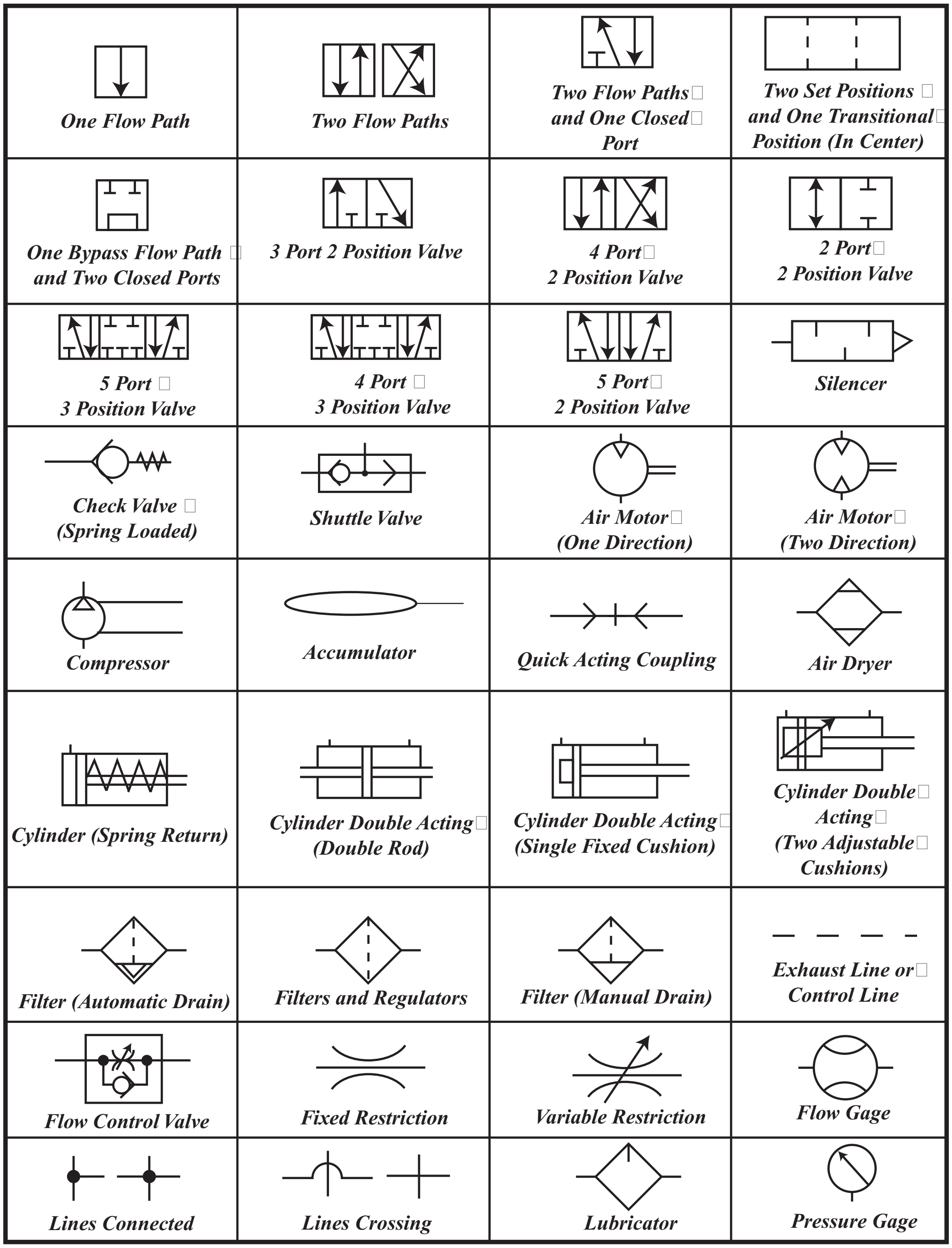
1. positive-displacement, dynamic
2. reciprocal compressor
3. intercooler
4. moisture

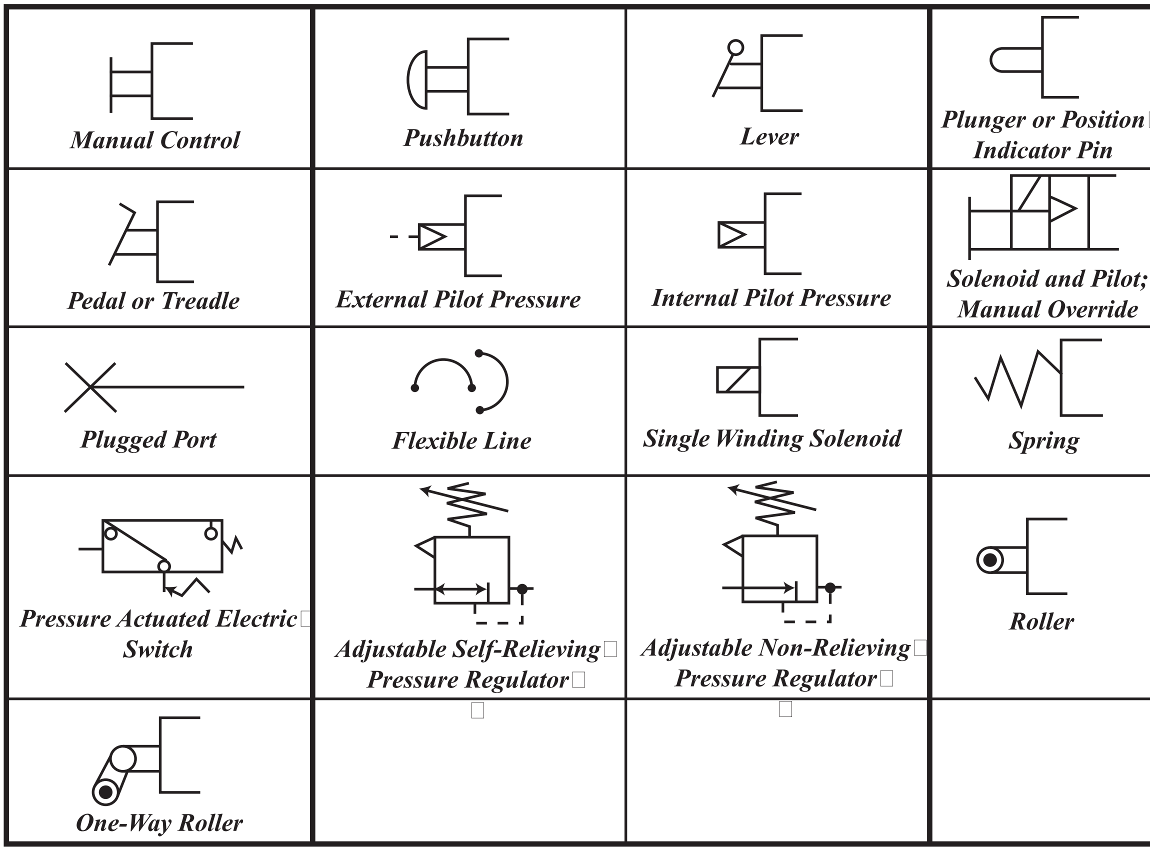
Answers

5. filtering, regulating, lubricating
6. FRL
7. relieving, nonrelieving
8. rigid, semirigid, flexible tubing
9. schedule
10. quick-connect
11. 1, P
12. 4/2 valve
13. poppet, spool, rotary
14. air pressure, cylinder bore diameter
15. Bourdon-tube

APPENDIX A

Common Symbols for Pneumatic Equipment




Manual Control
Pushbutton
Lever
Plunger or Position Indicator Pin
Pedal or Treadle
External Pilot Pressure
Internal Pilot Pressure
Solenoid and Pilot; Manual Override
Plugged Port
Flexible Line
Single Winding Solenoid
Spring
Pressure Actuated Electric Switch
Adjustable Self-Relieving Pressure Regulator
Adjustable Non-Relieving Pressure Regulator
Roller
One-Way Roller

Examination

Pneumatics, Part 1

EXAMINATION NUMBER:

28609800

Whichever method you use in submitting your exam answers to the school, you must use the number above.

For the quickest test results, go to http://www.pennfoster.edu

When you feel confident that you have mastered the material in this study unit, complete the following examination. Then *submit only your answers to the school* for grading, using one of the examination answer options described in your "Test Materials" envelope. Send your answers for this examination as soon as you complete it. *Do not wait until another examination is ready.*

Questions 1–20: Select the one best answer to each question.

1. Two hundred cubic feet of air at 14.7 psia is compressed to 90 psig. What volume of receiver is required?

   A. 28.1 ft^3
   B. 32.7 ft^3
   C. 39.0 ft^3
   D. 41.3 ft^3

2. A pressure of 87 psig is measured on the inlet side of a pneumatic line filter, and a pressure of 83 psig is measured on the outlet side of the filter. Which of the following is correct?

   A. This is an example of static pressure, and no gas is flowing.
   B. This is an example of a pressure drop, and gas is flowing through the filter.
   C. The pressure should increase across the filter which therefore must need to be cleaned or replaced.
   D. The filter isn't working correctly; no pressure drop should be present at any time.

3. Sharp bends in pneumatic lines should be avoided because
   A. turbulent flow may cause excessive pressure drops.
   B. noise levels will be unacceptable.
   C. sharp bends require expensive fittings.
   D. sharp bends can only be made on special tubing benders.

4. A compressed nitrogen cylinder whose initial pressure was 1200 psig at a room temperature of 68°F is left in a hot truck, where it eventually reaches 140°F. Approximately what pressure is reached by the nitrogen in the hot truck?
   A. 1254 psig
   B. 1365 psig
   C. 2471 psig
   D. 583 psig

5. Which of the following statements is true?
   A. Atmospheric pressure is about 29.4 psig.
   B. 101 kPa is about 10.1 psi.
   C. 30 psia is the same as 15.3 psig.
   D. 2.1 MPa is the same pressure as 21 kPa.

6. A closed receiver of compressed air has a volume of 10 cubic feet and a pressure of 90 psig. A valve is open that then connects an additional 5 cubic feet of volume due to the piping and tubing from the system. What will the new gauge pressure be?
   A. 45 psig
   B. 55 psig
   C. 69 psig
   D. 180 psig

7. Dryers are an important part of a pneumatic system because
   A. trapped moisture can freeze or cause rust on internal parts.
   B. lubricants must be cleaned and dried before use.
   C. filters must be at elevated temperatures to work properly.
   D. moisture must be added to specific locations in the system.

8. An air motor produces 60 lb-in of torque at 360 RPM. What is the horsepower produced?
   A. 0.17 Hp
   B. 0.26 Hp
   C. 0.343 Hp
   D. 0.52 Hp

9. A tire that's inflated to 32.0 psig will have an absolute pressure of
   A. 46.7 psia.
   B. 17.3 psia.
   C. 14.7 psia.
   D. 101 KPa.

10. The type of compressor that compresses a fixed volume of air for every cycle of the machine is called a _______ compressor.
   A. dynamic
   B. centrifugal
   C. blower-type
   D. positive-displacement

11. Two thousand cubic feet of gas that's compressed from a free pressure of 14.7 psia to a working pressure of 90 psig

A. will have a much greater volume.
B. won't have much energy stored in its volume.
C. requires special compressors to reach the desired pressure.
D. will likely have its temperature raised significantly as it's compressed.

12. In a closed pneumatic system (maintaining a constant volume), you know from the general gas law that if you decrease the

A. volume, the temperature will remain the same.
B. temperature of the gas, the pressure will increase.
C. pressure, the temperature will increase.
D. pressure, the temperature will decrease.

13. An early method of measuring pressure that's still used today is the

A. Bourdon tube.
B. Torricelli column.
C. venturi pipe.
D. MAF sensor.

14. A control valve schematic is marked with the letters P, A, R, and X. If the valve functions as an on/off valve, this valve is a _______ valve.

A. 4/2
B. 3/2
C. 3/3
D. 2/2

15. A cylinder has a 3.0-inch bore and a 0.75-inch diameter rod extending from both sides of the piston. If the cylinder is pressurized by 100 psig air so that the rod is extended, what force is developed by the cylinder?

A. 100 lbs.
B. 300 lbs.
C. 663 lbs.
D. 707 lbs.

16. Air is flowing through an intake line to a compressor. If the inside diameter of the line is 2.5 inches and the air is moving at a velocity of 40 feet per second, what is the volumetric flow in cubic feet per minute (CFM)?

A. 0.114 CFM
B. 196.3 CFM
C. 40 CFM
D. 81.8 CFM

17. A pipe must carry about 10 CFM of air at a maximum velocity of 25 feet per second. What should the minimum pipe inside diameter be?

A. $^{3}/_{4}$ inches
B. 1.0 inches
C. 1.1 inches
D. $1^{1}/_{2}$ inches

18. Gas is put into a receiver at a temperature of 150°F and a pressure of 120 psia. After being cooled to 60°F, what is the pressure of the gas in the receiver?

A. 48 psia
B. 102.3 psia
C. 140.8 psia
D. 300 psia

19. An air cylinder has a 4.0-inch bore and a 1.25-inch rod diameter. How much must the pressurization on the retraction stroke be increased to maintain the same force for both extending and retracting?

A. 10.8%
B. 12.5%
C. 22.4%
D. 68.8%

20. Compressed air systems in a factory

A. eliminate electrical energy costs.
B. are more expensive to operate than hydraulic or electrical systems.
C. store potential energy for later use at many locations.
D. have greater power capabilities than other systems.