This handbook examines two interrelated segments of pneumatic power: pressure and vacuum. That is, the development and utilization of air pressure and vacuum to meet specific work needs.

In terms of system equipment, this translates largely (but not exclusively) into the proper selection and sizing of commercial air compressors and vacuum pumps. The focus here is on smaller units—those appropriate to powering an individual machine or, at most, a small shop.

The basic principles are equally applicable to the much larger units supplying compressed air or vacuum as a utility to an entire plant, but this book makes no attempt to deal with the practical aspects of selecting and utilizing these large—sometimes very large—machines. The emphasis throughout is on practical approaches to designing small pneumatic power systems for today's complex and sophisticated needs.

While this handbook treats vacuum and pressure systems in separate sections, keep in mind that some applications require both vacuum and pressure. For example, in thermoforming plastic cups, first air pressure, then vacuum is required. Instead of installing separate systems, a combination compressor/vacuum pump can provide pneumatic power for both functions.

When a unit is used to provide pressure and vacuum simultaneously rather than sequentially, however, the loads must be carefully balanced. Separate units are usually preferred for this type of application.

Handbook Sections

Whatever the application, the correct pneumatic power system can help meet today's increasing demands for greater machine productivity, reliability and operator safety and convenience. The information in this handbook will help you attain these objectives.

The basic concepts of pressure and vacuum are covered in Section 1. Separate sections are devoted to the selection and operation of air compressors (Section 11) and vacuum pumps (Section IV).

Sections III and V cover accessories, work devices, and overall considerations for pressure and vacuum systems, respectively. Section VI covers combination compressor/vacuum pump systems. Section VII includes some representative problem/solution applications.

The appendix summarizes gas laws and related data. It also includes tables giving data on pressure loss due to friction, pipe bends and components, and on air flow through various-size orifices. A glossary appears at the end of the volume.
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Pneumatics and Pneumatic Power

"Pneumatics" is the general term used to describe the mechanics of gases. And "pneumatic power" can be defined as: production or control of mechanical outputs for useful work by means of a pressurized gas in a closed circuit. In simpler language, Fluid power provides a very reliable "muscle" function—ranging from something as simple as pressure for blowing an air horn to vacuum for lifting a huge metal workpiece into a precise position on a worktable.

Although the definition allows for any gas, air is almost always used in practical industrial systems. Only air is considered in the remainder of the book.

Pneumatic power is one of the two branches of "fluid power." The other is "hydraulic power," in which the working fluid is a liquid. In pneumatic systems, unlike hydraulic systems, the pressures can be positive or negative.

In pneumatic systems, the pressure differentials necessary to do work are produced by air compressors. They push more air into the system, increasing the pressure above that of atmospheric air.

In vacuum systems, the pressure differentials are produced by vacuum pumps. These pull air out of the system, decreasing the pressure below atmospheric.

Even though we sometimes refer to vacuum as negative pressure, this can be misleading. In an absolute sense, pressure is always positive. Pressure can be "negative" only in relation to some other, higher, pressure. But since we are constantly surrounded by the atmosphere, it’s often natural to describe below atmospheric pressures as negative.

Compressed Air and Vacuum Systems— Fig. 1 compares the basic operation of compressed air and vacuum systems. In both systems a prime mover such as an electric motor or gasoline engine operates an air compressor or vacuum pump, converting electrical or chemical energy into pneumatic energy.

Note how atmospheric air enters and leaves each system, and the direction of the arrows indicating transmission of pneumatic energy. At the end of each system, an appropriate control valve and work device (air cylinder, air motor, etc.) converts the pneumatic energy into useful mechanical force or power. In either case, the air is a working fluid that is unchanged over a complete operating cycle.
Simplified comparison of pressure and vacuum systems, showing routing of atmospheric air into, through, and out of each.

Although the pressure differentials generated are exactly opposite in vacuum and pressure systems, there is considerable similarity in the equipment used. Air compressors and vacuum pumps use the same basic mechanisms.

In principle they can be considered the same machine but with the inlet and outlet ports reversed. That is, each takes air at a lower inlet pressure and transforms it to air at a higher outlet pressure. But in a compressor the inlet is usually at atmospheric pressure and the outlet is connected to the system; in a vacuum pump it is the outlet that is at atmospheric pressure.

Sometimes compressors and vacuum pumps are assembled in part from the same interchangeable stock of components. Valving, porting, and oilers usually differ, however.

Another major difference is in the drive power needed. Depending on its pressure rating, an air compressor may require from 150 to 400 percent more power than a vacuum pump of the same open-capacity rating.

**System Categories** – A clear understanding of the basic types of compressor and vacuum pump systems and their relationships should be helpful. These are summarized in Fig. 2. Keep in mind that, in all cases, a power-driven device transforms air at some initial intake pressure to air at a higher outlet pressure.
Why are pneumatic power systems so popular in such a wide range of work functions? Electronic systems certainly have a much faster response to control signals. Mechanical systems can be more economical. Hydraulic systems can be more powerful.

The answer lies in the unusual combination of advantages pneumatic systems offer. A basic advantage is their high efficiency. For example, a relatively small compressor can fill a large storage tank to meet intermittent high demands for compressed air. Unlike hydraulic systems, no return lines are required.

Other advantages include: high reliability, mainly because of fewer moving parts; compactness; forces, torques and speeds readily variable over a widely useful range; easy control and coordination with other machine/system functions; low cost; easy installation and maintenance; and the availability of a wide range of standard sizes and capacities.

Another, often decisive, advantage in some applications is that air devices create no sparks in explosive atmospheres. They can also be used under wet conditions with no electrical shock hazard.

It is often advantageous to add pneumatic power to machines that have electricity as their primary power source. This may be done to economically provide supplementary functions such as automatic clamping, locking, closing, opening, etc., of various components or devices. The design problems involved are usually not difficult to solve, and equipment selection procedures are simple and straightforward. Installation is simple, too.
When the air compressor or vacuum pump is driven by a power takeoff from the machine it is being added to, the mounting location may be critical (although accessory air components may be placed almost anywhere). But if the unit is provided with its own drive motor, then virtually the entire system can be installed at any point—even away from the machine—as long as that point can be reached by a hose, pipe, or tube to transmit the pneumatic power.

What are some of the drawbacks of pneumatic power systems?

One is the need for a compressor and for distribution lines, compared to the convenience of plugging an electric motor into an existing electric system.

Another is the inevitable energy loss in converting electrical or chemical energy into pneumatic energy, which is then used to do work that the prime mover could have done directly. In addition, pneumatic work devices are often not very energy efficient (20 percent efficiency is typical of air motors, for example). But in variable-load applications, this is offset by pneumatic devices drawing only the power actually needed. Most electric motors, by contrast, draw almost the same power regardless of load.

And, of course, reasonably sized pneumatic devices cannot exert the forces and torques that hydraulic devices can. In most applications, a horsepower rating somewhere in the tens represents the crossover point at which the increasing size and cost of pneumatic devices begin to exceed the basic cost of a hydraulic power generation and transmission system.

In summary, then, electric, hydraulic, and pneumatic systems each have their place. But the advantages of pneumatic power make it the system of choice in many applications.

Pressure Levels and Terminology

Fig. 3 summarizes the basic relationships and definitions needed to understand the pressure terminology used in this handbook.

**Atmospheric Pressure**—The atmosphere that surrounds the earth can be considered a reservoir of low-pressure air. Its weight exerts a pressure that varies with temperature, humidity, and altitude.

For thousands of years, air was considered weightless. This is understandable, since the net atmospheric pressure exerted on us is zero. The air in our lungs and the blood in our cardiovascular system has an outward pressure equal to (or perhaps slightly greater than) the inward pressure of the outside air. Since we feel no pressure, we are unaware of the air's weight.

The weight of the earth's atmosphere pressing on each unit of surface constitutes atmospheric pressure, which is 14.7 psi (1101.3 Pa or 0.1013 MPa) at sea level. This pressure is called one atmosphere. In other commonly used units, one
Summary of basic pressure measurement relationships.

Atmospheric pressure equals 29.92 inches of mercury (in. Hg), 760 mm Hg (or 760 torr), and 1.013 bar = 0.1 MPa.

Since atmospheric pressure results from the weight of the overlying air, it is less at higher altitudes. As Fig. 3 shows, atmospheric pressure in Denver, Colorado (altitude 5,280 feet), is only 12.2 psi. And in Mexico City, Mexico (altitude 7,800 feet), it is 11.1 psi. On top of Mount Everest, the pressure has fallen to one-third of an atmosphere. Fig. 4 shows this in a different way.

Atmospheric pressure also varies from time to time at a single location, due to the movement of weather patterns. While these changes in barometric pressure are usually less than one-half inch of mercury, they need to be taken into account when precise measurements are required.

Gauge Pressure—Atmospheric pressure serves as a reference level for other types of pressure measurements. One of these is "gauge pressure."

As Fig. 3 shows, gauge pressure is either positive or negative, depending on its level above...
Graph shows the effect of altitude on atmospheric pressure. For each thousand feet of elevation, atmospheric pressure is reduced by approximately 1 in. Hg.

or below the atmospheric pressure reference. For example, an ordinary tire gauge showing 30 pounds (actually, 30 psi) is showing the excess pressure above atmospheric. In other words, what the gauge shows is the difference between atmospheric pressure and the pressure of the air pumped into the tire. Gauge pressures can be either positive (above atmospheric) or negative (below atmospheric). Atmospheric pressure represents zero gauge pressure.

**Absolute Pressure** – A different reference level is used to obtain a value for "absolute pressure." This is pressure measured above a perfect vacuum. It is composed of the sum of the gauge pressure (positive or negative) and the atmospheric pressure. Where there might be confusion, gauge and absolute pressures are distinguished by adding the letter "g" or "a," respectively, to the abbreviation for the units ("psig" or "psia").
To obtain the absolute pressure, simply add the value of atmospheric pressure (which averages 14.7 psi at sea level) to the gauge pressure reading. To find the current value of atmospheric pressure in psia at a given location, multiply the barometer reading in in. Hg by 0.491. This conversion factor arises from the fact that a cube of mercury with one inch sides weighs 0.491 pound and thus exerts a pressure of 0.491 psi.

Using the simple tire pressure example, the absolute pressure –including the atmospheric pressure–exerted by the air within the tire is 44.7 psia (30 psig plus 14.7 psi). Thus, the absolute pressure is 14.7 psi more than would be read on a tire-pressure gauge. Absolute pressure must be used in virtually all calculations involving pressure ratios.

**Vacuum**—Vacuum is a pressure lower than atmospheric. Except in outer space, vacuums occur only in closed systems.

In the simplest terms, any reduction in atmospheric pressure in a closed system may be called a partial vacuum. In effect, vacuum is the pressure differential produced by evacuating air from the system.

To illustrate the basic concept of using the atmosphere to create a vacuum, Fig. 5 shows a simple example: a rubber suction cup pressed against a smooth wall. It remains there because a vacuum has been created.

In drawing A, before the cup is pressed against the wall, the opposing arrows denote balanced atmospheric pressure. There is

![Figure 5](image)

In (A), a suction pad is placed against a wall; no vacuum is generated – the atmospheric forces are balanced. In (B), a vacuum is produced by expelling air from between the pad and the wall; the pad clings to the wall because outside pressure is greater than the inside pressure.
no vacuum yet because the air pressure inside the cup is equal to the air pressure outside. Both values are at atmospheric pressure.

This balance changes when the cup is pressed against the wall. Drawing B shows that a vacuum now exists in the remaining open space. After most of the air has been expelled, partial expansion of the cup leaves less air per unit volume inside the cup than outside. With less thrust against the cup's inside surface, the pressures are now unbalanced. Outside atmospheric pressure forces the cup against the wall. And since pressure is also holding the edge of the cup firmly to the wall, no air can leak in to relieve the partial vacuum inside.

In a vacuum system more sophisticated than a suction cup, the enclosed space would be a valve actuator or some appropriate work device. A vacuum pump would be used to reduce atmospheric pressure in the closed space. The same principle would apply, however.

By removing air from one side of an air-tight barrier of some sort, atmospheric pressure can act against the other side. Just as with the suction cup, this action creates a pressure differential between the closed system and the open atmosphere. The pressure differential can be used to do work.

For example, in liquid packaging (bottling), reducing the pressure in a bottle (the enclosed space) makes the filling operation go much faster because the liquid or other material is literally pulled into the bottle, rather than simply failing by gravity.

Vacuum is usually divided into four levels:

**Low vacuum** represents pressures above one torr absolute. Flow in this range is viscous, as represented by most common fluids. Mechanical vacuum pumps are used for low vacuum, and represent the large majority of pumps in industrial practice.

**Medium vacuum** represents pressures between 1 and 10 torr absolute. This is a transition range between viscous and molecular flow. Most pumps serving this range are also mechanical.

**High vacuum** represents pressures between 10⁻¹ and 10⁻⁴ torr absolute. Flow in this region is molecular or Newtonian, with very little interaction between individual molecules. A number of specialized industrial applications, such as ion implantation in the semiconductor industry, fall in this range. Nonmechanical ejector or cryogenic pumps (which are not discussed in this book) are usually used.

**Very high vacuum** represents absolute pressures below 10⁻¹ torr. This is primarily for laboratory applications and space simulation.

Keep in mind that a "perfect" vacuum—that is, a space with no molecules or atoms—is a purely theoretical condition. Only in interstellar space is this condition approached at all closely, and even there a few atoms per cubic meter will be found. In practice, all vacuums are partial.
Units of Pressure/Vacuum Measurement

In the physical sciences, pressure is usually defined as the perpendicular force per unit area, or the stress at a point within a confined fluid. This force per unit area acting on a surface is expressed in metric units as Newtons per square meter (N/m²) or Pascals (Pa). The corresponding expression in the English system is pounds per square inch (psi); remember that the pound is a unit of weight, or force, not of mass.

However, many other units are still commonly used for pressure and vacuum measurements. This is understandable because each offers specific advantages in some instances.

For example, "standard atmosphere" as a unit of measurement relates directly to a physical feature of the Earth's surface (strictly speaking, only at sea level). This feature may be the most prominent aspect of some situations. And the bar combines a value near one atmosphere with the simplicity of metric units. It is defined as $10^5$ Pascals.

In some vacuum applications the most salient fact may be the fraction of air originally present that has been evacuated (percent vacuum). And when mercury manometers were the usual instrument for vacuum/pressure measurements, the directly observable unit—requiring no further calculations—was the length of the mercury column in inches or millimeters. (Torr is the modern name for mm Hg.)

Table 1 shows the equivalences for selected values of the common units. Other values can be calculated using the conversion factors:

- $1 \text{ atm} = 14.70 \text{ psi}$
- $1 \text{ bar} = 14.50 \text{ psi}$
- $1 \text{ MPa} = 145 \text{ psi}$
- $1 \text{ in. H}_2\text{O} = 0.0361 \text{ psi}$
- $1 \text{ torr} = 0.01934 \text{ psi}$

Measurement of Pressure and Vacuum

A number of devices are available to measure vacuum and pressure levels. The most common are described here.

**Absolute Pressure Gauge** – As its name indicates, an absolute pressure gauge shows the pressure above a theoretical perfect vacuum condition. It thus provides an absolute reading.

The most basic absolute pressure gauge is the barometer shown in Fig. 6. The arrows denote atmospheric pressure acting on the surface of mercury in a dish. This pressure is transmitted in all directions within the body of mercury, including pressure upward into the tube. The height of the column supported this way directly measures the current atmospheric pressure.

There is no inherent requirement that only atmospheric pressure be measured. When the apparatus is arranged so that some other pressure acts on the mercury surface, that pressure can be measured equally well. It does not
A basic mercury barometer. The bottom of the tube is immersed in a pool of mercury that is exposed to atmospheric pressure (arrows). This pushes the mercury up into the tube until the downward pressure of its weight is exactly equal to the pressure exerted by the atmosphere.

matter whether the pressure is above or below atmospheric; the only requirement is that the tube be long enough to accommodate the mercury column.

Another type of absolute pressure gauge is used for vacuum measurements only. This gauge (Fig. 7) has the same U shape as the manometer (next page), but leg A is sealed. Mercury fills this end when the gauge is not in use.

When leg B is connected to a vacuum source, the mercury level in leg A is pulled down. The sliding scale is then placed so that the zero mark is opposite the level in leg B. Matching the level in leg A against the scale then gives the absolute pressure directly in in. Hg.

Mercury U-Tube Manometer – A manometer indicates the difference between two pressures. If one is atmospheric pressure, the result is a direct reading of positive or negative gauge pressure. In its simplest form, the device is a U-tube about half-filled with mercury (Fig. 8)
Absolute pressure gauge (for vacuum only) uses a sliding scale to measure the difference in height between mercury in the two legs. Since the mercury completely fills the left-hand leg when the right-hand leg is connected to the atmosphere, the absolute pressure on this leg is always close to zero. Hence, the difference in height of the two legs measures the absolute pressure (in in. Hg) on the right-hand leg.

With both ends of the tube open to the atmosphere, the liquid is at the same height in each leg. This is a zero value because the atmospheric pressure is equal and has balanced the two columns.

But when a vacuum source is applied to one leg, the mercury rises in that leg and falls in the other leg. The total difference, \( h (2 + 2 = 4 \text{ in this instance}) \), in height between the two new levels is the gauge pressure—in this case, negative.

Had a positive pressure been applied to the left leg, then the mercury would have fallen there and risen in the right leg. Again, the total difference in height between the two new levels would represent the gauge pressure.

**Plunger Gauge**—A plunger gauge consists of a plunger connected to system pressure, a bias spring, and a calibrated indicator. An auto tire gauge would be an example.
Mercury U-tube manometer. With the right-hand log connected to the atmosphere, the difference in height of the two legs measures the gauge pressure (in In. Hg) on the left-hand leg.

As pressure in the system rises, it moves the plunger against the force exerted by the bias spring. This movement also moves the indicator to show the appropriate pressure on the scale.

With suitable calibration and a spring that can work in extension as well as compression, a plunger gauge can be used for either positive or negative pressure.

**Bourdon Gauge**—This is the most widely used instrument for measuring both positive pressure and vacuum. Measurement is based on the deformation of an elastic element (a curved tube) by the pressure being measured. The radius of curvature increases with increasing positive pressure and decreases with increasing vacuum. The resulting deflection is indicated by a pointer on a calibrated dial through a ratchet linkage.

Similar gauges may be based on the deformation of diaphragms or other flexible barriers.

**McLeod Gauge**—For extremely accurate measurements of very low pressures (high vacuums), the McLeod vacuum gauge is the most widely used device. It’s also used to calibrate other types of gauges.

This design uses Boyle’s Law (see below) to determine pressure in a system. A sample of the gas is isolated in the gauge and reduced in volume by a known amount. This causes a proportional increase in pressure, which, in turn, produces a readable difference in the height of a mercury column.

The McLeod gauge is rarely used for industrial applications. It is better suited to laboratory studies where very high vacuums are involved.

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**Figure 8**

![Diagram of Mercury U-tube manometer and Bourdon Gauge](image)
Pressure/Volume/ Temperature Relationships

Pressure, volume, and temperature are basic measurable properties of air. They are not completely independent properties but are interrelated in specific, simple ways. When designing a pneumatic system, it is helpful to understand these relationships.

**Boyle's Law**—This law describes compression. It states that, at a fixed temperature, the volume of a given quantity of gas varies inversely with the pressure exerted on it. To state this as an equation:

\[ P_1 V_1 = P_2 V_2 \]

where the subscripts refer to the initial and final states, respectively.

In other words, if the pressure on a gas is doubled, then the volume will be reduced by one-half. The product of the two quantities remains constant. Similarly, if a gas is compressed to half its previous volume, the pressure it exerts will be doubled. In Fig. 9, when 8 cu ft of gas is compressed to 4 cu ft, the 30 psia reading will double to 60 psia.

Designers use Boyle’s Law calculations in a variety of situations: when selecting an air compressor, for calculating the consumption of compressed air in reciprocating air cylinders, and for determining the length of time required for storing air. Boyle’s Law, however, may not always be practical because of temperature changes. Temperature increases with compression, and Charles’ Law then applies.

**Charles’ Law**—This law states that, at constant pressure, the volume of a gas varies directly with its absolute temperature. Absolute temperature is defined on a scale where zero represents the temperature at which all thermal motion

---

**Figure 9**

Boyle’s Law: Pressure doubles when the volume of a closed container is decreased by one-half.
-460°F). The two absolute temperature scales in common use are the Kelvin scale, which uses the same degree as the Celsius scale, and the Rankine scale, which uses the Fahrenheit degree.

Expressed as an equation, Charles' Law states:

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

where, again, the subscripts refer to the initial and final states.

Fig. 10 summarizes the basic concepts of Charles' Law. When the temperature of a gas is increased, the volume changes proportionately (as long as the pressure does not change). The same relationship holds with temperature and pressure, as long as volume does not change.

**Combined Gas Law** - What if both temperature and pressure are changed at the same time? Another important mathematical description, the Combined Gas Law, can be derived from Boyle's and Charles' Laws. It states that:

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

This makes it possible to calculate any one of the three quantities - pressure, volume, and temperature - as long as the other two are known.

**General Gas Law (Equation of State for an Ideal Gas)** - All the above laws compare the state of a given quantity of gas in one condition with that in another. But what if the quantity of gas changes? In that case we use the General Gas Law:

$$PV = mRT$$

Here, \( m \) is the quantity of gas and \( R \) is a factor known as the Gas Constant.

The value of \( R \) depends on the units used, and perhaps on the gas involved. For air, when \( m \) is in pounds mass, \( P \) in pounds per square foot absolute (not pounds per square inch), \( V \) in cubic feet, and \( T \) in degrees Rankine, the numeric value of \( R \) is 53.3.

As an alternative, rather than using the mass, \( m \), it is possible to use the number of moles, \( n \). One mole contains \( 6.02 \times 10^{23} \) molecules and weighs the gas's molecular weight in grams. Then, when \( P \) is in atmospheres, \( V \) in liters, and \( T \) in degrees Celsius, \( R \) has the value 0.08207. When moles are used, the value of \( R \) is independent of the gas.
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