# Lecture no. 7

1.6 PRESSURE

Pressures, like temperatures, can be expressed by either absolute or relative scales. Pressure is defined as "normal force per unit area." Figure 1.5 shows a cylinder of water. Pressure is exerted on the top of the water by the atmosphere, and on the bottom of the cylinder by the water. If a hole were drilled in the side of the cylinder, you would have to exert a force against the water surface area by means of a plug to prevent the water from exiting the cylinder through the hole.
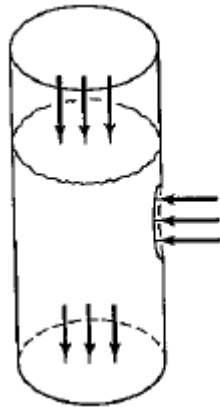
Figure 1.5 Pressure is the normal force per unit area. Arrows show the force exerted on the respective areas.

Figure 1.6 shows a column of mercury held in place by a sealing plate. Recall from physics that at the bottom of the column of mercury

$$p = \frac{F}{A} = \rho g h + p_0 \qquad (1.22)$$

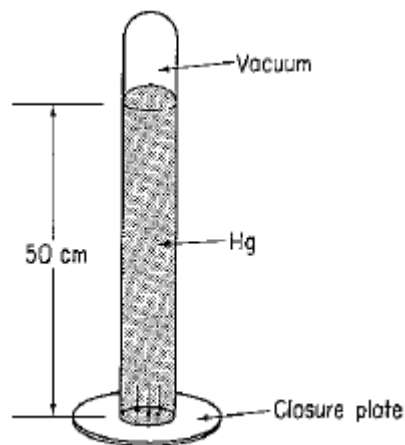where p = pressure at the bottom of the column of the fluid
F = force
A = area
p = density of the fluid
g = acceleration of gravity
h = height of the fluid column
p_0 = pressure at the top of the column of fluid

Figure 1.6 Pressure of a column of mercury.

Suppose that the column of mercury has an area of I em' and is 50 em high. From Table D.I we can find that the sp gr at 20°C and hence the density, essentially, of the

Hg is 13.55 g/cm", Thus the force exerted on the I-em" section of that plate by the column of mercury is

$$F = \frac{13.55 \text{ g}}{\text{cm}^3} \left| \frac{980 \text{ cm}}{\text{s}^2} \right| 50 \text{ cm} \left| 1 \text{ cm}^2 \right| \frac{1 \text{ kg}}{1000 \text{ g}} \left| \frac{1 \text{ m}}{100 \text{ cm}} \right| \frac{1 \text{ N}}{\frac{1 \text{ (kg)(m)}}{\text{s}^2}}$$

$$= 6.64 \text{ N}$$

The pressure on the section of the plate covered by the mercury is

$$p = \frac{6.64 \text{ N}}{1 \text{ cm}^2} \left| \left(\frac{100 \text{ cm}}{1 \text{ m}} \right)^2 = 6.64 \times 10^4 \frac{\text{N}}{\text{m}^2} \right.$$

If we had started with units in the American engineering system, the pressure would be computed as

$$p = \frac{845.5 \text{ lb}_m}{1 \text{ ft}^3} \left| \frac{32.2 \text{ ft}}{\text{s}^2} \right| 50 \text{ cm} \left| \frac{1 \text{ in.}}{2.54 \text{ cm}} \right| \frac{1 \text{ ft}}{12 \text{ in.}} \left| \frac{}{\frac{32.174(\text{ft})(\text{lb}_m)}{(\text{s})^2(\text{lb}_f)}} \right.$$

$$= 1388 \frac{\text{lb}_f}{\text{ft}^2}$$

Sometimes in engineering practice, a liquid column is referred to as head of liquid, the head being the height of the column of liquid. A pressure cau be interpreted as the head, *h,* of a hypothetic column of liquid, so that the pressure at the base of a column of liquid would be calculated, say in inches of mercury, as

$$p \text{ (in inches of Hg)} = Po \text{ (in inches of Hg)} + h \text{ (in inches of Hg)} \qquad (1.23)$$

where *po* is the gas pressure on the top of the column of mercury. Water, oil, or any other liqnid could be substituted for Hg in Eq. (1.23). For example, suppose that you measure the pressure in a tank of water 2 ft down from the surface as 404.92 in. H_2O . What is.the pressure 4 ft down from the surface? You can use Eq. (1.22) to calculate the pressure, but it is just as easy to use Eq. (1.23).

$$p = 404.92\text{- in. } H_2O + 2 \text{ ft (12 in.rft)} = 428.92 \text{ in. } H_2O \qquad (1.24)$$

Whether relative or absolute pressure is measured iu a pressure-measuring device depends on the. nature of the instrument used to make the measurements. For example, an open-end manometer (Fig. 1.7a) would measure a relative pressure, since the reference for the open end is the pressure of the atmosphere at the open end of the manometer. On the other hand, closing off the end of the manometer (Fig. 1.7b) andcreating a vacuum in the end results in a measurement against a complete vacuum, or against "no pressure." This measurement is called absolute pressure. Since absolute pressure is based on a complete vacuum, a fixed reference point which is unchanged regardless of location or temperature or weather or other factors, absolute pressure then establishes a precise, invariable value which can be readily identified. Thus, the zero point for an absolute pressure scale corresponds to a perfect vacuum, whereas the zero point for a relative pressure scale usually corresponds to the pressure of the air which surrounds us at all times, and as you know, varies slightly.
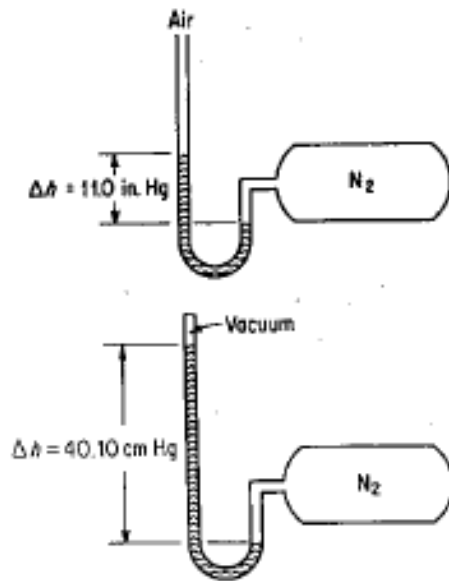
Figure 1.7 (a) Open-end manometer showing a pressure above atmospheric pressure. (b) Absolute pressure manometer.

$\Delta h = 11.0$ in. Hg

$\Delta h = 40.10$ cm Hg

If a mercury reading is set up as illustrated in Fig. 1.8, with the dish open to the atmosphere, the device is called a *barometer* and the reading of atmospheric pressure is termed barometric pressure.
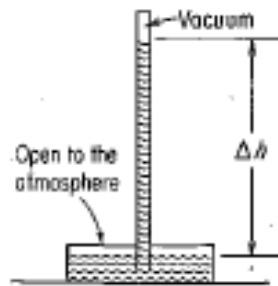
Figure 1.8 A barometer.

An understanding of the principle upon which a manometer operates will aid you in recognizing the nature of the pressure measurement taken from it. As shown in Fig. 1.7a for an open-end U-tube manometer, if the pressure measured for the N2 is greater than atmospheric, the liquid is forced downward in the leg to which the pressure source is connected and upward in the open leg. Eventually, a point of hydrostatic balance is reached in which the manometer fluid stabilizes. The pressure exerted at the bottom of the U-tube in the part of the tube open to the atmosphere exactly balances the pressure exerted at the bottom of the U-tube in the part of the tube connected to the tank of *Ni*. Furthermore, the difference between the height of fluid in the leg open to the atmosphere and the height. of fluid in the leg attached to the tank is exactly equal to the difference between the pressure in the tank and atmospheric pressure (expressed in units of fluid column length). If some degree of vacuum instead of a high pressure existed in a tank in an arrangement similar to that shown in Fig. 1.7a, the fluid column would rise on the vacuum side. Again, the difference in pressure between the pressure source in the tank and atmospheric pressure would be measured by the difference in the height of the two legs of fluid. Water and mercury are commonly used indicating fluids for manometers; the readings thus can be expressed in "inches or em of water," "inches or em of mercury," "mm of fluid flowing," and so on. (In ordinary engineering calculations we ignore the vapor

pressure of mercury and minor changes in the density of mercury due to temperature changes in making pressure measurements.) .

Another type of common measuring device is the visual *Bourdon gauge* (Fig.1.9), which normally (but not always) reads zero pressure when open to the atmosphere. The pressure-sensing device in the Bourdon gauge is a thin metal tube with an elliptical cross section closed at one end which has been bent into an arc. As the pressure increases at the open end of the tube, it tries to straighten out, and the movement of the tube is converted into a dial movement by gears and levers. Figure1.9 also illustrates a diaphragm capsule gauge. Figure 1.10 indicates the pressure ranges for the various pressure-measuring devices.

Pressure scales may be temporarily somewhat more confusing than temperature scales since **the reference point or zero point for the relative pressure scales is not constant,** whereas in the temperature scales the boiling point or the freezing point of water is always a fixed value. However, you will become accustomed to this feature with practice.

The relationship between relative and absolute pressure is illustrated in Figs. 1.11 and 1.12 and is given by the following expression:

gauge pressure + barometer pressure = absolute pressure   (1. 25)

(a) "C" Bourdon

(b) Spiral Bourdon

(c) Convex Diaphragm Capsule
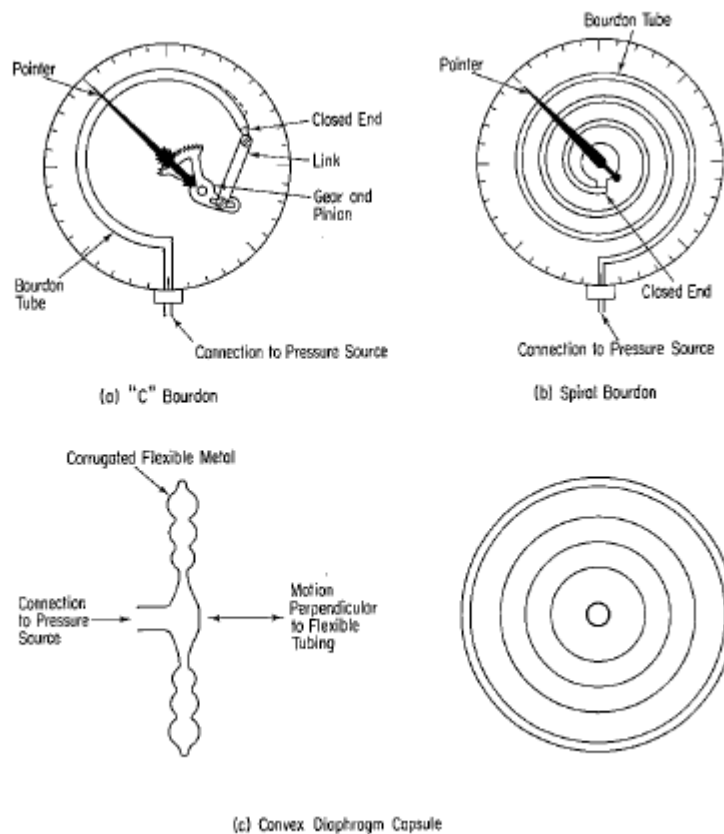
Figure 1.9 Bourdon and diaphragm pressure-measuring devices.

Equation (1.25) can be used only with consistent units. Note that you must add the atmospheric pressure (i.e., the barometric pressure) to the gauge, or relative pressure (or manometer reading if open on one end), in order to get the absolute pressure.

Another term applied in measuring pressure which is illustrated in Figs. 1.11 and 1.12 is vacuum. In effect, when you measure pressure as "inches of mercury vacuum," you reverse the usual direction of measurement and measure from the barometric pressure down to zero absolute pressure, in which case a perfect vacuum would be the highest vacuum that you could achieve. The vacuum system of measurement of pressure is commonly used in apparatus which operate at pressures less than atmospheric-such as a vacuum evaporator or vacuum filter. A pressure that is only slightly below barometric pressure may sometimes be expressed as a "draft"
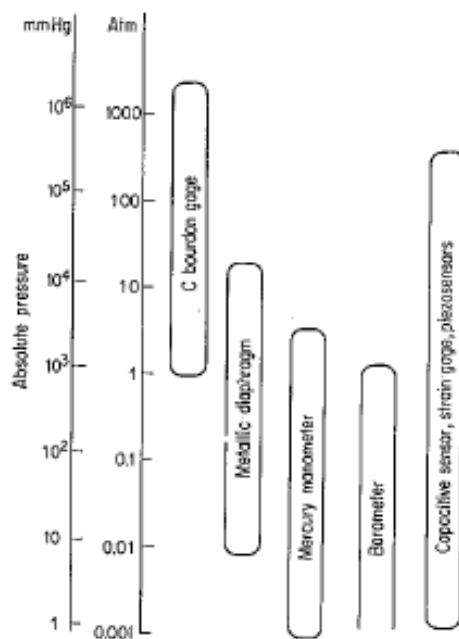

Figure 1.10   Ranges of application for pressure-measuring devices.

Figure 1.11   Pressure comparisons when barometer reading is 29.1 in Hg.
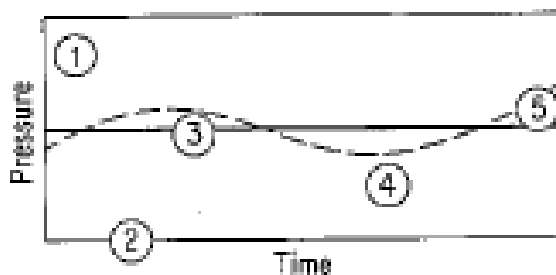
Figure 1.12 Pressure terminology. The standard atmosphere is shown by the heavy horizontal line. The dashed line illnstrates the atmospheric (barometric) pressure, which changes from time to time. Point CD in the figure is a pressure of 19.3 psi referred to a complete vacuum or 5 psi referred to the barometric pressure: ~ is the complete vacuum. a> represents the standard atmosphere, and @ illustrates a negative relative pressure or a pressure less than atmospheric. This type of measurement is described in the textas a vacuum type of measurement. Point® also indicates a vacuum measurement, but one that is equivalent to an absolute pressure abovethe standard atmosphere.

(which is identical to the vacuum system) in inches of water, as, for example, in the air supply to a furnace or a water cooling tower.

As to the units of pressure, Fig. 1.11 shows three common systems: pounds per square inch (psi), inches of mercury (in. Hg), and pascals. Pounds per square inch absolute is normally abbreviated "psia," and "psig" stands for "pounds per square inch gauge." For other units, be certain to carefully specify whether they are gauge or absolute; for example, state "300 kPa absolute" or "12 em Hg gauge." Figure 1.11 compares the relative and absolute pressure scales in terms of the three systems of measurement when the barometric pressure is 29.1 in Hg (14.3 psia, 0.985 x 10' pascal). Other systems of expressing pressure exist; in fact, you will discover that there are as many different units of pressure as there are means of measuring pressure. Some of the other most frequently used systems are

(a) Millimeters of mercury (mm Hg)

(b) Feet of water (ft H2 0)

(c) Atmospheres (atm)

(d) Bars (bar): 100 kPa = I bar

(e) Kilograms (force) per square centimeter (kgdcm2)-a common but theoretically prohibited measure'

To sum up our discussion of pressure and its measurement, you should now be acquainted with:

(a) *Atmosphericpressure-the* pressure of the air and the atmosphere surrounding us which changes from day to day

Although the units of pressure in the SI system arepascal, youfrequently find in common usage pressures denoted in the units of kg/ern> (i.e.• kgdcm2) , units that have to be multiplied by

$$9.80 \times 10^4 \left(\frac{(kg_m)(m)}{(kg_f)(s^2)} \right) \left(\frac{cm^2}{m^2} \right) \quad \text{to get pascal.}$$

(b) *Barometric pressure-the* same as atmospheric pressure, called "barometric pressure" because a barometer is used to measure atmospheric pressure

(c) *Absolute pressure-a* measure of pressure referred to a complete vacuum, or zero pressure

(d) *Gauge pressure-pressure* expressed as a quantity measured upward from atmospheric pressure (or some other reference pressure)

(e) *Vacuum-a* method of expressing pressure measured downward from atmospheric pressure (or some other reference pressure)

You definitely must not confuse the standard atmosphere with atmospheric pressure. The *standardatmosphere* is defined as the pressure (in a standard gravitational field) equivalent to 1 atm or 760 mm Hg at DoC or other equivalent value, whereas atmospheric pressure is a variable and must be obtained from a barometer each time you need it. The standard atmosphere may not equal the barametric pressure in any part of the world except perhaps at sea level on certain days, but it is extremely nseful in converting from one system of pressure measurement to another (as well as being useful in several other ways to be considered later).

Expressed in various units, the *standardatmosphere* is equal to

1.000 atmospheres (atm)

33.91 feet of water (ft $H_2 0$)

14.7 (14.696, more exactly) pounds per square inch absolute (psia)

29.92 (29.921, more exactly) inches of mercury (in. Hg)

760.0 millimeters of mercury (mm Hg)

1.013 X 10' pascal (pa) or newtons per square meter (N/m^2);.or 101.3 kPa

You can convert from one set of pressure measurements to another by using pairs of standard atmospheres as conversion factors, as shown in the examples below. If pressures are measured by a height of a column of one liquid A, and po is the same for both columns, you can convert the pressure to the height of another column of liquid B by the use of Eq. (1.22).

$$p_0 + \rho_A g h_A = p_0 + \rho_B g h_B$$

Or

$$\frac{h_A}{h_B} = \frac{\rho_B}{\rho_A}$$

How can you arrange to get the same po for each column?Willleaving the upper end of each of the columns open to the atmosphere accomplish this objective?