جامعة بابل – كلية هندسة المواد –قسم هندسة البوليمرات والصناعات البتروكيمياوية

مبادئ الهندسة الكيمياوية

Principle of Chemical Engineering

المرحلة الثانية

"Temperature and Pressure"

Temperature

The objective from studying of this sections are to be able to:

1. Define what temperature is.
2. Explain the difference between absolute and relative temperature
3. Convert a temperature in any of the four common scales (°C, K, °F, °R) to any of the others.
4. Convert an expression involving units of temperature and temperature difference to other units of temperature and temperature difference.
5. Know the reference points for the four temperature scales.

- Relative scale temperature (Fahrenheit °F, Celsius °C)
- Absolute scale temperature (Rankine °R, Kelvin K)

Relative temperature scales are based on a specific reference temperature (32 °F or 0 °C) that occurs in an ice-water mixture (the freezing point of water).

Absolute temperature scales are based on Celsius degree units (°C) is called the Kelvin scale or based on Fahrenheit degree units (°F).

The **standard conditions of temperature (0°C).**

Δ^{o}F = Δ^{o}R

Δ^{o}C = ΔK

$$\frac{\Delta^{\circ}C}{\Delta^{\circ}F} = 1.8 \qquad \frac{\Delta K}{\Delta^{o}R} = 1.8$$

$$T_{°R} = T_{°F}\left(\frac{1\ \Delta°R}{1\ \Delta°F}\right) + 460°R$$

$$T_{^oR} = T_{^oF} + 460^oR$$

$$T_K = T_{°C}\left(\frac{1\ \Delta K}{1\ \Delta°C}\right) + 273\ K$$

$$T_K = T_{^oC} + 273K$$

$$T_{°F} - 32°F = T_{°C}\left(\frac{1.8\ \Delta°F}{1\ \Delta°C}\right)$$

$$T_{^oF} - 32^oF = 1.8T_{^oC}$$

$$T_{°C} = (T_{°F} - 32°F)\left(\frac{1\ \Delta°C}{1.8\ \Delta°F}\right)$$

$$T_{^oC} = \frac{T_{^oF} - 32^oF}{1.8}$$

Example. 4.1 Temperature conversion

Convert 100 ºC to (a) K, (b) ºF, and (c) R.

Solution:

(a) T_K =100+273=373 K

(a) $T_{^oF}$=1.8 (100) + 32 = 212 ºF

(a) $T_{^oR}$ = 212 +460 = 672 ºR

EXAMPLE 4.2 Temperature Conversion

The heat capacity of sulfuric acid has the units J/(g mol)(°C), and is given by the relation

$$\text{heat capacity} = 139.1 + 1.56 \times 10^{-1}T$$

where T is expressed in °C. Modify the formula so that the resulting expression has the associated units of Btu/(lb mol) (°R) and T is in °R.

Solution

heat capacity =

$$\left\{139.1 + 1.56\text{X}10^{-1}\left[T_{\circ R} - 460 - 32\right]\right\}\text{X}\,\frac{1J}{(gmol)(°C)}\,\frac{1BTU}{1055J}\,\frac{454gmol}{1lbmol}\,\frac{1°C}{1.8°R} = 23.06 + 2.07\text{X}10^{-2}T_{\circ R}$$

Questions

1. What are the reference points of (a) the Celsius and (b) the Fahrenheit scales?

(a) 0 ºC and 100 ºC
(b) 32º F and 212 ºF

2. How do you convert a *temperature difference*, Δ, from Fahrenheit to Celsius?

Δ°F (1.8) = Δ °C

3. Is the unit temperature difference Δ°C a larger interval than Δ°F? Is 10°C higher than 10°F?

Yes, yes

4. The heat capacity of sulfur is C_p = 15.2 + 2.68 *T*, Where C_p is in J/(g mol)(K) and *T* is in K. convert this expression to C_p in cal/(g mol) (°*F) with T in °F.*

$$C_p = \left\{15.2 + 2.68\left(\frac{T_{\circ F} - 32}{1.8} + 273\right)\right\}\frac{J}{gmol.K}\,\frac{1cal}{4.18J}\,\frac{K}{1.8°F} = 93 + 0.19T_{\circ F}$$

5. Answer the following questions:
(a) In relation to absolute zero, which is higher, 1 °C or 1 °F
(b) In relation to 0C, which is higher, 1 °C or 1°F
(c) Which is larger, 1 Δ°C or 1 Δ°F

Solution:
(a) 1°C; (b) 1°C; (c) 1Δ°F

H.W

**4.3 The heat capacity C_p of acetic acid in J/(g mol)(K) can be calculated from the equation

$$C_p = 8.41 + 2.4346 \times 10^{-5} T$$

where T is in K. Convert the equation so that T can be introduced into the equation in °R instead of K. Keep the units of C_p the same.

Ans. $C_p = 8.41 + 1.353 \times 10^{-5}\ T_{°R}$

Hint: $1.8\ T_K = T_{°R}$

Pressure

The objective from studying of this sections are to be able to:

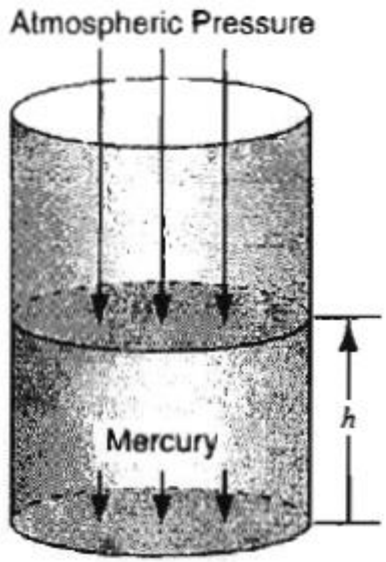
1. Define pressure, atmospheric pressure, barometric pressure, standard pressure, and vacuum.
2. Explain the difference between absolute and relative (gauge pressure).
3. List four ways to measure pressure.
4. Convert from gauge to absolute pressure and vice versa.
5. Convert a pressure measured in one set of units to another set, including kPa, mm Hg, ft H_2O, atm, in. Hg, and psi using the standard atmosphere or density ratios of liquids.
6. Calculate the pressure from the density and height of a column of static fluid.

$$P = \rho\, g\, h$$

Where: ρ = density of fluid
h = height of the fluid
g = acceleration of gravity

pressure)= Force /Area

P = F / A (N/m^2) or Pascal (Pa)



$$p = \frac{F}{A} = \rho g h + p_0$$

Figure 5.1 Pressure is the normal force per unit area. Arrows show the force exerted on the respective areas.

Some common nonstandard variations of pressure measurement used with the SI system are

a. Bars (bar): 100 kPa = 1 bar

b. Kilograms (force) per square centimeter (kg_f/cm^2)*—a very common measure of pressure but not standard in SI (often called just "kilos")

c. Torr (Torr): 760 Torr = 1 atm

In the AE system pressure can be expressed in a variety of ways, including

a. Millimeters of mercury (mm Hg)
b. Inches of mercury (in. Hg)
c. Feet of water (ft H_2O)
d. Inches of water (in. H_2O)
e. Atmospheres (atm)
f. Pounds (force) per square inch (often called just "pounds") (psi)

lb/in^2 = psi

Example: suppose that the cylinder of fluid in Figure 5.1 is a column of mercury that has an area of **1 cm^2** and is **50 cm** high. The density of the Hg is 13.55 g/cm^3. Estimate the force exerted by the mercury alone on the **1 cm^2** section of the bottom plate by the column of mercury.

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

$$= 6.64\ \text{N}$$

The pressure on the section of the plate covered by the mercury is the force per unit area of the mercury *plus* the pressure of the atmosphere

$$p = \frac{6.64\ \text{N}}{1\ \text{cm}^2}\left|\left(\frac{100\ \text{cm}}{1\ \text{m}}\right)^2\right|\frac{(1\ \text{m}^2)(1\ \text{Pa})}{(1\ \text{N})}\left|\frac{1\ \text{kPa}}{1000\ \text{Pa}}\right. + p_0 = 66.4\ \text{kPa} + p_0$$

If we had started with units in the AE system, the pressure would be computed as [the density of mercury is $(13.55)(62.4)\text{lb}_m/\text{ft}^3 = 845.5\ \text{lb}_m/\text{ft}^3$]

$$p = \frac{845.5\ \text{lb}_m}{1\ \text{ft}^3}\left|\frac{32.2\ \text{ft}}{\text{s}^2}\right|\frac{50\ \text{cm}}{}\left|\frac{1\ \text{in.}}{2.54\ \text{cm}}\right|\frac{1\text{ft}}{12\ \text{in.}}\left|\frac{(\text{s})^2(\text{lb}_f)}{32.174(\text{ft})(\text{lb}_m)}\right. + p_0$$

$$= 1388\frac{\text{lb}_f}{\text{ft}^2} + p_0$$

2. Figure SAT5.1Q2 shows four closed containers completely filled with water. Order the containers from the one exerting the highest pressure to the lowest on their respective bases.

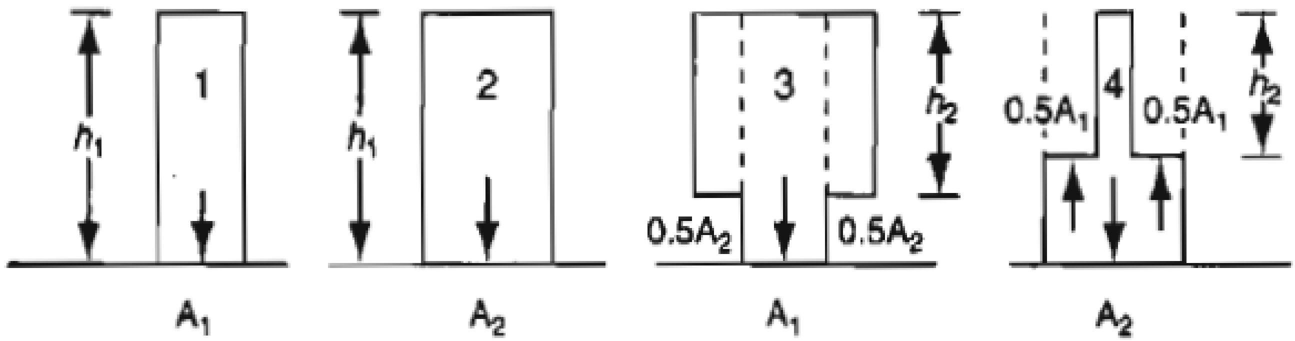


Figure SAT5.1Q2

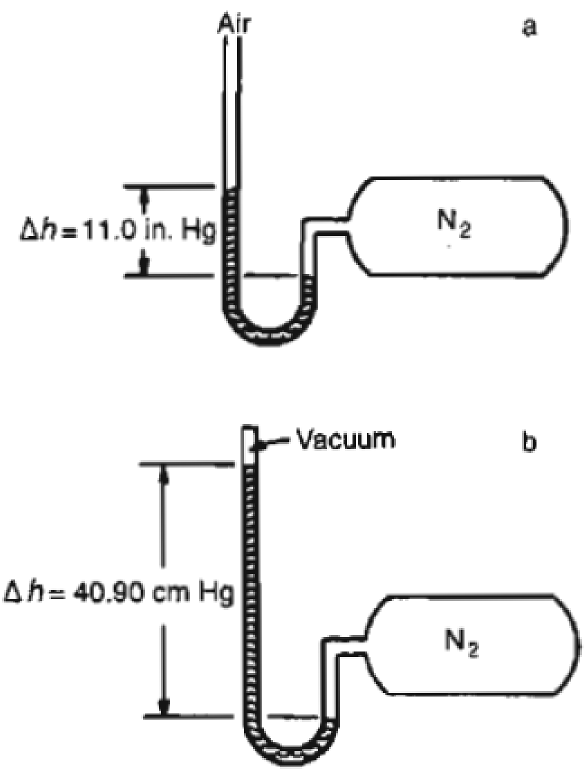
Solution

3 is the highest pressure; next are 1 and 2, which are the same; and 4 is last. The decisions are made by dividing the weight of water by the base area.

Measurement of Pressure

gauge pressure + barometer pressure = absolute pressure

Pressure, like temperature, can be expressed using either an absolute or a relative scale. **Whether relative or absolute pressure is measured in a pressure-measuring device depends on the nature of the instrument used to make the measurements.** For example, an open-end **manometer** (Figure 5.2a) would measure a **relative (gauge) 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



Measure Gauge (relative) Pressure

Measure absolute Pressure

Figure 5.2 (a) Open-end manometer showing a pressure above atmospheric pressure. (b) Manometer measuring an absolute pressure.

the open end of the manometer (Figure 5.2b) and creating a vacuum in that end results in a measurement against a complete vacuum, or against "no pressure"; p_0 in Equation (5.1) is zero. Such a measurement is called **absolute pressure.**

EXAMPLE 5.1 Pressure Conversion

In problem, if you are not given the barometric pressure, you usually assume that the barometric pressure equal the standard atmosphere. The **standard atmosphere** is equal to:

1 atm. = 33.91 ft H2O = 14.7 psia (lb_f / in^2) = 760 mm Hg = 29.92 in Hg = 101.3 kPa = 1.013 x 10^5 Pa (N/m^2)

What is the equivalent pressure to 60 Gpa in

(a) atmospheres
(b) psia
(c) inches of Hg
(d) mm of Hg

Solution

For the solution, use the standard atmosphere.

Basis: 60 GPa

(a) $$\frac{60\ \text{GPa}}{}\left|\frac{10^6\ \text{kPa}}{1\ \text{GPa}}\right|\frac{1\ \text{atm}}{101.3\ \text{kPa}} = 0.59 \times 10^6\ \text{atm}$$

(b) $$\frac{60\ \text{GPa}}{}\left|\frac{10^6\ \text{kPa}}{1\ \text{GPa}}\right|\frac{14.696\ \text{psia}}{101.3\ \text{kPa}} = 8.70 \times 10^6\ \text{psia}$$

(c) $$\frac{60\ \text{GPa}}{}\left|\frac{10^6\ \text{kPa}}{1\ \text{GPa}}\right|\frac{29.92\ \text{in. Hg}}{101.3\ \text{kPa}} = 1.77 \times 10^7\ \text{in. Hg}$$

(d) $$\frac{60\ \text{GPa}}{}\left|\frac{10^6\ \text{kPa}}{1\ \text{GPa}}\right|\frac{760\ \text{mm Hg}}{101.3\ \text{kPa}} = 4.50 \times 10^8\ \text{mm Hg}$$

EXAMPLE 5.2 Pressure Conversion

The pressure gauge on a tank of CO_2 used to fill soda-water bottles reads 51.0 psi. At the same time the barometer reads 28.0 in. Hg. What is the absolute pressure in the tank in psia? See Figure E5.2.

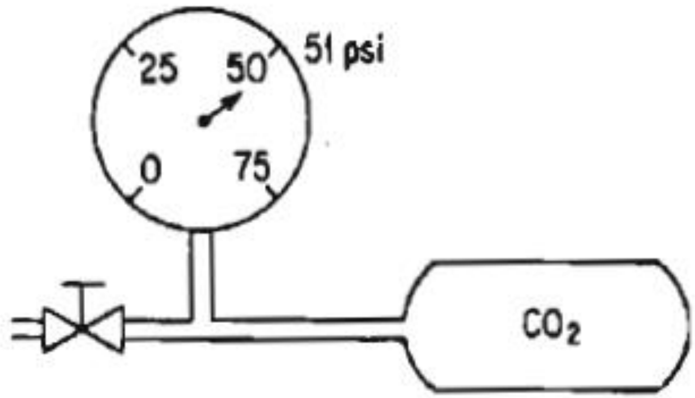


Figure E5.2

Solution

$$\text{Atmospheric pressure} = \frac{28.0 \text{ in. Hg}}{} \left| \frac{14.7 \text{ psia}}{29.92 \text{ in Hg}} \right. = 13.76 \text{ psia}$$

The absolute pressure in the tank is

$$51.0 \text{ psia} + 13.76 \text{ psia} = 64.8 \text{ psia}$$

EXAMPLE 5.3 Vacuum Pressure Reading

Small animals such as mice can live (although not comfortably) at reduced air pressures down to 20 kPa absolute. In a test, a mercury manometer attached to a tank, as shown in Figure E5.3, reads 64.5 cm Hg and the barometer reads 100 kPa. Will the mice survive?

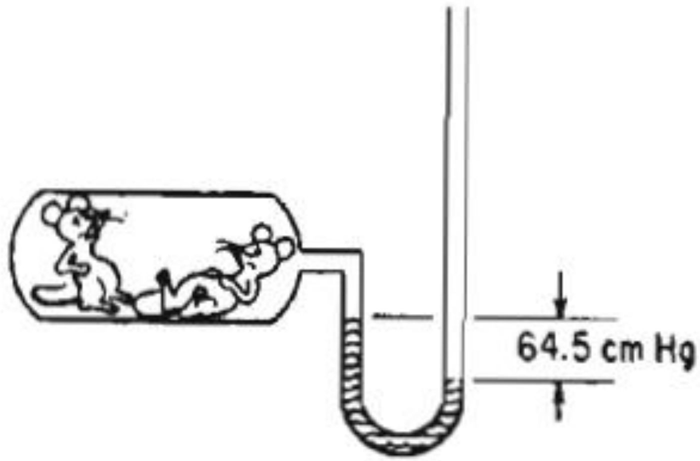


Figure E5.3

Solution

Barometric pressure − vacuum pressure = absolute pressure

Since the vacuum reading on the tank is **64.5 cm Hg** below atm., the absolute pressure in the tank is:

$$100\ \text{kPa} - \frac{64.5\ \text{cm Hg}}{} \left| \frac{101.3\ \text{kPa}}{76.0\ \text{cm Hg}} \right. = 100 - 86 = 14\ \text{kPa absolute}$$

Questions

1. Answer the following questions true or false:
   a. Atmospheric pressure is the pressure of the air surrounding us and changes from day to day.
   b. The standard atmosphere is a constant reference atmosphere equal to 1.000 atm or the equivalent pressure in other units.
   c. Absolute pressure is measured relative to a vacuum.
   d. Gauge pressure is measured upward relative to atmospheric pressure.
   e. Vacuum and draft pressures are measured downward from atmospheric pressure.
   f. You can convert from one type of pressure measurement to another using the standard atmosphere.
   g. A manometer measures the pressure difference in terms of the height of fluid(s) in the manometer tube.

Ans. All are true

Problems

1. Convert a pressure of 800 mm Hg to the following units:
   a. psia
   b. kPa
   c. atm
   d. ft H_2O

Solution. (a) 15.5; (b) 106.6; (c) 1.052; (d) 35.6

2. Your textbook lists five types of pressures: atmospheric pressure, barometric pressure, gauge pressure, absolute pressure, and vacuum pressure.
   a. What kind of pressure is measured by the device in Figure SAT5.2P2A?

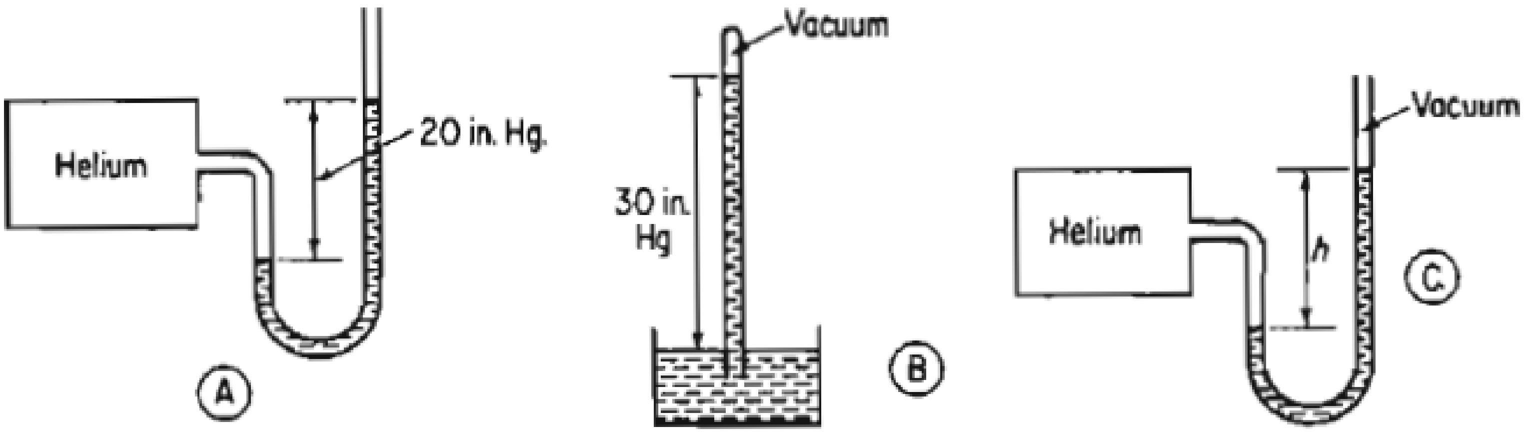


Figure SAT5.2P2A

   b. What kind of pressure is measured by the device in Figure SAT5.2P2B?
   c. What would be the reading in Figure SAT5.2P2C assuming that the pressure and temperature inside and outside the helium tank are the same as in parts (a) and (b)?

Solution.

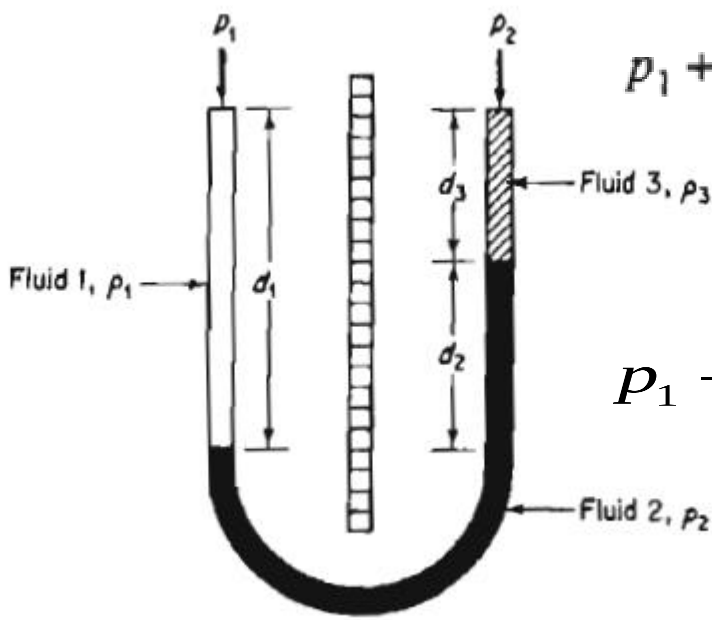
(A) Gauge pressure; (B) barometric pressure, absolute pressure; (C) 50 in. Hg

3. An evaporator shows a reading of 40 kPa vacuum. What is the absolute pressure in the evaporator in kPa?

Solution Barometric pressure − vacuum pressure = absolute pressure

In the absence of a barometric pressure value, assume 101.3 kPa. The absolute pressure is 61.3 kPa.

Differential Pressure Measurements



$$p_1 + \rho_1 d_1 g = p_2 + \rho_2 g d_2 + \rho_3 g d_3 \quad \text{----(5.3)}$$

if $\rho_1 = \rho_3 = \rho$; $d_2 = d_1 - d_3$

$$p_1 - p_2 = g d_2 (\rho_2 - \rho) \quad \text{----(5.4)}$$

Figure 5.9 Manometer with three fluids.

EXAMPLE 5.4 Calculation of Pressure Differences

In measuring the flow of fluid in a pipeline as shown in Figure E5.4, a differential manometer was used to determine the pressure difference across the orifice plate.

The flow rate was to be calibrated with the observed pressure drop (difference). Calculate the pressure drop $p_1 - p_2$ in pascals for the manometer reading in Figure E5.4.

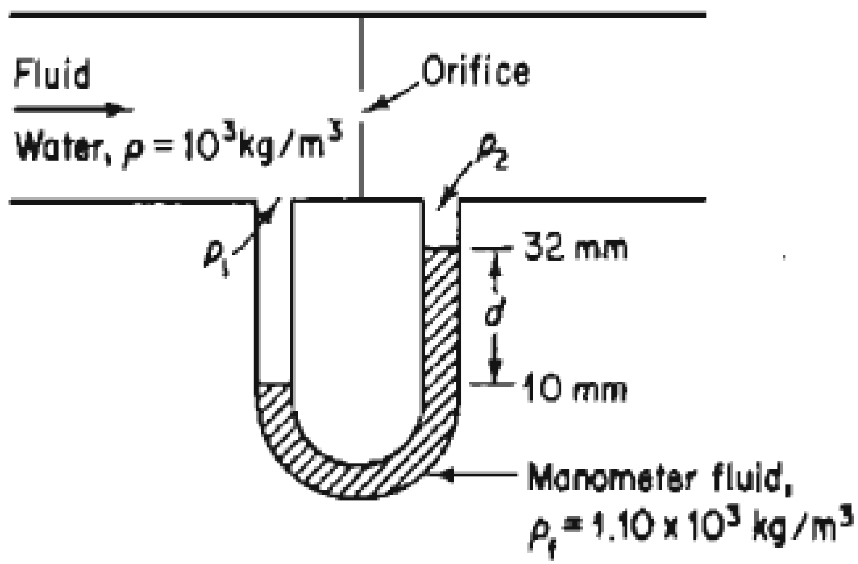


Figure E5.4

Solution

In this problem you cannot ignore the water density above the manometer fluid. Thus, we apply Equation (5.3) or (5.4), because the densities of the fluids above the manometer fluid are the same in both legs of the manometer. The basis for solving the problem is the information given in Figure E5.4. Apply Equation (5.4)

$$p_1 - p_2 = (\rho_f - \rho)gd$$

$$= \frac{(1.10 - 1.00)10^3\ \text{kg}}{\text{m}^3}\left|\frac{9.807\ \text{m}}{\text{s}^2}\right|\frac{(22)(10^{-3})\text{m}}{}\left|\frac{1(\text{N})(\text{s}^2)}{(\text{kg})(\text{m})}\right|\frac{1(\text{Pa})(\text{m}^2)}{1(\text{N})}$$

EXAMPLE 5.5 Pressure Conversion

Air is flowing through a duct under a draft of 4.0 cm H_2O. The barometer indicates that the atmospheric pressure is 730 mm Hg. What is the absolute pressure of the air in inches of mercury? See Figure E5.5

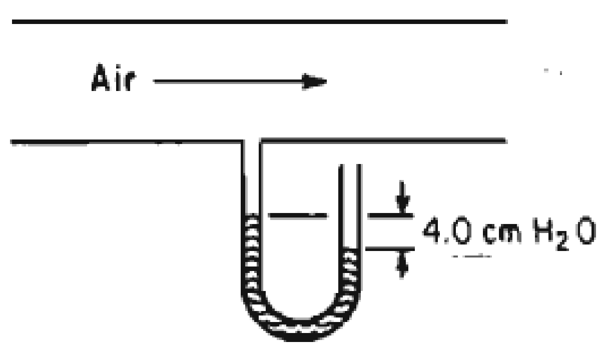


Figure E5.5

Solution

Can you ignore the gas density above the manometer fluid and the air above the open end of the manometer? Probably. In the calculations you must employ consistent units, and it appears in this case that the most convenient units are those of inches of mercury, so let's convert the barometer reading and the manometer reading to in. Hg using the standard atmosphere as the conversion factor.

$$\text{Atmospheric pressure} = \frac{730 \text{ mm Hg}}{} \left| \frac{29.92 \text{ in. Hg}}{760 \text{ mm Hg}} \right. = 28.7 \text{ in. Hg}$$

Next, convert 4.0 cm H_2O to in. Hg:

$$\frac{4.0 \text{ cm } H_2O}{} \left| \frac{1 \text{ in.}}{2.54 \text{ cm}} \right| \frac{1 \text{ ft}}{12 \text{ in.}} \left| \frac{29.92 \text{ in. Hg}}{33.91 \text{ ft } H_2O} \right. = 0.12 \text{ in. Hg}$$

Since the reading is 4.0 cm H_2O draft (under atmospheric), the absolute reading in uniform units is

$$28.7 \text{ in. Hg} - 0.12 \text{ in. Hg} = 28.6 \text{ in. Hg absolute}$$

Tutorial (2)

*5.8 Suppose that a submarine inadvertently sinks to the bottom of the ocean at a depth of 1000 m. It is proposed to lower a diving bell to the submarine and attempt to enter the conning tower. What must the minimum air pressure be in the diving bell at the level of the submarine to prevent water from entering into the bell when the opening valve at the bottom is cracked open slightly? Give your answer in absolute kilopascal. Assume that seawater has a constant density of 1.024 g/cm^3.

*5.13 A Bourdon pressure gauge is connected to a large tank and reads 440 kPa when the barometer reads 750 mm Hg. What will the gauge reading be if the atmospheric pressure increases to 765 mm Hg?

*5.33 Examine Figure P5.33. Water flows through an orifice.

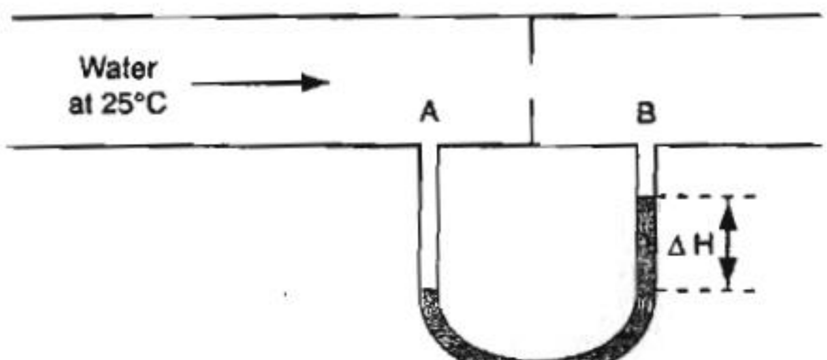


Figure P5.33

The manometer fluid has a specific gravity of 1.30. What is the pressure difference between points A and B in kPa if there is a 3.1 cm difference in the heights of the two columns of manometer fluid?

5.8 Basis: Dept = 1000 m $\quad p = p_o + \rho g h$

$$p = 1 \text{ atm} + $$

$$\frac{1000 \text{ m}}{} \left| \frac{1.024 \text{ g}}{\text{cm}^3} \right| \frac{9.8 \text{ m}}{\text{s}^2} \left| \frac{1 \text{ kg}}{10^3 \text{ g}} \right| \left(\frac{100 \text{ cm}}{1 \text{ m}}\right)^3 \left| \frac{1 \text{ N}}{\frac{(\text{kg})(\text{m})}{\text{s}^2}} \right| \frac{1 \text{ kPa}}{\frac{1\text{N}}{\frac{(\text{kg})(\text{m})}{\text{s}^2}}} \left| \frac{1 \text{ atm}}{1.013 \times 10^5 \text{N/m}^2} \right.$$

$$= \frac{100.1 \text{ atm}}{} \left| \frac{101.3 \text{ kPa}}{1 \text{ atm}} \right. = \boxed{1.014 \times 10^4 \text{kPa}}$$

Alternative solution:

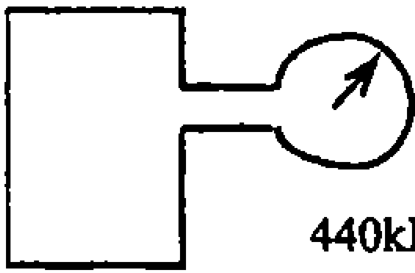
$$101.3 \text{ kPa} + \frac{1000 \text{ m sea } H_2O}{} \left| \frac{1.024 \text{ g } H_2O}{1.00 \text{ g sea } H_2O} \right| \frac{3.28 \text{ ft}}{1 \text{ m}} \left| \frac{101.3 \text{ kPa}}{33.91 \text{ ft } H_2O} \right. = 1.003 \times 10^4$$

$$+ 0.01 \times 10^4$$

$$= 1.013 \times 10^4$$

5.13 Basis: 750 mm Hg

Atmospheric pressure + gauge pressure = absolute pressure



$$\frac{750 \text{ mm Hg}}{} \left| \frac{101.3\text{kPa}}{760 \text{ mm Hg}} \right. = 100\text{kPa}$$

$$\underline{440\text{kPa}}$$

absolute pressure = 540kPa

$$\frac{765 \text{ mm Hg}}{} \left| \frac{101.3\text{kPa}}{760 \text{ mm Hg}} \right. = 102\text{kPa}$$

$$540-102 = \boxed{438 \text{ kPa}}$$

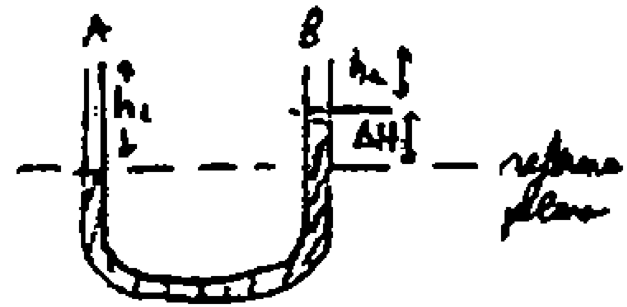
Alternate Solution: $\dfrac{15 \text{ mm Hg}}{} \left| \dfrac{101.3 \text{ kPa}}{760 \text{ mm Hg}} \right. \cong 2 \text{ kPa}$ so $440 - 2 = 438$ kPa

5.33 Basis: 3.1 cm fluid

$$\frac{3.1\ \text{cm fluid}}{}\left|\frac{(1.30-1.00)\ \text{cm}\ H_2O}{1.00\ \text{cm fluid}}\right|\frac{1\ \text{in}}{2.54\ \text{cm}}\left|\frac{1\ \text{ft}}{12\ \text{in.}}\right|\frac{101.3\ \text{kPa}}{33.91\ \text{ft}\ H_2O} = \boxed{0.091\ \text{kPa}}$$

Alternate solution:

$$p_A + \rho_W g h_1 = p_B + \rho_W g h_2 + \rho_{fluid} g \Delta H$$
$$p_A - p_B = \rho_W g h_2 + \rho_{fluid} g \Delta H - \rho_W g h_2 - \rho_W g \Delta H$$
$$= \rho_{fluid} g \Delta H - \rho_W g \Delta H = g \Delta H(\rho_{fluid} - \rho_W)$$



$$= \left(\frac{1.30\ \text{g} - 1.00\text{g}}{\text{cm}^3}\left|\frac{980\ \text{cm}}{\text{s}^2}\right|\frac{3.1\ \text{cm fluid}}{}\left|\frac{1\ \text{kg}}{10^3\ \text{g}}\right|\frac{100\text{cm}}{1\ \text{m}}\left|\frac{1\ \text{Pa}(\text{s}^2)(\text{m})}{}\right.\right)$$

$= 0.091$ kPa