Fundamentals of Thermal Fluid Sciences 6th edition Cengel Solutions Manual

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SOLUTIONS MANUAL

Fundamentals of Thermal Fluid Sciences

6th Edition

Yunus A. Çengel, John M. Cimbala, Afshin J. Ghajar

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Chapter 2

BASIC CONCEPTS OF THERMODYNAMICS

Systems, Properties, State, and Processes

2-1C How would you define a system to determine the rate at which an automobile adds carbon dioxide to the atmosphere?

Carbon dioxide is generated by the combustion of fuel in the engine. Any system selected for this analysis must include the fuel and air while it is undergoing combustion. The volume that contains this air-fuel mixture within piston-cylinder device can be used for this purpose. One can also place the entire engine in a control boundary and trace the system-surroundings interactions to determine the rate at which the engine generates carbon dioxide.

2-2C A large fraction of the thermal energy generated in the engine of a car is rejected to the air by the radiator through the circulating water. Should the radiator be analyzed as a closed system or as an open system? Explain.

FIGURE P2–2C

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The radiator should be analyzed as an open system since mass is crossing the boundaries of the system.

2-3C A can of soft drink at room temperature is put into the refrigerator so that it will cool. Would you model the can of soft drink as a closed system or as an open system? Explain.

A can of soft drink should be analyzed as a closed system since no mass is crossing the boundaries of the system.

2-4C How would you define a system to determine the temperature rise created in a lake when a portion of its water is used to cool a nearby electrical power plant?

When analyzing the control volume selected, we must account for all forms of water entering and leaving the control volume. This includes all streams entering or leaving the lake, any rain falling on the lake, any water evaporated to the air above the lake, any seepage to the underground earth, and any springs that may be feeding water to the lake.

2-5C How would you describe the state of the air in the atmosphere? What kind of process does this air undergo from a cool morning to a warm afternoon?

In order to describe the state of the air, we need to know the value of all its properties. Pressure, temperature, and water content (i.e., relative humidity or dew point temperature) are commonly cited by weather forecasters. But, other properties like wind speed and chemical composition (i.e., pollen count and smog index, for example} are also important under certain circumstances.

Assuming that the air composition and velocity do not change and that no pressure front motion occurs during the day, the warming process is one of constant pressure (i.e., isobaric).

2-6C What is the difference between intensive and extensive properties?

Intensive properties do not depend on the size (extent) of the system but extensive properties do.

2-7C The specific weight of a system is defined as the weight per unit volume (note that this definition violates the normal specific property-naming convention). Is the specific weight an extensive or intensive property?

The original specific weight is

$$g_1 = \frac{W}{V}$$

If we were to divide the system into two halves, each half weighs $W/2$ and occupies a volume of $V/2$. The specific weight of one of these halves is

$$g = \frac{W/2}{V/2} = g_1$$

which is the same as the original specific weight. Hence, specific weight is an *intensive property*.

2-8C Is the number of moles of a substance contained in a system an extensive or intensive property?

The number of moles of a substance in a system is directly proportional to the number of atomic particles contained in the system. If we divide a system into smaller portions, each portion will contain fewer atomic particles than the original system. The number of moles is therefore an *extensive property*.

2-9C Is the state of the air in an isolated room completely specified by the temperature and the pressure? Explain.

Yes, because temperature and pressure are two independent properties and the air in an isolated room is a simple compressible system.

2-10C What is a quasi-equilibrium process? What is its importance in engineering?

A process during which a system remains almost in equilibrium at all times is called a quasi-equilibrium process. Many engineering processes can be approximated as being quasi-equilibrium. The work output of a device is maximum and the work input to a device is minimum when quasi-equilibrium processes are used instead of nonquasi-equilibrium processes.

2-11C Define the isothermal, isobaric, and isochoric processes.

A process during which the temperature remains constant is called isothermal; a process during which the pressure remains constant is called isobaric; and a process during which the volume remains constant is called isochoric.

2-12C What is specific gravity? How is it related to density?

The **specific gravity,** or **relative density,** and is defined as the ratio of the density of a substance to the density of some standard substance at a specified temperature (usually water at 4°C, for which ρ_{H2O} = 1000 kg/m^3). That is, $SG = r / r_{H2O}$. When specific gravity is known, density is determined from $r = SG ´ r_{H2O}$.

2-13 The density of atmospheric air varies with elevation, decreasing with increasing altitude. (*a*) Using the data given in the table, obtain a relation for the variation of density with elevation, and calculate the density at an elevation of 7000 m. (*b*) Calculate the mass of the atmosphere using the correlation you obtained. Assume the earth to be a perfect sphere with a radius of 6377 km, and take the thickness of the atmosphere to be 25 km.

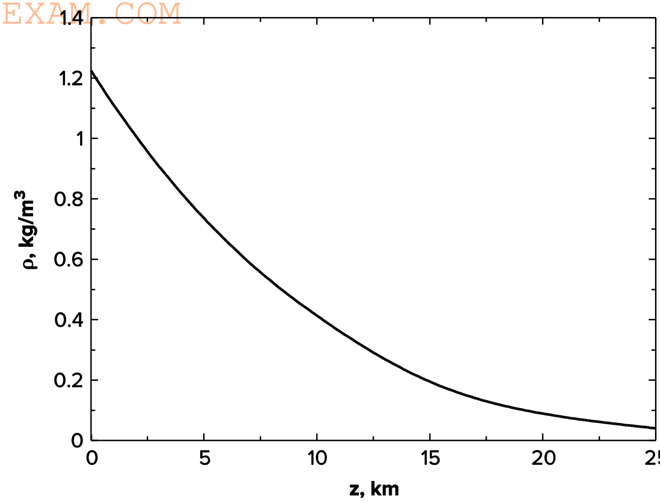
z, km	ρ, kg/m^3
6377	1.225
6378	1.112
6379	1.007
6380	0.9093
6381	0.8194
6382	0.7364
6383	0.6601
6385	0.5258
6387	0.4135
6392	0.1948
6397	0.08891
6402	0.04008

The variation of density of atmospheric air with elevation is given in tabular form. A relation for the variation of density with elevation is to be obtained, the density at 7 km elevation is to be calculated, and the mass of the atmosphere using the correlation is to be estimated.

Assumptions **1** Atmospheric air behaves as an ideal gas. **2** The earth is perfectly sphere with a radius of 6377 km, and the thickness of the atmosphere is 25 km.

Properties The density data are given in tabular form as

r, km	z, km	ρ, kg/m^3
6377	0	1.225
6378	1	1.112
6379	2	1.007
6380	3	0.9093
6381	4	0.8194
6382	5	0.7364
6383	6	0.6601
6385	8	0.5258
6387	10	0.4135
6392	15	0.1948
6397	20	0.08891
6402	25	0.04008



Analysis Using EES, (1) Define a trivial function rho = a+z in equation window, (2) select new parametric table from Tables, and type the data in a two-column table, (3) select Plot and plot the data, and (4) select plot and click on "curve fit" to get curve fit window. Then specify 2nd order polynomial and enter/edit equation. The results are:

$\rho(z) = a + bz + cz^2 = 1.20252 - 0.101674z + 0.0022375z^2$ for the unit of kg/m^3,

(or, $\rho(z) = (1.20252 - 0.101674z + 0.0022375z^2)\times 10^9$ for the unit of kg/km^3)

where z is the vertical distance from the earth surface at sea level. At z = 7 km, the equation would give $\rho = 0.60$ kg/m^3.

(*b*) The mass of atmosphere can be evaluated by integration to be

$$m = \int_V \rho\, dV = \int_{z=0}^{h} (a + bz + cz^2)4\pi(r_0 + z)^2 dz = 4\pi \int_{z=0}^{h} (a + bz + cz^2)(r_0^2 + 2r_0 z + z^2)dz$$

$$= 4\pi\left[ar_0^2 h + r_0(2a + br_0)h^2/2 + (a + 2br_0 + cr_0^2)h^3/3 + (b + 2cr_0)h^4/4 + ch^5/5\right]$$

where r_0 = 6377 km is the radius of the earth, h = 25 km is the thickness of the atmosphere, and a = 1.20252, b = -0.101674, and c = 0.0022375 are the constants in the density function. Substituting and multiplying by the factor 10^9 for the density unity kg/km^3, the mass of the atmosphere is determined to be

m = $\mathbf{5.092 \times 10^{18}}$ **kg**

Performing the analysis with excel would yield exactly the same results.

```
"Using linear regression feature of EES based on the data on parametric table, we obtain"
rho=1.20251659E+00-1.01669722E-01*z+2.23747073E-03*z^2
z=7 [km]
"The mass of the atmosphere is obtained by integration to be"
m=4*pi*(a*r0^2*h+r0*(2*a+b*r0)*h^2/2+(a+2*b*r0+c*r0^2)*h^3/3+(b+2*c*r0)*h^4/4+c*h^5/5)*1E9
a=1.20252
b=-0.101670
c=0.0022375
r0=6377 [km]
h=25 [km]
```

Temperature

2-14C What are the ordinary and absolute temperature scales in the SI and the English system?

They are Celsius (°C) and kelvin (K) in the SI, and fahrenheit (°F) and rankine (R) in the English system.

2-15C Consider an alcohol and a mercury thermometer that read exactly 0°C at the ice point and 100°C at the steam point. The distance between the two points is divided into 100 equal parts in both thermometers. Do you think these thermometers will give exactly the same reading at a temperature of, say, 60°C? Explain.

Probably, but not necessarily. The operation of these two thermometers is based on the thermal expansion of a fluid. If the thermal expansion coefficients of both fluids vary linearly with temperature, then both fluids will expand at the same rate with temperature, and both thermometers will always give identical readings. Otherwise, the two readings may deviate.

2-16C Consider two closed systems A and B. System A contains 3000 kJ of thermal energy at 20°C, whereas system B contains 200 kJ of thermal energy at 50°C. Now the systems are brought into contact with each other. Determine the direction of any heat transfer between the two systems.

Two systems having different temperatures and energy contents are brought in contact. The direction of heat transfer is to be determined.

Analysis Heat transfer occurs from warmer to cooler objects. Therefore, heat will be transferred from system B to system A until both systems reach the same temperature.

2-17E Consider a system whose temperature is 18°C. Express this temperature in R, K, and °F.

A temperature is given in °C. It is to be expressed in °F, K, and R.

Analysis Using the conversion relations between the various temperature scales,

$$T(\text{K}) = T(°\text{C}) + 273 = 18°\text{C} + 273 = \mathbf{291\ K}$$

$$T(°\text{F}) = 1.8T(°\text{C}) + 32 = (1.8)(18) + 32 = \mathbf{64.4°F}$$

$$T(\text{R}) = T(°\text{F}) + 460 = 64.4 + 460 = \mathbf{524.4\ R}$$

EES SOLUTION

```
"Given"
T_C=18 [C]

"Analysis"
T_K=T_C+273
T_F=1.8*T_C+32
T_R=T_F+460
```

2-18E Steam enters a heat exchanger at 300 K. What is the temperature of this steam in °F?

The temperature of steam given in K unit is to be converted to °F unit.

Analysis Using the conversion relations between the various temperature scales,

$$T(°C) = T(K) - 273 = 300 - 273 = 27°C$$

$$T(°F) = 1.8T(°C) + 32 = (1.8)(27) + 32 = \mathbf{80.6°F}$$

EES SOLUTION

```
"Given"
T_K=300 [K]

"Analysis"
T_C=T_K-273
T_F=1.8*T_C+32
```

2-19 The temperature of a system rises by 130°C during a heating process. Express this rise in temperature in kelvins.

A temperature change is given in °C. It is to be expressed in K.

Analysis This problem deals with temperature changes, which are identical in Kelvin and Celsius scales. Thus,

$$\Delta T(K) = \Delta T(°C) = \mathbf{130\ K}$$

EES SOLUTION

```
"Given"
DELTAT_C=130 [C]

"Analysis"
DELTAT_K=DELTAT_C
```


2-20E The temperature of a system drops by 45°F during a cooling process. Express this drop in temperature in K, R, and °C.

A temperature change is given in °F. It is to be expressed in °C, K, and R.

Analysis This problem deals with temperature changes, which are identical in Rankine and Fahrenheit scales. Thus,

$$\Delta T(R) = \Delta T(°F) = \mathbf{45\ R}$$

The temperature changes in Celsius and Kelvin scales are also identical, and are related to the changes in Fahrenheit and Rankine scales by

$$\Delta T(K) = \Delta T(R)/1.8 = 45/1.8 = \mathbf{25\ K}$$

and

$$\Delta T(°C) = \Delta T(K) = \mathbf{25°C}$$

EES SOLUTION

```
"Given"
DELTAT_F=45 [F]

"Analysis"
DELTAT_R=DELTAT_F
DELTAT_K=DELTAT_R/1.8
DELTAT_C=DELTAT_K
```

2-21E The temperature of the lubricating oil in an automobile engine is measured as 150°F. What is the temperature of this oil in °C?

The temperature of oil given in °F unit is to be converted to °C unit.

Analysis Using the conversion relation between the temperature scales,

$$T(°\text{C}) = \frac{T(°\text{F}) - 32}{1.8} = \frac{150 - 32}{1.8} = \mathbf{65.6°C}$$

EES SOLUTION

"Given"
T_F=150 [F]

"Analysis"
T_C=(T_F-32)/1.8

2-22E Heated air is at 150°C. What is the temperature of this air in °F?

The temperature of air given in °C unit is to be converted to °F unit.

Analysis Using the conversion relation between the temperature scales,

$$T(°\text{F}) = 1.8T(°\text{C}) + 32 = (1.8)(150) + 32 = \mathbf{302°F}$$

EES SOLUTION

"Given"
T_C=150 [C]

"Analysis"
T_F=1.8*T_C+32

Pressure, Manometer, and Barometer

2-23C What is the difference between gage pressure and absolute pressure?

The pressure relative to the atmospheric pressure is called the *gage pressure*, and the pressure relative to an absolute vacuum is called *absolute pressure*.

2-24C Explain why some people experience nose bleeding and some others experience shortness of breath at high elevations.

The atmospheric pressure, which is the external pressure exerted on the skin, decreases with increasing elevation. Therefore, the pressure is lower at higher elevations. As a result, the difference between the blood pressure in the veins and the air pressure outside increases. This pressure imbalance may cause some thin-walled veins such as the ones in the nose to burst, causing bleeding. The shortness of breath is caused by the lower air density at higher elevations, and thus lower amount of oxygen per unit volume.

2-25C A health magazine reported that physicians measured 100 adults' blood pressure using two different arm positions: parallel to the body (along the side) and perpendicular to the body (straight out). Readings in the parallel position were up to 10 percent higher than those in the perpendicular position, regardless of whether the patient was standing, sitting, or lying down. Explain the possible cause for the difference.

The blood vessels are more restricted when the arm is parallel to the body than when the arm is perpendicular to the body. For a constant volume of blood to be discharged by the heart, the blood pressure must increase to overcome the increased resistance to flow.

2-26C Someone claims that the absolute pressure in a liquid of constant density doubles when the depth is doubled. Do you agree? Explain.

No, the absolute pressure in a liquid of constant density does not double when the depth is doubled. It is the *gage pressure* that doubles when the depth is doubled.

2-27C Consider two identical fans, one at sea level and the other on top of a high mountain, running at identical speeds. How would you compare (*a*) the volume flow rates and (*b*) the mass flow rates of these two fans?

The density of air at sea level is higher than the density of air on top of a high mountain. Therefore, the volume flow rates of the two fans running at identical speeds will be the same, but the mass flow rate of the fan at sea level will be higher.

2-28E The absolute pressure in a compressed air tank is 200 kPa. What is this pressure in psia?

The pressure given in kPa unit is to be converted to psia.

Analysis Using the kPa to psia units conversion factor,

$$P = (200\text{ kPa})\left(\frac{1\text{ psia}}{6.895\text{ kPa}}\right) = \mathbf{29.0\ psia}$$

EES SOLUTION

"Given"
P_kPa=200 [kPa]

"Analysis"
P_psia=P_kPa/(6.895 [kPa/psia])

2-29E A manometer measures a pressure difference as 40 inches of water. What is this pressure difference in pound-force per square inch, psi?

A manometer measures a pressure difference as inches of water. This is to be expressed in psia unit.

Properties The density of water is taken to be 62.4 lbm/ft^3 (Table A-3E).

Analysis Applying the hydrostatic equation,

$$\Delta P = \rho g h$$

$$= (62.4\text{ lbm/ft}^3)(32.174\text{ ft/s}^2)(40/12\text{ ft})\left(\frac{1\text{ lbf}}{32.174\text{ lbm}\cdot\text{ft/s}^2}\right)\left(\frac{1\text{ ft}^2}{144\text{ in}^2}\right)$$

$$= 1.44\text{ lbf/in}^2 = \mathbf{1.44\ psia}$$

EES SOLUTION

"Given"
h_in=40 [in] "or 40 inWater"

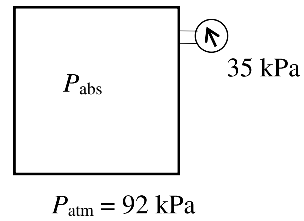
"Analysis"
g=32.174 [ft/s^2] "acceleration of gravity"
rho_w=62.4 [lbm/ft^3]
h=h_in*Convert(in, ft)
DELTAP=rho_w*g*h*Convert(lbm/ft-s^2, psia)

2-30 A vacuum gage connected to a chamber reads 35 kPa at a location where the atmospheric pressure is 92 kPa. Determine the absolute pressure in the chamber.

The pressure in a vacuum chamber is measured by a vacuum gage. The absolute pressure in the chamber is to be determined.

Analysis The absolute pressure in the chamber is determined from

$$P_{abs} = P_{atm} - P_{vac} = 92 - 35 = \mathbf{57\ kPa}$$



EES SOLUTION

"Given"
P_vac=35 [kPa]
P_atm=92 [kPa]

"Analysis"
P_abs=P_atm-P_vac

2-31E The maximum safe air pressure of a tire is typically written on the tire itself. The label on a tire indicates that the maximum pressure is 35 psi (gage). Express this maximum pressure in kPa.

FIGURE P2–31E

The maximum pressure of a tire is given in English units. It is to be converted to SI units.

Assumptions The listed pressure is gage pressure.

Analysis Noting that 1 atm = 101.3 kPa = 14.7 psi, the listed maximum pressure can be expressed in SI units as

$$P_{max} = 35\text{ psi} = (35\text{ psi})\left(\frac{101.3\text{ kPa}}{14.7\text{ psi}}\right) = \mathbf{241\ kPa}$$

Discussion We could also solve this problem by using the conversion factor 1 psi = 6.895 kPa.

EES SOLUTION

"Given"
P_psia=35 [psia]

"Analysis"
P_kPa=P_psia*(101.3 [kPa])/(14.7 [psia])

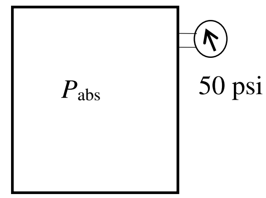
2-32E A pressure gage connected to a tank reads 50 psi at a location where the barometric reading is 29.1 in Hg. Determine the absolute pressure in the tank. Take ρ_{Hg} = 848.4 lbm/ft^3.

A pressure gage connected to a tank reads 50 psi. The absolute pressure in the tank is to be determined.

Properties The density of mercury is given to be ρ = 848.4 lbm/ft^3.

Analysis The atmospheric (or barometric) pressure can be expressed as

$$\begin{aligned} P_{atm} &= \rho g h \\ &= (848.4 \text{ lbm/ft}^3)(32.2 \text{ ft/s}^2)(29.1/12 \text{ ft})\left(\frac{1 \text{ lbf}}{32.2 \text{ lbm}\cdot\text{ft/s}^2}\right)\left(\frac{1 \text{ ft}^2}{144 \text{ in}^2}\right) \\ &= 14.29 \text{ psia} \end{aligned}$$



Then the absolute pressure in the tank is

$$P_{abs} = P_{gage} + P_{atm} = 50 + 14.29 = \mathbf{64.3 \text{ psia}}$$

EES SOLUTION

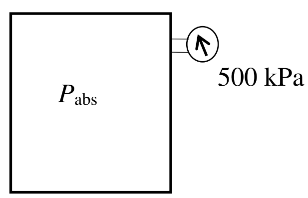
```
"Given"
P_gage=50 [psi]
h_in=29.1 [in] "or 29.1 inHg"
rho_mercury=848.4 [lbm/ft^3]

"Analysis"
g=32.174 [ft/s^2] "acceleration of gravity"
h=h_in*Convert(in, ft)
P_atm=rho_mercury*g*h*Convert(lbm/ft-s^2, psia)
P_abs=P_atm+P_gage
```

2-33 A pressure gage connected to a tank reads 500 kPa at a location where the atmospheric pressure is 94 kPa. Determine the absolute pressure in the tank.

A pressure gage connected to a tank reads 500 kPa. The absolute pressure in the tank is to be determined.

Analysis The absolute pressure in the tank is determined from

$$P_{abs} = P_{gage} + P_{atm} = 500 + 94 = \mathbf{594 \text{ kPa}}$$



P_{atm} = 94 kPa

EES SOLUTION

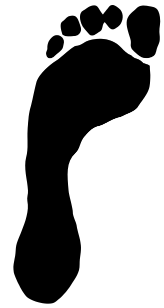
```
"Given"
P_gage=500 [kPa]
P_atm=94 [kPa]

"Analysis"
P_abs=P_atm+P_gage
```

2-34E A 200-pound man has a total foot imprint area of 72 in^2. Determine the pressure this man exerts on the ground if (*a*) he stands on both feet and (*b*) he stands on one foot.

The weight and the foot imprint area of a person are given. The pressures this man exerts on the ground when he stands on one and on both feet are to be determined.

Assumptions The weight of the person is distributed uniformly on foot imprint area.

Analysis The weight of the man is given to be 200 lbf. Noting that pressure is force per unit area, the pressure this man exerts on the ground is



(*a*) On both feet: $P = \dfrac{W}{2A} = \dfrac{200 \text{ lbf}}{2 \times 36 \text{ in}^2} = 2.78 \text{ lbf/in}^2 = \mathbf{2.78 \text{ psi}}$

(*b*) On one foot: $P = \dfrac{W}{A} = \dfrac{200 \text{ lbf}}{36 \text{ in}^2} = 5.56 \text{ lbf/in}^2 = \mathbf{5.56 \text{ psi}}$

Discussion Note that the pressure exerted on the ground (and on the feet) is reduced by half when the person stands on both feet.

EES SOLUTION

```
"Given"
W=200 [lbf]
A=1/2*72 [in^2]

"Analysis"
"(a)"
P_a=W/A*Convert(lbf/in^2, psi)
"(b)"
P_b=W/(2*A)*Convert(lbf/in^2, psi)
```

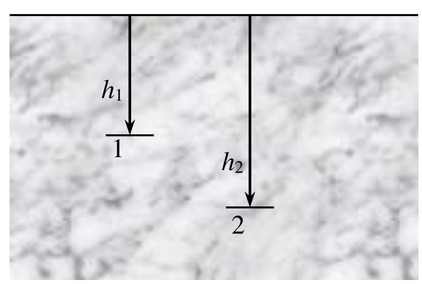

2-35 The gage pressure in a liquid at a depth of 3 m is read to be 42 kPa. Determine the gage pressure in the same liquid at a depth of 9 m.

The gage pressure in a liquid at a certain depth is given. The gage pressure in the same liquid at a different depth is to be determined.

Assumptions The variation of the density of the liquid with depth is negligible.

Analysis The gage pressure at two different depths of a liquid can be expressed as

$$P_1 = \rho g h_1 \quad \text{and} \quad P_2 = \rho g h_2$$



Taking their ratio,

$$\frac{P_2}{P_1} = \frac{\rho g h_2}{\rho g h_1} = \frac{h_2}{h_1}$$

Solving for P_2 and substituting gives

$$P_2 = \frac{h_2}{h_1} P_1 = \frac{9 \text{ m}}{3 \text{ m}}(42 \text{ kPa}) = \mathbf{126 \text{ kPa}}$$

Discussion Note that the gage pressure in a given fluid is proportional to depth.

EES SOLUTION

```
"Given"
h1=3 [m]
P1_gage=42 [kPa]
h2=9 [m]

"Analysis"
P2_gage=(h2/h1)*P1_gage
```

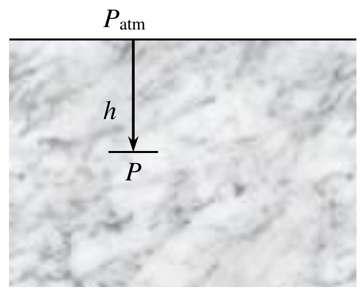
2-36 The absolute pressure in water at a depth of 9 m is read to be 185 kPa. Determine (*a*) the local atmospheric pressure and (*b*) the absolute pressure at a depth of 5 m in a liquid whose specific gravity is 0.85 at the same location.

The absolute pressure in water at a specified depth is given. The local atmospheric pressure and the absolute pressure at the same depth in a different liquid are to be determined.

Assumptions The liquid and water are incompressible.

Properties The specific gravity of the fluid is given to be SG = 0.85. We take the density of water to be 1000 kg/m^3. Then density of the liquid is obtained by multiplying its specific gravity by the density of water,

$$\rho = \text{SG} \times \rho_{H_2O} = (0.85)(1000\ \text{kg/m}^3) = 850\ \ \text{kg/m}^3$$



Analysis (*a*) Knowing the absolute pressure, the atmospheric pressure can be determined from

$$\begin{aligned} P_{atm} &= P - \rho g h \\ &= (185\ \text{kPa}) - (1000\ \text{kg/m}^3)(9.81\ \text{m/s}^2)(9\ \text{m})\left(\frac{1\ \text{kPa}}{1000\ \text{N/m}^2}\right) \\ &= \mathbf{96.7\ \ kPa} \end{aligned}$$

(*b*) The absolute pressure at the same depth in the other liquid is

$$\begin{aligned} P &= P_{atm} + \rho g h \\ &= (96.7\ \text{kPa}) + (850\ \text{kg/m}^3)(9.81\ \text{m/s}^2)(9\ \text{m})\left(\frac{1\ \text{kPa}}{1000\ \text{N/m}^2}\right) \\ &= \mathbf{171.8\ \ kPa} \end{aligned}$$

Discussion Note that at a given depth, the pressure in the lighter fluid is lower, as expected.

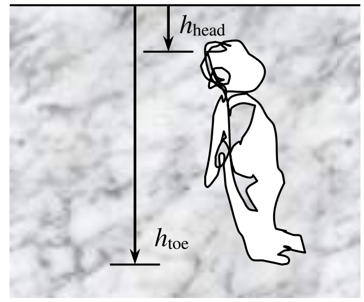
EES SOLUTION

```
"Given"
h=9 [m]
P=185 [kPa]
rho_s=0.85

"Analysis"
rho=rho_s*rho_water
rho_water=1000 [kg/m^3] "taken"
"(a)"
P_atm=P-rho_water*g*h*Convert(kg/m-s^2, kPa)
g=9.81 [m/s^2] "acceleration of gravity"
"(b)"
P_abs=P_atm+rho*g*h*Convert(kg/m-s^2, kPa)
```

2-37 Consider a 1.75-m-tall man standing vertically in water and completely submerged in a pool. Determine the difference between the pressures acting at the head and at the toes of the man, in kPa.

A man is standing in water vertically while being completely submerged. The difference between the pressures acting on the head and on the toes is to be determined.

Assumptions Water is an incompressible substance, and thus the density does not change with depth.



Properties We take the density of water to be $\rho = 1000$ kg/m^3.

Analysis The pressures at the head and toes of the person can be expressed as

$$P_{head} = P_{atm} + \rho g h_{head} \quad \text{and} \quad P_{toe} = P_{atm} + \rho g h_{toe}$$

where h is the vertical distance of the location in water from the free surface. The pressure difference between the toes and the head is determined by subtracting the first relation above from the second,

$$P_{toe} - P_{head} = \rho g h_{toe} - \rho g h_{head} = \rho g (h_{toe} - h_{head})$$

Substituting,

$$P_{toe} - P_{head} = (1000 \text{ kg/m}^3)(9.81 \text{ m/s}^2)(1.75 \text{ m} - 0)\left(\frac{1 \text{ N}}{1 \text{ kg}\cdot\text{m/s}^2}\right)\left(\frac{1 \text{ kPa}}{1000 \text{ N/m}^2}\right) = \mathbf{17.2\,kPa}$$

Discussion This problem can also be solved by noting that the atmospheric pressure (1 atm = 101.325 kPa) is equivalent to 10.3-m of water height, and finding the pressure that corresponds to a water height of 1.75 m.

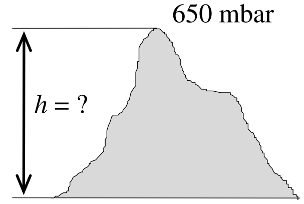
EES SOLUTION

```
"Given"
h=1.75 [m]

"Analysis"
g=9.81 [m/s^2]
DELTAP=rho_water*g*h*Convert(kg/m-s^2, kPa)
rho_water=1000 [kg/m^3] "taken"
```

2-38 The barometer of a mountain hiker reads 750 mbars at the beginning of a hiking trip and 650 mbars at the end. Neglecting the effect of altitude on local gravitational acceleration, determine the vertical distance climbed. Assume an average air density of 1.20 kg/m^3.

A mountain hiker records the barometric reading before and after a hiking trip. The vertical distance climbed is to be determined.

Assumptions The variation of air density and the gravitational acceleration with altitude is negligible.



Properties The density of air is given to be ρ = 1.20 kg/m^3.

Analysis Taking an air column between the top and the bottom of the mountain and writing a force balance per unit base area, we obtain

$$W_{air} / A = P_{bottom} - P_{top}$$

$$(\rho gh)_{air} = P_{bottom} - P_{top}$$

$$(1.20 \text{ kg/m}^3)(9.81 \text{ m/s}^2)(h)\left(\frac{1 \text{ N}}{1 \text{ kg}\cdot\text{m/s}^2}\right)\left(\frac{1 \text{ bar}}{100{,}000 \text{ N/m}^2}\right) = (0.750 - 0.650) \text{ bar}$$

It yields

h = **850 m**

which is also the distance climbed.

EES SOLUTION

```
"Given"
P_bottom=0.750 [bar]
P_top=0.650 [bar]
rho=1.2 [kg/m^3]

"Analysis"
rho*g*h*Convert(kg/m-s^2, bar)=(P_bottom-P_top)
g=9.81 [m/s^2]
```

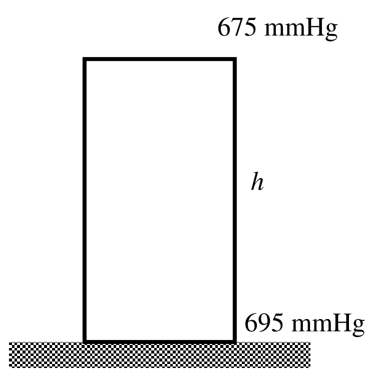
2-39 The basic barometer can be used to measure the height of a building. If the barometric readings at the top and at the bottom of a building are 675 and 695 mmHg, respectively, determine the height of the building. Take the densities of air and mercury to be 1.18 kg/m^3 and 13,600 kg/m^3, respectively.

FIGURE P2–39
©*McGraw-Hill Education*

A barometer is used to measure the height of a building by recording reading at the bottom and at the top of the building. The height of the building is to be determined.

Assumptions The variation of air density with altitude is negligible.

Properties The density of air is given to be $\rho = 1.18$ kg/m^3. The density of mercury is 13,600 kg/m^3.



Analysis Atmospheric pressures at the top and at the bottom of the building are

$$\begin{aligned} P_{\text{top}} &= (\rho g h)_{\text{top}} \\ &= (13{,}600\ \text{kg/m}^3)(9.81\ \text{m/s}^2)(0.675\ \text{m})\left(\frac{1\ \text{N}}{1\ \text{kg}\cdot\text{m/s}^2}\right)\left(\frac{1\ \text{kPa}}{1000\ \text{N/m}^2}\right) \\ &= 90.06\ \text{kPa} \end{aligned}$$

$$\begin{aligned} P_{\text{bottom}} &= (\rho g h)_{\text{bottom}} \\ &= (13{,}600\ \text{kg/m}^3)(9.81\ \text{m/s}^2)(0.695\ \text{m})\left(\frac{1\ \text{N}}{1\ \text{kg}\cdot\text{m/s}^2}\right)\left(\frac{1\ \text{kPa}}{1000\ \text{N/m}^2}\right) \\ &= 92.72\ \text{kPa} \end{aligned}$$

Taking an air column between the top and the bottom of the building and writing a force balance per unit base area, we obtain

$$W_{air} / A = P_{bottom} - P_{top}$$
$$(\rho gh)_{air} = P_{bottom} - P_{top}$$
$$(1.18\text{ kg/m}^3)(9.81\text{ m/s}^2)(h)\left(\frac{1\text{ N}}{1\text{ kg}\cdot\text{m/s}^2}\right)\left(\frac{1\text{ kPa}}{1000\text{ N/m}^2}\right) = (92.72 - 90.06)\text{ kPa}$$

It yields

h = **231 m**

which is also the height of the building.

EES SOLUTION

```
"Given"
h_top=0.675 [m] "or 675 mmHg"
h_bottom=0.695 [m] "or 695 mmHg"
rho_air=1.18 [kg/m^3]
rho_mercury=13600 [kg/m^3]

"Analysis"
g=9.81 [m/s^2]
P_top=rho_mercury*g*h_top*Convert(kg/m-s^2, kPa)
P_bottom=rho_mercury*g*h_bottom*Convert(kg/m-s^2, kPa)
(P_bottom-P_top)=rho_air*g*h*Convert(kg/m-s^2, kPa)
```

2-40 Solve Prob. 2–39 using appropriate software. Print out the entire solution, including the numerical results with proper units.

Problem 2-39 is reconsidered. The entire software solution is to be printed out, including the numerical results with proper units.

Analysis The problem is solved using EES, and the solution is given below.

```
P_bottom=695 [mmHg]
P_top=675 [mmHg]
g=9.81 [m/s^2]
rho=1.18  [kg/m^3]
DELTAP_abs=(P_bottom-P_top)*CONVERT(mmHg, kPa) "Delta P reading from the barometers, converted from mmHg to kPa"
DELTAP_h=rho*g*h*Convert(Pa, kPa) "Delta P due to the air fluid column height, h, between the top and bottom of the building"
DELTAP_abs=DELTAP_h
DELTAP_abs=2.666 [kPa]
DELTAP_h=2.666 [kPa]
g=9.81 [m/s^2]
h=230.3 [m]
P_bottom=695 [mmHg]
P_top=675 [mmHg]
rho=1.18 [kg/m^3]
```

2-41 A gas is contained in a vertical, frictionless piston–cylinder device. The piston has a mass of 3.2 kg and a cross-sectional area of 35 cm^2. A compressed spring above the piston exerts a force of 150 N on the piston. If the atmospheric pressure is 95 kPa, determine the pressure inside the cylinder.

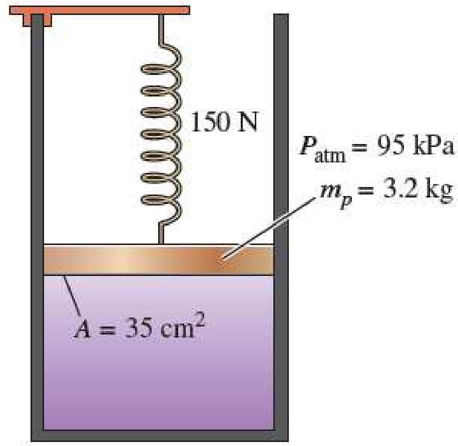


FIGURE P2–41

A gas contained in a vertical piston-cylinder device is pressurized by a spring and by the weight of the piston. The pressure of the gas is to be determined.

Analysis Drawing the free body diagram of the piston and balancing the vertical forces yield

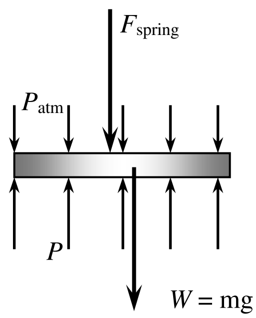
$$PA = P_{atm}A + W + F_{spring}$$

Thus,

$$P = P_{atm} + \frac{mg + F_{spring}}{A}$$

$$= (95\text{ kPa}) + \frac{(3.2\text{ kg})(9.81\text{ m/s}^2) + 150\text{ N}}{35 \times 10^{-4}\text{m}^2}\left(\frac{1\text{ kPa}}{1000\text{ N/m}^2}\right)$$

$$= \mathbf{147\ kPa}$$



EES SOLUTION

```
"Given"
m_piston=3.2 [kg]
A=35E-4 [m^2]
F_spring=150 [N]
P_atm=95 [kPa]

"Analysis"
g=9.807 [m/s^2]
W=m_piston*g
P*A=P_atm*A+(W+F_spring)*Convert(N/m^2, kPa) "force balance on the piston"
```

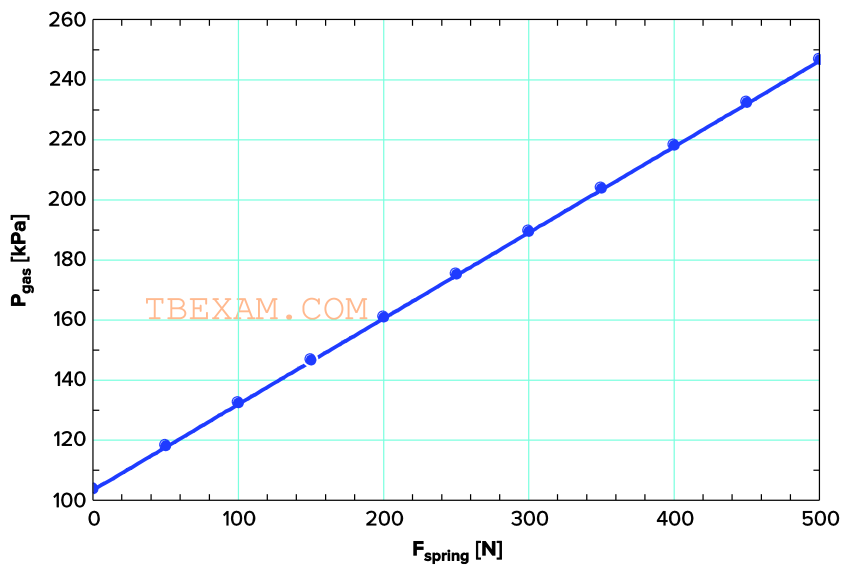
2-42 Reconsider Prob. 2–41. Using appropriate software, investigate the effect of the spring force in the range of 0 to 500 N on the pressure inside the cylinder. Plot the pressure against the spring force, and discuss the results.

Problem 2-41 is reconsidered. The effect of the spring force in the range of 0 to 500 N on the pressure inside the cylinder is to be investigated. The pressure against the spring force is to be plotted, and results are to be discussed.

Analysis The problem is solved using EES, and the solution is given below.

```
P_atm= 95 [kPa]
m_piston=3.2 [kg]
F_spring=150 [N]
A=35*CONVERT(cm^2, m^2)
g=9.81 [m/s^2]
W_piston=m_piston*g
F_atm=P_atm*A*CONVERT(kPa, N/m^2)
"From the free body diagram of the piston, the balancing vertical forces yield"
F_gas= F_atm+F_spring+W_piston
P_gas=F_gas/A*CONVERT(N/m^2, kPa)
```

F_{spring} [N]	P_{gas} [kPa]
0	104
50	118.3
100	132.5
150	146.8
200	161.1
250	175.4
300	189.7
350	204
400	218.3
450	232.5
500	246.8



2-43 The piston of a vertical piston–cylinder device containing a gas has a mass of 60 kg and a cross-sectional area of 0.04 m^2, as shown in Fig. P2–43. The local atmospheric pressure is 0.97 bar, and the gravitational acceleration is 9.81 m/s^2. (*a*) Determine the pressure inside the cylinder. (*b*) If some heat is transferred to the gas and its volume is doubled, do you expect the pressure inside the cylinder to change?

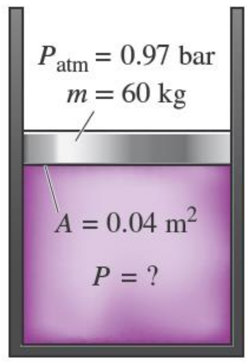


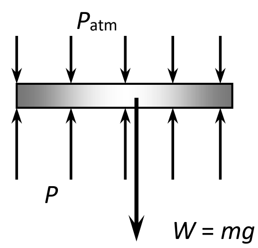
FIGURE P2–43

A gas is contained in a vertical cylinder with a heavy piston. The pressure inside the cylinder and the effect of volume change on pressure are to be determined.

Assumptions Friction between the piston and the cylinder is negligible.

Analysis (*a*) The gas pressure in the piston–cylinder device depends on the atmospheric pressure and the weight of the piston. Drawing the free-body diagram of the piston and balancing the vertical forces yield

$$PA = P_{atm}A + W$$



Thus,

$$\begin{aligned} P &= P_{atm} + \frac{mg}{A} \\ &= 0.97 \text{ bar} + \frac{(60 \text{ kg})(9.81 \text{ m/s}^2)}{0.04 \text{ m}^2}\left(\frac{1 \text{ N}}{1 \text{ kg}\cdot\text{m/s}^2}\right)\left(\frac{1 \text{ bar}}{10^5 \text{ N/m}^2}\right) \\ &= \mathbf{1.12\ bar} \end{aligned}$$

(*b*) The volume change will have no effect on the free-body diagram drawn inpart (a), and therefore the pressure inside the cylinder will remain the same.

Discussion If the gas behaves as an ideal gas, the absolute temperature doubles when the volume is doubled at constant pressure.

EES SOLUTION

```
"Given"
m_piston=60 [kg]
A=0.04 [m^2]
P_atm=97 [kPa]
g=9.81 [m/s^2]

"Analysis"
W=m_piston*g
P*A=P_atm*A+W*Convert(N/m^2, kPa) "force balance on the piston"
```

2-44 Both a gage and a manometer are attached to a gas tank to measure its pressure. If the reading on the pressure gage is 80 kPa, determine the distance between the two fluid levels of the manometer if the fluid is (*a*) mercury (ρ = 13,600 kg/m^3) or (*b*) water (ρ = 1000 kg/m^3).

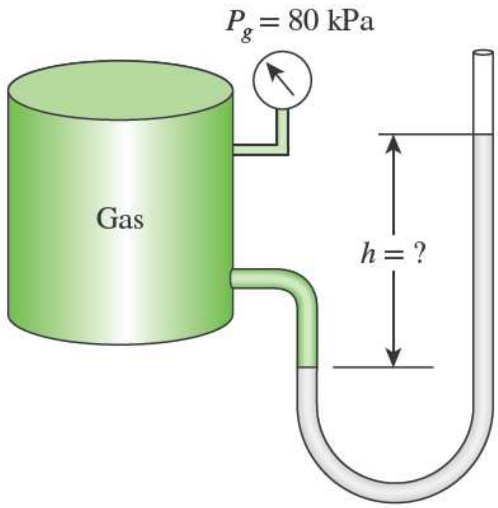
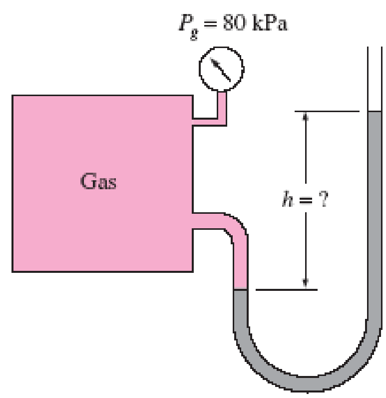


FIGURE P2–44

Both a gage and a manometer are attached to a gas to measure its pressure. For a specified reading of gage pressure, the difference between the fluid levels of the two arms of the manometer is to be determined for mercury and water.

Properties The densities of water and mercury are given to be ρ_{water} = 1000 kg/m^3 and be ρ_{Hg} = 13,600 kg/m^3.



Analysis The gage pressure is related to the vertical distance h between the two fluid levels by

$$P_{gage} = \rho g h \longrightarrow h = \frac{P_{gage}}{\rho g}$$

(*a*) For mercury,

$$h = \frac{P_{gage}}{\rho_{Hg} g} = \frac{80 \text{ kPa}}{(13{,}600 \text{ kg/m}^3)(9.81 \text{ m/s}^2)}\left(\frac{1 \text{ kN/m}^2}{1 \text{ kPa}}\right)\left(\frac{1000 \text{ kg/m}\cdot\text{s}^2}{1 \text{ kN}}\right) = \mathbf{0.60 \text{ m}}$$

(*b*) For water,

$$h = \frac{P_{gage}}{\rho_{H_2O} g} = \frac{80 \text{ kPa}}{(1000 \text{ kg/m}^3)(9.81 \text{ m/s}^2)}\left(\frac{1 \text{ kN/m}^2}{1 \text{ kPa}}\right)\left(\frac{1000 \text{ kg/m}\cdot\text{s}^2}{1 \text{ kN}}\right) = \mathbf{8.16 \text{ m}}$$

EES SOLUTION

```
Fluid$='Mercury'
P_atm = 101.325 [kPa]
DELTAP=80 [kPa] "Note how DELTAP is displayed on the Formatted Equations Window."

g=9.807 [m/s^2] "local acceleration of gravity at sea level"
rho=Fluid_density(Fluid$)"Get the fluid density, either Hg or H2O, from the function."

DELTAP = rho*g*h*CONVERT(Pa, kPa) "force balance"
"Instead of multiplying by CONVERT('Pa','kPa') we could have divided by 1000 but then the Check Units option would not work on this equation since the constant 1000 does not have units. "
```

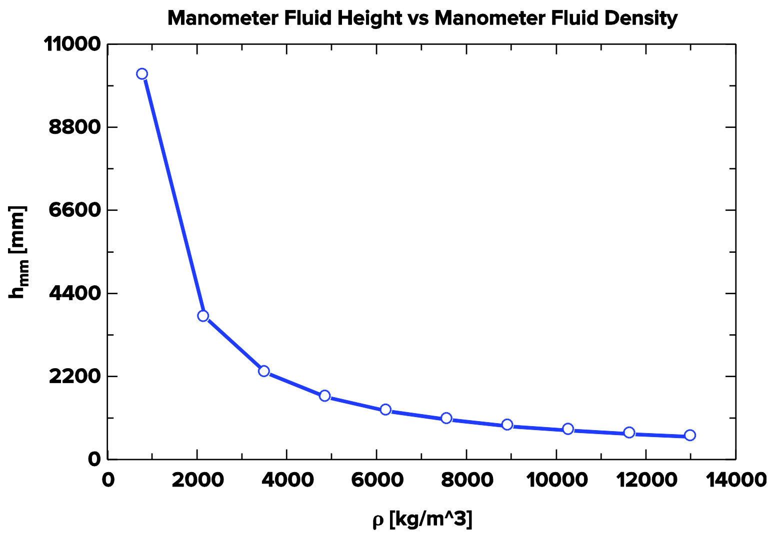
2-45 Reconsider Prob. 2–44. Using appropriate software, investigate the effect of the manometer fluid density in the range of 800 to 13,000 kg/m^3 on the differential fluid height of the manometer. Plot the differential fluid height against the density, and discuss the results.

Problem 2-44 is reconsidered. The effect of the manometer fluid density in the range of 800 to 13,000 kg/m^3 on the differential fluid height of the manometer is to be investigated. Differential fluid height against the density is to be plotted, and the results are to be discussed.

Analysis The problem is solved using EES, and the solution is given below.

```
"Let's modify this problem to also calculate the absolute pressure in the tank by supplying the atmospheric
pressure."

Function fluid_density(Fluid$)
"This function is needed since if-then-else logic can only be used in functions or procedures.
The underscore displays whatever follows as subscripts in the Formatted Equations Window."
    If fluid$='Mercury' then  fluid_density=13600 else fluid_density=1000
end

Fluid$='Mercury'
P_atm = 101.325 [kPa]
DELTAP=80 [kPa] "Note how DELTAP is displayed on the Formatted Equations Window."
g=9.807 [m/s^2] "local acceleration of gravity at sea level"
rho=Fluid_density(Fluid$)   "Get the fluid density, either Hg or H2O, from the function"
DELTAP = RHO*g*h/1000 "Instead of dividiing by 1000 Pa/kPa we could have multiplied by the EES function,
CONVERT(Pa,kPa)"
h_mm=h*convert(m, mm) "The fluid height in mm is found using the built-in CONVERT function."
P_abs= P_atm + DELTAP
```


ρ [kg/m^3]	h_{mm} [mm]
800	10197
2156	3784
3511	2323
4867	1676
6222	1311
7578	1076
8933	913.1
10289	792.8
11644	700.5
13000	627.5



2-46 A manometer containing oil ($\rho = 850$ kg/m^3) is attached to a tank filled with air. If the oil-level difference between the two columns is 80 cm and the atmospheric pressure is 98 kPa, determine the absolute pressure of the air in the tank.

The air pressure in a tank is measured by an oil manometer. For a given oil-level difference between the two columns, the absolute pressure in the tank is to be determined.

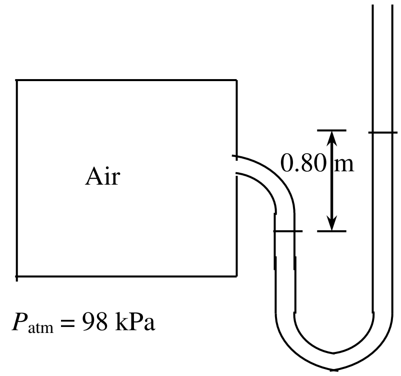
Properties The density of oil is given to be $\rho = 850$ kg/m^3.

Analysis The absolute pressure in the tank is determined from

$$P = P_{atm} + \rho gh$$

$$= (98 \text{ kPa}) + (850 \text{ kg/m}^3)(9.81 \text{ m/s}^2)(0.80 \text{ m})\left(\frac{1 \text{ kPa}}{1000 \text{ N/m}^2}\right)$$

$$= \mathbf{104.7\ kPa}$$



EES SOLUTION

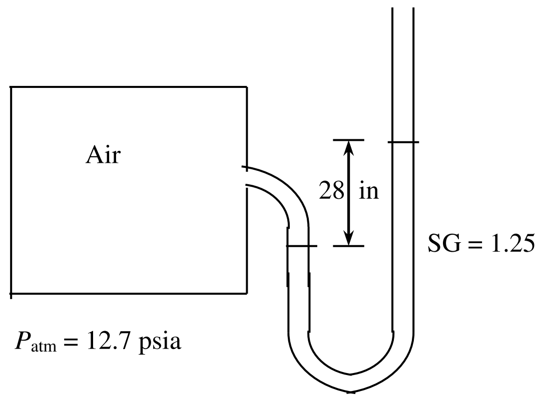
```
"Given"
h=0.80 [m]
P_atm=98 [kPa]
rho_oil=850 [kg/m^3]

"Analysis"
g=9.81 [m/s^2]
P=P_atm+rho_oil*g*h*Convert(kg/m-s^2, kPa)
```

2-47E A manometer is used to measure the air pressure in a tank. The fluid used has a specific gravity of 1.25, and the differential height between the two arms of the manometer is 28 in. If the local atmospheric pressure is 12.7 psia, determine the absolute pressure in the tank for the cases of the manometer arm with the (*a*) higher and (*b*) lower fluid level being attached to the tank.

The pressure in a tank is measured with a manometer by measuring the differential height of the manometer fluid. The absolute pressure in the tank is to be determined for the cases of the manometer arm with the higher and lower fluid level being attached to the tank.

Assumptions The fluid in the manometer is incompressible.

Properties The specific gravity of the fluid is given to be SG = 1.25. The density of water at 32°F is 62.4 lbm/ft^3 (Table A-3E)



Analysis The density of the fluid is obtained by multiplying its specific gravity by the density of water,

$$\rho = \mathrm{SG} \times \rho_{\mathrm{H_2O}} = (1.25)(62.4\ \mathrm{lbm/ft^3}) = 78.0\ \mathrm{lbm/ft^3}$$

The pressure difference corresponding to a differential height of 28 in between the two arms of the manometer is

$$\Delta P = \rho g h = (78\ \mathrm{lbm/ft^3})(32.174\ \mathrm{ft/s^2})(28/12\ \mathrm{ft})\left(\frac{1\ \mathrm{lbf}}{32.174\ \mathrm{lbm \cdot ft/s^2}}\right)\left(\frac{1\ \mathrm{ft^2}}{144\ \mathrm{in^2}}\right) = 1.26\ \mathrm{psia}$$

Then the absolute pressures in the tank for the two cases become:

(*a*) The fluid level in the arm attached to the tank is higher (vacuum):

$$P_{abs} = P_{atm} - P_{vac} = 12.7 - 1.26 = \mathbf{11.44\ psia}$$

(*b*) The fluid level in the arm attached to the tank is lower:

$$P_{abs} = P_{gage} + P_{atm} = 12.7 + 1.26 = \mathbf{13.96\ psia}$$

Discussion Note that we can determine whether the pressure in a tank is above or below atmospheric pressure by simply observing the side of the manometer arm with the higher fluid level.

EES SOLUTION

```
"Given"
rho_s=1.25
h=28[in]*Convert(in, ft)
P_atm=12.7 [psia]

"Properties"
rho_water=density(water, T=80, P=14.7)
g=32.174 [ft/s^2]  "acceleration of gravity"

"Analysis"
rho=rho_s*rho_water
DELTAP=rho*g*h*Convert(lbm/ft-s^2, psia)
"(a)"
P_abs_a=P_atm-DELTAP
"(b)"
P_abs_b=P_atm+DELTAP
```

2-48 A mercury manometer (ρ = 13,600 kg/m^3) is connected to an air duct to measure the pressure inside. The difference in the manometer levels is 30 mm, and the atmospheric pressure is 100 kPa. (*a*) Judging from Fig. P2–48, determine if the pressure in the duct is above or below the atmospheric pressure. (*b*) Determine the absolute pressure in the duct.

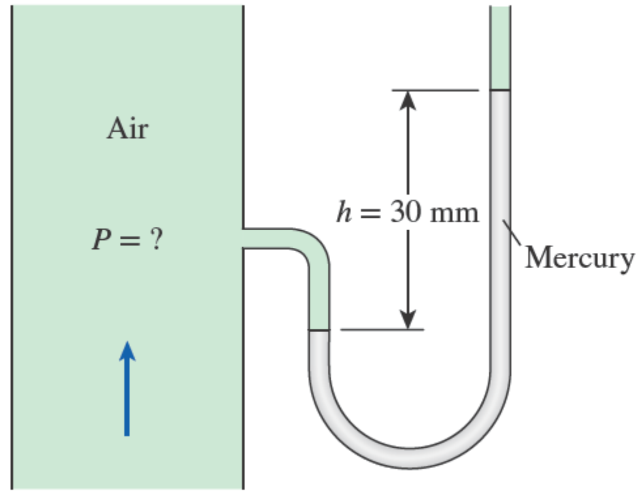
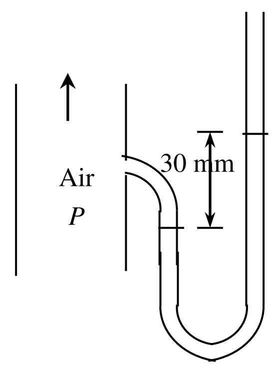


FIGURE P2–48

The air pressure in a duct is measured by a mercury manometer. For a given mercury-level difference between the two columns, the absolute pressure in the duct is to be determined.



Properties The density of mercury is given to be ρ = 13,600 kg/m^3.

Analysis (*a*) The pressure in the duct is above atmospheric pressure since the fluid column on the duct side is at a lower level.

(*b*) The absolute pressure in the duct is determined from

$$
\begin{aligned}
P &= P_{\text{atm}} + \rho gh \\
&= (100\text{ kPa}) + (13{,}600\text{ kg/m}^3)(9.81\text{ m/s}^2)(0.030\text{ m})\left(\frac{1\text{ N}}{1\text{ kg}\cdot\text{m/s}^2}\right)\left(\frac{1\text{ kPa}}{1000\text{ N/m}^2}\right) \\
&= \mathbf{104\ kPa}
\end{aligned}
$$

EES SOLUTION

```
"Given"
h=0.030 [m]
P_atm=100 [kPa]
rho_mercury=13600 [kg/m^3]

"Analysis"
g=9.81 [m/s^2]
"(a)"
"above the P_atm since the fluid column is at a lower level"
"(b)"
P=P_atm+rho_mercury*g*h*Convert(kg/m-s^2, kPa)
```

2-49 Repeat Prob. 2–48 for a differential mercury height of 45 mm.

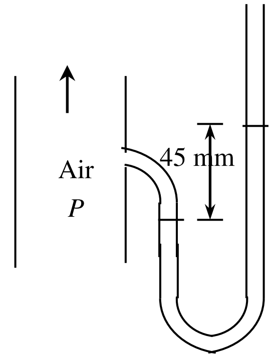
The air pressure in a duct is measured by a mercury manometer. For a given mercury-level difference between the two columns, the absolute pressure in the duct is to be determined.

Properties The density of mercury is given to be $\rho = 13{,}600$ kg/m^3.

Analysis (*a*) The pressure in the duct is above atmospheric pressure since the fluid column on the duct side is at a lower level.

(*b*) The absolute pressure in the duct is determined from

$$\begin{aligned} P &= P_{atm} + \rho gh \\ &= (100 \text{ kPa}) + (13{,}600 \text{ kg/m}^3)(9.81 \text{ m/s}^2)(0.045 \text{ m})\left(\frac{1 \text{ N}}{1 \text{ kg}\cdot\text{m/s}^2}\right)\left(\frac{1 \text{ kPa}}{1000 \text{ N/m}^2}\right) \\ &= \mathbf{106 \text{ kPa}} \end{aligned}$$



EES SOLUTION

```
"Given"
h=0.045 [m]
P_atm=100 [kPa]
rho_mercury=13600 [kg/m^3]"given"

"Analysis"
g=9.81 [m/s^2]
"(a)"
"above the P_atm since the fluid column is at a lower level"
"(b)"
P=P_atm+rho_mercury*g*h*Convert(kg/m-s^2, kPa)
```

2-50E The pressure in a natural gas pipeline is measured by the manometer shown in Fig. P2–50E with one of the arms open to the atmosphere where the local atmospheric pressure is 14.2 psia. Determine the absolute pressure in the pipeline.

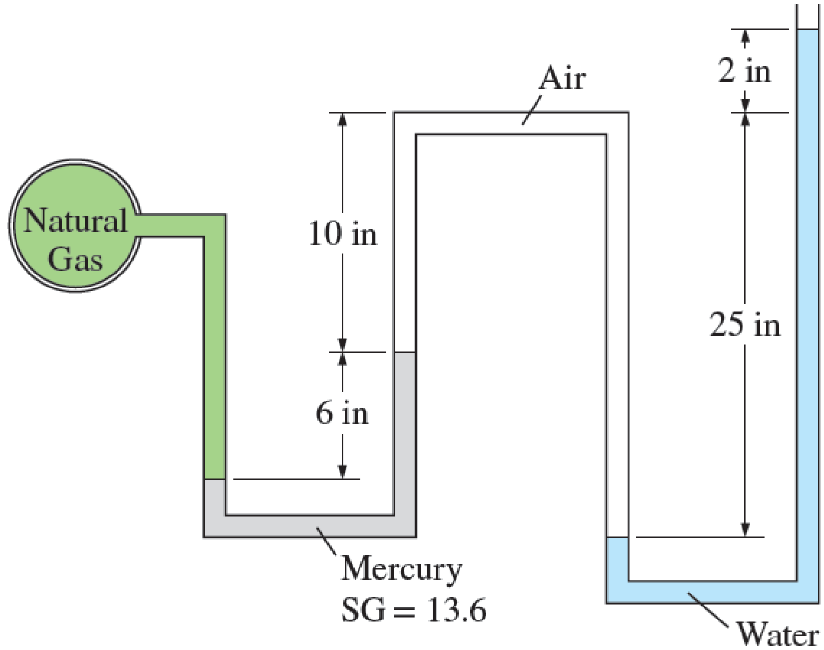
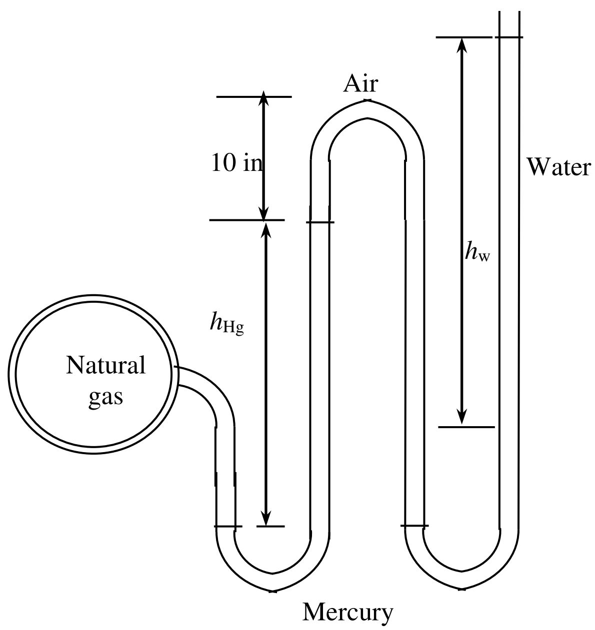


FIGURE P2–50E

The pressure in a natural gas pipeline is measured by a double U-tube manometer with one of the arms open to the atmosphere. The absolute pressure in the pipeline is to be determined.

Assumptions **1** All the liquids are incompressible. **2** The effect of air column on pressure is negligible. **3** The pressure throughout the natural gas (including the tube) is uniform since its density is low.

Properties We take the density of water to be $\rho_w = 62.4$ lbm/ft^3. The specific gravity of mercury is given to be 13.6, and thus its density is $\rho_{Hg} = 13.6 \times 62.4 = 848.6$ lbm/ft^3.



Analysis Starting with the pressure at point 1 in the natural gas pipeline, and moving along the tube by adding (as we go down) or subtracting (as we go up) the ρgh terms until we reach the free surface of oil where the oil tube is exposed to the atmosphere, and setting the result equal to P_{atm} gives

$$P_1 - \rho_{\text{Hg}} g h_{\text{Hg}} - \rho_{\text{water}} g h_{\text{water}} = P_{atm}$$

Solving for P_1,

$$P_1 = P_{\text{atm}} + \rho_{\text{Hg}} g h_{\text{Hg}} + \rho_{\text{water}} g h_1$$

Substituting,

$$P = 14.2\text{ psia} + (32.2\text{ ft/s}^2)[(848.6\text{ lbm/ft}^3)(6/12\text{ ft}) + (62.4\text{ lbm/ft}^3)(27/12\text{ ft})]\left(\frac{1\text{ lbf}}{32.2\text{ lbm}\cdot\text{ft/s}^2}\right)\left(\frac{1\text{ ft}^2}{144\text{ in}^2}\right)$$
$$= \mathbf{18.1\ psia}$$

Discussion Note that jumping horizontally from one tube to the next and realizing that pressure remains the same in the same fluid simplifies the analysis greatly. Also, it can be shown that the 15-in high air column with a density of 0.075 lbm/ft^3 corresponds to a pressure difference of 0.00065 psi. Therefore, its effect on the pressure difference between the two pipes is negligible.

EES SOLUTION

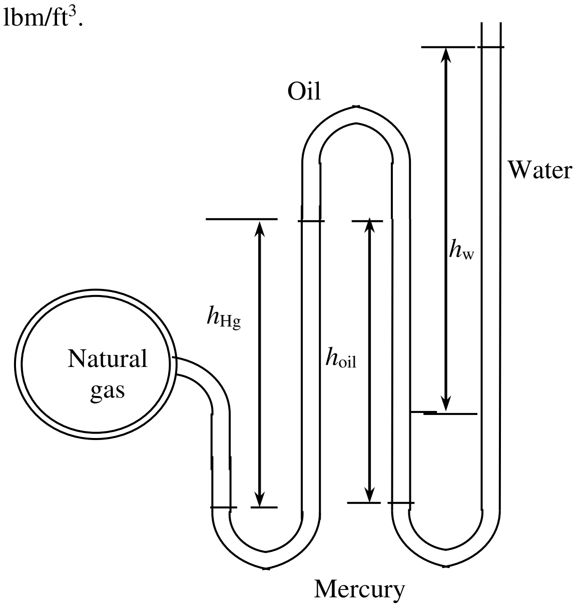
```
"Given"
P_atm=14.2 [psia]
h_Hg=6[in]*Convert(in,ft)
h_w=27[in]*Convert(in,ft)
rho_s=13.6

"Analysis"
P=P_atm+g*(rho_Hg*h_Hg+rho_w*h_w)*Convert(lbm/ft-s^2, psia)
rho_w=62.4 [lbm/ft^3] "taken"
rho_Hg=rho_s*rho_w
g=32.174 [ft/s^2]
```

2-51E Repeat Prob. 2–50E by replacing air with oil with a specific gravity of 0.69.

The pressure in a natural gas pipeline is measured by a double U-tube manometer with one of the arms open to the atmosphere. The absolute pressure in the pipeline is to be determined.

Assumptions **1** All the liquids are incompressible. **2** The pressure throughout the natural gas (including the tube) is uniform since its density is low.

Properties We take the density of water to be $\rho_w = 62.4 \text{ lbm/ft}^3$. The specific gravity of mercury is given to be 13.6, and thus its density is $\rho_{Hg} = 13.6 \times 62.4 = 848.6 \text{ lbm/ft}^3$. The specific gravity of oil is given to be 0.69, and thus its density is $\rho_{oil} = 0.69 \times 62.4 = 43.1 \text{ lbm/ft}^3$.



Analysis Starting with the pressure at point 1 in the natural gas pipeline, and moving along the tube by adding (as we go down) or subtracting (as we go up) the ρgh terms until we reach the free surface of oil where the oil tube is exposed to the atmosphere, and setting the result equal to P_{atm} gives

$$P_1 - \rho_{Hg} g h_{Hg} + \rho_{oil} g h_{oil} - \rho_{water} g h_{water} = P_{atm}$$

Solving for P_1,

$$P_1 = P_{atm} + \rho_{Hg} g h_{Hg} + \rho_{water} g h_1 - \rho_{oil} g h_{oil}$$

Substituting,

$$P_1 = 14.2 \text{ psia} + (32.2 \text{ ft/s}^2)[(848.6 \text{ lbm/ft}^3)(6/12 \text{ ft}) + (62.4 \text{ lbm/ft}^3)(27/12 \text{ ft})$$

$$- (43.1 \text{ lbm/ft}^3)(15/12 \text{ ft})]\left(\frac{1 \text{ lbf}}{32.2 \text{ lbm} \cdot \text{ft/s}^2}\right)\left(\frac{1 \text{ ft}^2}{144 \text{ in}^2}\right)$$

$$= \mathbf{17.7 \text{ psia}}$$

Discussion Note that jumping horizontally from one tube to the next and realizing that pressure remains the same in the same fluid simplifies the analysis greatly.

EES SOLUTION

```
"Given"
P_atm=14.2 [psia]
h_Hg=6/12 "[ft]"
h_w=27/12 "[ft]"
h_oil=15/12 "[ft]"
rho_s=13.6
rho_s_oil=0.69
"Analysis"
P=P_atm+g*(rho_Hg*h_Hg+rho_w*h_w-rho_oil*h_oil)*Convert(lbm/ft-s^2, psia)
rho_w=62.4 [lbm/ft^3] "taken"
rho_Hg=rho_s*rho_w
rho_oil=rho_s_oil*rho_w
g=32.174 [ft/s^2]
```

2-52E Blood pressure is usually measured by wrapping a closed air-filled jacket equipped with a pressure gage around the upper arm of a person at the level of the heart. Using a mercury manometer and a stethoscope, the systolic pressure (the maximum pressure when the heart is pumping) and the diastolic pressure (the minimum pressure when the heart is resting) are measured in mmHg. The systolic and diastolic pressures of a healthy person are about 120 mmHg and 80 mmHg, respectively, and are indicated as 120/80. Express both of these gage pressures in kPa, psi, and meter water column

The systolic and diastolic pressures of a healthy person are given in mmHg. These pressures are to be expressed in kPa, psi, and meter water column.

Assumptions Both mercury and water are incompressible substances.

Properties We take the densities of water and mercury to be 1000 kg/m^3 and 13,600 kg/m^3, respectively.

Analysis Using the relation $P = \rho gh$ for gage pressure, the high and low pressures are expressed as

$$P_{\text{high}} = \rho gh_{\text{high}} = (13{,}600\ \text{kg/m}^3)(9.81\ \text{m/s}^2)(0.12\ \text{m})\left(\frac{1\ \text{N}}{1\ \text{kg}\cdot\text{m/s}^2}\right)\left(\frac{1\ \text{kPa}}{1000\ \text{N/m}^2}\right) = \mathbf{16.0\ kPa}$$

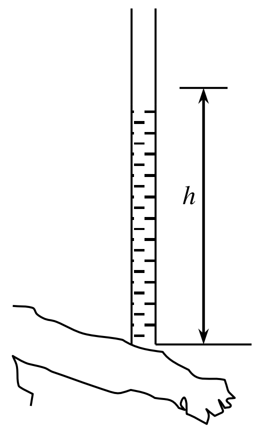
$$P_{\text{low}} = \rho gh_{\text{low}} = (13{,}600\ \text{kg/m}^3)(9.81\ \text{m/s}^2)(0.08\ \text{m})\left(\frac{1\ \text{N}}{1\ \text{kg}\cdot\text{m/s}^2}\right)\left(\frac{1\ \text{kPa}}{1000\ \text{N/m}^2}\right) = \mathbf{10.7\ kPa}$$

Noting that 1 psi = 6.895 kPa,

$$P_{\text{high}} = (16.0\ \text{Pa})\left(\frac{1\ \text{psi}}{6.895\ \text{kPa}}\right) = \mathbf{2.32\ psi}$$

and

$$P_{\text{low}} = (10.7\ \text{Pa})\left(\frac{1\ \text{psi}}{6.895\ \text{kPa}}\right) = \mathbf{1.55\ psi}$$



For a given pressure, the relation $P = \rho gh$ can be expressed for mercury and water as $P = \rho_{\text{water}} gh_{\text{water}}$ and $P = \rho_{\text{mercury}} gh_{\text{mercury}}$. Setting these two relations equal to each other and solving for water height gives

$$P = \rho_{\text{water}} gh_{\text{water}} = \rho_{\text{mercury}} gh_{\text{mercury}} \rightarrow h_{\text{water}} = \frac{\rho_{\text{mercury}}}{\rho_{\text{water}}} h_{\text{mercury}}$$

Therefore,

$$h_{\text{water, high}} = \frac{\rho_{\text{mercury}}}{\rho_{\text{water}}} h_{\text{mercury, high}} = \frac{13{,}600\ \text{kg/m}^3}{1000\ \text{kg/m}^3}(0.12\ \text{m}) = \mathbf{1.63\ m}$$

$$h_{\text{water, low}} = \frac{\rho_{\text{mercury}}}{\rho_{\text{water}}} h_{\text{mercury, low}} = \frac{13{,}600\ \text{kg/m}^3}{1000\ \text{kg/m}^3}(0.08\ \text{m}) = \mathbf{1.09\ m}$$

Discussion Note that measuring blood pressure with a "water" monometer would involve differential fluid heights higher than the person, and thus it is impractical. This problem shows why mercury is a suitable fluid for blood pressure measurement devices.

EES SOLUTION

```
"Given"
h_high=0.120 [m] "or 120 mmHg"
h_low=0.080 [m] "or 80 mmHg"

"Properties"
rho_water=1000 [kg/m^3] "taken"
rho_mercury=13600 [kg/m^3] "taken"
g=9.81 [m/s^2]

"Analysis"
P_high_kPa=rho_mercury*g*h_high*Convert(kg/m-s^2, kPa)
P_low_kPa=rho_mercury*g*h_low*Convert(kg/m-s^2, kPa)
P_high_psia=P_high_kPa*Convert(kPa, psia)
P_low_psia=P_low_kPa*Convert(kPa, psia)
h_water_high=rho_mercury/rho_water*h_high  "from P = rho_water*g*h_water = rho_mercury*g*h_mercury"
h_water_low=rho_mercury/rho_water*h_low
```

2-53 The maximum blood pressure in the upper arm of a healthy person is about 120 mmHg. If a vertical tube open to the atmosphere is connected to the vein in the arm of the person, determine how high the blood will rise in the tube. Take the density of the blood to be 1050 kg/m^3.

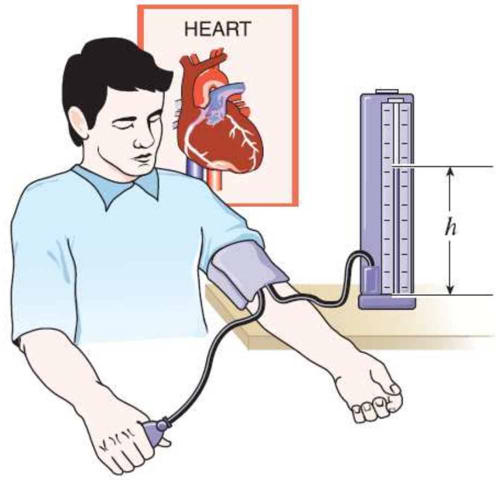


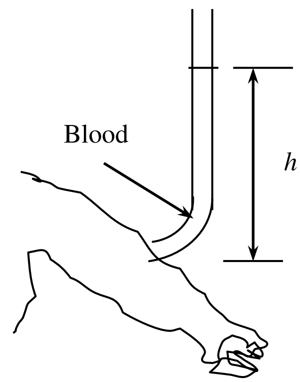
FIGURE P2–53

A vertical tube open to the atmosphere is connected to the vein in the arm of a person. The height that the blood will rise in the tube is to be determined.

Assumptions **1** The density of blood is constant. **2** The gage pressure of blood is 120 mmHg.

Properties The density of blood is given to be $\rho = 1050$ kg/m^3.

Analysis For a given gage pressure, the relation $P = r gh$ can be expressed for mercury and blood as $P = r_{\text{blood}} g h_{\text{blood}}$ and $P = r_{\text{mercury}} g h_{\text{mercury}}$. Setting these two relations equal to each other we get



$$P = r_{\text{blood}} g h_{\text{blood}} = r_{\text{mercury}} g h_{\text{mercury}}$$

Solving for blood height and substituting gives

$$h_{\text{blood}} = \frac{r_{\text{mercury}}}{r_{\text{blood}}} h_{\text{mercury}} = \frac{13{,}600 \text{ kg/m}^3}{1050 \text{ kg/m}^3}(0.12 \text{ m}) = \mathbf{1.55\,m}$$

Discussion Note that the blood can rise about one and a half meters in a tube connected to the vein. This explains why IV tubes must be placed high to force a fluid into the vein of a patient.

EES SOLUTION

```
"Given"
h_mercury=0.120 [m] "or 120 mmHg"
rho_blood=1050 [kg/m^3]
rho_mercury=13600 [kg/m^3]

"Analysis"
h_blood=rho_mercury/rho_blood*h_mercury
"from P = rho_blood*g*h_blood = rho_mercury*g*h_mercury"
```

2-54 Consider a U-tube whose arms are open to the atmosphere. Now water is poured into the U-tube from one arm, and light oil (ρ = 790 kg/m^3) from the other. One arm contains 70-cm-high water, while the other arm contains both fluids with an oil-to-water height ratio of 4. Determine the height of each fluid in that arm.

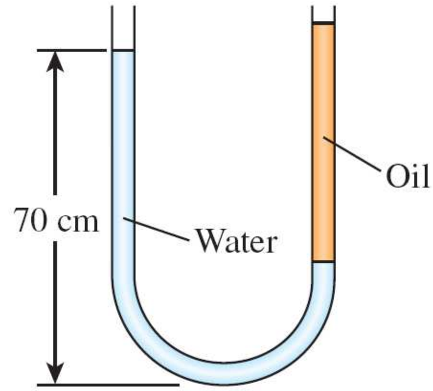


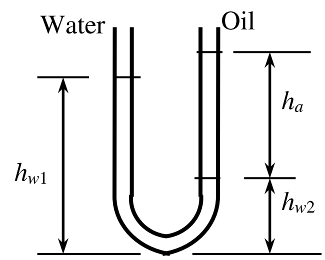
FIGURE P2–54

Water is poured into the U-tube from one arm and oil from the other arm. The water column height in one arm and the ratio of the heights of the two fluids in the other arm are given. The height of each fluid in that arm is to be determined.

Assumptions Both water and oil are incompressible substances.

Properties The density of oil is given to be ρ = 790 kg/m^3. We take the density of water to be ρ = 1000 kg/m^3.

Analysis The height of water column in the left arm of the monometer is given to be h_{w1} = 0.70 m. We let the height of water and oil in the right arm to be h_{w2} and h_a, respectively. Then, $h_a = 4h_{w2}$. Noting that both arms are open to the atmosphere, the pressure at the bottom of the U-tube can be expressed as



$$P_{\text{bottom}} = P_{\text{atm}} + \rho_w g h_{w1} \quad \text{and} \quad P_{\text{bottom}} = P_{\text{atm}} + \rho_w g h_{w2} + \rho_a g h_a$$

Setting them equal to each other and simplifying,

$$\rho_w g h_{w1} = \rho_w g h_{w2} + \rho_a g h_a \;\rightarrow\; \rho_w h_{w1} = \rho_w h_{w2} + \rho_a h_a \;\rightarrow\; h_{w1} = h_{w2} + (\rho_a / \rho_w) h_a$$

Noting that $h_a = 4h_{w2}$, the water and oil column heights in the second arm are determined to be

$$0.7 \text{ m} = h_{w2} + (790/1000)\, 4h_{w2} \;\rightarrow\; h_{w2} = \mathbf{0.168\ m}$$

$$0.7 \text{ m} = 0.168 \text{ m} + (790/1000) h_a \;\rightarrow\; h_a = \mathbf{0.673\ m}$$

Discussion Note that the fluid height in the arm that contains oil is higher. This is expected since oil is lighter than water.

EES SOLUTION

```
"Given"
h_w1=0.70 [m]
h_a/h_w2=4
rho_a=790 [kg/m^3]

"Analysis"
rho_w=1000 [kg/m^3] "taken"
h_w1=h_w2+(rho_a/rho_w)*h_a
"from  P_bottom = P_atm+rho_w*g*h_w1 = P_atm+rho_w*g*h_w2+rho_a*g*h_a"
```

2-55 Consider a double-fluid manometer attached to an air pipe shown in Fig. P2–55. If the specific gravity of one fluid is 13.55, determine the specific gravity of the other fluid for the indicated absolute pressure of air. Take the atmospheric pressure to be 100 kPa.

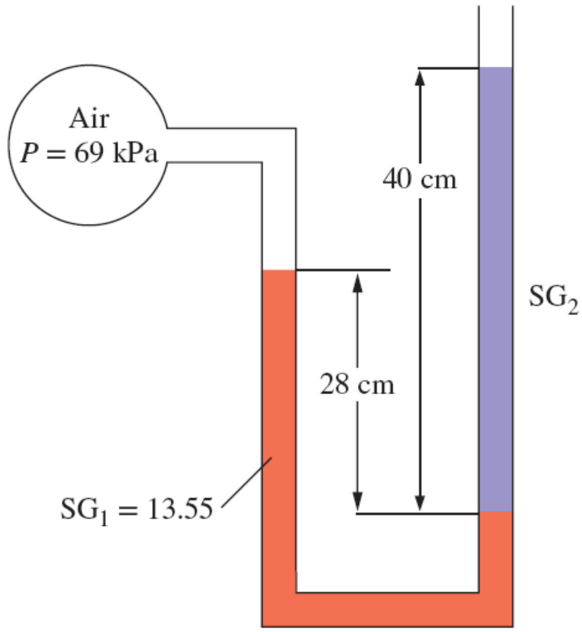
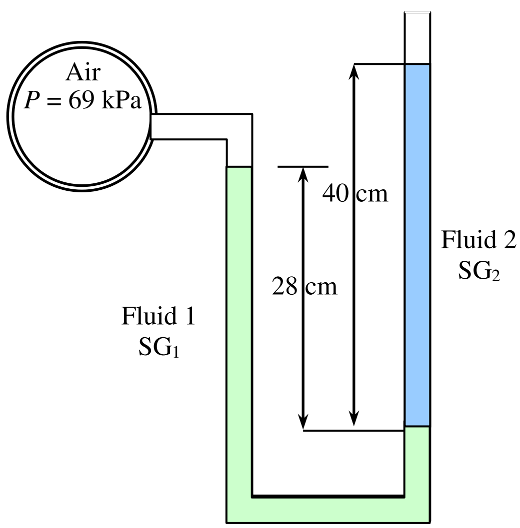


FIGURE P2–55

A double-fluid manometer attached to an air pipe is considered. The specific gravity of one fluid is known, and the specific gravity of the other fluid is to be determined.

Assumptions **1** Densities of liquids are constant. **2** The air pressure in the tank is uniform (i.e., its variation with elevation is negligible due to its low density), and thus the pressure at the air-water interface is the same as the indicated gage pressure.

Properties The specific gravity of one fluid is given to be 13.55. We take the standard density of water to be 1000 kg/m^3.



Analysis Starting with the pressure of air in the tank, and moving along the tube by adding (as we go down) or subtracting (as we go up) the ρgh terms until we reach the free surface where the oil tube is exposed to the atmosphere, and setting the result equal to P_{atm} give

$$P_{air} + \rho_1 gh_1 - \rho_2 gh_2 = P_{atm} \rightarrow P_{air} - P_{atm} = SG_2 \rho_w gh_2 - SG_1 \rho_w gh_1$$

Rearranging and solving for SG_2,

$$SG_2 = SG_1 \frac{h_1}{h_2} + \frac{P_{air} - P_{atm}}{\rho_w gh_2} = 13.55 \frac{0.28 \text{ m}}{0.40 \text{ m}} + \left(\frac{69 - 100 \text{ kPa}}{(1000 \text{ kg/m}^3)(9.81 \text{ m/s}^2)(0.40 \text{ m})} \right) \left(\frac{1000 \text{ kg} \cdot \text{m/s}^2}{1 \text{ kPa} \cdot \text{m}^2} \right) = \mathbf{1.59}$$

Discussion Note that the right fluid column is higher than the left, and this would imply above atmospheric pressure in the pipe for a single-fluid manometer.

EES SOLUTION

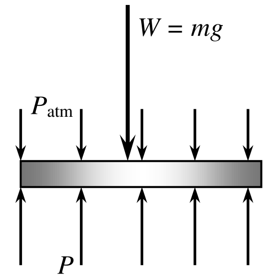
```
"Given"
SG_1=13.55
h1=0.28 [m]
h2=0.40 [m]
P_air=69 [kPa]
P_atm=100 [kPa]

"Analysis"
rho_w=1000 [kg/m^3] "taken"
g=9.81 [m/s^2]
SG_2=SG_1*h1/h2+(P_air-P_atm)/(rho_w*g*h2)*Convert(kPa-m^2, kg-m/s^2)
```

2-56 The hydraulic lift in a car repair shop has an output diameter of 30 cm and is to lift cars up to 2500 kg. Determine the fluid gage pressure that must be maintained in the reservoir.

The hydraulic lift in a car repair shop is to lift cars. The fluid gage pressure that must be maintained in the reservoir is to be determined.

Assumptions The weight of the piston of the lift is negligible.

Analysis Pressure is force per unit area, and thus the gage pressure required is simply the ratio of the weight of the car to the area of the lift,



$$P_{gage} = \frac{W}{A} = \frac{mg}{\pi D^2/4}$$

$$= \frac{(2500\ \text{kg})(9.81\ \text{m/s}^2)}{\pi(0.30\ \text{m})^2/4}\left(\frac{1\ \text{kN}}{1000\ \text{kg}\cdot\text{m/s}^2}\right) = 347\ \text{kN/m}^2 = \mathbf{347\ kPa}$$

Discussion Note that the pressure level in the reservoir can be reduced by using a piston with a larger area.

EES SOLUTION

```
"Given"
D=0.30 [m]
m=2500 [kg]

"Analysis"
g=9.81 [m/s^2]
W=m*g
A=pi*D^2/4
P_gage=W/A*Convert(N/m^2, kPa)
```

2-57 Consider the system shown in Fig. P2–57. If a change of 0.7 kPa in the pressure of air causes the brine–mercury interface in the right column to drop by 5 mm in the brine level in the right column while the pressure in the brine pipe remains constant, determine the ratio of A_2/A_1.

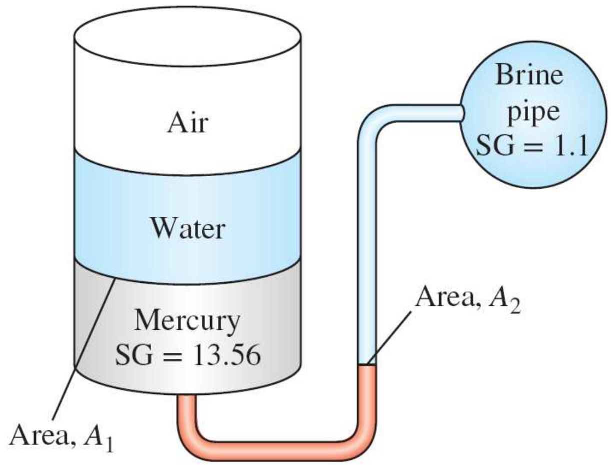
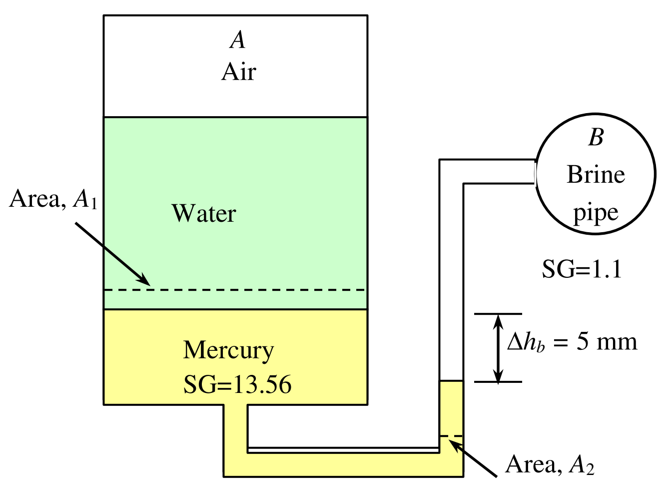


FIGURE P2–57

The fluid levels in a multi-fluid U-tube manometer change as a result of a pressure drop in the trapped air space. For a given pressure drop and brine level change, the area ratio is to be determined.

Assumptions **1** All the liquids are incompressible. **2** Pressure in the brine pipe remains constant. **3** The variation of pressure in the trapped air space is negligible.

Properties The specific gravities are given to be 13.56 for mercury and 1.1 for brine. We take the standard density of water to be ρ_w = 1000 kg/m^3.



Analysis It is clear from the problem statement and the figure that the brine pressure is much higher than the air pressure, and when the air pressure drops by 0.7 kPa, the pressure difference between the brine and the air space increases also by the same amount.

Starting with the air pressure (point A) and moving along the tube by adding (as we go down) or subtracting (as we go up) the $r\,gh$ terms until we reach the brine pipe (point B), and setting the result equal to P_B before and after the pressure change of air give

Before: $P_{A1} + r_w g h_w + r_{Hg} g h_{Hg,1} - r_{br} g h_{br,1} = P_B$

After: $P_{A2} + r_w g h_w + r_{Hg} g h_{Hg,2} - r_{br} g h_{br,2} = P_B$

Subtracting,

$$P_{A2} - P_{A1} + \rho_{Hg} g \Delta h_{Hg} - \rho_{br} g \Delta h_{br} = 0 \rightarrow \frac{P_{A1} - P_{A2}}{\rho_w g} = SG_{Hg} \Delta h_{Hg} - SG_{br} \Delta h_{br} = 0 \qquad (1)$$

where Δh_{Hg} and Δh_{br} are the changes in the differential mercury and brine column heights, respectively, due to the drop in air pressure. Both of these are positive quantities since as the mercury-brine interface drops, the differential fluid heights for both mercury and brine increase. Noting also that the volume of mercury is constant, we have $A_1 \Delta h_{Hg,\,left} = A_2 \Delta h_{Hg,\,right}$ and

$$P_{A2} - P_{A1} = -0.7 \text{ kPa} = -700 \text{ N/m}^2 = -700 \text{ kg/m} \cdot \text{s}^2$$

$$\Delta h_{br} = 0.005 \text{ m}$$

$$\Delta h_{Hg} = \Delta h_{Hg,right} + \Delta h_{Hg,left} = \Delta h_{br} + \Delta h_{br} A_2 / A_1 = \Delta h_{br} (1 + A_2 / A_1)$$

Substituting,

$$\frac{700 \text{ kg/m} \cdot \text{s}^2}{(1000 \text{ kg/m}^3)(9.81 \text{ m/s}^2)} = [13.56 \times 0.005(1 + A_2/A_1) - (1.1 \times 0.005)] \text{ m}$$

It gives $A_2/A_1 =$ **0.134**

EES SOLUTION

```
"Given"
DELTAP=0.7 [kPa]*Convert(kPa, kg/m-s^2)
DELTAh_br=0.005 [m]

"Analysis"
rho_w=1000 [kg/m^3]
g=9.81 [m/s^2]
DELTAP/(rho_w*g)=13.56*DELTAh_br*(1+Ratio)-(1.1*DELTAh_br)
```

2-58 The gage pressure of the air in the tank shown in Fig. P2–58 is measured to be 80 kPa. Determine the differential height h of the mercury column.

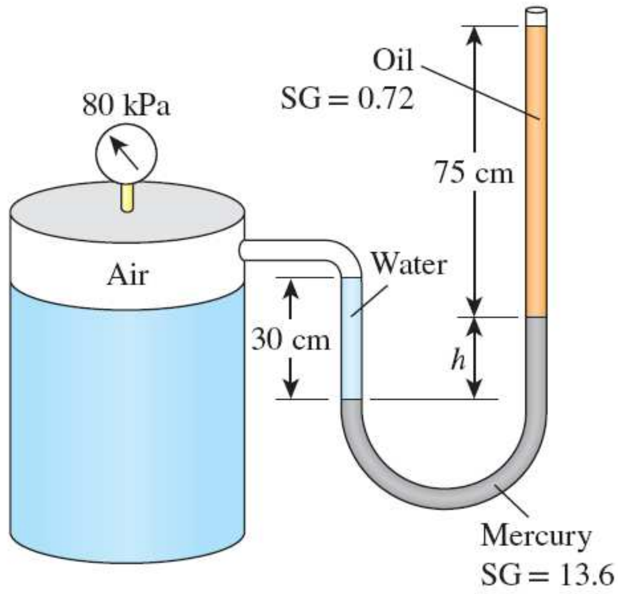
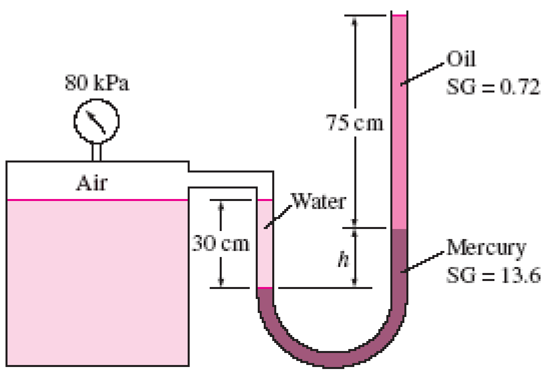


FIGURE P2–58

The gage pressure of air in a pressurized water tank is measured simultaneously by both a pressure gage and a manometer. The differential height h of the mercury column is to be determined.

Assumptions The air pressure in the tank is uniform (i.e., its variation with elevation is negligible due to its low density), and thus the pressure at the air-water interface is the same as the indicated gage pressure.

Properties We take the density of water to be ρ_w =1000 kg/m^3. The specific gravities of oil and mercury are given to be 0.72 and 13.6, respectively.



Analysis Starting with the pressure of air in the tank (point 1), and moving along the tube by adding (as we go down) or subtracting (as we go up) the $r\,gh$ terms until we reach the free surface of oil where the oil tube is exposed to the atmosphere, and setting the result equal to P_{atm} gives

$$P_1 + r_{\text{w}} gh_w - r_{\text{Hg}} gh_{\text{Hg}} - r_{\text{oil}} gh_{\text{oil}} = P_{\text{atm}}$$

Rearranging,

$$P_1 - P_{\text{atm}} = r_{\text{oil}} gh_{\text{oil}} + r_{\text{Hg}} gh_{\text{Hg}} - r_{\text{w}} gh_w$$

or,

$$\frac{P_{1,\text{gage}}}{r_{\text{w}} g} = \text{SG}_{\text{oil}} h_{\text{oil}} + \text{SG}_{\text{Hg}} h_{\text{Hg}} - h_w$$

Substituting,

$$\left(\frac{80\text{ kPa}}{(1000\text{ kg/m}^3)(9.81\text{ m/s}^2)}\right)\left(\frac{1000\text{ kg}\cdot\text{m/s}^2}{1\text{ kPa.}\cdot\text{m}^2}\right) = 0.72\times(0.75\text{ m}) + 13.6\times h_{Hg} - 0.3\text{ m}$$

Solving for h_{Hg} gives

h_{Hg} = **0.582 m**

Therefore, the differential height of the mercury column must be 58.2 cm.

Discussion Double instrumentation like this allows one to verify the measurement of one of the instruments by the measurement of another instrument.

EES SOLUTION

```
"Given"
P_gage=80 [kPa]
h_w=0.3 [m]
h_oil=0.75 [m]
rho_s_oil=0.72
rho_s_Hg=13.6
"Properties"
rho_w=1000 [kg/m^3] "taken"
rho_oil=rho_s_oil*rho_w
rho_Hg=rho_s_Hg*rho_w
g=9.807 [m/s^2]
"Analysis"
P_gage=g*(rho_oil*h_oil+rho_Hg*h_Hg-rho_w*h_w)*Convert(kg/m-s^2, kPa)
```

2-59 Repeat Prob. 2–58 for a gage pressure of 40 kPa.

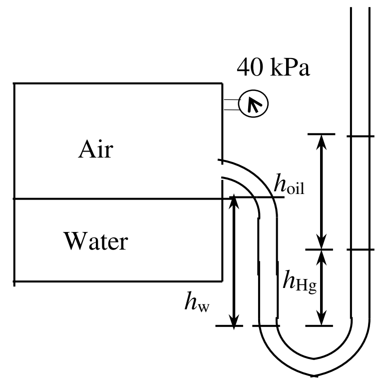
The gage pressure of air in a pressurized water tank is measured simultaneously by both a pressure gage and a manometer. The differential height h of the mercury column is to be determined.

Assumptions The air pressure in the tank is uniform (i.e., its variation with elevation is negligible due to its low density), and thus the pressure at the air-water interface is the same as the indicated gage pressure.

Properties We take the density of water to be $\rho_w = 1000$ kg/m^3. The specific gravities of oil and mercury are given to be 0.72 and 13.6, respectively.

Analysis Starting with the pressure of air in the tank (point 1), and moving along the tube by adding (as we go down) or subtracting (as we go up) the ρgh terms until we reach the free surface of oil where the oil tube is exposed to the atmosphere, and setting the result equal to P_{atm} gives

$$P_1 + \rho_w g h_w - \rho_{Hg} g h_{Hg} - \rho_{oil} g h_{oil} = P_{atm}$$



Rearranging,

$$P_1 - P_{atm} = \rho_{oil} g h_{oil} + \rho_{Hg} g h_{Hg} - \rho_w g h_w$$

or,
$$\frac{P_{1,gage}}{\rho_w g} = SG_{oil} h_{oil} + SG_{Hg} h_{Hg} - h_w$$

Substituting,

$$\left[\frac{40 \text{ kPa}}{(1000 \text{ kg/m}^3)(9.81 \text{ m/s}^2)}\right]\left(\frac{1000 \text{ kg}\cdot\text{m/s}^2}{1 \text{ kPa}\cdot\text{m}^2}\right) = 0.72 \times (0.75 \text{ m}) + 13.6 \times h_{Hg} - 0.3 \text{ m}$$

Solving for h_{Hg} gives

$$h_{Hg} = \mathbf{0.282\ m}$$

Therefore, the differential height of the mercury column must be 28.2 cm.

Discussion Double instrumentation like this allows one to verify the measurement of one of the instruments by the measurement of another instrument.

EES SOLUTION

```
"Given"
P_gage=40 [kPa]
h_w=0.3 [m]
h_oil=0.75 [m]
rho_s_oil=0.72
rho_s_Hg=13.6

"Properties"
rho_w=1000 [kg/m^3] "taken"
rho_oil=rho_s_oil*rho_w
rho_Hg=rho_s_Hg*rho_w
g=9.81 [m/s^2]

"Analysis"
P_gage=g*(rho_oil*h_oil+rho_Hg*h_Hg-rho_w*h_w)*Convert(kg/m-s^2, kPa)
```

Review Problems

2-60E The pressure in a steam boiler is given to be 92 kgf/cm^2. Express this pressure in psi, kPa, atm, and bars.

The pressure in a steam boiler is given in kgf/cm^2. It is to be expressed in psi, kPa, atm, and bars.

Analysis We note that 1 atm = 1.03323 kgf/cm^2, 1 atm = 14.696 psi, 1 atm = 101.325 kPa, and 1 atm = 1.01325 bar (inner cover page of text). Then the desired conversions become:

In atm: $$P = (92\ \text{kgf/cm}^2)\left(\frac{1\ \text{atm}}{1.03323\ \text{kgf/cm}^2}\right) = \mathbf{89.04\ atm}$$

In psi: $$P = (92\ \text{kgf/cm}^2)\left(\frac{1\ \text{atm}}{1.03323\ \text{kgf/cm}^2}\right)\left(\frac{14.696\ \text{psi}}{1\ \text{atm}}\right) = \mathbf{1309\ psi}$$

In kPa: $$P = (92\ \text{kgf/cm}^2)\left(\frac{1\ \text{atm}}{1.03323\ \text{kgf/cm}^2}\right)\left(\frac{101.325\ \text{kPa}}{1\ \text{atm}}\right) = \mathbf{9022\ kPa}$$

In bars: $$P = (92\ \text{kgf/cm}^2)\left(\frac{1\ \text{atm}}{1.03323\ \text{kgf/cm}^2}\right)\left(\frac{1.01325\ \text{bar}}{1\ \text{atm}}\right) = \mathbf{90.22\ bar}$$

Discussion Note that the units atm, kgf/cm^2, and bar are almost identical to each other.

EES SOLUTION

```
"Given"
P=92 "kgf/cm^2"

"Analysis"
P_atm=P*1/1.03323 "since 1 atm = 1.03323 kgf/cm^2"
Ppsi=P*1/1.03323*Convert(atm, psi)
P_kPa=P*1/1.03323*Convert(atm, kPa)
Pbars=P*1/1.03323*Convert(atm, bar)
```

2-61 A hydraulic lift is to be used to lift a 1900-kg weight by putting a weight of 25 kg on a piston with a diameter of 10 cm. Determine the diameter of the piston on which the weight is to be placed.

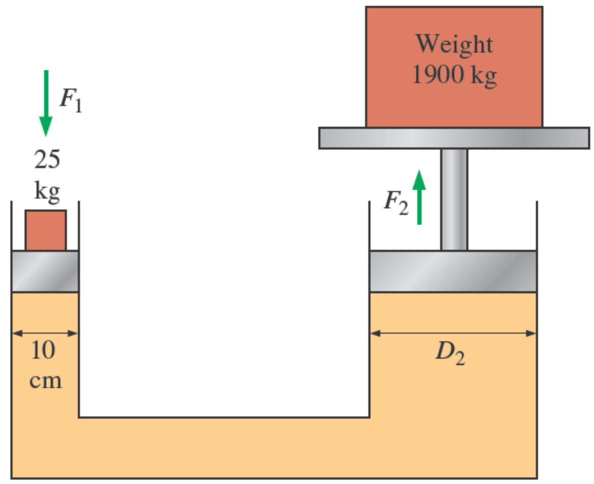
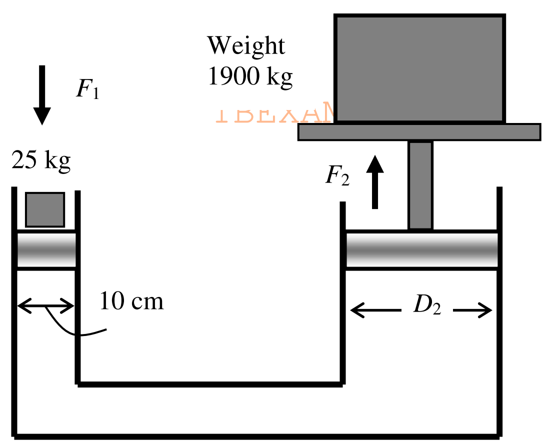


FIGURE P2–61

A hydraulic lift is used to lift a weight. The diameter of the piston on which the weight to be placed is to be determined.

Assumptions **1** The cylinders of the lift are vertical. **2** There are no leaks. **3** Atmospheric pressure act on both sides, and thus it can be disregarded.



Analysis Noting that pressure is force per unit area, the pressure on the smaller piston is determined from

$$P_1 = \frac{F_1}{A_1} = \frac{m_1 g}{\pi D_1^2/4} = \frac{(25\text{ kg})(9.81\text{ m/s}^2)}{\pi(0.10\text{ m})^2/4}\left(\frac{1\text{ kN}}{1000\text{ kg}\cdot\text{m/s}^2}\right) = 31.23\text{ kN/m}^2 = 31.23\text{ kPa}$$

From Pascal's principle, the pressure on the greater piston is equal to that in the smaller piston. Then, the needed diameter is determined from

$$P_1 = P_2 = \frac{F_2}{A_2} = \frac{m_2 g}{\pi D_2^2/4} \longrightarrow 31.23\text{ kN/m}^2 = \frac{(1900\text{ kg})(9.81\text{ m/s}^2)}{\pi D_2^2/4}\left(\frac{1\text{ kN}}{1000\text{ kg}\cdot\text{m/s}^2}\right) \longrightarrow D_2 = \mathbf{0.872\text{ m}}$$

Discussion Note that large weights can be raised by little effort in hydraulic lift by making use of Pascal's principle.

EES SOLUTION

```
"GIVEN"
m_2=1900 [kg]
m_1=25 [kg]
D_1=0.10 [m]

"ANALYSIS"
g=9.81 [m/s^2]
F_1=m_1*g
A_1=pi*D_1^2/4
P_1=F_1/A_1
P_2=P_1
F_2=m_2*g
A_2=F_2/P_2
A_2=pi*D_2^2/4
```

2-62 The average atmospheric pressure on earth is approximated as a function of altitude by the relation $P_{atm} = 101.325 (1 - 0.02256z)^{5.256}$, where P_{atm} is the atmospheric pressure in kPa and z is the altitude in km with $z = 0$ at sea level. Determine the approximate atmospheric pressures at Atlanta (z = 306 m), Denver (z = 1610 m), Mexico City (z = 2309 m), and the top of Mount Everest (z = 8848 m).

The average atmospheric pressure is given as $P_{atm} = 101.325(1- \ 0.02256z)^{5.256}$ where z is the altitude in km. The atmospheric pressures at various locations are to be determined.

Analysis The atmospheric pressures at various locations are obtained by substituting the altitude z values in km into the relation

$$P_{atm} = 101.325(1- \ 0.02256z)^{5.256}$$

Atlanta: (z = 0.306 km): $P_{atm} = 101.325(1 - 0.02256 \square 0.306)^{5.256} =$ **97.7 kPa**

Denver: (z = 1.610 km): $P_{atm} = 101.325(1 - 0.02256 \square 1.610)^{5.256} =$ **83.4 kPa**

M. City: (z = 2.309 km): $P_{atm} = 101.325(1 - 0.02256 \square 2.309)^{5.256} =$ **76.5 kPa**

Mt. Ev.: (z = 8.848 km): $P_{atm} = 101.325(1 - 0.02256 \square 8.848)^{5.256} =$ **31.4 kPa**

EES SOLUTION

```
"Given"
z_Atlanta=0.306 [km]
z_Denver=1.610 [km]
z_MexicoCity=2.309 [km]
z_Everest=8.848 [km]

"Analysis"
P_atm_Atlanta=101.325*(1-0.02256*z_Atlanta)^5.256
P_atm_Denver=101.325*(1-0.02256*z_Denver)^5.256
P_atm_MexicoCity=101.325*(1-0.02256*z_MexicoCity)^5.256
P_atm_Everest=101.325*(1-0.02256*z_Everest)^5.256
```


2-63E Hyperthermia of 5°C (i.e., 5°C rise above the normal body temperature) is considered fatal. Express this fatal level of hyperthermia in (*a*) K, (*b*) °F, and (*c*) R.

Hyperthermia of 5°C is considered fatal. This fatal level temperature change of body temperature is to be expressed in °F, K, and R.

Analysis The magnitudes of 1 K and 1°C are identical, so are the magnitudes of 1 R and 1°F. Also, a change of 1 K or 1°C in temperature corresponds to a change of 1.8 R or 1.8°F. Therefore, the fatal level of hypothermia is

(a) **5 K**

(b) $5 \times 1.8 =$ **9°F**

(c) $5 \times 1.8 =$ **9 R**

EES SOLUTION

```
"Given"
DELTAT_C=5 [C]

"Analysis"
"(a)"
DELTAT_K=DELTAT_C*Convert(C, K)
"(b)"
DELTAT_F=DELTAT_C*Convert(C, F)
"(c)"
DELTAT_R=DELTAT_C*Convert(C, R)
```

2-64E The boiling temperature of water decreases by about 3°C for each 1000-m rise in altitude. What is the decrease in the boiling temperature in (*a*) K, (*b*) °F, and (*c*) R for each 1000-m rise in altitude?

The boiling temperature of water decreases by 3°C for each 1000 m rise in altitude. This decrease in temperature is to be expressed in °F, K, and R.

Analysis The magnitudes of 1 K and 1°C are identical, so are the magnitudes of 1 R and 1°F. Also, a change of 1 K or 1°C in temperature corresponds to a change of 1.8 R or 1.8°F. Therefore, the decrease in the boiling temperature is

(*a*) **3 K** for each 1000 m rise in altitude, and

(*b*), (*c*) 3×1.8 = **5.4°F = 5.4 R** for each 1000 m rise in altitude.

EES SOLUTION

```
"Given"
DELTAT_C=3 [C]

"Analysis"
"(a)"
DELTAT_K=DELTAT_C*Convert(C, K)
"(b)"
DELTAT_F=DELTAT_C*Convert(C, F)
"(c)"
DELTAT_R=DELTAT_C*Convert(C, R)
```


2-65E A house is losing heat at a rate of 1800 kJ/h per °C temperature difference between the indoor and the outdoor temperatures. Express the rate of heat loss from this house per (*a*) K, (*b*) °F, and (*c*) R difference between the indoor and the outdoor temperature.

A house is losing heat at a rate of 1800 kJ/h per °C temperature difference between the indoor and the outdoor temperatures. The rate of heat loss is to be expressed per °F, K, and R of temperature difference between the indoor and the outdoor temperatures.

Analysis The magnitudes of 1 K and 1°C are identical, so are the magnitudes of 1 R and 1°F. Also, a change of 1 K or 1°C in temperature corresponds to a change of 1.8 R or 1.8°F. Therefore, the rate of heat loss from the house is

(*a*) **1800 kJ/h** per K difference in temperature, and

(*b*), (*c*) 1800/1.8 = **1000 kJ/h** per R or °F rise in temperature.

EES SOLUTION

```
"Given"
Q_dot_loss_C=1800 [kJ/h-C]

"Analysis"
"(a)"
Q_dot_loss_K=Q_dot_loss_C*Convert(C, K)
"(b)"
Q_dot_loss_F=Q_dot_loss_C*Convert(1/C, 1/F)
"(c)"
Q_dot_loss_R=Q_dot_loss_C*Convert(1/C, 1/R)
```

2-66E The average body temperature of a person rises by about 2°C during strenuous exercise. What is the rise in the body temperature in (*a*) K, (*b*) °F, and (*c*) R during strenuous exercise?

The average body temperature of a person rises by about 2°C during strenuous exercise. This increase in temperature is to be expressed in °F, K, and R.

Analysis The magnitudes of 1 K and 1°C are identical, so are the magnitudes of 1 R and 1°F. Also, a change of 1 K or 1°C in temperature corresponds to a change of 1.8 R or 1.8°F. Therefore, the rise in the body temperature during strenuous exercise is

(*a*) **2 K**

(*b*) $2\times1.8 = \mathbf{3.6°F}$

(*c*) $2\times1.8 = \mathbf{3.6\ R}$

EES SOLUTION

```
"Given"
DELTAT_C=2 [C]

"Analysis"
"(a)"
DELTAT_K=DELTAT_C*Convert(C, K)
"(b)"
DELTAT_F=DELTAT_C*Convert(C, F)
"(c)"
DELTAT_R=DELTAT_C*Convert(C, R)
```

2-67 The average temperature of the atmosphere in the world is approximated as a function of altitude by the relation

$$T_{\text{atm}} = 288.15 - 6.5z$$

where T_{atm} is the temperature of the atmosphere in K and z is the altitude in km with $z = 0$ at sea level. Determine the average temperature of the atmosphere outside an airplane that is cruising at an altitude of 12,000 m.

The average temperature of the atmosphere is expressed as $T_{\text{atm}} = 288.15 - 6.5z$ where z is altitude in km. The temperature outside an airplane cruising at 12,000 m is to be determined.

Analysis Using the relation given, the average temperature of the atmosphere at an altitude of 12,000 m is determined to be

$$T_{\text{atm}} = 288.15 - 6.5z$$
$$= 288.15 - 6.5\times12$$
$$= \mathbf{210.15\ K = -63□C}$$

Discussion This is the "average" temperature. The actual temperature at different times can be different.

EES SOLUTION

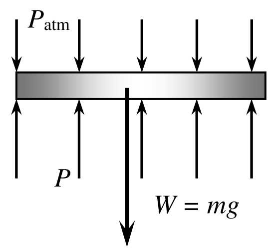
```
"Given"
z=12000*Convert(m, km)

"Analysis"
T_atm_K=288.15-6.5*z
T_atm_C=T_atm_K-273.15
```

2-68 A vertical, frictionless piston–cylinder device contains a gas at 180 kPa absolute pressure. The atmospheric pressure outside is 100 kPa, and the piston area is 25 cm^2. Determine the mass of the piston.

The pressure of a gas contained in a vertical piston-cylinder device is measured to be 180 kPa. The mass of the piston is to be determined.

Assumptions There is no friction between the piston and the cylinder.

Analysis Drawing the free body diagram of the piston and balancing the vertical forces yield



$$W = PA - P_{atm}A$$

$$mg = (P - P_{atm})A$$

$$(m)(9.81\ \text{m/s}^2) = (180 - 100\ \text{kPa})(25 \times 10^{-4}\ \text{m}^2)\left(\frac{1000\ \text{kg/m}\cdot\text{s}^2}{1\ \text{kPa}}\right)$$

It yields

$m =$ **20.4 kg**

EES SOLUTION

```
"Given"
P=180 [kPa]
P_atm=100 [kPa]
A=25E-4 [m^2]

"Analysis"
g=9.81 [m/s^2]
W=m*g
W=(P*A-P_atm*A)*Convert(kPa, kg/m-s^2)
```

2-69 A vertical piston–cylinder device contains a gas at a pressure of 100 kPa. The piston has a mass of 10 kg and a diameter of 14 cm. Pressure of the gas is to be increased by placing some weights on the piston. Determine the local atmospheric pressure and the mass of the weights that will double the pressure of the gas inside the cylinder.

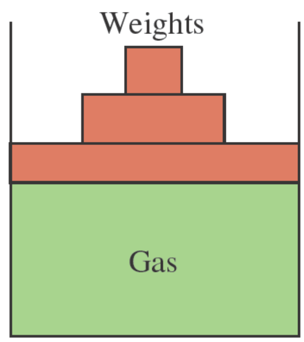
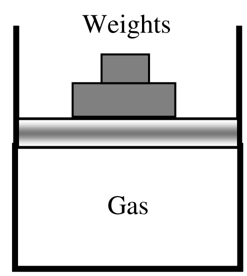


FIGURE P2–69

A vertical piston-cylinder device contains a gas. Some weights are to be placed on the piston to increase the gas pressure. The local atmospheric pressure and the mass of the weights that will double the pressure of the gas are to be determined.

Assumptions Friction between the piston and the cylinder is negligible.



Analysis The gas pressure in the piston-cylinder device initially depends on the local atmospheric pressure and the weight of the piston. Balancing the vertical forces yield

$$P_{\text{atm}} = P - \frac{m_{\text{piston}}\,g}{A} = 100\text{ kPa} - \frac{(10\text{ kg})(9.81\text{ m/s}^2)}{\pi(0.12\text{ m}^2)/4}\left(\frac{1\text{ kN}}{1000\text{ kg}\cdot\text{m/s}^2}\right)$$

$$= 93.63\text{ kN/m}^2 \cong \mathbf{93.6\ kPa}$$

The force balance when the weights are placed is used to determine the mass of the weights

$$P = P_{\text{atm}} + \frac{(m_{\text{piston}} + m_{\text{weights}})g}{A}$$

$$200\text{ kPa} = 93.63\text{ kPa} + \frac{(10\text{ kg} + m_{\text{weights}})(9.81\text{ m/s}^2)}{\pi(0.12\text{ m}^2)/4}\left(\frac{1\text{ kN}}{1000\text{ kg}\cdot\text{m/s}^2}\right) \longrightarrow m_{\text{weights}} = \mathbf{157\ kg}$$

A large mass is needed to double the pressure.

EES SOLUTION

```
"GIVEN"
P_1=100 [kPa]
m_p=10 [kg]
D=0.14 [m]
P_2=2*P_1

"ANALYSIS"
A_p=pi*D^2/4
P_1=P_atm+(m_p*g)/A_p*Convert(Pa, kPa) "vertical force balance without weights"
P_2=P_atm+((m_p+m_weights)*g)/A_p*Convert(Pa, kPa) "vertical force balance with weights"
g=9.81 [m/s^2]
```

2-70 The force generated by a spring is given by $F = kx$, where k is the spring constant and x is the deflection of the spring. The spring of Fig. P2–70 has a spring constant of 8 kN/cm. The pressures are P_1 = 5000 kPa, P_2 = 10,000 kPa, and P_3 = 1000 kPa. If the piston diameters are D_1 = 8 cm and D_2 = 3 cm, how far will the spring be deflected?

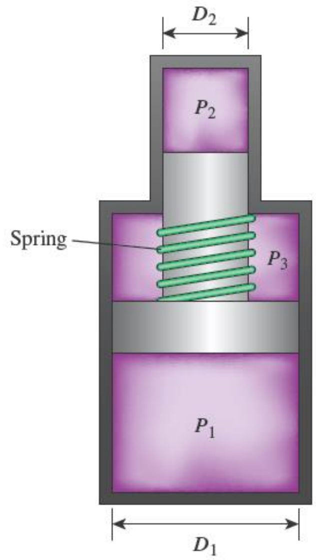


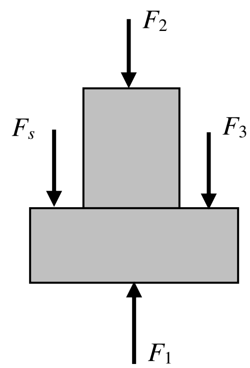
FIGURE P2–70

The deflection of the spring of the two-piston cylinder with a spring shown in the figure is to be determined.

Analysis Summing the forces acting on the piston in the vertical direction gives

$$F_s + F_2 + F_3 = F_1$$

$$kx + P_2A_2 + P_3(A_1 - A_2) = P_1A_1$$



which when solved for the deflection of the spring and substituting $A = \pi D^2/4$ gives

$$x = \frac{\pi}{4k}\left[P_1D_1^2 - P_2D_2^2 - P_3(D_1^2 - D_2^2)\right]$$

$$= \frac{\pi}{4\times 800}\left[5000\times 0.08^2 - 10{,}000\times 0.03^2 - 1000(0.08^2 - 0.03^2)\right]$$

$$= 0.0172 \text{ m}$$

$$= \mathbf{1.72\ cm}$$

We expressed the spring constant k in kN/m, the pressures in kPa (i.e., kN/m^2) and the diameters in m units.

EES SOLUTION

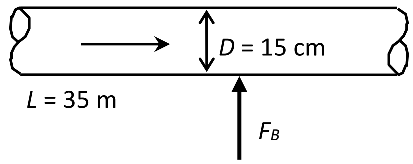
```
"Given"
k=8 [kN/cm]
P1=5000 [kPa]
P2=10000 [kPa]
P3=1000 [kPa]
D1=0.08 [m]
D2=0.03 [m]

"Analysis"
A1=pi*D1^2/4
A2=pi*D2^2/4
A3=A1-A2
F1=P1*A1
F2=P2*A2
F3=P3*A3
F_s+F2+F3=F1
F_s=k*x
```

2-71 An air-conditioning system requires a 35-m-long section of 15-cm-diameter ductwork to be laid underwater. Determine the upward force the water will exert on the duct. Take the densities of air and water to be 1.3 kg/m^3 and 1000 kg/m^3, respectively.

One section of the duct of an air-conditioning system is laid underwater. The upward force the water will exert on the duct is to be determined.

Assumptions **1** The diameter given is the outer diameter of the duct (or, the thickness of the duct material is negligible). **2** The weight of the duct and the air in is negligible.

Properties The density of air is given to be $\rho = 1.30$ kg/m^3. We take the density of water to be 1000 kg/m^3.



Analysis Noting that the weight of the duct and the air in it is negligible, the net upward force acting on the duct is the buoyancy force exerted by water. The volume of the underground section of the duct is

$$V = AL = (\pi D^2/4)L = [\pi(0.15\text{ m})^2/4](35\text{ m}) = 0.6185\text{ m}^3$$

Then the buoyancy force becomes

$$F_B = \rho g V = (1000\text{ kg/m}^3)(9.81\text{ m/s}^2)(0.6185\text{ m}^3)\left(\frac{1\text{ kN}}{1000\text{ kg}\cdot\text{m/s}^2}\right) = \mathbf{6.07\ kN}$$

Discussion The upward force exerted by water on the duct is 6.07 kN, which is equivalent to the weight of a mass of 619 kg. Therefore, this force must be treated seriously.

EES SOLUTION


```
"Given"
L=35 [m]
D=0.15 [m]
rho_air=1.3 [kg/m^3]
rho_water=1000 [kg/m^3]

"Analysis"
g=9.81 [m/s^2]
V=pi*D^2/4*L
F_B=rho_water*g*V*Convert(kg/m-s^2, kPa)
```

2-72 Balloons are often filled with helium gas because it weighs only about one-seventh of what air weighs under identical conditions. The buoyancy force, which can be expressed as $F_b = \rho_{air} g V_{balloon}$, will push the balloon upward. If the balloon has a diameter of 12 m and carries two people, 85 kg each, determine the acceleration of the balloon when it is first released. Assume the density of air is $\rho = 1.16$ kg/m^3, and neglect the weight of the ropes and the cage.

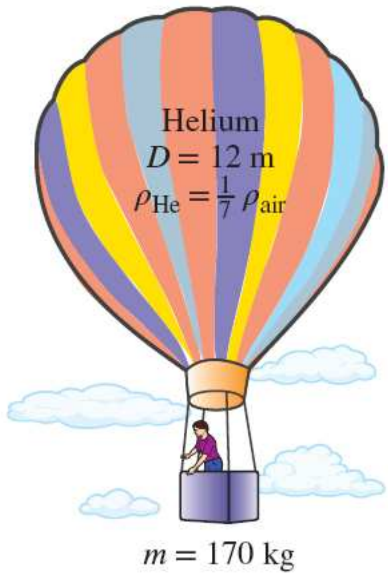


FIGURE P2–72

A helium balloon tied to the ground carries 2 people. The acceleration of the balloon when it is first released is to be determined.

Assumptions The weight of the cage and the ropes of the balloon is negligible.

Properties The density of air is given to be $\rho = 1.16$ kg/m^3. The density of helium gas is 1/7th of this.

Analysis The buoyancy force acting on the balloon is

$$V_{balloon} = 4\pi r^3/3 = 4\pi(6\text{ m})^3/3 = 904.8\text{ m}^3$$

$$F_B = \rho_{air} g V_{balloon} = (1.16\text{ kg/m}^3)(9.81\text{ m/s}^2)(904.8\text{ m}^3)\left(\frac{1\text{ N}}{1\text{ kg}\cdot\text{m/s}^2}\right) = 10{,}296\text{ N}$$

The total mass is

$$m_{He} = \rho_{He} V = \left(\frac{1.16}{7}\text{ kg/m}^3\right)(904.8\text{ m}^3) = 149.9\text{ kg}$$

$$m_{total} = m_{He} + m_{people} = 149.9 + 2 \times 85 = 319.9\text{ kg}$$

The total weight is

$$W = m_{total} g = (319.9\text{ kg})(9.81\text{ m/s}^2)\left(\frac{1\text{ N}}{1\text{ kg}\cdot\text{m/s}^2}\right) = 3138\text{ N}$$

Thus the net force acting on the balloon is

$$F_{\text{net}} = F_B - W = 10{,}296 - 3138 = 7157 \text{ N}$$

Then the acceleration becomes

$$a = \frac{F_{\text{net}}}{m_{\text{total}}} = \frac{7157 \text{ N}}{319.9 \text{ kg}}\left(\frac{1 \text{ kg} \cdot \text{m/s}^2}{1 \text{ N}}\right) = \mathbf{22.4 \ m/s^2}$$

EES SOLUTION

```
"Given"
D=12 [m]
N_person=2
m_person=85 [kg]
rho_air=1.16 [kg/m^3]
rho_He=rho_air/7

"Analysis"
g=9.81 [m/s^2]
V_ballon=pi*D^3/6
F_B=rho_air*g*V_ballon
m_He=rho_He*V_ballon
m_people=N_person*m_person
m_total=m_He+m_people
W=m_total*g
F_net=F_B-W
a=F_net/m_total
```

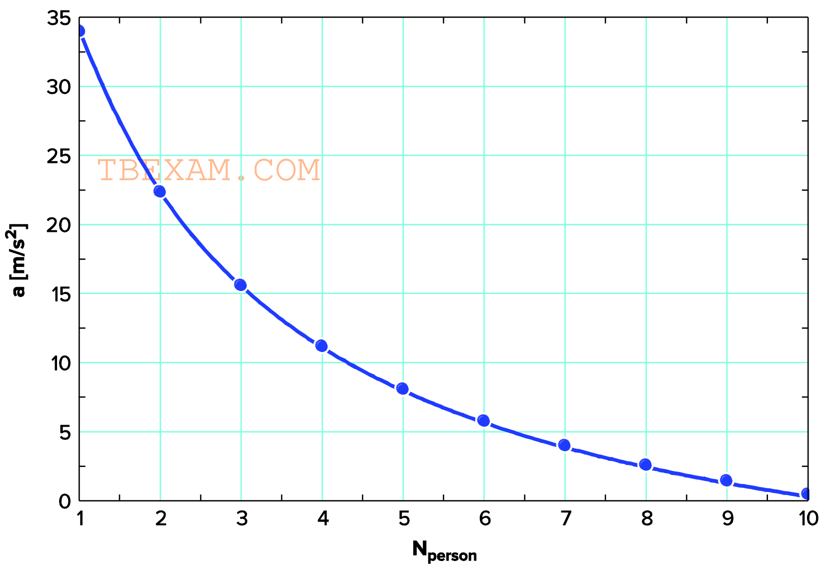
2-73 Reconsider Prob. 2–72. Using appropriate software, investigate the effect of the number of people carried in the balloon on acceleration. Plot the acceleration against the number of people, and discuss the results.

Problem 2-72 is reconsidered. The effect of the number of people carried in the balloon on acceleration is to be investigated. Acceleration is to be plotted against the number of people, and the results are to be discussed.

Analysis The problem is solved using EES, and the solution is given below.

```
"Given"
D=12 [m]
N_person=2
m_person=85 [kg]
rho_air=1.16 [kg/m^3]
rho_He=rho_air/7

"Analysis"
g=9.81 [m/s^2]
V_ballon=pi*D^3/6
F_B=rho_air*g*V_ballon
m_He=rho_He*V_ballon
m_people=N_person*m_person
m_total=m_He+m_people
W=m_total*g
F_net=F_B-W
a=F_net/m_total
```

N_{person}	a [m/s^2]
1	34
2	22.36
3	15.61
4	11.2
5	8.096
6	5.79
7	4.01
8	2.595
9	1.443
10	0.4865



2-74 Determine the maximum amount of load, in kg, the balloon described in Prob. 2–72 can carry.

A balloon is filled with helium gas. The maximum amount of load the balloon can carry is to be determined.

Assumptions The weight of the cage and the ropes of the balloon is negligible.

Properties The density of air is given to be $\rho = 1.16$ kg/m^3. The density of helium gas is 1/7th of this.

Analysis The buoyancy force acting on the balloon is

$$V_{balloon} = 4\pi r^3/3 = 4\pi(6\text{ m})^3/3 = 904.8\text{ m}^3$$

$$F_B = \rho_{air} g V_{balloon}$$
$$= (1.16\text{ kg/m}^3)(9.81\text{ m/s}^2)(904.8\text{ m}^3)\left(\frac{1\text{ N}}{1\text{ kg}\cdot\text{m/s}^2}\right) = 10{,}296\text{ N}$$

The mass of helium is

$$m_{He} = \rho_{He} V = \left(\frac{1.16}{7}\text{ kg/m}^3\right)(904.8\text{ m}^3) = 149.9\text{ kg}$$

In the limiting case, the net force acting on the balloon will be zero. That is, the buoyancy force and the weight will balance each other:

$$W = mg = F_B$$

$$m_{total} = \frac{F_B}{g} = \frac{10{,}296\text{ N}}{9.81\text{ m/s}^2} = 1050\text{ kg}$$

Thus,

$$m_{people} = m_{total} - m_{He} = 1050 - 149.9 = \mathbf{900\text{ kg}}$$

EES SOLUTION

```
"Given"
D=12 [m]
N_person=2
m_person=85 [kg]
rho_air=1.16 [kg/m^3]
rho_He=rho_air/7

"Analysis"
g=9.81 [m/s^2]
m_total_a=F_B/g
m_people_a=m_total_a-m_He
V_ballon=pi*D^3/6
F_B=rho_air*g*V_ballon
m_He=rho_He*V_ballon
m_people=N_person*m_person
m_total=m_He+m_people
W=m_total*g
F_net=F_B-W
a=F_net/m_total
```

2-75 The lower half of a 6-m-high cylindrical container is filled with water (ρ = 1000 kg/m^3) and the upper half with oil that has a specific gravity of 0.85. Determine the pressure difference between the top and bottom of the cylinder.

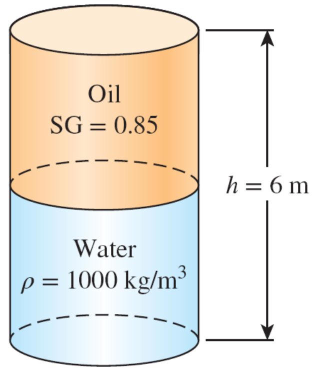
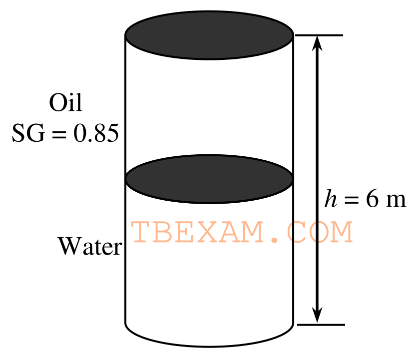


FIGURE P2–75

A 6-m high cylindrical container is filled with equal volumes of water and oil. The pressure difference between the top and the bottom of the container is to be determined.

Properties The density of water is given to be ρ = 1000 kg/m^3. The specific gravity of oil is given to be 0.85.



Analysis The density of the oil is obtained by multiplying its specific gravity by the density of water,

$$\rho = \text{SG} \times \rho_{H_2O} = (0.85)(1000 \text{ kg/m}^3) = 850 \text{ kg/m}^3$$

The pressure difference between the top and the bottom of the cylinder is the sum of the pressure differences across the two fluids,

$$\begin{aligned} \Delta P_{\text{total}} &= \Delta P_{\text{oil}} + \Delta P_{\text{water}} = (\rho gh)_{\text{oil}} + (\rho gh)_{\text{water}} \\ &= \left[(850 \text{ kg/m}^3)(9.81 \text{ m/s}^2)(3 \text{ m}) + (1000 \text{ kg/m}^3)(9.81 \text{ m/s}^2)(3 \text{ m})\right]\left(\frac{1 \text{ kPa}}{1000 \text{ N/m}^2}\right) \\ &= \mathbf{54.4 \text{ kPa}} \end{aligned}$$

EES SOLUTION

```
"Given"
h_water=3 [m]
h_oil=3 [m]
rho_water=1000 [kg/m^3]
rho_s_oil=0.85

"Analysis"
g=9.807 [m/s^2]
rho_oil=rho_s_oil*rho_water
DELTAP_oil=rho_oil*g*h_oil*Convert(kg/m-s^2, kPa)
DELTAP_water=rho_water*g*h_water*Convert(kg/m-s^2, kPa)
DELTAP_total=DELTAP_oil+DELTAP_water
```

2-76 A pressure cooker cooks a lot faster than an ordinary pan by maintaining a higher pressure and temperature inside. The lid of a pressure cooker is well sealed, and steam can escape only through an opening in the middle of the lid. A separate metal piece, the petcock, sits on top of this opening and prevents steam from escaping until the pressure force overcomes the weight of the petcock. The periodic escape of the steam in this manner prevents any potentially dangerous pressure buildup and keeps the pressure inside at a constant value. Determine the mass of the petcock of a pressure cooker whose operation pressure is 100 kPa gage and has an opening cross-sectional area of 4 mm^2. Assume an atmospheric pressure of 101 kPa, and draw the free-body diagram of the petcock.

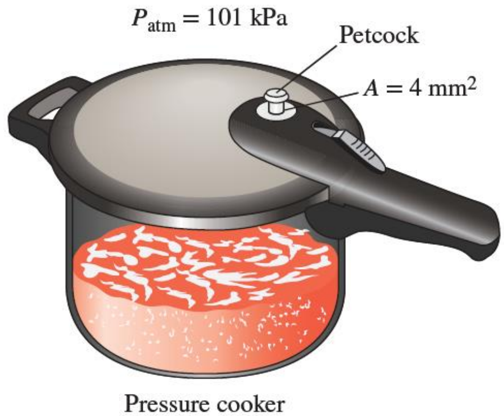
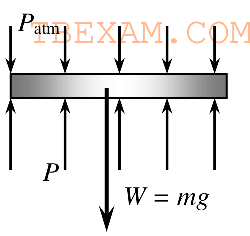


FIGURE P2–76

The gage pressure in a pressure cooker is maintained constant at 100 kPa by a petcock. The mass of the petcock is to be determined.

Assumptions There is no blockage of the pressure release valve.



Analysis Atmospheric pressure is acting on all surfaces of the petcock, which balances itself out. Therefore, it can be disregarded in calculations if we use the gage pressure as the cooker pressure. A force balance on the petcock ($\Sigma F_y = 0$) yields

$$W = P_{gage} A$$

$$m = \frac{P_{gage} A}{g} = \frac{(100 \text{ kPa})(4 \times 10^{-6} \text{ m}^2)}{9.81 \text{ m/s}^2}\left(\frac{1000 \text{ kg/m}\cdot\text{s}^2}{1 \text{ kPa}}\right)$$

$$= \mathbf{0.0408\ kg}$$

EES SOLUTION

```
"Given"
P_gage=100 [kPa]
A=4E-6 [m^2]
P_atm=101 [kPa]

"Analysis"
g=9.807 [m/s^2]
W=m*g
W=P_gage*A*Convert(kPa, kg/m-s^2)
```

2-77 The pilot of an airplane reads the altitude 6400 m and the absolute pressure 45 kPa when flying over a city. Calculate the local atmospheric pressure in that city in kPa and in mmHg. Take the densities of air and mercury to be 0.828 kg/m^3 and 13,600 kg/m^3, respectively.

FIGURE P2–77

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An airplane is flying over a city. The local atmospheric pressure in that city is to be determined.

Assumptions The gravitational acceleration does not change with altitude.

Properties The densities of air and mercury are given to be 1.15 kg/m^3 and 13,600 kg/m^3.

Analysis The local atmospheric pressure is determined from

$$P_{\text{atm}} = P_{\text{plane}} + \rho gh$$

$$= 45 \text{ kPa} + (0.828 \text{ kg/m}^3)(9.81 \text{ m/s}^2)(6400 \text{ m})\left(\frac{1 \text{ kN}}{1000 \text{ kg}\cdot\text{m/s}^2}\right) = \mathbf{97.0 \text{ kPa}}$$

The atmospheric pressure may be expressed in mmHg as

$$h_{\text{Hg}} = \frac{P_{\text{atm}}}{\rho g} = \frac{97.0 \text{ kPa}}{(13{,}600 \text{ kg/m}^3)(9.81 \text{ m/s}^2)}\left(\frac{1000 \text{ Pa}}{1 \text{ kPa}}\right)\left(\frac{1000 \text{ mm}}{1 \text{ m}}\right) = \mathbf{727 \text{ mmHg}}$$

EES SOLUTION

```
"GIVEN"
h=6400 [m]
P_plane=25 [kPa]
rho=1.15 [kg/m^3]
rho_Hg=13600 [kg/m^3]

"ANALYSIS"
g=9.81 [m/s^2]
P_atm-P_plane=rho*g*h*Convert(Pa, kPa)
h_Hg=P_atm/(rho_Hg*g)*Convert(kPa, Pa)*Convert(m, mm)
```

2-78 A glass tube is attached to a water pipe, as shown in Fig. P2–78. If the water pressure at the bottom of the tube is 107 kPa and the local atmospheric pressure is 99 kPa, determine how high the water will rise in the tube, in m. Take the density of water to be 1000 kg/m^3.

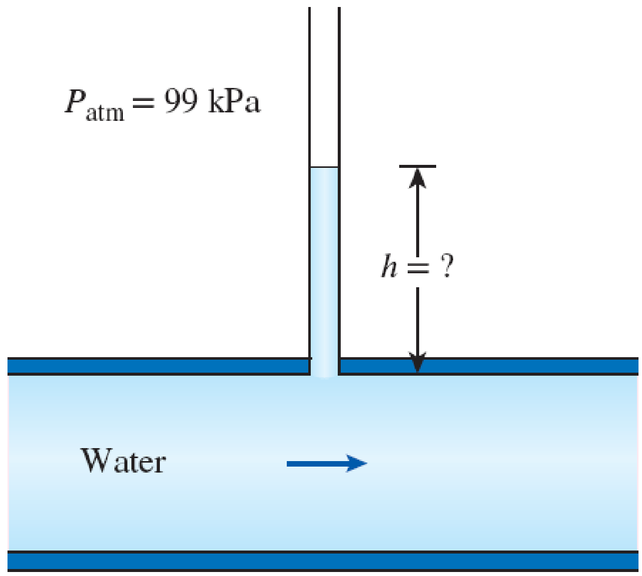


FIGURE P2–78

A glass tube open to the atmosphere is attached to a water pipe, and the pressure at the bottom of the tube is measured. It is to be determined how high the water will rise in the tube.

Properties The density of water is given to be ρ = 1000 kg/m^3.

Analysis The pressure at the bottom of the tube can be expressed as

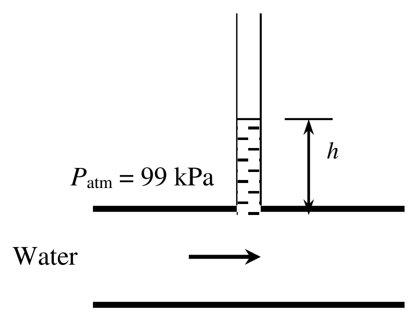
$$P = P_{atm} + (\rho g h)_{tube}$$

Solving for h,

$$h = \frac{P - P_{atm}}{\rho g}$$

$$= \frac{(107 - 99)\text{ kPa}}{(1000\text{ kg/m}^3)(9.81\text{ m/s}^2)}\left(\frac{1\text{ kg}\cdot\text{m/s}^2}{1\text{ N}}\right)\left(\frac{1000\text{ N/m}^2}{1\text{ kPa}}\right)$$

$$= \mathbf{0.82\ m}$$



EES SOLUTION

```
"Given"
P=107 [kPa]
P_atm=99 [kPa]
rho=1000 [kg/m^3]
g=9.81 [m/s^2]

"Analysis"
(P-P_atm)*Convert(kPa, kg/m-s^2)=rho*g*h
```

2-79E Consider a U-tube whose arms are open to the atmosphere. Now equal volumes of water and light oil (ρ = 49.3 lbm/ft^3) are poured from different arms. A person blows from the oil side of the U-tube until the contact surface of the two fluids moves to the bottom of the U-tube, and thus the liquid levels in the two arms are the same. If the fluid height in each arm is 30 in, determine the gage pressure the person exerts on the oil by blowing.

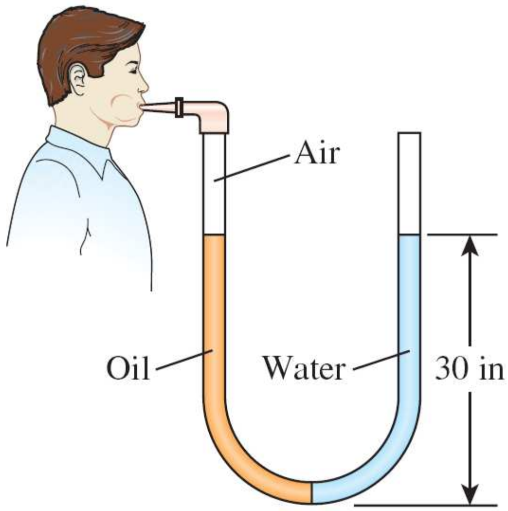
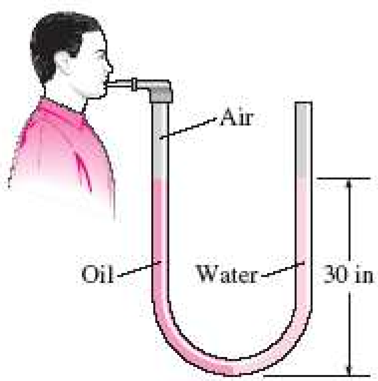


FIGURE P2–79E

Equal volumes of water and oil are poured into a U-tube from different arms, and the oil side is pressurized until the contact surface of the two fluids moves to the bottom and the liquid levels in both arms become the same. The excess pressure applied on the oil side is to be determined.

Assumptions **1** Both water and oil are incompressible substances. **2** Oildoes not mix with water. **3** The cross-sectional area of the U-tube is constant.

Properties The density of oil is given to be ρ_{oil} = 49.3 lbm/ft^3. We take the density of water to be ρ_w = 62.4 lbm/ft^3.



Analysis Noting that the pressure of both the water and the oil is the same at the contact surface, the pressure at this surface can be expressed as

$$P_{contact} = P_{blow} + r_a g h_a = P_{atm} + r_w g h_w$$

Noting that $h_a = h_w$ and rearranging,

$$P_{\text{gage,blow}} = P_{\text{blow}} - P_{\text{atm}} = (\rho_w - \rho_{oil})gh$$
$$= (62.4\text{-}49.3 \text{ lbm/ft}^3)(32.2 \text{ ft/s}^2)(30/12 \text{ ft})\left(\frac{1 \text{ lbf}}{32.2 \text{ lbm}\cdot\text{ft/s}^2}\right)\left(\frac{1 \text{ ft}^2}{144 \text{ in}^2}\right)$$
$$= \mathbf{0.227 \text{ psi}}$$

Discussion When the person stops blowing, the oil will rise and some water will flow into the right arm. It can be shown that when the curvature effects of the tube are disregarded, the differential height of water will be 23.7 in to balance 30-in of oil.

EES SOLUTION

```
"Given"
h_a=(30/12) [ft]
h_w=(30/12) [ft]
rho_a=49.3 [lbm/ft^3]

"Analysis"
P_gage_blow=(rho_w*g*h_w-rho_a*g*h_a)*Convert(lbm/ft-s^2, psia)
rho_w=62.4 [lbm/ft^3] "taken"
g=32.174 [ft/s^2]
```

2-80E A water pipe is connected to a double-U manometer as shown in Fig. P2–80E at a location where the local atmospheric pressure is 14.2 psia. Determine the absolute pressure at the center of the pipe.

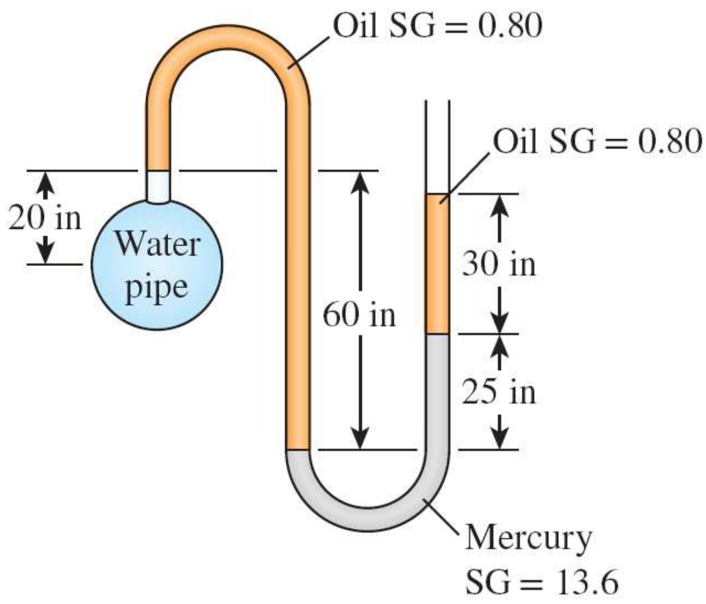
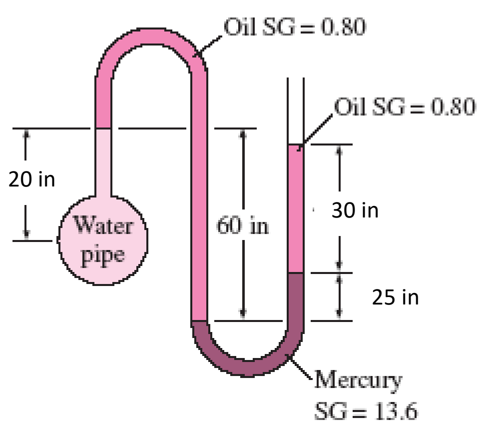


FIGURE P2–80E

A water pipe is connected to a double-U manometer whose free arm is open to the atmosphere. The absolute pressure at the center of the pipe is to be determined.

Assumptions **1** All the liquids are incompressible. **2** The solubility of the liquids in each other is negligible.

Properties The specific gravities of mercury and oil are given to be 13.6 and 0.80, respectively. We take the density of water to be ρ_w = 62.4 lbm/ft^3.



Analysis Starting with the pressure at the center of the water pipe, and moving along the tube by adding (as we go down) or subtracting (as we go up) the ρgh terms until we reach the free surface of oil where the oil tube is exposed to the atmosphere, and setting the result equal to P_{atm} gives

$$P_{\text{water pipe}} - \rho_{\text{water}} gh_{\text{water}} + \rho_{\text{oil}} gh_{\text{oil}} - \rho_{\text{Hg}} gh_{\text{Hg}} - \rho_{\text{oil}} gh_{\text{oil}} = P_{atm}$$

Solving for $P_{\text{water pipe}}$,

$$P_{\text{water pipe}} = P_{atm} + \rho_{\text{water}} g(h_{\text{water}} - SG_{\text{oil}} h_{\text{oil}} + SG_{\text{Hg}} h_{\text{Hg}} + SG_{\text{oil}} h_{\text{oil}})$$

Substituting,

$$P_{\text{water pipe}} = 14.2 \text{ psia} + (62.4 \text{ lbm/ft}^3)(32.2 \text{ ft/s}^2)[(20/12 \text{ ft}) - 0.8(60/12 \text{ ft}) + 13.6(25/12 \text{ ft})$$

$$+ 0.8(30/12 \text{ ft})] \times \left(\frac{1 \text{ lbf}}{32.2 \text{ lbm} \cdot \text{ft/s}^2}\right)\left(\frac{1 \text{ ft}^2}{144 \text{ in}^2}\right)$$

$$= \mathbf{26.4 \text{ psia}}$$

Therefore, the absolute pressure in the water pipe is 26.4 psia.

Discussion Note that jumping horizontally from one tube to the next and realizing that pressure remains the same in the same fluid simplifies the analysis greatly.

EES SOLUTION

```
"Given"
P_atm=14.2 [psia]
h_w=20/12 "[ft]"
h_alc=60/12 "[ft]"
h_Hg=25/12 "[ft]"
h_oil=30/12 "[ft]"
rho_s_alc=0.79
rho_s_Hg=13.6
rho_s_oil=0.8
"Properties"
rho_w=62.4 [lbm/ft^3] "taken"
rho_alc=rho_s_alc*rho_w
rho_Hg=rho_s_Hg*rho_w
rho_oil=rho_s_oil*rho_w
g=32.174 [ft/s^2]
"Analysis"
P_atm=P_waterpipe+(-rho_w*g*h_w+rho_alc*g*h_alc-rho_Hg*g*h_Hg-rho_oil*g*h_oil)*Convert(lbm/ft-s^2, psia)
```

2-81 A gasoline line is connected to a pressure gage through a double-U manometer, as shown in Fig. P2–81. If the reading of the pressure gage is 370 kPa, determine the gage pressure of the gasoline line.

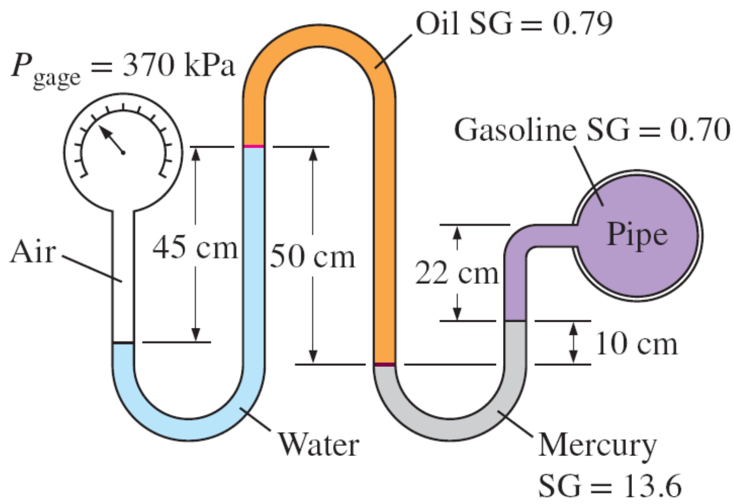
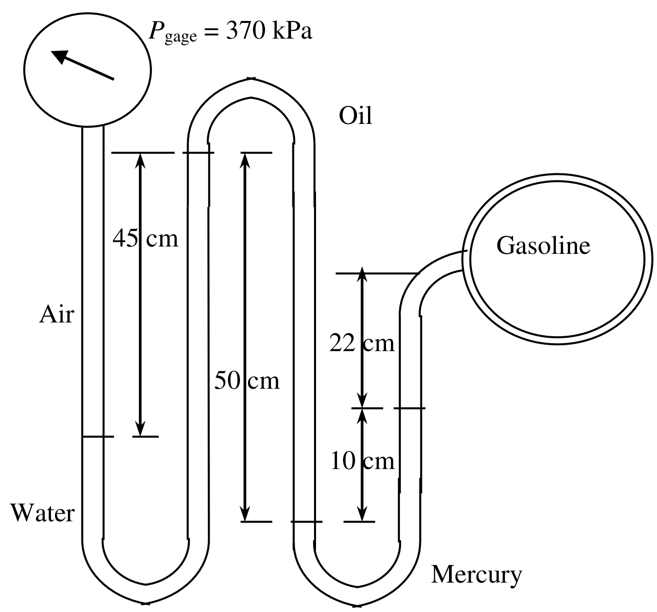


FIGURE P2–81

A gasoline line is connected to a pressure gage through a double-U manometer. For a given reading of the pressure gage, the gage pressure of the gasoline line is to be determined.

Assumptions **1** All the liquids are incompressible. **2** The effect of air column on pressure is negligible.

Properties The specific gravities of oil, mercury, and gasoline are given to be 0.79, 13.6, and 0.70, respectively. We take the density of water to be ρ_w = 1000 kg/m^3.



Analysis Starting with the pressure indicated by the pressure gage and moving along the tube by adding (as we go down) or subtracting (as we go up) the ρgh terms until we reach the gasoline pipe, and setting the result equal to P_{gasoline} gives

$$P_{\text{gage}} - \rho_{\text{w}} g h_w + \rho_{\text{oil}} g h_{\text{oil}} - \rho_{\text{Hg}} g h_{\text{Hg}} - \rho_{\text{gasoline}} g h_{\text{gasoline}} = P_{\text{gasoline}}$$

Rearranging,

$$P_{\text{gasoline}} = P_{\text{gage}} - \rho_{\text{w}} g (h_w - \text{SG}_{\text{oil}} h_{\text{oil}} + \text{SG}_{\text{Hg}} h_{\text{Hg}} + \text{SG}_{\text{gasoline}} h_{\text{gasoline}})$$

Substituting,

$$P_{\text{gasoline}} = 370 \text{ kPa} - (1000 \text{ kg/m}^3)(9.81 \text{ m/s}^2)[(0.45 \text{ m}) - 0.79(0.5 \text{ m}) + 13.6(0.1 \text{ m}) + 0.70(0.22 \text{ m})]$$
$$\times \left(\frac{1 \text{ kN}}{1000 \text{ kg} \cdot \text{m/s}^2}\right)\left(\frac{1 \text{ kPa}}{1 \text{ kN/m}^2}\right)$$
$$= \mathbf{354.6 \text{ kPa}}$$

Therefore, the pressure in the gasoline pipe is 15.4 kPa lower than the pressure reading of the pressure gage.

Discussion Note that sometimes the use of specific gravity offers great convenience in the solution of problems that involve several fluids.

EES SOLUTION

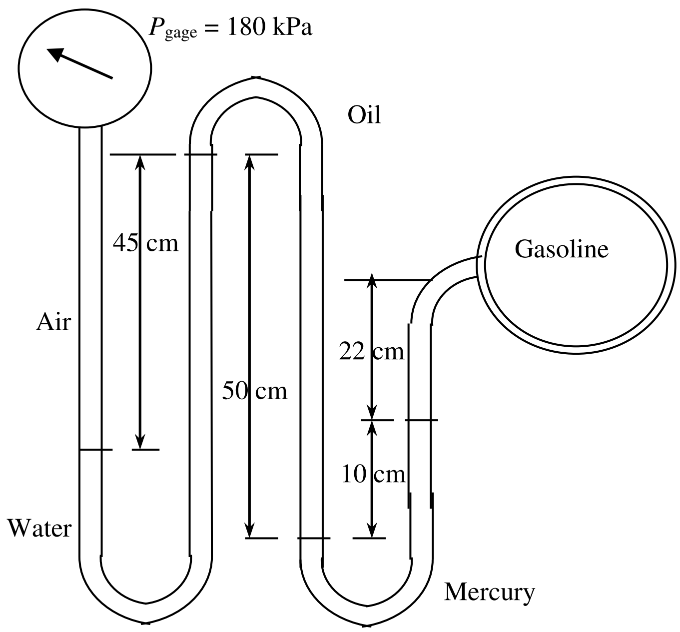
```
"Given"
P_gage=370 [kPa]
h_w=0.45 [m]
h_alc=0.5 [m]
h_Hg=0.1 [m]
h_gas=0.22 [m]
rho_s_alc=0.79
rho_s_Hg=13.6
rho_s_gas=0.70

"Properties"
rho_w=1000 [kg/m^3] "taken"
rho_alc=rho_s_alc*rho_w
rho_Hg=rho_s_Hg*rho_w
rho_gas=rho_s_gas*rho_w
g=9.807 [m/s^2]
```

2-82 Repeat Prob. 2–81 for a pressure gage reading of 180 kPa.

A gasoline line is connected to a pressure gage through a double-U manometer. For a given reading of the pressure gage, the gage pressure of the gasoline line is to be determined.

Assumptions **1** All the liquids are incompressible. **2** The effect of air column on pressure is negligible.

Properties The specific gravities of oil, mercury, and gasoline are given to be 0.79, 13.6, and 0.70, respectively. We take the density of water to be $\rho_w = 1000\ \text{kg/m}^3$.



Analysis Starting with the pressure indicated by the pressure gage and moving along the tube by adding (as we go down) or subtracting (as we go up) the ρgh terms until we reach the gasoline pipe, and setting the result equal to $P_{gasoline}$ gives

$$P_{gage} - \rho_w g h_w + \rho_{oil} g h_{oil} - \rho_{Hg} g h_{Hg} - \rho_{gasoline} g h_{gasoline} = P_{gasoline}$$

Rearranging,

$$P_{gasoline} = P_{gage} - \rho_w g (h_w - SG_{oil} h_{oil} + SG_{Hg} h_{Hg} + SG_{gasoline} h_{gasoline})$$

Substituting,

$$P_{gasoline} = 180\ \text{kPa} - (1000\ \text{kg/m}^3)(9.807\ \text{m/s}^2)[(0.45\ \text{m}) - 0.79(0.5\ \text{m}) + 13.6(0.1\ \text{m}) + 0.70(0.22\ \text{m})]$$

$$\times \left(\frac{1\ \text{kN}}{1000\ \text{kg}\cdot\text{m/s}^2}\right)\left(\frac{1\ \text{kPa}}{1\ \text{kN/m}^2}\right)$$

$$= \mathbf{164.6\ kPa}$$

Therefore, the pressure in the gasoline pipe is 15.4 kPa lower than the pressure reading of the pressure gage.

Discussion Note that sometimes the use of specific gravity offers great convenience in the solution of problems that involve several fluids.

EES SOLUTION

"Given"
P_gage=180 [kPa]
h_w=0.45 [m]
h_alc=0.5 [m]
h_Hg=0.1 [m]
h_gas=0.22 [m]
rho_s_alc=0.79
rho_s_Hg=13.6
rho_s_gas=0.70

"Properties"
rho_w=1000 [kg/m^3] "taken"
rho_alc=rho_s_alc*rho_w
rho_Hg=rho_s_Hg*rho_w
rho_gas=rho_s_gas*rho_w
g=9.807 [m/s^2]

2-83 When measuring small pressure differences with a manometer, often one arm of the manometer is inclined to improve the accuracy of reading. (The pressure difference is still proportional to the *vertical* distance and not the actual length of the fluid along the tube.) The air pressure in a circular duct is to be measured using a manometer whose open arm is inclined 45° from the horizontal, as shown in Fig. P2–83. The density of the liquid in the manometer is 0.81 kg/L, and the vertical distance between the fluid levels in the two arms of the manometer is 12 cm. Determine the gage pressure of air in the duct and the length of the fluid column in the inclined arm above the fluid level in the vertical arm.

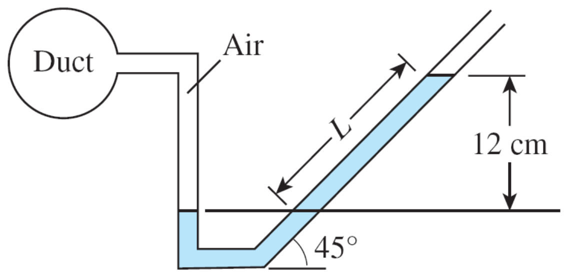
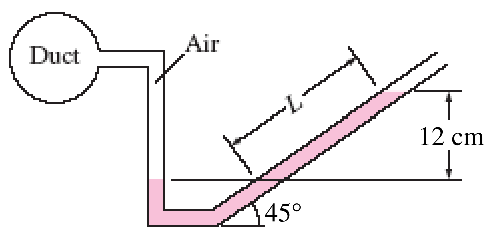


FIGURE P2–83

The air pressure in a duct is measured by an inclined manometer. For a given vertical level difference, the gage pressure in the duct and the length of the differential fluid column are to be determined.

Assumptions The manometer fluid is an incompressible substance.

Properties The density of the liquid is given to be $\rho = 0.81$ kg/L = 810 kg/m^3.



Analysis The gage pressure in the duct is determined from

$$\begin{aligned} P_{gage} &= P_{abs} - P_{atm} = \rho g h \\ &= (810\ \text{kg/m}^3)(9.81\ \text{m/s}^2)(0.12\ \text{m})\left(\frac{1\ \text{N}}{1\ \text{kg}\cdot\text{m/s}^2}\right)\left(\frac{1\ \text{Pa}}{1\ \text{N/m}^2}\right) \\ &= \mathbf{954\ Pa} \end{aligned}$$

The length of the differential fluid column is

$$L = h/\sin\theta = (12\ \text{cm})/\sin 45° = \mathbf{17.0\ cm}$$

Discussion Note that the length of the differential fluid column is extended considerably by inclining the manometer arm for better readability.

EES SOLUTION

```
"Given"
theta=45 [degrees]
h=0.12 [m]
P=115 [kPa]
P_atm=92 [kPa]
rho=0.81 [kg/L]

"Analysis"
g=9.81 [m/s^2]
P_gage=rho*Convert(kg/L, kg/m^3)*g*h*Convert(kg/m-s^2, Pa)
L=h/sin(theta)*Convert(m, cm)
```

2-84E It is well known that cold air feels much colder in windy weather than what the thermometer reading indicates because of the "chilling effect" of the wind. This effect is due to the increase in the convection heat transfer coefficient with increasing air velocities. The *equivalent wind chill temperature* in °F is given by [ASHRAE, *Handbook of Fundamentals* (Atlanta, GA, 1993), p. 8.15]

$$T_{\text{equiv}} = 91.4 - (91.4 - T_{\text{ambient}}) \times (0.475 - 0.0203V + 0.304\sqrt{V})$$

where V is the wind velocity in mi/h and T_{ambient} is the ambient air temperature in °F in calm air, which is taken to be air with light winds at speeds up to 4 mi/h. The constant 91.4°F in the given equation is the mean skin temperature of a resting person in a comfortable environment. Windy air at temperature T_{ambient} and velocity V will feel as cold as the calm air at temperature T_{equiv}. Using proper conversion factors, obtain an equivalent relation in SI units where V is the wind velocity in km/h and T_{ambient} is the ambient air temperature in °C.

An expression for the equivalent wind chill temperature is given in English units. It is to be converted to SI units.

Analysis The required conversion relations are 1 mph = 1.609 km/h and T(°F) = 1.8T(°C) + 32. The first thought that comes to mind is to replace T(°F) in the equation by its equivalent 1.8T(°C) + 32, and V in mph by 1.609 km/h, which is the "regular" way of converting units. However, the equation we have is not a regular dimensionally homogeneous equation, and thus the regular rules do not apply. The V in the equation is a constant whose value is equal to the numerical value of the velocity in mph. Therefore, if V is given in km/h, we should divide it by 1.609 to convert it to the desired unit of mph. That is,

$$T_{\text{equiv}}(°\text{F}) = 91.4 - [91.4 - T_{\text{ambient}}(°\text{F})][0.475 - 0.0203(V/1.609) + 0.304\sqrt{V/1.609}]$$

or

$$T_{\text{equiv}}(°\text{F}) = 91.4 - [91.4 - T_{\text{ambient}}(°\text{F})][0.475 - 0.0126V + 0.240\sqrt{V}]$$

where V is in km/h. Now the problem reduces to converting a temperature in □F to a temperature in □C, using the proper convection relation:

$$1.8T_{\text{equiv}}(°\text{C}) + 32 = 91.4 - [91.4 - (1.8T_{\text{ambient}}(°\text{C}) + 32)][0.475 - 0.0126V + 0.240\sqrt{V}]$$

which simplifies to

$$T_{\text{equiv}}(°\text{C}) = 33.0 - (33.0 - T_{\text{ambient}})(0.475 - 0.0126V + 0.240\sqrt{V})$$

where the ambient air temperature is in °C.

EES SOLUTION

```
"Given"
T_equiv_F=91.4-(91.4-T_ambient_F)*(0.475-0.0203*Vel_mph+0.304*sqrt(Vel_mph))
"where T_ambient in F and Vel in mph"

"Analysis"
1.8*T_equiv_C+32=91.4-(91.4-(1.8*T_ambient_C+32))*(0.475-
0.0203*Vel_kmh/1.609+0.304*sqrt(Vel_kmh/1.609))
"where T_ambient in C and Vel in km/h. Also 1 mph = 1.609 km/h and T(F) = 1.8*T(C)+32"

"Let us find T_equiv using these formulas for the following values"
T_ambient_F=70 [F]
Vel_mph=40 [mph]
T_ambient_C=(T_ambient_F-32)/1.8
Vel_kmh=Vel_mph*Convert(mph, km/h)
```

2-85E Reconsider Prob. 2–84E. Using appropriate software, plot the equivalent wind chill temperatures in °F as a function of wind velocity in the range of 4 to 40 mph for the ambient temperatures of 20, 40, and 60°F. Discuss the results.

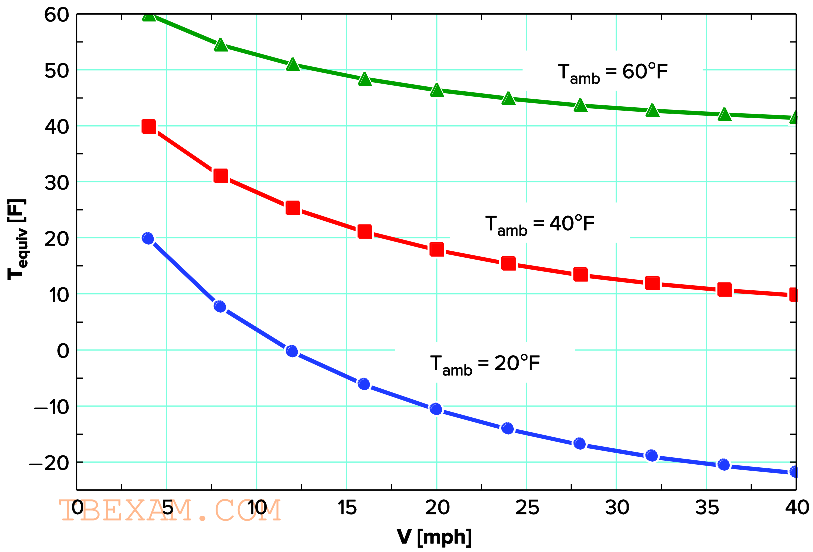
Problem 2-84E is reconsidered. The equivalent wind-chill temperatures in °F as a function of wind velocity in the range of 4 mph to 40 mph for the ambient temperatures of 20, 40, and 60°F are to be plotted, and the results are to be discussed.

Analysis The problem is solved using EES, and the solution is given below.

```
T_ambient=60 [F]
V=20 [mph]
T_equiv=91.4-(91.4-T_ambient)*(0.475 - 0.0203*V + 0.304*sqrt(V))
```

V [mph]	T_{equiv} [F]
4	59.94
8	54.59
12	51.07
16	48.5
20	46.54
24	45.02
28	43.82
32	42.88
36	42.16
40	41.61

The table is for $T_{ambient}$ = 60°F



2-86 Design and Essay Problems