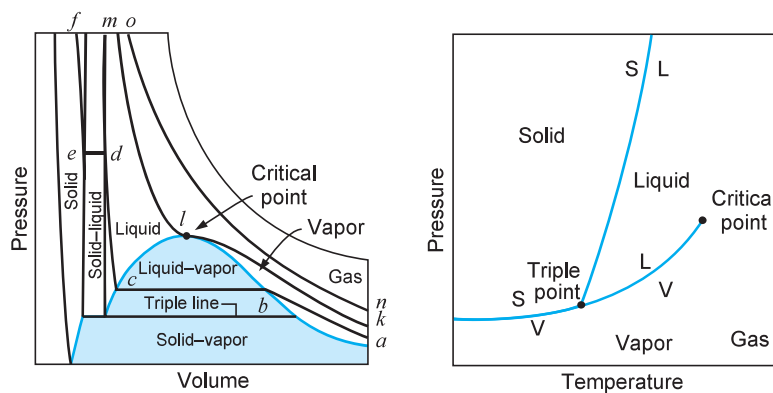**FIGURE 3.19** *P–v–T* surface for a substance that contracts on freezing.

expands on freezing first becomes solid and then liquid. For the substance that contracts on freezing, the corresponding constant-temperature line (Fig. 3.19) indicates that as the pressure on the vapor is increased, it first becomes liquid and then solid.

3.6 THE *P–V–T* BEHAVIOR OF LOW- AND MODERATE-DENSITY GASES

One form of energy possession by a system discussed in Section 2.6 is intermolecular (IM) potential energy, that energy associated with the forces between molecules. It was stated there that at very low densities the average distance between molecules is so large that the

IM potential energy may effectively be neglected. In such a case, the particles would be independent of one another, a situation referred to as an ideal gas. Under this approximation, it has been observed experimentally that, to a close approximation, a very-low-density gas behaves according to the ideal-gas equation of state

$$PV = n\bar{R}T, \qquad P\bar{v} = \bar{R}T \qquad (3.3)$$

in which n is the number of kmol of gas, or

$$n = \frac{m}{M}\frac{\text{kg}}{\text{kg/kmol}} \qquad (3.4)$$

In Eq. 3.3, $\bar{R}$ is the universal gas constant, the value of which is, for any gas,

$$\bar{R} = 8.3145\frac{\text{kN m}}{\text{kmol K}} = 8.3145\frac{\text{kJ}}{\text{kmol K}}$$

and T is the absolute (ideal-gas scale) temperature in kelvins (i.e., $T(\text{K}) = T(°\text{C}) + 273.15$). It is important to note that T must always be the absolute temperature whenever it is being used to multiply or divide in an equation. The ideal-gas absolute temperature scale will be discussed in more detail in Chapter 7. In the English Engineering System,

$$\bar{R} = 1545\frac{\text{ft lbf}}{\text{lb mol } R}$$

Substituting Eq. 3.4 into Eq. 3.3 and rearranging, we find that the ideal-gas equation of state can be written conveniently in the form

$$PV = mRT, \qquad Pv = RT \qquad (3.5)$$

where

$$R = \frac{\bar{R}}{M} \qquad (3.6)$$

in which R is a different constant for each particular gas. The value of R for a number of substances is given in Table A.5 and in English units in Table F.4.

EXAMPLE 3.8   What is the mass of air contained in a room 6 m × 10 m × 4 m if the pressure is 100 kPa and the temperature is 25°C?

Solution

Assume air to be an ideal gas. By using Eq. 3.5 and the value of R from Table A.5, we have

$$m = \frac{PV}{RT} = \frac{100\text{ kN/m}^2 \times 240\text{ m}^3}{0.287\text{ kN m/kg K} \times 298.2\text{ K}} = 280.5\text{ kg}$$

EXAMPLE 3.9   A tank has a volume of 0.5 m^3 and contains 10 kg of an ideal gas having a molecular mass of 24. The temperature is 25°C. What is the pressure?

Solution

The gas constant is determined first:

$$R = \frac{\bar{R}}{M} = \frac{8.3145 \text{ kN m/kmol K}}{24 \text{ kg/kmol}}$$

$$= 0.346\,44 \text{ kN m/kg K}$$

We now solve for P:

$$P = \frac{mRT}{V} = \frac{10 \text{ kg} \times 0.346\,44 \text{ kN m/kg K} \times 298.2 \text{ K}}{0.5 \text{ m}^3}$$

$$= 2066 \text{ kPa}$$

EXAMPLE 3.9E   A tank has a volume of 15 ft^3 and contains 20 lbm of an ideal gas having a molecular mass of 24. The temperature is 80 F. What is the pressure?

Solution

The gas constant is determined first:

$$R = \frac{\bar{R}}{M} = \frac{1545 \text{ ft lbf/lb mol R}}{24 \text{ lbm/lb mol}} = 64.4 \text{ ft lbf/lbm } R$$

We now solve for P:

$$P = \frac{mRT}{V} = \frac{20 \text{ lbm} \times 64.4 \text{ ft lbf/lbm R} \times 540 \text{ R}}{144 \text{ in.}^2/\text{ft}^2 \times 15 \text{ ft}^3} = 321 \text{ lbf/in.}^2$$

EXAMPLE 3.10   A gas bell is submerged in liquid water, with its mass counterbalanced with rope and pulleys, as shown in Fig. 3.20. The pressure inside is measured carefully to be 105 kPa, and the temperature is 21°C. A volume increase is measured to be 0.75 m^3 over a period of 185 s. What is the volume flow rate and the mass flow rate of the flow into the bell, assuming it is carbon dioxide gas?
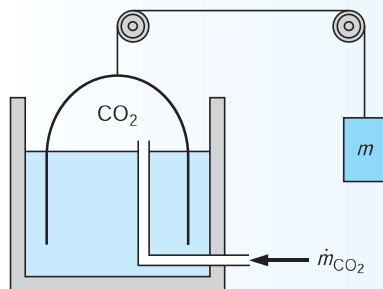

FIGURE 3.20   Sketch for Example 3.10.

Solution

The volume flow rate is

$$\dot{V} = \frac{dV}{dt} = \frac{\Delta V}{\Delta t} = \frac{0.75}{185} = 0.040\ 54\ \mathrm{m^3/s}$$

and the mass flow rate is $\dot{m} = \rho\,\dot{V} = \dot{V}/v$. At close to room conditions the carbon dioxide is an ideal gas, so $PV = mRT$ or $v = RT/P$, and from Table A.5 we have the ideal-gas constant $R = 0.1889$ kJ/kg K. The mass flow rate becomes

$$\dot{m} = \frac{P\dot{V}}{RT} = \frac{105 \times 0.040\ 54}{0.1889(273.15 + 21)}\ \frac{\mathrm{kPa\ m^3/s}}{\mathrm{kJ/kg}} = 0.0766\ \mathrm{kg/s}$$

Because of its simplicity, the ideal-gas equation of state is very convenient to use in thermodynamic calculations. However, two questions are now appropriate. The ideal-gas equation of state is a good approximation at low density. But what constitutes low density? In other words, over what range of density will the ideal-gas equation of state hold with accuracy? The second question is, how much does an actual gas at a given pressure and temperature deviate from ideal-gas behavior?

One specific example in response to these questions is shown in Fig. 3.21, a T–v diagram for water that indicates the error in assuming ideal gas for saturated vapor and for superheated vapor. As would be expected, at very low pressure or high temperature the error is small, but it becomes severe as the density increases. The same general trend would occur in referring to Figs. 3.18 or 3.19. As the state becomes further removed from the saturation region (i.e., high T or low P), the behavior of the gas becomes closer to that of the ideal-gas model.
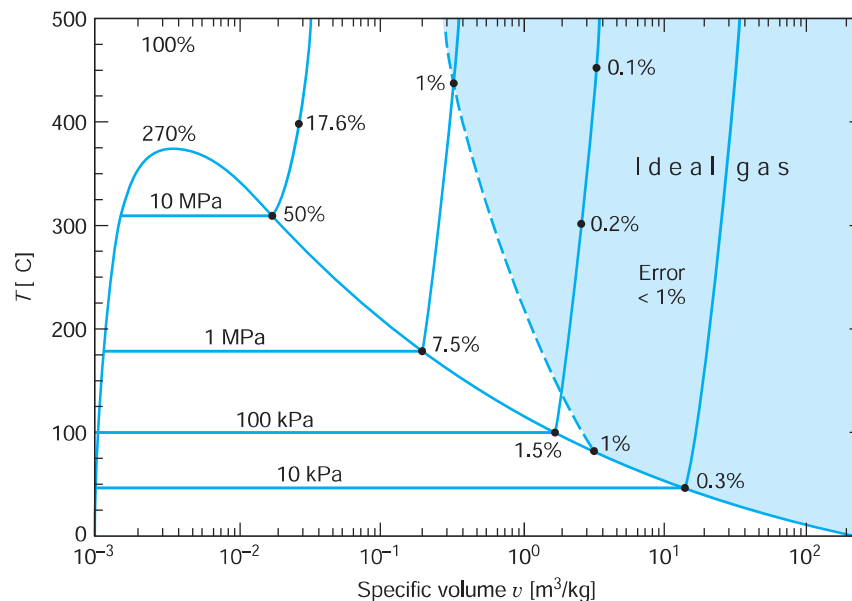

FIGURE 3.21
Temperature-specific volume diagram for water.

3.7 THE COMPRESSIBILITY FACTOR

A more quantitative study of the question of the ideal-gas approximation can be conducted by introducing the compressibility factor Z, defined as

$$Z = \frac{Pv}{RT}$$

or

$$Pv = ZRT \tag{3.7}$$

Note that for an ideal gas $Z = 1$, and the deviation of Z from unity is a measure of the deviation of the actual relation from the ideal-gas equation of state.

Figure 3.22 shows a skeleton compressibility chart for nitrogen. From this chart we make three observations. The first is that at all temperatures $Z \rightarrow 1$ as $P \rightarrow 0$. That is, as the pressure approaches zero, the P–v–T behavior closely approaches that predicted by the ideal-gas equation of state. Second, at temperatures of 300 K and above (that is, room temperature and above), the compressibility factor is near unity up to a pressure of about 10 MPa. This means that the ideal-gas equation of state can be used for nitrogen (and, as it happens, air) over this range with considerable accuracy.

Third, at lower temperatures or at very high pressures, the compressibility factor deviates significantly from the ideal-gas value. Moderate-density forces of attraction tend to pull molecules together, resulting in a value of $Z < 1$, whereas very-high-density forces of repulsion tend to have the opposite effect.

If we examine compressibility diagrams for other pure substances, we find that the diagrams are all similar in the characteristics described above for nitrogen, at least in a qualitative sense. Quantitatively the diagrams are all different, since the critical temperatures and pressures of different substances vary over wide ranges, as indicated by the values listed
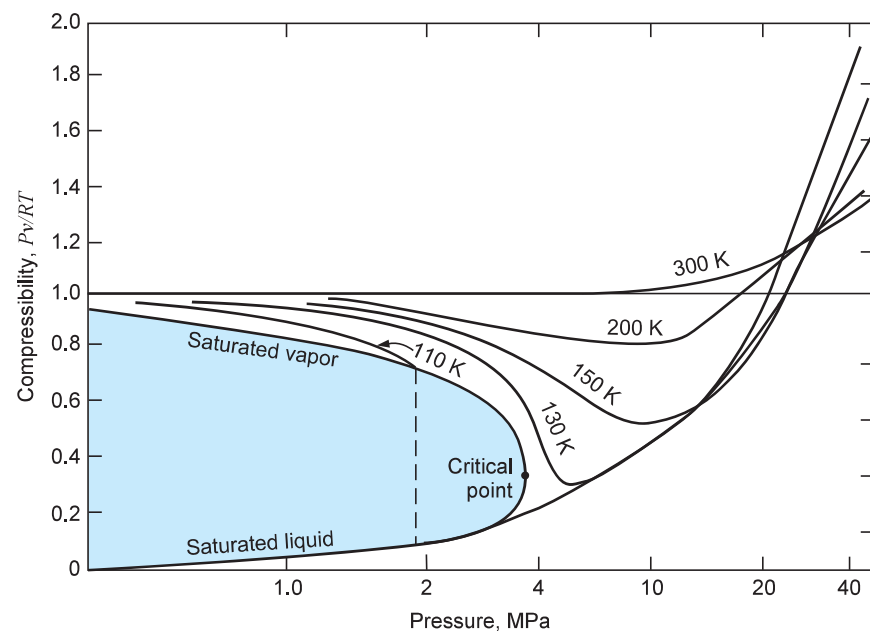

FIGURE 3.22
Compressibility of nitrogen.

in Table A.2. Is there a way we can put all of these substances on a common basis? To do so, we "reduce" the properties with respect to the values at the critical point. The reduced properties are defined as

$$\text{reduced pressure} = P_r = \frac{P}{P_c}, \qquad P_c = \text{critical pressure}$$

$$\text{reduced temperature} = T_r = \frac{T}{T_c}, \qquad T_c = \text{critical temperature} \tag{3.8}$$

These equations state that the reduced property for a given state is the value of this property in this state divided by the value of this same property at the critical point.

If lines of constant T_r are plotted on a Z versus P_r diagram, a plot such as that in Fig. D.1 is obtained. The striking fact is that when such Z versus P_r diagrams are prepared for a number of substances, all of them nearly coincide, especially when the substances have simple, essentially spherical molecules. Correlations for substances with more complicated molecules are reasonably close, except near or at saturation or at high density. Thus, Fig. D.1 is actually a generalized diagram for simple molecules, which means that it represents the average behavior for a number of simple substances. When such a diagram is used for a particular substance, the results will generally be somewhat in error. However, if P–v–T information is required for a substance in a region where no experimental measurements have been made, this generalized compressibility diagram will give reasonably accurate results. We need to know only the critical pressure and critical temperature to use this basic generalized chart.

In our study of thermodynamics, we will use Fig. D.1 primarily to help us decide whether, in a given circumstance, it is reasonable to assume ideal-gas behavior as a model. For example, we note from the chart that if the pressure is very low (that is, $<<P_c$), the ideal-gas model can be assumed with good accuracy, regardless of the temperature. Furthermore, at high temperatures (that is, greater than about twice T_c), the ideal-gas model can be assumed with good accuracy up to pressures as high as four or five times P_c. When the temperature is less than about twice the critical temperature and the pressure is not extremely low, we are in a region, commonly termed *superheated vapor*, in which the deviation from ideal-gas behavior may be considerable. In this region it is preferable to use tables of thermodynamic properties or charts for a particular substance, as discussed in Section 3.4.

EXAMPLE 3.11 Is it reasonable to assume ideal-gas behavior at each of the given states?

a. Nitrogen at 20°C, 1.0 MPa
b. Carbon dioxide at 20°C, 1.0 MPa
c. Ammonia at 20°C, 1.0 MPa

Solution

In each case, it is first necessary to check phase boundary and critical state data.

a. For nitrogen, the critical properties are, from Table A.2, 126.2 K, 3.39 MPa. Since the given temperature, 293.2 K, is more than twice T_c and the reduced pressure is less than 0.3, ideal-gas behavior is a very good assumption.

b. For carbon dioxide, the critical properties are 304.1 K, 7.38 MPa. Therefore, the reduced properties are 0.96 and 0.136. From Fig. D.1, carbon dioxide is a gas (although $T < T_c$) with a Z of about 0.95, so the ideal-gas model is accurate to within about 5% in this case.

c. The ammonia tables, Table B.2, give the most accurate information. From Table B.2.1 at 20°C, $P_g = 858$ kPa. Since the given pressure of 1 MPa is greater than P_g, this state is a compressed liquid, not a gas.

EXAMPLE 3.12   Determine the specific volume for R-134a at 100°C, 3.0 MPa for the following models:

a. The R-134a tables, Table B.5
b. Ideal gas
c. The generalized chart, Fig. D.1

Solution

a. From Table B.5.2 at 100°C, 3 MPa

$$v = 0.006\ 65\ \text{m}^3/\text{kg} \quad (\text{most accurate value})$$

b. Assuming ideal gas, we have

$$R = \frac{\bar{R}}{M} = \frac{8.3145}{102.03} = 0.081\ 49 \frac{\text{kJ}}{\text{kg K}}$$

$$v = \frac{RT}{P} = \frac{0.081\ 49 \times 373.2}{3000} = 0.010\ 14\ \text{m}^3/\text{kg}$$

which is more than 50% too large.

c. Using the generalized chart, Fig. D.1, we obtain

$$T_r = \frac{373.2}{374.2} = 1.0, \qquad P_r = \frac{3}{4.06} = 0.74, \qquad Z = 0.67$$

$$v = Z \times \frac{RT}{P} = 0.67 \times 0.010\ 14 = 0.006\ 79\ \text{m}^3/\text{kg}$$

which is only 2% too large.

EXAMPLE 3.13   Propane in a steel bottle of volume 0.1 m³ has a quality of 10% at a temperature of 15°C. Use the generalized compressibility chart to estimate the total propane mass and to find the pressure.

Solution

To use Fig. D.1, we need the reduced pressure and temperature. From Table A.2 for propane, $P_c = 4250$ kPa and $T_c = 369.8$ K. The reduced temperature is, from Eq. 3.8,

$$T_r = \frac{T}{T_c} = \frac{273.15 + 15}{369.8} = 0.779\ 2 = 0.78$$

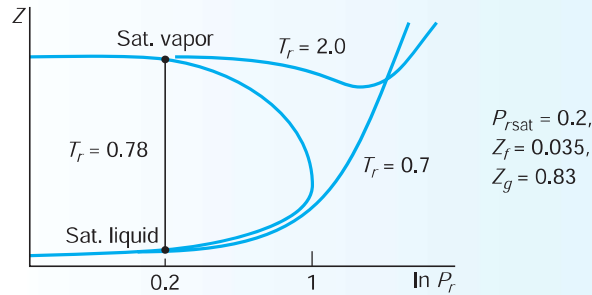From Fig. D.1, shown in Fig. 3.23, we can read for the saturated states

FIGURE 3.23 Diagram for Example 3.13.

For the two-phase state the pressure is the saturated pressure:

$$P = P_{r\,sat} \times P_c = 0.2 \times 4250 \text{ kPa} = 850 \text{ kPa}$$

The overall compressibility factor becomes, as Eq. 3.1 for v,

$$Z = (1 - x)Z_f + xZ_g = 0.9 \times 0.035 + 0.1 \times 0.83 = 0.1145$$

The gas constant from Table A.5 is $R = 0.1886$ kJ/kg K, so the gas law is Eq. 3.7:

$$PV = mZRT$$

$$m = \frac{PV}{ZRT} = \frac{850 \times 0.1}{0.1145 \times 0.1886 \times 288.15} \frac{\text{kPa m}^3}{\text{kJ/kg}} = 13.66 \text{ kg}$$

In-Text Concept Questions

i. How accurate is it to assume that methane is an ideal gas at room conditions?

j. I want to determine a state of some substance, and I know that $P = 200$ kPa; is it helpful to write $PV = mRT$ to find the second property?

k. A bottle at 298 K should have liquid propane; how high a pressure is needed? (Use Fig. D.1.)

3.8 EQUATIONS OF STATE

Instead of the ideal-gas model to represent gas behavior, or even the generalized compressibility chart, which is approximate, it is desirable to have an equation of state that accurately represents the P–v–T behavior for a particular gas over the entire superheated vapor region. Such an equation is necessarily more complicated and consequently more difficult to use. Many such equations have been proposed and used to correlate the observed behavior of gases. As an example, consider the class of relatively simple equation known as *cubic equations of state*

$$P = \frac{RT}{v - b} - \frac{a}{v^2 + cbv + db^2} \tag{3.9}$$

in terms of the four parameters *a*, *b*, *c*, and *d*. (Note that if all four are zero, this reduces to the ideal-gas model.) Several other different models in this class are given in Appendix D. In some of these models, the parameters are functions of temperature. A more complicated equation of state, the Lee-Kesler equation, is of particular interest, since this equation, expressed in reduced properties, is the one used to correlate the generalized compressibility chart, Fig. D.1. This equation and its 12 empirical constants are also given in Appendix D. When we use a digital computer to determine and tabulate pressure, specific volume, and temperature, as well as other thermodynamic properties, as in the tables presented in Appendix B, modern equations are much more complicated, often containing 40 or more empirical constants. This subject is discussed in detail in Chapter 14.

3.9 | COMPUTERIZED TABLES

Most of the tables in the appendix are supplied in a computer program on the disk accompanying this book. The main program operates with a visual interface in the Windows environment on a PC-type computer and is generally self-explanatory.

The main program covers the full set of tables for water, refrigerants, and cryogenic fluids, as in Tables B.1 to B.7, including the compressed liquid region, which is printed only for water. For these substances a small graph with the P–v diagram shows the region around the critical point down toward the triple line covering the compressed liquid, two-phase liquid–vapor, dense fluid, and superheated vapor regions. As a state is selected and the properties are computed, a thin crosshair set of lines indicates the state in the diagram so that this can be seen with a visual impression of the state's location.

Ideal gases corresponding to Tables A.7 for air and A.8 or A.9 for other ideal gases are covered. You can select the substance and the units to work in for all the table sections, providing a wider choice than the printed tables. Metric units (SI) or standard English units for the properties can be used, as well as a mass basis (kg or lbm) or a mole basis, satisfying the need for the most common applications.

The generalized chart, Fig. D.1, with the compressibility factor, is included to allow a more accurate value of Z to be obtained than can be read from the graph. This is particularly useful for a two-phase mixture where the saturated liquid and saturated vapor values are needed. Besides the compressibility factor, this part of the program includes correction terms beyond ideal-gas approximations for changes in the other thermodynamic properties.

The only mixture application that is included with the program is moist air.

EXAMPLE 3.14   Find the states in Examples 3.1 and 3.2 with the computer-aided thermodynamics tables, (CATT), and list the missing property of P–v–T and x if applicable.

Solution

Water states from Example 3.1: Click Water, click Calculator, and then select Case 1 (T, P). Input $(T, P) = (120, 0.5)$. The result is as shown in Fig. 3.24.

$$\Rightarrow \text{Compressed liquid} \qquad v = 0.0106 \text{ m}^3/\text{kg (as in Table B.1.4)}$$

Click Calculator and then select Case 2 (T, v). Input $(T, v) = (120, 0.5)$:

$$\Rightarrow \text{Two-phase} \qquad x = 0.5601, \ P = 198.5 \text{ kPa}$$
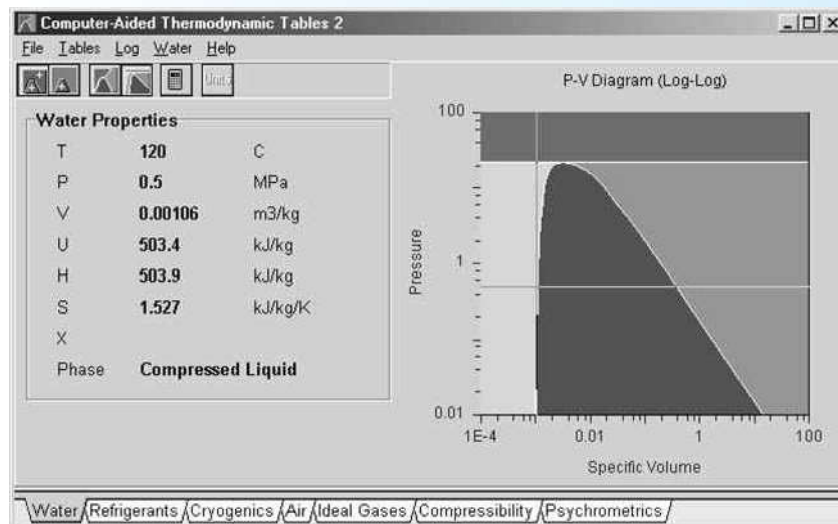
FIGURE 3.24 CATT result for Example 3.1.

Ammonia state from Example 3.2: Click Cryogenics; check that it is ammonia. Otherwise, select Ammonia, click Calculator, and then select Case 1 (T, P). Input $(T, P) = (30, 1)$:

$$\Rightarrow \text{Superheated vapor} \qquad v = 0.1321 \text{ m}^3/\text{kg (as in Table B.2.2)}$$

R-134a state from Example 3.2: Click Refrigerants; check that it is R-134a. Otherwise, select R-134a (Alt-R), click Calculator, and then select Case 5 (P, v). Input $(P, v) = (0.2, 0.125)$:

$$\Rightarrow \text{Superheated vapor} \qquad T = 44.0°\text{C}$$

In-Text Concept Question

l. A bottle at 298 K should have liquid propane; how high a pressure is needed? (Use the software.)

3.10 | ENGINEERING APPLICATIONS

Information about the phase boundaries is important for storage of substances in a two-phase state like a bottle of gas. The pressure in the container is the saturation pressure for the prevailing temperature, so an estimate of the maximum temperature the system will be subject to gives the maximum pressure for which the container must be dimensioned (Figs. 3.25, 3.26).

In a refrigerator a compressor pushes the refrigerant through the system, and this determines the highest fluid pressure. The harder the compressor is driven, the higher
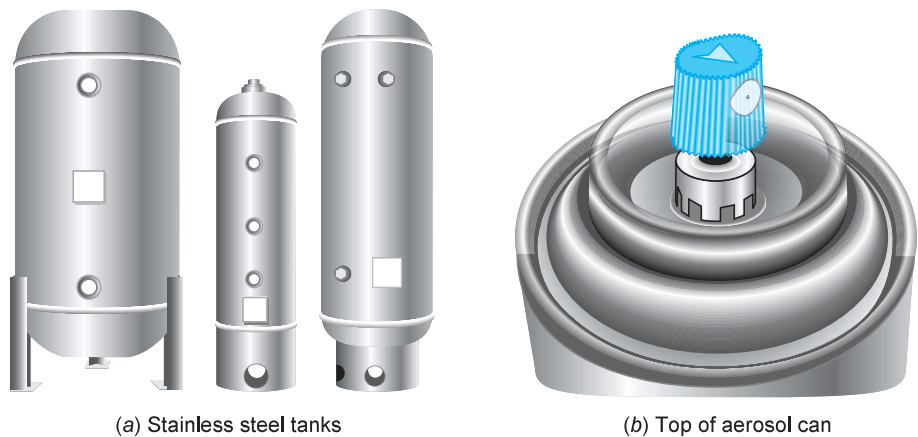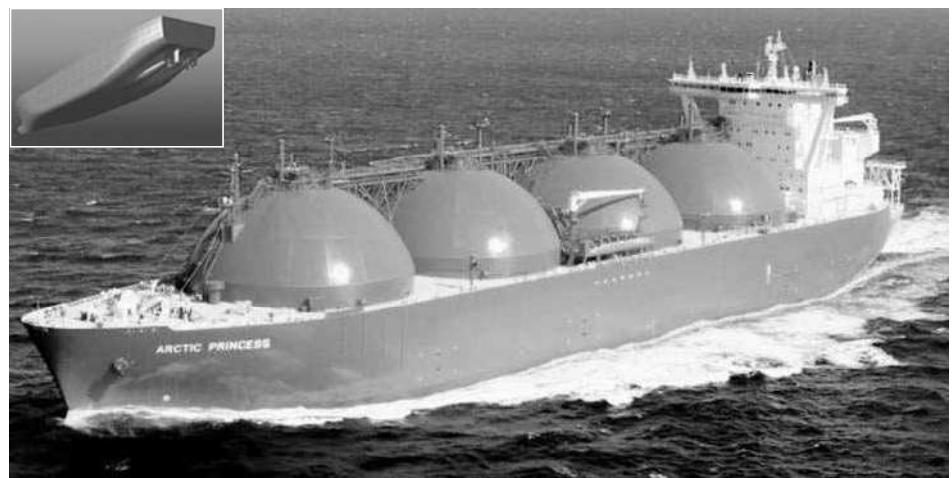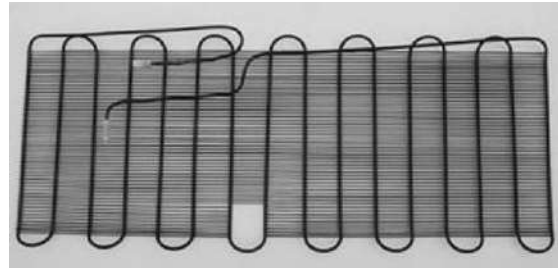

FIGURE 3.25 Storage tanks.

(a) Stainless steel tanks

(b) Top of aerosol can

FIGURE 3.26 A tanker to transport liquefied natural gas (LNG), which is mainly methane.

FIGURE 3.27
Household refrigerator components.

(*a*) Compressor

(*b*) Condenser

FIGURE 3.28
Thermal expansion joints.

(*a*) Railroad tracks

(*b*) Bridge expansion joint

FIGURE 3.29 Hot air balloon.

the pressure becomes. When the refrigerant condenses, the temperature is determined by the saturation temperature for that pressure, so the system must be designed to hold the temperature and pressure within a desirable range (Fig. 3.27).

The effect of expansion-contraction of matter with temperature is important in many different situations. Two of those are shown in Fig. 3.28; the railroad tracks have small gaps to allow for expansion, which leads to the familiar clunk-clunk sound from the train wheels when they roll over the gap. A bridge may have a finger joint that provides a continuous support surface for automobile tires so that they do not bump, as the train does.

When air expands at constant pressure, it occupies a larger volume; thus, the density is smaller. This is how a hot air balloon can lift a gondola and people with a total mass equal to the difference in air mass between the hot air inside the balloon and the surrounding colder air; this effect is called buoyancy (Fig. 3.29).

SUMMARY

Thermodynamic properties of a pure substance and the phase boundaries for solid, liquid, and vapor states are discussed. Phase equilibrium for vaporization (boiling liquid to vapor), or the opposite, condensation (vapor to liquid); sublimation (solid to vapor) or the opposite, solidification (vapor to solid); and melting (solid to liquid) or the opposite, solidifying (liquid to solid), should be recognized. The three-dimensional P–v–T surface and the two-dimensional representations in the (P, T), (T, v) and (P, v) diagrams, and the vaporization, sublimation, and fusion lines, are related to the printed tables in Appendix B. Properties from printed and computer tables covering a number of substances are introduced, including two-phase mixtures, for which we use the mass fraction of vapor (quality). The ideal-gas law approximates the limiting behavior for low density. An extension of the ideal-gas law is shown with the compressibility factor Z, and other, more complicated equations of state are mentioned.

You should have learned a number of skills and acquired abilities from studying this chapter that will allow you to

- Know phases and the nomenclature used for states and interphases.
- Identify a phase given a state (T, P).
- Locate states relative to the critical point and know Tables A.2 (F.1) and 3.2.
- Recognize phase diagrams and interphase locations.
- Locate states in the Appendix B tables with any entry: (T, P), (T, v), or (P, v)
- Recognize how the tables show parts of the (T, P), (T, v), or (P, v) diagrams.
- Find properties in the two-phase regions; use quality x.
- Locate states using any combination of (T, P, v, x) including linear interpolation.
- Know when you have a liquid or solid and the properties in Tables A.3 and A.4 (F.2 and F.3).
- Know when a vapor is an ideal gas (or how to find out).
- Know the ideal-gas law and Table A.5 (F.4).
- Know the compressibility factor Z and the compressibility chart, Fig. D.1.
- Know the existence of more general equations of state.
- Know how to get properties from the computer program.

KEY CONCEPTS AND FORMULAS	Phases	Solid, liquid, and vapor (gas)
	Phase equilibrium	T_{sat}, P_{sat}, v_f, v_g, v_i
	Multiphase boundaries	Vaporization, sublimation, and fusion lines:
		Figs. 3.5 (general), 3.6 (CO_2), and 3.7 (water)
		Critical point: Table 3.1, Table A.2 (F.1)
		Triple point: Table 3.2
	Equilibrium state	Two independent properties (#1, #2)
	Quality	$x = m_{vap}/m$ (vapor mass fraction)
		$1 - x = m_{liq}/m$ (liquid mass fraction)
	Average specific volume	$v = (1 - x)v_f + xv_g$ (only two-phase mixture)
	Equilibrium surface	P–v–T Tables or equation of state
	Ideal-gas law	$Pv = RT$ $PV = mRT = n\bar{R}T$
	Universal gas constant	$\bar{R} = 8.3145 \text{ kJ/kmol K}$
	Gas constant	$R = \bar{R}/M$ kJ/kg K, Table A.5 or M from Table A.2
		ft lbf/lbm R, Table F.4 or M from Table F.1
	Compressibility factor Z	$Pv = ZRT$ Chart for Z in Fig. D.1
	Reduced properties	$P_r = \dfrac{P}{P_c}$ $T_r = \dfrac{T}{T_c}$ Entry to compressibility chart
	Equations of state	Cubic, pressure explicit: Appendix D, Table D.1
		Lee Kesler: Appendix D, Table D.2, and Fig. D.1

CONCEPT-STUDY GUIDE PROBLEMS

3.1 Are the pressures in the tables absolute or gauge pressures?

3.2 What is the minimum pressure for liquid carbon dioxide?

3.3 When you skate on ice, a thin liquid film forms under the skate; why?

3.4 At higher elevations, as in mountains, air pressure is lower; how does that affect the cooking of food?

3.5 Water at room temperature and room pressure has $v \approx 1 \times 10^n$ m³/kg; what is n?

3.6 In Example 3.1 b, is there any mass at the indicated specific volume? Explain.

3.7 Sketch two constant-pressure curves (500 kPa and 30 000 kPa) in a T–v diagram and indicate on the curves where in the water tables the properties are found.

3.8 If I have 1 L of ammonia at room pressure and temperature (100 kPa, 20°C), what is the mass?

3.9 Locate the state of ammonia at 200 kPa, −10°C. Indicate in both the P–v and T–v diagrams the location of the nearest states listed in Table B.2.

3.10 Why are most compressed liquid or solid regions not included in the printed tables?

3.11 How does a constant-v process for an ideal gas appear in a P–T diagram?

3.12 If $v = RT/P$ for an ideal gas, what is the similar equation for a liquid?

3.13 How accurate (find Z) is it to assume that propane is an ideal gas at room conditions?

3.14 With $T_r = 0.80$, what is the ratio of v_g/v_f using Fig. D.1 or Table D.4?

3.15 To solve for v given (P, T) in Eq. 3.9, what is the mathematical problem?

HOMEWORK PROBLEMS

Phase Diagrams, Triple and Critical Points

3.16 Carbon dioxide at 280 K can be in three different phases: vapor, liquid, and solid. Indicate the pressure range for each phase.

3.17 Modern extraction techniques can be based on dissolving material in supercritical fluids such as carbon dioxide. How high are the pressure and density of carbon dioxide when the pressure and temperature are around the critical point? Repeat for ethyl alcohol.

3.18 The ice cap at the North Pole may be 1000 m thick, with a density of 920 kg/m^3. Find the pressure at the bottom and the corresponding melting temperature.

3.19 Find the lowest temperature at which it is possible to have water in the liquid phase. At what pressure must the liquid exist?

3.20 Water at 27°C can exist in different phases, depending on the pressure. Give the approximate pressure range in kPa for water in each of the three phases: vapor, liquid, and solid.

3.21 Dry ice is the name of solid carbon dioxide. How cold must it be at atmospheric (100 kPa) pressure? If it is heated at 100 kPa, what eventually happens?

3.22 Find the lowest temperature in Kelvin for which metal can exist as a liquid if the metal is (a) silver or (b) copper.

3.23 A substance is at 2 MPa and 17°C in a rigid tank. Using only the critical properties, can the phase of the mass be determined if the substance is nitrogen, water, or propane?

3.24 Give the phase for the following states:
a. CO_2 at $T = 40$°C and $P = 0.5$ MPa
b. Air at $T = 20$°C and $P = 200$ kPa
c. NH_3 at $T = 170$°C and $P = 600$ kPa

General Tables

3.25 Determine the phase of water at
a. $T = 260$°C, $P = 5$ MPa
b. $T = -2$°C, $P = 100$ kPa

3.26 Determine the phase of the substance at the given state using Appendix B tables.
a. Water: 100°C, 500 kPa
b. Ammonia: −10°C, 150 kPa
c. R-410a: 0°C, 350 kPa

3.27 Determine whether water at each of the following states is a compressed liquid, a superheated vapor, or a mixture of saturated liquid and vapor:
a. 10 MPa, 0.003 m^3/kg   c. 200°C, 0.1 m^3/kg
b. 1 MPa, 190°C   d. 10 kPa, 10°C

3.28 For water at 100 kPa with a quality of 10%, find the volume fraction of vapor.

3.29 Determine whether refrigerant R-410a in each of the following states is a compressed liquid, a superheated vapor, or a mixture of saturated liquid and vapor.
a. 50°C, 0.05 m^3/kg   c. 0.1 MPa, 0.1 m^3/kg
b. 1.0 MPa, 20°C   d. −20°C, 200 kPa

3.30 Show the states in Problem 3.29 in a sketch of the P–v diagram.

3.31 How great is the change in the liquid specific volume for water at 20°C as you move up from state i toward state j in Fig. 3.12, reaching 15 000 kPa?

3.32 Fill out the following table for substance ammonia:

	P[kPa]	T[°C]	v[m^3/kg]	x
a.		50	0.1185	
b.		50		0.5

3.33 Place the two states a–b listed in Problem 3.32 as labeled dots in a sketch of the P–v and T–v diagrams.

3.34 Give the missing property of P, T, v, and x for R-134a at
a. $T = -20$°C, $P = 150$ kPa
b. $P = 300$ kPa, $v = 0.072$ m^3/kg

3.35 Fill out the following table for substance water:

	P[kPa]	T[°C]	v[m^3/kg]	x
a.	500	20		
b.	500		0.20	
c.	1400	200		
d.		300		0.8

3.36 Place the four states a–d listed in Problem 3.35 as labeled dots in a sketch of the P–v and T–v diagrams.

3.37 Determine the specific volume for R-410a at these states:
a. $-15°C$, 500 kPa
b. $20°C$, 1000 kPa
c. $20°C$, quality 25%

3.38 Give the missing property of P, T, v, and x for CH_4 at
a. $T = 155$ K, $v = 0.04$ m³/kg
b. $T = 350$ K, $v = 0.25$ m³/kg

3.39 Give the specific volume of carbon dioxide at $-20°C$ for 2000 kPa and for 1400 kPa.

3.40 Calculate the following specific volumes:
a. Carbon dioxide: $10°C$, 80% quality
b. Water: 4 MPa, 90% quality
c. Nitrogen: 120 K, 60% quality

3.41 Give the phase and P, x for nitrogen at
a. $T = 120$ K, $v = 0.006$ m³/kg
b. $T = 140$ K, $v = 0.002$ m³/kg

3.42 You want a pot of water to boil at $105°C$. How heavy a lid should you put on the 15-cm-diameter pot when $P_{atm} = 101$ kPa?

3.43 Water at $120°C$ with a quality of 25% has its temperature raised $20°C$ in a constant-volume process. What is the new quality and pressure?

3.44 A sealed rigid vessel has volume of 1 m³ and contains 2 kg of water at $100°C$. The vessel is now heated. If a safety pressure valve is installed, at what pressure should the valve be set to have a maximum temperature of $200°C$?

3.45 Saturated water vapor at 200 kPa is in a constant-pressure piston/cylinder assembly. At this state the piston is 0.1 m from the cylinder bottom. How much is this distance and what is the temperature if the water is cooled to occupy half of the original volume?

3.46 Saturated liquid water at $60°C$ is put under pressure to decrease the volume by 1% while keeping the temperature constant. To what pressure should it be compressed?

3.47 Water at 200 kPa with a quality of 25% has its temperature raised $20°C$ in a constant-pressure process. What is the new quality and volume?

3.48 In your refrigerator, the working substance evaporates from liquid to vapor at $-20°C$ inside a pipe around the cold section. Outside (on the back or below) is a black grille, inside of which the working substance condenses from vapor to liquid at $+40°C$. For each location, find the pressure and the change in specific volume (v) if the substance is ammonia.

3.49 Repeat the previous problem with the substances
a. R-134a
b. R-410a

3.50 Repeat Problem 3.48 with carbon dioxide, condenser at $+20°C$ and evaporator at $-30°C$.

3.51 A glass jar is filled with saturated water at 500 kPa of quality 25%, and a tight lid is put on. Now it is cooled to $-10°C$. What is the mass fraction of solid at this temperature?

3.52 Two tanks are connected as shown in Fig. P3.52, both containing water. Tank A is at 200 kPa, $v = 0.5$ m³/kg, $V_A = 1$ m³, and tank B contains 3.5 kg at 0.5 MPa and $400°C$. The valve is now opened and the two tanks come to a uniform state. Find the final specific volume.

FIGURE P3.52

3.53 Saturated vapor R-134a at $50°C$ changes volume at constant temperature. Find the new pressure, and quality if saturated, if the volume doubles. Repeat the problem for the case where the volume is reduced to half of the original volume.

3.54 A steel tank contains 6 kg of propane (liquid + vapor) at $20°C$ with a volume of 0.015 m³. The tank is now slowly heated. Will the liquid level inside eventually rise to the top or drop to the bottom of the tank? What if the initial mass is 1 kg instead of 6 kg?

3.55 Saturated water vapor at $60°C$ has its pressure decreased to increase the volume by 10% while keeping the temperature constant. To what pressure should it be expanded?

3.56 Ammonia at $20°C$ with a quality of 50% and a total mass of 2 kg is in a rigid tank with an outlet valve at the bottom. How much liquid mass can be removed through the valve, assuming that the temperature stays constant?

3.57 A sealed, rigid vessel of 2 m³ contains a saturated mixture of liquid and vapor R-134a at 10°C. If it is heated to 50°C, the liquid phase disappears. Find the pressure at 50°C and the initial mass of the liquid.

3.58 A storage tank holds methane at 120 K, with a quality of 25%, and it warms up by 5°C per hour due to a failure in the refrigeration system. How much time will it take before the methane becomes single phase, and what is the pressure then?

3.59 Ammonia at 10°C with a mass of 10 kg is in a piston/cylinder assembly with an initial volume of 1 m³. The piston initially resting on the stops has a mass such that a pressure of 900 kPa will float it. Now the ammonia is slowly heated to 50°C. Find the final pressure and volume.

3.60 A 400-m³ storage tank is being constructed to hold liquified natural gas (LGN), which may be assumed to be essentially pure methane. If the tank is to contain 90% liquid and 10% vapor, by volume, at 100 kPa, what mass of LNG (kg) will the tank hold? What is the quality in the tank?

3.61 A boiler feed pump delivers 0.05 m³/s of water at 240°C, 20 MPa. What is the mass flow rate (kg/s)? What would be the percent error if the properties of saturated liquid at 240°C were used in the calculation? What if the properties of saturated liquid at 20 MPa were used?

3.62 A piston/cylinder arrangement is loaded with a linear spring and the outside atmosphere. It contains water at 5 MPa, 400°C, with the volume being 0.1 m³, as shown in Fig. P3.62. If the piston is at the bottom, the spring exerts a force such that $P_{lift} = 200$ kPa. The system now cools until the pressure reaches 1200 kPa. Find the mass of water and the final state (T_2, v_2) and plot the P–v diagram for the process.
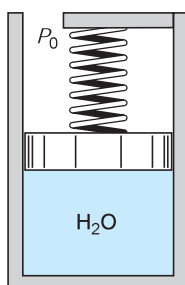

FIGURE P3.62

3.63 A pressure cooker (closed tank) contains water at 100°C, with the liquid volume being 1/10th of the vapor volume. It is heated until the pressure reaches 2.0 MPa. Find the final temperature. Has the final state more or less vapor than the initial state?

3.64 A pressure cooker has the lid screwed on tight. A small opening with $A = 5$ mm² is covered with a petcock that can be lifted to let steam escape. How much mass should the petcock have to allow boiling at 120°C with an outside atmosphere at 101.3 kPa?
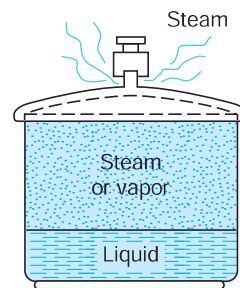

FIGURE P3.64

Ideal Gas

3.65 What is the relative (%) change in P if we double the absolute temperature of an ideal gas, keeping the mass and volume constant? Repeat if we double V, keeping m and T constant.

3.66 A 1-m³ tank is filled with a gas at room temperature (20°C) and pressure (100 kPa). How much mass is there if the gas is (a) air, (b) neon, or (c) propane?

3.67 Calculate the ideal-gas constant for argon and hydrogen based on Table A.2 and verify the value with Table A.5.

3.68 A pneumatic cylinder (a piston/cylinder with air) must close a door with a force of 500 N. The cylinder's cross-sectional area is 5 cm² and its volume is 50 cm³. What is the air pressure and its mass?

3.69 Is it reasonable to assume that at the given states the substance behaves as an ideal gas?
   a. Oxygen at 30°C, 3 MPa
   b. Methane at 30°C, 3 MPa
   c. Water at 30°C, 3 MPa
   d. R-134a at 30°C, 3 MPa
   e. R-134a at 30°C, 100 kPa

3.70 Helium in a steel tank is at 250 kPa, 300 K with a volume of 0.1 m³. It is used to fill a balloon. When the pressure drops to 150 kPa, the flow of helium

stops by itself. If all the helium is still at 300 K, how big a balloon is produced?

3.71 A hollow metal sphere with an inside diameter of 150 mm is weighed on a precision beam balance when evacuated and again after being filled to 875 kPa with an unknown gas. The difference in mass is 0.0025 kg, and the temperature is 25°C. What is the gas, assuming it is a pure substance listed in Table A.5?

3.72 A spherical helium balloon 10 m in diameter is at ambient T and P, 15°C and 100 kPa. How much helium does it contain? It can lift a total mass that equals the mass of displaced atmospheric air. How much mass of the balloon fabric and cage can then be lifted?

3.73 A glass is cleaned in hot water at 45°C and placed on the table bottom up. The room air at 20°C that was trapped in the glass is heated up to 40°C and some of it leaks out, so the net resulting pressure inside is 2 kPa above the ambient pressure of 101 kPa. Now the glass and the air inside cool down to room temperature. What is the pressure inside the glass?

3.74 Air in an internal-combustion engine has 227°C, 1000 kPa, with a volume of 0.1 m³. Combustion heats it to 1500 K in a constant-volume process. What is the mass of air, and how high does the pressure become?

3.75 Air in an automobile tire is initially at −10°C and 190 kPa. After the automobile is driven awhile, the temperature rises to 10°C. Find the new pressure. You must make one assumption on your own.
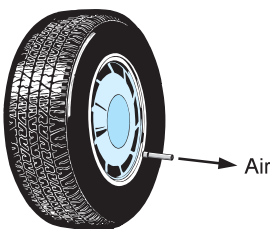

FIGURE P3.75

3.76 A rigid tank of 1 m³ contains nitrogen gas at 600 kPa, 400 K. By mistake, someone lets 0.5 kg flow out. If the final temperature is 375 K, what is the final pressure?

3.77 Assume we have three states of saturated vapor R-134a at +40°C, 0°C, and −40°C. Calculate the

specific volume at the set of temperatures and corresponding saturated pressure assuming ideal-gas behavior. Find the percent relative error $= 100(v − v_g)/v_g$ with v_g from the saturated R-134a table.

3.78 Do Problem 3.77 for R-410a.

3.79 Do Problem 3.77, but for the substance ammonia.

3.80 A 1-m³ rigid tank has propane at 100 kPa, 300 K and connected by a valve to another tank of 0.5 m³ with propane at 250 kPa, 400 K. The valve is opened, and the two tanks come to a uniform state at 325 K. What is the final pressure?
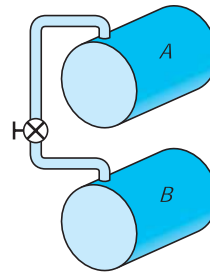

FIGURE P3.80

3.81 A vacuum pump is used to evacuate a chamber where some specimens are dried at 50°C. The pump rate of volume displacement is 0.5 m³/s, with an inlet pressure of 0.1 kPa and a temperature of 50°C. How much water vapor has been removed over a 30-min period?

3.82 A 1-m³ rigid tank with air at 1 MPa and 400 K is connected to an air line as shown in Fig. P3.82. The valve is opened and air flows into the tank until the pressure reaches 5 MPa, at which point the valve is closed and the temperature inside is 450 K.
   a. What is the mass of air in the tank before and after the process?
   b. The tank eventually cools to room temperature, 300 K. What is the pressure inside the tank then?
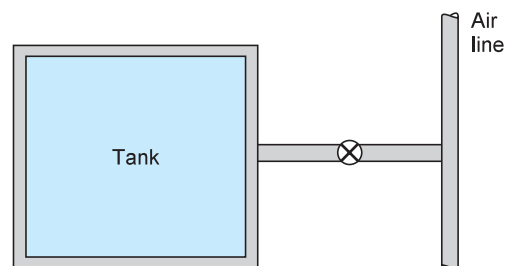

FIGURE P3.82

3.83 A cylindrical gas tank 1 m long, with an inside diameter of 20 cm, is evacuated and then filled with carbon dioxide gas at 20°C. To what pressure should it be charged if there is 1.2 kg of carbon dioxide?

3.84 Ammonia in a piston/cylinder arrangement is at 700 kPa and 80°C. It is now cooled at constant pressure to saturated vapor (state 2), at which point the piston is locked with a pin. The cooling continues to −10°C (state 3). Show the processes 1 to 2 and 2 to 3 on both a P–v and a T–v diagram.

Compressibility Factor

3.85 Find the compressibility factor (Z) for saturated vapor ammonia at 100 kPa and at 2000 kPa.

3.86 Carbon dioxide at 60°C is pumped at a very high pressure, 10 MPa, into an oil well to reduce the viscosity of oil for better flow. What is its compressibility?

3.87 Find the compressibility for carbon dioxide at 60°C and 10 MPa using Fig. D.1.

3.88 What is the percent error in specific volume if the ideal-gas model is used to represent the behavior of superheated ammonia at 40°C and 500 kPa? What if the generalized compressibility chart, Fig. D.1, is used instead?

3.89 A cylinder fitted with a frictionless piston contains butane at 25°C, 500 kPa. Can the butane reasonably be assumed to behave as an ideal gas at this state?

3.90 Estimate the saturation pressure of chlorine at 300 K.

3.91 A bottle with a volume of 0.1 m³ contains butane with a quality of 75% and a temperature of 300 K. Estimate the total butane mass in the bottle using the generalized compressibility chart.

3.92 Find the volume of 2 kg of ethylene at 270 K, 2500 kPa using Z from Fig. D.1.

3.93 With $T_r = 0.85$ and a quality of 0.6, find the compressibility factor using Fig. D.1.

3.94 Argon is kept in a rigid 5-m³ tank at −30°C and 3 MPa. Determine the mass using the compressibility factor. What is the error (%) if the ideal-gas model is used?

3.95 Refrigerant R-32 is at −10°C with a quality of 15%. Find the pressure and specific volume.

3.96 To plan a commercial refrigeration system using R-123, we would like to know how much more volume saturated vapor R-123 occupies per kg at −30°C compared to the saturated liquid state.

3.97 A new refrigerant, R-125, is stored as a liquid at −20°C with a small amount of vapor. For 1.5 kg of R-125, find the pressure and volume.

Equations of State

For these problems see Appendix D for the equation of state (EOS) and Chapter 14.

3.98 Determine the pressure of nitrogen at 160 K, $v = 0.00291$ m³/kg using ideal gas, the van der Waals EOS, and the nitrogen table.

3.99 Determine the pressure of nitrogen at 160 K, $v = 0.00291$ m³/kg using the Redlich-Kwong EOS and the nitrogen table.

3.100 Determine the pressure of nitrogen at 160 K, $v = 0.00291$ m³/kg using the Soave EOS and the nitrogen table.

3.101 Carbon dioxide at 60°C is pumped at a very high pressure, 10 MPa, into an oil well to reduce the viscosity of oil for better flow. Find its specific volume from the carbon dioxide table, ideal gas, and van der Waals EOS by iteration.

3.102 Solve the previous problem using the Redlich-Kwong EOS. Notice that this becomes a trial-and-error process.

3.103 Solve Problem 3.101 using the Soave EOS. Notice that this becomes a trial-and-error process.

3.104 A tank contains 8.35 kg of methane in 0.1 m³ at 250 K. Find the pressure using ideal gas, the van der Waals EOS, and the methane table.

3.105 Do the previous problem using the Redlich-Kwong EOS.

3.106 Do Problem 3.104 using the Soave EOS.

Review Problems

3.107 Determine the quality (if saturated) or temperature (if superheated) of the following substances at the given two states:
   a. Water at
      1: 120°C, 1 m³/kg; 2: 10 MPa, 0.01 m³/kg
   b. Nitrogen at
      1: 1 MPa, 0.03 m³/kg; 2: 100 K, 0.03 m³/kg

3.108 Give the phase and the missing properties of P, T, v, and x for
   a. R-410a at 10°C with $v = 0.01$ m³/kg
   b. Water at $T = 350$°C with $v = 0.2$ m³/kg

c. R-410a at $-5°C$ and $P = 600$ kPa

d. R-134a at 294 kPa and $v = 0.05$ m³/kg

3.109 Find the phase, the quality x if applicable, and the missing property P or T.

a. H_2O at $T = 120°C$ with $v = 0.5$ m³/kg

b. H_2O at $P = 100$ kPa with $v = 1.8$ m³/kg

c. H_2O at $T = 263$ K with $v = 200$ m³/kg

3.110 Find the phase, quality x, if applicable, and the missing property P or T.

a. NH_3 at $P = 800$ kPa with $v = 0.2$ m³/kg

b. NH_3 at $T = 20°C$ with $v = 0.1$ m³/kg

3.111 Give the phase and the missing properties of P, T, v, and x. These may be a little more difficult to determine if the appendix tables are used instead of the software.

a. R-410a, $T = 10°C$, $v = 0.02$ m³/kg

b. H_2O, $v = 0.2$ m³/kg, $x = 0.5$

c. H_2O, $T = 60°C$, $v = 0.001016$ m³/kg

d. NH_3, $T = 30°C$, $P = 60$ kPa

e. R-134a, $v = 0.005$ m³/kg, $x = 0.5$

3.112 Refrigerant-410a in a piston/cylinder arrangement is initially at $15°C$ with $x = 1$. It is then expanded in a process so that $P = Cv^{-1}$ to a pressure of 200 kPa. Find the final temperature and specific volume.

3.113 Consider two tanks, A and B, connected by a valve, as shown in Fig. P3.113. Each has a volume of 200 L, and tank A has R-410a at $25°C$, 10% liquid and 90% vapor by volume, while tank B is evacuated. The valve is now opened, and saturated vapor flows from A to B until the pressure in B has reached that in A, at which point the valve is closed. This process occurs slowly such that all temperatures stay at $25°C$ throughout the process. How much has the quality changed in tank A during the process?
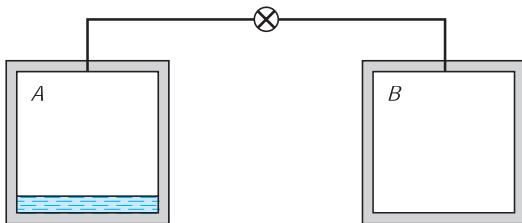

FIGURE P3.113

3.114 Water in a piston/cylinder is at $90°C$, 100 kPa, and the piston loading is such that pressure is proportional to volume, $P = CV$. Heat is now added until the temperature reaches $200°C$. Find the final

pressure and also the quality if the water is in the two-phase region.

3.115 A tank contains 2 kg of nitrogen at 100 K with a quality of 50%. Through a volume flowmeter and valve, 0.5 kg is now removed while the temperature remains constant. Find the final state inside the tank and the volume of nitrogen removed if the valve/meter is located at

a. the top of the tank

b. the bottom of the tank

3.116 A spring-loaded piston/cylinder assembly contains water at $500°C$ and 3 MPa. The setup is such that pressure is proportional to volume, $P = CV$. It is now cooled until the water becomes saturated vapor. Sketch the P–v diagram and find the final pressure.

3.117 A container with liquid nitrogen at 100 K has a cross-sectional area of 0.5 m², as shown in Fig. P3.117. Due to heat transfer, some of the liquid evaporates, and in 1 hour the liquid level drops 30 mm. The vapor leaving the container passes through a valve and a heater and exits at 500 kPa, 260 K. Calculate the volume rate of flow of nitrogen gas exiting the heater.
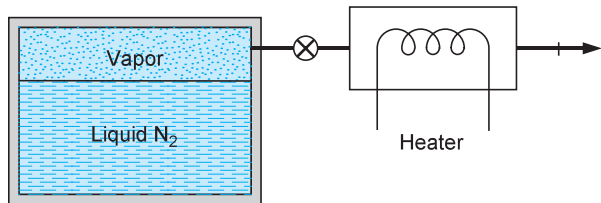

FIGURE P3.117

3.118 For a certain experiment, R-410a vapor is contained in a sealed glass tube at $20°C$. We want to know the pressure at this condition, but there is no means of measuring it, since the tube is sealed. However, if the tube is cooled to $-20°C$, small droplets of liquid are observed on the glass walls. What is the initial pressure?

3.119 A cylinder/piston arrangement contains water at $105°C$, 85% quality, with a volume of 1 L. The system is heated, causing the piston to rise and encounter a linear spring, as shown in Fig. P3.119. At this point the volume is 1.5 L, the piston diameter is 150 mm, and the spring constant is 100 N/mm. The heating continues, so the piston compresses the

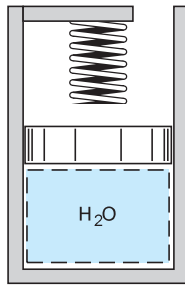spring. What is the cylinder temperature when the pressure reaches 200 kPa?

FIGURE P3.119

3.120 Determine the mass of methane gas stored in a 2-m^3 tank at $-30°$C, 2 MPa. Estimate the percent error in the mass determination if the ideal-gas model is used.

3.121 A cylinder containing ammonia is fitted with a piston restrained by an external force that is proportional to the cylinder volume squared. Initial conditions are $10°$C, 90% quality, and a volume of 5 L. A valve on the cylinder is opened and additional ammonia flows into the cylinder until the mass inside has doubled. If at this point the pressure is 1.2 MPa, what is the final temperature?

3.122 A cylinder has a thick piston initially held by a pin, as shown in Fig. P.3.122. The cylinder contains carbon dioxide at 200 kPa and ambient temperature of 290 K. The metal piston has a density of 8000 kg/m^3 and the atmospheric pressure is 101 kPa. The pin is now removed, allowing the piston to move, and
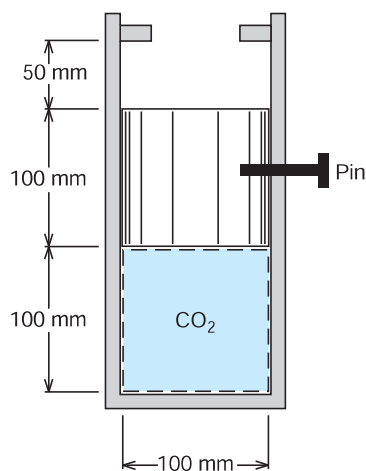

FIGURE P3.122

after a while the gas returns to ambient temperature. Is the piston against the stops?

3.123 What is the percent error in pressure if the ideal-gas model is used to represent the behavior of superheated vapor R-410a at $60°$C, 0.03470 m^3/kg? What if the generalized compressibility chart, Fig. D.1, is used instead? (Note that iterations are needed.)

3.124 An initially deflated and now flat balloon is connected by a valve to a 12-m^3 storage tank containing helium gas at 2 MPa and ambient temperature, $20°$C. The valve is opened and the balloon is inflated at constant pressure, $P_0 = 100$ kPa, equal to ambient pressure, until it becomes spherical at $D_1 = 1$ m. If the balloon is larger than this, the balloon material is stretched, giving an inside pressure of

$$P = P_0 + C\left(1 - \frac{D_1}{D}\right)\frac{D_1}{D}$$

The balloon is inflated to a final diameter of 4 m, at which point the pressure inside is 400 kPa. The temperature remains constant at $20°$C. What is the maximum pressure inside the balloon at any time during the inflation process? What is the pressure inside the helium storage tank at this time?

3.125 A piston/cylinder arrangement, shown in Fig. P3.125, contains air at 250 kPa and $300°$C. The 50-kg piston has a diameter of 0.1 m and initially pushes against the stops. The atmosphere is at 100 kPa and $20°$C. The cylinder now cools as heat is transferred to the ambient surroundings.

a. At what temperature does the piston begin to move down?

b. How far has the piston dropped when the temperature reaches ambient?

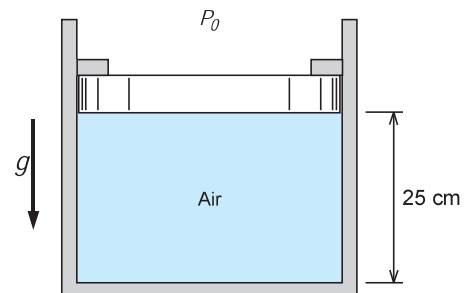c. Show the process in a $P-v$ and a $T-v$ diagram.

FIGURE P3.125

Linear Interpolation

3.126 Find the pressure and temperature for saturated vapor R-410a with $v = 0.1$ m^3/kg.

3.127 Use a linear interpolation to estimate properties of ammonia to fill out the table below.

	P[kPa]	T[°C]	v[m^3/kg]	x
a.	550			0.75
b.	80	20		
c.		10	0.4	

3.128 Use a linear interpolation to estimate T_{sat} at 900 kPa for nitrogen. Sketch by hand the curve $P_{sat}(T)$ by using a few table entries around 900 kPa from Table B.6.1. Is your linear interpolation above or below the actual curve?

3.129 Use a double linear interpolation to find the pressure for superheated R-134a at 13°C with $v = 0.3$ m^3/kg.

3.130 Find the specific volume for carbon dioxide at 0°C and 625 kPa.

Computer Tables

3.131 Use the computer software to find the properties for water at the four states in Problem 3.35.

3.132 Use the computer software to find the properties for ammonia at the four states listed in Problem 3.32.

3.133 Use the computer software to find the properties for ammonia at the three states listed in Problem 3.127.

3.134 Find the value of the saturated temperature for nitrogen by linear interpolation in Table B.6.1 for a pressure of 900 kPa. Compare this to the value given by the computer software.

3.135 Use the computer software to sketch the variation of pressure with temperature in Problem 3.44. Extend the curve slightly into the single-phase region.

ENGLISH UNIT PROBLEMS

English Unit Concept Problems

3.136E Cabbage needs to be cooked (boiled) at 250 F. What pressure should the pressure cooker be set for?

3.137E If I have 1 ft^3 of ammonia at 15 psia, 60 F, what is the mass?

3.138E For water at 1 atm with a quality of 10%, find the volume fraction of vapor.

3.139E Locate the state of R-134a at 30 psia, 20 F. Indicate in both the $P–v$ and $T–v$ diagrams the location of the nearest states listed in Table F.10.

3.140E Calculate the ideal-gas constant for argon and hydrogen based on Table F.1 and verify the value with Table F.4.

English Unit Problems

3.141E Water at 80 F can exist in different phases, depending on the pressure. Give the approximate pressure range in lbf/in.^{2} for water in each of the three phases: vapor, liquid, or solid.

3.142E A substance is at 300 lbf/in.^{2}, 65 F in a rigid tank. Using only the critical properties, can the phase of the mass be determined if the substance is nitrogen, water, or propane?

3.143E Determine the missing property (of P, T, v, and x if applicable) for water at
   a. 680 psia, 0.03 ft^3/lbm
   b. 150 psia, 320 F
   c. 400 F, 3 ft^3/lbm

3.144E Determine whether water at each of the following states is a compressed liquid, a superheated vapor, or a mixture of saturated liquid and vapor.
   a. 2 lbf/in.^{2}, 50 F
   b. 270 F, 30 lbf/in.^{2}
   c. 160 F, 10 ft^3/lbm

3.145E Give the phase and the missing property of P, T, v, and x for R-134a at
   a. $T = -10$ F, $P = 18$ psia
   b. $P = 40$ psia, $v = 1.3$ ft^3/lbm

3.146E Give the phase and the missing property of P, T, v, and x for ammonia at
   a. $T = 120$ F, $v = 0.9$ ft^3/lbm
   b. $T = 200$ F, $v = 11$ ft^3/lbm

3.147E Give the phase and the specific volume for the following:
   a. R-410a, $T = -25$ F, $P = 30$ lbf/in.^{2}
   b. R-410a, $T = -25$ F, $P = 40$ lbf/in.^{2}
   c. H$_2$O, $T = 280$ F, $P = 35$ lbf/in.^{2}
   d. NH$_3$, $T = 60$ F, $P = 15$ lbf/in.^{2}

3.148E Determine the specific volume for R-410a at these states:
a. 5 F, 75 psia
b. 70 F, 200 psia
c. 70 F, quality 25%

3.149E Give the specific volume of R-410a at 0 F for 70 psia and repeat for 60 psia.

3.150E Saturated liquid water at 150 F is put under pressure to decrease the volume by 1% while keeping the temperature constant. To what pressure should it be compressed?

3.151E A sealed rigid vessel has volume of 35 ft^3 and contains 2 lbm of water at 200 F. The vessel is now heated. If a safety pressure valve is installed, at what pressure should the valve be set to have a maximum temperature of 400 F?

3.152E You want a pot of water to boil at 220 F. How heavy a lid should you put on the 6-in.-diameter pot when $P_{atm} = 14.7$ psia?

3.153E Saturated water vapor at 200 F has its pressure decreased to increase the volume by 10%, keeping the temperature constant. To what pressure should it be expanded?

3.154E A glass jar is filled with saturated water at 300 F and quality 25%, and a tight lid is put on. Now it is cooled to 10 F. What is the mass fraction of solid at this temperature?

3.155E A boiler feed pump delivers 100 ft^3/min of water at 400 F, 3000 lbf/in.^{2} What is the mass flowrate (lbm/s)? What would be the percent error if the properties of saturated liquid at 400 F were used in the calculation? What if the properties of saturated liquid at 3000 lbf/in.^{2} were used?

3.156E A pressure cooker has the lid screwed on tight. A small opening with $A = 0.0075$ in.^{2} is covered with a petcock that can be lifted to let steam escape. How much mass should the petcock have to allow boiling at 250 F with an outside atmosphere of 15 psia?

3.157E Two tanks are connected together as shown in Fig. P3.52, both containing water. Tank A is at 30 lbf/in.^{2}, $v = 8$ ft^3/lbm, $V = 40$ ft^3, and tank B contains 8 lbm at 80 lbf/in.^{2}, 750 F. The valve is now opened, and the two come to a uniform state. Find the final specific volume.

3.158E A steel tank contains 14 lbm of propane (liquid + vapor) at 70 F with a volume of 0.25 ft^3. The tank is now slowly heated. Will the liquid level inside eventually rise to the top or drop to the bottom of the tank? What if the initial mass is 2 lbm instead of 14 lbm?

3.159E Give the phase and the specific volume for the following:
a. CO_2, $T = 510$ F, $P = 75$ lbf/in.^{2}
b. Air, $T = 68$ F, $P = 2$ atm
c. Ar, $T = 300$ F, $P = 30$ lbf/in.^{2}

3.160E A cylindrical gas tank 3 ft long, with an inside diameter of 8 in., is evacuated and then filled with carbon dioxide gas at 77 F. To what pressure should it be charged if there should be 2.6 lbm of carbon dioxide?

3.161E A spherical helium balloon 30 ft in diameter is at ambient T and P, 60 F and 14.69 psia. How much helium does it contain? It can lift a total mass that equals the mass of displaced atmospheric air. How much mass of the balloon fabric and cage can then be lifted?

3.162E Helium in a steel tank is at 36 psia, 540 R with a volume of 4 ft^3. It is used to fill a balloon. When the pressure drops to 20 psia, the flow of helium stops by itself. If all the helium is still at 540 R, how big a balloon is produced?

3.163E A 35-ft^3 rigid tank has propane at 15 psia, 540 R and is connected by a valve to another tank of 20 ft^3 with propane at 40 psia, 720 R. The valve is opened and the two tanks come to a uniform state at 600 R. What is the final pressure?

3.164E What is the percent error in specific volume if the ideal-gas model is used to represent the behavior of superheated ammonia at 100 F, 80 lbf/in.^{2}? What if the generalized compressibility chart, Fig. D.1, is used instead?

3.165E Air in an internal-combustion engine has 440 F, 150 psia, with a volume of 3 ft. Combustion heats it to 2700 R in a constant-volume process. What is the mass of air, and how high does the pressure become?

3.166E A 35-ft^3 rigid tank has air at 225 psia and ambient 600 R connected by a valve to a piston/cylinder. The piston of area 1 ft^2 requires 40 psia below it to float (see Fig. P3.166E). The valve is opened, the piston moves slowly 7 ft up, and the valve

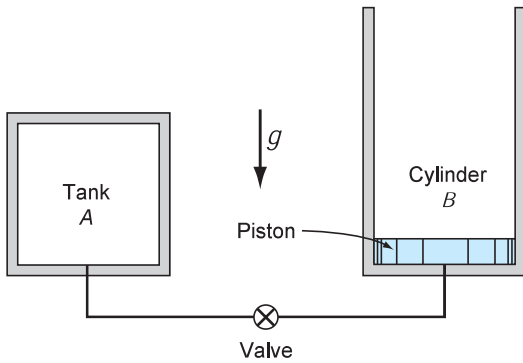is closed. During the process, air temperature remains at 600 R. What is the final pressure in the tank?

FIGURE P3.166E

3.167E Give the phase and the missing properties of P, T, v, and x. These may be a little more difficult to determine if the appendix tables are used instead of the software.
   a. R-410a, $T = 50$ F, $v = 0.4$ ft^3/lbm
   b. H$_2$O, $v = 2$ ft^3/lbm, $x = 0.5$
   c. H$_2$O, $T = 150$ F, $v = 0.01632$ ft^3/lbm
   d. NH$_3$, $T = 80$ F, $P = 13$ lbf/in.^{2}
   e. R-134a, $v = 0.08$ ft^3/lbm, $x = 0.5$

3.168E A pressure cooker (closed tank) contains water at 200 F, with the liquid volume being 1/10th of the vapor volume. It is heated until the pressure reaches 300 lbf/in.^{2} Find the final temperature. Has the final state more or less vapor than the initial state?

3.169E Refrigerant-410a in a piston/cylinder arrangement is initially at 60 F, $x = 1$. It is then expanded in a process so that $P = Cv^{-1}$ to a pressure of 30 lbf/in.^{2} Find the final temperature and specific volume.

3.170E A substance is at 70 F, 300 lbf/in.^{2} in a 10-ft^3 tank. Estimate the mass from the compressibility chart if the substance is (a) air, (b) butane, or (c) propane.

3.171E Determine the mass of an ethane gas stored in a 25-ft^3 tank at 250 F, 440 lbf/in.^{2} using the compressibility chart. Estimate the error (%) if the ideal-gas model is used.

3.172E Determine the pressure of R-410a at 100 F, $v = 0.2$ ft^3/lbm using ideal gas and the van der Waal EOS.

3.173E Determine the pressure of R-410a at 100 F, $v = 0.2$ ft^3/lbm using ideal gas and the Redlich-Kwong EOS.

COMPUTER, DESIGN AND OPEN-ENDED PROBLEMS

3.174 Make a spreadsheet that will tabulate and plot saturated pressure versus temperature for ammonia starting at $T = -40°C$ and ending at the critical point in steps of 10°C.

3.175 Make a spreadsheet that will tabulate and plot values of P and T along a constant specific volume line for water. The starting state is 100 kPa, the quality is 50%, and the ending state is 800 kPa.

3.176 Use the computer software to sketch the variation of pressure with temperature in Problem 3.58. Extend the curve a little into the single-phase region.

3.177 Using the computer software, find a few of the states between the beginning and end states and show the variation of pressure and temperature as a function of volume for Problem 3.114.

3.178 In Problem 3.112 follow the path of the process for the R-410a for any state between the initial and final states inside the cylinder.

3.179 For any specified substance in Tables B.1–B.7, fit a polynomial equation of degree n to tabular data for pressure as a function of density along any given isotherm in the superheated vapor region.

3.180 The refrigerant fluid in a household refrigerator changes phase from liquid to vapor at the low temperature in the refrigerator. It changes phase from vapor to liquid at the higher temperature in the heat exchanger that gives the energy to the room air. Measure or otherwise estimate these temperatures. Based on these temperatures, make a table with the refrigerant pressures for the refrigerants for which tables are available in Appendix B. Discuss the results and the requirements for a substance to be a potential refrigerant.

3.181 Repeat the previous problem for refrigerants listed in Table A.2 and use the compressibility chart, Fig. D.1, to estimate the pressures.

3.182 Saturated pressure as a function of temperature follows the correlation developed by Wagner as

$$\ln P_r = [w_1 \tau + w_2 \tau^{1.5} + w_3 \tau^3 + w_4 \tau^6] / T_r$$

where the reduced pressure and temperature are $P_r = P/P_c$ and $T_r = T/T_c$. The temperature variable is $\tau = 1 - T_r$. The parameters are found for R-134a as

	w_1	w_2	w_3	w_4
R-134a	-7.59884	1.48886	-3.79873	1.81379

Compare this correlation to the table in Appendix B.

3.183 Find the constants in the curve fit for the saturation pressure using Wagner's correlation, as shown in the previous problem for water and methane. Find other correlations in the literature, compare them to the tables, and give the maximum deviation.

3.184 The specific volume of saturated liquid can be approximated by the Rackett equation as

$$v_f = \frac{\bar{R}T_c}{MP_c} Z_c^n; n = 1 + (1 - T_r)^{2/7}$$

with the reduced temperature, $T_r = T/T_c$, and the compressibility factor, $Z_c = P_c v_c / RT_c$. Using values from Table A.2 with the critical constants, compare the formula to the tables for substances where the saturated specific volume is available.