3-61 The properties of compressed liquid water at a specified state are to be determined using the compressed liquid tables, and also by using the saturated liquid approximation, and the results are to be compared.

Analysis Compressed liquid can be approximated as saturated liquid at the given temperature. Then from Table A-4,

$$T = 100°C \quad \Rightarrow \quad v \cong v_{f\,@\,100°C} = 0.001043 \text{ m}^3/\text{kg} \quad (0.72\% \text{ error})$$
$$u \cong u_{f\,@\,100°C} = 419.06 \text{ kJ/kg} \quad (1.02\% \text{ error})$$
$$h \cong h_{f\,@\,100°C} = 419.17 \text{ kJ/kg} \quad (2.61\% \text{ error})$$

From compressed liquid table (Table A-7),

$$\left. \begin{array}{l} P = 15 \text{ MPa} \\ T = 100°C \end{array} \right\} \begin{array}{l} v = 0.001036 \text{ m}^3/\text{kg} \\ u = 414.85 \text{ kJ/kg} \\ h = 430.39 \text{ kJ/kg} \end{array}$$

The percent errors involved in the saturated liquid approximation are listed above in parentheses.

3-62 EES Problem 3-61 is reconsidered. Using EES, the indicated properties of compressed liquid are to be determined, and they are to be compared to those obtained using the saturated liquid approximation.

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

```
Fluid$='Steam_IAPWS'
T = 100 [C]
P = 15000 [kPa]
v = VOLUME(Fluid$,T=T,P=P)
u = INTENERGY(Fluid$,T=T,P=P)
h = ENTHALPY(Fluid$,T=T,P=P)
v_app = VOLUME(Fluid$,T=T,x=0)
u_app = INTENERGY(Fluid$,T=T,x=0)
h_app_1 = ENTHALPY(Fluid$,T=T,x=0)
h_app_2 = ENTHALPY(Fluid$,T=T,x=0)+v_app*(P-pressure(Fluid$,T=T,x=0))
```

```
SOLUTION
Fluid$='Steam_IAPWS'
h=430.4 [kJ/kg]
h_app_1=419.2 [kJ/kg]
h_app_2=434.7 [kJ/kg]
P=15000 [kPa]
T=100 [C]
u=414.9 [kJ/kg]
u_app=419.1 [kJ/kg]
v=0.001036 [m^3/kg]
v_app=0.001043 [m^3/kg]
```

3-63E A rigid tank contains saturated liquid-vapor mixture of R-134a. The quality and total mass of the refrigerant are to be determined.

Analysis At 50 psia, $v_f = 0.01252$ ft^3/lbm and $v_g = 0.94791$ ft^3/lbm (Table A-12E). The volume occupied by the liquid and the vapor phases are

$$V_f = 3 \text{ ft}^3 \quad \text{and} \quad V_g = 12 \text{ ft}^3$$
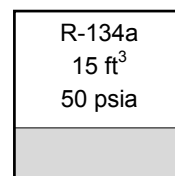
Thus the mass of each phase is

$$m_f = \frac{V_f}{v_f} = \frac{3 \text{ ft}^3}{0.01252 \text{ ft}^3/\text{lbm}} = 239.63 \text{ lbm}$$

$$m_g = \frac{V_g}{v_g} = \frac{12 \text{ ft}^3}{0.94791 \text{ ft}^3/\text{lbm}} = 12.66 \text{ lbm}$$

```
┌─────────────┐
│  R-134a     │
│  15 ft³     │
│  50 psia    │
│             │
│▒▒▒▒▒▒▒▒▒▒▒▒▒│
└─────────────┘
```

Then the total mass and the quality of the refrigerant are

$$m_t = m_f + m_g = 239.63 + 12.66 = \textbf{252.29 lbm}$$

$$x = \frac{m_g}{m_t} = \frac{12.66 \text{ lbm}}{252.29 \text{ lbm}} = \textbf{0.05018}$$

3-64 Superheated steam in a piston-cylinder device is cooled at constant pressure until half of the mass condenses. The final temperature and the volume change are to be determined, and the process should be shown on a T-v diagram.

Analysis (*b*) At the final state the cylinder contains saturated liquid-vapor mixture, and thus the final temperature must be the saturation temperature at the final pressure,

$$T = T_{sat@1 \text{ MPa}} = \textbf{179.88°C} \qquad \text{(Table A-5)}$$

(*c*) The quality at the final state is specified to be $x_2 = 0.5$. The specific volumes at the initial and the final states are
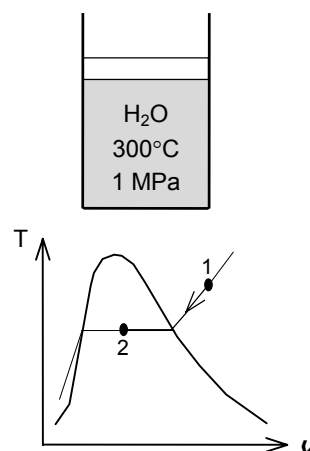
$$\left. \begin{array}{l} P_1 = 1.0 \text{ MPa} \\ T_1 = 300°C \end{array} \right\} v_1 = 0.25799 \text{ m}^3/\text{kg} \qquad \text{(Table A-6)}$$

$$\left. \begin{array}{l} P_2 = 1.0 \text{ MPa} \\ x_2 = 0.5 \end{array} \right\} \begin{array}{l} v_2 = v_f + x_2 v_{fg} \\ = 0.001127 + 0.5 \times (0.19436 - 0.001127) \\ = 0.09775 \text{ m}^3/\text{kg} \end{array}$$

Thus,

$$\Delta V = m(v_2 - v_1) = (0.8 \text{ kg})(0.09775 - 0.25799)\text{m}^3/\text{kg} = \textbf{-0.1282 m}^3$$

```
┌─────────┐
│         │
│─────────│
│  H₂O    │
│  300°C  │
│  1 MPa  │
└─────────┘
```

3-65 The water in a rigid tank is cooled until the vapor starts condensing. The initial pressure in the tank is to be determined.

Analysis This is a constant volume process ($v = V/m$ = constant), and the initial specific volume is equal to the final specific volume that is

$$v_1 = v_2 = v_{g@150°C} = 0.39248 \text{ m}^3/\text{kg} \quad \text{(Table A-4)}$$

since the vapor starts condensing at 150°C. Then from Table A-6,

$$\left. \begin{array}{l} T_1 = 250°C \\ v_1 = 0.39248 \text{ m}^3/\text{kg} \end{array} \right\} \quad P_1 = \textbf{0.60 MPa}$$

H₂O
T₁= 250°C
P₁ = ?
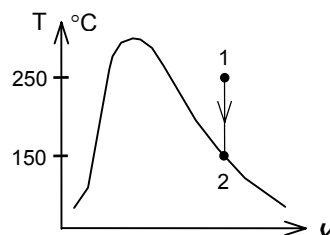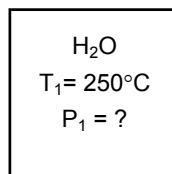
3-66 Water is boiled in a pan by supplying electrical heat. The local atmospheric pressure is to be estimated.

Assumptions 75 percent of electricity consumed by the heater is transferred to the water.

Analysis The amount of heat transfer to the water during this period is

$$Q = fE_{\text{elect}}\text{time} = (0.75)(2 \text{ kJ/s})(30 \times 60 \text{ s}) = 2700 \text{ kJ}$$

The enthalpy of vaporization is determined from

$$h_{fg} = \frac{Q}{m_{\text{boil}}} = \frac{2700 \text{ kJ}}{1.19 \text{ kg}} = 2269 \text{ kJ/kg}$$

Using the data by a trial-error approach in saturation table of water (Table A-5) or using EES as we did, the saturation pressure that corresponds to an enthalpy of vaporization value of 2269 kJ/kg is

$$P_{\text{sat}} = \textbf{85.4 kPa}$$

which is the local atmospheric pressure.

3-67 Heat is supplied to a rigid tank that contains water at a specified state. The volume of the tank, the final temperature and pressure, and the internal energy change of water are to be determined.

Properties The saturated liquid properties of water at 200°C are: v_f = 0.001157 m³/kg and u_f = 850.46 kJ/kg (Table A-4).

Analysis (*a*) The tank initially contains saturated liquid water and air. The volume occupied by water is

$$V_1 = mv_1 = (1.4\,\text{kg})(0.001157\,\text{m}^3/\text{kg}) = 0.001619\,\text{m}^3$$

which is the 25 percent of total volume. Then, the total volume is determined from

$$V = \frac{1}{0.25}(0.001619) = \textbf{0.006476 m}^3$$

(*b*) Properties after the heat addition process are

$$v_2 = \frac{V}{m} = \frac{0.006476\,\text{m}^3}{1.4\,\text{kg}} = 0.004626\,\text{m}^3/\text{kg}$$

$$\left.\begin{array}{l} v_2 = 0.004626\,\text{m}^3/\text{kg} \\ x_2 = 1 \end{array}\right\} \begin{array}{l} T_2 = \textbf{371.3°C} \\ P_2 = \textbf{21,367 kPa} \\ u_2 = 2201.5\,\text{kJ/kg} \end{array} \quad \text{(Table A-4 or A-5 or EES)}$$

(*c*) The total internal energy change is determined from

$$\Delta U = m(u_2 - u_1) = (1.4\,\text{kg})(2201.5 - 850.46)\,\text{kJ/kg} = \textbf{1892 kJ}$$

3-68 Heat is lost from a piston-cylinder device that contains steam at a specified state. The initial temperature, the enthalpy change, and the final pressure and quality are to be determined.

Analysis (*a*) The saturation temperature of steam at 3.5 MPa is

$$T_{\text{sat@3.5 MPa}} = 242.6°C \quad \text{(Table A-5)}$$

Then, the initial temperature becomes

$$T_1 = 242.6 + 5 = \textbf{247.6°C}$$

Also,
$$\left.\begin{array}{l} P_1 = 3.5\,\text{MPa} \\ T_1 = 247.6°C \end{array}\right\} h_1 = 2821.1\,\text{kJ/kg} \quad \text{(Table A-6)}$$

(*b*) The properties of steam when the piston first hits the stops are

$$\left.\begin{array}{l} P_2 = P_1 = 3.5\,\text{MPa} \\ x_2 = 0 \end{array}\right| \begin{array}{l} h_2 = 1049.7\,\text{kJ/kg} \\ v_2 = 0.001235\,\text{m}^3/\text{kg} \end{array} \quad \text{(Table A-5)}$$
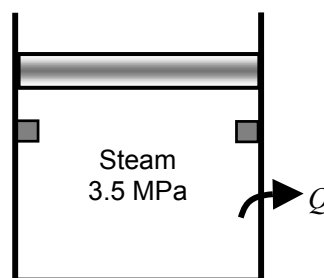
Then, the enthalpy change of steam becomes

$$\Delta h = h_2 - h_1 = 1049.7 - 2821.1 = \textbf{-1771 kJ/kg}$$

(*c*) At the final state

$$\left.\begin{array}{l} v_3 = v_2 = 0.001235\,\text{m}^3/\text{kg} \\ T_3 = 200°C \end{array}\right| \begin{array}{l} P_3 = \textbf{1555 kPa} \\ x_3 = \textbf{0.0006} \end{array} \quad \text{(Table A-4 or EES)}$$

The cylinder contains saturated liquid-vapor mixture with a small mass of vapor at the final state.

Ideal Gas

3-69C Propane (molar mass = 44.1 kg/kmol) poses a greater fire danger than methane (molar mass = 16 kg/kmol) since propane is heavier than air (molar mass = 29 kg/kmol), and it will settle near the floor. Methane, on the other hand, is lighter than air and thus it will rise and leak out.

3-70C A gas can be treated as an ideal gas when it is at a high temperature or low pressure relative to its critical temperature and pressure.

3-71C R_u is the universal gas constant that is the same for all gases whereas R is the specific gas constant that is different for different gases. These two are related to each other by $R = R_u / M$, where M is the molar mass of the gas.

3-72C Mass m is simply the amount of matter; molar mass M is the mass of one mole in grams or the mass of one kmol in kilograms. These two are related to each other by $m = NM$, where N is the number of moles.

3-73 A balloon is filled with helium gas. The mole number and the mass of helium in the balloon are to be determined.

Assumptions At specified conditions, helium behaves as an ideal gas.

Properties The universal gas constant is R_u = 8.314 kPa.m³/kmol.K. The molar mass of helium is 4.0 kg/kmol (Table A-1).
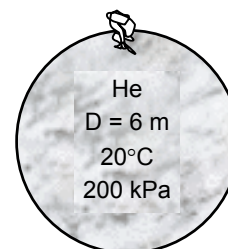
Analysis The volume of the sphere is

$$V = \frac{4}{3}\pi r^3 = \frac{4}{3}\pi(3 \text{ m})^3 = 113.1 \text{ m}^3$$

Assuming ideal gas behavior, the mole numbers of He is determined from

$$N = \frac{PV}{R_u T} = \frac{(200 \text{ kPa})(113.1 \text{ m}^3)}{(8.314 \text{ kPa} \cdot \text{m}^3/\text{kmol} \cdot \text{K})(293 \text{ K})} = \textbf{9.28 kmol}$$

Then the mass of He can be determined from

$$m = NM = (9.28 \text{ kmol})(4.0 \text{ kg/kmol}) = \textbf{37.15 kg}$$

He
D = 6 m
20°C
200 kPa

3-74 EES Problem 3-73 is to be reconsidered. The effect of the balloon diameter on the mass of helium contained in the balloon is to be determined for the pressures of (a) 100 kPa and (b) 200 kPa as the diameter varies from 5 m to 15 m. The mass of helium is to be plotted against the diameter for both cases.

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

"Given Data"
{D=6 [m]}
{P=200 [kPa]}
T=20 [C]
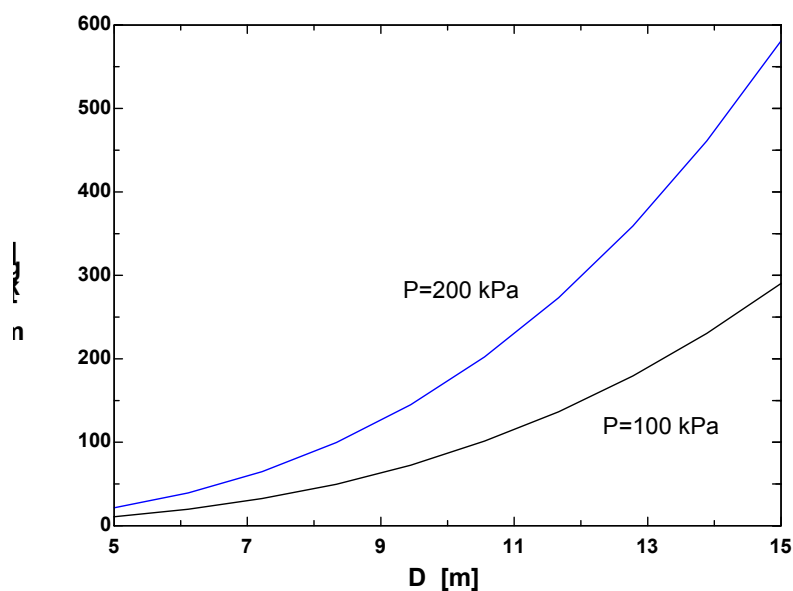P=200 [kPa]
R_u=8.314 [kJ/kmol-K]

"Solution"
P*V=N*R_u*(T+273)
V=4*pi*(D/2)^3/3
m=N*MOLARMASS(Helium)

D [m]	m [kg]
5	21.51
6.111	39.27
7.222	64.82
8.333	99.57
9.444	145
10.56	202.4
11.67	273.2
12.78	359
13.89	461
15	580.7

3-75 An automobile tire is inflated with air. The pressure rise of air in the tire when the tire is heated and the amount of air that must be bled off to reduce the temperature to the original value are to be determined.

Assumptions **1** At specified conditions, air behaves as an ideal gas. **2** The volume of the tire remains constant.

Properties The gas constant of air is $R = 0.287$ kPa.m³/kg.K (Table A-1).

Analysis Initially, the absolute pressure in the tire is

$$P_1 = P_g + P_{atm} = 210 + 100 = 310\text{kPa}$$

Treating air as an ideal gas and assuming the volume of the tire to remain constant, the final pressure in the tire can be determined from

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2} \longrightarrow P_2 = \frac{T_2}{T_1}P_1 = \frac{323 \text{ K}}{298 \text{ K}}(310 \text{ kPa}) = 336 \text{ kPa}$$
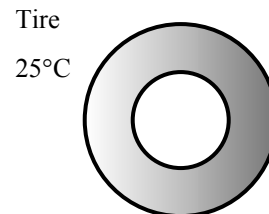
Thus the pressure rise is

$$\Delta P = P_2 - P_1 = 336 - 310 = \textbf{26 kPa}$$

The amount of air that needs to be bled off to restore pressure to its original value is

$$m_1 = \frac{P_1 V}{RT_1} = \frac{(310 \text{ kPa})(0.025 \text{ m}^3)}{(0.287 \text{ kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K})(298 \text{ K})} = 0.0906 \text{ kg}$$

$$m_2 = \frac{P_1 V}{RT_2} = \frac{(310 \text{ kPa})(0.025 \text{ m}^3)}{(0.287 \text{ kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K})(323 \text{ K})} = 0.0836 \text{ kg}$$

$$\Delta m = m_1 - m_2 = 0.0906 - 0.0836 = \textbf{0.0070 kg}$$

Tire
25°C

3-76E An automobile tire is under inflated with air. The amount of air that needs to be added to the tire to raise its pressure to the recommended value is to be determined.

Assumptions **1** At specified conditions, air behaves as an ideal gas. **2** The volume of the tire remains constant.

Properties The gas constant of air is $R = 0.3704$ psia.ft³/lbm.R (Table A-1E).

Analysis The initial and final absolute pressures in the tire are

$$P_1 = P_{g1} + P_{atm} = 20 + 14.6 = 34.6 \text{ psia}$$
$$P_2 = P_{g2} + P_{atm} = 30 + 14.6 = 44.6 \text{ psia}$$

Treating air as an ideal gas, the initial mass in the tire is

$$m_1 = \frac{P_1 V}{RT_1} = \frac{(34.6 \text{ psia})(0.53 \text{ ft}^3)}{(0.3704 \text{ psia} \cdot \text{ft}^3/\text{lbm} \cdot \text{R})(550 \text{ R})} = 0.0900 \text{ lbm}$$

Noting that the temperature and the volume of the tire remain constant, the final mass in the tire becomes

$$m_2 = \frac{P_2 V}{RT_2} = \frac{(44.6 \text{ psia})(0.53 \text{ ft}^3)}{(0.3704 \text{ psia} \cdot \text{ft}^3/\text{lbm} \cdot \text{R})(550 \text{ R})} = 0.1160 \text{ lbm}$$

Thus the amount of air that needs to be added is

$$\Delta m = m_2 - m_1 = 0.1160 - 0.0900 = \textbf{0.0260 lbm}$$

Tire
0.53 ft³
90°F
20 psig
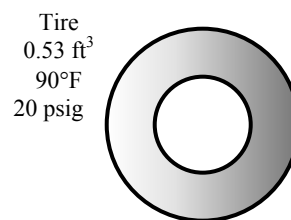
3-77 The pressure and temperature of oxygen gas in a storage tank are given. The mass of oxygen in the tank is to be determined.

Assumptions   At specified conditions, oxygen behaves as an ideal gas
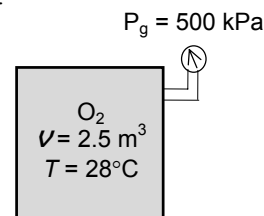
Properties The gas constant of oxygen is $R = 0.2598$ kPa.m^3/kg.K (Table A-1).

Analysis The absolute pressure of O_2 is

$P = P_g + P_{atm} = 500 + 97 = 597$ kPa

Treating O_2 as an ideal gas, the mass of O_2 in tank is determined to be

$$m = \frac{P\mathcal{V}}{RT} = \frac{(597 \text{ kPa})(2.5 \text{ m}^3)}{(0.2598 \text{ kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(28+273)\text{K}} = \textbf{19.08 kg}$$

$P_g = 500$ kPa

O_2
$\mathcal{V} = 2.5$ m^3
$T = 28°C$

3-78E A rigid tank contains slightly pressurized air. The amount of air that needs to be added to the tank to raise its pressure and temperature to the recommended values is to be determined.

Assumptions **1** At specified conditions, air behaves as an ideal gas. **2** The volume of the tank remains constant.

Properties The gas constant of air is $R = 0.3704$ psia.ft^3/lbm.R (Table A-1E).
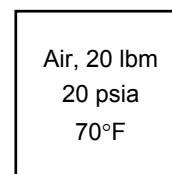
Analysis Treating air as an ideal gas, the initial volume and the final mass in the tank are determined to be

$$\mathcal{V} = \frac{m_1 R T_1}{P_1} = \frac{(20 \text{ lbm})(0.3704 \text{ psia}\cdot\text{ft}^3/\text{lbm}\cdot\text{R})(530 \text{ R})}{20 \text{ psia}} = 196.3 \text{ ft}^3$$

$$m_2 = \frac{P_2\mathcal{V}}{RT_2} = \frac{(35 \text{ psia})(196.3 \text{ ft}^3)}{(0.3704 \text{ psia}\cdot\text{ft}^3/\text{lbm}\cdot\text{R})(550 \text{ R})} = 33.73 \text{ lbm}$$

Air, 20 lbm
20 psia
70°F

Thus the amount of air added is

$\Delta m = m_2 - m_1 = 33.73 - 20.0 = \textbf{13.73 lbm}$

3-79 A rigid tank contains air at a specified state. The gage pressure of the gas in the tank is to be determined.

Assumptions At specified conditions, air behaves as an ideal gas.

Properties The gas constant of air is $R = 0.287$ kPa.m^3/kg.K (Table A-1).

Analysis Treating air as an ideal gas, the absolute pressure in the tank is determined from

$$P = \frac{mRT}{\mathcal{V}} = \frac{(5 \text{ kg})(0.287 \text{ kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(298 \text{ K})}{0.4 \text{ m}^3} = 1069.1 \text{ kPa}$$

P_g

Air
400 L
25°C

Thus the gage pressure is

$P_g = P - P_{atm} = 1069.1 - 97 = \textbf{972.1 kPa}$
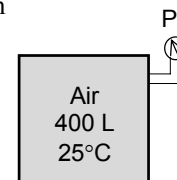
3-80 Two rigid tanks connected by a valve to each other contain air at specified conditions. The volume of the second tank and the final equilibrium pressure when the valve is opened are to be determined.

Assumptions   At specified conditions, air behaves as an ideal gas.

Properties   The gas constant of air is $R = 0.287$ kPa.m³/kg.K (Table A-1).

Analysis Let's call the first and the second tanks A and B. Treating air as an ideal gas, the volume of the second tank and the mass of air in the first tank are determined to be

$$V_B = \left(\frac{m_1 R T_1}{P_1} \right)_B = \frac{(5 \text{ kg})(0.287 \text{ kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K})(308 \text{ K})}{200 \text{ kPa}} = \textbf{2.21 m}^3$$

$$m_A = \left(\frac{P_1 V}{R T_1} \right)_A = \frac{(500 \text{ kPa})(1.0 \text{ m}^3)}{(0.287 \text{ kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K})(298 \text{ K})} = 5.846 \text{ kg}$$

Thus,

$$V = V_A + V_B = 1.0 + 2.21 = 3.21 \text{ m}^3$$
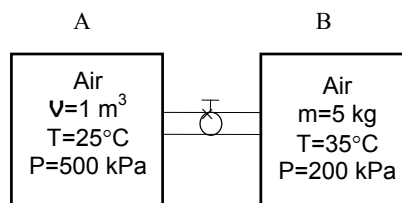
$$m = m_A + m_B = 5.846 + 5.0 = 10.846 \text{ kg}$$

Then the final equilibrium pressure becomes

$$P_2 = \frac{mRT_2}{V} = \frac{(10.846 \text{ kg})(0.287 \text{ kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K})(293 \text{ K})}{3.21 \text{ m}^3} = \textbf{284.1 kPa}$$

A   B

Air	Air
V=1 m³	m=5 kg
T=25°C	T=35°C
P=500 kPa	P=200 kPa

Compressibility Factor

3-81C It represent the deviation from ideal gas behavior. The further away it is from 1, the more the gas deviates from ideal gas behavior.

3-82C All gases have the same compressibility factor Z at the same reduced temperature and pressure.

3-83C Reduced pressure is the pressure normalized with respect to the critical pressure; and reduced temperature is the temperature normalized with respect to the critical temperature.

3-84 The specific volume of steam is to be determined using the ideal gas relation, the compressibility chart, and the steam tables. The errors involved in the first two approaches are also to be determined.

Properties The gas constant, the critical pressure, and the critical temperature of water are, from Table A-1,
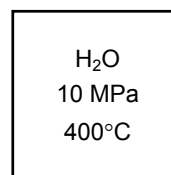
$$R = 0.4615 \text{ kPa·m}^3/\text{kg·K}, \qquad T_{cr} = 647.1 \text{ K}, \qquad P_{cr} = 22.06 \text{ MPa}$$

Analysis (*a*) From the ideal gas equation of state,

$$v = \frac{RT}{P} = \frac{(0.4615 \text{ kPa·m}^3/\text{kg·K})(673 \text{ K})}{(10,000 \text{ kPa})} = \textbf{0.03106 } \text{ m}^3/\text{kg} \quad \textbf{(17.6\% error)}$$

(*b*) From the compressibility chart (Fig. A-15),

$$\left. \begin{aligned} P_R &= \frac{P}{P_{cr}} = \frac{10 \text{ MPa}}{22.06 \text{ MPa}} = 0.453 \\ T_R &= \frac{T}{T_{cr}} = \frac{673 \text{ K}}{647.1 \text{ K}} = 1.04 \end{aligned} \right\} Z = 0.84$$

> H₂O
> 10 MPa
> 400°C

Thus,

$$v = Z v_{\text{ideal}} = (0.84)(0.03106 \text{ m}^3/\text{kg}) = \textbf{0.02609 } \text{ m}^3/\text{kg} \quad \textbf{(1.2\% error)}$$

(*c*) From the superheated steam table (Table A-6),

$$\left. \begin{aligned} P &= 10 \text{ MPa} \\ T &= 400°C \end{aligned} \right\} v = \textbf{0.02644 } \text{ m}^3/\text{kg}$$

3-85 EES Problem 3-84 is reconsidered. The problem is to be solved using the general compressibility factor feature of EES (or other) software. The specific volume of water for the three cases at 10 MPa over the temperature range of 325°C to 600°C in 25°C intervals is to be compared, and the %error involved in the ideal gas approximation is to be plotted against temperature.

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

```
P=10 [MPa]*Convert(MPa,kPa)
{T_Celsius= 400 [C]}
T=T_Celsius+273 "[K]"
T_critical=T_CRIT(Steam_iapws)
P_critical=P_CRIT(Steam_iapws)
{v=Vol/m}
P_table=P; P_comp=P;P_idealgas=P
T_table=T; T_comp=T;T_idealgas=T
v_table=volume(Steam_iapws,P=P_table,T=T_table) "EES data for steam as a real gas"
{P_table=pressure(Steam_iapws, T=T_table,v=v)}
{T_sat=temperature(Steam_iapws,P=P_table,v=v)}
MM=MOLARMASS(water)
R_u=8.314 [kJ/kmol-K]  "Universal gas constant"
R=R_u/MM "[kJ/kg-K], Particular gas constant"
P_idealgas*v_idealgas=R*T_idealgas  "Ideal gas equation"
z = COMPRESS(T_comp/T_critical,P_comp/P_critical)
P_comp*v_comp=z*R*T_comp "generalized Compressibility factor"
Error_idealgas=Abs(v_table-v_idealgas)/v_table*Convert(, %)
Error_comp=Abs(v_table-v_comp)/v_table*Convert(, %)
```

$Error_{comp}$ [%]	$Error_{ideal\ gas}$ [%]	$T_{Celcius}$ [C]
6.088	38.96	325
2.422	28.2	350
0.7425	21.83	375
0.129	17.53	400
0.6015	14.42	425
0.8559	12.07	450
0.9832	10.23	475
1.034	8.755	500
1.037	7.55	525
1.01	6.55	550
0.9652	5.712	575
0.9093	5	600
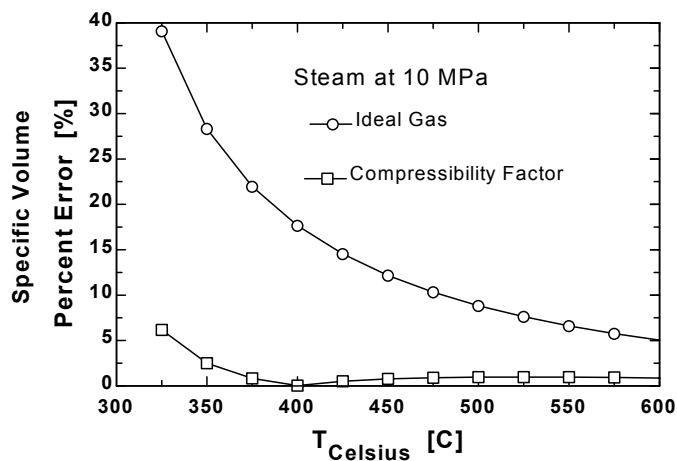
3-86 The specific volume of R-134a is to be determined using the ideal gas relation, the compressibility chart, and the R-134a tables. The errors involved in the first two approaches are also to be determined.

Properties The gas constant, the critical pressure, and the critical temperature of refrigerant-134a are, from Table A-1,

$$R = 0.08149 \text{ kPa·m}^3/\text{kg·K}, \qquad T_{cr} = 374.2 \text{ K}, \qquad P_{cr} = 4.059 \text{ MPa}$$

Analysis (*a*) From the ideal gas equation of state,

$$v = \frac{RT}{P} = \frac{(0.08149 \text{ kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K})(343 \text{ K})}{900 \text{ kPa}} = \textbf{0.03105 m}^3\textbf{/kg} \quad (\textbf{13.3\% error})$$

(*b*) From the compressibility chart (Fig. A-15),

$$P_R = \frac{P}{P_{cr}} = \frac{0.9 \text{ MPa}}{4.059 \text{ MPa}} = 0.222 \left.\right\}$$
$$T_R = \frac{T}{T_{cr}} = \frac{343 \text{ K}}{374.2 \text{ K}} = 0.917 \left.\right\} \quad Z = 0.894$$

R-134a
0.9 MPa
70°C

Thus,

$$v = Zv_{\text{ideal}} = (0.894)(0.03105 \text{ m}^3/\text{kg}) = \textbf{0.02776 m}^3\textbf{/kg} \quad (\textbf{1.3\% error})$$

(*c*) From the superheated refrigerant table (Table A-13),

$$\left.\begin{matrix} P = 0.9 \text{ MPa} \\ T = 70°C \end{matrix}\right\} v = \textbf{0.027413 m}^3\textbf{/kg}$$

3-87 The specific volume of nitrogen gas is to be determined using the ideal gas relation and the compressibility chart. The errors involved in these two approaches are also to be determined.

Properties The gas constant, the critical pressure, and the critical temperature of nitrogen are, from Table A-1,

$$R = 0.2968 \text{ kPa·m}^3/\text{kg·K}, \qquad T_{cr} = 126.2 \text{ K}, \qquad P_{cr} = 3.39 \text{ MPa}$$

Analysis (a) From the ideal gas equation of state,

$$v = \frac{RT}{P} = \frac{(0.2968 \text{ kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K})(150 \text{ K})}{10,000 \text{ kPa}} = \textbf{0.004452 m}^3\textbf{/kg} \quad (86.4\% \text{ error})$$

(*b*) From the compressibility chart (Fig. A-15),

$$P_R = \frac{P}{P_{cr}} = \frac{10 \text{ MPa}}{3.39 \text{ MPa}} = 2.95 \left.\right\}$$
$$T_R = \frac{T}{T_{cr}} = \frac{150 \text{ K}}{126.2 \text{ K}} = 1.19 \left.\right\} \quad Z = 0.54$$

N₂
10 MPa
150 K

Thus,

$$v = Zv_{\text{ideal}} = (0.54)(0.004452 \text{ m}^3/\text{kg}) = \textbf{0.002404 m}^3\textbf{/kg} \quad (0.7\% \text{ error})$$

3-88 The specific volume of steam is to be determined using the ideal gas relation, the compressibility chart, and the steam tables. The errors involved in the first two approaches are also to be determined.

Properties The gas constant, the critical pressure, and the critical temperature of water are, from Table A-1,

$$R = 0.4615 \text{ kPa·m}^3/\text{kg·K}, \qquad T_{cr} = 647.1 \text{ K}, \qquad P_{cr} = 22.06 \text{ MPa}$$

Analysis (*a*) From the ideal gas equation of state,

$$v = \frac{RT}{P} = \frac{(0.4615 \text{ kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K})(723 \text{ K})}{3500 \text{ kPa}} = \textbf{0.09533 m}^3\textbf{/kg} \quad \textbf{(3.7\% error)}$$

(*b*) From the compressibility chart (Fig. A-15),

$$\left. \begin{array}{l} P_R = \dfrac{P}{P_{cr}} = \dfrac{3.5 \text{ MPa}}{22.06 \text{ MPa}} = 0.159 \\[2mm] T_R = \dfrac{T}{T_{cr}} = \dfrac{723 \text{ K}}{647.1 \text{ K}} = 1.12 \end{array} \right\} Z = 0.961$$

> H₂O
> 3.5 MPa
> 450°C

Thus,

$$v = Zv_{\text{ideal}} = (0.961)(0.09533 \text{ m}^3/\text{kg}) = \textbf{0.09161 m}^3\textbf{/kg} \quad \textbf{(0.4\% error)}$$

(*c*) From the superheated steam table (Table A-6),

$$\left. \begin{array}{l} P = 3.5 \text{ MPa} \\ T = 450°\text{C} \end{array} \right\} \ v = \textbf{0.09196 m}^3\textbf{/kg}$$

3-89E The temperature of R-134a is to be determined using the ideal gas relation, the compressibility chart, and the R-134a tables.

Properties The gas constant, the critical pressure, and the critical temperature of refrigerant-134a are, from Table A-1E,

$$R = 0.10517 \text{ psia·ft}^3/\text{lbm·R}, \qquad T_{cr} = 673.6 \text{ R}, \qquad P_{cr} = 588.7 \text{ psia}$$

Analysis (*a*) From the ideal gas equation of state,

$$T = \frac{Pv}{R} = \frac{(400 \text{ psia})(0.1386 \text{ ft}^3/\text{lbm})}{(0.10517 \text{ psia} \cdot \text{ft}^3/\text{lbm} \cdot \text{R})} = \textbf{527.2 R}$$

(*b*) From the compressibility chart (Fig. A-15a),

$$\left. \begin{array}{l} P_R = \dfrac{P}{P_{cr}} = \dfrac{400 \text{ psia}}{588.7 \text{ psia}} = 0.678 \\[3mm] v_R = \dfrac{v_{\text{actual}}}{RT_{cr}/P_{cr}} = \dfrac{(0.1386 \text{ ft}^3/\text{lbm})(588.7 \text{ psia})}{(0.10517 \text{ psia} \cdot \text{ft}^3/\text{lbm} \cdot \text{R})(673.65 \text{ R})} = 1.15 \end{array} \right\} T_R = 1.03$$

Thus,

$$T = T_R T_{cr} = 1.03 \times 673.6 = \textbf{693.8 R}$$

(*c*) From the superheated refrigerant table (Table A-13E),

$$\left. \begin{array}{l} P = 400 \text{ psia} \\ v = 0.13853 \text{ ft}^3/\text{lbm} \end{array} \right\} T = \textbf{240°F (700 R)}$$

3-90 The pressure of R-134a is to be determined using the ideal gas relation, the compressibility chart, and the R-134a tables.

Properties The gas constant, the critical pressure, and the critical temperature of refrigerant-134a are, from Table A-1,

$$R = 0.08149 \text{ kPa·m}^3/\text{kg·K}, \qquad T_{cr} = 374.2 \text{ K}, \qquad P_{cr} = 4.059 \text{ MPa}$$

Analysis The specific volume of the refrigerant is

$$\nu = \frac{V}{m} = \frac{0.016773 \text{ m}^3}{1 \text{ kg}} = 0.016773 \text{ m}^3/\text{kg}$$

(*a*) From the ideal gas equation of state,

$$P = \frac{RT}{\nu} = \frac{(0.08149 \text{ kPa·m}^3/\text{kg·K})(383 \text{ K})}{0.016773 \text{ m}^3/\text{kg}} = \textbf{1861 kPa}$$

R-134a
0.016773 m³/kg
110°C

(*b*) From the compressibility chart (Fig. A-15),

$$T_R = \frac{T}{T_{cr}} = \frac{383 \text{ K}}{374.2 \text{ K}} = 1.023$$

$$\nu_R = \frac{\nu_{actual}}{RT_{cr}/P_{cr}} = \frac{0.016773 \text{ m}^3/\text{kg}}{(0.08149 \text{ kPa·m}^3/\text{kg·K})(374.2 \text{ K})/(4059 \text{ kPa})} = 2.24$$

$$\left. \right\} P_R = 0.39$$

Thus,

$$P = P_R P_{cr} = (0.39)(4059 \text{ kPa}) = \textbf{1583 kPa}$$

(*c*) From the superheated refrigerant table (Table A-13),

$$\left. \begin{array}{l} T = 110°\text{C} \\ \nu = 0.016773 \text{ m}^3/\text{kg} \end{array} \right\} P = \textbf{1600 kPa}$$

3-91 Somebody claims that oxygen gas at a specified state can be treated as an ideal gas with an error less than 10%. The validity of this claim is to be determined.

Properties The critical pressure, and the critical temperature of oxygen are, from Table A-1,

$$T_{cr} = 154.8 \text{ K} \quad \text{and} \quad P_{cr} = 5.08 \text{ MPa}$$

Analysis From the compressibility chart (Fig. A-15),

$$P_R = \frac{P}{P_{cr}} = \frac{3 \text{ MPa}}{5.08 \text{ MPa}} = 0.591$$

$$T_R = \frac{T}{T_{cr}} = \frac{160 \text{ K}}{154.8 \text{ K}} = 1.034$$

$$\left. \right\} Z = 0.79$$

O₂
3 MPa
160 K

Then the error involved can be determined from

$$\text{Error} = \frac{\nu - \nu_{ideal}}{\nu} = 1 - \frac{1}{Z} = 1 - \frac{1}{0.79} = -26.6\%$$

Thus the claim is **false**.

3-92 The percent error involved in treating CO_2 at a specified state as an ideal gas is to be determined.

Properties The critical pressure, and the critical temperature of CO_2 are, from Table A-1,

$T_{cr} = 304.2\text{K and } P_{cr} = 7.39\text{MPa}$

Analysis From the compressibility chart (Fig. A-15),

$$\left.\begin{array}{l} P_R = \dfrac{P}{P_{cr}} = \dfrac{3\text{ MPa}}{7.39\text{ MPa}} = 0.406 \\[3mm] T_R = \dfrac{T}{T_{cr}} = \dfrac{283\text{ K}}{304.2\text{ K}} = 0.93 \end{array}\right\} Z = 0.80$$

```
┌──────────┐
│   CO₂    │
│  3 MPa   │
│  10°C    │
└──────────┘
```

Then the error involved in treating CO_2 as an ideal gas is

$$\text{Error} = \frac{v - v_{ideal}}{v} = 1 - \frac{1}{Z} = 1 - \frac{1}{0.80} = -0.25 \text{ or } \mathbf{25.0\%}$$

3-93 The % error involved in treating CO_2 at a specified state as an ideal gas is to be determined.

Properties The critical pressure, and the critical temperature of CO_2 are, from Table A-1,

$T_{cr} = 304.2\text{ K and } P_{cr} = 7.39\text{ MPa}$

Analysis From the compressibility chart (Fig. A-15),

$$\left.\begin{array}{l} P_R = \dfrac{P}{P_{cr}} = \dfrac{7\text{ MPa}}{7.39\text{ MPa}} = 0.947 \\[3mm] T_R = \dfrac{T}{T_{cr}} = \dfrac{380\text{ K}}{304.2\text{ K}} = 1.25 \end{array}\right\} Z = 0.84$$

```
┌──────────┐
│   CO₂    │
│  7 MPa   │
│  380 K   │
└──────────┘
```

Then the error involved in treating CO_2 as an ideal gas is

$$\text{Error} = \frac{v - v_{ideal}}{v} = 1 - \frac{1}{Z} = 1 - \frac{1}{0.84} = -0.190 \text{ or } \mathbf{19.0\%}$$

3-94 CO_2 gas flows through a pipe. The volume flow rate and the density at the inlet and the volume flow rate at the exit of the pipe are to be determined.

3 MPa		
500 K	CO_2 $\longrightarrow$	450 K
2 kg/s		

Properties The gas constant, the critical pressure, and the critical temperature of CO_2 are (Table A-1)

$$R = 0.1889 \text{ kPa·m}^3/\text{kg·K}, \qquad T_{cr} = 304.2 \text{ K}, \qquad P_{cr} = 7.39 \text{ MPa}$$

Analysis (*a*) From the ideal gas equation of state,

$$\dot{V}_1 = \frac{\dot{m}RT_1}{P_1} = \frac{(2 \text{ kg/s})(0.1889 \text{ kPa·m}^3/\text{kg·K})(500 \text{ K})}{(3000 \text{ kPa})} = \textbf{0.06297 m}^3\textbf{/kg} \quad \textbf{(2.1\% error)}$$

$$\rho_1 = \frac{P_1}{RT_1} = \frac{(3000 \text{ kPa})}{(0.1889 \text{ kPa·m}^3/\text{kg·K})(500 \text{ K})} = \textbf{31.76 kg/m}^3 \quad \textbf{(2.1\% error)}$$

$$\dot{V}_2 = \frac{\dot{m}RT_2}{P_2} = \frac{(2 \text{ kg/s})(0.1889 \text{ kPa·m}^3/\text{kg·K})(450 \text{ K})}{(3000 \text{ kPa})} = \textbf{0.05667 m}^3\textbf{/kg} \quad \textbf{(3.6\% error)}$$

(*b*) From the compressibility chart (EES function for compressibility factor is used)

$$\left. \begin{aligned} P_R &= \frac{P_1}{P_{cr}} = \frac{3 \text{ MPa}}{7.39 \text{ MPa}} = 0.407 \\ T_{R,1} &= \frac{T_1}{T_{cr}} = \frac{500 \text{ K}}{304.2 \text{ K}} = 1.64 \end{aligned} \right\} \quad Z_1 = 0.9791$$

$$\left. \begin{aligned} P_R &= \frac{P_2}{P_{cr}} = \frac{3 \text{ MPa}}{7.39 \text{ MPa}} = 0.407 \\ T_{R,2} &= \frac{T_2}{T_{cr}} = \frac{450 \text{ K}}{304.2 \text{ K}} = 1.48 \end{aligned} \right\} \quad Z_2 = 0.9656$$

Thus, $\quad \dot{V}_1 = \frac{Z_1 \dot{m}RT_1}{P_1} = \frac{(0.9791)(2 \text{ kg/s})(0.1889 \text{ kPa·m}^3/\text{kg·K})(500 \text{ K})}{(3000 \text{ kPa})} = \textbf{0.06165 m}^3\textbf{/kg}$

$$\rho_1 = \frac{P_1}{Z_1 RT_1} = \frac{(3000 \text{ kPa})}{(0.9791)(0.1889 \text{ kPa·m}^3/\text{kg·K})(500 \text{ K})} = \textbf{32.44 kg/m}^3$$

$$\dot{V}_2 = \frac{Z_2 \dot{m}RT_2}{P_2} = \frac{(0.9656)(2 \text{ kg/s})(0.1889 \text{ kPa·m}^3/\text{kg·K})(450 \text{ K})}{(3000 \text{ kPa})} = \textbf{0.05472 m}^3\textbf{/kg}$$

Other Equations of State

3-95C The constant a represents the increase in pressure as a result of intermolecular forces; the constant b represents the volume occupied by the molecules. They are determined from the requirement that the critical isotherm has an inflection point at the critical point.

3-96 The pressure of nitrogen in a tank at a specified state is to be determined using the ideal gas, van der Waals, and Beattie-Bridgeman equations. The error involved in each case is to be determined.

Properties The gas constant, molar mass, critical pressure, and critical temperature of nitrogen are (Table A-1)

$$R = 0.2968 \text{ kPa·m}^3/\text{kg·K}, \quad M = 28.013 \text{ kg/kmol}, \quad T_{cr} = 126.2 \text{ K}, \quad P_{cr} = 3.39 \text{ MPa}$$

Analysis The specific volume of nitrogen is

$$v = \frac{V}{m} = \frac{3.27 \text{ m}^3}{100 \text{ kg}} = 0.0327 \text{ m}^3/\text{kg}$$

N₂
0.0327 m³/kg
175 K

(*a*) From the ideal gas equation of state,

$$P = \frac{RT}{v} = \frac{(0.2968 \text{ kPa·m}^3/\text{kg·K})(175 \text{ K})}{0.0327 \text{ m}^3/\text{kg}} = \textbf{1588 kPa (5.5\% error)}$$

(*b*) The van der Waals constants for nitrogen are determined from

$$a = \frac{27 R^2 T_{cr}^2}{64 P_{cr}} = \frac{(27)(0.2968 \text{ kPa·m}^3/\text{kg·K})^2 (126.2 \text{ K})^2}{(64)(3390 \text{ kPa})} = 0.175 \text{ m}^6 \cdot \text{kPa}/\text{kg}^2$$

$$b = \frac{R T_{cr}}{8 P_{cr}} = \frac{(0.2968 \text{ kPa·m}^3/\text{kg·K})(126.2 \text{ K})}{8 \times 3390 \text{ kPa}} = 0.00138 \text{ m}^3/\text{kg}$$

Then,

$$P = \frac{RT}{v-b} - \frac{a}{v^2} = \frac{0.2968 \times 175}{0.0327 - 0.00138} - \frac{0.175}{(0.0327)^2} = \textbf{1495 kPa (0.7\% error)}$$

(*c*) The constants in the Beattie-Bridgeman equation are

$$A = A_o\left(1 - \frac{a}{v}\right) = 136.2315\left(1 - \frac{0.02617}{0.9160}\right) = 132.339$$

$$B = B_o\left(1 - \frac{b}{v}\right) = 0.05046\left(1 - \frac{-0.00691}{0.9160}\right) = 0.05084$$

$$c = 4.2 \times 10^4 \text{ m}^3 \cdot \text{K}^3/\text{kmol}$$

since $\bar{v} = Mv = (28.013 \text{ kg/kmol})(0.0327 \text{ m}^3/\text{kg}) = 0.9160 \text{ m}^3/\text{kmol}$. Substituting,

$$P = \frac{R_u T}{\bar{v}^2}\left(1 - \frac{c}{\bar{v} T^3}\right)(\bar{v} + B) - \frac{A}{\bar{v}^2}$$

$$= \frac{8.314 \times 175}{(0.9160)^2}\left(1 - \frac{4.2 \times 10^4}{0.9160 \times 175^3}\right)(0.9160 + 0.05084) - \frac{132.339}{(0.9160)^2}$$

$$= \textbf{1504 kPa (0.07\% error)}$$

3-97 The temperature of steam in a tank at a specified state is to be determined using the ideal gas relation, van der Waals equation, and the steam tables.

Properties The gas constant, critical pressure, and critical temperature of steam are (Table A-1)

$$R = 0.4615 \text{ kPa·m}^3/\text{kg·K}, \qquad T_{cr} = 647.1 \text{ K}, \qquad P_{cr} = 22.06 \text{ MPa}$$

Analysis The specific volume of steam is

$$v = \frac{V}{m} = \frac{1 \text{ m}^3}{2.841 \text{ kg}} = 0.3520 \text{ m}^3/\text{kg}$$

> H₂O
> 1 m³
> 2.841 kg
> 0.6 MPa

(*a*) From the ideal gas equation of state,

$$T = \frac{Pv}{R} = \frac{(600 \text{ kPa})(0.352 \text{ m}^3/\text{kg})}{0.4615 \text{ kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K}} = \textbf{457.6 K}$$

(*b*) The van der Waals constants for steam are determined from

$$a = \frac{27R^2 T_{cr}^2}{64 P_{cr}} = \frac{(27)(0.4615 \text{ kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K})^2 (647.1 \text{ K})^2}{(64)(22{,}060 \text{ kPa})} = 1.705 \text{ m}^6 \cdot \text{kPa/kg}^2$$

$$b = \frac{RT_{cr}}{8 P_{cr}} = \frac{(0.4615 \text{ kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K})(647.1 \text{ K})}{8 \times 22{,}060 \text{ kPa}} = 0.00169 \text{ m}^3/\text{kg}$$

Then,

$$T = \frac{1}{R}\left(P + \frac{a}{v^2}\right)(v - b) = \frac{1}{0.4615}\left(600 + \frac{1.705}{(0.3520)^2}\right)(0.352 - 0.00169) = \textbf{465.9 K}$$

(*c*) From the superheated steam table (Tables A-6),

$$\left.\begin{matrix} P = 0.6 \text{ MPa} \\ v = 0.3520 \text{ m}^3/\text{kg} \end{matrix}\right\} T = \textbf{200°C} \quad (= 473 \text{ K})$$

3-98 EES Problem 3-97 is reconsidered. The problem is to be solved using EES (or other) software. The temperature of water is to be compared for the three cases at constant specific volume over the pressure range of 0.1 MPa to 1 MPa in 0.1 MPa increments. The %error involved in the ideal gas approximation is to be plotted against pressure.

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

Function vanderWaals(T,v,M,R_u,T_cr,P_cr)
v_bar=v*M "Conversion from m^3/kg to m^3/kmol"

"The constants for the van der Waals equation of state are given by equation 3-24"
a=27*R_u^2*T_cr^2/(64*P_cr)
b=R_u*T_cr/(8*P_cr)
"The van der Waals equation of state gives the pressure as"
vanderWaals:=R_u*T/(v_bar-b)-a/v_bar**2

End

m=2.841[kg]
Vol=1 [m^3]
{P=6*convert(MPa,kPa)}

T_cr=T_CRIT(Steam_iapws)
P_cr=P_CRIT(Steam_iapws)

v=Vol/m
P_table=P; P_vdW=P;P_idealgas=P
T_table=temperature(Steam_iapws,P=P_table,v=v) "EES data for steam as a real gas"
{P_table=pressure(Steam_iapws, T=T_table,v=v)}
{T_sat=temperature(Steam_iapws,P=P_table,v=v)}
MM=MOLARMASS(water)
R_u=8.314 [kJ/kmol-K] "Universal gas constant"
R=R_u/MM "Particular gas constant"
P_idealgas=R*T_idealgas/v "Ideal gas equation"
"The value of P_vdW is found from van der Waals equation of state Function"
P_vdW=vanderWaals(T_vdW,v,MM,R_u,T_cr,P_cr)

Error_idealgas=Abs(T_table-T_idealgas)/T_table*Convert(, %)
Error_vdW=Abs(T_table-T_vdW)/T_table*Convert(, %)

P [kPa]	$T_{ideal\ gas}$ [K]	T_{table} [K]	T_{vdW} [K]	$Error_{ideal\ gas}$ [K]
100	76.27	372.8	86.35	79.54
200	152.5	393.4	162.3	61.22
300	228.8	406.7	238.2	43.74
400	305.1	416.8	314.1	26.8
500	381.4	425	390	10.27
600	457.6	473	465.9	3.249
700	533.9	545.3	541.8	2.087
800	610.2	619.1	617.7	1.442
900	686.4	693.7	693.6	1.041
1000	762.7	768.6	769.5	0.7725

T vs. v for Steam at 600 kPa

T vs v for Steam at 6000 kPa
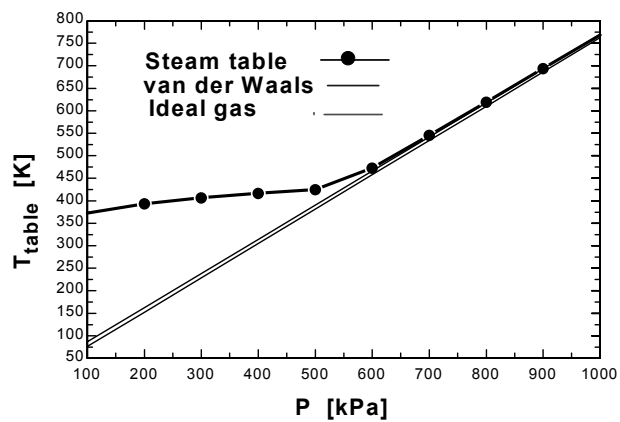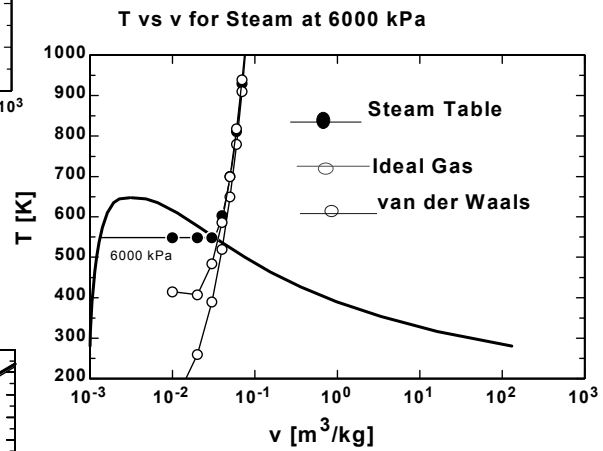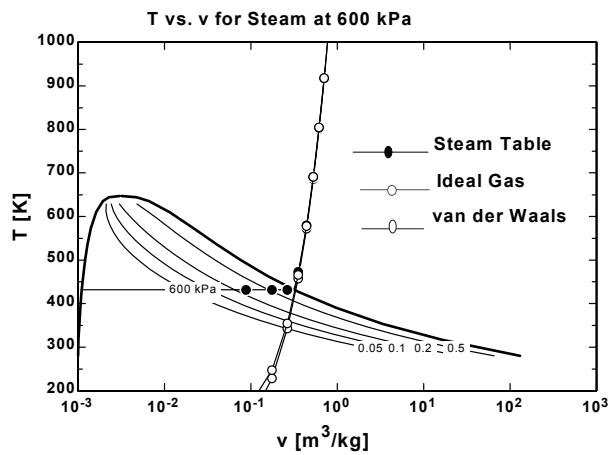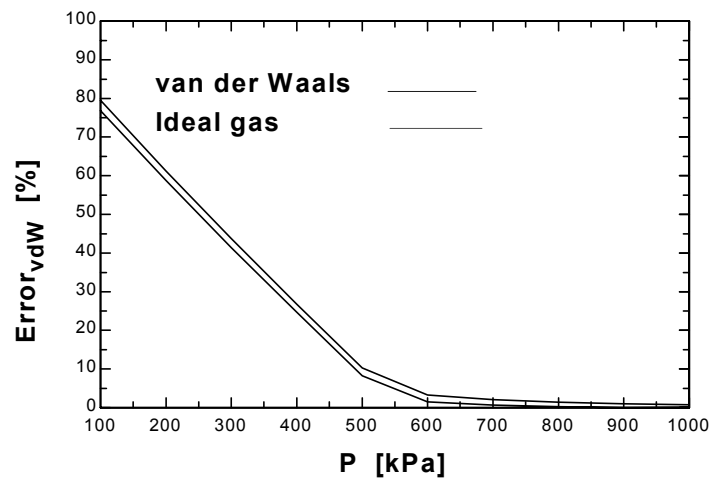
3-99E The temperature of R-134a in a tank at a specified state is to be determined using the ideal gas relation, the van der Waals equation, and the refrigerant tables.

Properties The gas constant, critical pressure, and critical temperature of R-134a are (Table A-1E)

$$R = 0.1052 \text{ psia·ft}^3/\text{lbm·R}, \qquad T_{cr} = 673.6 \text{ R}, \qquad P_{cr} = 588.7 \text{ psia}$$

Analysis (a) From the ideal gas equation of state,

$$T = \frac{P\nu}{R} = \frac{(100 \text{ psia})(0.54022 \text{ ft}^3/\text{lbm})}{0.1052 \text{ psia} \cdot \text{ft}^3/\text{lbm} \cdot \text{R}} = \textbf{513.5 R}$$

(*b*) The van der Waals constants for the refrigerant are determined from

$$a = \frac{27 R^2 T_{cr}^2}{64 P_{cr}} = \frac{(27)(0.1052 \text{ psia} \cdot \text{ft}^3/\text{lbm} \cdot \text{R})^2 (673.6 \text{ R})^2}{(64)(588.7 \text{ psia})} = 3.591 \text{ ft}^6 \cdot \text{psia/lbm}^2$$

$$b = \frac{R T_{cr}}{8 P_{cr}} = \frac{(0.1052 \text{ psia} \cdot \text{ft}^3/\text{lbm} \cdot \text{R})(673.6 \text{ R})}{8 \times 588.7 \text{ psia}} = 0.0150 \text{ ft}^3/\text{lbm}$$

Then, $$T = \frac{1}{R}\left(P + \frac{a}{\nu^2}\right)(\nu - b) = \frac{1}{0.1052}\left(100 + \frac{3.591}{(0.54022)^2}\right)(0.54022 - 0.0150) = \textbf{560.7 R}$$

(c) From the superheated refrigerant table (Table A-13E),

$$\left. \begin{array}{l} P = 100 \text{ psia} \\ \nu = 0.54022 \text{ ft}^3/\text{lbm} \end{array} \right\} T = \textbf{120°F} \quad (580\text{R})$$

3-100 [*Also solved by EES on enclosed CD*] The pressure of nitrogen in a tank at a specified state is to be determined using the ideal gas relation and the Beattie-Bridgeman equation. The error involved in each case is to be determined.

Properties The gas constant and molar mass of nitrogen are (Table A-1)

$$R = 0.2968 \text{ kPa·m}^3/\text{kg·K} \quad \text{and} \quad M = 28.013 \text{ kg/kmol}$$

Analysis (*a*) From the ideal gas equation of state,

$$P = \frac{RT}{\nu} = \frac{(0.2968 \text{ kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K})(150 \text{ K})}{0.041884 \text{ m}^3/\text{kg}} = \textbf{1063 kPa} \quad (6.3\% \text{ error})$$

$$\boxed{\begin{array}{c} \text{N}_2 \\ 0.041884 \text{ m}^3/\text{kg} \\ 150 \text{ K} \end{array}}$$

(*b*) The constants in the Beattie-Bridgeman equation are

$$A = A_o\left(1 - \frac{a}{\overline{\nu}}\right) = 136.2315\left(1 - \frac{0.02617}{1.1733}\right) = 133.193$$

$$B = B_o\left(1 - \frac{b}{\overline{\nu}}\right) = 0.05046\left(1 - \frac{-0.00691}{1.1733}\right) = 0.05076$$

$$c = 4.2 \times 10^4 \text{ m}^3 \cdot \text{K}^3/\text{kmol}$$

since $$\overline{\nu} = M\nu = (28.013 \text{ kg/kmol})(0.041884 \text{ m}^3/\text{kg}) = 1.1733 \text{ m}^3/\text{kmol}.$$

Substituting,

$$P = \frac{R_u T}{\overline{\nu}^2}\left(1 - \frac{c}{\overline{\nu} T^3}\right)(\overline{\nu} + B) - \frac{A}{\overline{\nu}^2} = \frac{8.314 \times 150}{(1.1733)^2}\left(1 - \frac{4.2 \times 10^4}{1.1733 \times 150^3}\right)(1.1733 + 0.05076) - \frac{133.193}{(1.1733)^2}$$

$$= \textbf{1000.4 kPa} \quad (\text{negligible error})$$

3-101 EES Problem 3-100 is reconsidered. Using EES (or other) software, the pressure results of the ideal gas and Beattie-Bridgeman equations with nitrogen data supplied by EES are to be compared. The temperature is to be plotted versus specific volume for a pressure of 1000 kPa with respect to the saturated liquid and saturated vapor lines of nitrogen over the range of 110 K < T < 150 K.

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

```
Function BeattBridg(T,v,M,R_u)
v_bar=v*M  "Conversion from m^3/kg to m^3/kmol"
"The constants for the Beattie-Bridgeman equation of state are found in text"
Ao=136.2315; aa=0.02617; Bo=0.05046; bb=-0.00691; cc=4.20*1E4
B=Bo*(1-bb/v_bar)
A=Ao*(1-aa/v_bar)
"The Beattie-Bridgeman equation of state is"
BeattBridg:=R_u*T/(v_bar**2)*(1-cc/(v_bar*T**3))*(v_bar+B)-A/v_bar**2
End


T=150  [K]
v=0.041884 [m^3/kg]
P_exper=1000 [kPa]
T_table=T; T_BB=T;T_idealgas=T
P_table=PRESSURE(Nitrogen,T=T_table,v=v)  "EES data for nitrogen as a real gas"
{T_table=temperature(Nitrogen, P=P_table,v=v)}
M=MOLARMASS(Nitrogen)
R_u=8.314 [kJ/kmol-K] "Universal gas constant"
R=R_u/M  "Particular gas constant"
P_idealgas=R*T_idealgas/v  "Ideal gas equation"
P_BB=BeattBridg(T_BB,v,M,R_u) "Beattie-Bridgeman equation of state Function"
```

P_{BB} [kPa]	P_{table} [kPa]	$P_{idealgas}$ [kPa]	v [m3/kg]	T_{BB} [K]	$T_{ideal\,gas}$ [K]	T_{table} [K]
1000	1000	1000	0.01	91.23	33.69	103.8
1000	1000	1000	0.02	95.52	67.39	103.8
1000	1000	1000	0.025	105	84.23	106.1
1000	1000	1000	0.03	116.8	101.1	117.2
1000	1000	1000	0.035	130.1	117.9	130.1
1000	1000	1000	0.04	144.4	134.8	144.3
1000	1000	1000	0.05	174.6	168.5	174.5

Nitrogen, T vs v for P=1000 kPa