

*Solutions Manual for*  
**Thermodynamics: An Engineering Approach**  
Seventh Edition  
Yunus A. Cengel, Michael A. Boles  
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## **Chapter 3**

# **PROPERTIES OF PURE SUBSTANCES**

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**Pure Substances, Phase Change Processes, Property Diagrams**

**3-1C** A liquid that is about to vaporize is saturated liquid; otherwise it is compressed liquid.

**3-2C** A vapor that is about to condense is saturated vapor; otherwise it is superheated vapor.

**3-3C** No.

**3-4C** The temperature will also increase since the boiling or saturation temperature of a pure substance depends on pressure.

**3-5C** Because one cannot be varied while holding the other constant. In other words, when one changes, so does the other one.

**3-6C** At critical point the saturated liquid and the saturated vapor states are identical. At triple point the three phases of a pure substance coexist in equilibrium.

**3-7C** Yes.

**3-8C** Case (c) when the pan is covered with a heavy lid. Because the heavier the lid, the greater the pressure in the pan, and thus the greater the cooking temperature.

**3-9C** At supercritical pressures, there is no distinct phase change process. The liquid uniformly and gradually expands into a vapor. At subcritical pressures, there is always a distinct surface between the phases.

## Property Tables

**3-10C** A perfectly fitting pot and its lid often stick after cooking as a result of the vacuum created inside as the temperature and thus the corresponding saturation pressure inside the pan drops. An easy way of removing the lid is to reheat the food. When the temperature rises to boiling level, the pressure rises to atmospheric value and thus the lid will come right off.

**3-11C** The molar mass of gasoline ( $C_8H_{18}$ ) is 114 kg/kmol, which is much larger than the molar mass of air that is 29 kg/kmol. Therefore, the gasoline vapor will settle down instead of rising even if it is at a much higher temperature than the surrounding air. As a result, the warm mixture of air and gasoline on top of an open gasoline will most likely settle down instead of rising in a cooler environment

**3-12C** Yes. Otherwise we can create energy by alternately vaporizing and condensing a substance.

**3-13C** No. Because in the thermodynamic analysis we deal with the changes in properties; and the changes are independent of the selected reference state.

**3-14C** The term  $h_{fg}$  represents the amount of energy needed to vaporize a unit mass of saturated liquid at a specified temperature or pressure. It can be determined from  $h_{fg} = h_g - h_f$ .

**3-15C** Yes. It decreases with increasing pressure and becomes zero at the critical pressure.

**3-16C** Yes; the higher the temperature the lower the  $h_{fg}$  value.

**3-17C** Quality is the fraction of vapor in a saturated liquid-vapor mixture. It has no meaning in the superheated vapor region.

**3-18C** Completely vaporizing 1 kg of saturated liquid at 1 atm pressure since the higher the pressure, the lower the  $h_{fg}$ .

**3-19C** No. Quality is a mass ratio, and it is not identical to the volume ratio.

**3-20C** The compressed liquid can be approximated as a saturated liquid at the given temperature. Thus  $\nu_{T,P} \cong \nu_{f@T}$ .

**3-21C** Ice can be made by evacuating the air in a water tank. During evacuation, vapor is also thrown out, and thus the vapor pressure in the tank drops, causing a difference between the vapor pressures at the water surface and in the tank. This pressure difference is the driving force of vaporization, and forces the liquid to evaporate. But the liquid must absorb the heat of vaporization before it can vaporize, and it absorbs it from the liquid and the air in the neighborhood, causing the temperature in the tank to drop. The process continues until water starts freezing. The process can be made more efficient by insulating the tank well so that the entire heat of vaporization comes essentially from the water.



**3-22** Complete the following table for  $H_2O$ :

$T, ^\circ\text{C}$	$P, \text{kPa}$	$\nu, \text{m}^3/\text{kg}$	Phase description
50	<b>12.35</b>	7.72	<b>Saturated mixture</b>
<b>143.6</b>	400	<b>0.4624</b>	Saturated vapor
250	500	<b>0.4744</b>	<b>Superheated vapor</b>
110	350	<b>0.001051</b>	<b>Compressed liquid</b>



**3-23** Problem 3-22 is reconsidered. The missing properties of water are to be determined using EES, and the solution is to be repeated for refrigerant-134a, refrigerant-22, and ammonia.

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

**"Given"**

T[1]=50 [C]  
 v[1]=7.72 [m<sup>3</sup>/kg]  
 P[2]=400 [kPa]  
 x[2]=1  
 T[3]=250 [C]  
 P[3]=500 [kPa]  
 T[4]=110 [C]  
 P[4]=350 [kPa]

**"Analysis"**

Fluid\$='steam\_iapws' **"Change the Fluid to R134a, R22 and Ammonia and solve"**  
 P[1]=pressure(Fluid\$, T=T[1], v=v[1])  
 x[1]=quality(Fluid\$, T=T[1], v=v[1])  
 T[2]=temperature(Fluid\$, P=P[2], x=x[2])  
 v[2]=volume(Fluid\$, P=P[2], x=x[2])  
 v[3]=volume(Fluid\$, P=P[3], T=T[3])  
 x[3]=quality(Fluid\$, P=P[3], T=T[3])  
 v[4]=volume(Fluid\$, P=P[4], T=T[4])  
 x[4]=quality(Fluid\$, P=P[4], T=T[4])  
**"x = 100 for superheated vapor and x = -100 for compressed liquid"**

**SOLUTION for water**

T [C]	P [kPa]	x	v [kg/m <sup>3</sup> ]
50.00	12.35	0.6419	7.72
143.61	400.00	1	0.4624
250.00	500.00	100	0.4744
110.00	350.00	-100	0.001051

**SOLUTION for R-134a**

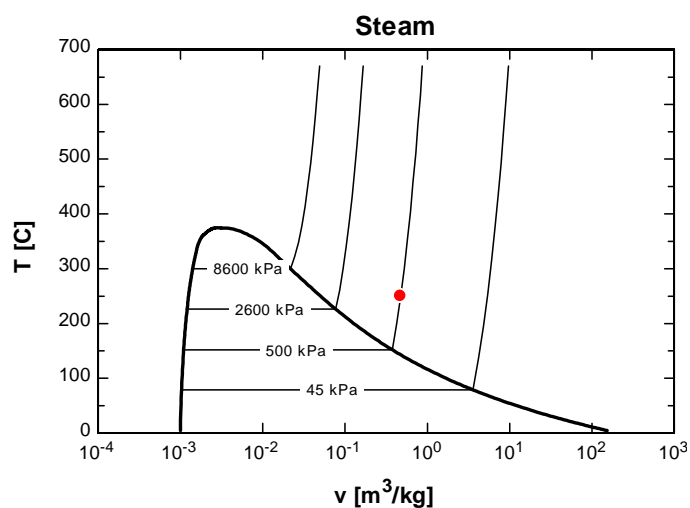
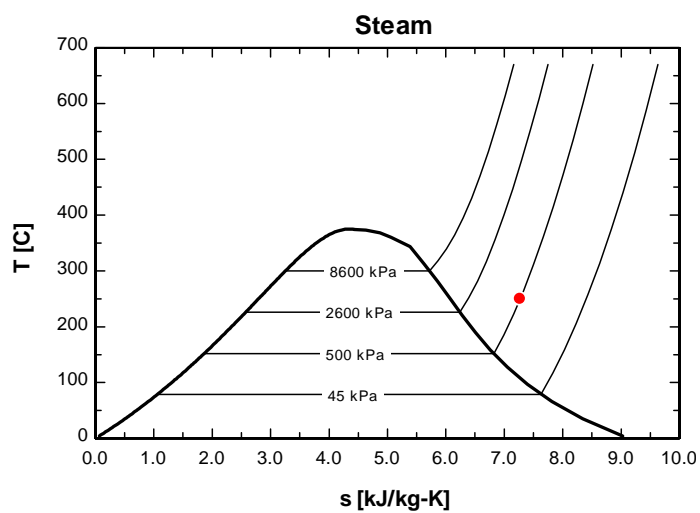
T [C]	P [kPa]	x	v [kg/m <sup>3</sup> ]
50.00	3.41	100	7.72
8.91	400.00	1	0.0512
250.00	500.00	-	-
110.00	350.00	100	0.08666

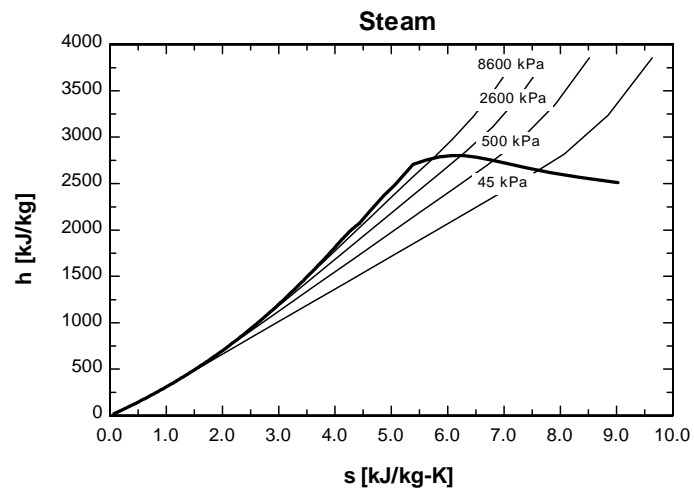
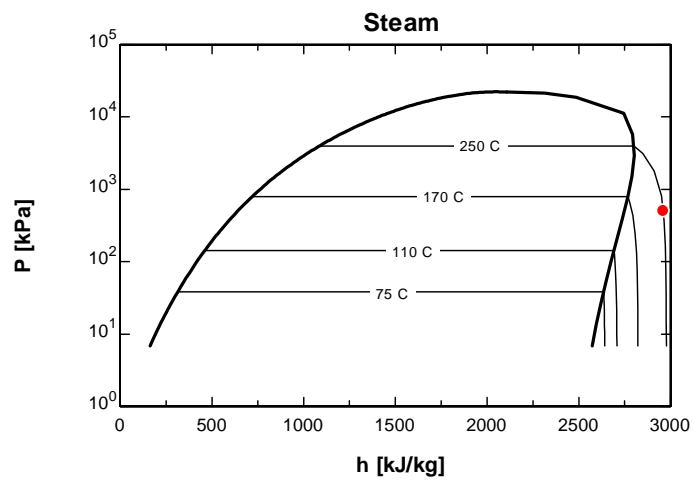
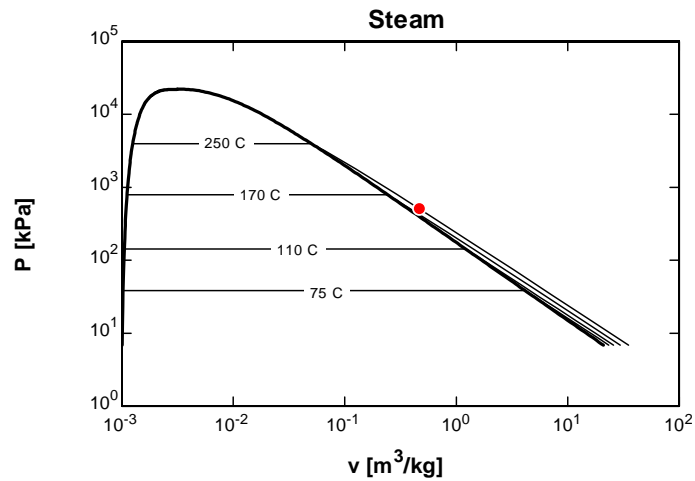
## SOLUTION for R-22

T [C]	P [kPa]	X	$v$ [kg/m <sup>3</sup> ]
50.00	4.02	100	7.72
-6.56	400.00	1	0.05817
250.0 0	500.00	100	0.09959
110.0 0	350.00	100	0.103

## SOLUTION for Ammonia

T [C]	P [kPa]	X	$v$ [kg/m <sup>3</sup> ]
50.00	20.40	100	7.72
-1.89	400.00	1	0.3094
250.0 0	500.00	100	0.5076
110.0 0	350.00	100	0.5269





**3-24E** Complete the following table for  $H_2O$ :

T, °F	P, psia	u, Btu / lbm	Phase description
300	<b>67.03</b>	782	<i>Saturated mixture</i>
<b>267.22</b>	40	<b>236.02</b>	Saturated liquid
500	120	<b>1174.4</b>	<i>Superheated vapor</i>
400	400	<b>373.84</b>	<i>Compressed liquid</i>



**3-25E** Problem 3-24E is reconsidered. The missing properties of water are to be determined using EES, and the solution is to be repeated for refrigerant-134a, refrigerant-22, and ammonia.

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

"Given"

T[1]=300 [F]  
u[1]=782 [Btu/lbm]  
P[2]=40 [psia]  
x[2]=0  
T[3]=500 [F]  
P[3]=120 [psia]  
T[4]=400 [F]  
P[4]=420 [psia]

"Analysis"

Fluid\$='steam\_iapws'  
P[1]=pressure(Fluid\$, T=T[1], u=u[1])  
x[1]=quality(Fluid\$, T=T[1], u=u[1])  
T[2]=temperature(Fluid\$, P=P[2], x=x[2])  
u[2]=intenergy(Fluid\$, P=P[2], x=x[2])  
u[3]=intenergy(Fluid\$, P=P[3], T=T[3])  
x[3]=quality(Fluid\$, P=P[3], T=T[3])  
u[4]=intenergy(Fluid\$, P=P[4], T=T[4])  
x[4]=quality(Fluid\$, P=P[4], T=T[4])  
"x = 100 for superheated vapor and x = -100 for compressed liquid"

Solution for steam

T, °F	P, psia	x	u, Btu/lbm
300	67.028	0.6173	782
267.2	40	0	236
500	120	100	1174
400	400	-100	373.8



**3-26** Complete the following table for  $H_2O$ :

T, °C	P, kPa	h, kJ / kg	x	Phase description
<b>120.21</b>	200	<b>2045.8</b>	0.7	<i>Saturated mixture</i>
140	<b>361.53</b>	1800	<b>0.565</b>	<i>Saturated mixture</i>
<b>177.66</b>	950	<b>752.74</b>	0.0	<i>Saturated liquid</i>
80	500	<b>335.37</b>	- - -	<i>Compressed liquid</i>
<b>350.0</b>	800	3162.2	- - -	<i>Superheated vapor</i>

**3-27** Complete the following table for Refrigerant-134a:

T, °C	P, kPa	$\nu$ , m <sup>3</sup> / kg	Phase description
-12	320	<b>0.000750</b>	<i>Compressed liquid</i>
30	<b>770.64</b>	0.0065	<i>Saturated mixture</i>
<b>18.73</b>	550	<b>0.03741</b>	Saturated vapor
60	600	<b>0.04139</b>	<i>Superheated vapor</i>

**3-28** Complete the following table for water:

P, kPa	T, °C	$\nu$ , m <sup>3</sup> /kg	h, kJ/kg	Condition description and quality, if applicable
200	<b>120.2</b>	0.8858	2706.3	<b>x = 1, Saturated vapor</b>
<b>270.3</b>	130		1959.3	<b>x = 0.650, Two-phase mixture</b>
<b>201.8</b>	400	1.5358	3277.0	<b>Superheated vapor</b>
800	30	<b>0.001004*</b>	<b>125.74*</b>	<b>Compressed liquid</b>
450	147.90	-	-	<b>Insufficient information</b>

\* Approximated as saturated liquid at the given temperature of 30°C

**3-29E** Complete the following table for Refrigerant-134a:

T, °F	P, psia	h, Btu / lbm	x	Phase description
65.89	80	78	0.566	Saturated mixture
15	29.759	69.92	0.6	Saturated mixture
10	70	15.35	- - -	Compressed liquid
160	180	129.46	- - -	Superheated vapor
110	161.16	117.23	1.0	Saturated vapor

**3-30** A piston-cylinder device contains R-134a at a specified state. Heat is transferred to R-134a. The final pressure, the volume change of the cylinder, and the enthalpy change are to be determined.

**Analysis** (a) The final pressure is equal to the initial pressure, which is determined from

$$P_2 = P_1 = P_{\text{atm}} + \frac{m_p g}{\pi D^2 / 4} = 88 \text{ kPa} + \frac{(12 \text{ kg})(9.81 \text{ m/s}^2)}{\pi (0.25 \text{ m})^2 / 4} \left( \frac{1 \text{ kN}}{1000 \text{ kg.m/s}^2} \right) = \mathbf{90.4 \text{ kPa}}$$

(b) The specific volume and enthalpy of R-134a at the initial state of 90.4 kPa and -10°C and at the final state of 90.4 kPa and 15°C are (from EES)

$$v_1 = 0.2302 \text{ m}^3/\text{kg} \quad h_1 = 247.76 \text{ kJ/kg}$$

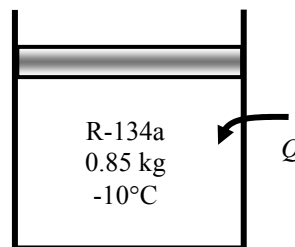
$$v_2 = 0.2544 \text{ m}^3/\text{kg} \quad h_2 = 268.16 \text{ kJ/kg}$$

The initial and the final volumes and the volume change are

$$V_1 = m v_1 = (0.85 \text{ kg})(0.2302 \text{ m}^3/\text{kg}) = 0.1957 \text{ m}^3$$

$$V_2 = m v_2 = (0.85 \text{ kg})(0.2544 \text{ m}^3/\text{kg}) = 0.2162 \text{ m}^3$$

$$\Delta V = 0.2162 - 0.1957 = \mathbf{0.0205 \text{ m}^3}$$



(c) The total enthalpy change is determined from

$$\Delta H = m(h_2 - h_1) = (0.85 \text{ kg})(268.16 - 247.76) \text{ kJ/kg} = \mathbf{17.4 \text{ kJ/kg}}$$

**3-31E** The temperature of R-134a at a specified state is to be determined.

**Analysis** Since the specified specific volume is higher than  $v_g$  for 120 psia, this is a superheated vapor state. From R-134a tables,

$$\left. \begin{array}{l} P = 120 \text{ psia} \\ v = 0.4619 \text{ ft}^3/\text{lbm} \end{array} \right\} T = \mathbf{140^\circ\text{F}} \text{ (Table A-13E)}$$

**3-32** A rigid container that is filled with water is cooled. The initial temperature and the final pressure are to be determined.

**Analysis** This is a constant volume process. The specific volume is

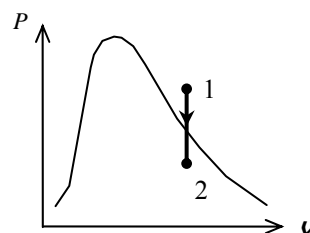
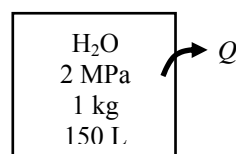
$$\nu_1 = \nu_2 = \frac{\nu}{m} = \frac{0.150 \text{ m}^3}{1 \text{ kg}} = 0.150 \text{ m}^3/\text{kg}$$

The initial state is superheated vapor. The temperature is determined to be

$$\left. \begin{array}{l} P_1 = 2 \text{ MPa} \\ \nu_1 = 0.150 \text{ m}^3/\text{kg} \end{array} \right\} T_1 = \mathbf{395^\circ\text{C}} \quad (\text{Table A - 6})$$

This is a constant volume cooling process ( $\nu = \nu/m = \text{constant}$ ). The final state is saturated mixture and thus the pressure is the saturation pressure at the final temperature:

$$\left. \begin{array}{l} T_2 = 40^\circ\text{C} \\ \nu_2 = \nu_1 = 0.150 \text{ m}^3/\text{kg} \end{array} \right\} P_2 = P_{\text{sat}@40^\circ\text{C}} = \mathbf{7.385 \text{ kPa}} \quad (\text{Table A - 4})$$



**3-33** A rigid container that is filled with R-134a is heated. The final temperature and initial pressure are to be determined.

**Analysis** This is a constant volume process. The specific volume is

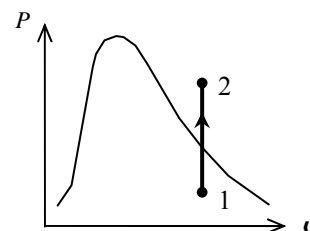
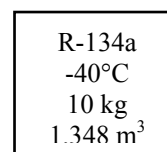
$$\nu_1 = \nu_2 = \frac{\nu}{m} = \frac{1.348 \text{ m}^3}{10 \text{ kg}} = 0.1348 \text{ m}^3/\text{kg}$$

The initial state is determined to be a mixture, and thus the pressure is the saturation pressure at the given temperature

$$P_1 = P_{\text{sat}@-40^\circ\text{C}} = \mathbf{51.25 \text{ kPa}} \quad (\text{Table A - 11})$$

The final state is superheated vapor and the temperature is determined by interpolation to be

$$\left. \begin{array}{l} P_2 = 200 \text{ kPa} \\ \nu_2 = 0.1348 \text{ m}^3/\text{kg} \end{array} \right\} T_2 = \mathbf{66.3^\circ\text{C}} \quad (\text{Table A - 13})$$



**3-34E** Left chamber of a partitioned system contains water at a specified state while the right chamber is evacuated. The partition is now ruptured and heat is transferred to the water. The pressure and the total internal energy at the final state are to be determined.

**Analysis** The final specific volume is

$$\nu_2 = \frac{\nu_2}{m} = \frac{3 \text{ ft}^3}{2 \text{ lbm}} = 1.5 \text{ ft}^3/\text{lbm}$$

Water 500 psia 2 lbm 1.5 ft <sup>3</sup>	Evacuated 1.5 ft <sup>3</sup>
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At this specific volume and the final temperature, the state is a saturated mixture, and the pressure is the saturation pressure

$$P_2 = P_{\text{sat @ } 300^\circ\text{F}} = \mathbf{67.03 \text{ psia}} \quad (\text{Table A - 4E})$$

The quality and internal energy at the final state are

$$x_2 = \frac{\nu_2 - \nu_f}{\nu_{fg}} = \frac{(1.5 - 0.01745) \text{ ft}^3/\text{lbm}}{(6.4663 - 0.01745) \text{ ft}^3/\text{lbm}} = 0.2299$$

$$u_2 = u_f + x_2 u_{fg} = 269.51 + (0.2299)(830.25) = 460.38 \text{ Btu/lbm}$$

The total internal energy is then

$$U_2 = m u_2 = (2 \text{ lbm})(460.38 \text{ Btu/lbm}) = \mathbf{920.8 \text{ Btu}}$$

**3-35** The enthalpy of R-134a at a specified state is to be determined.

**Analysis** The specific volume is

$$\nu = \frac{\nu}{m} = \frac{9 \text{ m}^3}{300 \text{ kg}} = 0.03 \text{ m}^3/\text{kg}$$

Inspection of Table A-11 indicates that this is a mixture of liquid and vapor. Using the properties at 10°C line, the quality and the enthalpy are determined to be

$$x = \frac{\nu - \nu_f}{\nu_{fg}} = \frac{(0.03 - 0.0007930) \text{ m}^3/\text{kg}}{(0.049403 - 0.0007930) \text{ m}^3/\text{kg}} = 0.6008$$

$$h = h_f + x h_{fg} = 65.43 + (0.6008)(190.73) = \mathbf{180.02 \text{ kJ/kg}}$$

**3-36** The specific volume of R-134a at a specified state is to be determined.

**Analysis** Since the given temperature is higher than the saturation temperature for 200 kPa, this is a superheated vapor state. The specific volume is then

$$\left. \begin{array}{l} P = 200 \text{ kPa} \\ T = 25^\circ\text{C} \end{array} \right\} \nu = \mathbf{0.11646 \text{ m}^3/\text{kg}} \quad (\text{Table A - 13})$$

**3-37E** A spring-loaded piston-cylinder device is filled with R-134a. The water now undergoes a process until its volume increases by 40%. The final temperature and the enthalpy are to be determined.

**Analysis** From Table A-11E, the initial specific volume is

$$\nu_1 = \nu_f + x_1 \nu_{fg} = 0.01143 + (0.80)(4.4300 - 0.01143) = 3.5463 \text{ ft}^3/\text{lbm}$$

and the initial volume will be

$$\mathcal{V}_1 = m \nu_1 = (0.2 \text{ lbm})(3.5463 \text{ ft}^3/\text{lbm}) = 0.7093 \text{ ft}^3$$

With a 40% increase in the volume, the final volume will be

$$\mathcal{V}_2 = 1.4 \mathcal{V}_1 = 1.4(0.7093 \text{ ft}^3) = 0.9930 \text{ ft}^3$$

The distance that the piston moves between the initial and final conditions is

$$\Delta x = \frac{\Delta \mathcal{V}}{A_p} = \frac{\Delta \mathcal{V}}{\pi D^2 / 4} = \frac{4(0.9930 - 0.7093) \text{ ft}^3}{\pi (1 \text{ ft})^2} = 0.3612 \text{ ft}$$

As a result of the compression of the spring, the pressure difference between the initial and final states is

$$\Delta P = \frac{\Delta F}{A_p} = \frac{k \Delta x}{A_p} = \frac{k \Delta x}{\pi D^2 / 4} = \frac{4(37 \text{ lbf/in})(0.3612 \times 12 \text{ in})}{\pi (12 \text{ in})^2} = 1.42 \text{ lbf/in}^2 = 1.42 \text{ psia}$$

The initial pressure is

$$P_1 = P_{\text{sat}@-30^\circ\text{F}} = 9.87 \text{ psia} \quad (\text{Table A-11E})$$

The final pressure is then

$$P_2 = P_1 + \Delta P = 9.87 + 1.42 = 11.29 \text{ psia}$$

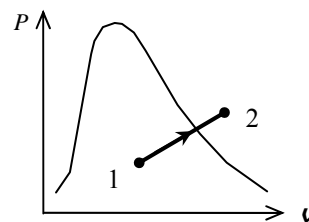
and the final specific volume is

$$\nu_2 = \frac{\mathcal{V}_2}{m} = \frac{0.9930 \text{ ft}^3}{0.2 \text{ lbm}} = 4.965 \text{ ft}^3/\text{lbm}$$

At this final state, the temperature and enthalpy are

$$\left. \begin{array}{l} P_2 = 11.29 \text{ psia} \\ \nu_2 = 4.965 \text{ ft}^3/\text{lbm} \end{array} \right\} \begin{array}{l} T_1 = \mathbf{81.5^\circ\text{F}} \\ h_1 = \mathbf{119.9 \text{ Btu/lbm}} \end{array} \quad (\text{from EES})$$

Note that it is very difficult to get the temperature and enthalpy from Table A-13E accurately.



**3-38E** A piston-cylinder device that is filled with water is cooled. The final pressure and volume of the water are to be determined.

**Analysis** The initial specific volume is

$$\nu_1 = \frac{V_1}{m} = \frac{2.4264 \text{ ft}^3}{1 \text{ lbm}} = 2.4264 \text{ ft}^3/\text{lbm}$$

This is a constant-pressure process. The initial state is determined to be superheated vapor and thus the pressure is determined to be

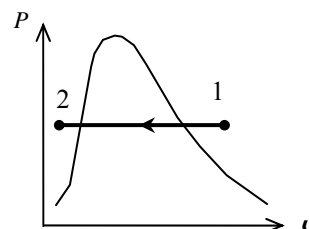
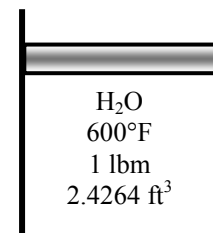
$$\left. \begin{array}{l} T_1 = 600^\circ\text{F} \\ \nu_1 = 2.4264 \text{ ft}^3/\text{lbm} \end{array} \right\} P_1 = P_2 = \mathbf{250 \text{ psia}} \quad (\text{Table A - 6E})$$

The saturation temperature at 250 psia is 400.1°F. Since the final temperature is less than this temperature, the final state is compressed liquid. Using the incompressible liquid approximation,

$$\nu_2 = \nu_f @ 200^\circ\text{F} = 0.01663 \text{ ft}^3/\text{lbm} \quad (\text{Table A - 4E})$$

The final volume is then

$$V_2 = m\nu_2 = (1 \text{ lbm})(0.01663 \text{ ft}^3/\text{lbm}) = \mathbf{0.01663 \text{ ft}^3}$$



**3-39** A piston-cylinder device that is filled with R-134a is heated. The final volume is to be determined.

**Analysis** This is a constant pressure process. The initial specific volume is

$$\nu_1 = \frac{V}{m} = \frac{1.595 \text{ m}^3}{10 \text{ kg}} = 0.1595 \text{ m}^3/\text{kg}$$

The initial state is determined to be a mixture, and thus the pressure is the saturation pressure at the given temperature

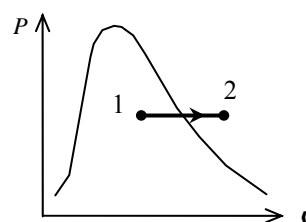
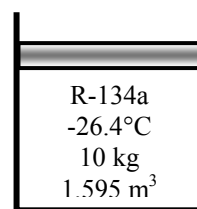
$$P_1 = P_{\text{sat}} @ -26.4^\circ\text{C} = 100 \text{ kPa} \quad (\text{Table A - 12})$$

The final state is superheated vapor and the specific volume is

$$\left. \begin{array}{l} P_2 = 100 \text{ kPa} \\ T_2 = 100^\circ\text{C} \end{array} \right\} \nu_2 = 0.30138 \text{ m}^3/\text{kg} \quad (\text{Table A - 13})$$

The final volume is then

$$V_2 = m\nu_2 = (10 \text{ kg})(0.30138 \text{ m}^3/\text{kg}) = \mathbf{3.0138 \text{ m}^3}$$



**3-40E** The total internal energy and enthalpy of water in a container are to be determined.

**Analysis** The specific volume is

$$\nu = \frac{V}{m} = \frac{2 \text{ ft}^3}{1 \text{ lbm}} = 2 \text{ ft}^3/\text{lbm}$$

At this specific volume and the given pressure, the state is a saturated mixture. The quality, internal energy, and enthalpy at this state are (Table A-5E)

$$x = \frac{\nu - \nu_f}{\nu_{fg}} = \frac{(2 - 0.01774) \text{ ft}^3/\text{lbm}}{(4.4327 - 0.01774) \text{ ft}^3/\text{lbm}} = 0.4490$$

$$u = u_f + xu_{fg} = 298.19 + (0.4490)(807.29) = 660.7 \text{ Btu/lbm}$$

$$h = h_f + xh_{fg} = 298.51 + (0.4490)(888.99) = 697.7 \text{ Btu/lbm}$$

Water 100 psia 2 ft <sup>3</sup>
--

The total internal energy and enthalpy are then

$$U = mu = (1 \text{ lbm})(660.7 \text{ Btu/lbm}) = \mathbf{660.7 \text{ Btu}}$$

$$H = mh = (1 \text{ lbm})(697.7 \text{ Btu/lbm}) = \mathbf{697.7 \text{ Btu}}$$

**3-41** The volume of a container that contains water at a specified state is to be determined.

**Analysis** The specific volume is determined from steam tables by interpolation to be

$$\left. \begin{array}{l} P = 100 \text{ kPa} \\ T = 250^\circ\text{C} \end{array} \right\} \nu = 2.4062 \text{ m}^3/\text{kg} \text{ (Table A - 6)}$$

The volume of the container is then

$$V = m\nu = (3 \text{ kg})(2.4062 \text{ m}^3/\text{kg}) = \mathbf{7.22 \text{ m}^3}$$

Water 3 kg 100 kPa 250°C
-----------------------------------

**3-42** A rigid container that is filled with R-134a is heated. The temperature and total enthalpy are to be determined at the initial and final states.

**Analysis** This is a constant volume process. The specific volume is

$$\nu_1 = \nu_2 = \frac{\nu}{m} = \frac{0.014 \text{ m}^3}{10 \text{ kg}} = 0.0014 \text{ m}^3/\text{kg}$$

The initial state is determined to be a mixture, and thus the temperature is the saturation temperature at the given pressure. From Table A-12 by interpolation

$$T_1 = T_{\text{sat @ 300 kPa}} = \mathbf{0.61^\circ\text{C}}$$

and

$$x_1 = \frac{\nu_1 - \nu_f}{\nu_{fg}} = \frac{(0.0014 - 0.0007736) \text{ m}^3/\text{kg}}{(0.067978 - 0.0007736) \text{ m}^3/\text{kg}} = 0.009321$$

$$h_1 = h_f + x_1 h_{fg} = 52.67 + (0.009321)(198.13) = 54.52 \text{ kJ/kg}$$

The total enthalpy is then

$$H_1 = m h_1 = (10 \text{ kg})(54.52 \text{ kJ/kg}) = \mathbf{545.2 \text{ kJ}}$$

The final state is also saturated mixture. Repeating the calculations at this state,

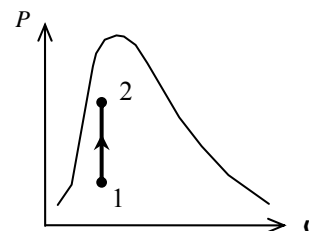
$$T_2 = T_{\text{sat @ 600 kPa}} = \mathbf{21.55^\circ\text{C}}$$

$$x_2 = \frac{\nu_2 - \nu_f}{\nu_{fg}} = \frac{(0.0014 - 0.0008199) \text{ m}^3/\text{kg}}{(0.034295 - 0.0008199) \text{ m}^3/\text{kg}} = 0.01733$$

$$h_2 = h_f + x_2 h_{fg} = 81.51 + (0.01733)(180.90) = 84.64 \text{ kJ/kg}$$

$$H_2 = m h_2 = (10 \text{ kg})(84.64 \text{ kJ/kg}) = \mathbf{846.4 \text{ kJ}}$$

R-134a
300 kPa
10 kg
14 L





**3-43** A piston-cylinder device that is filled with R-134a is cooled at constant pressure. The final temperature and the change of total internal energy are to be determined.

**Analysis** The initial specific volume is

$$\nu_1 = \frac{\nu}{m} = \frac{12.322 \text{ m}^3}{100 \text{ kg}} = 0.12322 \text{ m}^3/\text{kg}$$

The initial state is superheated and the internal energy at this state is

$$\left. \begin{array}{l} P_1 = 200 \text{ kPa} \\ \nu_1 = 0.12322 \text{ m}^3/\text{kg} \end{array} \right\} u_1 = 263.08 \text{ kJ/kg} \text{ (Table A-13)}$$

The final specific volume is

$$\nu_2 = \frac{\nu_1}{2} = \frac{0.12322 \text{ m}^3/\text{kg}}{2} = 0.06161 \text{ m}^3/\text{kg}$$

This is a constant pressure process. The final state is determined to be saturated mixture whose temperature is

$$T_2 = T_{\text{sat @ } 200 \text{ kPa}} = -10.09^\circ\text{C} \text{ (Table A-12)}$$

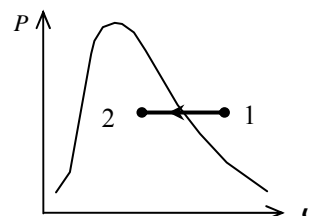
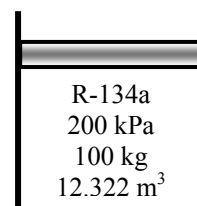
The internal energy at the final state is (Table A-12)

$$x_2 = \frac{\nu_2 - \nu_f}{\nu_{fg}} = \frac{(0.06161 - 0.0007533) \text{ m}^3/\text{kg}}{(0.099867 - 0.0007533) \text{ m}^3/\text{kg}} = 0.6140$$

$$u_2 = u_f + x_2 u_{fg} = 38.28 + (0.6140)(186.21) = 152.61 \text{ kJ/kg}$$

Hence, the change in the internal energy is

$$\Delta u = u_2 - u_1 = 152.61 - 263.08 = -110.47 \text{ kJ/kg}$$



**3-44** A piston-cylinder device fitted with stops contains water at a specified state. Now the water is cooled until a final pressure. The process is to be indicated on the  $T$ - $\nu$  diagram and the change in internal energy is to be determined.

**Analysis** The process is shown on  $T$ - $\nu$  diagram. The internal energy at the initial state is

$$\left. \begin{array}{l} P_1 = 300 \text{ kPa} \\ T_1 = 250^\circ\text{C} \end{array} \right\} u_1 = 2728.9 \text{ kJ/kg} \quad (\text{Table A - 6})$$

State 2 is saturated vapor at the initial pressure. Then,

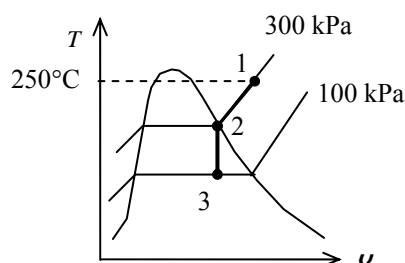
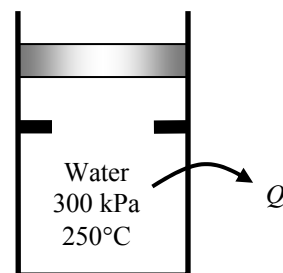
$$\left. \begin{array}{l} P_2 = 300 \text{ kPa} \\ x_2 = 1 \text{ (sat. vapor)} \end{array} \right\} \nu_2 = 0.6058 \text{ m}^3/\text{kg} \quad (\text{Table A - 5})$$

Process 2-3 is a constant-volume process. Thus,

$$\left. \begin{array}{l} P_3 = 100 \text{ kPa} \\ \nu_3 = 0.6058 \text{ m}^3/\text{kg} \end{array} \right\} u_3 = 1163.3 \text{ kJ/kg} \quad (\text{Table A - 5})$$

The overall change in internal energy is

$$\Delta u = u_1 - u_3 = 2728.9 - 1163.3 = \mathbf{1566 \text{ kJ/kg}}$$



**3-45E** The local atmospheric pressure, and thus the boiling temperature, changes with the weather conditions. The change in the boiling temperature corresponding to a change of 0.2 in of mercury in atmospheric pressure is to be determined.

**Properties** The saturation pressures of water at 200 and 212°F are 11.538 and 14.709 psia, respectively (Table A-4E). One in. of mercury is equivalent to 1 inHg = 3.387 kPa = 0.491 psia (inner cover page).

**Analysis** A change of 0.2 in of mercury in atmospheric pressure corresponds to

$$\Delta P = (0.2 \text{ inHg}) \left( \frac{0.491 \text{ psia}}{1 \text{ inHg}} \right) = 0.0982 \text{ psia}$$

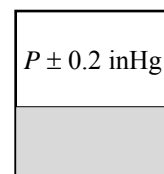
At about boiling temperature, the change in boiling temperature per 1 psia change in pressure is determined using data at 200 and 212°F to be

$$\frac{\Delta T}{\Delta P} = \frac{(212 - 200)^\circ\text{F}}{(14.709 - 11.538) \text{ psia}} = 3.783^\circ\text{F/psia}$$

Then the change in saturation (boiling) temperature corresponding to a change of 0.147 psia becomes

$$\Delta T_{\text{boiling}} = (3.783^\circ\text{F/psia}) \Delta P = (3.783^\circ\text{F/psia})(0.0982 \text{ psia}) = \mathbf{0.37^\circ\text{F}}$$

which is very small. Therefore, the effect of variation of atmospheric pressure on the boiling temperature is negligible.



**3-46** A person cooks a meal in a pot that is covered with a well-fitting lid, and leaves the food to cool to the room temperature. It is to be determined if the lid will open or the pan will move up together with the lid when the person attempts to open the pan by lifting the lid up.

**Assumptions** **1** The local atmospheric pressure is  $1 \text{ atm} = 101.325 \text{ kPa}$ . **2** The weight of the lid is small and thus its effect on the boiling pressure and temperature is negligible. **3** No air has leaked into the pan during cooling.

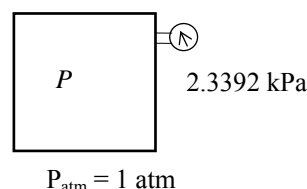
**Properties** The saturation pressure of water at  $20^\circ\text{C}$  is  $2.3392 \text{ kPa}$  (Table A-4).

**Analysis** Noting that the weight of the lid is negligible, the reaction force  $F$  on the lid after cooling at the pan-lid interface can be determined from a force balance on the lid in the vertical direction to be

$$PA + F = P_{\text{atm}}A$$

or,

$$\begin{aligned} F &= A(P_{\text{atm}} - P) = (\pi D^2 / 4)(P_{\text{atm}} - P) \\ &= \frac{\pi(0.3 \text{ m})^2}{4}(101,325 - 2339.2) \text{ Pa} \\ &= 6997 \text{ m}^2\text{Pa} = \mathbf{6997 \text{ N}} \quad (\text{since } 1 \text{ Pa} = 1 \text{ N/m}^2) \end{aligned}$$



The weight of the pan and its contents is

$$W = mg = (8 \text{ kg})(9.81 \text{ m/s}^2) = \mathbf{78.5 \text{ N}}$$

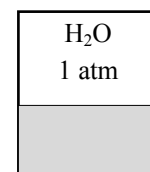
which is much less than the reaction force of  $6997 \text{ N}$  at the pan-lid interface. Therefore, the pan will **move up** together with the lid when the person attempts to open the pan by lifting the lid up. In fact, it looks like the lid will not open even if the mass of the pan and its contents is several hundred kg.

**3-47** Water is boiled at  $1 \text{ atm}$  pressure in a pan placed on an electric burner. The water level drops by  $10 \text{ cm}$  in  $45 \text{ min}$  during boiling. The rate of heat transfer to the water is to be determined.

**Properties** The properties of water at  $1 \text{ atm}$  and thus at a saturation temperature of  $T_{\text{sat}} = 100^\circ\text{C}$  are  $h_{\text{fg}} = 2256.5 \text{ kJ/kg}$  and  $\nu_f = 0.001043 \text{ m}^3/\text{kg}$  (Table A-4).

**Analysis** The rate of evaporation of water is

$$\begin{aligned} m_{\text{evap}} &= \frac{V_{\text{evap}}}{\nu_f} = \frac{(\pi D^2 / 4)L}{\nu_f} = \frac{[\pi(0.25 \text{ m})^2 / 4](0.10 \text{ m})}{0.001043} = 4.704 \text{ kg} \\ \dot{m}_{\text{evap}} &= \frac{m_{\text{evap}}}{\Delta t} = \frac{4.704 \text{ kg}}{45 \times 60 \text{ s}} = 0.001742 \text{ kg/s} \end{aligned}$$



Then the rate of heat transfer to water becomes

$$\dot{Q} = \dot{m}_{\text{evap}} h_{\text{fg}} = (0.001742 \text{ kg/s})(2256.5 \text{ kJ/kg}) = \mathbf{3.93 \text{ kW}}$$

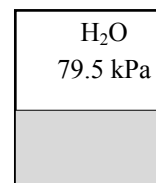
**3-48** Water is boiled at a location where the atmospheric pressure is 79.5 kPa in a pan placed on an electric burner. The water level drops by 10 cm in 45 min during boiling. The rate of heat transfer to the water is to be determined.

**Properties** The properties of water at 79.5 kPa are  $T_{\text{sat}} = 93.3^\circ\text{C}$ ,  $h_{\text{fg}} = 2273.9 \text{ kJ/kg}$  and  $\nu_f = 0.001038 \text{ m}^3/\text{kg}$  (Table A-5).

**Analysis** The rate of evaporation of water is

$$m_{\text{evap}} = \frac{\nu_{\text{evap}}}{\nu_f} = \frac{(\pi D^2 / 4)L}{\nu_f} = \frac{[\pi(0.25 \text{ m})^2 / 4](0.10 \text{ m})}{0.001038} = 4.727 \text{ kg}$$

$$\dot{m}_{\text{evap}} = \frac{m_{\text{evap}}}{\Delta t} = \frac{4.727 \text{ kg}}{45 \times 60 \text{ s}} = 0.001751 \text{ kg/s}$$



Then the rate of heat transfer to water becomes

$$\dot{Q} = \dot{m}_{\text{evap}} h_{\text{fg}} = (0.001751 \text{ kg/s})(2273.9 \text{ kJ/kg}) = \mathbf{3.98 \text{ kW}}$$

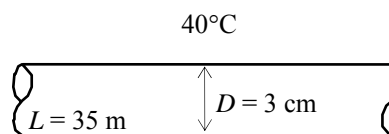
**3-49** Saturated steam at  $T_{\text{sat}} = 40^\circ\text{C}$  condenses on the outer surface of a cooling tube at a rate of 130 kg/h. The rate of heat transfer from the steam to the cooling water is to be determined.

**Assumptions** 1 Steady operating conditions exist. 2 The condensate leaves the condenser as a saturated liquid at  $30^\circ\text{C}$ .

**Properties** The properties of water at the saturation temperature of  $40^\circ\text{C}$  are  $h_{\text{fg}} = 2406.0 \text{ kJ/kg}$  (Table A-4).

**Analysis** Noting that 2406.0 kJ of heat is released as 1 kg of saturated vapor at  $40^\circ\text{C}$  condenses, the rate of heat transfer from the steam to the cooling water in the tube is determined directly from

$$\begin{aligned} \dot{Q} &= \dot{m}_{\text{evap}} h_{\text{fg}} \\ &= (130 \text{ kg/h})(2406.0 \text{ kJ/kg}) = 312,780 \text{ kJ/h} \\ &= \mathbf{86.9 \text{ kW}} \end{aligned}$$



**3-50** The boiling temperature of water in a 5-cm deep pan is given. The boiling temperature in a 40-cm deep pan is to be determined.

**Assumptions** Both pans are full of water.

**Properties** The density of liquid water is approximately  $\rho = 1000 \text{ kg/m}^3$ .

**Analysis** The pressure at the bottom of the 5-cm pan is the saturation pressure corresponding to the boiling temperature of  $98^\circ\text{C}$ :

$$P = P_{\text{sat}@98^\circ\text{C}} = 94.39 \text{ kPa} \quad (\text{Table A-4})$$

The pressure difference between the bottoms of two pans is

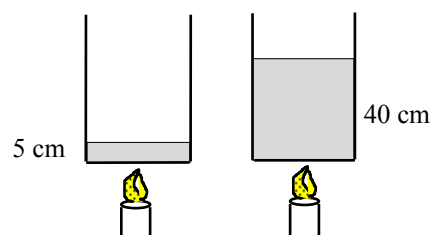
$$\Delta P = \rho gh = (1000 \text{ kg/m}^3)(9.807 \text{ m/s}^2)(0.35 \text{ m}) \left( \frac{1 \text{ kPa}}{1000 \text{ kg/m} \cdot \text{s}^2} \right) = 3.43 \text{ kPa}$$

Then the pressure at the bottom of the 40-cm deep pan is

$$P = 94.39 + 3.43 = 97.82 \text{ kPa}$$

Then the boiling temperature becomes

$$T_{\text{boiling}} = T_{\text{sat}@97.82 \text{ kPa}} = \mathbf{99.0^\circ\text{C}} \quad (\text{Table A-5})$$



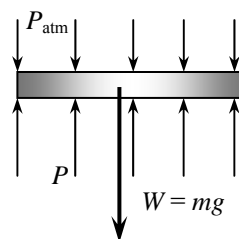
**3-51** A vertical piston-cylinder device is filled with water and covered with a 20-kg piston that serves as the lid. The boiling temperature of water is to be determined.

**Analysis** The pressure in the cylinder is determined from a force balance on the piston,

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

or,

$$\begin{aligned} P &= P_{\text{atm}} + \frac{mg}{A} \\ &= (100 \text{ kPa}) + \frac{(20 \text{ kg})(9.81 \text{ m/s}^2)}{0.01 \text{ m}^2} \left( \frac{1 \text{ kPa}}{1000 \text{ kg/m} \cdot \text{s}^2} \right) \\ &= 119.61 \text{ kPa} \end{aligned}$$



The boiling temperature is the saturation temperature corresponding to this pressure,

$$T = T_{\text{sat}@119.61 \text{ kPa}} = \mathbf{104.7^\circ\text{C}} \quad (\text{Table A-5})$$

**3-52** A rigid tank that is filled with saturated liquid-vapor mixture is heated. The temperature at which the liquid in the tank is completely vaporized is to be determined, and the  $T$ - $\nu$  diagram is to be drawn.

**Analysis** This is a constant volume process ( $\nu = V/m = \text{constant}$ ), and the specific volume is determined to be

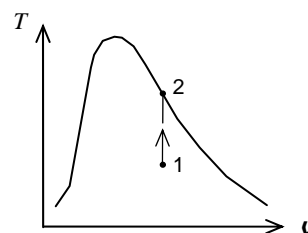
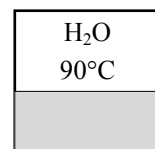
$$\nu = \frac{V}{m} = \frac{1.8 \text{ m}^3}{15 \text{ kg}} = 0.12 \text{ m}^3/\text{kg}$$

When the liquid is completely vaporized the tank will contain saturated vapor only. Thus,

$$\nu_2 = \nu_g = 0.12 \text{ m}^3/\text{kg}$$

The temperature at this point is the temperature that corresponds to this  $\nu_g$  value,

$$T = T_{\text{sat}@ \nu_g = 0.12 \text{ m}^3/\text{kg}} = \mathbf{202.9^\circ\text{C}} \quad (\text{Table A-4})$$



**3-53** A piston-cylinder device contains a saturated liquid-vapor mixture of water at 800 kPa pressure. The mixture is heated at constant pressure until the temperature rises to 200°C. The initial temperature, the total mass of water, the final volume are to be determined, and the  $P$ - $\nu$  diagram is to be drawn.

**Analysis** (a) Initially two phases coexist in equilibrium, thus we have a saturated liquid-vapor mixture. Then the temperature in the tank must be the saturation temperature at the specified pressure,

$$T = T_{\text{sat}@ 800 \text{ kPa}} = \mathbf{158.8^\circ\text{C}}$$

(b) The total mass in this case can easily be determined by adding the mass of each phase,

$$m_f = \frac{\nu_f}{\nu_f} = \frac{0.005 \text{ m}^3}{0.001101 \text{ m}^3/\text{kg}} = 4.543 \text{ kg}$$

$$m_g = \frac{\nu_g}{\nu_g} = \frac{0.9 \text{ m}^3}{0.3156 \text{ m}^3/\text{kg}} = 2.852 \text{ kg}$$

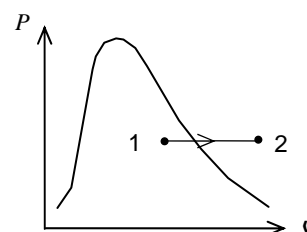
$$m_t = m_f + m_g = 4.543 + 2.852 = \mathbf{7.395 \text{ kg}}$$

(c) At the final state water is superheated vapor, and its specific volume is

$$\left. \begin{array}{l} P_2 = 800 \text{ kPa} \\ T_2 = 200^\circ\text{C} \end{array} \right\} \nu_2 = 0.3521 \text{ m}^3/\text{kg} \quad (\text{Table A-6})$$

Then,

$$V_2 = m_t \nu_2 = (7.395 \text{ kg})(0.3521 \text{ m}^3/\text{kg}) = \mathbf{2.604 \text{ m}^3}$$





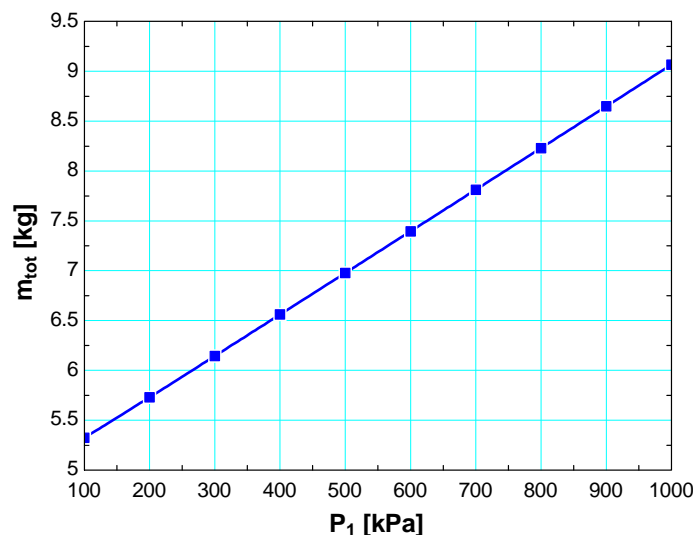
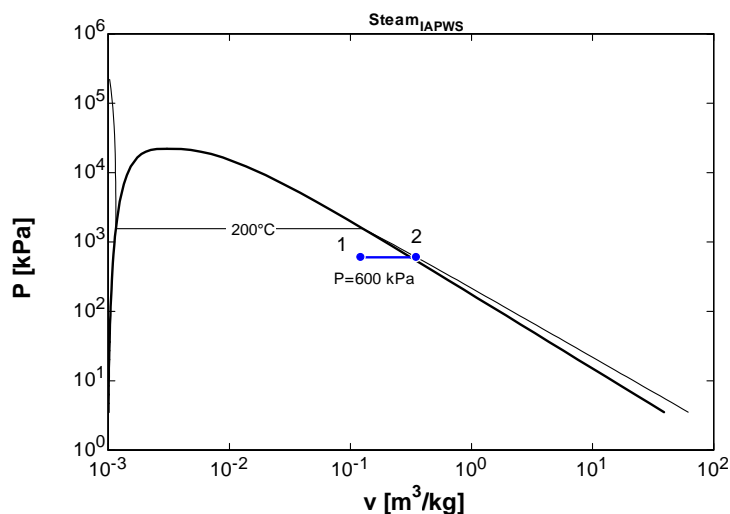
**3-54** Problem 3-53 is reconsidered. The effect of pressure on the total mass of water in the tank as the pressure varies from 0.1 MPa to 1 MPa is to be investigated. The total mass of water is to be plotted against pressure, and results are to be discussed.

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

```

P[1]=600 [kPa]
P[2]=P[1]
T[2]=200 [C]
V_f1 = 0.005 [m^3]
V_g1=0.9 [m^3]
spvsat_f1=volume(Steam_iapws, P=P[1],x=0) "sat. liq. specific volume, m^3/kg"
spvsat_g1=volume(Steam_iapws,P=P[1],x=1) "sat. vap. specific volume, m^3/kg"
m_f1=V_f1/spvsat_f1 "sat. liq. mass, kg"
m_g1=V_g1/spvsat_g1 "sat. vap. mass, kg"
m_tot=m_f1+m_g1
V[1]=V_f1+V_g1
spvol[1]=V[1]/m_tot "specific volume1, m^3"
T[1]=temperature(Steam_iapws, P=P[1],v=spvol[1])"C"
"The final volume is calculated from the specific volume at the final T and P"
spvol[2]=volume(Steam_iapws, P=P[2], T=T[2]) "specific volume2, m^3/kg"
V[2]=m_tot*spvol[2]
  
```

$P_1$ [kPa]	$m_{\text{tot}}$ [kg]
100	5.324
200	5.731
300	6.145
400	6.561
500	6.978
600	7.395
700	7.812
800	8.23
900	8.648
1000	9.066



**3-55E** Superheated water vapor cools at constant volume until the temperature drops to 250°F. At the final state, the pressure, the quality, and the enthalpy are to be determined.

**Analysis** This is a constant volume process ( $v = V/m = \text{constant}$ ), and the initial specific volume is determined to be

$$\left. \begin{array}{l} P_1 = 180 \text{ psia} \\ T_1 = 500^\circ \text{F} \end{array} \right\} v_1 = 3.0433 \text{ ft}^3/\text{lbm} \quad (\text{Table A-6E})$$

At 250°F,  $v_f = 0.01700 \text{ ft}^3/\text{lbm}$  and  $v_g = 13.816 \text{ ft}^3/\text{lbm}$ . Thus at the final state, the tank will contain saturated liquid-vapor mixture since  $v_f < v < v_g$ , and the final pressure must be the saturation pressure at the final temperature,

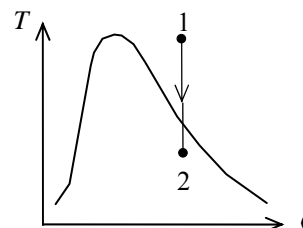
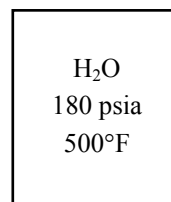
$$P = P_{\text{sat}@250^\circ \text{F}} = \mathbf{29.84 \text{ psia}}$$

(b) The quality at the final state is determined from

$$x_2 = \frac{v_2 - v_f}{v_{fg}} = \frac{3.0433 - 0.01700}{13.816 - 0.01700} = \mathbf{0.219}$$

(c) The enthalpy at the final state is determined from

$$h = h_f + xh_{fg} = 218.63 + 0.219 \times 945.41 = \mathbf{426.0 \text{ Btu/lbm}}$$







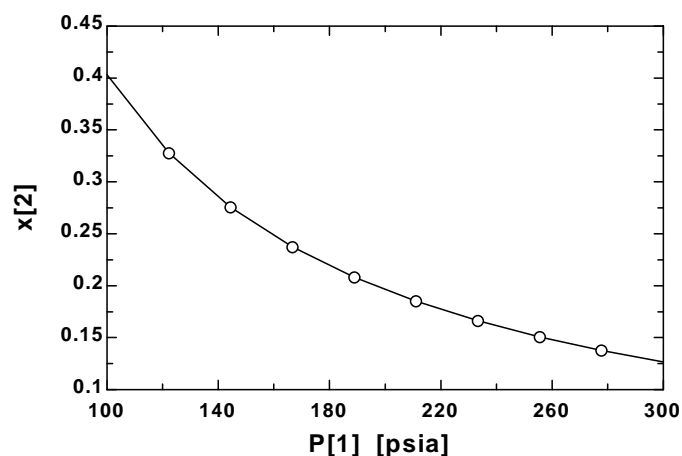
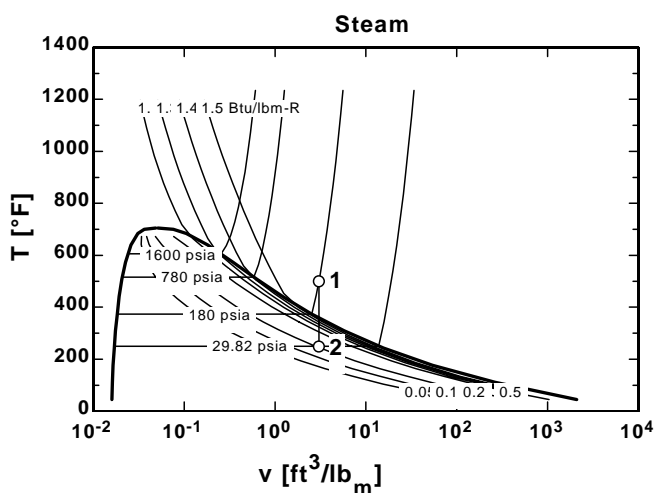
**3-56E** Problem 3-55E is reconsidered. The effect of initial pressure on the quality of water at the final state as the pressure varies from 100 psi to 300 psi is to be investigated. The quality is to be plotted against initial pressure, and the results are to be discussed.

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

```

T[1]=500 [F]
P[1]=180 [psia]
T[2]=250 [F]
v[1]=volume(steam_iapws,T=T[1],P=P[1])
v[2]=v[1]
P[2]=pressure(steam_iapws,T=T[2],v=v[2])
h[2]=enthalpy(steam_iapws,T=T[2],v=v[2])
x[2]=quality(steam_iapws,T=T[2],v=v[2])
  
```

$P_1$ [psia]	$x_2$
100	0.4037
122.2	0.3283
144.4	0.2761
166.7	0.2378
188.9	0.2084
211.1	0.1853
233.3	0.1665
255.6	0.151
277.8	0.1379
300	0.1268



**3-57** 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,

$$\begin{aligned} T = 80^\circ\text{C} \Rightarrow \quad \nu &\cong \nu_{f@80^\circ\text{C}} = 0.001029 \text{ m}^3/\text{kg} \quad (0.90\% \text{ error}) \\ u &\cong u_{f@80^\circ\text{C}} = 334.97 \text{ kJ/kg} \quad (1.35\% \text{ error}) \\ h &\cong h_{f@80^\circ\text{C}} = 335.02 \text{ kJ/kg} \quad (4.53\% \text{ error}) \end{aligned}$$

From compressed liquid table (Table A-7),

$$\left. \begin{array}{l} P = 20 \text{ MPa} \\ T = 80^\circ\text{C} \end{array} \right\} \begin{array}{l} \nu = 0.00102 \text{ m}^3/\text{kg} \\ u = 330.50 \text{ kJ/kg} \\ h = 350.90 \text{ kJ/kg} \end{array}$$

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



**3-58** Problem 3-57 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.

"Given"

T=80 [C]

P=20000 [kPa]

"Analysis"

Fluid\$='steam\_iapws'

"Saturated liquid assumption"

v\_f=volume(Fluid\$, T=T, x=0)

u\_f=intenergy(Fluid\$, T=T, x=0)

h\_f=enthalpy(Fluid\$, T=T, x=0)

"Compressed liquid treatment"

v=volume(Fluid\$, T=T, P=P)

u=intenergy(Fluid\$, T=T, P=P)

h=enthalpy(Fluid\$, T=T, P=P)

"Percentage Errors"

error\_v=100\*(v\_f-v)/v

error\_u=100\*(u\_f-u)/u

error\_h=100\*(h-h\_f)/h

SOLUTION

error\_h=4.527

error\_u=1.351

error\_v=0.8987

Fluid\$='steam\_iapws'

h=350.90 [kJ/kg]

h\_f=335.02 [kJ/kg]

P=20000 [kPa]

T=80 [C]

u=330.50 [kJ/kg]

u\_f=334.97 [kJ/kg]

v=0.00102 [m^3/kg]

v\_f=0.001029 [m^3/kg]

**3-59** 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  $T$ - $\nu$  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,

$$T = T_{\text{sat}@1 \text{ MPa}} = \mathbf{179.88^\circ\text{C}} \quad (\text{Table A-5})$$

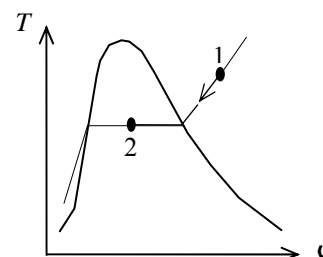
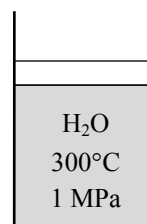
(c) The quality at the final state is specified to be  $x_2 = 0.5$ . The specific volumes at the initial and the final states are

$$\left. \begin{array}{l} P_1 = 1.0 \text{ MPa} \\ T_1 = 300^\circ\text{C} \end{array} \right\} \nu_1 = 0.25799 \text{ m}^3/\text{kg} \quad (\text{Table A-6})$$

$$\left. \begin{array}{l} P_2 = 1.0 \text{ MPa} \\ x_2 = 0.5 \end{array} \right\} \begin{aligned} \nu_2 &= \nu_f + x_2 \nu_{fg} \\ &= 0.001127 + 0.5 \times (0.19436 - 0.001127) \\ &= 0.09775 \text{ m}^3/\text{kg} \end{aligned}$$

Thus,

$$\Delta V = m(\nu_2 - \nu_1) = (0.8 \text{ kg})(0.09775 - 0.25799) \text{ m}^3/\text{kg} = \mathbf{-0.1282 \text{ m}^3}$$



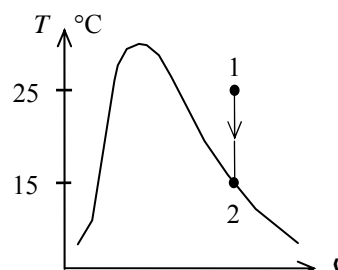
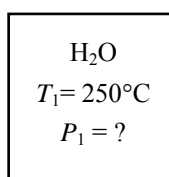
**3-60** The water in a rigid tank is cooled until the vapor starts condensing. The initial pressure in the tank is to be determined.

**Analysis** This is a constant volume process ( $\nu = V/m = \text{constant}$ ), and the initial specific volume is equal to the final specific volume that is

$$\nu_1 = \nu_2 = \nu_{g@124^\circ\text{C}} = 0.79270 \text{ m}^3/\text{kg} \quad (\text{Table A-4})$$

since the vapor starts condensing at  $150^\circ\text{C}$ . Then from Table A-6,

$$\left. \begin{array}{l} T_1 = 250^\circ\text{C} \\ \nu_1 = 0.79270 \text{ m}^3/\text{kg} \end{array} \right\} P_1 = \mathbf{0.30 \text{ MPa}}$$



**3-61** Heat is supplied to a piston-cylinder device 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:  $\nu_f = 0.001157 \text{ m}^3/\text{kg}$  and  $u_f = 850.46 \text{ kJ/kg}$  (Table A-4).

**Analysis** (a) The cylinder initially contains saturated liquid water. The volume of the cylinder at the initial state is

$$\nu_1 = m\nu_1 = (1.4 \text{ kg})(0.001157 \text{ m}^3/\text{kg}) = 0.001619 \text{ m}^3$$

The volume at the final state is

$$\nu = 4(0.001619) = \mathbf{0.006476 \text{ m}^3}$$

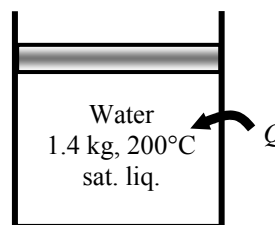
(b) The final state properties are

$$\nu_2 = \frac{\nu}{m} = \frac{0.006476 \text{ m}^3}{1.4 \text{ kg}} = 0.004626 \text{ m}^3/\text{kg}$$

$$\left. \begin{array}{l} \nu_2 = 0.004626 \text{ m}^3/\text{kg} \\ x_2 = 1 \end{array} \right\} \begin{array}{l} T_2 = \mathbf{371.3^\circ\text{C}} \\ P_2 = \mathbf{21,367 \text{ kPa}} \\ u_2 = 2201.5 \text{ kJ/kg} \end{array} \quad (\text{Table A-4 or A-5 or EES})$$

(c) The total internal energy change is determined from

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



**3-62E** The error involved in using the enthalpy of water by the incompressible liquid approximation is to be determined.

**Analysis** The state of water is compressed liquid. From the steam tables,

$$\left. \begin{array}{l} P = 1500 \text{ psia} \\ T = 400^\circ\text{F} \end{array} \right\} h = 376.51 \text{ Btu/lbm} \quad (\text{Table A - 7E})$$

Based upon the incompressible liquid approximation,

$$\left. \begin{array}{l} P = 1500 \text{ psia} \\ T = 400^\circ\text{F} \end{array} \right\} h \cong h_f @ 400^\circ\text{F} = 375.04 \text{ Btu/lbm} \quad (\text{Table A - 4E})$$

The error involved is

$$\text{Percent Error} = \frac{376.51 - 375.04}{376.51} \times 100 = \mathbf{0.39\%}$$

which is quite acceptable in most engineering calculations.

**3-63** The errors involved in using the specific volume and enthalpy of water by the incompressible liquid approximation are to be determined.

**Analysis** The state of water is compressed liquid. From the steam tables,

$$\left. \begin{array}{l} P = 20 \text{ MPa} \\ T = 140^\circ\text{C} \end{array} \right\} \begin{array}{l} \nu = 0.0010679 \text{ m}^3/\text{kg} \\ h = 602.07 \text{ kJ/kg} \end{array} \quad (\text{Table A - 7})$$

Based upon the incompressible liquid approximation,

$$\left. \begin{array}{l} P = 20 \text{ MPa} \\ T = 140^\circ\text{C} \end{array} \right\} \begin{array}{l} \nu \cong \nu_f @ 140^\circ\text{C} = 0.001080 \text{ m}^3/\text{kg} \\ h \cong h_f @ 140^\circ\text{C} = 589.16 \text{ kJ/kg} \end{array} \quad (\text{Table A - 4})$$

The errors involved are

$$\text{Percent Error (specific volume)} = \frac{0.0010679 - 0.001080}{0.0010679} \times 100 = -1.13\%$$

$$\text{Percent Error (enthalpy)} = \frac{602.07 - 589.16}{602.07} \times 100 = 2.14\%$$

which are quite acceptable in most engineering calculations.

**3-64** A piston-cylinder device that is filled with R-134a is heated. The volume change is to be determined.

**Analysis** The initial specific volume is

$$\left. \begin{array}{l} P_1 = 60 \text{ kPa} \\ T_1 = -20^\circ\text{C} \end{array} \right\} \nu_1 = 0.33608 \text{ m}^3/\text{kg} \quad (\text{Table A - 13})$$

and the initial volume is

$$\nu_1 = m\nu_1 = (0.100 \text{ kg})(0.33608 \text{ m}^3/\text{kg}) = 0.033608 \text{ m}^3$$

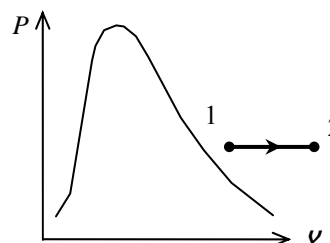
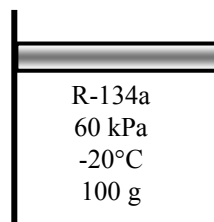
At the final state, we have

$$\left. \begin{array}{l} P_2 = 60 \text{ kPa} \\ T_2 = 100^\circ\text{C} \end{array} \right\} \nu_2 = 0.50410 \text{ m}^3/\text{kg} \quad (\text{Table A - 13})$$

$$\nu_2 = m\nu_2 = (0.100 \text{ kg})(0.50410 \text{ m}^3/\text{kg}) = 0.050410 \text{ m}^3$$

The volume change is then

$$\Delta \nu = \nu_2 - \nu_1 = 0.050410 - 0.033608 = 0.0168 \text{ m}^3$$



**3-65** A rigid vessel is filled with refrigerant-134a. The total volume and the total internal energy are to be determined.

**Properties** The properties of R-134a at the given state are (Table A-13).

$$\left. \begin{array}{l} P = 800 \text{ kPa} \\ T = 120^\circ \text{C} \end{array} \right\} \begin{array}{l} u = 327.87 \text{ kJ/kg} \\ \nu = 0.037625 \text{ m}^3/\text{kg} \end{array}$$

R-134a
2 kg
800 kPa
120°C

**Analysis** The total volume and internal energy are determined from

$$V = m\nu = (2 \text{ kg})(0.037625 \text{ m}^3/\text{kg}) = \mathbf{0.0753 \text{ m}^3}$$

$$U = mu = (2 \text{ kg})(327.87 \text{ kJ/kg}) = \mathbf{655.7 \text{ kJ}}$$

**3-66** A rigid vessel contains R-134a at specified temperature. The pressure, total internal energy, and the volume of the liquid phase are to be determined.

**Analysis** (a) The specific volume of the refrigerant is

$$\nu = \frac{V}{m} = \frac{0.5 \text{ m}^3}{10 \text{ kg}} = 0.05 \text{ m}^3/\text{kg}$$

At  $-20^\circ\text{C}$ ,  $\nu_f = 0.0007362 \text{ m}^3/\text{kg}$  and  $\nu_g = 0.14729 \text{ m}^3/\text{kg}$  (Table A-11). Thus the tank contains saturated liquid-vapor mixture since  $\nu_f < \nu < \nu_g$ , and the pressure must be the saturation pressure at the specified temperature,

$$P = P_{\text{sat}@-20^\circ\text{C}} = \mathbf{132.82 \text{ kPa}}$$

(b) The quality of the refrigerant-134a and its total internal energy are determined from

$$x = \frac{\nu - \nu_f}{\nu_{fg}} = \frac{0.05 - 0.0007362}{0.14729 - 0.0007362} = 0.3361$$

$$u = u_f + xu_{fg} = 25.39 + 0.3361 \times 193.45 = 90.42 \text{ kJ/kg}$$

$$U = mu = (10 \text{ kg})(90.42 \text{ kJ/kg}) = \mathbf{904.2 \text{ kJ}}$$

(c) The mass of the liquid phase and its volume are determined from

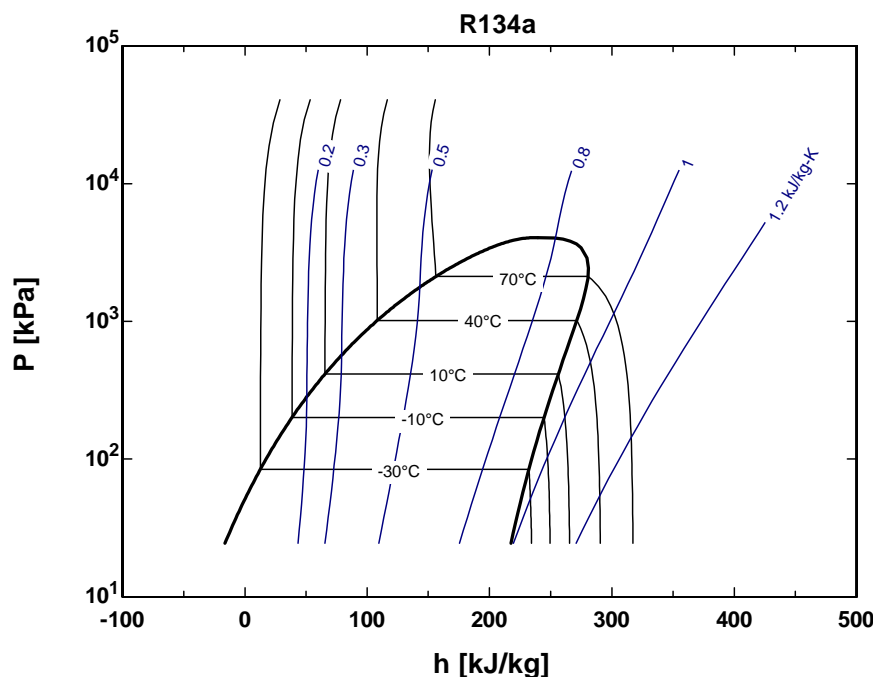
$$m_f = (1 - x)m_t = (1 - 0.3361) \times 10 = 6.639 \text{ kg}$$

$$V_f = m_f \nu_f = (6.639 \text{ kg})(0.0007362 \text{ m}^3/\text{kg}) = \mathbf{0.00489 \text{ m}^3}$$

R-134a
10 kg
$-20^\circ\text{C}$



**3-67** The Pressure-Enthalpy diagram of R-134a showing some constant-temperature and constant-entropy lines are obtained using Property Plot feature of EES.



**3-68** A rigid vessel that contains a saturated liquid-vapor mixture is heated until it reaches the critical state. The mass of the liquid water and the volume occupied by the liquid at the initial state are to be determined.

**Analysis** This is a constant volume process ( $v = V/m = \text{constant}$ ) to the critical state, and thus the initial specific volume will be equal to the final specific volume, which is equal to the critical specific volume of water,

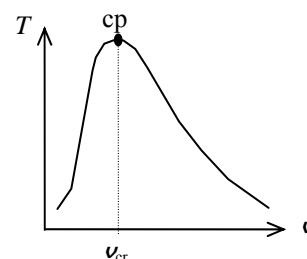
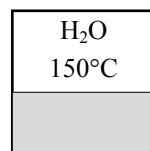
$$v_1 = v_2 = v_{cr} = 0.003106 \text{ m}^3/\text{kg} \quad (\text{last row of Table A-4})$$

The total mass is

$$m = \frac{V}{v} = \frac{0.3 \text{ m}^3}{0.003106 \text{ m}^3/\text{kg}} = 96.60 \text{ kg}$$

At 150°C,  $v_f = 0.001091 \text{ m}^3/\text{kg}$  and  $v_g = 0.39248 \text{ m}^3/\text{kg}$  (Table A-4). Then the quality of water at the initial state is

$$x_1 = \frac{v_1 - v_f}{v_{fg}} = \frac{0.003106 - 0.001091}{0.39248 - 0.001091} = 0.005149$$



Then the mass of the liquid phase and its volume at the initial state are determined from

$$m_f = (1 - x_1)m_t = (1 - 0.005149)(96.60) = \mathbf{96.10 \text{ kg}}$$

$$V_f = m_f v_f = (96.10 \text{ kg})(0.001091 \text{ m}^3/\text{kg}) = \mathbf{0.105 \text{ m}^3}$$



## Ideal Gas

**3-69C** 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.

**3-70C** 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** 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.

**3-73** The specific volume of nitrogen at a specified state is to be determined.

**Assumptions** At specified conditions, nitrogen behaves as an ideal gas.

**Properties** The gas constant of nitrogen is  $R = 0.2968 \text{ kJ/kg}\cdot\text{K}$  (Table A-1).

**Analysis** According to the ideal gas equation of state,

$$\nu = \frac{RT}{P} = \frac{(0.2968 \text{ kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K})(227 + 273 \text{ K})}{300 \text{ kPa}} = \mathbf{0.495 \text{ m}^3/\text{kg}}$$

**3-74E** The temperature in a container that is filled with oxygen is to be determined.

**Assumptions** At specified conditions, oxygen behaves as an ideal gas.

**Properties** The gas constant of oxygen is  $R = 0.3353 \text{ psia}\cdot\text{ft}^3/\text{lbm}\cdot\text{R}$  (Table A-1E).

**Analysis** The definition of the specific volume gives

$$\nu = \frac{V}{m} = \frac{3 \text{ ft}^3}{2 \text{ lbm}} = 1.5 \text{ ft}^3/\text{lbm}$$

Using the ideal gas equation of state, the temperature is

$$T = \frac{P\nu}{R} = \frac{(80 \text{ psia})(1.5 \text{ ft}^3/\text{lbm})}{0.3353 \text{ psia} \cdot \text{ft}^3/\text{lbm} \cdot \text{R}} = \mathbf{358 \text{ R}}$$

**3-75** The volume of a container that is filled with helium at a specified state is to be determined.

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

**Properties** The gas constant of helium is  $R = 2.0769 \text{ kJ/kg}\cdot\text{K}$  (Table A-1).

**Analysis** According to the ideal gas equation of state,

$$V = \frac{mRT}{P} = \frac{(2 \text{ kg})(2.0769 \text{ kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(27 + 273 \text{ K})}{300 \text{ kPa}} = \mathbf{4.154 \text{ m}^3}$$

**3-76** 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  $R_u = 8.314 \text{ kPa}\cdot\text{m}^3/\text{kmol}\cdot\text{K}$ . The molar mass of helium is  $4.0 \text{ kg/kmol}$  (Table A-1).

**Analysis** The volume of the sphere is

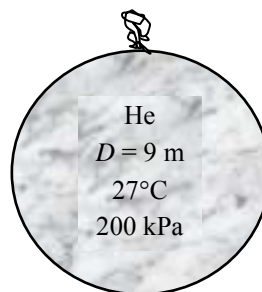
$$V = \frac{4}{3}\pi r^3 = \frac{4}{3}\pi(4.5 \text{ m})^3 = 381.7 \text{ m}^3$$

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

$$N = \frac{PV}{R_u T} = \frac{(200 \text{ kPa})(381.7 \text{ m}^3)}{(8.314 \text{ kPa}\cdot\text{m}^3/\text{kmol}\cdot\text{K})(300 \text{ K})} = \mathbf{30.61 \text{ kmol}}$$

Then the mass of He can be determined from

$$m = NM = (30.61 \text{ kmol})(4.0 \text{ kg/kmol}) = \mathbf{123 \text{ kg}}$$





**3-77** Problem 3-76 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=9 [m]}

T=27 [C]

P=200 [kPa]

R\_u=8.314 [kJ/kmol-K]

"Solution"

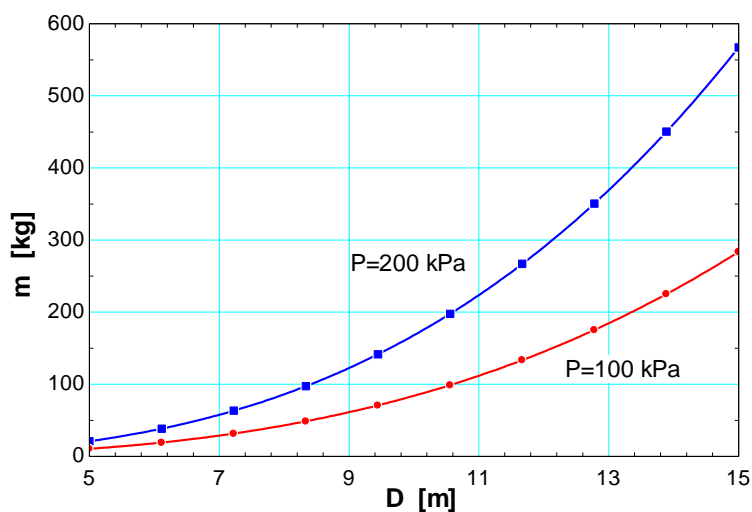
$P \cdot V = N \cdot R_u \cdot (T + 273)$

$V = 4 \cdot \pi \cdot (D/2)^3 / 3$

$m = N \cdot \text{MOLARMASS}(\text{Helium})$

D [m]	m [kg]
5	21.01
6.111	38.35
7.222	63.31
8.333	97.25
9.444	141.6
10.56	197.6
11.67	266.9
12.78	350.6
13.89	450.2
15	567.2

P=200 kPa



**3-78** 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  $R = 0.287 \text{ kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K}$  (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

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

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

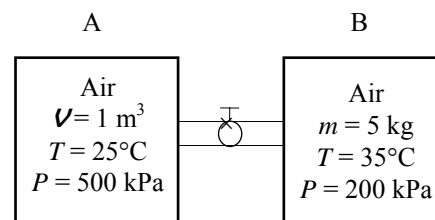
Thus,

$$V = V_A + V_B = 1.0 + 2.21 = 3.21 \text{ m}^3$$

$$m = m_A + m_B = 5.846 + 5.0 = 10.846 \text{ kg}$$

Then the final equilibrium pressure becomes

$$P_2 = \frac{m R T_2}{V} = \frac{(10.846 \text{ kg})(0.287 \text{ kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K})(293 \text{ K})}{3.21 \text{ m}^3} = \mathbf{284.1 \text{ kPa}}$$



**3-79E** An elastic tank contains air at a specified state. The volume is doubled at the same pressure. The initial volume and the final temperature are to be determined.

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

**Analysis** According to the ideal gas equation of state,

$$P V = n R_u T$$

$$(32 \text{ psia}) V = (2.3 \text{ lbmol})(10.73 \text{ psia} \cdot \text{ft}^3/\text{lbmol} \cdot \text{R})(65 + 460) \text{ R}$$

$$V = \mathbf{404.9 \text{ ft}^3}$$

$$\frac{V_2}{V_1} = \frac{T_2}{T_1} \longrightarrow 2 = \frac{T_2}{(65 + 460) \text{ R}} \longrightarrow T_2 = \mathbf{1050 \text{ R} = 590^\circ\text{F}}$$

**3-80** An ideal gas in a rigid tank is cooled to a final gage pressure. The final temperature is to be determined.

**Assumptions** The gas is specified as an ideal gas so that ideal gas relation can be used.

**Analysis** According to the ideal gas equation of state at constant volume,

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$$

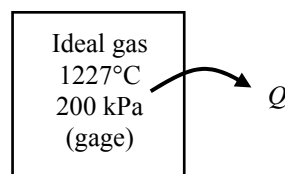
Since  $V_1 = V_2$

Then,

$$\frac{P_1}{T_1} = \frac{P_2}{T_2}$$

$$T_2 = T_1 \frac{P_2}{P_1} = [(1227 + 273) \text{ K}] \frac{(50 + 100) \text{ kPa}}{(200 + 100) \text{ kPa}} = 750 \text{ K} = \mathbf{477^\circ\text{C}}$$

$$P_{\text{atm}} = 100 \text{ kPa}$$



**3-81** One side of a two-sided tank contains an ideal gas while the other side is evacuated. The partition is removed and the gas fills the entire tank. The gas is also heated to a final pressure. The final temperature is to be determined.

**Assumptions** The gas is specified as an ideal gas so that ideal gas relation can be used.

**Analysis** According to the ideal gas equation of state,

$$P_2 = P_1$$

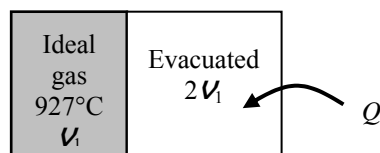
$$V_2 = V_1 + 2V_1 = 3V_1$$

Applying these,

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$$

$$\frac{V_1}{T_1} = \frac{V_2}{T_2}$$

$$T_2 = T_1 \frac{V_2}{V_1} = T_1 \frac{3V_1}{V_1} = 3T_1 = 3[927 + 273) \text{ K}] = 3600 \text{ K} = \mathbf{3327^\circ\text{C}}$$



**3-82** A piston-cylinder device containing argon undergoes an isothermal process. The final pressure is to be determined.

**Assumptions** At specified conditions, argon behaves as an ideal gas.

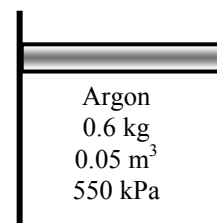
**Properties** The gas constant of argon is  $R = 0.2081 \text{ kJ/kg}\cdot\text{K}$  (Table A-1).

**Analysis** Since the temperature remains constant, the ideal gas equation gives

$$m = \frac{P_1 V_1}{RT} = \frac{P_2 V_2}{RT} \longrightarrow P_1 V_1 = P_2 V_2$$

which when solved for final pressure becomes

$$P_2 = P_1 \frac{V_1}{V_2} = P_1 \frac{V_1}{2V_1} = 0.5P_1 = 0.5(550 \text{ kPa}) = \mathbf{275 \text{ kPa}}$$



**3-83** 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  $R = 0.287 \text{ kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K}$  (Table A-1).

**Analysis** Initially, the absolute pressure in the tire is

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

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

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

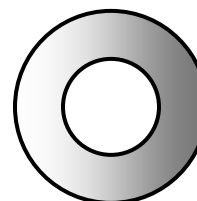
The amount of air that needs to be bled off to restore pressure to its original value is

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

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

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

Tire  
25°C



## Compressibility Factor

**3-84C** It represent the deviation from ideal gas behavior. The further away it is from 1, the more the gas deviates from ideal gas behavior.

**3-85C** All gases have the same compressibility factor  $Z$  at the same reduced temperature and pressure.

**3-86C** 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.

**3-87** 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,

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

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

$$\nu = \frac{RT}{P} = \frac{(0.4615 \text{ kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K})(623.15 \text{ K})}{15,000 \text{ kPa}} = \mathbf{0.01917 \text{ m}^3/\text{kg} \text{ (67.0\% error)}}$$

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

$$\left. \begin{aligned} P_R &= \frac{P}{P_{cr}} = \frac{10 \text{ MPa}}{22.06 \text{ MPa}} = 0.453 \\ T_R &= \frac{T}{T_{cr}} = \frac{673 \text{ K}}{647.1 \text{ K}} = 1.04 \end{aligned} \right\} Z = 0.65$$

H <sub>2</sub> O
15 MPa
350°C

Thus,

$$\nu = Z\nu_{ideal} = (0.65)(0.01917 \text{ m}^3/\text{kg}) = \mathbf{0.01246 \text{ m}^3/\text{kg} \text{ (8.5\% error)}}$$

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

$$\left. \begin{aligned} P &= 15 \text{ MPa} \\ T &= 350^\circ\text{C} \end{aligned} \right\} \nu = \mathbf{0.01148 \text{ m}^3/\text{kg}}$$

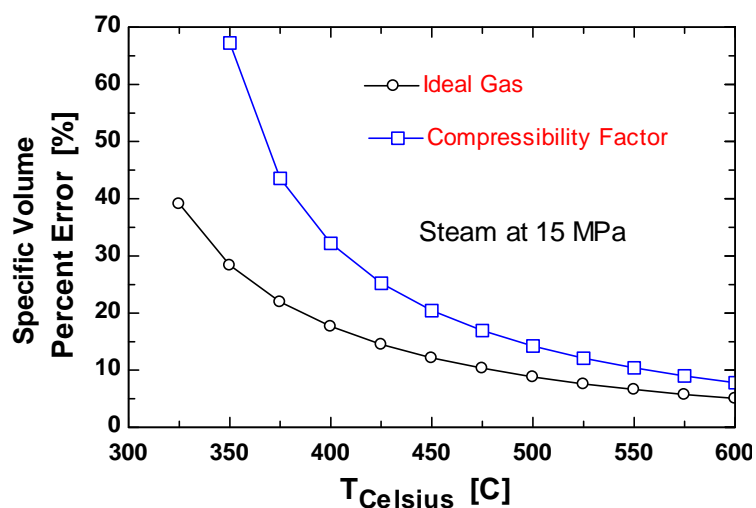


**3-88** Problem 3-87 is reconsidered. The problem is to be solved using the general compressibility factor feature of EES (or other) software. The specific volume of water for the three cases at 15 MPa over the temperature range of 350°C to 600°C in 25°C intervals is to be compared, and the % error 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=15 [MPa]*Convert(MPa,kPa)
{T_Celsius= 350 [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 <sub>comp</sub> [%]	Error <sub>ideal gas</sub> [%]	T <sub>Celsius</sub> [C]
9.447	67.22	350
2.725	43.53	375
0.4344	32.21	400
0.5995	25.23	425
1.101	20.44	450
1.337	16.92	475
1.428	14.22	500
1.437	12.1	525
1.397	10.39	550
1.329	8.976	575
1.245	7.802	600





**3-89** 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,

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

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

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

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

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

R-134a
0.9 MPa
70°C

Thus,

$$\nu = Z\nu_{\text{ideal}} = (0.894)(0.03105 \text{ m}^3/\text{kg}) = \mathbf{0.02776 \text{ m}^3/\text{kg}} \quad (1.3\% \text{ error})$$

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

$$\left. \begin{aligned} P &= 0.9 \text{ MPa} \\ T &= 70^\circ\text{C} \end{aligned} \right\} \nu = \mathbf{0.027413 \text{ m}^3/\text{kg}}$$

**3-90** 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,

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

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

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

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

$$\left. \begin{aligned} P_R = \frac{P}{P_{\text{cr}}} &= \frac{3.5 \text{ MPa}}{22.06 \text{ MPa}} = 0.159 \\ T_R = \frac{T}{T_{\text{cr}}} &= \frac{723 \text{ K}}{647.1 \text{ K}} = 1.12 \end{aligned} \right\} Z = 0.961$$

H <sub>2</sub> O
3.5 MPa
450°C

Thus,

$$\nu = Z\nu_{\text{ideal}} = (0.961)(0.09533 \text{ m}^3/\text{kg}) = \mathbf{0.09161 \text{ m}^3/\text{kg}} \quad (0.4\% \text{ error})$$

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

$$\left. \begin{aligned} P &= 3.5 \text{ MPa} \\ T &= 450^\circ\text{C} \end{aligned} \right\} \nu = \mathbf{0.09196 \text{ m}^3/\text{kg}}$$

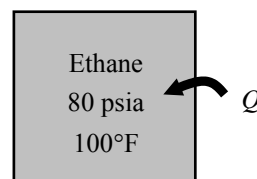
**3-91E** Ethane in a rigid vessel is heated. The final pressure is to be determined using the compressibility chart.

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

$$R = 0.3574 \text{ psia} \cdot \text{ft}^3/\text{lbm} \cdot \text{R}, \quad T_{\text{cr}} = 549.8 \text{ R}, \quad P_{\text{cr}} = 708 \text{ psia}$$

**Analysis** From the compressibility chart at the initial state (Fig. A-15),

$$\left. \begin{aligned} T_{R1} &= \frac{T_1}{T_{\text{cr}}} = \frac{560 \text{ R}}{549.8 \text{ R}} = 1.019 \\ P_{R1} &= \frac{P_1}{P_{\text{cr}}} = \frac{80 \text{ psia}}{708 \text{ psia}} = 0.1130 \end{aligned} \right\} Z_1 = 0.963$$



The specific volume does not change during the process. Then,

$$\nu_1 = \nu_2 = \frac{Z_1 R T_1}{P_1} = \frac{(0.963)(0.3574 \text{ psia} \cdot \text{ft}^3/\text{lbm} \cdot \text{R})(560 \text{ R})}{80 \text{ psia}} = 2.409 \text{ ft}^3/\text{lbm}$$

At the final state,

$$\left. \begin{aligned} T_{R2} &= \frac{T_2}{T_{\text{cr}}} = \frac{1000 \text{ R}}{549.8 \text{ R}} = 1.819 \\ \nu_{R2} &= \frac{\nu_{2,\text{actual}}}{R T_{\text{cr}}/P_{\text{cr}}} = \frac{2.409 \text{ ft}^3/\text{lbm}}{(0.3574 \text{ psia} \cdot \text{ft}^3/\text{lbm} \cdot \text{R})(549.8 \text{ R})/(708 \text{ psia})} = 8.68 \end{aligned} \right\} Z_2 = 1.0$$

Thus,

$$P_2 = \frac{Z_2 R T_2}{\nu_2} = \frac{(1.0)(0.3574 \text{ psia} \cdot \text{ft}^3/\text{lbm} \cdot \text{R})(1000 \text{ R})}{2.409 \text{ ft}^3/\text{lbm}} = \mathbf{148 \text{ psia}}$$

**3-92** Ethylene is heated at constant pressure. The specific volume change of ethylene is to be determined using the compressibility chart.

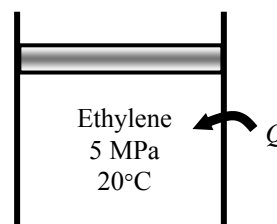
**Properties** The gas constant, the critical pressure, and the critical temperature of ethane are, from Table A-1,

$$R = 0.2964 \text{ kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K}, \quad T_{\text{cr}} = 282.4 \text{ K}, \quad P_{\text{cr}} = 5.12 \text{ MPa}$$

**Analysis** From the compressibility chart at the initial and final states (Fig. A-15),

$$\left. \begin{aligned} T_{R1} &= \frac{T_1}{T_{\text{cr}}} = \frac{293 \text{ K}}{282.4 \text{ K}} = 1.038 \\ P_{R1} &= \frac{P_1}{P_{\text{cr}}} = \frac{5 \text{ MPa}}{5.12 \text{ MPa}} = 0.977 \end{aligned} \right\} Z_1 = 0.56$$

$$\left. \begin{aligned} T_{R2} &= \frac{T_2}{T_{\text{cr}}} = \frac{473 \text{ K}}{282.4 \text{ K}} = 1.675 \\ P_{R2} &= P_{R1} = 0.977 \end{aligned} \right\} Z_2 = 0.961$$



The specific volume change is

$$\begin{aligned} \Delta v &= \frac{R}{P} (Z_2 T_2 - Z_1 T_1) \\ &= \frac{0.2964 \text{ kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K}}{5000 \text{ kPa}} [(0.961)(473 \text{ K}) - (0.56)(293 \text{ K})] \\ &= \mathbf{0.0172 \text{ m}^3/\text{kg}} \end{aligned}$$

**3-93** Water vapor is heated at constant pressure. The final temperature is to be determined using ideal gas equation, the compressibility charts, and the steam tables.

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

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

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

$$T_2 = T_1 \frac{\nu_2}{\nu_1} = (350 + 273 \text{ K})(2) = \mathbf{1246 \text{ K}}$$

(b) The pressure of the steam is

$$P_1 = P_2 = P_{\text{sat}@350^\circ\text{C}} = 16,529 \text{ kPa}$$

From the compressibility chart at the initial state (Fig. A-15),

$$\left. \begin{aligned} T_{R1} &= \frac{T_1}{T_{\text{cr}}} = \frac{623 \text{ K}}{647.1 \text{ K}} = 0.963 \\ P_{R1} &= \frac{P_1}{P_{\text{cr}}} = \frac{16.529 \text{ MPa}}{22.06 \text{ MPa}} = 0.749 \end{aligned} \right\} Z_1 = 0.593, \nu_{R1} = 0.75$$

At the final state,

$$\left. \begin{aligned} P_{R2} &= P_{R1} = 0.749 \\ \nu_{R2} &= 2\nu_{R1} = 2(0.75) = 1.50 \end{aligned} \right\} Z_2 = 0.88$$

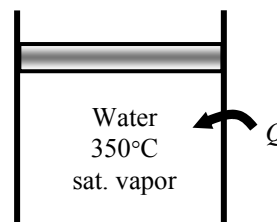
Thus,

$$T_2 = \frac{P_2 \nu_2}{Z_2 R} = \frac{P_2}{Z_2} \frac{\nu_{R2} T_{\text{cr}}}{P_{\text{cr}}} = \frac{16,529 \text{ kPa}}{0.88} \frac{(1.50)(647.1 \text{ K})}{22,060 \text{ kPa}} = \mathbf{826 \text{ K}}$$

(c) From the superheated steam table,

$$\left. \begin{aligned} T_1 &= 350^\circ\text{C} \\ x_1 &= 1 \end{aligned} \right\} \nu_1 = 0.008806 \text{ m}^3/\text{kg} \quad (\text{Table A-4})$$

$$\left. \begin{aligned} P_2 &= 16,529 \text{ kPa} \\ \nu_2 &= 2\nu_1 = 0.01761 \text{ m}^3/\text{kg} \end{aligned} \right\} T_2 = 477^\circ\text{C} = \mathbf{750 \text{ K}} \quad (\text{from Table A-6 or EES})$$



**3-94E** Water vapor is heated at constant pressure. The final temperature is to be determined using ideal gas equation, the compressibility charts, and the steam tables.

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

$$R = 0.5956 \text{ psia} \cdot \text{ft}^3/\text{lbm} \cdot \text{R}, \quad T_{\text{cr}} = 1164.8 \text{ R}, \quad P_{\text{cr}} = 3200 \text{ psia}$$

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

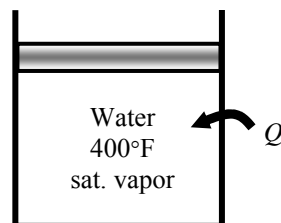
$$T_2 = T_1 \frac{\nu_2}{\nu_1} = (400 + 460 \text{ R})(2) = \mathbf{1720 \text{ R}}$$

(b) The properties of steam are (Table A-4E)

$$P_1 = P_2 = P_{\text{sat}@400^\circ\text{F}} = 247.26 \text{ psia}$$

$$\nu_1 = \nu_{\text{g}@400^\circ\text{F}} = 1.8639 \text{ ft}^3/\text{lbm}$$

$$\nu_2 = 2\nu_1 = 3.7278 \text{ ft}^3/\text{lbm}$$



At the final state, from the compressibility chart (Fig. A-15),

$$\left. \begin{aligned} P_{R2} &= \frac{P_2}{P_{\text{cr}}} = \frac{247.26 \text{ psia}}{3200 \text{ psia}} = 0.0773 \\ \nu_{R2} &= \frac{\nu_{2,\text{actual}}}{RT_{\text{cr}}/P_{\text{cr}}} = \frac{3.7278 \text{ ft}^3/\text{lbm}}{(0.5956 \text{ psia} \cdot \text{ft}^3/\text{lbm} \cdot \text{R})(1164.8 \text{ R})/(3200 \text{ psia})} = 17.19 \end{aligned} \right\} Z_2 = 0.985$$

Thus,

$$T_2 = \frac{P_2 \nu_2}{Z_2 R} = \frac{(247.26 \text{ psia})(3.7278 \text{ ft}^3/\text{lbm})}{(0.985)(0.5956 \text{ psia} \cdot \text{ft}^3/\text{lbm} \cdot \text{R})} = \mathbf{1571 \text{ R}}$$

(c) From the superheated steam table,

$$\left. \begin{aligned} P_2 &= 247.26 \text{ psia} \\ \nu_2 &= 3.7278 \text{ ft}^3/\text{lbm} \end{aligned} \right\} T_2 = 1100^\circ\text{F} = \mathbf{1560 \text{ R}} \quad (\text{from Table A-6E or EES})$$

**3-95** Methane is heated at constant pressure. The final temperature is to be determined using ideal gas equation and the compressibility charts.

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

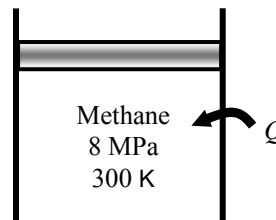
$$R = 0.5182 \text{ kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K}, \quad T_{\text{cr}} = 191.1 \text{ K}, \quad P_{\text{cr}} = 4.64 \text{ MPa}$$

**Analysis** From the ideal gas equation,

$$T_2 = T_1 \frac{\nu_2}{\nu_1} = (300 \text{ K})(1.5) = \mathbf{450 \text{ K}}$$

From the compressibility chart at the initial state (Fig. A-15),

$$\left. \begin{aligned} T_{R1} &= \frac{T_1}{T_{\text{cr}}} = \frac{300 \text{ K}}{191.1 \text{ K}} = 1.570 \\ P_{R1} &= \frac{P_1}{P_{\text{cr}}} = \frac{8 \text{ MPa}}{4.64 \text{ MPa}} = 1.724 \end{aligned} \right\} Z_1 = 0.88, \nu_{R1} = 0.80$$



At the final state,

$$\left. \begin{aligned} P_{R2} &= P_{R1} = 1.724 \\ \nu_{R2} &= 1.5\nu_{R1} = 1.5(0.80) = 1.2 \end{aligned} \right\} Z_2 = 0.975$$

Thus,

$$T_2 = \frac{P_2 \nu_2}{Z_2 R} = \frac{P_2}{Z_2} \frac{\nu_{R2} T_{\text{cr}}}{P_{\text{cr}}} = \frac{8000 \text{ kPa}}{0.975} \frac{(1.2)(191.1 \text{ K})}{4640 \text{ kPa}} = \mathbf{406 \text{ K}}$$

Of these two results, the accuracy of the second result is limited by the accuracy with which the charts may be read. Accepting the error associated with reading charts, the second temperature is the more accurate.

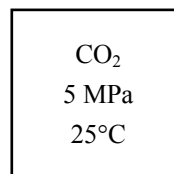
**3-96** The percent error involved in treating  $\text{CO}_2$  at a specified state as an ideal gas is to be determined.

**Properties** The critical pressure, and the critical temperature of  $\text{CO}_2$  are, from Table A-1,

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

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

$$\left. \begin{aligned} P_R &= \frac{P}{P_{\text{cr}}} = \frac{5 \text{ MPa}}{7.39 \text{ MPa}} = 0.677 \\ T_R &= \frac{T}{T_{\text{cr}}} = \frac{298 \text{ K}}{304.2 \text{ K}} = 0.980 \end{aligned} \right\} Z = 0.69$$



Then the error involved in treating  $\text{CO}_2$  as an ideal gas is

$$\text{Error} = \frac{\nu - \nu_{\text{ideal}}}{\nu} = 1 - \frac{1}{Z} = 1 - \frac{1}{0.69} = -0.44.9 \text{ or } \mathbf{44.9\%}$$

**3-97** CO<sub>2</sub> 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.

**Properties** The gas constant, the critical pressure, and the critical temperature of CO<sub>2</sub> are (Table A-1)

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

**Analysis**



(a) From the ideal gas equation of state,

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

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

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

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

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

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

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

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

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

**3-98** 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,

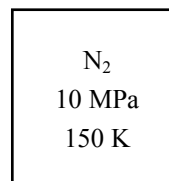
$$R = 0.2968 \text{ kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K}, \quad T_{\text{cr}} = 126.2 \text{ K}, \quad P_{\text{cr}} = 3.39 \text{ MPa}$$

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

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

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

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



Thus,

$$\nu = Z\nu_{\text{ideal}} = (0.54)(0.004452 \text{ m}^3/\text{kg}) = \mathbf{0.002404 \text{ m}^3/\text{kg}} \quad (0.7\% \text{ error})$$



## Other Equations of State

**3-99C** 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.

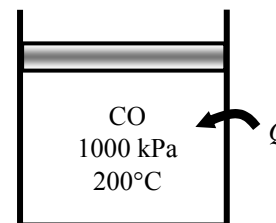
**3-100** Carbon monoxide is heated in a piston-cylinder device. The final volume of the carbon monoxide is to be determined using the ideal gas equation and the Benedict-Webb-Rubin equation of state.

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

$$R = 0.2968 \text{ kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K}, \quad M = 28.011 \text{ kg/kmol}$$

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

$$\nu_2 = \frac{mRT_2}{P} = \frac{(0.100 \text{ kg})(0.2968 \text{ kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K})(773 \text{ K})}{1000 \text{ kPa}} = \mathbf{0.02294 \text{ m}^3}$$



(b) Using the coefficients of Table 3-4 for carbon dioxide and the given data, the Benedict-Webb-Rubin equation of state for state 2 is

$$P_2 = \frac{R_u T_2}{\bar{\nu}_2} + \left( B_0 R_u T_2 - A_0 - \frac{C_0}{T_2^2} \right) \frac{1}{\bar{\nu}_2^2} + \frac{b R_u T_2 - a}{\bar{\nu}_2^3} + \frac{a \alpha}{\bar{\nu}_2^6} + \frac{c}{\bar{\nu}_2^3 T_2^2} \left( 1 + \frac{\gamma}{\bar{\nu}_2^2} \right) \exp(-\gamma / \bar{\nu}_2^2)$$

$$1000 = \frac{(8.314)(773)}{\bar{\nu}_2} + \left( 0.05454 \times 8.314 \times 773 - 135.9 - \frac{8.673 \times 10^5}{773^2} \right) \frac{1}{\bar{\nu}_2^2} + \frac{0.002632 \times 8.314 \times 773 - 3.71}{\bar{\nu}_2^3}$$

$$+ \frac{3.71 \times 0.000135}{\bar{\nu}_2^6} + \frac{1.054 \times 10^5}{\bar{\nu}_2^3 (773)^2} \left( 1 + \frac{0.0060}{\bar{\nu}_2^2} \right) \exp(-0.0060 / \bar{\nu}_2^2)$$

The solution of this equation by an equation solver such as EES gives

$$\bar{\nu}_2 = 6.460 \text{ m}^3/\text{kmol}$$

Then,

$$\nu_2 = \frac{\bar{\nu}_2}{M} = \frac{6.460 \text{ m}^3/\text{kmol}}{28.011 \text{ kg/kmol}} = 0.2306 \text{ m}^3/\text{kg}$$

$$\nu_2 = m \nu_2 = (0.100 \text{ kg})(0.2306 \text{ m}^3/\text{kg}) = \mathbf{0.02306 \text{ m}^3}$$

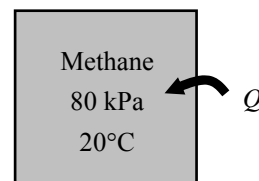
**3-101** Methane is heated in a rigid container. The final pressure of the methane is to be determined using the ideal gas equation and the Benedict-Webb-Rubin equation of state.

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

$$P_2 = P_1 \frac{T_2}{T_1} = (80 \text{ kPa}) \frac{573 \text{ K}}{293 \text{ K}} = \mathbf{156.5 \text{ kPa}}$$

(b) The specific molar volume of the methane is

$$\bar{v}_1 = \bar{v}_2 = \frac{R_u T_1}{P_1} = \frac{(8.314 \text{ kPa} \cdot \text{m}^3/\text{kmol} \cdot \text{K})(293 \text{ K})}{80 \text{ kPa}} = 30.45 \text{ m}^3/\text{kmol}$$



Using the coefficients of Table 3-4 for methane and the given data, the Benedict-Webb-Rubin equation of state for state 2 gives

$$\begin{aligned} P_2 &= \frac{R_u T_2}{\bar{v}_2} + \left( B_0 R_u T_2 - A_0 - \frac{C_0}{T_2^2} \right) \frac{1}{\bar{v}_2^2} + \frac{b R_u T_2 - a}{\bar{v}_2^3} + \frac{a \alpha}{\bar{v}_2^6} + \frac{c}{\bar{v}_2^3 T_2^2} \left( 1 + \frac{\gamma}{\bar{v}_2^2} \right) \exp(-\gamma / \bar{v}_2^2) \\ &= \frac{(8.314)(573)}{30.45} + \left( 0.04260 \times 8.314 \times 573 - 187.91 - \frac{2.286 \times 10^6}{573^2} \right) \frac{1}{30.45^2} + \frac{0.003380 \times 8.314 \times 573 - 5.00}{30.45^3} \\ &\quad + \frac{5.00 \times 1.244 \times 10^{-4}}{30.45^6} + \frac{2.578 \times 10^5}{30.45^3 (573)^2} \left( 1 + \frac{0.0060}{30.45^2} \right) \exp(-0.0060 / 30.45^2) \\ &= \mathbf{156.5 \text{ kPa}} \end{aligned}$$

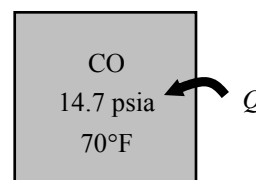
**3-102E** Carbon monoxide is heated in a rigid container. The final pressure of the CO is to be determined using the ideal gas equation and the Benedict-Webb-Rubin equation of state.

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

$$R = 0.2968 \text{ kPa} \cdot \text{m}^3 / \text{kg} \cdot \text{K}, \quad M = 28.011 \text{ kg/kmol}$$

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

$$P_2 = P_1 \frac{T_2}{T_1} = (14.7 \text{ psia}) \frac{1260 \text{ R}}{530 \text{ R}} = \mathbf{34.95 \text{ psia}}$$



(b) The specific molar volume of the CO in SI units is

$$\bar{v}_1 = \bar{v}_2 = \frac{R_u T_1}{P_1} = \frac{(8.314 \text{ kPa} \cdot \text{m}^3 / \text{kmol} \cdot \text{K})(294 \text{ K})}{101 \text{ kPa}} = 24.20 \text{ m}^3 / \text{kmol}$$

Using the coefficients of Table 3-4 for CO and the given data, the Benedict-Webb-Rubin equation of state for state 2 gives

$$\begin{aligned} P_2 &= \frac{R_u T_2}{\bar{v}_2} + \left( B_0 R_u T_2 - A_0 - \frac{C_0}{T_2^2} \right) \frac{1}{\bar{v}_2^2} + \frac{b R_u T_2 - a}{\bar{v}_2^3} + \frac{a \alpha}{\bar{v}_2^6} + \frac{c}{\bar{v}_2^3 T_2^2} \left( 1 + \frac{\gamma}{\bar{v}_2^2} \right) \exp(-\gamma / \bar{v}_2^2) \\ &= \frac{(8.314)(700)}{24.20} + \left( 0.05454 \times 8.314 \times 700 - 135.87 - \frac{8.673 \times 10^5}{700^2} \right) \frac{1}{24.20^2} + \frac{0.002632 \times 8.314 \times 700 - 3.71}{24.20^3} \\ &\quad + \frac{3.71 \times 1.350 \times 10^{-4}}{24.20^6} + \frac{1.054 \times 10^5}{24.20^3 (700)^2} \left( 1 + \frac{0.0060}{24.20^2} \right) \exp(-0.0060 / 24.20^2) \\ &= 240.8 \text{ kPa} \end{aligned}$$

The pressure in English unit is

$$P_2 = (240.8 \text{ kPa}) \left( \frac{1 \text{ psia}}{6.8948 \text{ kPa}} \right) = \mathbf{34.92 \text{ psia}}$$

**3-103E** 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)

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

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

$$T = \frac{P\nu}{R} = \frac{(160 \text{ psia})(0.3479 \text{ ft}^3/\text{lbm})}{0.1052 \text{ psia} \cdot \text{ft}^3/\text{lbm} \cdot \text{R}} = \mathbf{529 \text{ R}}$$

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

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


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

Then,

$$T = \frac{1}{R} \left( P + \frac{a}{\nu^2} \right) (\nu - b) = \frac{1}{0.1052} \left( 160 + \frac{3.591}{(0.3479)^2} \right) (0.3479 - 0.0150) = \mathbf{600 \text{ R}}$$

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

$$\left. \begin{array}{l} P = 160 \text{ psia} \\ \nu = 0.3479 \text{ ft}^3/\text{lbm} \end{array} \right\} T = \mathbf{160^\circ\text{F}} \quad (620 \text{ R})$$

**3-104**  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)

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

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

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

$\begin{aligned} &\text{N}_2 \\ &0.041884 \text{ m}^3/\text{kg} \\ &150 \text{ K} \end{aligned}$
--

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

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

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

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

since

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

Substituting,

$$\begin{aligned} P &= \frac{R_u T}{\bar{\nu}^2} \left( 1 - \frac{c}{\bar{\nu} T^3} \right) (\bar{\nu} + B) - \frac{A}{\bar{\nu}^2} = \frac{8.314 \times 150}{(1.1733)^2} \left( 1 - \frac{4.2 \times 10^4}{1.1733 \times 150^3} \right) (1.1733 + 0.05076) - \frac{133.193}{(1.1733)^2} \\ &= \mathbf{1000.4 \text{ kPa}} \text{ (negligible error)} \end{aligned}$$



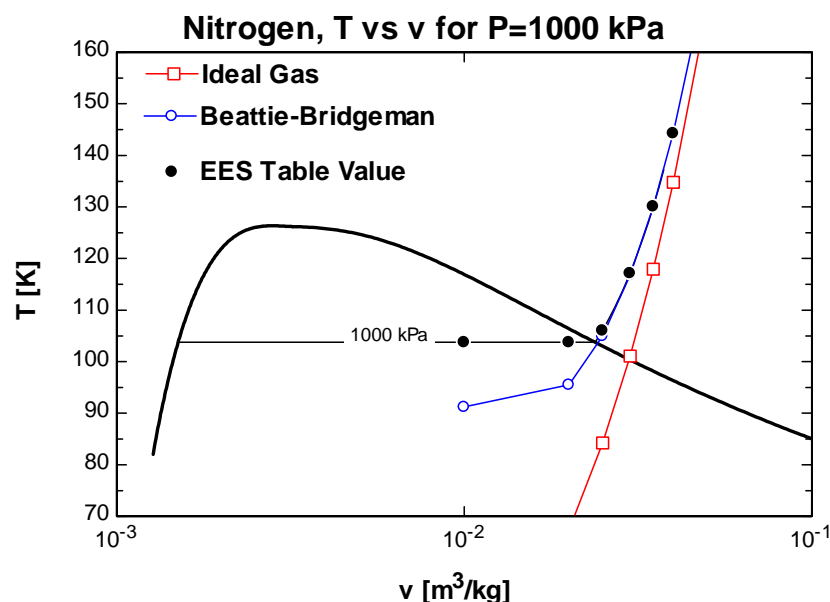
**3-105** Problem 3-104 is reconsidered. Using EES (or other) software, the pressure results of the ideal gas and Beattie-Bridgeman equations with nitrogen data supplied by EES are to be compared. The temperature is to be plotted versus specific volume for a pressure of 1000 kPa with respect to the saturated liquid and saturated vapor lines of nitrogen over the range of  $110\text{ K} < T < 150\text{ K}$ .

**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 <sub>BB</sub> [kPa]	P <sub>table</sub> [kPa]	P <sub>idealgas</sub> [kPa]	v [m <sup>3</sup> /kg]	T <sub>BB</sub> [K]	T <sub>ideal gas</sub> [K]	T <sub>table</sub> [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



**3-106** Carbon dioxide is compressed in a piston-cylinder device in a polytropic process. The final temperature is to be determined using the ideal gas and van der Waals equations.

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

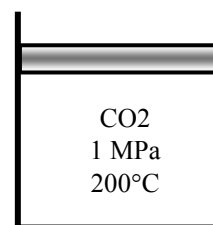
$$R = 0.1889 \text{ kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K}, \quad M = 44.01 \text{ kg/kmol}, \quad T_{\text{cr}} = 304.2 \text{ K}, \quad P_{\text{cr}} = 7.39 \text{ MPa}$$

**Analysis (a)** The specific volume at the initial state is

$$\nu_1 = \frac{RT_1}{P_1} = \frac{(0.1889 \text{ kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K})(473 \text{ K})}{1000 \text{ kPa}} = 0.08935 \text{ m}^3/\text{kg}$$

According to process specification,

$$\nu_2 = \nu_1 \left( \frac{P_1}{P_2} \right)^{1/n} = (0.08935 \text{ m}^3/\text{kg}) \left( \frac{1000 \text{ kPa}}{3000 \text{ kPa}} \right)^{1/1.2} = 0.03577 \text{ m}^3/\text{kg}$$



The final temperature is then

$$T_2 = \frac{P_2 \nu_2}{R} = \frac{(3000 \text{ kPa})(0.03577 \text{ m}^3/\text{kg})}{0.1889 \text{ kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K}} = \mathbf{568 \text{ K}}$$

(b) The van der Waals constants for carbon dioxide are determined from

$$a = \frac{27R^2T_{\text{cr}}^2}{64P_{\text{cr}}} = \frac{(27)(0.1889 \text{ kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K})^2 (304.2 \text{ K})^2}{(64)(7390 \text{ kPa})} = 0.1885 \text{ m}^6 \cdot \text{kPa}/\text{kg}^2$$

$$b = \frac{RT_{\text{cr}}}{8P_{\text{cr}}} = \frac{(0.1889 \text{ kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K})(304.2 \text{ K})}{8 \times 7390 \text{ kPa}} = 0.0009720 \text{ m}^3/\text{kg}$$

Applying the van der Waals equation to the initial state,

$$\left( P + \frac{a}{\nu^2} \right) (\nu - b) = RT$$

$$\left( 1000 + \frac{0.1885}{\nu^2} \right) (\nu - 0.0009720) = (0.1889)(473)$$

Solving this equation by trial-error or by EES gives

$$\nu_1 = 0.08821 \text{ m}^3/\text{kg}$$

According to process specification,

$$\nu_2 = \nu_1 \left( \frac{P_1}{P_2} \right)^{1/n} = (0.08821 \text{ m}^3/\text{kg}) \left( \frac{1000 \text{ kPa}}{3000 \text{ kPa}} \right)^{1/1.2} = 0.03531 \text{ m}^3/\text{kg}$$

Applying the van der Waals equation to the final state,

$$\left( P + \frac{a}{\nu^2} \right) (\nu - b) = RT$$

$$\left( 3000 + \frac{0.1885}{0.03531^2} \right) (0.03531 - 0.0009720) = (0.1889)T$$

Solving for the final temperature gives

$$T_2 = \mathbf{573 \text{ K}}$$

### Special Topic: Vapor Pressure and Phase Equilibrium

**3-107** A glass of water is left in a room. The vapor pressures at the free surface of the water and in the room far from the glass are to be determined.

**Assumptions** The water in the glass is at a uniform temperature.

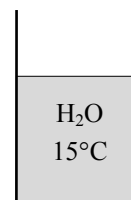
**Properties** The saturation pressure of water is 2.339 kPa at 20°C, and 1.706 kPa at 15°C (Table A-4).

**Analysis** The vapor pressure at the water surface is the saturation pressure of water at the water temperature,

$$P_{v, \text{ water surface}} = P_{\text{sat}@T_{\text{water}}} = P_{\text{sat}@15^\circ\text{C}} = \mathbf{1.706 \text{ kPa}}$$

Noting that the air in the room is not saturated, the vapor pressure in the room far from the glass is

$$P_{v, \text{ air}} = \phi P_{\text{sat}@T_{\text{air}}} = \phi P_{\text{sat}@20^\circ\text{C}} = (0.4)(2.339 \text{ kPa}) = \mathbf{0.936 \text{ kPa}}$$



**3-108** The vapor pressure in the air at the beach when the air temperature is 30°C is claimed to be 5.2 kPa. The validity of this claim is to be evaluated.

**Properties** The saturation pressure of water at 30°C is 4.247 kPa (Table A-4).

**Analysis** The maximum vapor pressure in the air is the saturation pressure of water at the given temperature, which is

$$P_{v, \text{ max}} = P_{\text{sat}@T_{\text{air}}} = P_{\text{sat}@30^\circ\text{C}} = \mathbf{4.247 \text{ kPa}}$$

which is less than the claimed value of 5.2 kPa. Therefore, the claim is **false**.



**3-109** The temperature and relative humidity of air over a swimming pool are given. The water temperature of the swimming pool when phase equilibrium conditions are established is to be determined.

**Assumptions** The temperature and relative humidity of air over the pool remain constant.

**Properties** The saturation pressure of water at 20°C is 2.339 kPa (Table A-4).

**Analysis** The vapor pressure of air over the swimming pool is

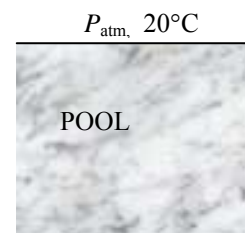
$$P_{v, \text{ air}} = \phi P_{\text{sat}@T_{\text{air}}} = \phi P_{\text{sat}@20^\circ\text{C}} = (0.4)(2.339 \text{ kPa}) = 0.9357 \text{ kPa}$$

Phase equilibrium will be established when the vapor pressure at the water surface equals the vapor pressure of air far from the surface. Therefore,

$$P_{v, \text{ water surface}} = P_{v, \text{ air}} = 0.9357 \text{ kPa}$$

and  $T_{\text{water}} = T_{\text{sat}@P_v} = T_{\text{sat}@0.9357 \text{ kPa}} = \mathbf{6.0^\circ\text{C}}$

**Discussion** Note that the water temperature drops to 6.0°C in an environment at 20°C when phase equilibrium is established.





**3-110** A person buys a supposedly cold drink in a hot and humid summer day, yet no condensation occurs on the drink. The claim that the temperature of the drink is below 10°C is to be evaluated.

**Properties** The saturation pressure of water at 35°C is 5.629 kPa (Table A-4).

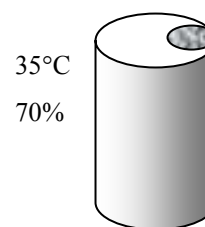
**Analysis** The vapor pressure of air is

$$P_{v, \text{air}} = \phi P_{\text{sat}@T_{\text{air}}} = \phi P_{\text{sat}@35^{\circ}\text{C}} = (0.7)(5.629 \text{ kPa}) = 3.940 \text{ kPa}$$

The saturation temperature corresponding to this pressure (called the dew-point temperature) is

$$T_{\text{sat}} = T_{\text{sat}@P_v} = T_{\text{sat}@3.940 \text{ kPa}} = \mathbf{28.7^{\circ}\text{C}}$$

That is, the vapor in the air will condense at temperatures below 28.7°C. Noting that no condensation is observed on the can, the claim that the drink is at 10°C is **false**.



**3-111E** A thermos bottle half-filled with water is left open to air in a room at a specified temperature and pressure. The temperature of water when phase equilibrium is established is to be determined.

**Assumptions** The temperature and relative humidity of air over the bottle remain constant.

**Properties** The saturation pressure of water at 70°F is 0.3633 psia (Table A-4E).

**Analysis** The vapor pressure of air in the room is

$$P_{v, \text{air}} = \phi P_{\text{sat}@T_{\text{air}}} = \phi P_{\text{sat}@70^{\circ}\text{F}} = (0.35)(0.3633 \text{ psia}) = 0.1272 \text{ psia}$$

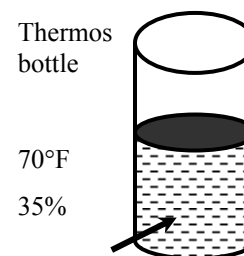
Phase equilibrium will be established when the vapor pressure at the water surface equals the vapor pressure of air far from the surface. Therefore,

$$P_{v, \text{water surface}} = P_{v, \text{air}} = 0.1272 \text{ psia}$$

and

$$T_{\text{water}} = T_{\text{sat}@P_v} = T_{\text{sat}@0.1272 \text{ psia}} = \mathbf{41.1^{\circ}\text{F}}$$

**Discussion** Note that the water temperature drops to 41°F in an environment at 70°F when phase equilibrium is established.



**3-112** Two rooms are identical except that they are maintained at different temperatures and relative humidities. The room that contains more moisture is to be determined.

**Properties** The saturation pressure of water is 2.339 kPa at 20°C, and 3.17 kPa at 25°C (Table A-4).

**Analysis** The vapor pressures in the two rooms are

$$\text{Room 1: } P_{v1} = \phi_1 P_{\text{sat}@T_1} = \phi_1 P_{\text{sat}@25^{\circ}\text{C}} = (0.4)(3.17 \text{ kPa}) = \mathbf{1.27 \text{ kPa}}$$

$$\text{Room 2: } P_{v2} = \phi_2 P_{\text{sat}@T_2} = \phi_2 P_{\text{sat}@20^{\circ}\text{C}} = (0.55)(2.339 \text{ kPa}) = \mathbf{1.29 \text{ kPa}}$$

Therefore, room 1 at 30°C and 40% relative humidity contains more moisture.

## Review Problems

**3-113** Nitrogen gas in a rigid tank is heated to a final gage pressure. The final temperature is to be determined.

**Assumptions** At specified conditions, nitrogen behaves as an ideal gas.

**Analysis** According to the ideal gas equation of state at constant volume,

$$m_1 = m_2$$

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$$

Since  $V_1 = V_2$

$$\frac{P_1}{T_1} = \frac{P_2}{T_2}$$

$$T_2 = T_1 \frac{P_2}{P_1} = [(227 + 273) \text{ K}] \frac{(250 + 100) \text{ kPa}}{(100 + 100) \text{ kPa}} = 875 \text{ K} = \mathbf{602^\circ\text{C}}$$

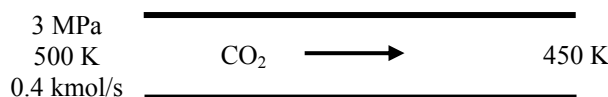
$P_{\text{atm}} = 100 \text{ kPa}$

Nitrogen gas  
 227°C  
 100 kPa  
 (gage)

$\curvearrowright Q$

**3-114** Carbon dioxide flows through a pipe at a given state. The volume and mass flow rates and the density of CO<sub>2</sub> at the given state and the volume flow rate at the exit of the pipe are to be determined.

**Analysis**



(a) The volume and mass flow rates may be determined from ideal gas relation as

$$\dot{V}_1 = \frac{\dot{N} R_u T_1}{P} = \frac{(0.4 \text{ kmol/s})(8.314 \text{ kPa}\cdot\text{m}^3/\text{kmol}\cdot\text{K})(500 \text{ K})}{3000 \text{ kPa}} = \mathbf{0.5543 \text{ m}^3/\text{s}}$$

$$\dot{m}_1 = \frac{P_1 \dot{V}_1}{R T_1} = \frac{(3000 \text{ kPa})(0.5543 \text{ m}^3/\text{s})}{(0.1889 \text{ kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(500 \text{ K})} = \mathbf{17.60 \text{ kg/s}}$$

The density is

$$\rho_1 = \frac{\dot{m}_1}{\dot{V}_1} = \frac{(17.60 \text{ kg/s})}{(0.5543 \text{ m}^3/\text{s})} = \mathbf{31.76 \text{ kg/m}^3}$$

(b) The volume flow rate at the exit is

$$\dot{V}_2 = \frac{\dot{N} R_u T_2}{P} = \frac{(0.4 \text{ kmol/s})(8.314 \text{ kPa}\cdot\text{m}^3/\text{kmol}\cdot\text{K})(450 \text{ K})}{3000 \text{ kPa}} = \mathbf{0.4988 \text{ m}^3/\text{s}}$$

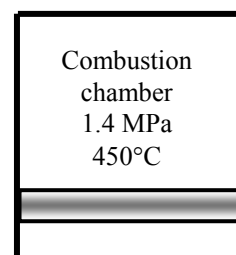
**3-115** The cylinder conditions before the heat addition process is specified. The pressure after the heat addition process is to be determined.

**Assumptions 1** The contents of cylinder are approximated by the air properties.

**2** Air is an ideal gas.

**Analysis** The final pressure may be determined from the ideal gas relation

$$P_2 = \frac{T_2}{T_1} P_1 = \left( \frac{1600 + 273 \text{ K}}{450 + 273 \text{ K}} \right) (1400 \text{ kPa}) = \mathbf{3627 \text{ kPa}}$$



**3-116** The cylinder conditions before the heat addition process is specified. The temperature after the heat addition process is to be determined.

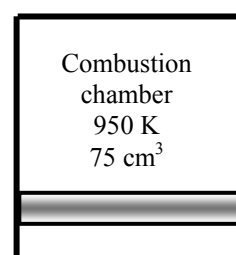
**Assumptions 1** The contents of cylinder is approximated by the air properties. **2** Air is an ideal gas.

**Analysis** The ratio of the initial to the final mass is

$$\frac{m_1}{m_2} = \frac{AF}{AF + 1} = \frac{22}{22 + 1} = \frac{22}{23}$$

The final temperature may be determined from ideal gas relation

$$T_2 = \frac{m_1}{m_2} \frac{\nu_2}{\nu_1} T_1 = \left( \frac{22}{23} \right) \left( \frac{150 \text{ cm}^3}{75 \text{ cm}^3} \right) (950 \text{ K}) = \mathbf{1817 \text{ K}}$$



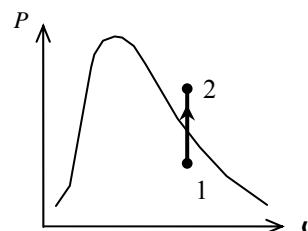
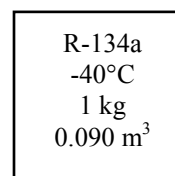
**3-117** A rigid container that is filled with R-134a is heated. The initial pressure and the final temperature are to be determined.

**Analysis** The initial specific volume is  $0.090 \text{ m}^3/\text{kg}$ . Using this with the initial temperature reveals that the initial state is a mixture. The initial pressure is then the saturation pressure,

$$\left. \begin{array}{l} T_1 = -40^\circ\text{C} \\ \nu_1 = 0.090 \text{ m}^3/\text{kg} \end{array} \right\} P_1 = P_{\text{sat @ } -40^\circ\text{C}} = \mathbf{51.25 \text{ kPa}} \text{ (Table A - 11)}$$

This is a constant volume cooling process ( $\nu = \nu/m = \text{constant}$ ). The final state is superheated vapor and the final temperature is then

$$\left. \begin{array}{l} P_2 = 280 \text{ kPa} \\ \nu_2 = \nu_1 = 0.090 \text{ m}^3/\text{kg} \end{array} \right\} T_2 = \mathbf{50^\circ\text{C}} \text{ (Table A - 13)}$$



**3-118E** A piston-cylinder device that is filled with water is cooled. The final pressure and volume of the water are to be determined.

**Analysis** The initial specific volume is

$$\nu_1 = \frac{V_1}{m} = \frac{2.649 \text{ ft}^3}{1 \text{ lbm}} = 2.649 \text{ ft}^3/\text{lbm}$$

This is a constant-pressure process. The initial state is determined to be superheated vapor and thus the pressure is determined to be

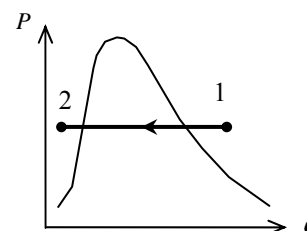
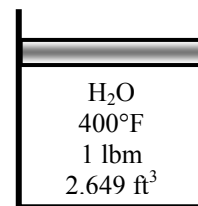
$$\left. \begin{array}{l} T_1 = 400^\circ\text{F} \\ \nu_1 = 2.649 \text{ ft}^3/\text{lbm} \end{array} \right\} P_1 = P_2 = \mathbf{180 \text{ psia}} \quad (\text{Table A - 6E})$$

The saturation temperature at 180 psia is  $373.1^\circ\text{F}$ . Since the final temperature is less than this temperature, the final state is compressed liquid. Using the incompressible liquid approximation,

$$\nu_2 = \nu_f @ 100^\circ\text{F} = 0.01613 \text{ ft}^3/\text{lbm} \quad (\text{Table A - 4E})$$

The final volume is then

$$V_2 = m\nu_2 = (1 \text{ lbm})(0.01613 \text{ ft}^3/\text{lbm}) = \mathbf{0.01613 \text{ ft}^3}$$



**3-119** The volume of chamber 1 of the two-piston cylinder shown in the figure is to be determined.

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

**Properties** The gas constant of helium is  $R = 2.0769 \text{ kJ/kg} \cdot \text{K}$  (Table A-1).

**Analysis** Since the water vapor in chamber 2 is condensing, the pressure in this chamber is the saturation pressure,

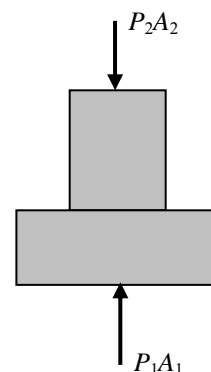
$$P_2 = P_{\text{sat}} @ 200^\circ\text{C} = 1555 \text{ kPa} \quad (\text{Table A-4})$$

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

$$P_1 = P_2 \frac{A_2}{A_1} = P_2 \left( \frac{D_2}{D_1} \right)^2 = (1555 \text{ kPa}) \left( \frac{4}{10} \right)^2 = 248.8 \text{ kPa}$$

According to the ideal gas equation of state,

$$\nu_1 = \frac{mRT}{P_1} = \frac{(1 \text{ kg})(2.0769 \text{ kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K})(200 + 273 \text{ K})}{248.8 \text{ kPa}} = \mathbf{3.95 \text{ m}^3}$$



**3-120E** The volume of chamber 1 of the two-piston cylinder shown in the figure is to be determined.

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

**Properties** The gas constant of air is  $R = 0.3704 \text{ psia} \cdot \text{ft}^3 / \text{lbm} \cdot \text{R}$  (Table A-1E).

**Analysis** Since R-134a in chamber 2 is condensing, the pressure in this chamber is the saturation pressure,

$$P_2 = P_{\text{sat}@120^\circ\text{F}} = 186.0 \text{ psia} \quad (\text{Table A-11E})$$

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

$$\begin{aligned} F_2 + F_3 &= F_1 \\ P_2 A_2 + P_3 (A_1 - A_2) &= P_1 A_1 \end{aligned}$$

which when solved for  $P_1$  gives

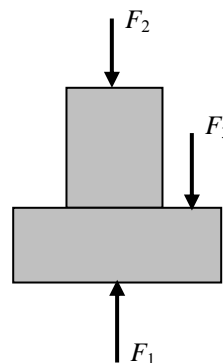
$$P_1 = P_2 \frac{A_2}{A_1} + P_3 \left[ 1 - \frac{A_2}{A_1} \right]$$

since the areas of the piston faces are given by  $A = \pi D^2 / 4$  the above equation becomes

$$\begin{aligned} P_1 &= P_2 \left( \frac{D_2}{D_1} \right)^2 + P_3 \left[ 1 - \left( \frac{D_2}{D_1} \right)^2 \right] \\ &= (186.0 \text{ psia}) \left( \frac{2}{3} \right)^2 + (30 \text{ psia}) \left[ 1 - \left( \frac{2}{3} \right)^2 \right] \\ &= 99.33 \text{ psia} \end{aligned}$$

According to the ideal gas equation of state,

$$v_1 = \frac{mRT}{P_1} = \frac{(0.5 \text{ lbm})(0.3704 \text{ psia} \cdot \text{ft}^3 / \text{lbm} \cdot \text{R})(120 + 460 \text{ R})}{99.33 \text{ psia}} = \mathbf{1.08 \text{ ft}^3}$$



**3-121E** The difference in the volume of chamber 1 for two cases of pressure in chamber 3 is to be determined.

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

**Properties** The gas constant of air is  $R = 0.3704 \text{ psia} \cdot \text{ft}^3/\text{lbm} \cdot \text{R}$  (Table A-1).

**Analysis** Since R-134a in chamber 2 is condensing, the pressure in this chamber is the saturation pressure,

$$P_2 = P_{\text{sat}@120^\circ\text{F}} = 186.0 \text{ psia} \quad (\text{Table A-11E})$$

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

$$\begin{aligned} F_2 + F_3 &= F_1 \\ P_2 A_2 + P_3 (A_1 - A_2) &= P_1 A_1 \end{aligned}$$

which when solved for  $P_1$  gives

$$P_1 = P_2 \frac{A_2}{A_1} + P_3 \left( 1 - \frac{A_2}{A_1} \right)$$

since the areas of the piston faces are given by  $A = \pi D^2 / 4$  the above equation becomes

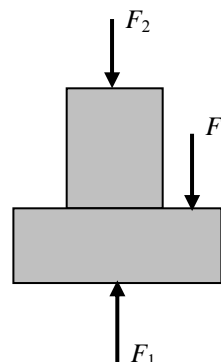
$$\begin{aligned} P_1 &= P_2 \left( \frac{D_2}{D_1} \right)^2 + P_3 \left[ 1 - \left( \frac{D_2}{D_1} \right)^2 \right] \\ &= (186.0 \text{ psia}) \left( \frac{2}{3} \right)^2 + (60 \text{ kPa}) \left[ 1 - \left( \frac{2}{3} \right)^2 \right] \\ &= 116 \text{ psia} \end{aligned}$$

According to the ideal gas equation of state,

$$V_1 = \frac{mRT}{P_1} = \frac{(0.5 \text{ lbm})(0.3704 \text{ psia} \cdot \text{ft}^3/\text{lbm} \cdot \text{R})(120 + 460 \text{ R})}{116 \text{ psia}} = 0.926 \text{ ft}^3$$

For a chamber 3 pressure of 30 psia, the volume of chamber 1 was determined to be  $1.08 \text{ ft}^3$ . Then the change in the volume of chamber 1 is

$$\Delta V = V_2 - V_1 = 1.08 - 0.926 = \mathbf{0.154 \text{ ft}^3}$$



**3-122** Ethane is heated at constant pressure. The final temperature is to be determined using ideal gas equation and the compressibility charts.

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

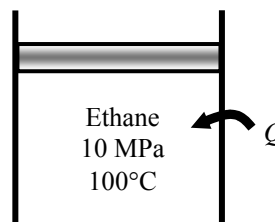
$$R = 0.2765 \text{ kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K}, \quad T_{\text{cr}} = 305.5 \text{ K}, \quad P_{\text{cr}} = 4.48 \text{ MPa}$$

**Analysis** From the ideal gas equation,

$$T_2 = T_1 \frac{\nu_2}{\nu_1} = (373 \text{ K})(1.6) = \mathbf{596.8 \text{ K}}$$

From the compressibility chart at the initial state (Fig. A-15),

$$\left. \begin{aligned} T_{R1} &= \frac{T_1}{T_{\text{cr}}} = \frac{373 \text{ K}}{305.5 \text{ K}} = 1.221 \\ P_{R1} &= \frac{P_1}{P_{\text{cr}}} = \frac{10 \text{ MPa}}{4.48 \text{ MPa}} = 2.232 \end{aligned} \right\} Z_1 = 0.61, \nu_{R1} = 0.35$$



At the final state,

$$\left. \begin{aligned} P_{R2} &= P_{R1} = 2.232 \\ \nu_{R2} &= 1.6\nu_{R1} = 1.6(0.35) = 0.56 \end{aligned} \right\} Z_2 = 0.83$$

Thus,

$$T_2 = \frac{P_2 \nu_2}{Z_2 R} = \frac{P_2}{Z_2} \frac{\nu_{R2} T_{\text{cr}}}{P_{\text{cr}}} = \frac{10,000 \text{ kPa}}{0.83} \frac{(0.56)(305.5 \text{ K})}{4480 \text{ kPa}} = \mathbf{460 \text{ K}}$$

Of these two results, the accuracy of the second result is limited by the accuracy with which the charts may be read. Accepting the error associated with reading charts, the second temperature is the more accurate.

**3-123** A large tank contains nitrogen at a specified temperature and pressure. Now some nitrogen is allowed to escape, and the temperature and pressure of nitrogen drop to new values. The amount of nitrogen that has escaped is to be determined.

**Properties** The gas constant for nitrogen is  $0.2968 \text{ kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K}$  (Table A-1).

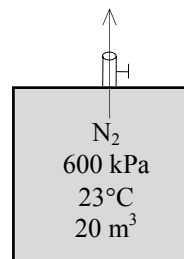
**Analysis** Treating  $\text{N}_2$  as an ideal gas, the initial and the final masses in the tank are determined to be

$$m_1 = \frac{P_1 \nu}{RT_1} = \frac{(600 \text{ kPa})(20 \text{ m}^3)}{(0.2968 \text{ kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K})(296 \text{ K})} = 136.6 \text{ kg}$$

$$m_2 = \frac{P_2 \nu}{RT_2} = \frac{(400 \text{ kPa})(20 \text{ m}^3)}{(0.2968 \text{ kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K})(293 \text{ K})} = 92.0 \text{ kg}$$

Thus the amount of  $\text{N}_2$  that escaped is

$$\Delta m = m_1 - m_2 = 136.6 - 92.0 = \mathbf{44.6 \text{ kg}}$$



**3-124** The rigid tank contains saturated liquid-vapor mixture of water. The mixture is heated until it exists in a single phase. For a given tank volume, it is to be determined if the final phase is a liquid or a vapor.

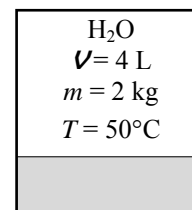
**Analysis** This is a constant volume process ( $v = V/m = \text{constant}$ ), and thus the final specific volume will be equal to the initial specific volume,

$$v_2 = v_1$$

The critical specific volume of water is  $0.003106 \text{ m}^3/\text{kg}$ . Thus if the final specific volume is smaller than this value, the water will exist as a liquid, otherwise as a vapor.

$$V = 4 \text{ L} \longrightarrow v = \frac{V}{m} = \frac{0.004 \text{ m}^3}{2 \text{ kg}} = 0.002 \text{ m}^3/\text{kg} < v_{\text{cr}} \quad \text{Thus, liquid.}$$

$$V = 400 \text{ L} \longrightarrow v = \frac{V}{m} = \frac{0.4 \text{ m}^3}{2 \text{ kg}} = 0.2 \text{ m}^3/\text{kg} > v_{\text{cr}} \quad \text{Thus, vapor.}$$

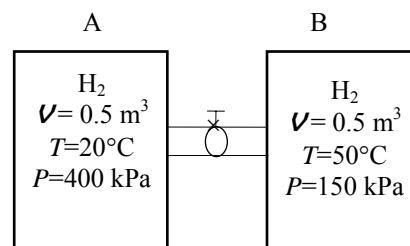


**3-125** Two rigid tanks that contain hydrogen at two different states are connected to each other. Now a valve is opened, and the two gases are allowed to mix while achieving thermal equilibrium with the surroundings. The final pressure in the tanks is to be determined.

**Properties** The gas constant for hydrogen is  $4.124 \text{ kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K}$  (Table A-1).

**Analysis** Let's call the first and the second tanks A and B. Treating  $\text{H}_2$  as an ideal gas, the total volume and the total mass of  $\text{H}_2$  are

$$\begin{aligned}
 V &= V_A + V_B = 0.5 + 0.5 = 1.0 \text{ m}^3 \\
 m_A &= \left( \frac{P_1 V}{RT_1} \right)_A = \frac{(400 \text{ kPa})(0.5 \text{ m}^3)}{(4.124 \text{ kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(293 \text{ K})} = 0.1655 \text{ kg} \\
 m_B &= \left( \frac{P_1 V}{RT_1} \right)_B = \frac{(150 \text{ kPa})(0.5 \text{ m}^3)}{(4.124 \text{ kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(323 \text{ K})} = 0.0563 \text{ kg} \\
 m &= m_A + m_B = 0.1655 + 0.0563 = 0.2218 \text{ kg}
 \end{aligned}$$



Then the final pressure can be determined from

$$P = \frac{mRT_2}{V} = \frac{(0.2218 \text{ kg})(4.124 \text{ kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(288 \text{ K})}{1.0 \text{ m}^3} = \mathbf{264 \text{ kPa}}$$





**3-126** Problem 3-125 is reconsidered. The effect of the surroundings temperature on the final equilibrium pressure in the tanks is to be investigated. The final pressure in the tanks is to be plotted versus the surroundings temperature, and the results are to be discussed.

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

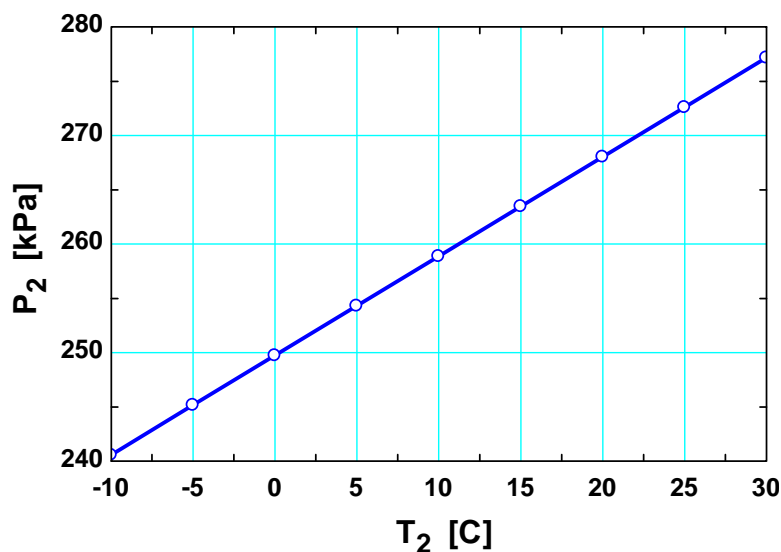
**"Given Data"**

V\_A=0.5 [m^3]  
 T\_A=20 [C]  
 P\_A=400 [kPa]  
 V\_B=0.5 [m^3]  
 T\_B=50 [C]  
 P\_B=150 [kPa]  
 {T\_2=15 [C]}

**"Solution"**

R=R\_u/MOLARMASS(H2)  
 R\_u=8.314 [kJ/kmol-K]  
 V\_total=V\_A+V\_B  
 m\_total=m\_A+m\_B  
 P\_A\*V\_A=m\_A\*R\*(T\_A+273)  
 P\_B\*V\_B=m\_B\*R\*(T\_B+273)  
 P\_2\*V\_total=m\_total\*R\*(T\_2+273)

P <sub>2</sub> [kPa]	T <sub>2</sub> [C]
240.6	-10
245.2	-5
249.7	0
254.3	5
258.9	10
263.5	15
268	20
272.6	25
277.2	30



**3-127** The pressure in an automobile tire increases during a trip while its volume remains constant. The percent increase in the absolute temperature of the air in the tire is to be determined.

**Assumptions 1** The volume of the tire remains constant. **2** Air is an ideal gas.

**Properties** The local atmospheric pressure is 90 kPa.

**Analysis** The absolute pressures in the tire before and after the trip are

$$P_1 = P_{\text{gage},1} + P_{\text{atm}} = 200 + 90 = 290 \text{ kPa}$$

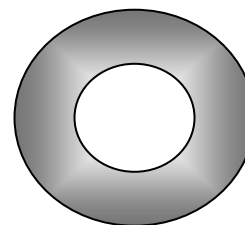
$$P_2 = P_{\text{gage},2} + P_{\text{atm}} = 220 + 90 = 310 \text{ kPa}$$

Noting that air is an ideal gas and the volume is constant, the ratio of absolute temperatures after and before the trip are

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2} \rightarrow \frac{T_2}{T_1} = \frac{P_2}{P_1} = \frac{310 \text{ kPa}}{290 \text{ kPa}} = 1.069$$

Therefore, the absolute temperature of air in the tire will increase by **6.9%** during this trip.

TIRE  
200 kPa  
0.035 m<sup>3</sup>



**3-128** The temperature of steam in a tank at a specified state is to be determined using the ideal gas relation, the generalized chart, and the steam tables.

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

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

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

$$P = \frac{RT}{v} = \frac{(0.4615 \text{ kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K})(673 \text{ K})}{0.02 \text{ m}^3/\text{kg}} = \mathbf{15,529 \text{ kPa}}$$

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

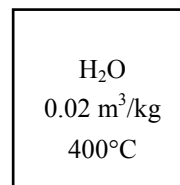
$$\left. \begin{aligned} T_R &= \frac{T}{T_{\text{cr}}} = \frac{673 \text{ K}}{647.1 \text{ K}} = 1.040 \\ v_R &= \frac{v_{\text{actual}}}{RT_{\text{cr}}/P_{\text{cr}}} = \frac{(0.02 \text{ m}^3/\text{kg})(22,060 \text{ kPa})}{(0.4615 \text{ kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K})(647.1 \text{ K})} = 1.48 \end{aligned} \right\} P_R = 0.57$$

Thus,

$$P = P_R P_{\text{cr}} = 0.57 \times 22,060 = \mathbf{12,574 \text{ kPa}}$$

(c) From the superheated steam table,

$$\left. \begin{aligned} T &= 400^\circ\text{C} \\ v &= 0.02 \text{ m}^3/\text{kg} \end{aligned} \right\} P = \mathbf{12,515 \text{ kPa}} \quad (\text{from EES})$$



**3-129** One section of a tank is filled with saturated liquid R-134a while the other side is evacuated. The partition is removed, and the temperature and pressure in the tank are measured. The volume of the tank is to be determined.

**Analysis** The mass of the refrigerant contained in the tank is

$$m = \frac{V_1}{v_1} = \frac{0.03 \text{ m}^3}{0.0008934 \text{ m}^3/\text{kg}} = 33.58 \text{ kg}$$

since

$$v_1 = v_{f@1.4 \text{ MPa}} = 0.0008934 \text{ m}^3/\text{kg}$$

At the final state (Table A-13),

$$\left. \begin{array}{l} P_2 = 400 \text{ kPa} \\ T_2 = 30^\circ\text{C} \end{array} \right\} v_2 = 0.05680 \text{ m}^3/\text{kg}$$

Thus,

$$V_{\text{tank}} = V_2 = m v_2 = (33.58 \text{ kg})(0.05680 \text{ m}^3/\text{kg}) = \mathbf{1.91 \text{ m}^3}$$

R-134a $P=1.2 \text{ MPa}$ $V=0.03 \text{ m}^3$	Evacuated
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**3-130** Problem 3-129 is reconsidered. The effect of the initial pressure of refrigerant-134 on the volume of the tank is to be investigated as the initial pressure varies from 0.5 MPa to 1.5 MPa. The volume of the tank is to be plotted versus the initial pressure, and the results are to be discussed.

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

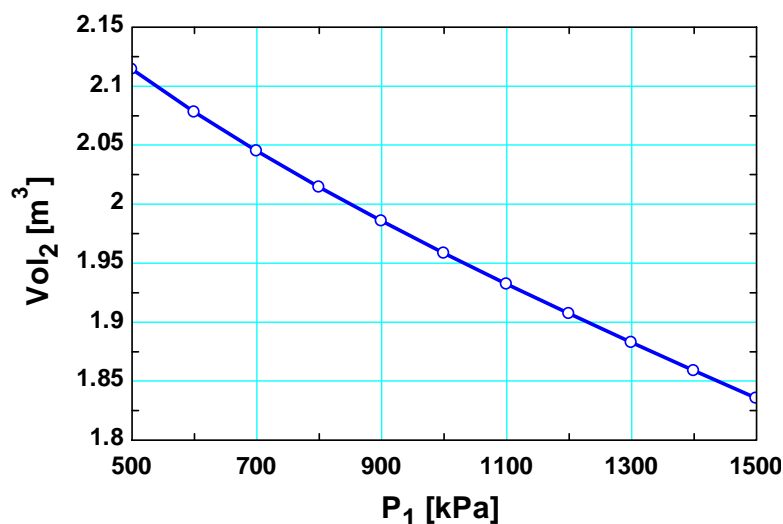
#### "Given Data"

$x_1 = 0.0$   
 $\text{Vol}_1 = 0.03 \text{ [m}^3\text{]}$   
 $P_1 = 1200 \text{ [kPa]}$   
 $T_2 = 30 \text{ [C]}$   
 $P_2 = 400 \text{ [kPa]}$

#### "Solution"

$v_1 = \text{volume}(\text{R134a}, P = P_1, x = x_1)$   
 $\text{Vol}_1 = m \cdot v_1$   
 $v_2 = \text{volume}(\text{R134a}, P = P_2, T = T_2)$   
 $\text{Vol}_2 = m \cdot v_2$

$P_1$ [kPa]	$\text{Vol}_2$ [m <sup>3</sup> ]	$m$ [kg]
500	2.114	37.23
600	2.078	36.59
700	2.045	36.01
800	2.015	35.47
900	1.986	34.96
1000	1.958	34.48
1100	1.932	34.02
1200	1.907	33.58
1300	1.883	33.15
1400	1.859	32.73
1500	1.836	32.32



**3-131** A propane tank contains 5 L of liquid propane at the ambient temperature. Now a leak develops at the top of the tank and propane starts to leak out. The temperature of propane when the pressure drops to 1 atm and the amount of heat transferred to the tank by the time the entire propane in the tank is vaporized are to be determined.

**Properties** The properties of propane at 1 atm are  $T_{\text{sat}} = -42.1^\circ\text{C}$ ,  $\rho = 581 \text{ kg/m}^3$ , and  $h_{\text{fg}} = 427.8 \text{ kJ/kg}$  (Table A-3).

**Analysis** The temperature of propane when the pressure drops to 1 atm is simply the saturation pressure at that temperature,

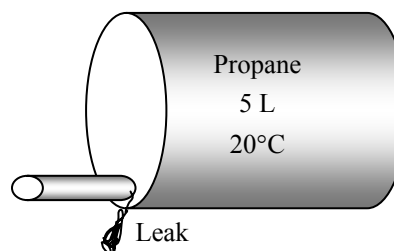
$$T = T_{\text{sat @ 1 atm}} = -42.1^\circ\text{C}$$

The initial mass of liquid propane is

$$m = \rho V = (581 \text{ kg/m}^3)(0.005 \text{ m}^3) = 2.905 \text{ kg}$$

The amount of heat absorbed is simply the total heat of vaporization,

$$Q_{\text{absorbed}} = mh_{\text{fg}} = (2.905 \text{ kg})(427.8 \text{ kJ/kg}) = \mathbf{1243 \text{ kJ}}$$



**3-132** An isobutane tank contains 5 L of liquid isobutane at the ambient temperature. Now a leak develops at the top of the tank and isobutane starts to leak out. The temperature of isobutane when the pressure drops to 1 atm and the amount of heat transferred to the tank by the time the entire isobutane in the tank is vaporized are to be determined.

**Properties** The properties of isobutane at 1 atm are  $T_{\text{sat}} = -11.7^\circ\text{C}$ ,  $\rho = 593.8 \text{ kg/m}^3$ , and  $h_{\text{fg}} = 367.1 \text{ kJ/kg}$  (Table A-3).

**Analysis** The temperature of isobutane when the pressure drops to 1 atm is simply the saturation pressure at that temperature,

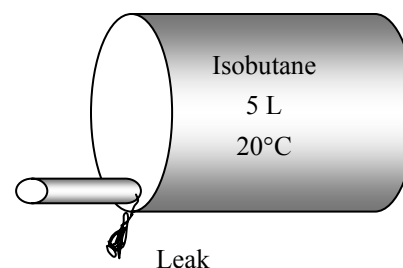
$$T = T_{\text{sat @ 1 atm}} = -11.7^\circ\text{C}$$

The initial mass of liquid isobutane is

$$m = \rho V = (593.8 \text{ kg/m}^3)(0.005 \text{ m}^3) = 2.969 \text{ kg}$$

The amount of heat absorbed is simply the total heat of vaporization,

$$Q_{\text{absorbed}} = mh_{\text{fg}} = (2.969 \text{ kg})(367.1 \text{ kJ/kg}) = \mathbf{1090 \text{ kJ}}$$



**3-133** A tank contains helium at a specified state. Heat is transferred to helium until it reaches a specified temperature. The final gage pressure of the helium is to be determined.

**Assumptions 1** Helium is an ideal gas.

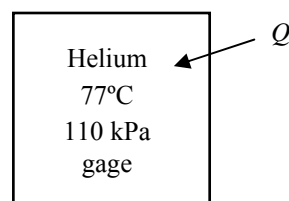
**Properties** The local atmospheric pressure is given to be 100 kPa.

**Analysis** Noting that the specific volume of helium in the tank remains constant, from ideal gas relation, we have

$$P_2 = P_1 \frac{T_2}{T_1} = (110 + 100 \text{ kPa}) \frac{(300 + 273) \text{ K}}{(77 + 273) \text{ K}} = 343.8 \text{ kPa}$$

Then the gage pressure becomes

$$P_{\text{gage},2} = P_2 - P_{\text{atm}} = 343.8 - 100 = \mathbf{244 \text{ kPa}}$$



**3-134** The first eight virial coefficients of a Benedict-Webb-Rubin gas are to be obtained.

**Analysis** The Benedict-Webb-Rubin equation of state is given by

$$P = \frac{R_u T}{\bar{v}} + \left( B_0 R_u T - A_0 - \frac{C_0}{T^2} \right) \frac{1}{\bar{v}^2} + \frac{b R_u T - a}{\bar{v}^3} + \frac{a \alpha}{\bar{v}^6} + \frac{c}{\bar{v}^3 T^2} \left( 1 + \frac{\gamma}{\bar{v}^2} \right) \exp(-\gamma / \bar{v}^2)$$

Expanding the last term in a series gives

$$\exp(-\gamma / \bar{v}^2) = 1 - \frac{\gamma}{\bar{v}^2} + \frac{1}{2!} \frac{\gamma^2}{\bar{v}^4} - \frac{1}{3!} \frac{\gamma^3}{\bar{v}^6} + \dots$$

Substituting this into the Benedict-Webb-Rubin equation of state and rearranging the first terms gives

$$P = \frac{R_u T}{\bar{v}} + \frac{R_u T B_0 - A_0 - C_0 / T^2}{\bar{v}^2} + \frac{b R_u T - a}{\bar{v}^3} + \frac{c(1 + \gamma)}{\bar{v}^5 T^2} + \frac{a \alpha}{\bar{v}^6} - \frac{c \gamma (1 + \gamma)}{\bar{v}^7 T^2} + \frac{1}{2!} \frac{c \gamma^2 (1 + \gamma)}{\bar{v}^9 T^2}$$

The virial equation of state is

$$P = \frac{R_u T}{\bar{v}} + \frac{a(T)}{\bar{v}^2} + \frac{b(T)}{\bar{v}^3} + \frac{c(T)}{\bar{v}^4} + \frac{d(T)}{\bar{v}^5} + \frac{e(T)}{\bar{v}^6} + \frac{f(T)}{\bar{v}^7} + \frac{g(T)}{\bar{v}^8} + \frac{h(T)}{\bar{v}^9} \dots$$

Comparing the Benedict-Webb-Rubin equation of state to the virial equation of state, the virial coefficients are

$$a(T) = R_u T B_0 - A_0 - C_0 / T^2$$

$$b(T) = b R_u T - a$$

$$c(T) = 0$$

$$d(T) = c(1 + \gamma) / T^2$$

$$e(T) = a \alpha$$

$$f(T) = c \gamma (1 + \gamma) / T^2$$

$$g(T) = 0$$

$$h(T) = \frac{1}{2!} \frac{c \gamma^2 (1 + \gamma)}{T^2}$$

**3-135** The table is completed as follows:

$P$ , kPa	$T$ , °C	$v$ , m <sup>3</sup> /kg	$u$ , kJ/kg	Condition description and quality, if applicable
<b>300</b>	250	<b>0.7921</b>	2728.9	<b>Superheated vapor</b>
300	<b>133.52</b>	<b>0.3058</b>	1560.0	<b><math>x = 0.504</math>, Two-phase mixture</b>
101.42	100	-	-	<b>Insufficient information</b>
3000	180	<b>0.001127*</b>	<b>761.92*</b>	<b>Compressed liquid</b>

\* Approximated as saturated liquid at the given temperature of 180°C

**3-136** The table is completed as follows:

$P$ , kPa	$T$ , °C	$v$ , m <sup>3</sup> /kg	$u$ , kJ/kg	Condition description and quality, if applicable
200	<b>120.2</b>	<b>0.8858</b>	2529.1	<b>Saturated vapor</b>
<b>232.23</b>	125	<b>0.5010</b>	<b>1831.0</b>	<b><math>x = 0.650</math>, Two-phase mixture</b>
<b>7829</b>	400	<b>0.0352</b>	2967.2	<b>Superheated vapor</b>
1000	30	<b>0.001004*</b>	<b>125.73*</b>	<b>Compressed liquid</b>
120.90	105	-	-	<b>Insufficient information</b>

\* Approximated as saturated liquid at the given temperature of 30°C

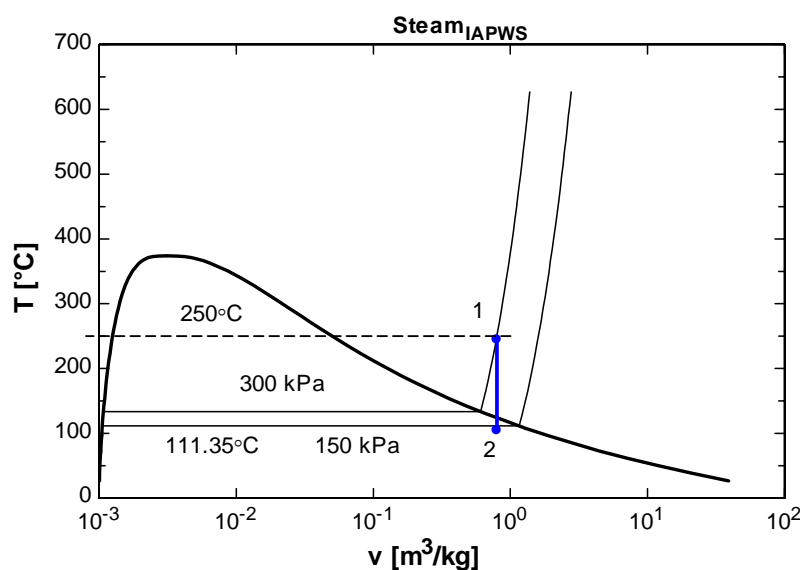
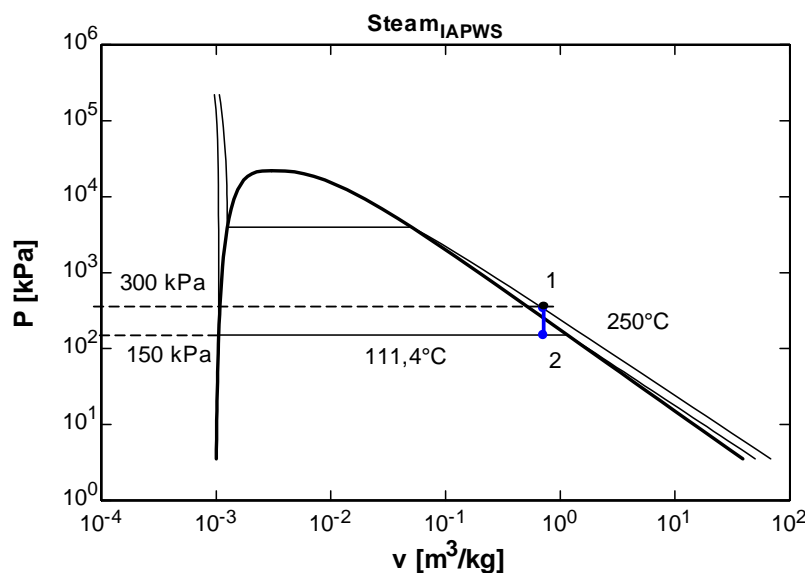
**3-137** Water at a specified state is contained in a tank. It is now cooled. The process will be indicated on the  $P$ - $v$  and  $T$ - $v$  diagrams.

**Analysis** The properties at the initial and final states are

$$\left. \begin{array}{l} P_1 = 300 \text{ kPa} \\ T_1 = 250^\circ\text{C} \end{array} \right\} v_1 = 0.7964 \text{ m}^3/\text{kg} \quad (\text{Table A - 6})$$

$$\left. \begin{array}{l} P_2 = 150 \text{ kPa} \\ v_2 = v_1 = 0.7964 \text{ m}^3/\text{kg} \end{array} \right\} T_2 = 111.35^\circ\text{C} \quad (\text{Table A - 5})$$

Using Property Plot feature of EES, and by adding state points we obtain following diagrams.





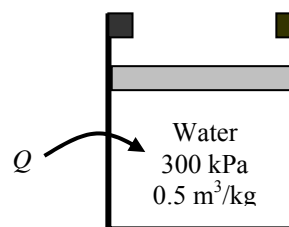
**3-138** Water at a specified state is contained in a piston-cylinder device fitted with stops. Water is now heated until a final pressure. The process will be indicated on the  $P$ - $v$  and  $T$ - $v$  diagrams.

**Analysis** The properties at the three states are

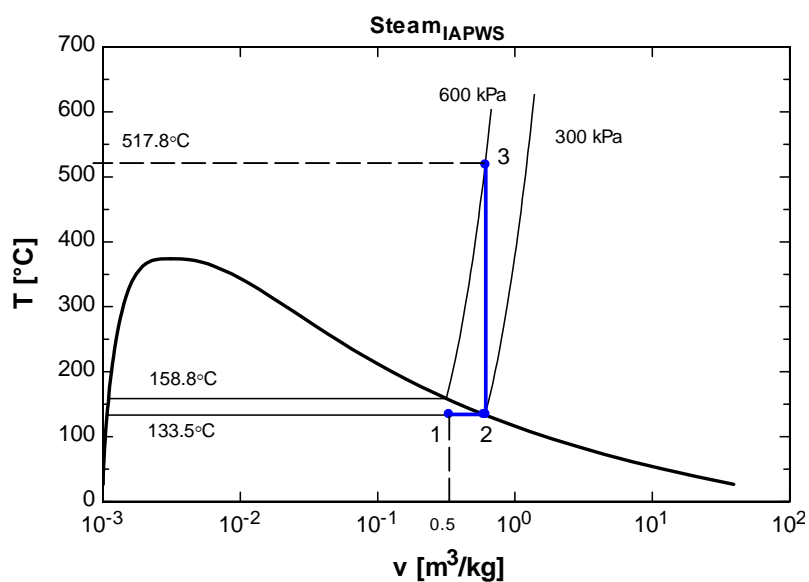
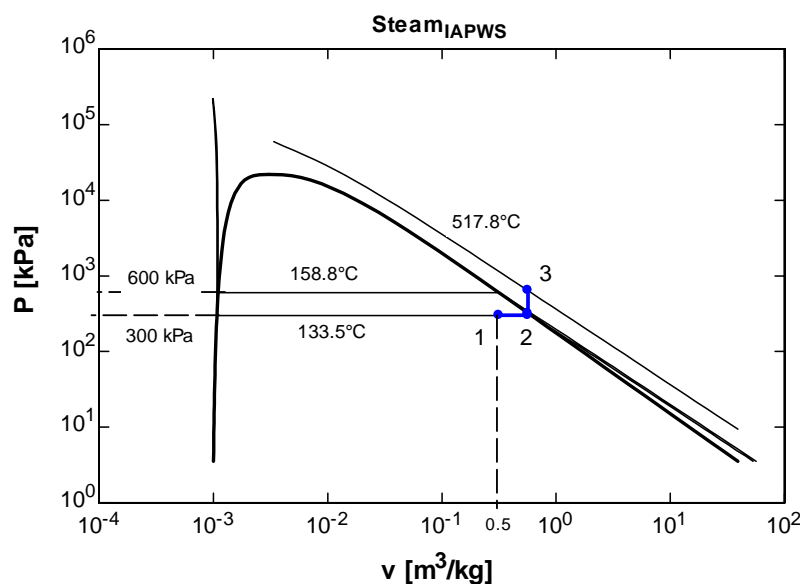
$$\left. \begin{array}{l} P_1 = 300 \text{ kPa} \\ v_1 = 0.5 \text{ m}^3/\text{kg} \end{array} \right\} T_1 = 133.5^\circ\text{C} \quad (\text{Table A - 5})$$

$$\left. \begin{array}{l} P_2 = 300 \text{ kPa} \\ x_2 = 1 \text{ (sat. vap.)} \end{array} \right\} v_2 = 0.6058 \text{ m}^3/\text{kg}, T_2 = 133.5^\circ\text{C} \quad (\text{Table A - 5})$$

$$\left. \begin{array}{l} P_3 = 600 \text{ kPa} \\ v_3 = 0.6058 \text{ m}^3/\text{kg} \end{array} \right\} T_3 = 517.8^\circ\text{C} \quad (\text{Table A - 6})$$



Using Property Plot feature of EES, and by adding state points we obtain following diagrams.



**3-139E** Argon contained in a piston-cylinder device at a given state undergoes a polytropic process. The final temperature is to be determined using the ideal gas relation and the Beattie-Bridgeman equation.

**Analysis** (a) The polytropic relations for an ideal gas give

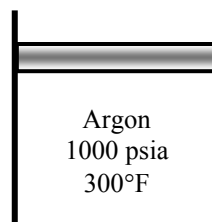
$$T_2 = T_1 \left( \frac{P_2}{P_1} \right)^{n-1/n} = (300 + 460 \text{ R}) \left( \frac{2000 \text{ psia}}{1000 \text{ psia}} \right)^{0.6/1.6} = \mathbf{986 \text{ R}}$$

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

$$A = A_o \left( 1 - \frac{a}{\bar{v}} \right) = 130.7802 \left( 1 - \frac{0.02328}{\bar{v}} \right)$$

$$B = B_o \left( 1 - \frac{b}{\bar{v}} \right) = 0.03931 \left( 1 - \frac{0}{\bar{v}} \right)$$

$$c = 5.99 \times 10^4 \text{ m}^3 \cdot \text{K}^3 / \text{kmol}$$



Substituting these coefficients into the Beattie-Bridgeman equation and using data in SI units ( $P = 1000 \text{ psia} = 6895 \text{ kPa}$ ,  $T = 760 \text{ R} = 422.2 \text{ K}$ ,  $R_u = 8.314 \text{ kJ/kmol} \cdot \text{K}$ )

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

and solving using an equation solver such as EES gives

$$\bar{v} = 0.5120 \text{ m}^3 / \text{kmol} = 8.201 \text{ ft}^3 / \text{lbmol}$$

From the polytropic equation

$$\bar{v}_2 = \bar{v}_1 \left( \frac{P_1}{P_2} \right)^{1/n} = (0.5120 \text{ m}^3 / \text{kmol}) \left( \frac{1}{2} \right)^{1/1.6} = 0.3319 \text{ m}^3 / \text{kmol}$$

Substituting this value into the Beattie-Bridgeman equation and using data in SI units ( $P = 2000 \text{ psia} = 13790 \text{ kPa}$  and  $R_u = 8.314 \text{ kJ/kmol} \cdot \text{K}$ ),

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

and solving using an equation solver such as EES gives

$$T_2 = 532.2 \text{ K} = \mathbf{958 \text{ R}}$$

**3-140E** The specific volume of nitrogen at a given state is to be determined using the ideal gas relation, the Benedict-Webb-Rubin equation, and the compressibility factor.

**Properties** The properties of nitrogen are (Table A-1E)

$$R = 0.3830 \text{ psia} \cdot \text{ft}^3 / \text{lbm} \cdot \text{R}, \quad M = 28.013 \text{ lbm} / \text{lbmol}, \quad T_{\text{cr}} = 227.1 \text{ R}, \quad P_{\text{cr}} = 492 \text{ psia}$$

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

$$\nu = \frac{RT}{P} = \frac{(0.3830 \text{ psia} \cdot \text{ft}^3 / \text{lbm} \cdot \text{R})(360 \text{ R})}{400 \text{ psia}} = \mathbf{0.3447 \text{ ft}^3 / \text{lbm}}$$

Nitrogen  
400 psia, -100°F

(b) Using the coefficients of Table 3-4 for nitrogen and the given data in SI units, the Benedict-Webb-Rubin equation of state is

$$P = \frac{R_u T}{\bar{\nu}} + \left( B_0 R_u T - A_0 - \frac{C_0}{T^2} \right) \frac{1}{\bar{\nu}^2} + \frac{b R_u T - a}{\bar{\nu}^3} + \frac{a \alpha}{\bar{\nu}^6} + \frac{c}{\bar{\nu}^3 T^2} \left( 1 + \frac{\gamma}{\bar{\nu}^2} \right) \exp(-\gamma / \bar{\nu}^2)$$

$$2758 = \frac{(8.314)(200)}{\bar{\nu}_2} + \left( 0.04074 \times 8.314 \times 200 - 106.73 - \frac{8.164 \times 10^5}{200^2} \right) \frac{1}{\bar{\nu}^2} + \frac{0.002328 \times 8.314 \times 200 - 2.54}{\bar{\nu}^3}$$

$$+ \frac{2.54 \times 1.272 \times 10^{-4}}{\bar{\nu}^6} + \frac{7.379 \times 10^4}{\bar{\nu}^3 (200)^2} \left( 1 + \frac{0.0053}{\bar{\nu}^2} \right) \exp(-0.0053 / \bar{\nu}^2)$$

The solution of this equation by an equation solver such as EES gives

$$\bar{\nu} = 0.5666 \text{ m}^3 / \text{kmol}$$

Then,

$$\nu = \frac{\bar{\nu}}{M} = \frac{0.5666 \text{ m}^3 / \text{kmol}}{28.013 \text{ kg} / \text{kmol}} \left( \frac{16.02 \text{ ft}^3 / \text{lbm}}{1 \text{ m}^3 / \text{kg}} \right) = \mathbf{0.3240 \text{ ft}^3 / \text{lbm}}$$

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

$$\left. \begin{aligned} T_R = \frac{T}{T_{\text{cr}}} &= \frac{360 \text{ R}}{227.1 \text{ R}} = 1.585 \\ P_R = \frac{P}{P_{\text{cr}}} &= \frac{400 \text{ psia}}{492 \text{ psia}} = 0.813 \end{aligned} \right\} Z = 0.94$$

Thus,

$$\nu = Z \nu_{\text{ideal}} = (0.94)(0.3447 \text{ ft}^3 / \text{lbm}) = \mathbf{0.3240 \text{ ft}^3 / \text{lbm}}$$

## Fundamentals of Engineering (FE) Exam Problems

**3-141** A rigid tank contains 2 kg of an ideal gas at 4 atm and 40°C. Now a valve is opened, and half of mass of the gas is allowed to escape. If the final pressure in the tank is 2.2 atm, the final temperature in the tank is

- (a) 71°C                      (b) 44°C                      (c) -100°C                      (d) 20°C                      (e) 172°C

*Answer* (a) 71°C

**Solution** Solved by EES Software. Solutions can be verified by copying-and-pasting the following lines on a blank EES screen. (Similar problems and their solutions can be obtained easily by modifying numerical values).

"When R=constant and V= constant,  $P_1/P_2=m_1*T_1/m_2*T_2$ "

$m_1=2$  "kg"

$P_1=4$  "atm"

$P_2=2.2$  "atm"

$T_1=40+273$  "K"

$m_2=0.5*m_1$  "kg"

$P_1/P_2=m_1*T_1/(m_2*T_2)$

$T_{2\_C}=T_2-273$  "C"

"Some Wrong Solutions with Common Mistakes:"

$P_1/P_2=m_1*(T_1-273)/(m_2*W1\_T2)$  "Using C instead of K"

$P_1/P_2=m_1*T_1/(m_1*(W2\_T2+273))$  "Disregarding the decrease in mass"

$P_1/P_2=m_1*T_1/(m_1*W3\_T2)$  "Disregarding the decrease in mass, and not converting to deg. C"

$W4\_T2=(T_1-273)/2$  "Taking T2 to be half of T1 since half of the mass is discharged"

**3-142** The pressure of an automobile tire is measured to be 190 kPa (gage) before a trip and 215 kPa (gage) after the trip at a location where the atmospheric pressure is 95 kPa. If the temperature of air in the tire before the trip is 25°C, the air temperature after the trip is

- (a) 51.1°C                      (b) 64.2°C                      (c) 27.2°C                      (d) 28.3°C                      (e) 25.0°C

*Answer* (a) 51.1°C

**Solution** Solved by EES Software. Solutions can be verified by copying-and-pasting the following lines on a blank EES screen. (Similar problems and their solutions can be obtained easily by modifying numerical values).

"When R, V, and m are constant,  $P_1/P_2=T_1/T_2$ "

$P_{atm}=95$

$P_1=190+P_{atm}$  "kPa"

$P_2=215+P_{atm}$  "kPa"

$T_1=25+273$  "K"

$P_1/P_2=T_1/T_2$

$T_{2\_C}=T_2-273$  "C"

"Some Wrong Solutions with Common Mistakes:"

$P_1/P_2=(T_1-273)/W1\_T2$  "Using C instead of K"

$(P_1-P_{atm})/(P_2-P_{atm})=T_1/(W2\_T2+273)$  "Using gage pressure instead of absolute pressure"

$(P_1-P_{atm})/(P_2-P_{atm})=(T_1-273)/W3\_T2$  "Making both of the mistakes above"

$W4\_T2=T_1-273$  "Assuming the temperature to remain constant"

**3-143** A 300-m<sup>3</sup> rigid tank is filled with saturated liquid-vapor mixture of water at 200 kPa. If 25% of the mass is liquid and the 75% of the mass is vapor, the total mass in the tank is

- (a) 451 kg                      (b) 556 kg                      (c) 300 kg                      (d) 331 kg                      (e) 195 kg

*Answer* (a) 451 kg

**Solution** Solved by EES Software. Solutions can be verified by copying-and-pasting the following lines on a blank EES screen. (Similar problems and their solutions can be obtained easily by modifying numerical values).

V\_tank=300 "m3"

P1=200 "kPa"

x=0.75

v\_f=VOLUME(Steam\_IAPWS, x=0,P=P1)

v\_g=VOLUME(Steam\_IAPWS, x=1,P=P1)

v=v\_f+x\*(v\_g-v\_f)

m=V\_tank/v "kg"

"Some Wrong Solutions with Common Mistakes:"

R=0.4615 "kJ/kg.K"

T=TEMPERATURE(Steam\_IAPWS,x=0,P=P1)

P1\*V\_tank=W1\_m\*R\*(T+273) "Treating steam as ideal gas"

P1\*V\_tank=W2\_m\*R\*T "Treating steam as ideal gas and using deg.C"

W3\_m=V\_tank "Taking the density to be 1 kg/m^3"

**3-144** Water is boiled at 1 atm pressure in a coffee maker equipped with an immersion-type electric heating element. The coffee maker initially contains 1 kg of water. Once boiling started, it is observed that half of the water in the coffee maker evaporated in 10 minutes. If the heat loss from the coffee maker is negligible, the power rating of the heating element is

- (a) 3.8 kW                      (b) 2.2 kW                      (c) 1.9 kW                      (d) 1.6 kW                      (e) 0.8 kW

*Answer* (c) 1.9 kW

**Solution** Solved by EES Software. Solutions can be verified by copying-and-pasting the following lines on a blank EES screen. (Similar problems and their solutions can be obtained easily by modifying numerical values).

m\_1=1 "kg"

P=101.325 "kPa"

time=10\*60 "s"

m\_evap=0.5\*m\_1

Power\*time=m\_evap\*h\_fg "kJ"

h\_f=ENTHALPY(Steam\_IAPWS, x=0,P=P)

h\_g=ENTHALPY(Steam\_IAPWS, x=1,P=P)

h\_fg=h\_g-h\_f

"Some Wrong Solutions with Common Mistakes:"

W1\_Power\*time=m\_evap\*h\_g "Using h\_g"

W2\_Power\*time/60=m\_evap\*h\_g "Using minutes instead of seconds for time"

W3\_Power=2\*Power "Assuming all the water evaporates"

**3-145** A 1-m<sup>3</sup> rigid tank contains 10 kg of water (in any phase or phases) at 160°C. The pressure in the tank is

- (a) 738 kPa                      (b) 618 kPa                      (c) 370 kPa                      (d) 2000 kPa                      (e) 1618 kPa

*Answer* (b) 618 kPa

**Solution** Solved by EES Software. Solutions can be verified by copying-and-pasting the following lines on a blank EES screen. (Similar problems and their solutions can be obtained easily by modifying numerical values).

```
V_tank=1 "m^3"
m=10 "kg"
v=V_tank/m
T=160 "C"
P=PRESSURE(Steam_IAPWS,v=v,T=T)
```

"Some Wrong Solutions with Common Mistakes:"

R=0.4615 "kJ/kg.K"

W1\_P\*V\_tank=m\*R\*(T+273) "Treating steam as ideal gas"

W2\_P\*V\_tank=m\*R\*T "Treating steam as ideal gas and using deg.C"

**3-146** Water is boiling at 1 atm pressure in a stainless steel pan on an electric range. It is observed that 2 kg of liquid water evaporates in 30 minutes. The rate of heat transfer to the water is

- (a) 2.51 kW                      (b) 2.32 kW                      (c) 2.97 kW                      (d) 0.47 kW                      (e) 3.12 kW

*Answer* (a) 2.51 kW

**Solution** Solved by EES Software. Solutions can be verified by copying-and-pasting the following lines on a blank EES screen. (Similar problems and their solutions can be obtained easily by modifying numerical values).

```
m_evap=2 "kg"
P=101.325 "kPa"
time=30*60 "s"
Q*time=m_evap*h_fg "kJ"
h_f=ENTHALPY(Steam_IAPWS, x=0,P=P)
h_g=ENTHALPY(Steam_IAPWS, x=1,P=P)
h_fg=h_g-h_f
```

"Some Wrong Solutions with Common Mistakes:"

W1\_Q\*time=m\_evap\*h\_g "Using h\_g"

W2\_Q\*time/60=m\_evap\*h\_g "Using minutes instead of seconds for time"

W3\_Q\*time=m\_evap\*h\_f "Using h\_f"

**3-147** Water is boiled in a pan on a stove at sea level. During 10 min of boiling, it is observed that 200 g of water has evaporated. Then the rate of heat transfer to the water is

- (a) 0.84 kJ/min      (b) 45.1 kJ/min      (c) 41.8 kJ/min      (d) 53.5 kJ/min      (e) 225.7 kJ/min

*Answer* (b) 45.1 kJ/min

**Solution** Solved by EES Software. Solutions can be verified by copying-and-pasting the following lines on a blank EES screen. (Similar problems and their solutions can be obtained easily by modifying numerical values).

```
m_evap=0.2 "kg"
P=101.325 "kPa"
time=10 "min"
Q*time=m_evap*h_fg "kJ"
h_f=ENTHALPY(Steam_IAPWS, x=0,P=P)
h_g=ENTHALPY(Steam_IAPWS, x=1,P=P)
h_fg=h_g-h_f
```

"Some Wrong Solutions with Common Mistakes:"

```
W1_Q*time=m_evap*h_g "Using h_g"
W2_Q*time*60=m_evap*h_g "Using seconds instead of minutes for time"
W3_Q*time=m_evap*h_f "Using h_f"
```

**3-148** A rigid 3-m<sup>3</sup> rigid vessel contains steam at 4 MPa and 500°C. The mass of the steam is

- (a) 3 kg      (b) 9 kg      (c) 26 kg      (d) 35 kg      (e) 52 kg

*Answer* (d) 35 kg

**Solution** Solved by EES Software. Solutions can be verified by copying-and-pasting the following lines on a blank EES screen. (Similar problems and their solutions can be obtained easily by modifying numerical values).

```
V=3 "m^3"
m=V/v1 "m^3/kg"
P1=4000 "kPa"
T1=500 "C"
v1=VOLUME(Steam_IAPWS,T=T1,P=P1)
```

"Some Wrong Solutions with Common Mistakes:"

```
R=0.4615 "kJ/kg.K"
P1*V=W1_m*R*(T1+273) "Treating steam as ideal gas"
P1*V=W2_m*R*T1 "Treating steam as ideal gas and using deg.C"
```

**3-149** Consider a sealed can that is filled with refrigerant-134a. The contents of the can are at the room temperature of 25°C. Now a leak develops, and the pressure in the can drops to the local atmospheric pressure of 90 kPa. The temperature of the refrigerant in the can is expected to drop to (rounded to the nearest integer)

- (a) 0°C                      (b) -29°C                      (c) -16°C                      (d) 5°C                      (e) 25°C

*Answer* (b) -29°C

**Solution** Solved by EES Software. Solutions can be verified by copying-and-pasting the following lines on a blank EES screen. (Similar problems and their solutions can be obtained easily by modifying numerical values).

```
T1=25 "C"  
P2=90 "kPa"  
T2=TEMPERATURE(R134a,x=0,P=P2)
```

"Some Wrong Solutions with Common Mistakes:"

W1\_T2=T1 "Assuming temperature remains constant"

### 3-150 ... 3-152 Design and Essay Problems

