Chapter 3

PROPERTIES OF PURE SUBSTANCES

Pure Substances, Phase Change Processes, Property Diagrams

3-1C Yes, since the chemical composition throughout the tank remain the same.

3-2C A liquid that is about to vaporize is saturated liquid; otherwise it is compressed liquid.

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

3-4C No.

3-5C The temperature will also increase since the boiling or saturation temperature of a pure substance depends on pressure.

3-6C Because one cannot be varied while holding the other constant. In other words, when one changes, so does the other one.

3-7C 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.

3-8C Yes.

3-9C 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.

3-10C 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

3-11C 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.

3-12C 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

3-13C 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.

3-14C Yes. Otherwise we can create energy by alternately vaporizing and condensing a substance.

3-15C No. Because in the thermodynamic analysis we deal with the changes in properties; and the changes are independent of the selected reference state.

3-16C 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 $h_{fg} = h_g - h_f$.

3-17C Yes; the higher the temperature the lower the h_{fg} value.

3-18C Quality is the fraction of vapor in a saturated liquid-vapor mixture. It has no meaning in the superheated vapor region.

3-19C Completely vaporizing 1 kg of saturated liquid at 1 atm pressure since the higher the pressure, the lower the h_{fg} .

3-20C Yes. It decreases with increasing pressure and becomes zero at the critical pressure.

3-21C No. Quality is a mass ratio, and it is not identical to the volume ratio.

3-22C The compressed liquid can be approximated as a saturated liquid at the given temperature. Thus $v_{T,P} \cong v_{f@T}$.

3-23 [*Also solved by EES on enclosed CD***]** *Complete the following table for H_2O:*

***T*, °C**	***P*, kPa**	***v*, m^3/ kg**	**Phase description**
50	***12.352***	4.16	***Saturated mixture***
120.21	200	***0.8858***	Saturated vapor
250	400	***0.5952***	***Superheated vapor***
110	600	***0.001051***	***Compressed liquid***

3-24 EES Problem 3-23 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.

```
$Warning off
{$Arrays off}
Procedure Find(Fluid$,Prop1$,Prop2$,Value1,Value2:T,p,h,s,v,u,x,State$)
"Due to the very general nature of this problem, a large number of 'if-then-else' statements are
necessary."
If Prop1$='Temperature, C' Then
    T=Value1
    If Prop2$='Temperature, C' then Call Error('Both properties cannot be Temperature,
T=xxxF2',T)
    if Prop2$='Pressure, kPa' then
        p=value2
        h=enthalpy(Fluid$,T=T,P=p)
        s=entropy(Fluid$,T=T,P=p)
        v=volume(Fluid$,T=T,P=p)
        u=intenergy(Fluid$,T=T,P=p)
        x=quality(Fluid$,T=T,P=p)
    endif
    if Prop2$='Enthalpy, kJ/kg' then
        h=value2
        p=Pressure(Fluid$,T=T,h=h)
        s=entropy(Fluid$,T=T,h=h)
        v=volume(Fluid$,T=T,h=h)
        u=intenergy(Fluid$,T=T,h=h)
        x=quality(Fluid$,T=T,h=h)
    endif
    if Prop2$='Entropy, kJ/kg-K' then
        s=value2
        p=Pressure(Fluid$,T=T,s=s)
        h=enthalpy(Fluid$,T=T,s=s)
        v=volume(Fluid$,T=T,s=s)
        u=intenergy(Fluid$,T=T,s=s)
        x=quality(Fluid$,T=T,s=s)
    endif
    if Prop2$='Volume, m^3/kg' then
        v=value2
        p=Pressure(Fluid$,T=T,v=v)
        h=enthalpy(Fluid$,T=T,v=v)
        s=entropy(Fluid$,T=T,v=v)
        u=intenergy(Fluid$,T=T,v=v)
        x=quality(Fluid$,T=T,v=v)
    endif
    if Prop2$='Internal Energy, kJ/kg' then
        u=value2
        p=Pressure(Fluid$,T=T,u=u)
        h=enthalpy(Fluid$,T=T,u=u)
        s=entropy(Fluid$,T=T,u=u)
        v=volume(Fluid$,T=T,s=s)
        x=quality(Fluid$,T=T,u=u)
    endif
    if Prop2$='Quality' then
```

```
        x=value2
        p=Pressure(Fluid$,T=T,x=x)
        h=enthalpy(Fluid$,T=T,x=x)
        s=entropy(Fluid$,T=T,x=x)
        v=volume(Fluid$,T=T,x=x)
        u=IntEnergy(Fluid$,T=T,x=x)
    endif
Endif
If Prop1$='Pressure, kPa' Then
    p=Value1
    If Prop2$='Pressure, kPa' then Call Error('Both properties cannot be Pressure, p=xxxF2',p)
    if Prop2$='Temperature, C' then
        T=value2
        h=enthalpy(Fluid$,T=T,P=p)
        s=entropy(Fluid$,T=T,P=p)
        v=volume(Fluid$,T=T,P=p)
        u=intenergy(Fluid$,T=T,P=p)
        x=quality(Fluid$,T=T,P=p)
    endif
    if Prop2$='Enthalpy, kJ/kg' then
        h=value2
        T=Temperature(Fluid$,p=p,h=h)
        s=entropy(Fluid$,p=p,h=h)
        v=volume(Fluid$,p=p,h=h)
        u=intenergy(Fluid$,p=p,h=h)
        x=quality(Fluid$,p=p,h=h)
    endif
    if Prop2$='Entropy, kJ/kg-K' then
        s=value2
        T=Temperature(Fluid$,p=p,s=s)
        h=enthalpy(Fluid$,p=p,s=s)
        v=volume(Fluid$,p=p,s=s)
        u=intenergy(Fluid$,p=p,s=s)
        x=quality(Fluid$,p=p,s=s)
    endif
    if Prop2$='Volume, m^3/kg' then
        v=value2
        T=Temperature(Fluid$,p=p,v=v)
        h=enthalpy(Fluid$,p=p,v=v)
        s=entropy(Fluid$,p=p,v=v)
        u=intenergy(Fluid$,p=p,v=v)
        x=quality(Fluid$,p=p,v=v)
    endif
    if Prop2$='Internal Energy, kJ/kg' then
        u=value2
        T=Temperature(Fluid$,p=p,u=u)
        h=enthalpy(Fluid$,p=p,u=u)
        s=entropy(Fluid$,p=p,u=u)
        v=volume(Fluid$,p=p,s=s)
        x=quality(Fluid$,p=p,u=u)
    endif
    if Prop2$='Quality' then
        x=value2
        T=Temperature(Fluid$,p=p,x=x)
        h=enthalpy(Fluid$,p=p,x=x)
        s=entropy(Fluid$,p=p,x=x)
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```
        v=volume(Fluid$,p=p,x=x)
        u=IntEnergy(Fluid$,p=p,x=x)
    endif
Endif
If Prop1$='Enthalpy, kJ/kg' Then
    h=Value1
    If Prop2$='Enthalpy, kJ/kg' then Call Error('Both properties cannot be Enthalpy, h=xxxF2',h)
    if Prop2$='Pressure, kPa' then
        p=value2
        T=Temperature(Fluid$,h=h,P=p)
        s=entropy(Fluid$,h=h,P=p)
        v=volume(Fluid$,h=h,P=p)
        u=intenergy(Fluid$,h=h,P=p)
        x=quality(Fluid$,h=h,P=p)
    endif
    if Prop2$='Temperature, C' then
        T=value2
        p=Pressure(Fluid$,T=T,h=h)
        s=entropy(Fluid$,T=T,h=h)
        v=volume(Fluid$,T=T,h=h)
        u=intenergy(Fluid$,T=T,h=h)
        x=quality(Fluid$,T=T,h=h)
    endif
    if Prop2$='Entropy, kJ/kg-K' then
        s=value2
        p=Pressure(Fluid$,h=h,s=s)
        T=Temperature(Fluid$,h=h,s=s)
        v=volume(Fluid$,h=h,s=s)
        u=intenergy(Fluid$,h=h,s=s)
        x=quality(Fluid$,h=h,s=s)
    endif
    if Prop2$='Volume, m^3/kg' then
        v=value2
        p=Pressure(Fluid$,h=h,v=v)
        T=Temperature(Fluid$,h=h,v=v)
        s=entropy(Fluid$,h=h,v=v)
        u=intenergy(Fluid$,h=h,v=v)
        x=quality(Fluid$,h=h,v=v)
    endif
    if Prop2$='Internal Energy, kJ/kg' then
        u=value2
        p=Pressure(Fluid$,h=h,u=u)
        T=Temperature(Fluid$,h=h,u=u)
        s=entropy(Fluid$,h=h,u=u)
        v=volume(Fluid$,h=h,s=s)
        x=quality(Fluid$,h=h,u=u)
    endif
    if Prop2$='Quality' then
        x=value2
        p=Pressure(Fluid$,h=h,x=x)
        T=Temperature(Fluid$,h=h,x=x)
        s=entropy(Fluid$,h=h,x=x)
        v=volume(Fluid$,h=h,x=x)
        u=IntEnergy(Fluid$,h=h,x=x)
    endif
endif
```

```
If Prop1$='Entropy, kJ/kg-K' Then
    s=Value1
    If Prop2$='Entropy, kJ/kg-K' then Call Error('Both properties cannot be Entrolpy, h=xxxF2',s)
    if Prop2$='Pressure, kPa' then
        p=value2
        T=Temperature(Fluid$,s=s,P=p)
        h=enthalpy(Fluid$,s=s,P=p)
        v=volume(Fluid$,s=s,P=p)
        u=intenergy(Fluid$,s=s,P=p)
        x=quality(Fluid$,s=s,P=p)
    endif
    if Prop2$='Temperature, C' then
        T=value2
        p=Pressure(Fluid$,T=T,s=s)
        h=enthalpy(Fluid$,T=T,s=s)
        v=volume(Fluid$,T=T,s=s)
        u=intenergy(Fluid$,T=T,s=s)
        x=quality(Fluid$,T=T,s=s)
    endif
    if Prop2$='Enthalpy, kJ/kg' then
        h=value2
        p=Pressure(Fluid$,h=h,s=s)
        T=Temperature(Fluid$,h=h,s=s)
        v=volume(Fluid$,h=h,s=s)
        u=intenergy(Fluid$,h=h,s=s)
        x=quality(Fluid$,h=h,s=s)
    endif
    if Prop2$='Volume, m^3/kg' then
        v=value2
        p=Pressure(Fluid$,s=s,v=v)
        T=Temperature(Fluid$,s=s,v=v)
        h=enthalpy(Fluid$,s=s,v=v)
        u=intenergy(Fluid$,s=s,v=v)
        x=quality(Fluid$,s=s,v=v)
    endif
    if Prop2$='Internal Energy, kJ/kg' then
        u=value2
        p=Pressure(Fluid$,s=s,u=u)
        T=Temperature(Fluid$,s=s,u=u)
        h=enthalpy(Fluid$,s=s,u=u)
        v=volume(Fluid$,s=s,s=s)
        x=quality(Fluid$,s=s,u=u)
    endif
    if Prop2$='Quality' then
        x=value2
        p=Pressure(Fluid$,s=s,x=x)
        T=Temperature(Fluid$,s=s,x=x)
        h=enthalpy(Fluid$,s=s,x=x)
        v=volume(Fluid$,s=s,x=x)
        u=IntEnergy(Fluid$,s=s,x=x)
    endif
Endif
if x<0 then State$='in the compressed liquid region.'
if x>1 then State$='in the superheated region.'
If (x<1) and (X>0) then State$='in the two-phase region.'
If (x=1) then State$='a saturated vapor.'
```

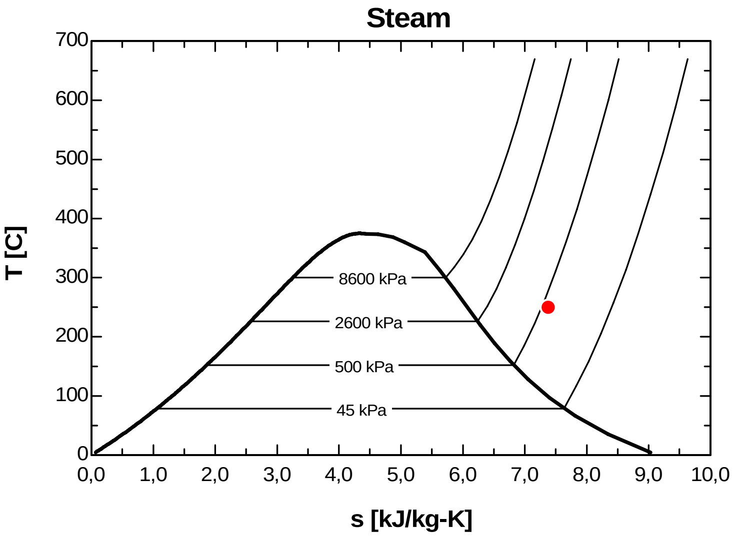
```
if (x=0) then State$='a saturated liquid.'
end
"Input from the diagram window"
{Fluid$='Steam'
Prop1$='Temperature'
Prop2$='Pressure'
Value1=50
value2=101.3}

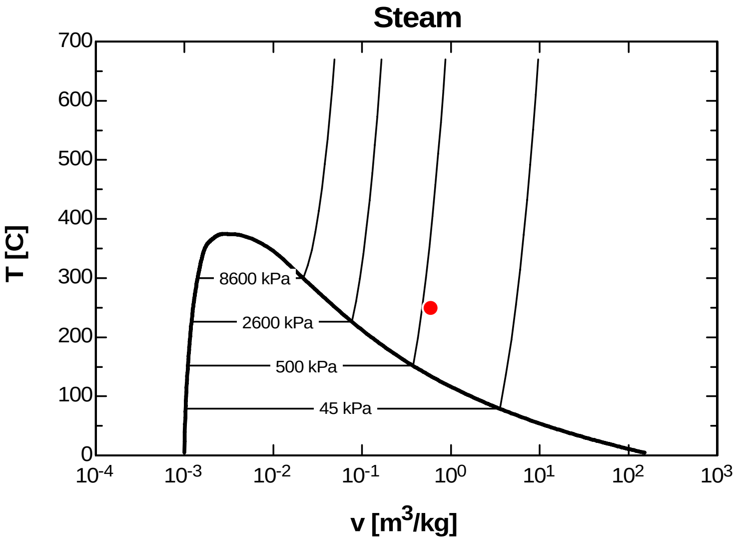
Call Find(Fluid$,Prop1$,Prop2$,Value1,Value2:T,p,h,s,v,u,x,State$)

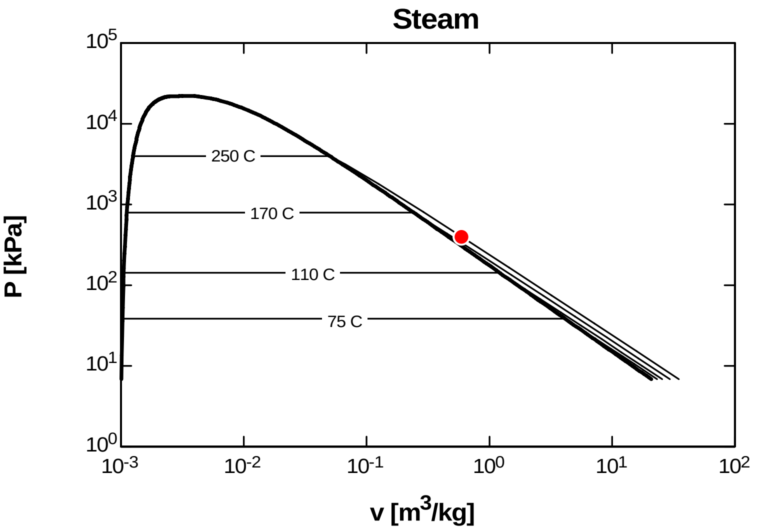
T[1]=T ;  p[1]=p ;  h[1]=h  ;  s[1]=s  ;  v[1]=v ; u[1]=u  ;  x[1]=x
"Array variables were used so the states can be plotted on property plots."
```

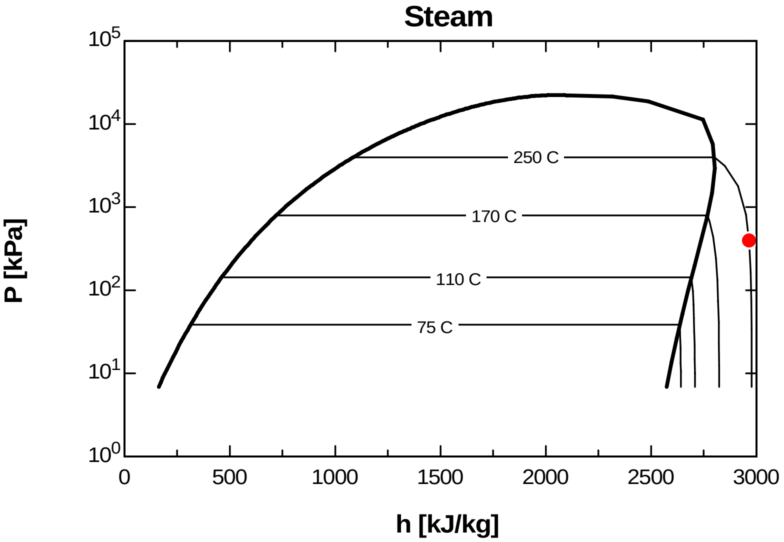
ARRAYS TABLE

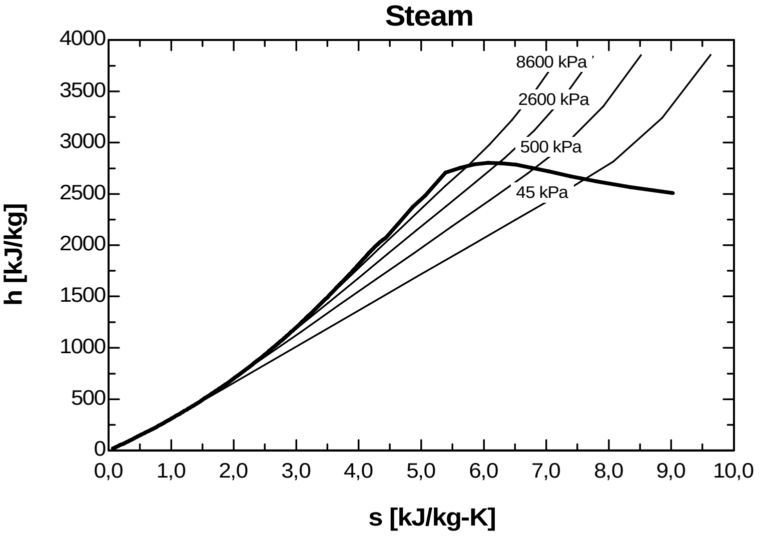
h KJ/kg	P kPa	s kJ/kgK	T C	u KJ/kg	v m^3/kg	x
2964.5	400	7.3804	250	2726.4	0.5952	100






Steam
P [kPa]
v [m³/kg]
10⁰
10¹
10²
10³
10⁴
10⁵
10⁻³
10⁻²
10⁻¹
10⁰
10¹
10²
250 C
170 C
110 C
75 C


Steam
P [kPa]
h [kJ/kg]
10⁰
10¹
10²
10³
10⁴
10⁵
0
500
1000
1500
2000
2500
3000
250 C
170 C
110 C
75 C


Steam
h [kJ/kg]
s [kJ/kg-K]
0
500
1000
1500
2000
2500
3000
3500
4000
0,0
1,0
2,0
3,0
4,0
5,0
6,0
7,0
8,0
9,0
10,0
8600 kPa
2600 kPa
500 kPa
45 kPa

3-25E *Complete the following table for* H_2O:

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

3-26E EES Problem 3-25E 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, ºF	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

3-27 *Complete the following table for H_2O:*

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

3-28 *Complete the following table for Refrigerant-134a:*

T, °C	**P, kPa**	**v, m^3 / kg**	**Phase description**
-8	320	***0.0007569***	***Compressed liquid***
30	***770.64***	0.015	***Saturated mixture***
-12.73	180	***0.11041***	Saturated vapor
80	600	***0.044710***	***Superheated vapor***

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

T, °C	**P, kPa**	***u*, kJ / kg**	**Phase description**
20	***572.07***	95	***Saturated mixture***
-12	***185.37***	***35.78***	Saturated liquid
86.24	400	300	***Superheated vapor***
8	600	***62.26***	***Compressed liquid***

3-30E *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***

3-31 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.

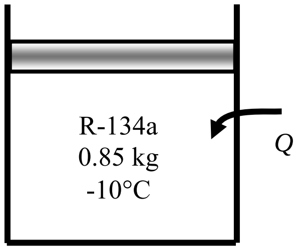
Analysis (a) The final pressure is equal to the initial pressure, which is determined from

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

(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)

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

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



The initial and the final volumes and the volume change are

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

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

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

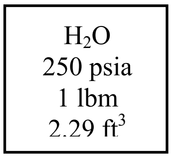
(c) The total enthalpy change is determined from

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

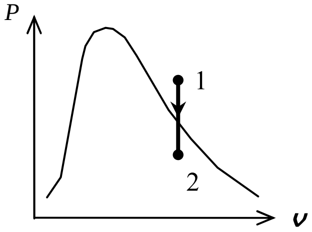
3-32E A rigid container that is filled with water is cooled. The initial temperature and final pressure are to be determined.

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

$$\left.\begin{array}{l} P_1 = 250\text{ psia} \\ v_1 = 2.29\text{ ft}^3/\text{lbm} \end{array}\right\} T_1 = \mathbf{550°F} \quad \text{(Table A - 6E)}$$



This is a constant volume cooling process ($v = V/m$ = constant). The final state is saturated mixture and thus the pressure is the saturation pressure at the final temperature:

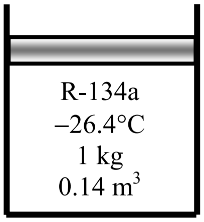


$$\left.\begin{array}{l} T_2 = 100°\text{F} \\ v_2 = v_1 = 2.29\text{ ft}^3/\text{lbm} \end{array}\right\} P_2 = P_{\text{sat @ 100°F}} = \mathbf{0.9505\ psia} \quad \text{(Table A - 4E)}$$

3-33 A piston-cylinder device that is filled with R-134a is heated. The final volume is to be determined.

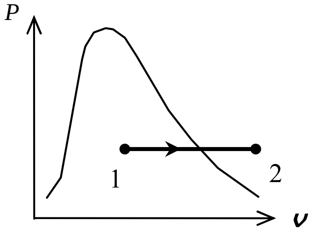
Analysis The initial specific volume is

$$v_1 = \frac{V_1}{m} = \frac{0.14\text{ m}^3}{1\text{ kg}} = 0.14\text{ m}^3/\text{kg}$$



This is a constant-pressure process. The initial state is determined to be a mixture, and thus the pressure is the saturation pressure at the given temperature

$$P_1 = P_2 = P_{\text{sat @ -26.4°C}} = 100\text{ kPa} \quad \text{(Table A - 12)}$$



The final state is superheated vapor and the specific volume is

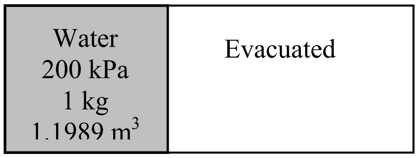
$$\left.\begin{array}{l} P_2 = 100\text{ kPa} \\ T_2 = 100°\text{C} \end{array}\right\} v_2 = 0.30138\text{ m}^3/\text{kg} \quad \text{(Table A - 13)}$$

The final volume is then

$$V_2 = m v_2 = (1\text{ kg})(0.30138\text{ m}^3/\text{kg}) = \mathbf{0.30138\ m^3}$$

3-34 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 from the water. The pressure at the final state is to be determined.

Analysis The initial specific volume is



$$\boldsymbol{v}_1 = \frac{\boldsymbol{V}_1}{m} = \frac{1.1989\,\text{m}^3}{1\,\text{kg}} = 1.1989\,\text{m}^3/\text{kg}$$

At the final state, the water occupies three times the initial volume. Then,

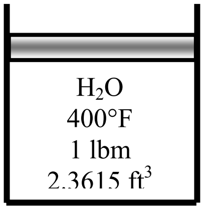
$$\boldsymbol{v}_2 = 3\boldsymbol{v}_1 = 3(1.1989\,\text{m}^3/\text{kg}) = 3.5967\,\text{m}^3/\text{kg}$$

Based on this specific volume and the final temperature, the final state is a saturated mixture and the pressure is

$$P_2 = P_{\text{sat @ 3°C}} = \mathbf{0.768\,kPa} \quad (\text{Table A-4})$$

3-35E A piston-cylinder device that is filled with water is cooled. The final pressure and volume of the water are to be determined.

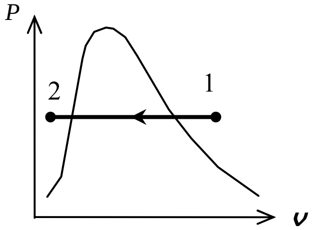
Analysis The initial specific volume is



$$\boldsymbol{v}_1 = \frac{\boldsymbol{V}_1}{m} = \frac{2.3615\,\text{ft}^3}{1\,\text{lbm}} = 2.3615\,\text{ft}^3/\text{lbm}$$

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

$$\left.\begin{aligned} T_1 &= 400°\text{F} \\ \boldsymbol{v}_1 &= 2.3615\,\text{ft}^3/\text{lbm} \end{aligned}\right\} P_1 = P_2 = \mathbf{200\,psia} \quad (\text{Table A-6E})$$



The saturation temperature at 200 psia is 381.8°F. Since the final temperature is less than this temperature, the final state is compressed liquid. Using the incompressible liquid approximation,

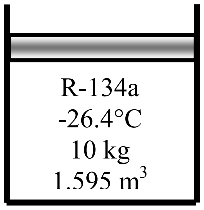
$$\boldsymbol{v}_2 = \boldsymbol{v}_{f\,@\,100°\text{F}} = 0.01613\,\text{ft}^3/\text{lbm} \quad (\text{Table A-4E})$$

The final volume is then

$$\boldsymbol{V}_2 = m\boldsymbol{v}_2 = (1\,\text{lbm})(0.01613\,\text{ft}^3/\text{lbm}) = \mathbf{0.01613\,ft^3}$$

3-36 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

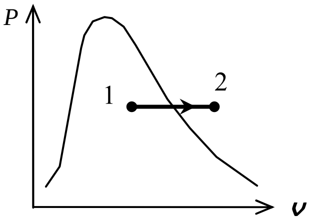


$$v_1 = \frac{V}{m} = \frac{1.595\,\text{m}^3}{10\,\text{kg}} = 0.1595\,\text{m}^3/\text{kg}$$

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

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

The final state is superheated vapor and the specific volume is



$$\left.\begin{aligned} P_2 &= 100\,\text{kPa} \\ T_2 &= 100°\text{C} \end{aligned}\right\} v_2 = 0.30138\,\text{m}^3/\text{kg} \quad \text{(Table A-13)}$$

The final volume is then

$$V_2 = m v_2 = (10\,\text{kg})(0.30138\,\text{m}^3/\text{kg}) = \mathbf{3.0138\,m^3}$$

3-37 The internal energy of water at a specified state is to be determined.

Analysis The state of water is superheated vapor. From the steam tables,

$$\left.\begin{aligned} P &= 50\,\text{kPa} \\ T &= 200°\text{C} \end{aligned}\right\} u = \mathbf{2660.0\,kJ/kg} \quad \text{(Table A-6)}$$

3-38 The specific volume of water at a specified state is to be determined using the incompressible liquid approximation and it is to be compared to the more accurate value.

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

$$\left.\begin{aligned} P &= 5\,\text{MPa} \\ T &= 100°\text{C} \end{aligned}\right\} v = \mathbf{0.001041\,m^3/kg} \quad \text{(Table A-7)}$$

Based upon the incompressible liquid approximation,

$$\left.\begin{aligned} P &= 2\,\text{MPa} \\ T &= 100°\text{C} \end{aligned}\right\} v \cong v_{f\,@\,100°\text{C}} = \mathbf{0.001043\,m^3/kg} \quad \text{(Table A-4)}$$

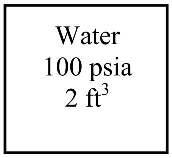
The error involved is

$$\text{Percent Error} = \frac{0.001043 - 0.001041}{0.001041} \times 100 = \mathbf{0.19\%}$$

which is quite acceptable in most engineering calculations.

3-39E The total internal energy and enthalpy of water in a container are to be determined.

Analysis The specific volume is



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

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)

$$x = \frac{\boldsymbol{v} - \boldsymbol{v}_f}{\boldsymbol{v}_{fg}} = \frac{(2 - 0.01774)\ \text{ft}^3/\text{lbm}}{(4.4327 - 0.01774)\ \text{ft}^3/\text{lbm}} = 0.4490$$

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

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

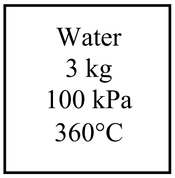
The total internal energy and enthalpy are then

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

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

3-40 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



$$\left.\begin{array}{l} P = 100\ \text{kPa} \\ T = 360°\text{C} \end{array}\right\} \boldsymbol{v} = 2.9172\ \text{m}^3/\text{kg}\ \ (\text{Table A-6})$$

The volume of the container is then

$$\boldsymbol{V} = m\boldsymbol{v} = (3\ \text{kg})(2.9172\ \text{m}^3/\text{kg}) = \mathbf{8.752\ m^3}$$

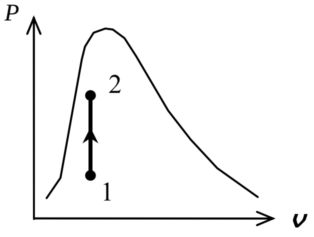
3-41 A rigid container that is filled with R-134a is heated. The temperature and total enthalpy are to be determined at the initial and final states.

R-134a
300 kPa
10 kg
14 L

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

$$v_1 = v_2 = \frac{V}{m} = \frac{0.014\ \mathrm{m}^3}{10\ \mathrm{kg}} = 0.0014\ \mathrm{m}^3/\mathrm{kg}$$

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



$$T_1 = T_{\mathrm{sat}\ @\ 300\ \mathrm{kPa}} = \mathbf{0.61°C}$$

and

$$x_1 = \frac{v_1 - v_f}{v_{fg}} = \frac{(0.0014 - 0.0007736)\ \mathrm{m}^3/\mathrm{kg}}{(0.067978 - 0.0007736)\ \mathrm{m}^3/\mathrm{kg}} = 0.009321$$

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

The total enthalpy is then

$$H_1 = mh_1 = (10\ \mathrm{kg})(54.52\ \mathrm{kJ/kg}) = \mathbf{545.2\ kJ}$$

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

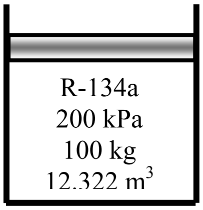
$$T_2 = T_{\mathrm{sat}\ @\ 600\ \mathrm{kPa}} = \mathbf{21.55°C}$$

$$x_2 = \frac{v_2 - v_f}{v_{fg}} = \frac{(0.0014 - 0.0008199)\ \mathrm{m}^3/\mathrm{kg}}{(0.034295 - 0.0008199)\ \mathrm{m}^3/\mathrm{kg}} = 0.01733$$

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

$$H_2 = mh_2 = (10\ \mathrm{kg})(84.64\ \mathrm{kJ/kg}) = \mathbf{846.4\ kJ}$$

3-42 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.

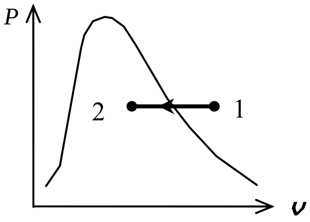


Analysis The initial specific volume is

$$v_1 = \frac{V}{m} = \frac{12.322\,\text{m}^3}{100\,\text{kg}} = 0.12322\,\text{m}^3/\text{kg}$$

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

$$\left.\begin{array}{l} P_1 = 200\,\text{kPa} \\ v_1 = 0.12322\,\text{m}^3/\text{kg} \end{array}\right\} u_1 = 263.08\,\text{kJ/kg}\ \ (\text{Table A-13})$$



The final specific volume is

$$v_2 = \frac{v_1}{2} = \frac{0.12322\,\text{m}^3/kg}{2} = 0.06161\,\text{m}^3/\text{kg}$$

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

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

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

$$x_2 = \frac{v_2 - v_f}{v_{fg}} = \frac{(0.06161 - 0.0007533)\,\text{m}^3/\text{kg}}{(0.099867 - 0.0007533)\,\text{m}^3/\text{kg}} = 0.6140$$

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

Hence, the change in the internal energy is

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

3-43 A spring-loaded piston-cylinder device is filled with water. The water now undergoes a process until its volume is one-half of the original volume. The final temperature and the entropy are to be determined.

Analysis From the steam tables,

$$\left.\begin{aligned} P_1 &= 4\text{ MPa} \\ T_1 &= 400°\text{C} \end{aligned}\right\} \boldsymbol{v}_1 = 0.07343\text{ m}^3/\text{kg} \quad (\text{Table A-6})$$

The process experienced by this system is a linear P-$\boldsymbol{v}$ process. The equation for this line is

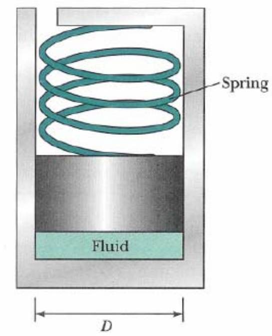
$$P - P_1 = c(\boldsymbol{v} - \boldsymbol{v}_1)$$

where P_1 is the system pressure when its specific volume is $\boldsymbol{v}_1$. The spring equation may be written as

$$P - P_1 = \frac{F_s - F_{s,1}}{A} = k\frac{x - x_1}{A} = \frac{kA}{A^2}(x - x_1) = \frac{k}{A^2}(\boldsymbol{V} - \boldsymbol{V}_1) = \frac{km}{A^2}(\boldsymbol{v} - \boldsymbol{v}_1)$$

Constant c is hence

$$c = \frac{km}{A^2} = \frac{4^2 km}{\pi^2 D^4} = \frac{(16)(90\text{ kN/m})(0.5\text{ kg})}{\pi^2(0.2\text{ m})^4} = 45{,}595\text{ kN}\cdot\text{kg/m}^5$$

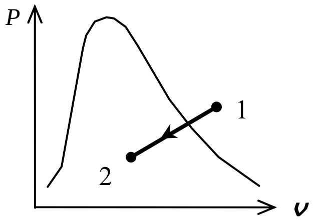


The final pressure is then

$$P_2 = P_1 + c(\boldsymbol{v}_2 - \boldsymbol{v}_1) = P_1 + c\left(\frac{\boldsymbol{v}_1}{2} - \boldsymbol{v}_1\right) = P_1 - \frac{c}{2}\boldsymbol{v}_1$$
$$= 4000\text{ kPa} - \frac{45{,}595\text{ kN}\cdot\text{kg/m}^5}{2}(0.07343\text{ m}^3/\text{kg}) = 2326\text{ kPa}$$

and

$$\boldsymbol{v}_2 = \frac{\boldsymbol{v}_1}{2} = \frac{0.07343\text{ m}^3/kg}{2} = 0.03672\text{ m}^3/\text{kg}$$



The final state is a mixture and the temperature is

$$T_2 = T_{\text{sat @ 2326 kPa}} \cong \mathbf{220°C} \quad (\text{Table A-5})$$

The quality and the entropy at the final state are

$$x_2 = \frac{\boldsymbol{v}_2 - \boldsymbol{v}_f}{\boldsymbol{v}_{fg}} = \frac{(0.03672 - 0.001190)\text{ m}^3/\text{kg}}{(0.086094 - 0.001190)\text{ m}^3/\text{kg}} = 0.4185$$

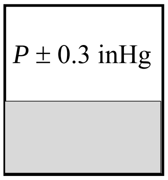
$$h_2 = h_f + x_2 h_{fg} = 943.55 + (0.4185)(1857.4) = \mathbf{1720.9\ kJ/kg}$$

3-44E 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 0.3 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 0.3 in of mercury in atmospheric pressure corresponds to

$$\Delta P = (0.3\,\text{inHg})\left(\frac{0.491\,\text{psia}}{1\,\text{inHg}}\right) = 0.147\text{ psia}$$



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

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

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

$$\Delta T_{\text{boiling}} = (3.783\,°\text{F/psia})\Delta P = (3.783\,°\text{F/psia})(0.147\text{ psia}) = \mathbf{0.56°F}$$

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

3-45 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.

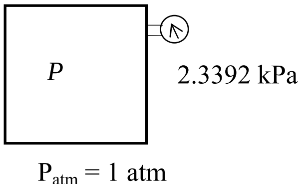
Assumptions **1** The local atmospheric pressure is 1 atm = 101.325 kPa. **2** The weight of the lid is small and thus its effect on the boiling pressure and temperature is negligible. **3** No air has leaked into the pan during cooling.

Properties The saturation pressure of water at 20°C is 2.3392 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

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

or,



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

The weight of the pan and its contents is

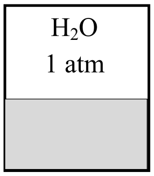
$$W = mg = (8\text{ kg})(9.81\text{ m/s}^2) = \mathbf{78.5\ N}$$

which is much less than the reaction force of 6997 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.

3-46 Water is boiled at 1 atm pressure 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 1 atm and thus at a saturation temperature of T_{sat} = 100°C are h_{fg} = 2256.5 kJ/kg and v_f = 0.001043 m^3/kg (Table A-4).

Analysis The rate of evaporation of water is



$$m_{\text{evap}} = \frac{V_{\text{evap}}}{v_f} = \frac{(\pi D^2/4)L}{v_f} = \frac{[\pi(0.25\text{ m})^2/4](0.10\text{ m})}{0.001043} = 4.704\text{ kg}$$

$$\dot{m}_{\text{evap}} = \frac{m_{\text{evap}}}{\Delta t} = \frac{4.704\text{ kg}}{45\times 60\text{ s}} = 0.001742\text{ kg/s}$$

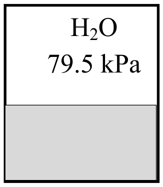
Then the rate of heat transfer to water becomes

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

3-47 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_{sat} = 93.3°C, h_{fg} = 2273.9 kJ/kg and v_f = 0.001038 m^3/kg (Table A-5).

Analysis The rate of evaporation of water is



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

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

Then the rate of heat transfer to water becomes

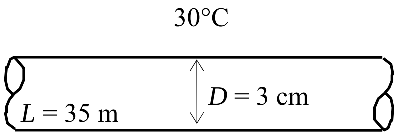
$$\dot{Q} = \dot{m}_{\text{evap}} h_{fg} = (0.001751\text{ kg/s})(2273.9\text{ kJ/kg}) = \mathbf{3.98\ kW}$$

3-48 Saturated steam at T_{sat} = 30°C condenses on the outer surface of a cooling tube at a rate of 45 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°C.

Properties The properties of water at the saturation temperature of 30°C are h_{fg} = 2429.8 kJ/kg (Table A-4).

Analysis Noting that 2429.8 kJ of heat is released as 1 kg of saturated vapor at 30°C condenses, the rate of heat transfer from the steam to the cooling water in the tube is determined directly from



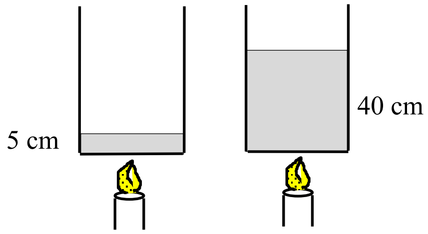
$$\begin{aligned}\dot{Q} &= \dot{m}_{\text{evap}} h_{fg} \\ &= (45\ \text{kg/h})(2429.8\ \text{kJ/kg}) = 109{,}341\ \text{kJ/h} \\ &= \mathbf{30.4\ kW}\end{aligned}$$

3-49 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 ρ = 1000 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°C:



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

The pressure difference between the bottoms of two pans is

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

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

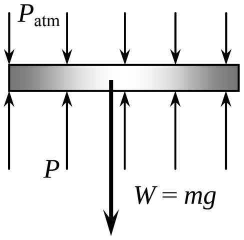
$$T_{\text{boiling}} = T_{\text{sat@}97.82\ \text{kPa}} = \mathbf{99.0^\circ C} \qquad \text{(Table A-5)}$$

3-50 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,



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

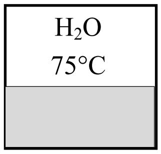
The boiling temperature is the saturation temperature corresponding to this pressure,

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

3-51 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*-v diagram is to be drawn.

Analysis This is a constant volume process ($v = V/m$ = constant),

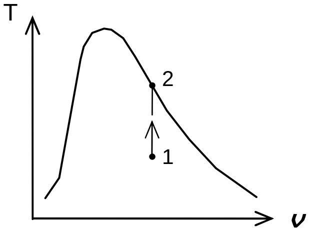
and the specific volume is determined to be



$$v = \frac{V}{m} = \frac{2.5\ \text{m}^3}{15\ \text{kg}} = 0.1667\ \text{m}^3/\text{kg}$$

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

$$v_2 = v_g = 0.1667\ \text{m}^3/\text{kg}$$



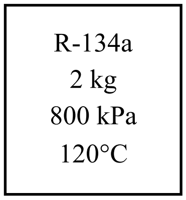
The temperature at this point is the temperature that corresponds to this v_g value,

$$T = T_{\text{sat@}v_g = 0.1667\ \text{m}^3/\text{kg}} = \mathbf{187.0°C} \quad \text{(Table A-4)}$$

3-52 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).

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



Analysis The total volume and internal energy are determined from

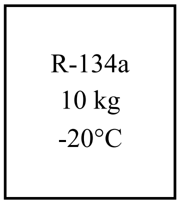
$$V = mv = (2 \text{ kg})(0.037625 \text{ m}^3\text{/kg}) = \mathbf{0.0753\ m^3}$$

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

3-53 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

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



At -20°C, $v_f = 0.0007362$ m³/kg and $v_g = 0.14729$ m³/kg (Table A-11). Thus the tank contains saturated liquid-vapor mixture since $v_f < v < v_g$, and the pressure must be the saturation pressure at the specified temperature,

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

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

$$x = \frac{v - v_f}{v_{fg}} = \frac{0.05 - 0.0007362}{0.14729 - 0.0007362} = 0.3361$$

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

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

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

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

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

3-54 [*Also solved by EES on enclosed CD***]** 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 350°C. The initial temperature, the total mass of water, the final volume are to be determined, and the *P*-v 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,

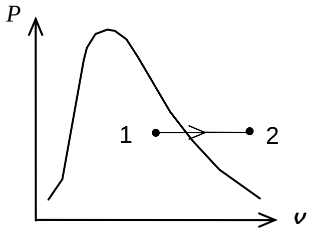
$$T = T_{\text{sat@800 kPa}} = \mathbf{170.41°C}$$

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

$$m_f = \frac{V_f}{v_f} = \frac{0.1\ \text{m}^3}{0.001115\ \text{m}^3/\text{kg}} = 89.704\ \text{kg}$$

$$m_g = \frac{V_g}{v_g} = \frac{0.9\ \text{m}^3}{0.24035\ \text{m}^3/\text{kg}} = 3.745\ \text{kg}$$

$$m_t = m_f + m_g = 89.704 + 3.745 = \mathbf{93.45\ kg}$$



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

$$\left.\begin{array}{l} P_2 = 800\ \text{kPa} \\ T_2 = 350^\circ\text{C} \end{array}\right\} v_2 = 0.35442\ \text{m}^3/\text{kg} \qquad \text{(Table A-6)}$$

Then,

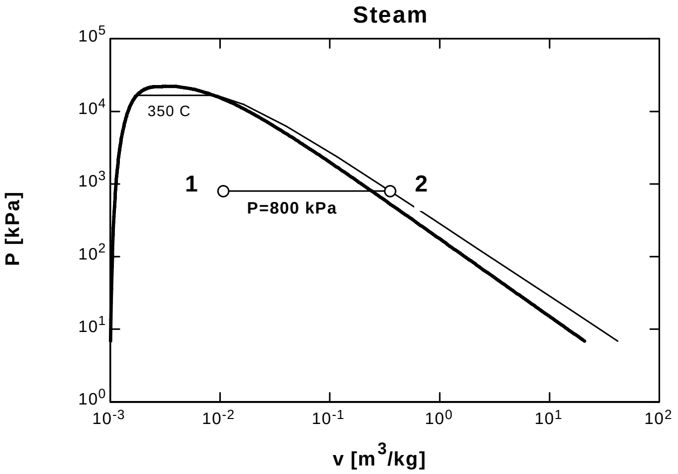
$$V_2 = m_t v_2 = (93.45\ \text{kg})(0.35442\ \text{m}^3/\text{kg}) = \mathbf{33.12\ m^3}$$

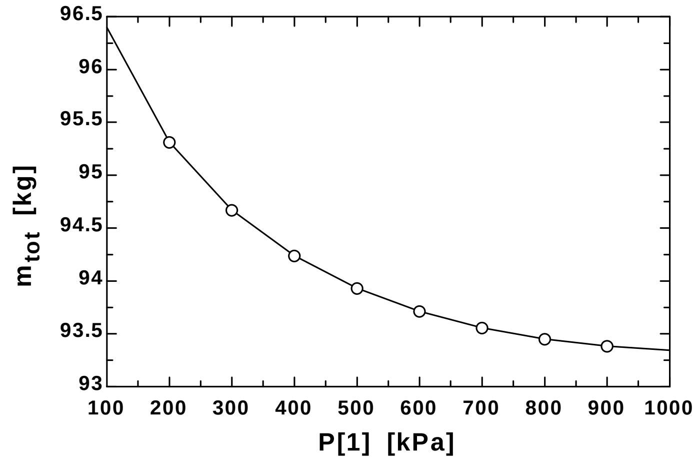
3-55 EES Problem 3-54 is reconsidered. The effect of pressure on the total mass of water in the tank as the pressure varies from 0.1 MPa to 1 MPa is to be investigated. The total mass of water is to be plotted against pressure, and results are to be discussed.

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

```
P[1]=800 [kPa]
P[2]=P[1]
T[2]=350 [C]
V_f1 = 0.1 [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]
```

m_{tot} [kg]	P_1 [kPa]
96.39	100
95.31	200
94.67	300
94.24	400
93.93	500
93.71	600
93.56	700
93.45	800
93.38	900
93.34	1000

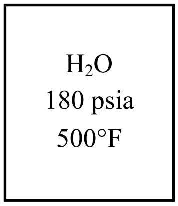




3-56E Superheated water vapor cools at constant volume until the temperature drops to 250°F. At the final state, the pressure, the quality, and the enthalpy are to be determined.

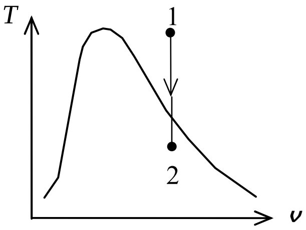
Analysis This is a constant volume process ($v = V/m$ = constant), and the initial specific volume is determined to be

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



At 250°F, $v_f = 0.01700$ ft^3/lbm and $v_g = 13.816$ ft^3/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,

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



(*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

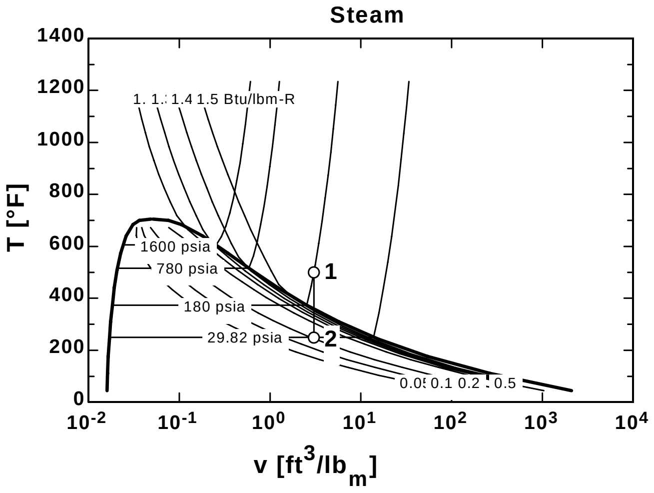
$$h = h_f + x h_{fg} = 218.63 + 0.219 \times 945.41 = \mathbf{426.0\ Btu/lbm}$$

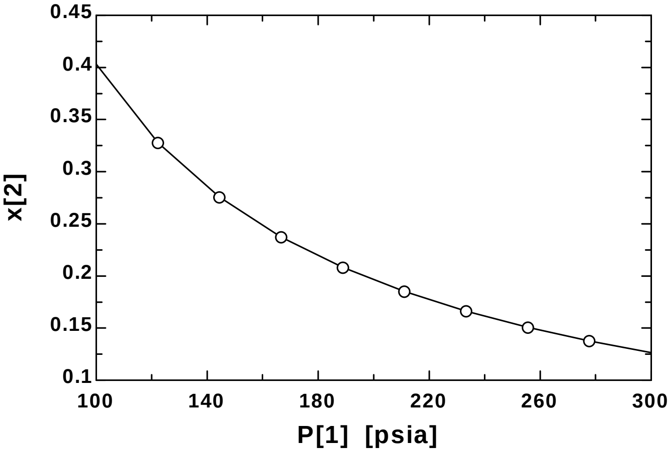
3-57E EES Problem 3-56E is reconsidered. The effect of initial pressure on the quality of water at the final state as the pressure varies from 100 psi to 300 psi is to be investigated. The quality is to be plotted against initial pressure, and the results are to be discussed.

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	0.1510
277.8	0.1379
300	0.1268





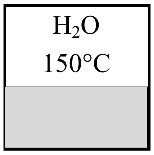
3-58 A rigid vessel that contains a saturated liquid-vapor mixture is heated until it reaches the critical state. The mass of the liquid water and the volume occupied by the liquid at the initial state are to be determined.

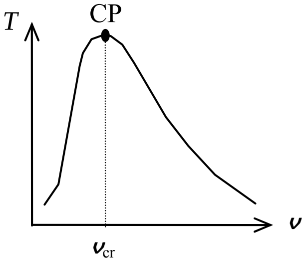
Analysis This is a constant volume process ($v = V/m$ = constant) to the critical state, and thus the initial specific volume will be equal to the final specific volume, which is equal to the critical specific volume of water,

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

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, $v_f = 0.001091$ m^3/kg and $v_g = 0.39248$ m^3/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

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

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

3-59 The properties of compressed liquid water at a specified state are to be determined using the compressed liquid tables, and also by using the saturated liquid approximation, and the results are to be compared.

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

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

From compressed liquid table (Table A-7),

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

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

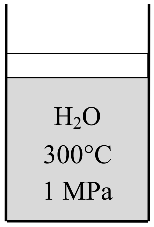
3-60 EES Problem 3-59 is reconsidered. Using EES, the indicated properties of compressed liquid are to be determined, and they are to be compared to those obtained using the saturated liquid approximation.

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

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

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

3-61 Superheated steam in a piston-cylinder device is cooled at constant pressure until half of the mass condenses. The final temperature and the volume change are to be determined, and the process should be shown on a *T*-v diagram.



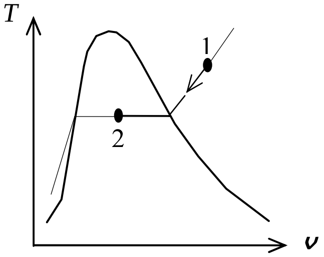
Analysis (*b*) At the final state the cylinder contains saturated liquid-vapor mixture, and thus the final temperature must be the saturation temperature at the final pressure,

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

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

$$\left.\begin{array}{l} P_1 = 1.0 \text{ MPa} \\ T_1 = 300^\circ\text{C} \end{array}\right\} v_1 = 0.25799 \text{ m}^3/\text{kg} \qquad \text{(Table A-6)}$$

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



Thus,

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

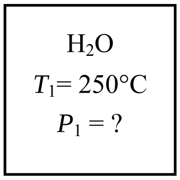
3-62 The water in a rigid tank is cooled until the vapor starts condensing. The initial pressure in the tank is to be determined.

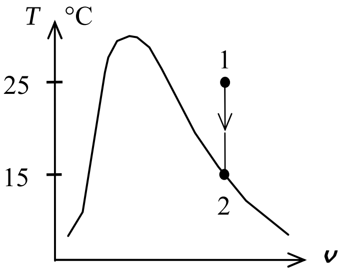
Analysis This is a constant volume process ($\upsilon = V/m$ = constant), and the initial specific volume is equal to the final specific volume that is

$$\upsilon_1 = \upsilon_2 = \upsilon_{g@150°C} = 0.39248\ \text{m}^3/\text{kg} \quad \text{(Table A-4)}$$

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

$$\left.\begin{array}{l} T_1 = 250°\text{C} \\ \upsilon_1 = 0.39248\ \text{m}^3/\text{kg} \end{array}\right\} P_1 = \mathbf{0.60\ MPa}$$





3-63 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.

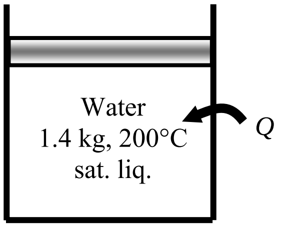
Properties The saturated liquid properties of water at 200°C are: $\upsilon_f = 0.001157$ m^3/kg and $u_f = 850.46$ kJ/kg (Table A-4).

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

$$V_1 = m\upsilon_1 = (1.4\ \text{kg})(0.001157\ \text{m}^3/\text{kg}) = 0.001619\ \text{m}^3$$

The volume at the final state is

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



(*b*) The final state properties are

$$\upsilon_2 = \frac{V}{m} = \frac{0.006476\ \text{m}^3}{1.4\ \text{kg}} = 0.004626\ \text{m}^3/\text{kg}$$

$$\left.\begin{array}{l} \upsilon_2 = 0.004626\ \text{m}^3/\text{kg} \\ x_2 = 1 \end{array}\right\} \begin{array}{l} T_2 = \mathbf{371.3°C} \\ P_2 = \mathbf{21{,}367\ kPa} \\ u_2 = 2201.5\ \text{kJ/kg} \end{array} \quad \text{(Table A-4 or A-5 or EES)}$$

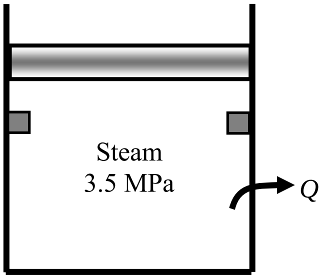
(*c*) The total internal energy change is determined from

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

3-64 Heat is lost from a piston-cylinder device that contains steam at a specified state. The initial temperature, the enthalpy change, and the final pressure and quality are to be determined.

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

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



Then, the initial temperature becomes

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

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

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

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

Then, the enthalpy change of steam becomes

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

(*c*) At the final state

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

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

3-65E 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,

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

Based upon the incompressible liquid approximation,

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

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.

3-66 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,

$$\left.\begin{array}{l} P = 10\text{ MPa} \\ T = 100°\text{C} \end{array}\right\} \begin{array}{l} \boldsymbol{v} = 0.0010385\text{ m}^3/\text{kg} \\ h = 426.62\text{ kJ/kg} \end{array} \quad \text{(Table A-7)}$$

Based upon the incompressible liquid approximation,

$$\left.\begin{array}{l} P = 10\text{ MPa} \\ T = 100°\text{C} \end{array}\right\} \begin{array}{l} \boldsymbol{v} \cong \boldsymbol{v}_{f\,@\,100°\text{C}} = 0.001043\text{ m}^3/\text{kg} \\ h \cong h_{f\,@\,100°\text{C}} = 419.17\text{ kJ/kg} \end{array} \quad \text{(Table A-4)}$$

The errors involved are

$$\text{Percent Error (specific volume)} = \frac{0.001043 - 0.0010385}{0.0010385} \times 100 = \mathbf{0.43\%}$$

$$\text{Percent Error (enthalpy)} = \frac{426.62 - 419.17}{426.62} \times 100 = \mathbf{1.75\%}$$

which are quite acceptable in most engineering calculations.

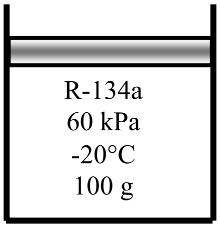
3-67 The specific volume and internal energy of R-134a at a specified state are to be determined.

Analysis The state of R-134a is compressed liquid. Based upon the incompressible liquid approximation,

$$\left.\begin{array}{l} P = 700\text{ kPa} \\ T = 20°\text{C} \end{array}\right\} \begin{array}{l} \boldsymbol{v} \cong \boldsymbol{v}_{f\,@\,20°\text{C}} = 0.0008161\text{ m}^3/\text{kg} \\ u \cong u_{f\,@\,20°\text{C}} = 78.86\text{ kJ/kg} \end{array} \quad \text{(Table A-11)}$$

3-68 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

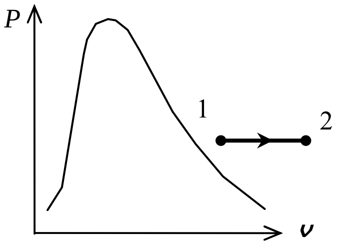


$$\left.\begin{array}{l} P_1 = 60\ \text{kPa} \\ T_1 = -20°\text{C} \end{array}\right\} v_1 = 0.33608\ \text{m}^3/\text{kg}\ \ (\text{Table A-13})$$

and the initial volume is

$$V_1 = m v_1 = (0.100\ \text{kg})(0.33608\ \text{m}^3/\text{kg}) = 0.033608\ \text{m}^3$$

At the final state, we have



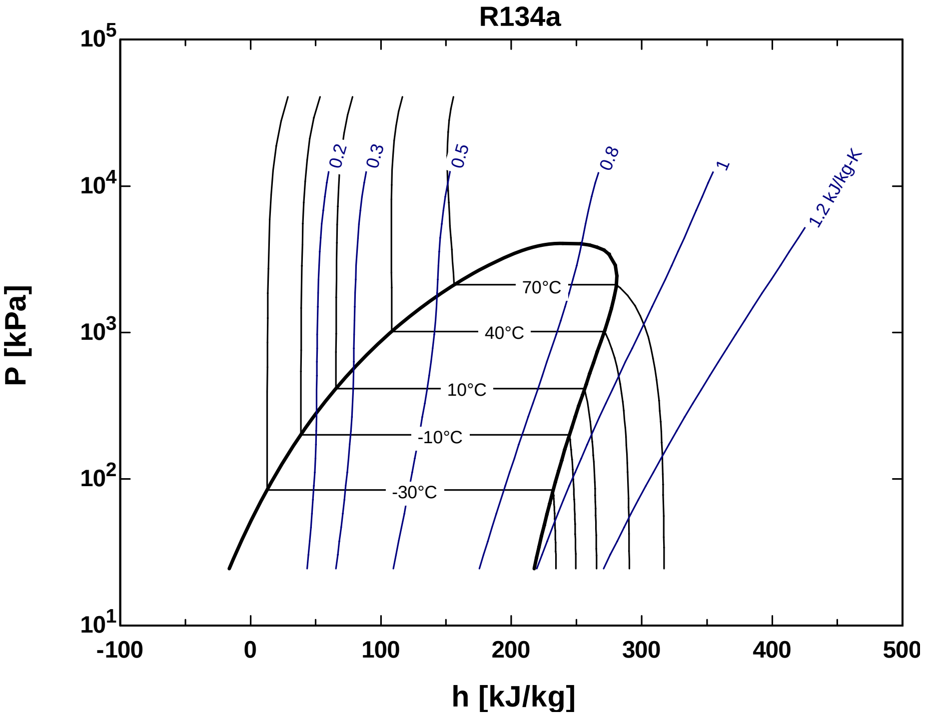
$$\left.\begin{array}{l} P_2 = 60\ \text{kPa} \\ T_2 = 100°\text{C} \end{array}\right\} v_2 = 0.50410\ \text{m}^3/\text{kg}\ \ (\text{Table A-13})$$

$$V_2 = m v_2 = (0.100\ \text{kg})(0.50410\ \text{m}^3/\text{kg}) = 0.050410\ \text{m}^3$$

The volume change is then

$$\Delta V = V_2 - V_1 = 0.050410 - 0.033608 = \mathbf{0.0168\ m^3}$$

3-69 EES The Pessure-Enthalpy diagram of R-134a showing some constant-temperature and constant-entropy lines are obtained using Property Plot feature of EES.



Ideal Gas

3-70C 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.

3-71C 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.

3-72C 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.

3-73C 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.

3-74E The specific volume of oxygen at a specified state is to be determined.

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

Properties The gas constant of oxygen is $R = 0.3353$ psia·ft^3/lbm·R (Table A-1E).

Analysis According to the ideal gas equation of state,

$$v = \frac{RT}{P} = \frac{(0.3353\,\text{psia}\cdot\text{ft}^3/\text{lbm}\cdot\text{R})(80+460\,\text{R})}{25\,\text{psia}} = \mathbf{7.242\ ft^3/lbm}$$

3-75 The pressure in a container that is filled with air is to be determined.

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

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

Analysis The definition of the specific volume gives

$$v = \frac{V}{m} = \frac{0.100\,\text{m}^3}{1\,\text{kg}} = 0.100\,\text{m}^3/\text{kg}$$

Using the ideal gas equation of state, the pressure is

$$P = \frac{RT}{v} = \frac{(0.287\,\text{kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(27+273\,\text{K})}{0.100\,\text{m}^3/\text{kg}} = \mathbf{861\,kPa}$$

3-76E The volume of a tank that is filled with argon at a specified state is to be determined.

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

Properties The gas constant of argon is R = 0.2686 psia·ft^3/lbm·R (Table A-1E)

Analysis According to the ideal gas equation of state,

$$V = \frac{mRT}{P} = \frac{(1\,\text{lbm})(0.2686\,\text{psia}\cdot\text{ft}^3/\text{lbm}\cdot\text{R})(100+460\,\text{R})}{200\,\text{psia}} = \mathbf{0.7521\,ft^3}$$

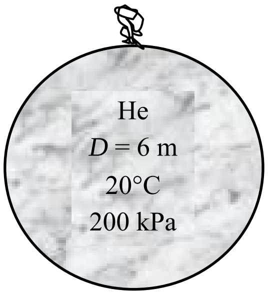
3-77 A balloon is filled with helium gas. The mole number and the mass of helium in the balloon are to be determined.

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

Properties The universal gas constant is R_u = 8.314 kPa.m^3/kmol.K. The molar mass of helium is 4.0 kg/kmol (Table A-1).

Analysis The volume of the sphere is

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



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

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

Then the mass of He can be determined from

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

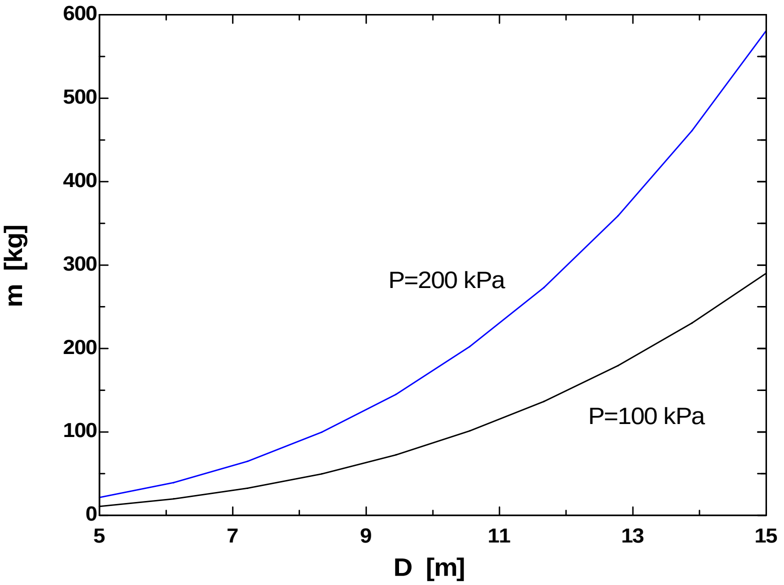
3-78 EES Problem 3-77 is to be reconsidered. The effect of the balloon diameter on the mass of helium contained in the balloon is to be determined for the pressures of (a) 100 kPa and (b) 200 kPa as the diameter varies from 5 m to 15 m. The mass of helium is to be plotted against the diameter for both cases.

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

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

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

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



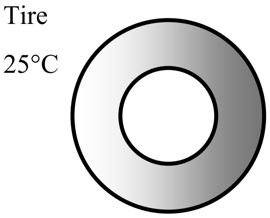
3-79 An automobile tire is inflated with air. The pressure rise of air in the tire when the tire is heated and the amount of air that must be bled off to reduce the temperature to the original value are to be determined.

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

Properties The gas constant of air is $R = 0.287$ kPa.m^3/kg.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

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

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

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

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

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

3-80 Two rigid tanks connected by a valve to each other contain air at specified conditions. The volume of the second tank and the final equilibrium pressure when the valve is opened are to be determined.

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

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

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

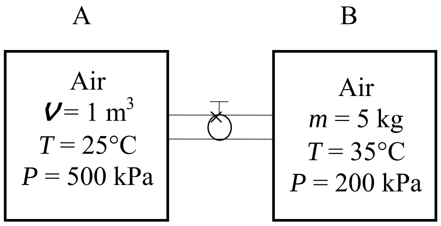
$$V_B = \left(\frac{m_1 R T_1}{P_1}\right)_B = \frac{(5\text{ kg})(0.287\text{ kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(308\text{ K})}{200\text{ kPa}} = \mathbf{2.21\ m^3}$$

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

Thus,

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

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



Then the final equilibrium pressure becomes

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

3-81E The validity of a statement that tires lose roughly 1 psi of pressure for every 10°F drop in outside temperature is to be investigated.

Assumptions **1**The air in the tire is an ideal gas. **2** The volume of air in the tire is constant. **3** The tire is in thermal equilibrium with the outside air. **4** The atmospheric conditions are 70°F and 1 atm = 14.7 psia.

Analysis The pressure in a tire should be checked at least once a month when a vehicle has sat for at least one hour to ensure that the tires are cool. The recommended gage pressure in cool tires is typically above 30 psi. Taking the initial gage pressure to be 32 psi, the gage pressure after the outside temperature drops by 10°F is determined from the ideal gas relation to be

$$\frac{P_1 V}{T_1} = \frac{P_2 V}{T_2} \quad \to \quad P_2 = \frac{T_2}{T_1} P_1 = \frac{(60+460)\text{ R}}{(70+460)\text{ R}}(32 + 14.7\text{ psia}) = 45.8\text{ psia} = 31.1\text{ psig (gage)}$$

Then the drop in pressure corresponding to a drop of 10°F in temperature becomes

$$\Delta P = P_1 - P_2 = 32.0 - 31.1 = \mathbf{0.9\ psi}$$

which is sufficiently close to 1 psi. Therefore, the statement is **valid**.

Discussion Note that we used *absolute* temperatures and pressures in ideal gas calculations. Using gage pressures would result in pressure drop of 0.6 psi, which is considerably lower than 1 psi. Therefore, it is important to use absolute temperatures and pressures in the ideal gas relation.

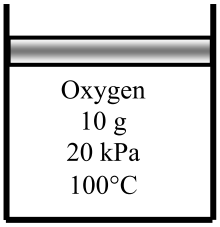
3-82 A piston-cylinder device containing oxygen is cooled. The change of the volume is to be determined.

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

Properties The gas constant of oxygen is $R = 0.2598$ kJ/kg·K (Table A-1).

Analysis According to the ideal gas equation of state, the initial volume of the oxygen is

$$V_1 = \frac{mRT_1}{P_1} = \frac{(0.010\,\text{kg})(0.2598\,\text{kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(100+273\,\text{K})}{20\,\text{kPa}} = 0.04845\,\text{m}^3$$



Similarly, the final volume is

$$V_2 = \frac{mRT_2}{P_2} = \frac{(0.010\,\text{kg})(0.2598\,\text{kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(0+273\,\text{K})}{20\,\text{kPa}} = 0.03546\,\text{m}^3$$

The change of volume is then

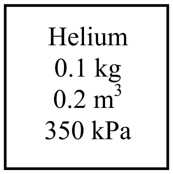
$$\Delta V = V_2 - V_1 = 0.03546 - 0.04845 = \mathbf{-0.013\,m^3}$$

3-83 A rigid vessel containing helium is heated. The temperature chang is to be determined.

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

Properties The gas constant of helium is $R = 2.0769$ kJ/kg·K (Table A-1).

Analysis According to the ideal gas equation of state, the initial temperature is



$$T_1 = \frac{P_1 V}{mR} = \frac{(350\,\text{kPa})(0.2\,\text{m}^3)}{(0.1\,\text{kg})(2.0769\,\text{kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})} = 337\,\text{K}$$

Since the specific volume remains constant, the ideal gas equation gives

$$v_1 = \frac{RT_1}{P_1} = v_2 = \frac{RT_2}{P_2} \longrightarrow T_2 = T_1\frac{P_2}{P_1} = (337\,\text{K})\frac{700\,\text{kPa}}{350\,\text{kPa}} = 674\,\text{K}$$

The temperature change is then

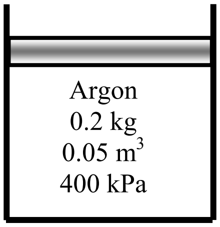
$$\Delta T = T_2 - T_1 = 674 - 337 = \mathbf{337\,K}$$

3-84 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 $R = 0.2081$ kJ/kg·K (Table A-1).

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



$$m = \frac{P_1\mathbf{V}_1}{RT} = \frac{P_2\mathbf{V}_2}{RT} \longrightarrow P_1\mathbf{V}_1 = P_2\mathbf{V}_2$$

which when solved for final pressure becomes

$$P_2 = P_1\frac{\mathbf{V}_1}{\mathbf{V}_2} = P_1\frac{\mathbf{V}_1}{2\mathbf{V}_1} = 0.5P_1 = 0.5(400\text{ kPa}) = \mathbf{200\text{ kPa}}$$

Compressibility Factor

3-85C It represent the deviation from ideal gas behavior. The further away it is from 1, the more the gas deviates from ideal gas behavior.

3-86C All gases have the same compressibility factor *Z* at the same reduced temperature and pressure.

3-87C 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.

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

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

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

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

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

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

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

H_2O
10 MPa
400°C

Thus,

$$v = Zv_{\text{ideal}} = (0.84)(0.03106 \text{ m}^3\text{/kg}) = \mathbf{0.02609 \ \ m^3/kg \ \ (1.2\% \ error)}$$

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

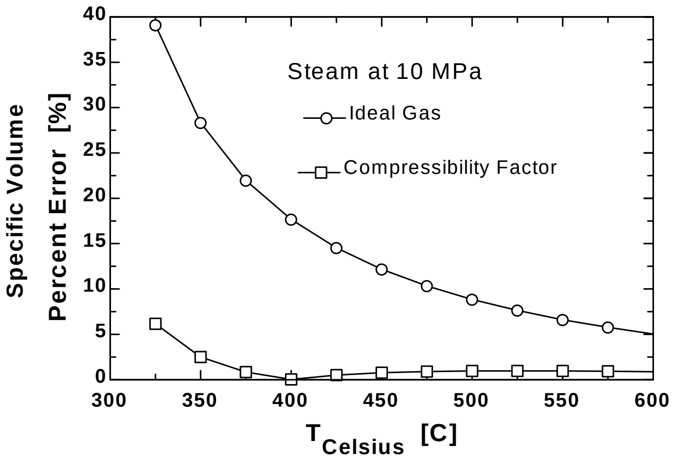
$$\left.\begin{aligned} P &= 10 \text{ MPa} \\ T &= 400°\text{C} \end{aligned}\right\} v = \mathbf{0.02644 \ \ m^3/kg}$$

3-89 EES Problem 3-88 is reconsidered. The problem is to be solved using the general compressibility factor feature of EES (or other) software. The specific volume of water for the three cases at 10 MPa over the temperature range of 325°C to 600°C in 25°C intervals is to be compared, and the %error involved in the ideal gas approximation is to be plotted against temperature.

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

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

Error$_{comp}$ [%]	Error$_{ideal\ gas}$ [%]	T$_{Celcius}$ [C]
6.088	38.96	325
2.422	28.2	350
0.7425	21.83	375
0.129	17.53	400
0.6015	14.42	425
0.8559	12.07	450
0.9832	10.23	475
1.034	8.755	500
1.037	7.55	525
1.01	6.55	550
0.9652	5.712	575
0.9093	5	600



3-90 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.

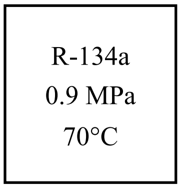
Properties The gas constant, the critical pressure, and the critical temperature of refrigerant-134a are, from Table A-1,

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

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

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

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



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

Thus,

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

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

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

3-91 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.

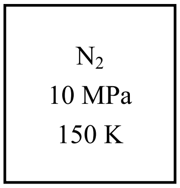
Properties The gas constant, the critical pressure, and the critical temperature of nitrogen are, from Table A-1,

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

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

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

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



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

Thus,

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

3-92 The specific volume of steam is to be determined using the ideal gas relation, the compressibility chart, and the steam tables. The errors involved in the first two approaches are also to be determined.

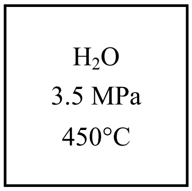
Properties The gas constant, the critical pressure, and the critical temperature of water are, from Table A-1,

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

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

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

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



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

Thus,

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

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

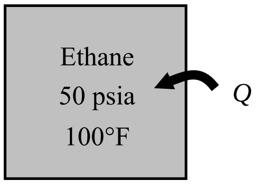
$$\left.\begin{array}{l} P = 3.5 \text{ MPa} \\ T = 450°\text{C} \end{array}\right\} v = \mathbf{0.09196\ m^3/kg}$$

3-93E 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,

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

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



$$\left.\begin{aligned} T_{R1} &= \frac{T_1}{T_{\text{cr}}} = \frac{560\,\text{R}}{549.8\,\text{R}} = 1.019 \\ P_{R1} &= \frac{P_1}{P_{\text{cr}}} = \frac{50\,\text{psia}}{708\,\text{psia}} = 0.0706 \end{aligned}\right\} Z_1 = 0.977$$

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

$$v_1 = v_2 = \frac{Z_1RT_1}{P_1} = \frac{(0.977)(0.3574\,\text{psia}\cdot\text{ft}^3/\text{lbm}\cdot\text{R})(560\,\text{R})}{50\,\text{psia}} = 3.911\,\text{ft}^3/\text{lbm}$$

At the final state,

$$\left.\begin{aligned} T_{R2} &= \frac{T_2}{T_{\text{cr}}} = \frac{1060\,\text{R}}{549.8\,\text{R}} = 1.928 \\ v_{R2} &= \frac{v_{2,\text{actual}}}{RT_{\text{cr}}/P_{\text{cr}}} = \frac{3.911\text{ft}^3/\text{lbm}}{(0.3574\,\text{psia}\cdot\text{ft}^3/\text{lbm}\cdot\text{R})(549.8\,\text{R})/(708\,\text{psia})} = 14.09 \end{aligned}\right\} Z_2 = 1.0$$

Thus,

$$P_2 = \frac{Z_2RT_2}{v_2} = \frac{(1.0)(0.3574\,\text{psia}\cdot\text{ft}^3/\text{lbm}\cdot\text{R})(1060\,\text{R})}{3.911\,\text{ft}^3/\text{lbm}} = \mathbf{96.9\,psia}$$

3-94 Ethylene is heated at constant pressure. The specific volume change of ethylene is to be determined using the compressibility chart.

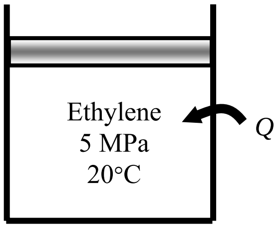
Properties The gas constant, the critical pressure, and the critical temperature of ethane are, from Table A-1,

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

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

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

$$\left.\begin{aligned} T_{R2} &= \frac{T_2}{T_{\text{cr}}} = \frac{473\ \text{K}}{282.4\ \text{KR}} = 1.675 \\ P_{R2} &= P_{R1} = 0.977 \end{aligned}\right\} Z_1 = 0.961$$



The specific volume change is

$$\begin{aligned} \Delta v &= \frac{R}{P}(Z_2T_2 - Z_1T_1) \\ &= \frac{0.2964\ \text{kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K}}{5000\ \text{kPa}}\left[(0.961)(473\ \text{K}) - (0.56)(293\ \text{K})\right] \\ &= \mathbf{0.0172\ m^3/kg} \end{aligned}$$

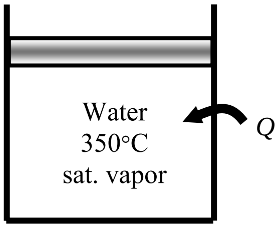
3-95 Water vapor is heated at constant pressure. The final temperature is to be determined using ideal gas equation, the compressibility charts, and the steam tables.

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

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

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

$$T_2 = T_1 \frac{v_2}{v_1} = (350 + 273\text{ K})(2) = \mathbf{1246\ K}$$



(*b*) The pressure of the steam is

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

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

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

At the final state,

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

Thus,

$$T_2 = \frac{P_2 v_2}{Z_2 R} = \frac{P_2}{Z_2}\frac{v_{R2} T_{cr}}{P_{cr}} = \frac{16{,}529\text{ kPa}}{0.88}\frac{(1.50)(647.1\text{ K})}{22{,}060\text{ kPa}} = \mathbf{826\ K}$$

(*c*) From the superheated steam table,

$$\left.\begin{aligned} T_1 &= 350°\text{C} \\ x_1 &= 1 \end{aligned}\right\} v_1 = 0.008806\text{ m}^3/\text{kg} \qquad \text{(Table A-4)}$$

$$\left.\begin{aligned} P_2 &= 16{,}529\text{ kPa} \\ v_2 &= 2v_1 = 0.01761\text{ m}^3/\text{kg} \end{aligned}\right\} T_2 = 477°\text{C} = \mathbf{750\ K} \qquad \text{(from Table A-6 or EES)}$$

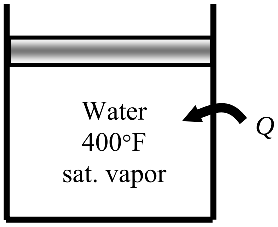
3-96E Water vapor is heated at constant pressure. The final temperature is to be determined using ideal gas equation, the compressibility charts, and the steam tables.

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

$R = 0.5956$ psia·ft^3/lbm·R, $T_{cr} = 1164.8$ R, $P_{cr} = 3200$ psia

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

$$T_2 = T_1 \frac{v_2}{v_1} = (400 + 460\text{ R})(2) = \mathbf{1720\ R}$$



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

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

$$v_1 = v_{\text{g@400°F}} = 1.8639\text{ ft}^3/\text{lbm}$$

$$v_2 = 2v_1 = 3.7278\text{ ft}^3/\text{lbm}$$

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

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

Thus,

$$T_2 = \frac{P_2 v_2}{Z_2 R} = \frac{(247.26\text{ psia})(3.7278\text{ ft}^3/\text{lbm})}{(0.985)(0.5956\text{ psia}\cdot\text{ft}^3/\text{lbm}\cdot\text{R})} = \mathbf{1571\,R}$$

(*c*) From the superheated steam table,

$$\left.\begin{aligned} P_2 &= 247.26\text{ psia} \\ v_2 &= 3.7278\text{ ft}^3/\text{lbm} \end{aligned}\right\} T_2 = 1100°\text{F} = \mathbf{1560\ R} \qquad \text{(from Table A-6E or EES)}$$

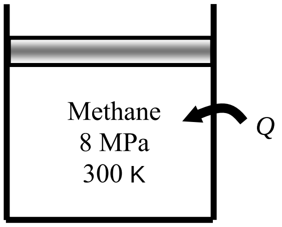
3-97 Methane is heated at constant pressure. The final temperature is to be determined using ideal gas equation and the compressibility charts.

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

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

Analysis From the ideal gas equation,

$$T_2 = T_1 \frac{v_2}{v_1} = (300\text{ K})(1.5) = \mathbf{450\ K}$$



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

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

At the final state,

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

Thus,

$$T_2 = \frac{P_2 v_2}{Z_2 R} = \frac{P_2}{Z_2}\frac{v_{R2} T_{cr}}{P_{cr}} = \frac{8000\text{ kPa}}{0.975}\frac{(1.2)(191.1\text{ K})}{4640\text{ kPa}} = \mathbf{406\ K}$$

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.

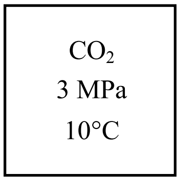
3-98 The percent error involved in treating CO$_2$ at a specified state as an ideal gas is to be determined.

Properties The critical pressure, and the critical temperature of CO$_2$ are, from Table A-1,

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

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

$$\left.\begin{aligned} P_R &= \frac{P}{P_{cr}} = \frac{3\text{ MPa}}{7.39\text{ MPa}} = 0.406 \\ T_R &= \frac{T}{T_{cr}} = \frac{283\text{ K}}{304.2\text{ K}} = 0.93 \end{aligned}\right\} Z = 0.80$$



Then the error involved in treating CO$_2$ as an ideal gas is

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

3-99 CO_2 gas flows through a pipe. The volume flow rate and the density at the inlet and the volume flow rate at the exit of the pipe are to be determined.

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

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

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

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

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

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

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

$$\left.\begin{array}{l} P_R = \dfrac{P_1}{P_{cr}} = \dfrac{3\text{ MPa}}{7.39\text{ MPa}} = 0.407 \\[2ex] T_{R,1} = \dfrac{T_1}{T_{cr}} = \dfrac{500\text{ K}}{304.2\text{ K}} = 1.64 \end{array}\right\} Z_1 = 0.9791$$

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

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

$$\rho_1 = \frac{P_1}{Z_1RT_1} = \frac{(3000\text{ kPa})}{(0.9791)(0.1889\text{ kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(500\text{ K})} = \mathbf{32.44\ kg/m^3}$$

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

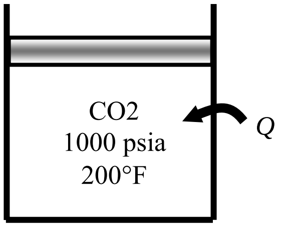
Other Equations of State

3-100C 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.

3-101E Carbon dioxide is heated in a constant pressure apparatus. The final volume of the carbon dioxide 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_2 are (Table A-1E)

$$R = 0.2438\ \text{psia·ft}^3\text{/lbm·R},\quad M = 44.01\ \text{lbm/lbmol}$$



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

$$V_2 = \frac{mRT_2}{P} = \frac{(1\,\text{lbm})(0.2438\,\text{psia}\cdot\text{ft}^3/\text{lbm}\cdot\text{R})(1260\,\text{R})}{1000\,\text{psia}} = \mathbf{0.3072\ ft^3}$$

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

$$P_2 = \frac{R_uT_2}{\bar{v}_2} + \left(B_0R_uT_2 - A_0 - \frac{C_0}{T_2^2}\right)\frac{1}{\bar{v}^2} + \frac{bR_uT_2 - a}{\bar{v}^3} + \frac{a\alpha}{\bar{v}^6} + \frac{c}{\bar{v}^3T_2^2}\left(1+\frac{\gamma}{\bar{v}^2}\right)\exp(-\gamma/\bar{v}^2)$$

$$6895 = \frac{(8.314)(700)}{\bar{v}_2} + \left(0.04991\times 8.314\times 700 - 277.30 - \frac{1.404\times 10^7}{700^2}\right)\frac{1}{\bar{v}^2} + \frac{0.007210\times 8.314\times 700 - 13.86}{\bar{v}^3}$$
$$+\frac{13.86\times 8.470\times 10^{-5}}{\bar{v}^6} + \frac{1.511\times 10^6}{\bar{v}^3(700)^2}\left(1+\frac{0.00539}{\bar{v}^2}\right)\exp(-0.00539/\bar{v}^2)$$

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

$$\bar{v}_2 = 0.8477\,\text{m}^3/\text{kmol}$$

Then,

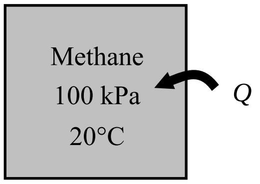
$$v_2 = \frac{\bar{v}_2}{M} = \frac{0.8477\,\text{m}^3/\text{kmol}}{44.01\,\text{kg/kmol}} = 0.01926\,\text{m}^3/\text{kg}$$

$$V_2 = mv_2 = (1/2.2046\,\text{kg})(0.01927\,\text{m}^3/\text{kg}) = 0.008741\,\text{m}^3$$

$$= (0.008741\,\text{m}^3)\left(\frac{35.315\,\text{ft}^3}{1\,\text{m}^3}\right) = \mathbf{0.3087\ ft^3}$$

3-102 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,



$$P_2 = P_1 \frac{T_2}{T_1} = (100\text{ kPa})\frac{673\text{ K}}{293\text{ K}} = \mathbf{229.7\ kPa}$$

The specific molar volume of the methane is

$$\bar{v}_1 = \bar{v}_2 = \frac{R_u T_1}{P_1} = \frac{(8.314\text{ kPa}\cdot\text{m}^3/\text{kmol}\cdot\text{K})(293\text{ K})}{100\text{ kPa}} = 24.36\text{ m}^3/\text{kmol}$$

(*b*) The specific molar volume of the methane is

$$\bar{v}_1 = \bar{v}_2 = \frac{R_u T_1}{P_1} = \frac{(8.314\text{ kPa}\cdot\text{m}^3/\text{kmol}\cdot\text{K})(293\text{ K})}{100\text{ kPa}} = 24.36\text{ m}^3/\text{kmol}$$

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

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

$$= \frac{(8.314)(673)}{24.36} + \left(0.04260\times 8.314\times 673 - 187.91 - \frac{2.286\times 10^6}{673^2}\right)\frac{1}{24.36^2} + \frac{0.003380\times 8.314\times 673 - 5.00}{24.36^3}$$

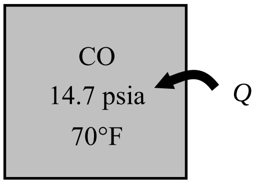
$$+ \frac{5.00\times 1.244\times 10^{-4}}{24.36^6} + \frac{2.578\times 10^5}{24.36^3(673)^2}\left(1 + \frac{0.0060}{24.36^2}\right)\exp(-0.0060/24.36^2)$$

$$= \mathbf{229.8\,kPa}$$

3-103E 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)

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



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

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

The specific molar volume of the CO in SI units is

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

(*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

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

The pressure in English unit is

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

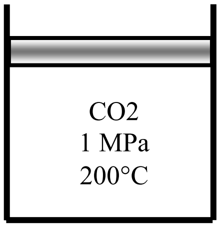
3-104 Carbon dioxide is compressed in a piston-cylinder device in a polytropic process. The final temperature is to be determined using the ideal gas and van der Waals equations.

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

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

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

$$\boldsymbol{v}_1 = \frac{RT_1}{P_1} = \frac{(0.1889\,\text{kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(473\,\text{K})}{1000\,\text{kPa}} = 0.08935\,\text{m}^3/\text{kg}$$



According to process specification,

$$\boldsymbol{v}_2 = \boldsymbol{v}_1\left(\frac{P_1}{P_2}\right)^{1/n} = (0.08935\,\text{m}^3/\text{kg})\left(\frac{1000\,\text{kPa}}{3000\,\text{kPa}}\right)^{1/1.2} = 0.03577\,\text{m}^3/\text{kg}$$

The final temperature is then

$$T_2 = \frac{P_2\boldsymbol{v}_2}{R} = \frac{(3000\,\text{kPa})(0.03577\,\text{m}^3/\text{kg})}{0.1889\,\text{kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K}} = \mathbf{568\,K}$$

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

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

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

Applying the van der Waals equation to the initial state,

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

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

Solving this equation by trial-error or by EES gives

$$\boldsymbol{v}_1 = 0.08821\,\text{m}^3/\text{kg}$$

According to process specification,

$$\boldsymbol{v}_2 = \boldsymbol{v}_1\left(\frac{P_1}{P_2}\right)^{1/n} = (0.08821\,\text{m}^3/\text{kg})\left(\frac{1000\,\text{kPa}}{3000\,\text{kPa}}\right)^{1/1.2} = 0.03531\,\text{m}^3/\text{kg}$$

Applying the van der Waals equation to the final state,

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

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

Solving for the final temperature gives

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

3-105E The temperature of R-134a in a tank at a specified state is to be determined using the ideal gas relation, the van der Waals equation, and the refrigerant tables.

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

$$R = 0.1052 \text{ psia·ft}^3\text{/lbm·R}, \qquad T_{\text{cr}} = 673.6 \text{ R}, \qquad P_{\text{cr}} = 588.\ 7 \text{ psia}$$

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

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

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

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

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

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

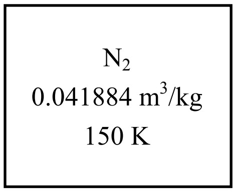
(c) From the superheated refrigerant table (Table A-13E),

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

3-106 [*Also solved by EES on enclosed CD***]** The pressure of nitrogen in a tank at a specified state is to be determined using the ideal gas relation and the Beattie-Bridgeman equation. The error involved in each case is to be determined.

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

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



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

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

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

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

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

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

since $\bar{v} = Mv = (28.013 \text{ kg/kmol})(0.041884 \text{ m}^3\text{/kg}) = 1.1733 \text{ m}^3\text{/kmol}$.

Substituting,

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

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

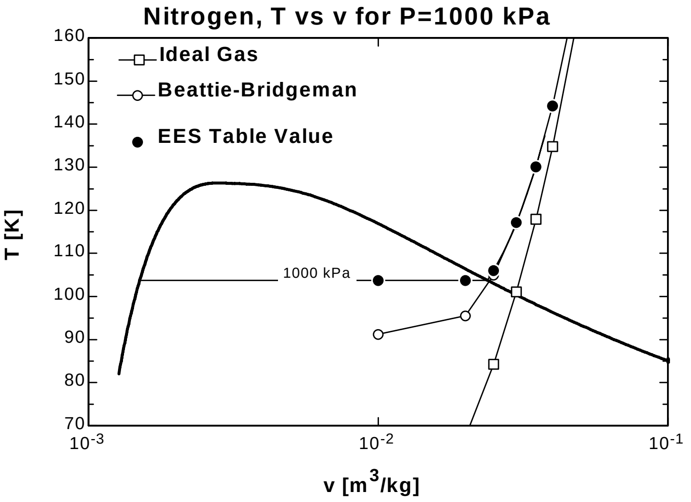
3-107 EES Problem 3-106 is reconsidered. Using EES (or other) software, the pressure results of the ideal gas and Beattie-Bridgeman equations with nitrogen data supplied by EES are to be compared. The temperature is to be plotted versus specific volume for a pressure of 1000 kPa with respect to the saturated liquid and saturated vapor lines of nitrogen over the range of 110 K < *T* < 150 K.

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

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

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

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



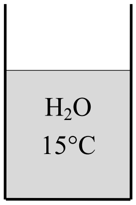
Special Topic: Vapor Pressure and Phase Equilibrium

3-108 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,



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

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

$$P_{v,\,\text{air}} = \phi P_{\text{sat @ }T_\text{air}} = \phi P_{\text{sat@20°C}} = (0.6)(2.339\,\text{kPa}) = \mathbf{1.404\ kPa}$$

3-109 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

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

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

3-110 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

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

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

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

3-111 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 4.247 kPa at 30°C (Table A-4).

Analysis The vapor pressures in the two rooms are

Room 1: $$P_{v1} = \phi_1 P_{\text{sat}@T_1} = \phi_1 P_{\text{sat}@30°\text{C}} = (0.4)(4.247\text{ kPa}) = \mathbf{1.699\ kPa}$$

Room 2: $$P_{v2} = \phi_2 P_{\text{sat}@T_2} = \phi_2 P_{\text{sat}@20°\text{C}} = (0.7)(2.339\text{ kPa}) = \mathbf{1.637\ kPa}$$

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

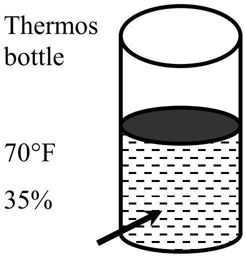
3-112E A thermos bottle half-filled with water is left open to air in a room at a specified temperature and pressure. The temperature of water when phase equilibrium is established is to be determined.

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

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



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

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

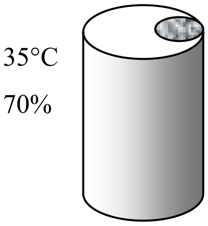
Discussion Note that the water temperature drops to 41°F in an environment at 70°F when phase equilibrium is established.

3-113 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

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



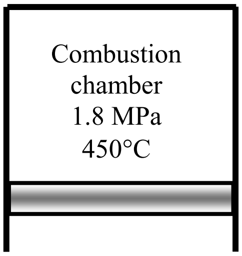
The saturation temperature corresponding to this pressure (called the dew-point temperature) is

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

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**.

Review Problems

3-114 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.

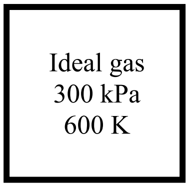
Analysis The final pressure may be determined from the ideal gas relation

$$P_2 = \frac{T_2}{T_1} P_1 = \left(\frac{1300 + 273\text{ K}}{450 + 273\text{ K}}\right)(1800\text{ kPa}) = \mathbf{3916\ kPa}$$

3-115 A rigid tank contains an ideal gas at a specified state. The final temperature is to be determined for two different processes.

Analysis (*a*) The first case is a constant volume process. When half of the gas is withdrawn from the tank, the final temperature may be determined from the ideal gas relation as

$$T_2 = \frac{m_1}{m_2}\frac{P_2}{P_1} T_1 = (2)\left(\frac{100\text{ kPa}}{300\text{ kPa}}\right)(600\text{ K}) = \mathbf{400\ K}$$

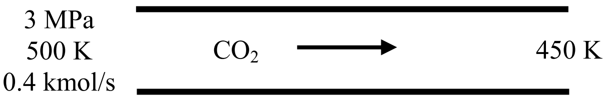


(*b*) The second case is a constant volume and constant mass process. The ideal gas relation for this case yields

$$P_2 = \frac{T_2}{T_1} P_1 = \left(\frac{400\text{ K}}{600\text{ K}}\right)(300\text{ kPa}) = \mathbf{200\ kPa}$$

3-116 Carbon dioxide flows through a pipe at a given state. The volume and mass flow rates and the density of CO_2 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



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

$$\dot{m}_1 = \frac{P_1\dot{V}_1}{RT_1} = \frac{(3000\text{ kPa})(0.5543\text{ m}^3/s)}{(0.1889\text{ kPa.m}^3\text{/kg.K})(500\text{ K})} = \mathbf{17.60\ kg/s}$$

The density is

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

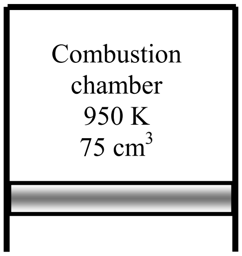
(b) The volume flow rate at the exit is

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

3-117 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

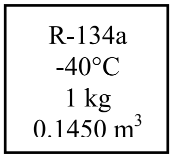


$$\frac{m_1}{m_2} = \frac{\text{AF}}{\text{AF}+1} = \frac{22}{22+1} = \frac{22}{23}$$

The final temperature may be determined from ideal gas relation

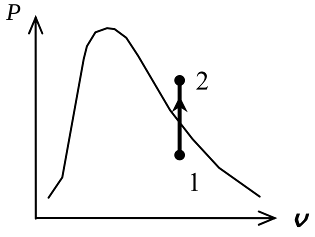
$$T_2 = \frac{m_1}{m_2}\frac{V_2}{V_1}T_1 = \left(\frac{22}{23}\right)\left(\frac{150\text{ cm}^3}{75\text{ cm}^3}\right)(950\text{ K}) = \mathbf{1817\ K}$$

3-118 A rigid container that is filled with R-13a is heated. The initial pressure and the final temperature are to be determined.



Analysis The initial specific volume is 0.1450 m^3/kg. Using this with the initial temperature reveals that the initial state is a mixture. The initial pressure is then the saturation pressure,

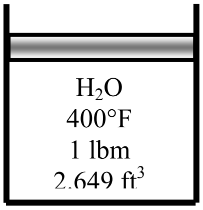
$$\left.\begin{array}{l} T_1 = -40°\text{C} \\ v_1 = 0.1450\ \text{m}^3/\text{kg} \end{array}\right\} P_1 = P_{\text{sat @ -40°C}} = \mathbf{51.25\ kPa}\ \ (\text{Table A-11})$$



This is a constant volume cooling process ($v = V/m$ = constant). The final state is superheated vapor and the final temperature is then

$$\left.\begin{array}{l} P_2 = 200\ \text{kPa} \\ v_2 = v_1 = 0.1450\ \text{m}^3/\text{kg} \end{array}\right\} T_2 = \mathbf{90°C}\ \ (\text{Table A-13})$$

3-119E A piston-cylinder device that is filled with water is cooled. The final pressure and volume of the water are to be determined.

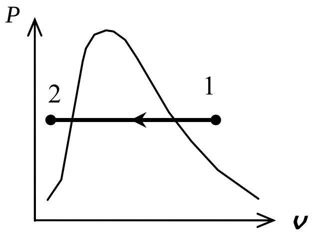


Analysis The initial specific volume is

$$v_1 = \frac{V_1}{m} = \frac{2.649\ \text{ft}^3}{1\ \text{lbm}} = 2.649\ \text{ft}^3/\text{lbm}$$

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

$$\left.\begin{array}{l} T_1 = 400°\text{F} \\ v_1 = 2.649\ \text{ft}^3/\text{lbm} \end{array}\right\} P_1 = P_2 = \mathbf{180\ psia}\ \ (\text{Table A-6E})$$



The saturation temperature at 180 psia is 373.1°F. Since the final temperature is less than this temperature, the final state is compressed liquid. Using the incompressible liquid approximation,

$$v_2 = v_{f\,@\,100°\text{F}} = 0.01613\ \text{ft}^3/\text{lbm}\ \ (\text{Table A-4E})$$

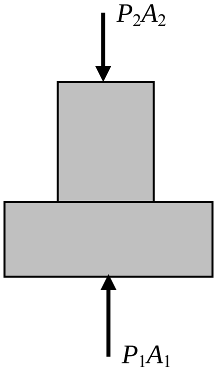
The final volume is then

$$V_2 = m v_2 = (1\ \text{lbm})(0.01613\ \text{ft}^3/\text{lbm}) = \mathbf{0.01613\ ft^3}$$

3-120 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 kJ/kg·K (Table A-1).



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

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

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,

$$V_1 = \frac{mRT}{P_1} = \frac{(1\ \text{kg})(2.0769\ \text{kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(200+273\ \text{K})}{248.8\ \text{kPa}} = \mathbf{3.95\ m^3}$$

3-121E 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 $R = 0.3704$ psia·ft^3/lbm·R (Table A-1E).

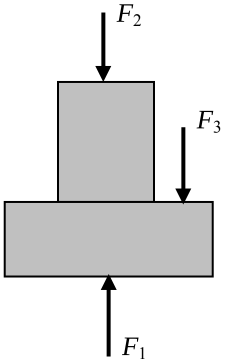
Analysis Since R-134a in chamber 2 is condensing, the pressure in this chamber is the saturation pressure,

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

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

$$F_2 + F_3 = F_1$$

$$P_2 A_2 + P_3 (A_1 - A_2) = P_1 A_1$$



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

$$P_1 = P_2 \left(\frac{D_2}{D_1}\right)^2 + P_3 \left[1 - \left(\frac{D_2}{D_1}\right)^2\right]$$

$$= (186.0\ \text{psia})\left(\frac{2}{3}\right)^2 + (30\ \text{psia})\left[1 - \left(\frac{2}{3}\right)^2\right]$$

$$= 99.33\ \text{psia}$$

According to the ideal gas equation of state,

$$V_1 = \frac{mRT}{P_1} = \frac{(0.5\ \text{lbm})(0.3704\ \text{psia}\cdot\text{ft}^3/\text{lbm}\cdot\text{R})(120+460\ \text{R})}{99.33\ \text{psia}} = \mathbf{1.08\ ft^3}$$

3-122E 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 $R = 0.3704$ psia·ft^3/lbm·R (Table A-1).

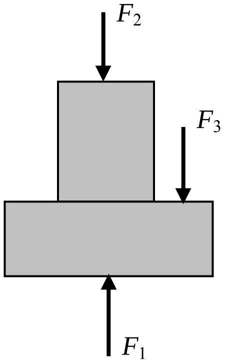
Analysis Since R-134a in chamber 2 is condensing, the pressure in this chamber is the saturation pressure,

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

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

$$F_2 + F_3 = F_1$$

$$P_2 A_2 + P_3 (A_1 - A_2) = P_1 A_1$$



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

$$P_1 = P_2 \left(\frac{D_2}{D_1}\right)^2 + P_3 \left[1 - \left(\frac{D_2}{D_1}\right)^2\right]$$

$$= (186.0 \text{ psia}) \left(\frac{2}{3}\right)^2 + (100 \text{ kPa}) \left[1 - \left(\frac{2}{3}\right)^2\right]$$

$$= 138.2 \text{ psia}$$

According to the ideal gas equation of state,

$$V_1 = \frac{mRT}{P_1} = \frac{(0.5 \text{ lbm})(0.3704 \text{ psia} \cdot \text{ft}^3/\text{lbm} \cdot \text{R})(120 + 460 \text{ R})}{138.2 \text{ psia}} = 0.777 \text{ ft}^3$$

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

$$\Delta V = V_2 - V_1 = 1.08 - 0.777 = \mathbf{0.303 \text{ ft}^3}$$

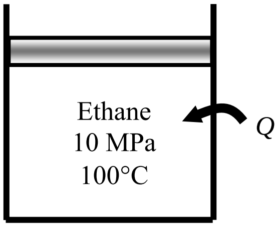
3-123 Ethane is heated at constant pressure. The final temperature is to be determined using ideal gas equation and the compressibility charts.

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

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

Analysis From the ideal gas equation,

$$T_2 = T_1 \frac{\boldsymbol{v}_2}{\boldsymbol{v}_1} = (373 \text{ K})(1.6) = \mathbf{596.8\ K}$$



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

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

At the final state,

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

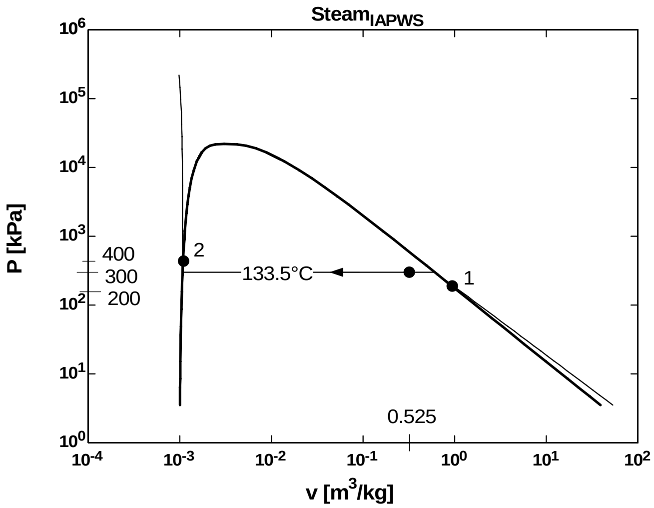
Thus,

$$T_2 = \frac{P_2 \boldsymbol{v}_2}{Z_2 R} = \frac{P_2}{Z_2} \frac{\boldsymbol{v}_{R2} T_{cr}}{P_{cr}} = \frac{10{,}000 \text{ kPa}}{0.83} \frac{(0.56)(305.5 \text{ K})}{4480 \text{ kPa}} = \mathbf{460\ K}$$

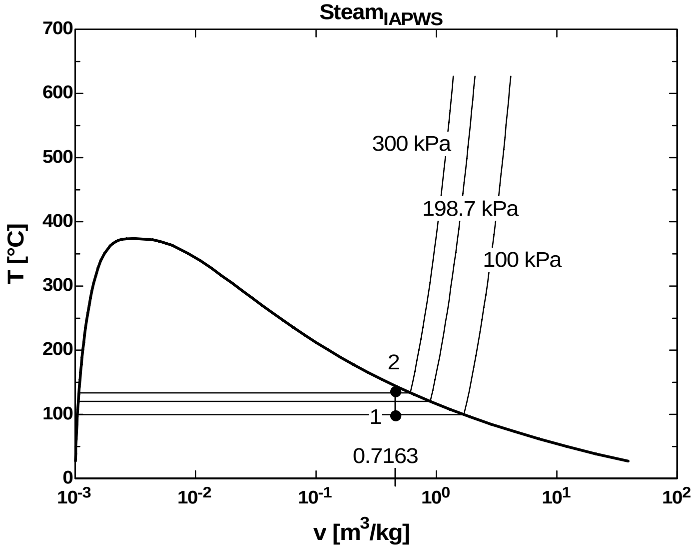
Of these two results, the accuracy of the second result is limited by the accuracy with which the charts may be read. Accepting the error associated with reading charts, the second temperature is the more accurate.

3-124

(*a*) On the P-v diagram, the constant temperature process through the state P= 300 kPa, v = 0.525 m^3/kg as pressure changes from P_1 = 200 kPa to P_2 = 400 kPa is to be sketched. The value of the temperature on the process curve on the P-v diagram is to be placed.



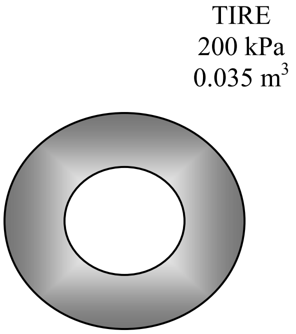
(*b*) On the T-v diagram the constant specific vol-ume process through the state T = 120°C, v = 0.7163 m^3/kg from P_1= 100 kPa to P_2 = 300 kPa is to be sketched.. For this data set, the temperature values at states 1 and 2 on its axis is to be placed. The value of the specific volume on its axis is also to be placed.



3-125 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

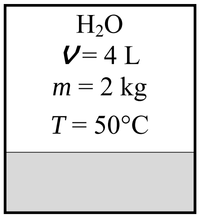
$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2} \rightarrow \frac{T_2}{T_1} = \frac{P_2}{P_1} = \frac{310 \text{ kPa}}{290 \text{ kPa}} = 1.069$$

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

3-126 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 ($v = V/m$ = 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 m^3/kg. Thus if the final specific volume is smaller than this value, the water will exist as a liquid, otherwise as a vapor.

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

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

3-127 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 kPa·m^3/kg·K (Table A-1).

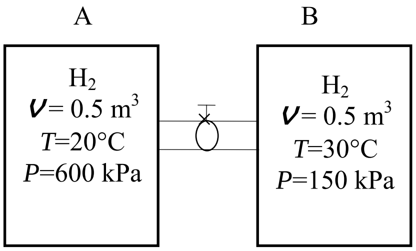
Analysis Let's call the first and the second tanks A and B. Treating H_2 as an ideal gas, the total volume and the total mass of H_2 are

$$V = V_A + V_B = 0.5 + 0.5 = 1.0 \text{ m}^3$$

$$m_A = \left(\frac{P_1 V}{RT_1}\right)_A = \frac{(600 \text{ kPa})(0.5 \text{ m}^3)}{(4.124 \text{ kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(293 \text{ K})} = 0.248 \text{ kg}$$

$$m_B = \left(\frac{P_1 V}{RT_1}\right)_B = \frac{(150 \text{ kPa})(0.5 \text{ m}^3)}{(4.124 \text{ kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(303 \text{ K})} = 0.060 \text{ kg}$$

$$m = m_A + m_B = 0.248 + 0.060 = 0.308\text{kg}$$



Then the final pressure can be determined from

$$P = \frac{mRT_2}{V} = \frac{(0.308 \text{ kg})(4.124 \text{ kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(288 \text{ K})}{1.0 \text{ m}^3} = \mathbf{365.8 \text{ kPa}}$$

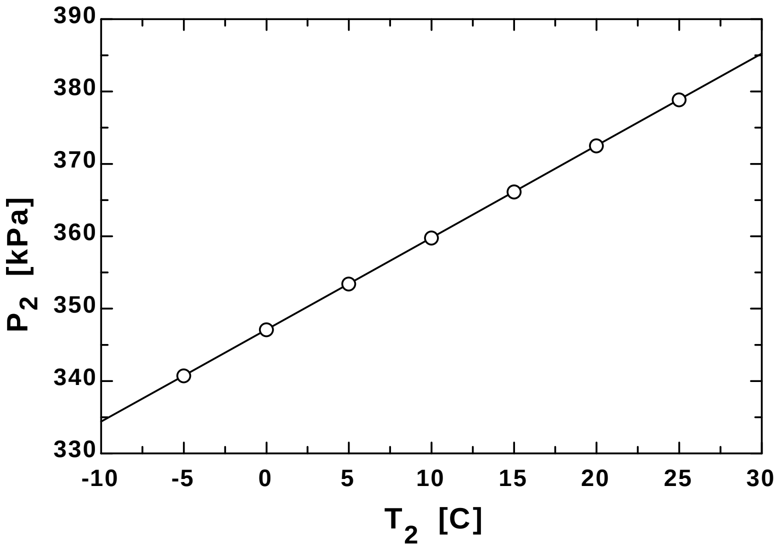
3-128 EES Problem 3-127 is reconsidered. The effect of the surroundings temperature on the final equilibrium pressure in the tanks is to be investigated. The final pressure in the tanks is to be plotted versus the surroundings temperature, and the results are to be discussed.

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=600 [kPa]
V_B=0.5 [m^3]
T_B=30 [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_2 [kPa]	T_2 [C]
334.4	-10
340.7	-5
347.1	0
353.5	5
359.8	10
366.2	15
372.5	20
378.9	25
385.2	30



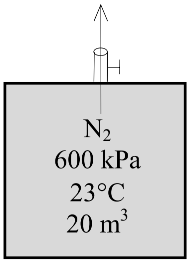
3-129 A large tank contains nitrogen at a specified temperature and pressure. Now some nitrogen is allowed to escape, and the temperature and pressure of nitrogen drop to new values. The amount of nitrogen that has escaped is to be determined.

Properties The gas constant for nitrogen is 0.2968 kPa·m^3/kg·K (Table A-1).

Analysis Treating N_2 as an ideal gas, the initial and the final masses in the tank are determined to be

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

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



Thus the amount of N_2 that escaped is

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

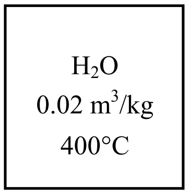
3-130 The temperature of steam in a tank at a specified state is to be determined using the ideal gas relation, the generalized chart, and the steam tables.

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

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

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

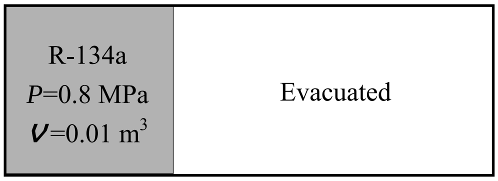
(*c*) From the superheated steam table,

$$\left.\begin{aligned} T &= 400°\text{C} \\ v &= 0.02\text{ m}^3/\text{kg} \end{aligned}\right\} P = \mathbf{12{,}576\text{ kPa}} \qquad \text{(from EES)}$$

3-131 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

$$m = \frac{V_1}{v_1} = \frac{0.01\ \text{m}^3}{0.0008458\ \text{m}^3/\text{kg}} = 11.82\ \text{kg}$$



since

$$v_1 = v_{f@0.8\text{MPa}} = 0.0008458\ \text{m}^3/\text{kg}$$

At the final state (Table A-13),

$$\left.\begin{array}{l} P_2 = 400\ \text{kPa} \\ T_2 = 20°\text{C} \end{array}\right\} v_2 = 0.05421\ \text{m}^3/\text{kg}$$

Thus, $V_{\text{tank}} = V_2 = m v_2 = (11.82\ \text{kg})(0.05421\ \text{m}^3/\text{kg}) = \mathbf{0.641\ m^3}$

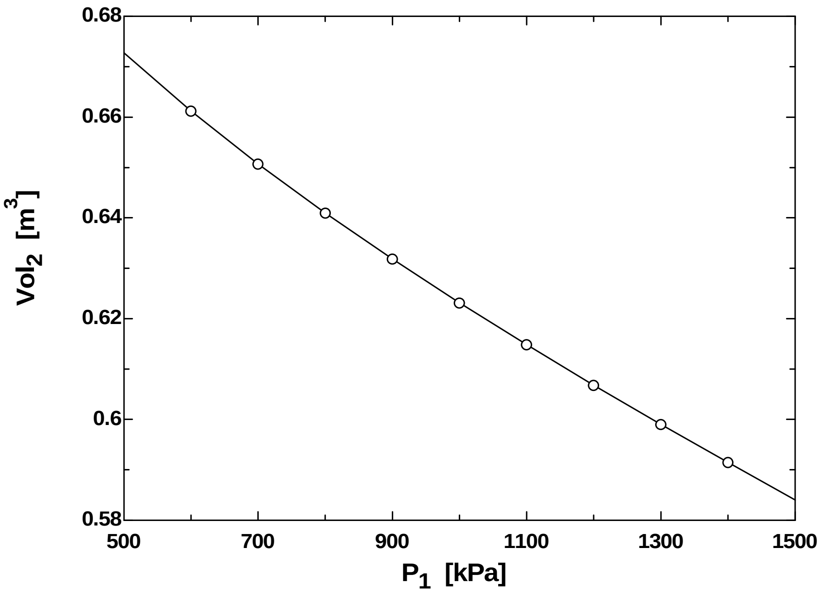
3-132 EES Problem 3-131 is reconsidered. The effect of the initial pressure of refrigerant-134 on the volume of the tank is to be investigated as the initial pressure varies from 0.5 MPa to 1.5 MPa. The volume of the tank is to be plotted versus the initial pressure, and the results are to be discussed.

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

```
"Given Data"
x_1=0.0
Vol_1=0.01[m^3]
P_1=800 [kPa]
T_2=20 [C]
P_2=400 [kPa]

"Solution"
v_1=volume(R134a,P=P_1,x=x_1)
Vol_1=m*v_1
v_2=volume(R134a,P=P_2,T=T_2)
Vol_2=m*v_2
```

P_1 [kPa]	Vol_2 [m^3]	m [kg]
500	0.6727	12.41
600	0.6612	12.2
700	0.6507	12
800	0.641	11.82
900	0.6318	11.65
1000	0.6231	11.49
1100	0.6148	11.34
1200	0.6068	11.19
1300	0.599	11.05
1400	0.5914	10.91
1500	0.584	10.77

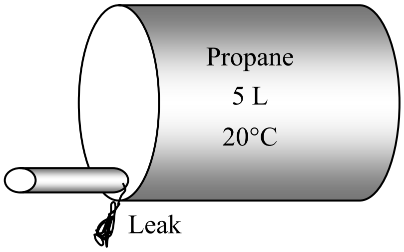


3-133 A propane tank contains 5 L of liquid propane at the ambient temperature. Now a leak develops at the top of the tank and propane starts to leak out. The temperature of propane when the pressure drops to 1 atm and the amount of heat transferred to the tank by the time the entire propane in the tank is vaporized are to be determined.

Properties The properties of propane at 1 atm are $T_{\text{sat}} = -42.1°\text{C}$, $\rho = 581\ \text{kg/m}^3$, and $h_{\text{fg}} = 427.8$ 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,

$$T = T_{\text{sat @1 atm}} = \mathbf{-42.1°C}$$



The initial mass of liquid propane is

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

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

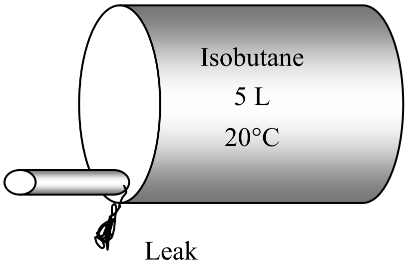
$$Q_{\text{absorbed}} = mh_{fg} = (2.905\ \text{kg})(427.8\ \text{kJ/kg}) = \mathbf{1243\ kJ}$$

3-134 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 $T_{\text{sat}} = -11.7°\text{C}$, $\rho = 593.8\ \text{kg/m}^3$, and $h_{\text{fg}} = 367.1$ 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,

$$T = T_{\text{sat @1 atm}} = \mathbf{-11.7°C}$$



The initial mass of liquid isobutane is

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

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

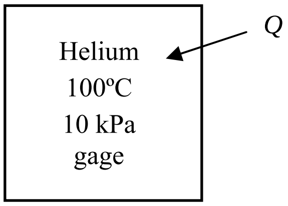
$$Q_{\text{absorbed}} = mh_{fg} = (2.969\ \text{kg})(367.1\ \text{kJ/kg}) = \mathbf{1090\ kJ}$$

3-135 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



$$P_2 = P_1 \frac{T_2}{T_1} = (10+100\,\text{kPa})\frac{(300+273)\text{K}}{(100+273)\text{K}} = 169.0\,\text{kPa}$$

Then the gage pressure becomes

$$P_{\text{gage},2} = P_2 - P_{\text{atm}} = 169.0 - 100 = \mathbf{69.0\,kPa}$$

3-136 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

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

Expanding the last term in a series gives

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

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

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

The virial equation of state is

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

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

$$a(T) = R_u T B_0 - A_0 - C_0/T^2$$
$$b(T) = bR_u T - a$$
$$c(T) = 0$$
$$d(T) = c(1+\gamma)/T^2$$
$$e(T) = a\alpha$$
$$f(T) = c\gamma(1+\gamma)/T^2$$
$$g(T) = 0$$
$$h(T) = \frac{1}{2!}\frac{c\gamma^2(1+\gamma)}{T^2}$$

3-137 The specific volume of oxygen at a given state is to be determined using the ideal gas relation, the Beattie-Bridgeman equation, and the compressibility factor.

Properties The properties of oxygen are (Table A-1)

$$R = 0.2598\ \text{kPa·m}^3/\text{kg·K},\quad M = 31.999\ \text{kg/kmol},\quad T_{\text{cr}} = 154.8\ \text{K},\qquad P_{\text{cr}} = 5.08\ \text{MPa}$$

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

$$v = \frac{RT}{P} = \frac{(0.2598\,\text{kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(293\,\text{K})}{4000\,\text{kPa}} = \mathbf{0.01903\ m^3/kg}$$

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

$$A = A_o\left(1-\frac{a}{\bar{v}}\right) = 151.0857\left(1-\frac{0.02562}{\bar{v}}\right)$$

$$B = B_o\left(1-\frac{b}{\bar{v}}\right) = 0.04624\left(1-\frac{0.004208}{\bar{v}}\right)$$

$$c = 4.80\times10^4\,\text{m}^3\cdot\text{K}^3/\text{kmol}$$

Oxygen
4 MPa, 20°C

Substituting these coefficients into the Beattie-Bridgeman equation

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

and solving using an equation solver such as EES gives

$$\bar{v} = 0.5931\,\text{m}^3/\text{kmol}$$

and

$$v = \frac{\bar{v}}{M} = \frac{0.5931\,\text{m}^3/\text{kmol}}{31.999\,\text{kg/kmol}} = \mathbf{0.01853\ m^3/kg}$$

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

$$\left.\begin{aligned} T_R &= \frac{T}{T_{\text{cr}}} = \frac{293\,\text{K}}{154.8\,\text{K}} = 1.893 \\ P_R &= \frac{P}{P_{\text{cr}}} = \frac{4\,\text{MPa}}{5.08\,\text{MPa}} = 0.787 \end{aligned}\right\}\ \text{Z} = 0.975$$

Thus,

$$v = Zv_{\text{ideal}} = (0.975)(0.01903\,\text{m}^3/\text{kg}) = \mathbf{0.01855\ m^3/kg}$$

3-138E 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)

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

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

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

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

$$P = \frac{R_uT}{\bar{v}} + \left(B_0R_uT - A_0 - \frac{C_0}{T^2}\right)\frac{1}{\bar{v}} + \frac{bR_uT - a}{\bar{v}^3} + \frac{a\alpha}{\bar{v}^6} + \frac{c}{\bar{v}^3T^2}\left(1 + \frac{\gamma}{\bar{v}^2}\right)\exp(-\gamma/\bar{v}^2)$$

$$2758 = \frac{(8.314)(200)}{\bar{v}_2} + \left(0.04074\times 8.314\times 200 - 106.73 - \frac{8.164\times 10^5}{200^2}\right)\frac{1}{\bar{v}^2} + \frac{0.002328\times 8.314\times 200 - 2.54}{\bar{v}^3}$$

$$+ \frac{2.54\times 1.272\times 10^{-4}}{\bar{v}^6} + \frac{7.379\times 10^4}{\bar{v}^3(200)^2}\left(1 + \frac{0.0053}{\bar{v}^2}\right)\exp(-0.0053/\bar{v}^2)$$

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

$$\bar{v}_2 = 0.5666\,\text{m}^3/\text{kmol}$$

Then,

$$v_2 = \frac{\bar{v}_2}{M} = \frac{0.5666\,\text{m}^3/\text{kmol}}{28.013\,\text{kg/kmol}}\left(\frac{16.02\,\text{ft}^3/\text{lbm}}{1\,\text{m}^3/\text{kg}}\right) = \mathbf{0.3240\ ft^3/lbm}$$

(*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,

$$v = Zv_{\text{ideal}} = (0.94)(0.3447\,\text{ft}^3/\text{lbm}) = \mathbf{0.3240\ ft^3/lbm}$$

3-139 *Complete the following table for* H_2O:

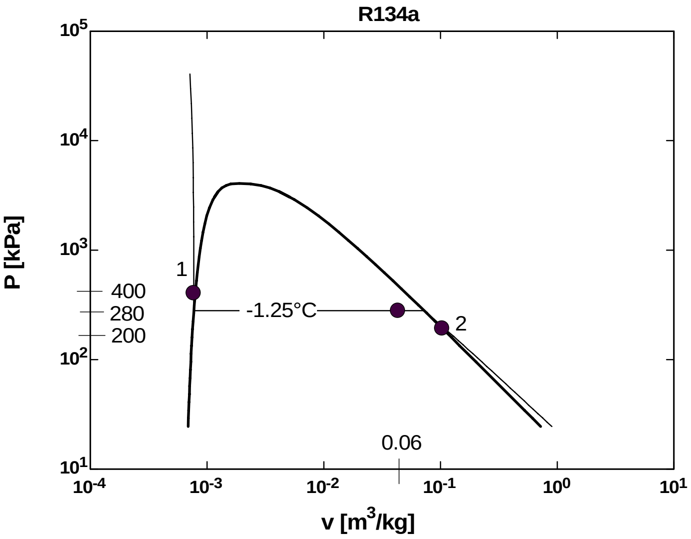
***P*, kPa**	***T*, °C**	***v*, m^3/ kg**	***u*, kJ/kg**	**Phase description**
200	30	**0.001004**	125.71	Compressed liquid
270.3	130	-	-	Insufficient information
200	400	1.5493	**2967.2**	Superheated steam
300	**133.52**	0.500	**2196.4**	Saturated mixture, x=0.825
500	**473.1**	**0.6858**	3084	Superheated steam

3-140 *Complete the following table for R-134a*:

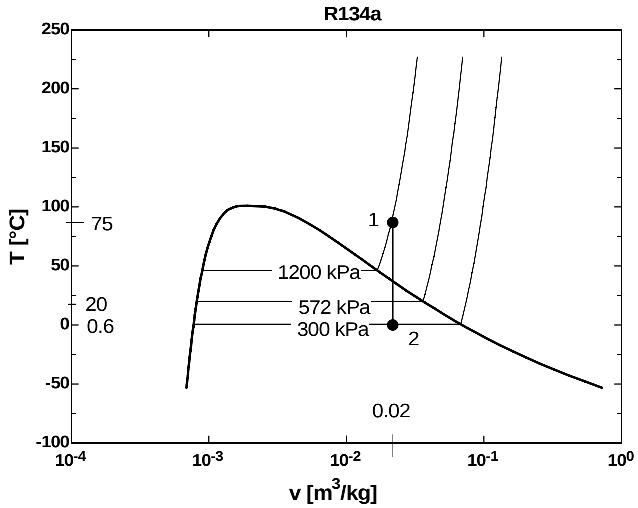
***P*, kPa**	***T*, °C**	***v*, m^3/ kg**	***u*, kJ/kg**	**Phase description**
320	-12	**0.0007497**	**35.72**	Compressed liquid
1000	39.37	-	-	Insufficient information
140	40	0.17794	**263.79**	Superheated vapor
180	**-12.73**	0.0700	**153.66**	Saturated mixture, x=0.6315
200	**22.13**	**0.1152**	249	Superheated vapor

3-141

(*a*) On the P-v diagram the constant temperature process through the state P = 280 kPa, v = 0.06 m^3/kg as pressure changes from P_1 = 400 kPa to P_2 = 200 kPa is to be sketched. The value of the temperature on the process curve on the P-v diagram is to be placed.



(*b*) On the T-v diagram the constant specific volume process through the state T = 20°C, v = 0.02 m^3/kg from P_1 = 1200 kPa to P_2 = 300 kPa is to be sketched. For this data set the temperature values at states 1 and 2 on its axis is to be placed. The value of the specific volume on its axis is also to be placed.



Fundamentals of Engineering (FE) Exam Problems

3-142 A rigid tank contains 6 kg of an ideal gas at 3 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) 186°C (b) 59°C (c) -43°C (d) 20°C (e) 230°C

Answer (a) 186°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, P1/P2=m1*T1/m2*T2"
m1=6 "kg"
P1=3 "atm"
P2=2.2 "atm"
T1=40+273 "K"
m2=0.5*m1 "kg"
P1/P2=m1*T1/(m2*T2)
T2_C=T2-273 "C"

"Some Wrong Solutions with Common Mistakes:"
P1/P2=m1*(T1-273)/(m2*W1_T2) "Using C instead of K"
P1/P2=m1*T1/(m1*(W2_T2+273)) "Disregarding the decrease in mass"
P1/P2=m1*T1/(m1*W3_T2) "Disregarding the decrease in mass, and not converting to deg. C"
W4_T2=(T1-273)/2 "Taking T2 to be half of T1 since half of the mass is discharged"
```

3-143 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, P1/P2=T1/T2"
Patm=95
P1=190+Patm "kPa"
P2=215+Patm "kPa"
T1=25+273 "K"
P1/P2=T1/T2
T2_C=T2-273 "C"

"Some Wrong Solutions with Common Mistakes:"
P1/P2=(T1-273)/W1_T2 "Using C instead of K"
(P1-Patm)/(P2-Patm)=T1/(W2_T2+273) "Using gage pressure instead of absolute pressure"
(P1-Patm)/(P2-Patm)=(T1-273)/W3_T2 "Making both of the mistakes above"
W4_T2=T1-273 "Assuming the temperature to remain constant"
```

3-144 A 300-m^3 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"
```

3-145 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 18 minutes. If the heat loss from the coffee maker is negligible, the power rating of the heating element is

(a) 0.90 kW (b) 1.52 kW (c) 2.09 kW (d) 1.05 kW (e) 1.24 kW

Answer (d) 1.05 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=18*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"
```

3-146 A 1-m^3 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"
```

3-147 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"
```

3-148 Water is boiled in a pan on a stove at sea level. During 10 min of boiling, its 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"
```

3-149 A rigid 3-m^3 rigid vessel contains steam at 10 MPa and 500°C. The mass of the steam is

(a) 3.0 kg (b) 19 kg (c) 84 kg (d) 91 kg (e) 130 kg

Answer (d) 91 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=10000 "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"
```

3-150 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 developes, 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"
```

3-151 … 3-153 Design, Essay and Experiment Problems

* * *