Chapter 3
PROPERTIES OF PURE SUBSTANCES

Pure Substances, Phase Change Processes, Property Diagrams

3-1C Yes. Because it has the same chemical composition throughout.

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 No.

3-6C Yes. The saturation temperature of a pure substance depends on pressure. The higher the pressure, the higher the saturation or boiling temperature.

3-7C The temperature will also increase since the boiling or saturation temperature of a pure substance depends on pressure.

3-8C Because one cannot be varied while holding the other constant. In other words, when one changes, so does the other one.

3-9C 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.

3-10C Yes.

3-11C 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.

3-12C 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

3-13C A given volume of water will boil at a higher temperature in a **tall and narrow pot** since the pressure at the bottom (and thus the corresponding saturation pressure) will be higher in that case.

3-14C 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.

3-15C 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

3-16C 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.

3-17C Yes. Otherwise we can create energy by alternately vaporizing and condensing a substance.

3-18C No. Because in the thermodynamic analysis we deal with the changes in properties; and the changes are independent of the selected reference state.

3-19C 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 $h_{fg} = h_g - h_f$.

3-20C Yes; the higher the temperature the lower the h_{fg} value.

3-21C Quality is the fraction of vapor in a saturated liquid-vapor mixture. It has no meaning in the superheated vapor region.

3-22C Completely vaporizing 1 kg of saturated liquid at 1 atm pressure since the higher the pressure, the lower the h_{fg}.

3-23C Yes. It decreases with increasing pressure and becomes zero at the critical pressure.

3-24C No. Quality is a mass ratio, and it is not identical to the volume ratio.

3-25C The compressed liquid can be approximated as a saturated liquid at the given temperature. Thus $\mathbf{v}_{T,P} \cong \mathbf{v}_{f@T}$.

3-26 [*Also solved by EES on enclosed CD***]** *Complete the following table for H_2O:*

T, °C	P, kPa	$\mathbf{v}$, m³ / 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*

3-27 EES Problem 3-26 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$,p=p,x=x)
        v=volume(Fluid$,p=p,x=x)
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            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.'
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end
"Input from the diagram window"
{Fluid$='Steam'
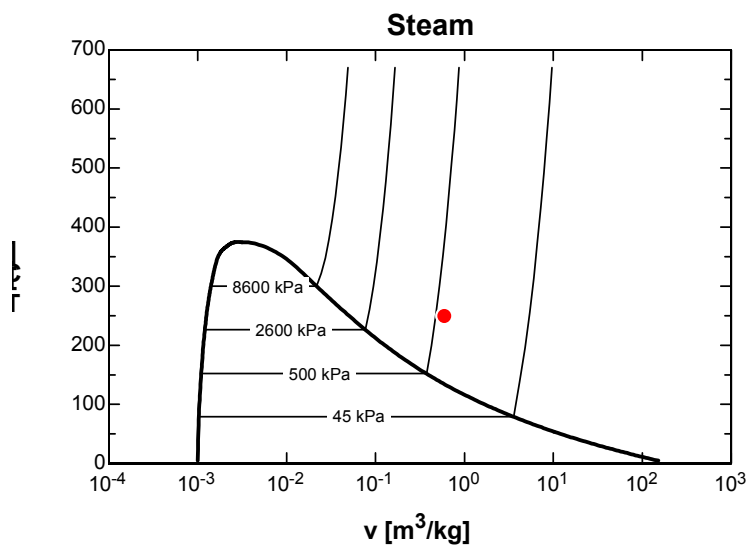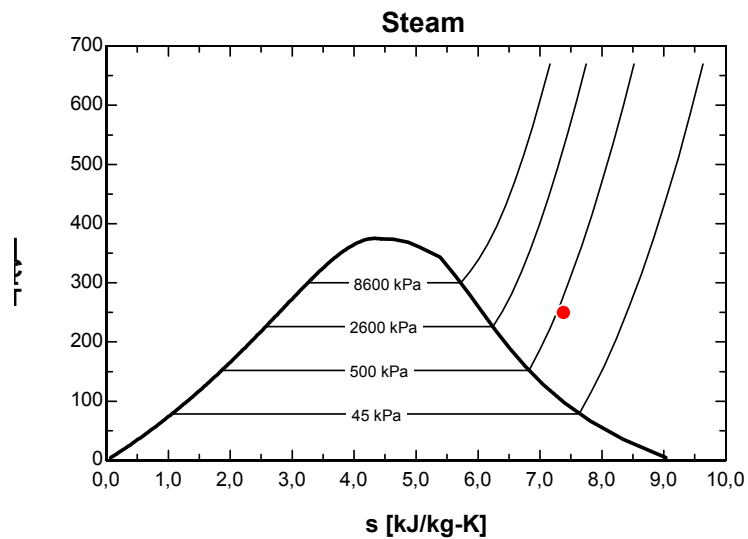Prop1$='Temperature'
Prop2$='Pressure'
Value1=50
value2=101.3}

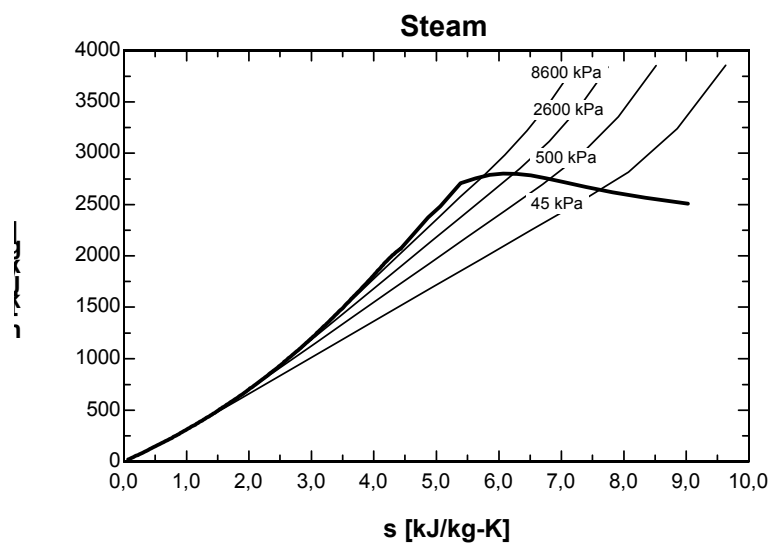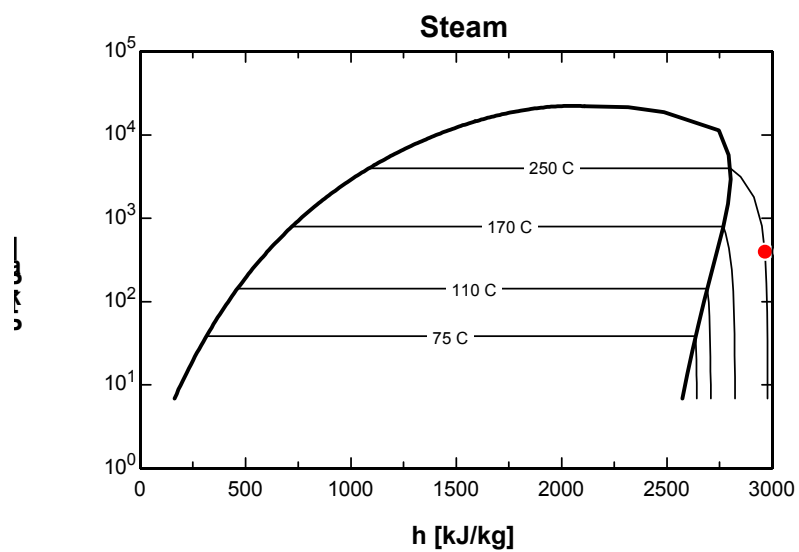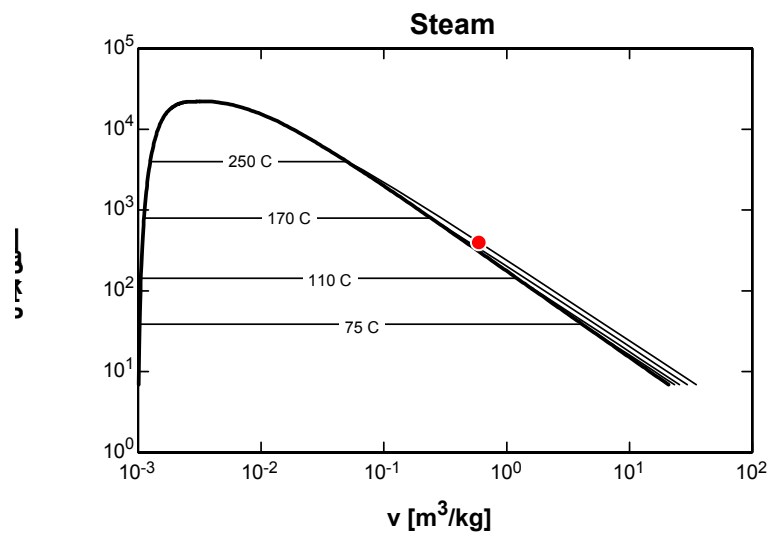Call Find(Fluid$,Prop1$,Prop2$,Value1,Value2:T,p,h,s,v,u,x,State$)

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] vs v [m³/kg]

250 C

170 C

110 C

75 C

Steam

P [kPa] vs h [kJ/kg]

250 C

170 C

110 C

75 C

Steam

h [kJ/kg] vs s [kJ/kg-K]

8600 kPa

2600 kPa

500 kPa

45 kPa

3-28E *Complete the following table for H₂O*:

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*

3-29E EES Problem 3-28E is reconsidered. The missing properties of water are to be determined using EES, and the solution is to be repeated for refrigerant-134a, refrigerant-22, and ammonia.

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

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

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

Solution for steam

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

3-30 *Complete the following table for H₂O*:

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*

3-31 *Complete the following table for Refrigerant-134a:*

T, °C	P, kPa	v, m³ / 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*

3-32 *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*

3-33E *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*

3-34 *Complete the following table for H_2O:*

T, °C	P, kPa	v, m³ / kg	Phase description
140	*361.53*	0.05	*Saturated mixture*
155.46	550	*0.001097*	Saturated liquid
125	750	*0.001065*	*Compressed liquid*
500	*2500*	0.140	*Superheated vapor*

3-35 *Complete the following table for H_2O:*

T, °C	P, kPa	u, kJ / kg	Phase description
143.61	400	1450	*Saturated mixture*
220	*2319.6*	*2601.3*	Saturated vapor
190	2500	*805.15*	*Compressed liquid*
466.21	4000	3040	*Superheated vapor*

3-36 A rigid tank contains steam at a specified state. The pressure, quality, and density of steam are to be determined.

Properties At 220°C $v_f = 0.001190$ m³/kg and $v_g = 0.08609$ m³/kg (Table A-4).

Analysis (*a*) Two phases coexist in equilibrium, thus we have a saturated liquid-vapor mixture. The pressure of the steam is the saturation pressure at the given temperature. Then the pressure in the tank must be the saturation pressure at the specified temperature,

$$P = T_{\text{sat}@220°C} = \textbf{2320 kPa}$$

(*b*) The total mass and the quality are determined as

```
Steam
1.8 m³
220°C
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$$m_f = \frac{V_f}{v_f} = \frac{1/3 \times (1.8 \text{ m}^3)}{0.001190 \text{ m}^3/\text{kg}} = 504.2 \text{ kg}$$

$$m_g = \frac{V_g}{v_g} = \frac{2/3 \times (1.8 \text{ m}^3)}{0.08609 \text{ m}^3/\text{kg}} = 13.94 \text{ kg}$$

$$m_t = m_f + m_g = 504.2 + 13.94 = 518.1 \text{ kg}$$

$$x = \frac{m_g}{m_t} = \frac{13.94}{518.1} = \textbf{0.0269}$$

(*c*) The density is determined from

$$v = v_f + x(v_g - v_f) = 0.001190 + (0.0269)(0.08609) = 0.003474 \text{ m}^3/\text{kg}$$

$$\rho = \frac{1}{v} = \frac{1}{0.003474} = \textbf{287.8 kg/m}^3$$
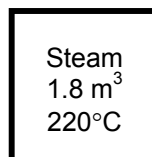
3-37 A piston-cylinder device contains R-134a at a specified state. Heat is transferred to R-134a. The final pressure, the volume change of the cylinder, and the enthalpy change are to be determined.

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

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

(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

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R-134a
0.85 kg
-10°C        Q
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$$V_1 = mv_1 = (0.85 \text{ kg})(0.2302 \text{ m}^3/\text{kg}) = 0.1957 \text{ m}^3$$

$$V_2 = mv_2 = (0.85 \text{ kg})(0.2544 \text{ m}^3/\text{kg}) = 0.2162 \text{ m}^3$$

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

(c) The total enthalpy change is determined from

$$\Delta H = m(h_2 - h_1) = (0.85 \text{ kg})(268.16 - 247.76) \text{ kJ/kg} = \textbf{17.4 kJ/kg}$$
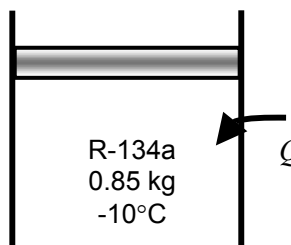
3-38E The temperature in a pressure cooker during cooking at sea level is measured to be 250°F. The absolute pressure inside the cooker and the effect of elevation on the answer are to be determined.

Assumptions Properties of pure water can be used to approximate the properties of juicy water in the cooker.
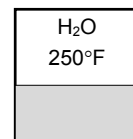
Properties The saturation pressure of water at 250°F is 29.84 psia (Table A-4E). The standard atmospheric pressure at sea level is 1 atm = 14.7 psia.

Analysis The absolute pressure in the cooker is simply the saturation pressure at the cooking temperature,

$$P_{\text{abs}} = P_{\text{sat@250°F}} = \textbf{29.84 psia}$$

It is equivalent to

$$P_{\text{abs}} = 29.84 \text{ psia} \left(\frac{1 \text{ atm}}{14.7 \text{ psia}} \right) = \textbf{2.03 atm}$$

```
┌──────────────┐
│    H₂O       │
│   250°F      │
├──────────────┤
│░░░░░░░░░░░░░░│
└──────────────┘
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The elevation has **no effect** on the absolute pressure inside when the temperature is maintained constant at 250°F.

3-39E 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

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

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┌──────────────┐
│  P±0.3 inHg  │
├──────────────┤
│░░░░░░░░░░░░░░│
└──────────────┘
```

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

$$\frac{\Delta T}{\Delta P} = \frac{(212 - 200)°F}{(14.709 - 11.538) \text{ psia}} = 3.783 \text{ °F/psia}$$
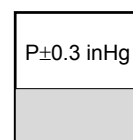
Then the change in saturation (boiling) temperature corresponding to a change of 0.147 psia becomes

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

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

3-40 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,

$$F = A(P_{atm} - P) = (\pi D^2 / 4)(P_{atm} - P)$$
$$= \frac{\pi(0.3\,\text{m})^2}{4}(101,325 - 2339.2)\,\text{Pa}$$
$$= 6997\,\text{m}^2\text{Pa} = \mathbf{6997\,N} \quad (\text{since } 1\,\text{Pa} = 1\,\text{N/m}^2)$$
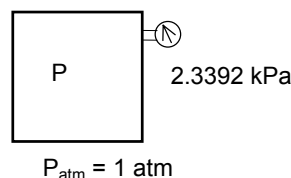
The weight of the pan and its contents is

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

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.

3-41 Water is boiled at sea level (1 atm pressure) in a pan placed on top of a 3-kW electric burner that transfers 60% of the heat generated to the water. The rate of evaporation of water is to be determined.

Properties The properties of water at 1 atm and thus at the saturation temperature of 100°C are h_{fg} = 2256.4 kJ/kg (Table A-4).

Analysis The net rate of heat transfer to the water is

$$\dot{Q} = 0.60 \times 3\,\text{kW} = 1.8\,\text{kW}$$

Noting that it takes 2256.4 kJ of energy to vaporize 1 kg of saturated liquid water, the rate of evaporation of water is determined to be

$$\dot{m}_{evaporation} = \frac{\dot{Q}}{h_{fg}} = \frac{1.8\,\text{kJ/s}}{2256.4\,\text{kJ/kg}} = 0.80 \times 10^{-3}\,\text{kg/s} = \mathbf{2.872\ kg/h}$$
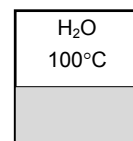
3-42 Water is boiled at 1500 m (84.5 kPa pressure) in a pan placed on top of a 3-kW electric burner that transfers 60% of the heat generated to the water. The rate of evaporation of water is to be determined.

Properties The properties of water at 84.5 kPa and thus at the saturation temperature of 95°C are h_{fg} = 2269.6 kJ/kg (Table A-4).

Analysis The net rate of heat transfer to the water is

$$\dot{Q} = 0.60 \times 3 \text{ kW} = 1.8 \text{ kW}$$

Noting that it takes 2269.6 kJ of energy to vaporize 1 kg of saturated liquid water, the rate of evaporation of water is determined to be

H₂O
95°C

$$\dot{m}_{\text{evaporation}} = \frac{\dot{Q}}{h_{fg}} = \frac{1.8 \text{ kJ/s}}{2269.6 \text{ kJ/kg}} = \mathbf{0.793 \times 10^{-3} \text{ kg/s} = 2.855 \text{ kg/h}}$$

3-43 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 m³/kg (Table A-4).

Analysis The rate of evaporation of water is

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

H₂O
1 atm

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

Then the rate of heat transfer to water becomes

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

3-44 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 m³/kg (Table A-5).

Analysis The rate of evaporation of water is

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

H₂O
79.5 kPa

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

Then the rate of heat transfer to water becomes

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

3-45 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

$$\dot{Q} = \dot{m}_{evap} h_{fg} = (45\ \text{kg/h})(2429.8\ \text{kJ/kg}) = 109{,}341\ \text{kJ/h} = \textbf{30.4 kW}$$
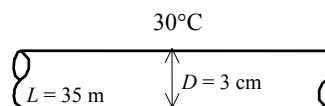
3-46 The average atmospheric pressure in Denver is 83.4 kPa. The boiling temperature of water in Denver is to be determined.

Analysis The boiling temperature of water in Denver is the saturation temperature corresponding to the atmospheric pressure in Denver, which is 83.4 kPa:

$$T = T_{sat@83.4\ \text{kPa}} = \textbf{94.6°C} \qquad \text{(Table A-5)}$$

3-47 The boiling temperature of water in a 5-cm deep pan is given. The boiling temperature in a 40-cm deep pan is to be determined.

Assumptions Both pans are full of water.

Properties The density of liquid water is approximately $\rho = 1000$ kg/m³.

Analysis The pressure at the bottom of the 5-cm pan is the saturation pressure corresponding to the boiling temperature of 98°C:

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

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
$$T_{boiling} = T_{sat@97.82\ \text{kPa}} = \textbf{99.0°C} \qquad \text{(Table A-5)}$$
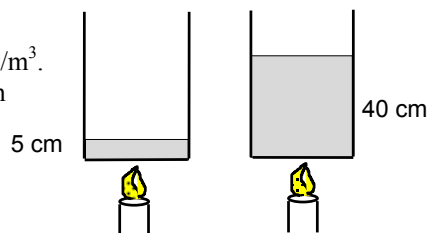
3-48 A cooking pan is filled with water and covered with a 4-kg lid. The boiling temperature of water is to be determined.

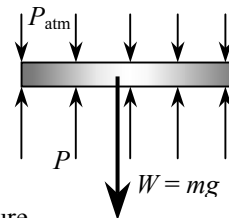*Analysis* The pressure in the pan is determined from a force balance on the lid,
$$PA = P_{atm}A + W$$
or,

$$P = P_{atm} + \frac{mg}{A}$$
$$= (101\ \text{kPa}) + \frac{(4\ \text{kg})(9.81\ \text{m/s}^2)}{\pi(0.1\ \text{m})^2}\left(\frac{1\ \text{kPa}}{1000\ \text{kg/m} \cdot \text{s}^2}\right)$$
$$= 102.25\ \text{kPa}$$

The boiling temperature is the saturation temperature corresponding to this pressure,
$$T = T_{sat@102.25\ \text{kPa}} = \textbf{100.2°C} \qquad \text{(Table A-5)}$$

3-49 EES Problem 3-48 is reconsidered. Using EES (or other) software, the effect of the mass of the lid on the boiling temperature of water in the pan is to be investigated. The mass is to vary from 1 kg to 10 kg, and the boiling temperature is to be plotted against the mass of the lid.

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

"Given data"
{P_atm=101[kPa]}
D_lid=20 [cm]
{m_lid=4 [kg]}

"Solution"

"The atmospheric pressure in kPa varies with altitude in km by the approximate function:"
P_atm=101.325*(1-0.02256*z)^5.256
"The local acceleration of gravity at 45 degrees latitude as a function of altitude in m is given by:"
g=9.807+3.32*10^(-6)*z*convert(km,m)

"At sea level:"
z=0 "[km]"
A_lid=pi*D_lid^2/4*convert(cm^2,m^2)
W_lid=m_lid*g*convert(kg*m/s^2,N)
P_lid=W_lid/A_lid*convert(N/m^2,kPa)
P_water=P_lid+P_atm
T_water=temperature(steam_iapws,P=P_water,x=0)

m_{lid} [kg]	T_{water} [C]
1	100.1
2	100.1
3	100.2
4	100.3
5	100.4
6	100.5
7	100.6
8	100.7
9	100.7
10	100.8

Effect of altitude on boiling temperature of water in pan with lid
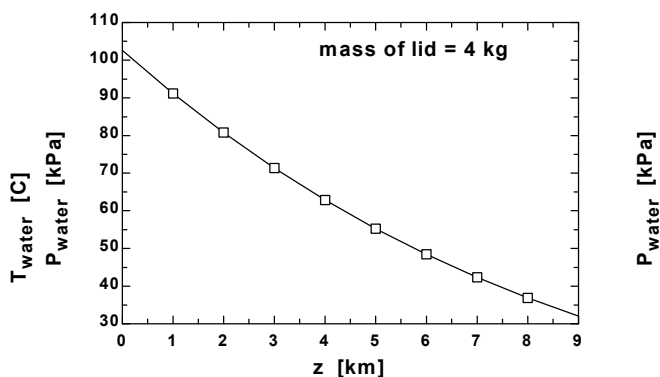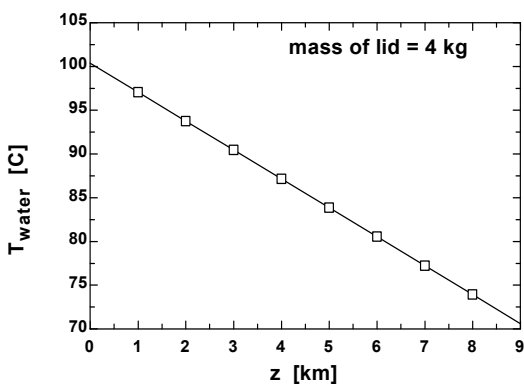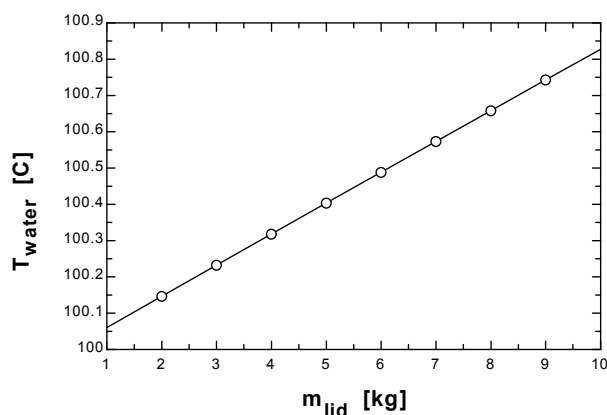
Effect of altitude on boiling pressure of water in pan with lid

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,

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

or,

$$P = P_{atm} + \frac{mg}{A}$$
$$= (100 \text{ kPa}) + \frac{(20 \text{ kg})(9.81 \text{ m/s}^2)}{0.01 \text{ m}^2}\left(\frac{1 \text{ kPa}}{1000 \text{ kg/m} \cdot \text{s}^2}\right)$$
$$= 119.61 \text{ kPa}$$
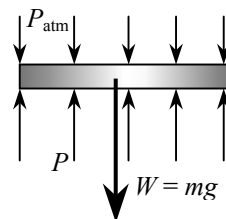
The boiling temperature is the saturation temperature corresponding to this pressure,

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

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),
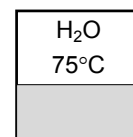
and the specific volume is determined to be

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

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,

$$T = T_{sat@v_g=0.1667 \text{ m}^3/\text{kg}} = \textbf{187.0°C} \quad \text{(Table A-4)}$$
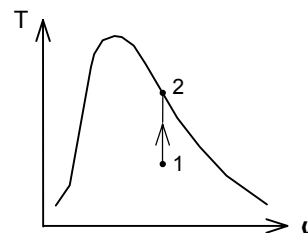
3-52 A rigid vessel is filled with refrigerant-134a. The total volume and the total internal energy are to be determined.
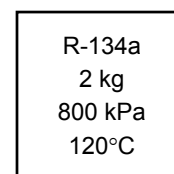
Properties The properties of R-134a at the given state are (Table A-13).

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

Analysis The total volume and internal energy are determined from

$$V = mv = (2 \text{ kg})(0.037625 \text{ m}^3/\text{kg}) = \textbf{0.0753 m}^3$$
$$U = mu = (2 \text{ kg})(327.87 \text{ kJ/kg}) = \textbf{655.7 kJ}$$

3-53E A rigid tank contains water at a specified pressure. The temperature, total enthalpy, and the mass of each phase are to be determined.

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

$$v = \frac{V}{m} = \frac{5 \text{ ft}^3}{5 \text{ lbm}} = 1.0 \text{ ft}^3/\text{lbm}$$

At 20 psia, $v_f = 0.01683$ ft^3/lbm and $v_g = 20.093$ ft^3/lbm (Table A-12E). Thus the tank contains saturated liquid-vapor mixture since $v_f < v < v_g$, and the temperature must be the saturation temperature at the specified pressure,

$$T = T_{\text{sat@20 psia}} = \textbf{227.92°F}$$

(*b*) The quality of the water and its total enthalpy are determined from

$$x = \frac{v - v_f}{v_{fg}} = \frac{1.0 - 0.01683}{20.093 - 0.01683} = 0.04897$$

$$h = h_f + x h_{fg} = 196.27 + 0.04897 \times 959.93 = 243.28 \text{ Btu/lbm}$$

$$H = mh = (5 \text{ lbm})(243.28 \text{ Btu/lbm}) = \textbf{1216.4 Btu}$$

H₂O
5 lbm
20 psia

(*c*) The mass of each phase is determined from

$$m_g = x m_t = 0.04897 \times 5 = \textbf{0.245 lbm}$$

$$m_f = m_t + m_g = 5 - 0.245 = \textbf{4.755 lbm}$$

3-54 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, $v_f = 0.0007362$ m^3/kg and $v_g = 0.14729$ m^3/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,

$$P = P_{\text{sat@-20°C}} = \textbf{132.82 kPa}$$

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

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

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

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

R-134a
10 kg
-20°C

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

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

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

3-55 [*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,

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

$$m_g = \frac{V_g}{v_g} = \frac{0.9 \text{ m}^3}{0.24035 \text{ m}^3/\text{kg}} = 3.745 \text{ kg}$$
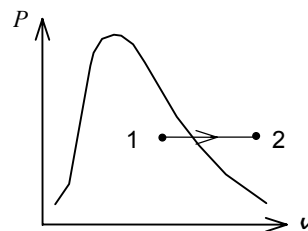
$$m_t = m_f + m_g = 89.704 + 3.745 = \mathbf{93.45 \text{ kg}}$$

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

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

Then,

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

3-56 EES Problem 3-55 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
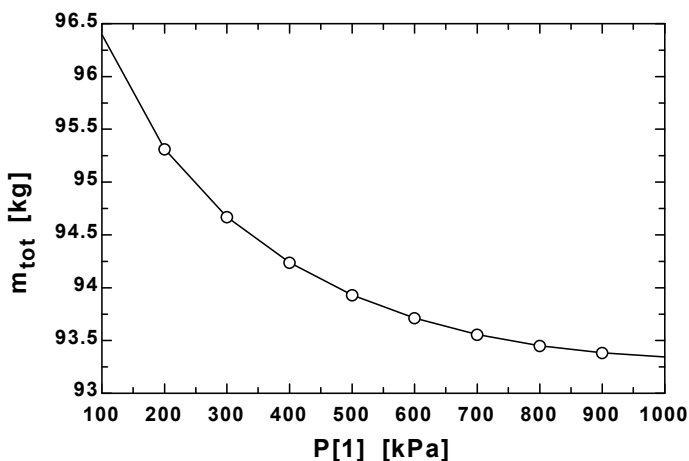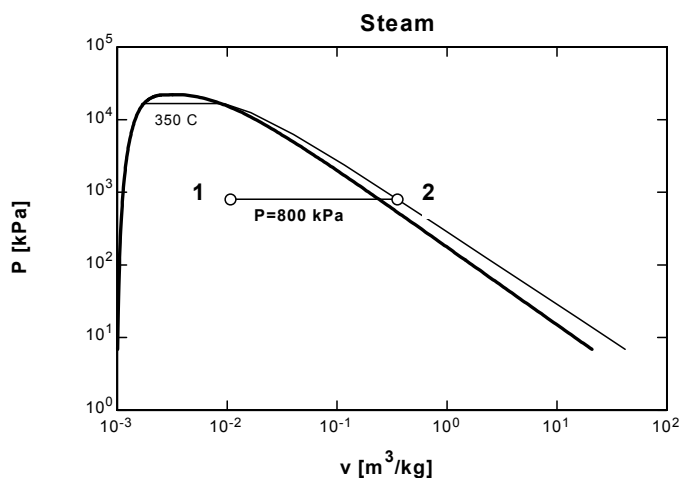
3-57E Superheated water vapor cools at constant volume until the temperature drops to 250°F. At the final state, the pressure, the quality, and the enthalpy are to be determined.

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, $v_f = 0.01700$ ft³/lbm and $v_g = 13.816$ ft³/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,
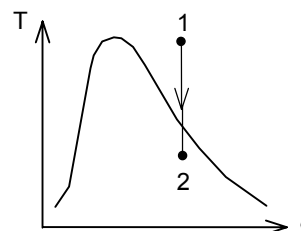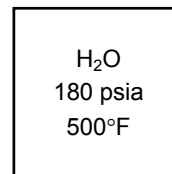
$$P = P_{\text{sat}@250\,^\circ\text{F}} = \textbf{29.84 psia}$$

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

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

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

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

3-58E EES Problem 3-57E 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.
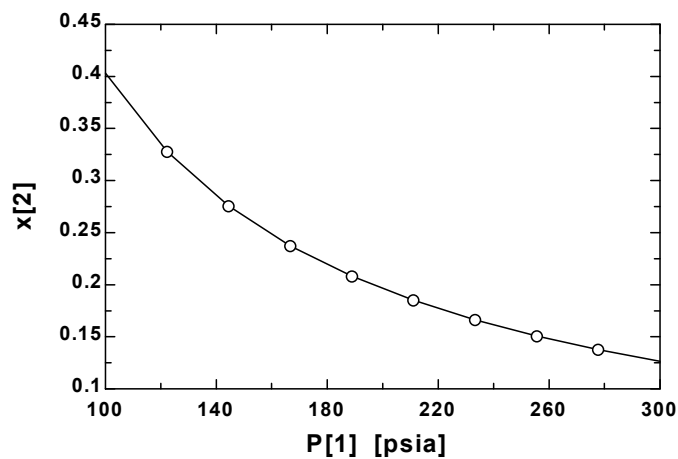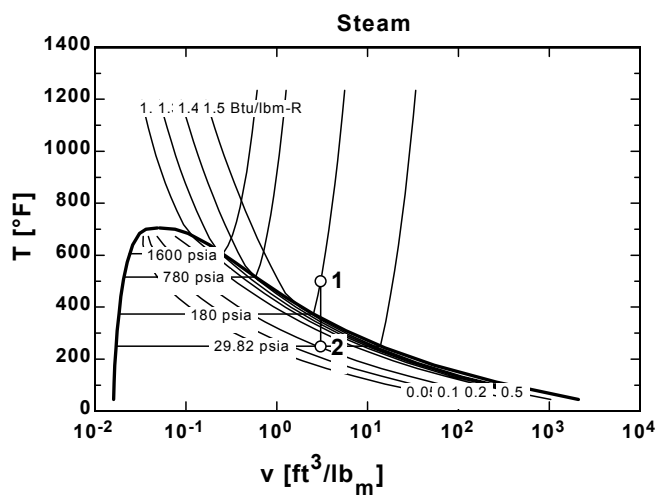
Analysis The problem is solved using EES, and the solution is given below.

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

3-59 A piston-cylinder device that is initially filled with water is heated at constant pressure until all the liquid has vaporized. The mass of water, the final temperature, and the total enthalpy change are to be determined, and the T-v diagram is to be drawn.
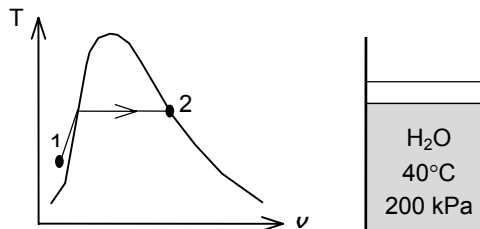
Analysis Initially the cylinder contains compressed liquid (since $P > P_{sat@40°C}$) that can be approximated as a saturated liquid at the specified temperature (Table A-4),

$$v_1 \cong v_{f@40°C} = 0.001008 \text{ m}^3/\text{kg}$$
$$h_1 \cong h_{f@40°C} = 167.53 \text{ kJ/kg}$$

(*a*) The mass is determined from

$$m = \frac{V_1}{v_1} = \frac{0.050 \text{ m}^3}{0.001008 \text{ m}^3/\text{kg}} = \textbf{49.61 kg}$$

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

$$T = T_{sat@200 \text{ kPa}} = \textbf{120.21°C}$$

(*c*) The final enthalpy is $h_2 = h_{g @ 200 \text{ kPa}} = 2706.3 \text{ kJ/kg}$. Thus,

$$\Delta H = m(h_2 - h_1) = (49.61 \text{ kg})(2706.3 - 167.53)\text{kJ/kg} = \textbf{125,943 kJ}$$

3-60 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,
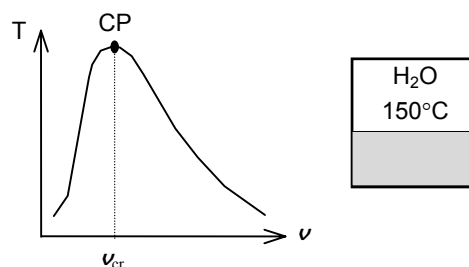
$$v_1 = v_2 = v_{cr} = 0.003106 \text{ m}^3/\text{kg} \qquad \text{(last row of Table A-4)}$$

The total mass is

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

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

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

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

$$m_f = (1 - x_1)m_t = (1 - 0.005149)(96.60) = \textbf{96.10 kg}$$
$$V_f = m_f v_f = (96.10 \text{ kg})(0.001091 \text{ m}^3/\text{kg}) = \textbf{0.105 m}^3$$