Ch2. PROPERTIES OF PURE SUBSTANCES

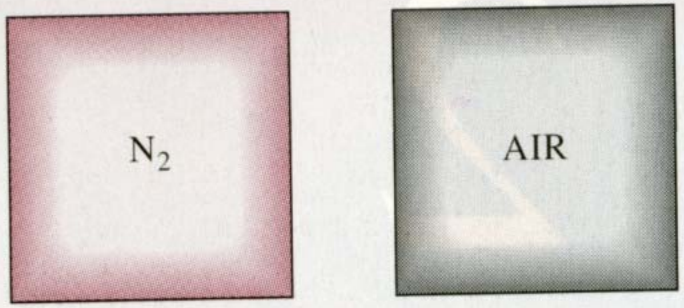


FIGURE 2–1
Nitrogen and gaseous air are pure substances.

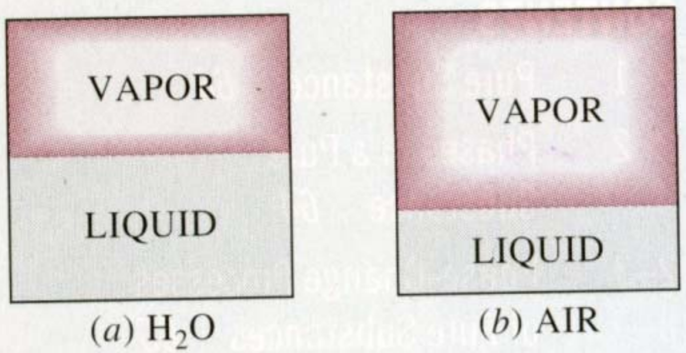


FIGURE 2–2
A mixture of liquid and gaseous water is a pure substance, but a mixture of liquid and gaseous air is not.

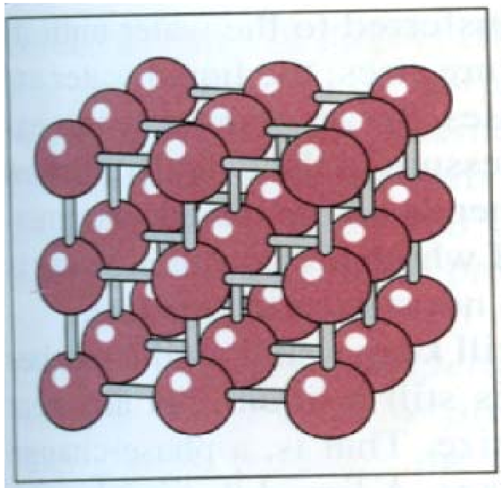
2-1 PURE SUBSTANCE

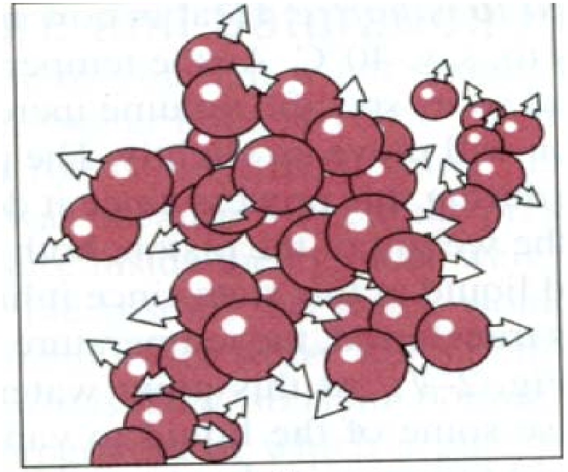
A substance that has a fixed chemical composition throughout is called ***a pure substance***. Water, Nitrogen, helium, and carbon dioxide, for example, are all pure substances

สารบริสุทธิ์ คือสารที่เป็นเนื้อเดียวกันและมีองค์ประกอบทางเคมีคงที่

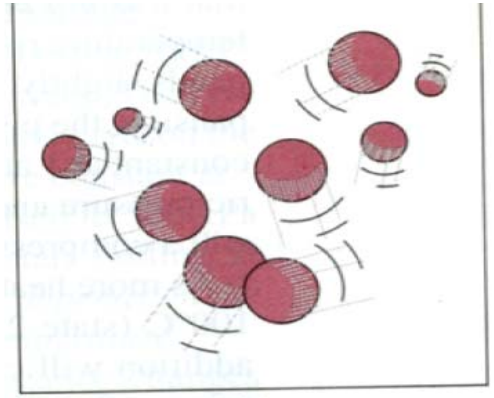
สามารถเกิดขึ้นได้มากว่า 1 เฟส แต่ทุกเฟสองค์ประกอบทางเคมีต้องเหมือนกัน

2-2. PHASES OF A PURE SUBSTANCE





(b)



(c)

2-2. PHASE-CHANGE PROCESSES OF PURE SUBSTANCES

There are many practical situations where two phases of a pure Substance coexist in equilibrium. Water exits as a mixture of liquid and vapor in the boiler and the condenser of a steam power plant. The refrigeration turn from liquid to vapor in the freezer in a refrigerator

Compressed Liquid and *subcooled*

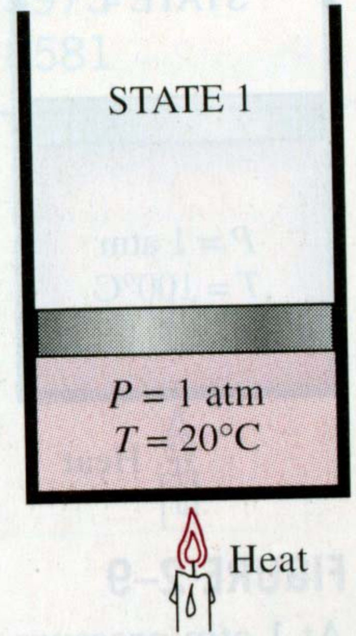


FIGURE 2–6
At 1 atm and 20°C, water exists in the liquid phase (*compressed liquid*).

Consider a position-cylinder device containing liquid water at 20 ºC and 1 atm pressure . Under these conditions, water exists in the liquid phase, and it is called a *compressed liquid,* or *a subcooled liquid.*

A liquid that is about to vaporize is called ***a saturated liquid.***

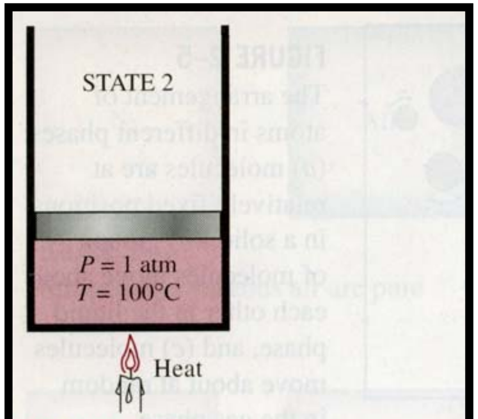


FIGURE 2–7
At 1 atm pressure and 100°C, water exists as a liquid that is ready to vaporize (*saturated liquid*).

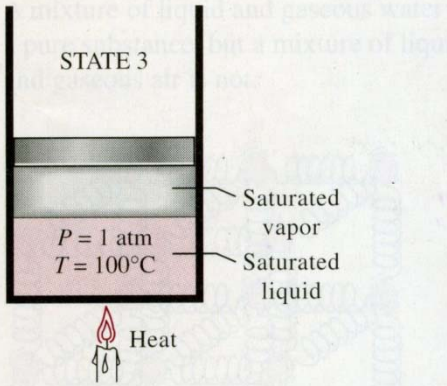


FIGURE 2–8
As more heat is transferred, part of the saturated liquid vaporizes (*saturated liquid–vapor mixture*).

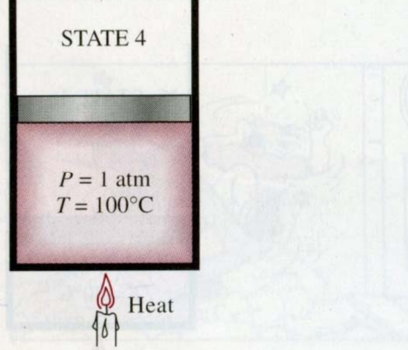


FIGURE 2–9
At 1 atm pressure, the temperature remains constant at 100°C until the last drop of liquid is vaporized (*saturated vapor*).

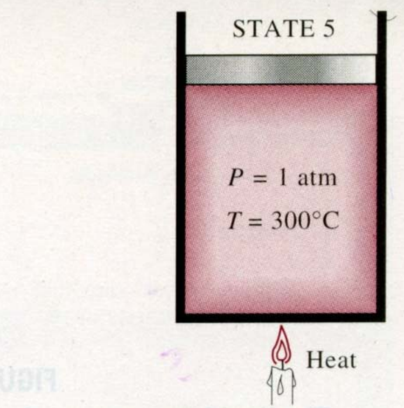


FIGURE 2–10
As more heat is transferred, the temperature of the vapor starts to rise (*superheated vapor*).

Latent heat

Sensible heat T_{sat}

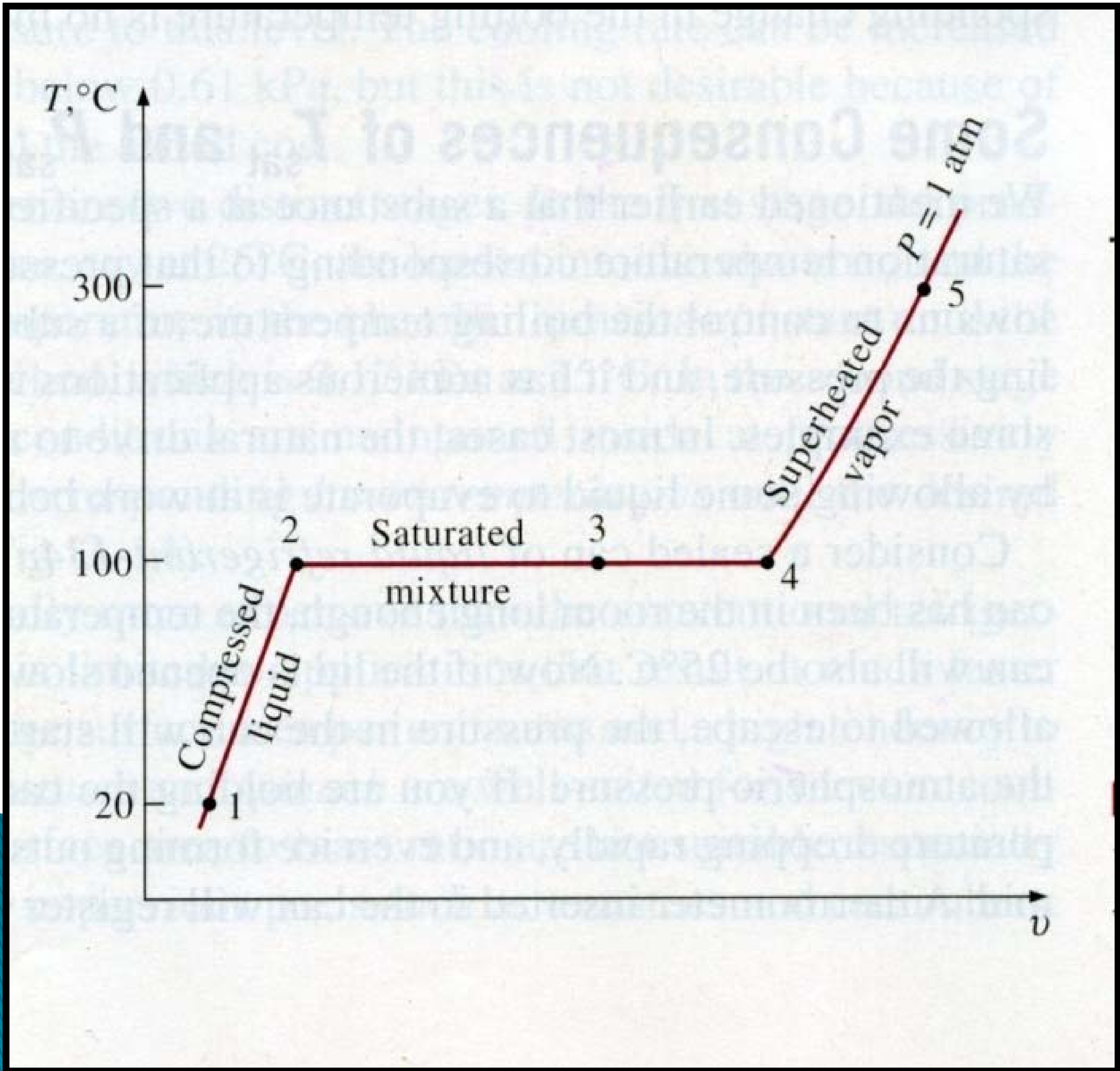
Saturation temperature, P_{sat}

Saturation pressure,

TABLE 2–1

Saturation (boiling) pressure of water at various temperatures

Temperature, T,°C	Saturation pressure, P_{sat}, kPa
−10	0.26
−5	0.40
0	0.61
5	0.87
10	1.23
15	1.71
20	2.34
25	3.17
30	4.25
40	7.38
50	12.35
100	101.3 (1 atm)
150	475.8
200	1554
250	3973
300	8581



T,°C
300
100
20
1
2
3
4
5
Compressed liquid
Saturated mixture
Superheated vapor
P = 1 atm
υ

Saturated Temperature and Saturation Pressure

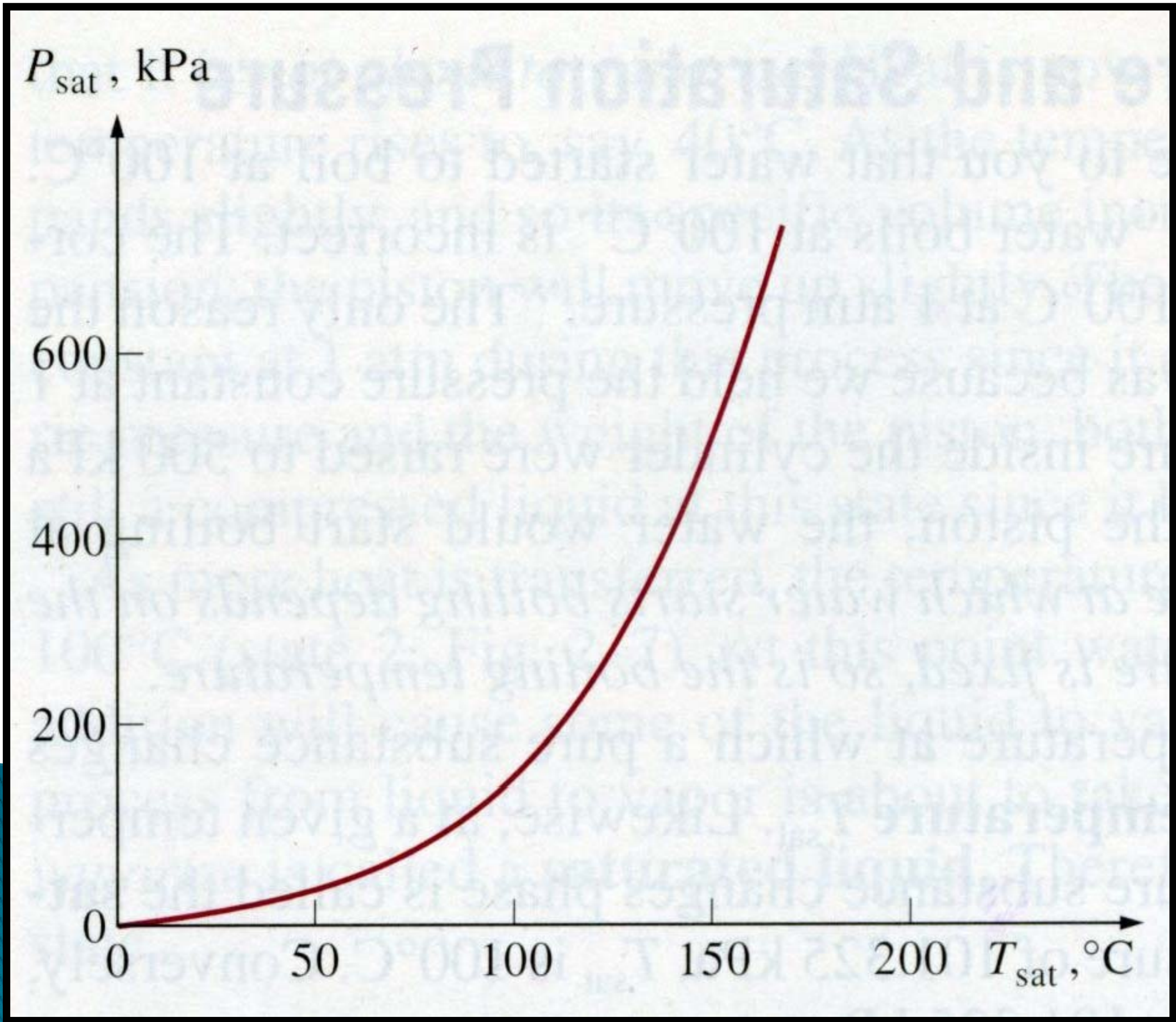


FIGURE 2–12
The liquid–vapor saturation curve of a pure substance (numerical values are for water).

TABLE 2–2

Variation of the standard atmospheric pressure and the boiling (saturation) temperature of water with altitude

Elevation, m	Atmospheric pressure, kPa	Boiling temperature, °C
0	101.33	100.0
1,000	89.55	96.3
2,000	79.50	93.2
5,000	54.05	83.0
10,000	26.50	66.2
20,000	5.53	34.5

Saturated Temperature and Saturation Pressure

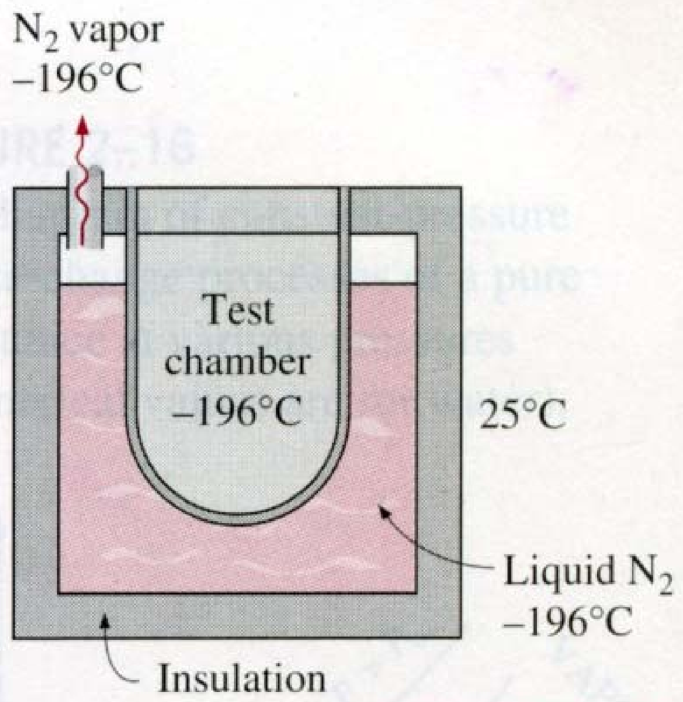


FIGURE 2–13

The temperature of liquid nitrogen exposed to the atmosphere remains constant at −196°C, and thus it maintains the test chamber at −196°C.

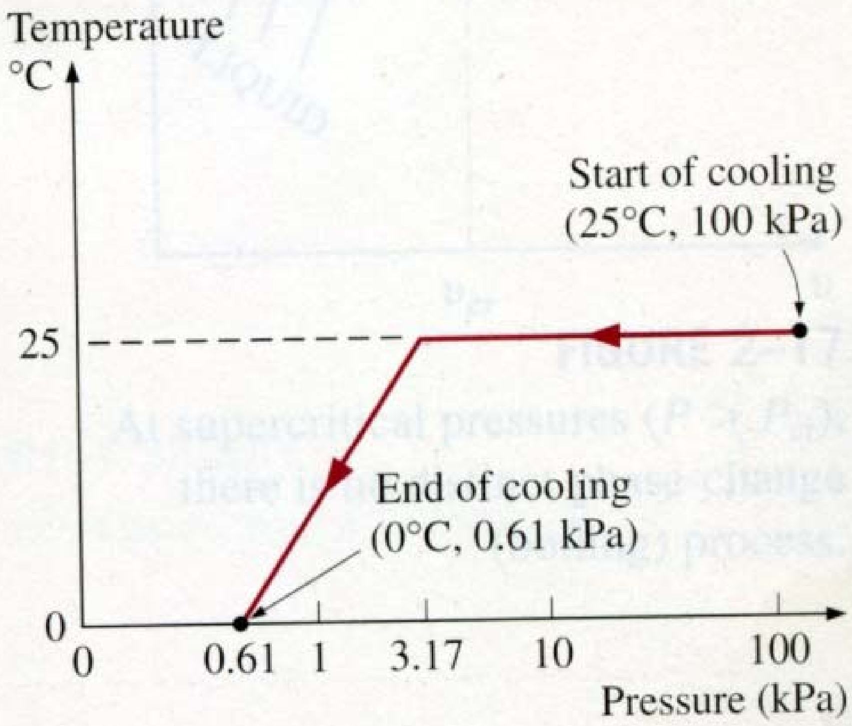


FIGURE 2–14

The variation of the temperature of fruits and vegetables with pressure during vacuum cooling from 25°C to 0°C.

Saturated Temperature and Saturation Pressure

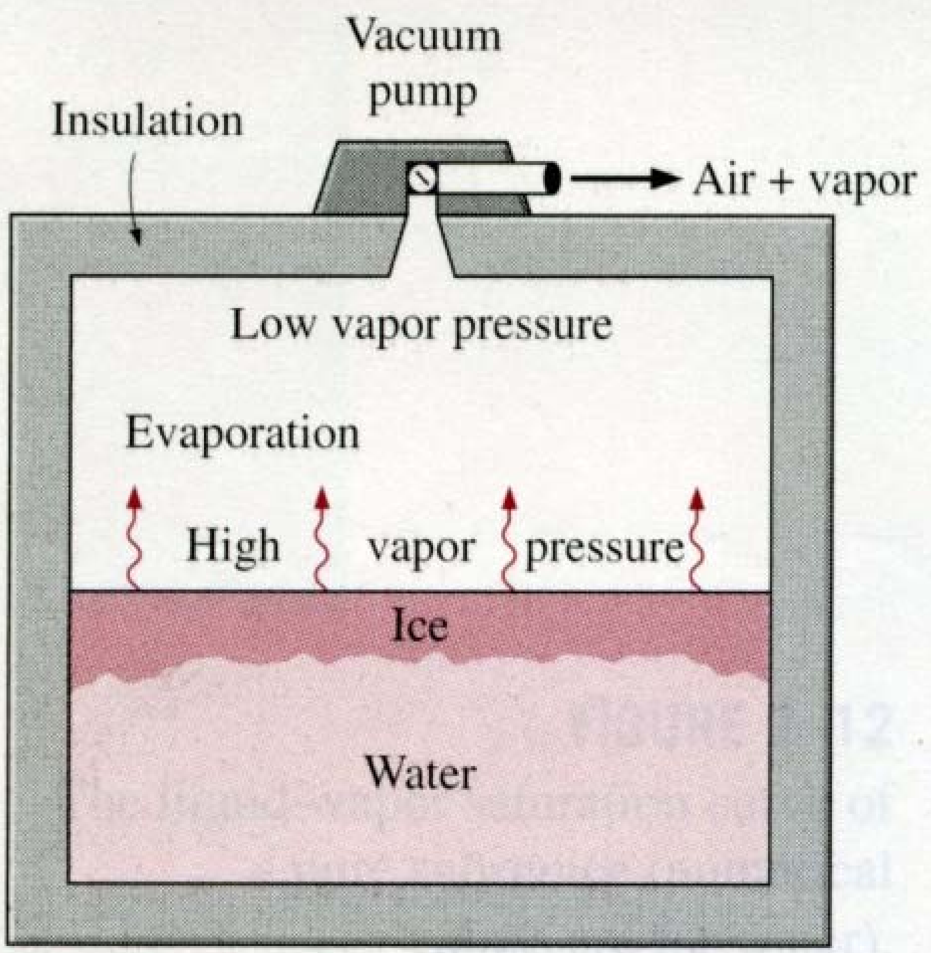


FIGURE 2–15

In 1775, ice was made by evacuating the air space in a water tank.

PROPERTY DIAGRAM FOR PHASE-CHANGE PROCESS

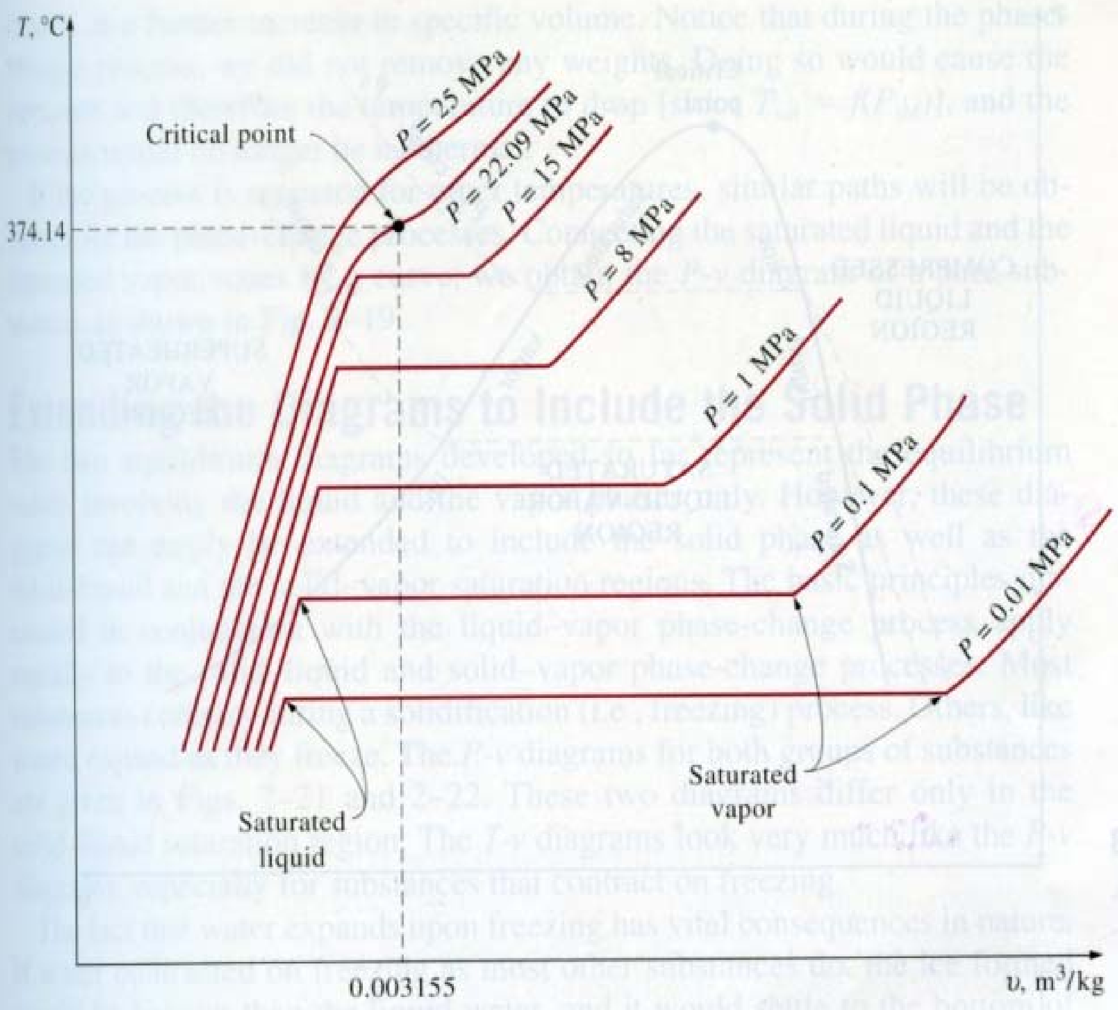


FIGURE 2–16
T-v diagram of constant-pressure phase-change processes of a pure substance at various pressures (numerical values are for water).

1. The T-v Diagram

จุดวิกฤต (Critical point) จุดนี้สภาวะของเหลวอิ่มตัวและสภาวะไออิ่มตัวเป็นสภาวะเดียวกัน อุณหภูมิ ความดัน และปริมาตรจำเพาะที่จุด**วิกฤต** เรียกว่า

อุณหภูมิวิกฤต (Critical Temperature)

ความดันวิกฤต (Critical Pressure)

ปริมาตรวิกฤต (Critical Volume)

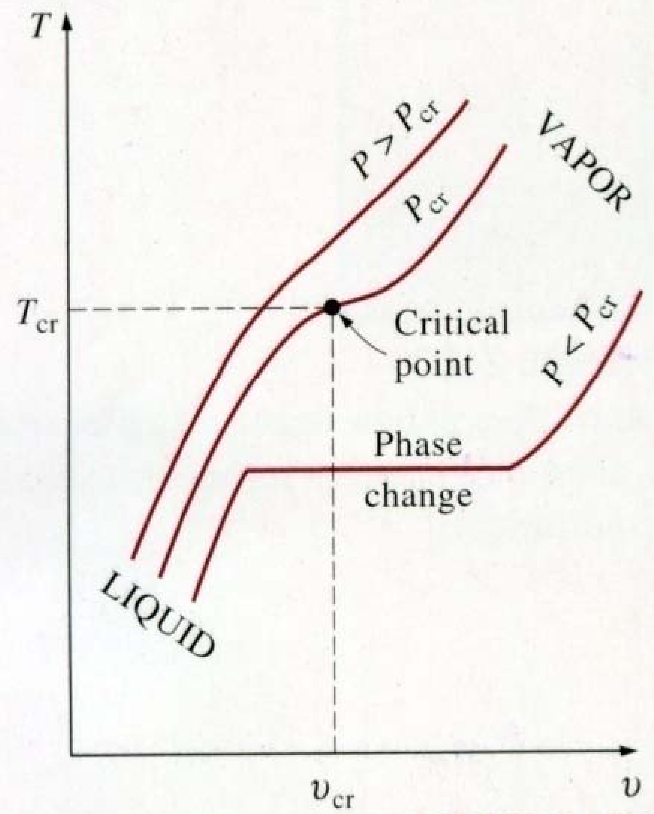


FIGURE 2–17

At supercritical pressures ($P > P_{cr}$), there is no distinct phase-change (boiling) process.

The T-v Diagram

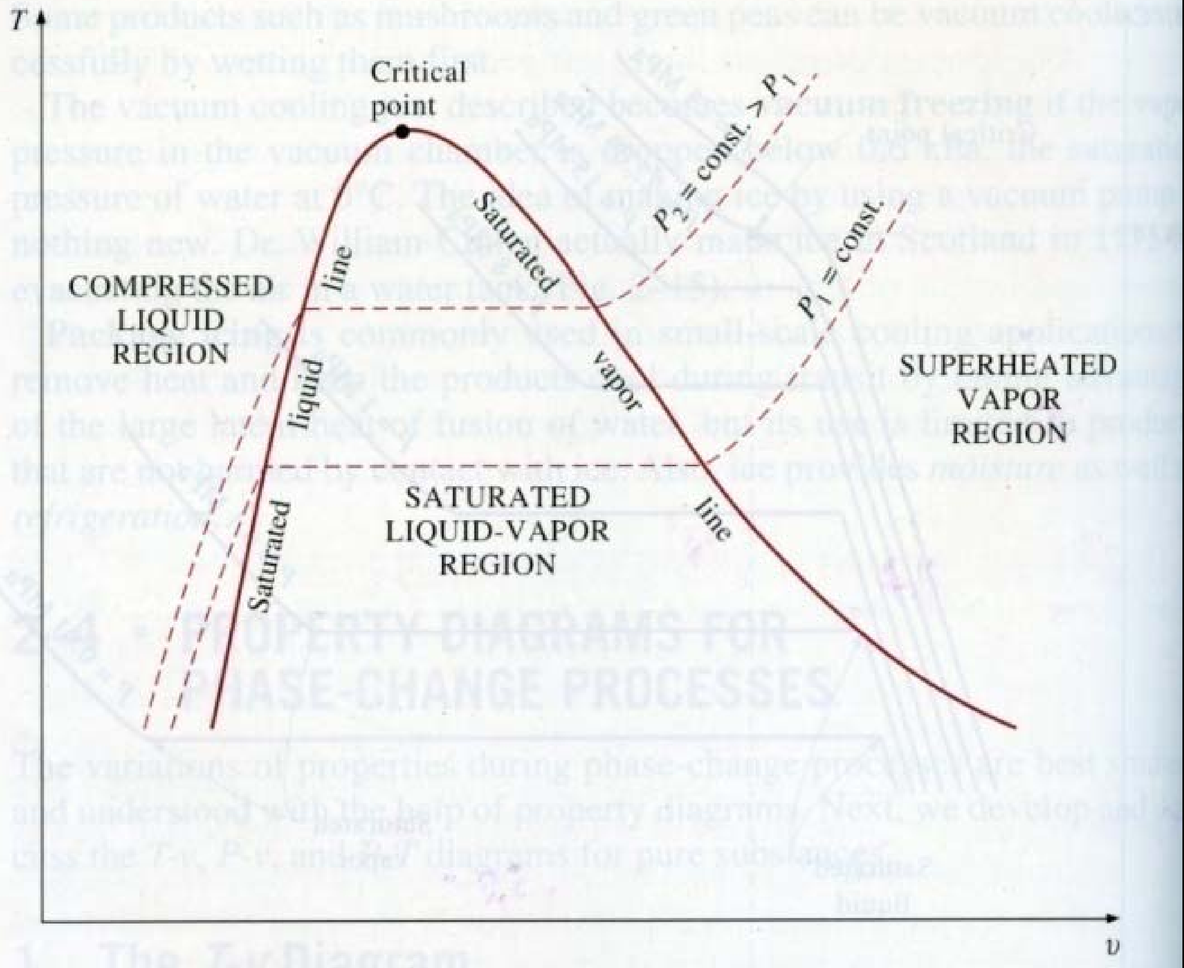


FIGURE 2–18
T-v diagram of a pure substance.

2. P-v Diagram

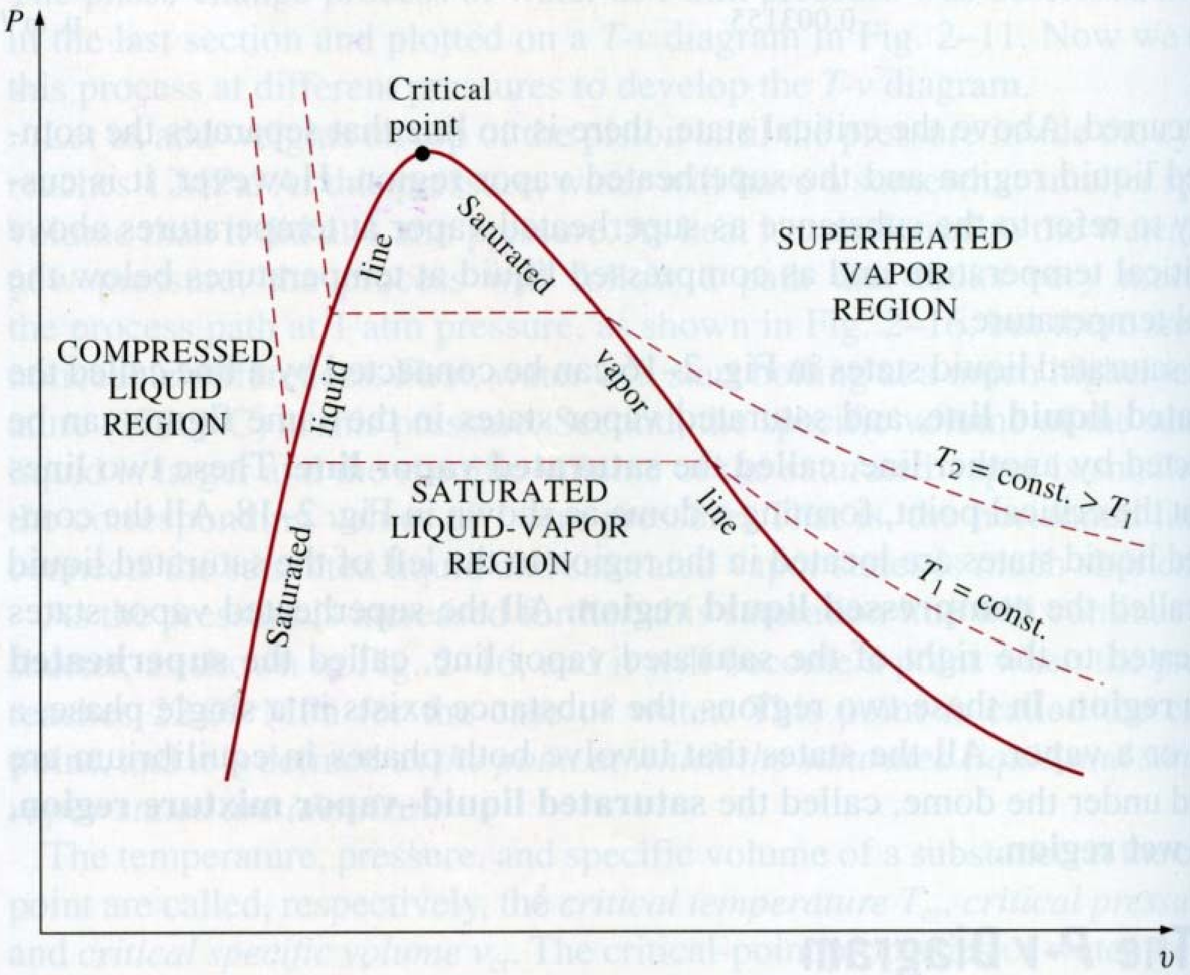


FIGURE 2–19
P-*v* diagram of a pure substance.

Saturated Temperature and Saturation Pressure

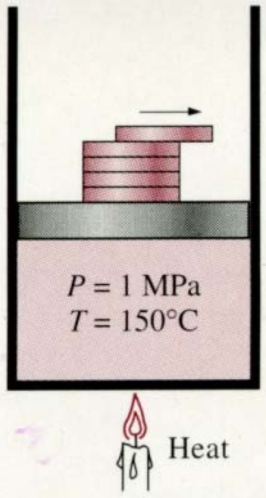


FIGURE 2–20
The pressure in a piston-cylinder device can be reduced by reducing the weight of the piston.

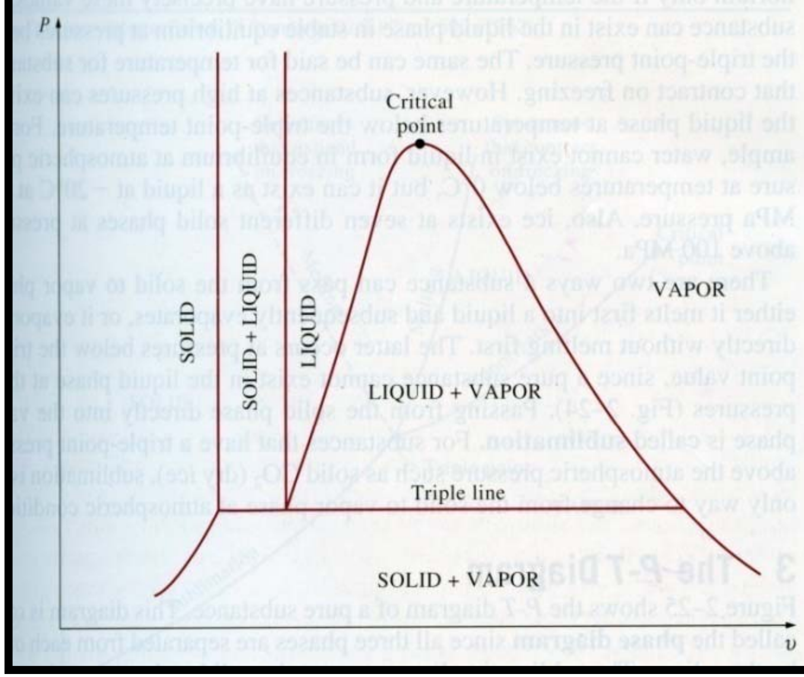


FIGURE 2–21
P-v diagram of a substance that contracts on freezing.

กระบวนการระเหิด (Sublimation process) **จุดนี้น้ำแข็งจะเปลี่ยนแปลงจากเฟสของแข็งไปเป็นเฟสของไอโดยตรง**

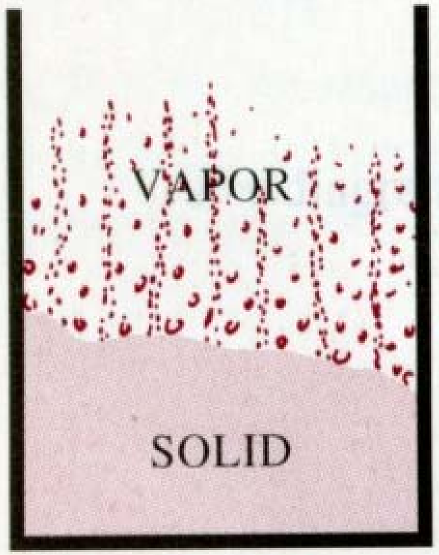


FIGURE 2–24
At low pressures (below the triple-point value), solids evaporate without melting first (*sublimation*).

Saturated Temperature and Saturation Pressure

yyy

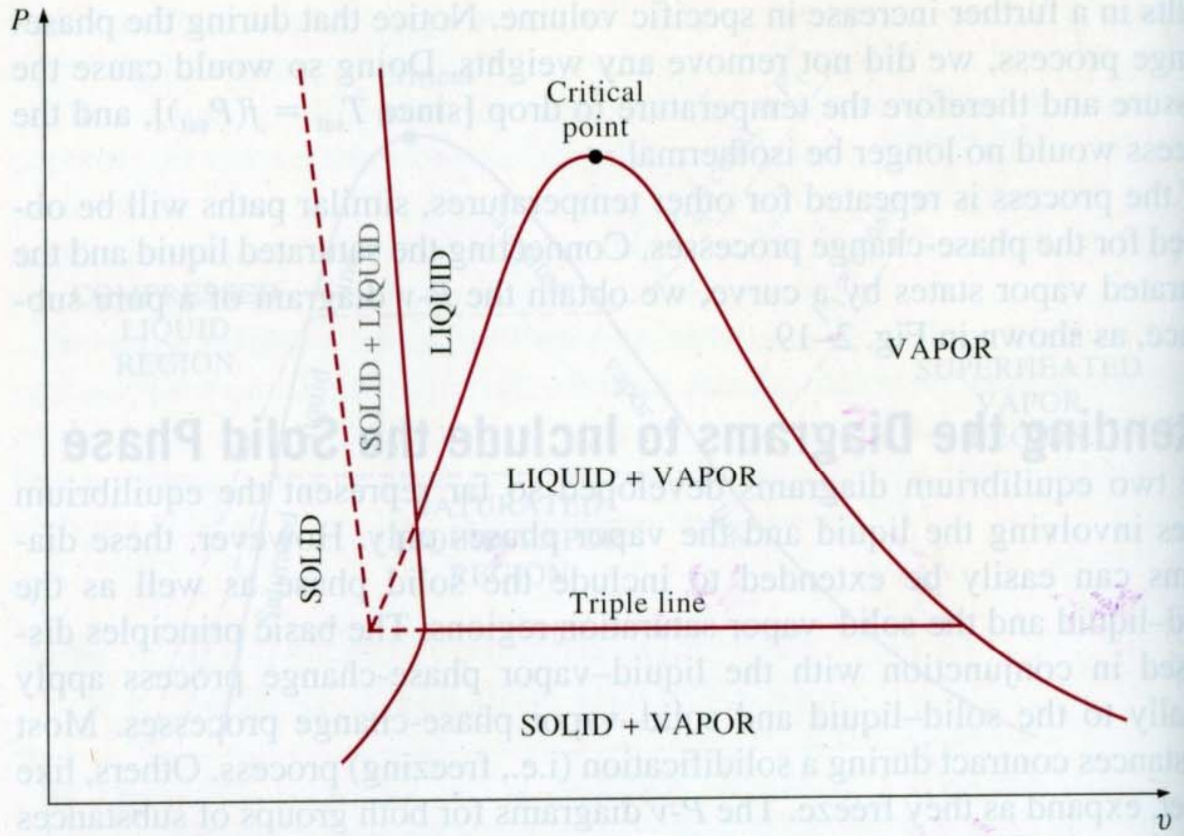


FIGURE 2–22

P-*v* diagram of a substance that expands on freezing (such as water).

เส้นการระเหิด (sublimation line) เส้นขอบเขตของเฟสซึ่งมีเฟสของแข็งและไออยู่ในสมดุลบนเส้นนี้
เส้นการหลอมตัว (fusion line) เส้นขอบเขตของเฟสของแข็งและของเหลวอยู่ในสมดุลบนเส้นนี้
เส้นการระเหย (vaporization line) เส้นขอบเขตของเฟสของเหลวและไออยู่ในสมดุลบนเส้นนี้

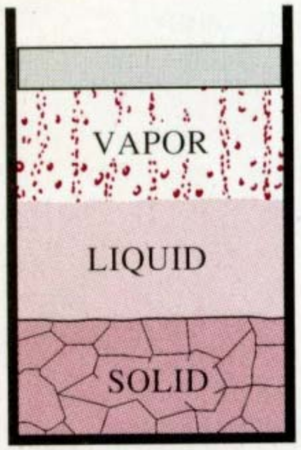


FIGURE 2–23
At triple-point pressure and temperature, a substance exists in three phases in equilibrium.

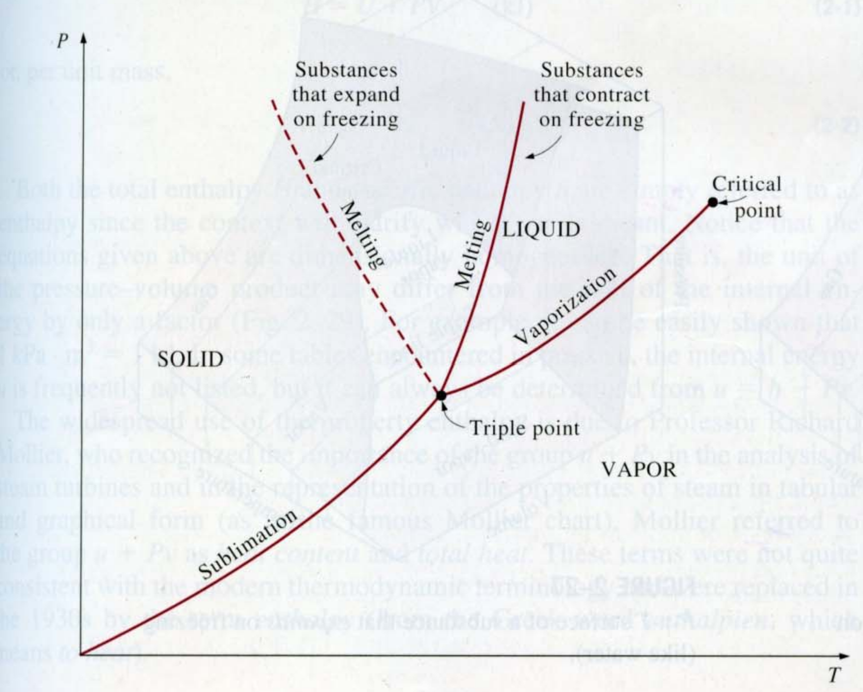


FIGURE 2-25
P-T diagram of pure substances.

Saturated Temperature and Saturation Pressure

TABLE 2–3

Triple-point temperatures and pressures of various substances

Substance	Formula	T_{tp}, K	P_{tp}, kPa
Acetylene	C_2H_2	192.4	120
Ammonia	NH_3	195.40	6.076
Argon	A	83.81	68.9
Carbon (graphite)	C	3900	10,100
Carbon dioxide	CO_2	216.55	517
Carbon monoxide	CO	68.10	15.37
Deuterium	D_2	18.63	17.1
Ethane	C_2H_6	89.89	8×10^{-4}
Ethylene	C_2H_4	104.0	0.12
Helium 4 (λ point)	He	2.19	5.1
Hydrogen	H_2	13.84	7.04
Hydrogen chloride	HCl	158.96	13.9
Mercury	Hg	234.2	1.65×10^{-7}
Methane	CH_4	90.68	11.7
Neon	Ne	24.57	43.2
Nitric oxide	NO	109.50	21.92
Nitrogen	N_2	63.18	12.6
Nitrous oxide	N_2O	182.34	87.85
Oxygen	O_2	54.36	0.152
Palladium	Pd	1825	3.5×10^{-3}
Platinum	Pt	2045	2.0×10^{-4}
Sulfur dioxide	SO_2	197.69	1.67
Titanium	Ti	1941	5.3×10^{-3}
Uranium hexafluoride	UF_6	337.17	151.7
Water	H_2O	273.16	0.61
Xenon	Xe	161.3	81.5
Zinc	Zn	692.65	0.065

Source: Data from National Bureau of Standards (U.S.) Circ., 500 (1952).

The P-v Surface

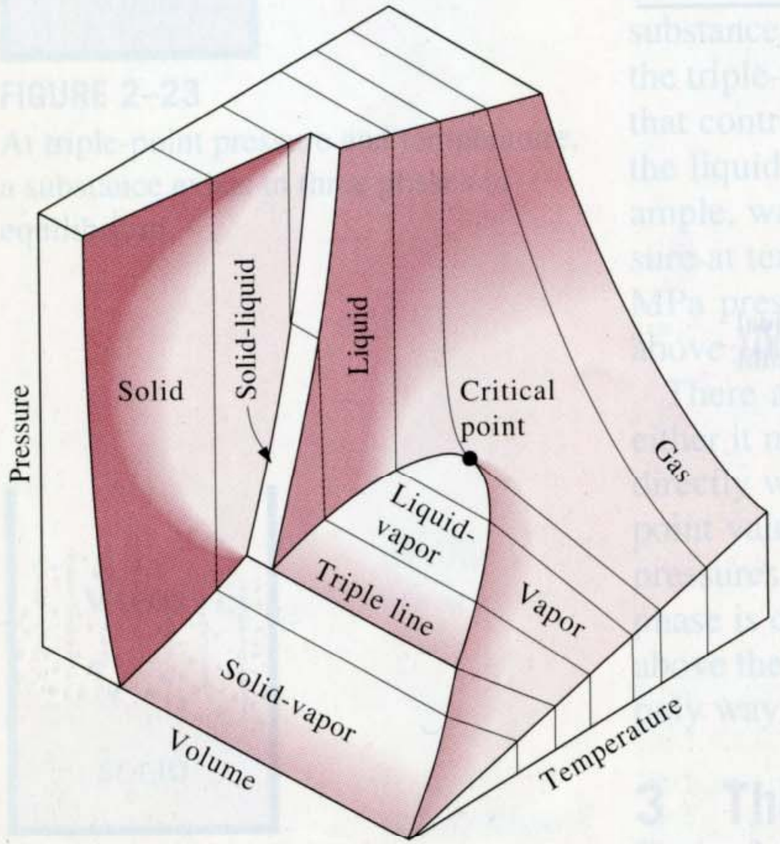


FIGURE 2–26
P-v-T surface of a substance that *contracts* on freezing.

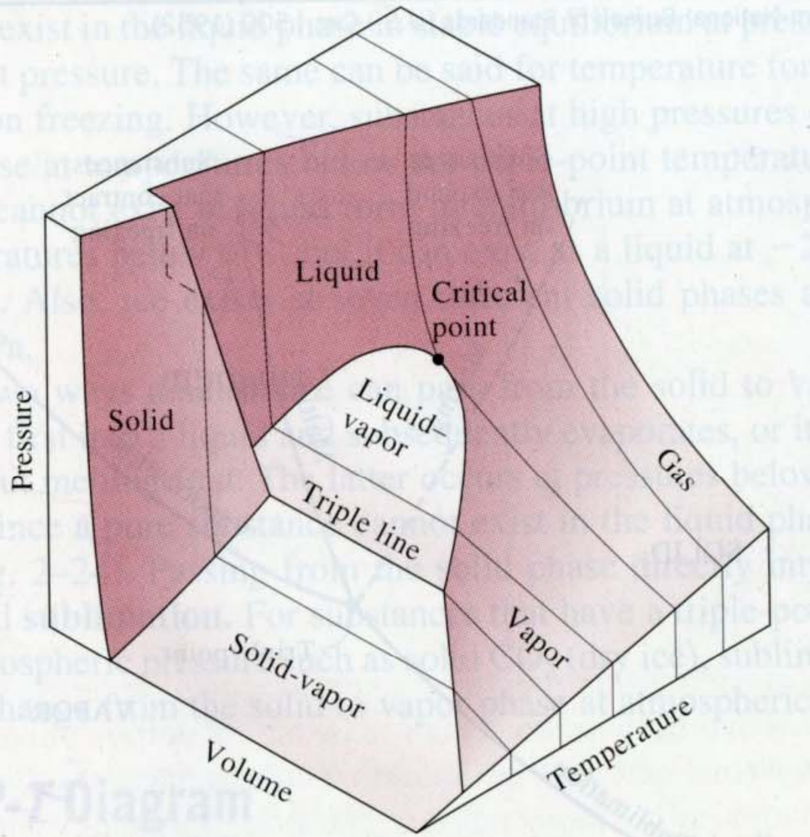


FIGURE 2–27
P-v-T surface of a substance that *expands* on freezing (like water).

2-5. PROPERTY TABLES

Defined as a new property, enthalpy, and given the symbol (H):

เอนทาลปี (Enthalpy, H)

เอนทาลปีเป็นคุณสมบัติที่ได้จากผลรวมของพลังงานภายในกับพลังงานที่เกิดจากการไหล (flow work) เขียนเป็นความสัมพันธ์ได้ดังนี้คือ

$$\mathbf{H = U + PV} \qquad \text{(kJ)}$$

Or

$$\mathbf{h = u + Pv} \qquad \text{(kJ/kg)}$$

โดยที่ PV คือพลังงานที่เกิดจากการไหลซึ่งจะกล่าวถึงในภายหลัง สำหรับค่าเอนทาลปีต่อหน่วยมวล หรือเอนทาลปีจำเพาะ (specific enthalpy) จะใช้สัญลักษณ์ h

คุณสมบัติทางเทอร์โมไดนามิกส์ ของสารในการเปลี่ยนสถานะจากของเหลวกลายเป็นไอ

$$v_{fg} = v_g - v_f$$

V_f = ปริมาตรจำเพาะของสารที่จุดของเหลวอิ่มตัว
V_g = ปริมาตรจำเพาะของสารที่จุดไออิ่มตัว
V_{fg} = ปริมาตรจำเพาะของสารขณะเปลี่ยนสถานะ

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คุณสมบัติทางเทอร์โมไดนามิกส์ ของสารในการเปลี่ยนสถานะจากของเหลวกลายเป็นไอ

$$h_{fg} = h_g - h_f$$

h_f = เอนทาลปีของสารที่จุดของเหลวอิ่มตัว

h_g =เอนทาลปีของสารที่จุดไออิ่มตัว

h_{fg} =เอนทาลปีของสารขณะเปลี่ยนสถานะ

คุณสมบัติทางเทอร์โมไดนามิกส์ ของสารในการเปลี่ยนสถานะจากของเหลวกลายเป็นไอ

$$u_{fg} = u_g - u_f$$

u_f = พลังงานภายในของสารที่จุดของเหลวอิ่มตัว

u_g = พลังงานภายในของสารที่จุดไออิ่มตัว

u_{fg} = พลังงานภายในขณะเปลี่ยนสถานะ

1a Saturated Liquid and Saturated Vapor States

Defined as a new property, enthalpy, and given the symbol (H):

Temp. °C T	Sat. press kPa P_{sat}	Specific volume m³/kg: Sat. liquid v_f	Specific volume m³/kg: Sat. vapor v_g
85	57.83	0.001 033	2.828
90	70.14	0.001 036	2.361
95	84.55	0.001 040	1.982

Specific temperature

Corresponding saturation pressure

Specific volume of saturated liquid

Specific volume of saturated vapor

FIGURE 2–30

A partial list of Table A–4.

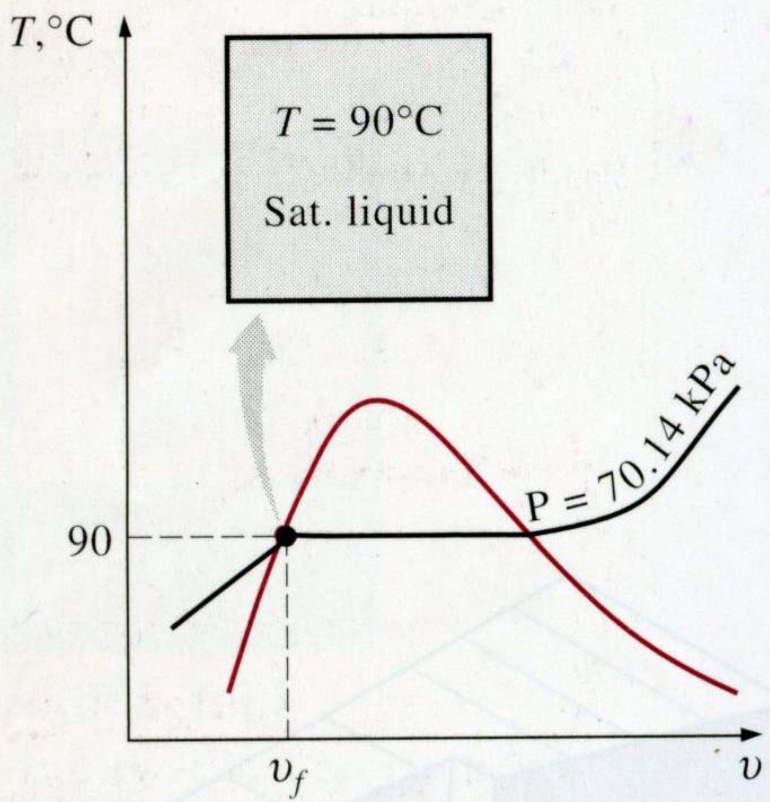

FIGURE 2–31

Schematic and *T*-*v* diagram for Example 2–1.

Ex 2-1 **A rigid tank contains 50 kg of *saturated liquid* water at 90 °C.**

Determine the *pressure* in the tank and the *volume* of the tank

SOLUTION

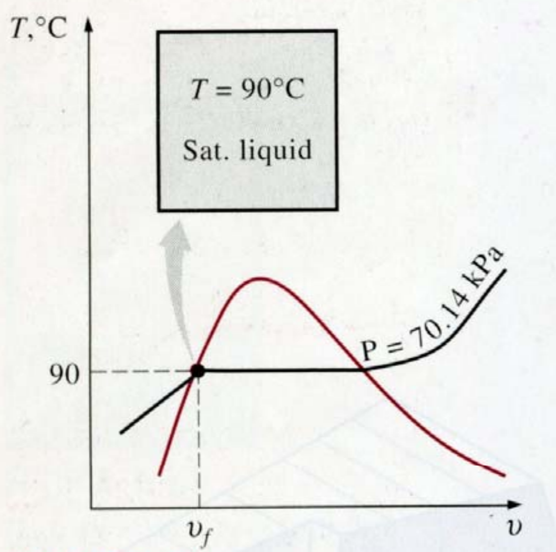

FIGURE 2–31
Schematic and T-v diagram for Example 2–1.

From Table (Table A-4)

$P = P_{sat@90\ oC}$ = ***70.14 kPa***

The specific volume of the saturated liquid at 90 °C

$\mathbf{v = v_{f@90\ oC} = 0.001036\ m^3/kg}$

Total volume of the tank is

$\mathbf{V = mv = (50kg)(0.001036 m^3/kg) =} \boldsymbol{0.0518\ m^3}$

Ex 2-2 **A piston-cylinder device contains 0.057 m^3 of saturated water vapor at 350 kPa pressure. Determine the *temperature* and the *mass* of the vapor inside the cylinder.**

SOLUTION

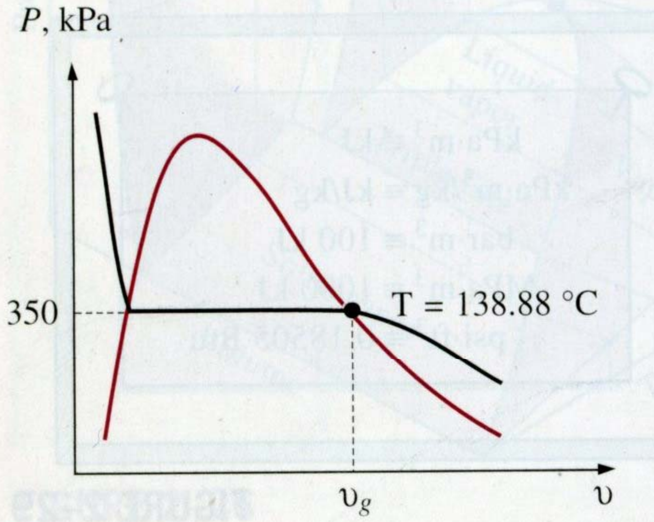

FIGURE 2–32
Schematic and P-v diagram for Example 2–2.

From Table (Table A-5)

$T = T_{sat@350kPa} = \mathit{138.88}\ ^oC$

The specific volume of the saturated vapor at 90 ^oC

$v = v_{g@350kPa} = 0.5243\ m^3/kg$

The mass of water vapor inside the cylinder

$m = V/v = (0.057\ m^3)/(0.5243\ m^3/kg) = \mathit{0.109\ kg}$

Ex 2-3 **A mass of 200 g of saturation liquid water is completely vaporized at a constant pressure of 100 kPa. Determine (a) *the volume change and* (b) *the amount of energy added to the water.***

SOLUTION

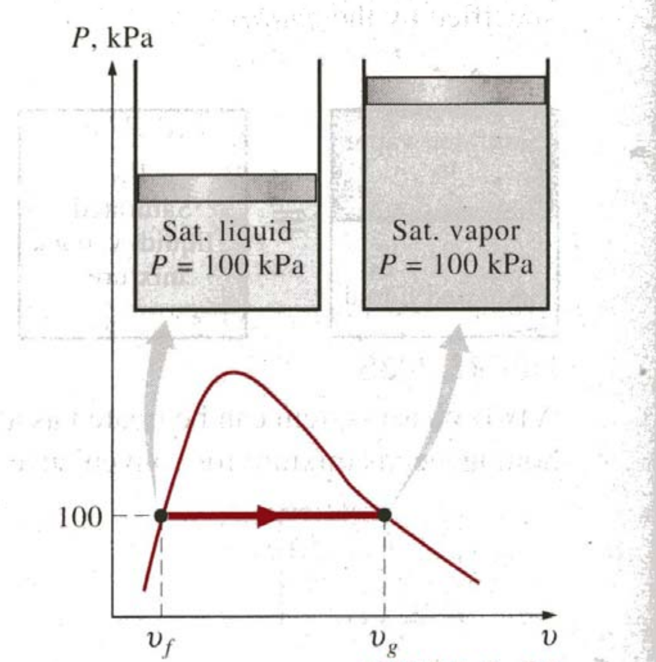

FIGURE 2–33
Schematic and *P-v* diagram for Example 2–3.

From Table (Table A-5)

$v_{fg} = v_g - v_f$ = **1.6940-0.001043 = 1.6930 m^3 /kg**

$$\Delta V = mv_{fg} = (0.2 kg)(1.6930 m^3/kg) = 0.3386 m^3$$

the amount of energy added to the water

$$mh_{fg} = (0.2 kg)(2258 kJ/kg) = 451.6 kJ$$

1b Saturated Liquid – Vapor Mixture

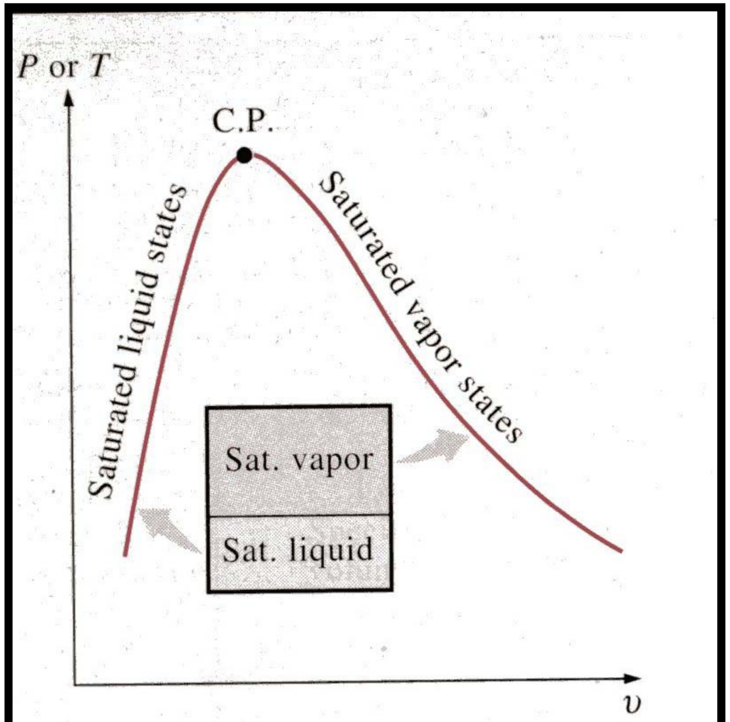

FIGURE 2–34
The relative amounts of liquid and vapor phases in a saturated mixture are specified by the *quality x*.

Analyze this mixture properly, we need to know the proportions of the liquid and vapor phases in the mixture. This is done by defining a new property called the *quality x* *as the mass of the mass of the vapor to the total mass of the mixture:*

$$x = \frac{m_{vapor}}{m_{total}}$$

where

$$m_{total} = m_{liquid} + m_{vapor} = m_f + m_g$$

1b Saturated Liquid – Vapor Mixture

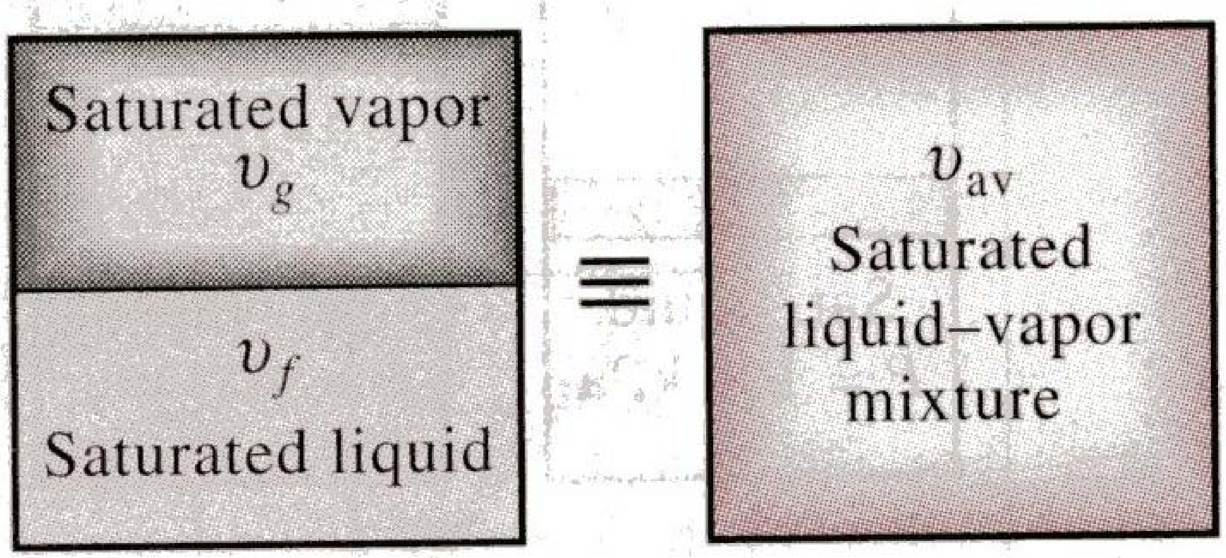

FIGURE 2–35

A two-phase system can be treated as a homogeneous mixture for convenience.

V_f = saturated liquid

V_g = saturated vapor

V = Total volume

$$V = V_f + V_g$$

$$V = mv \rightarrow m_t v_{av} = m_f v_f + m_g v_g$$

$$m_f = m_t - m_g \rightarrow m_t v_{av} = (m_t - m_g) v_f + m_g v_g$$

$$v_{av} = (1 - x) v_f + x v_g$$

$$x = m_g / m_t$$

$$v_{av} = v_f + x v_{fg} \qquad (m^3 / kg)$$

$$v_{fg} = v_g - v_f$$

$$x = \frac{v_{av} - v_f}{v_{fg}}$$

$$u_{av} = u_f + xu_{fg} \qquad \text{(kJ/kg)}$$

$$h_{av} = h_f + xh_{fg} \qquad \text{(kJ/kg)}$$

$$y_{av} = y_f + xy_{fg}$$

$$y_f \leq y_{av} \leq y_g$$

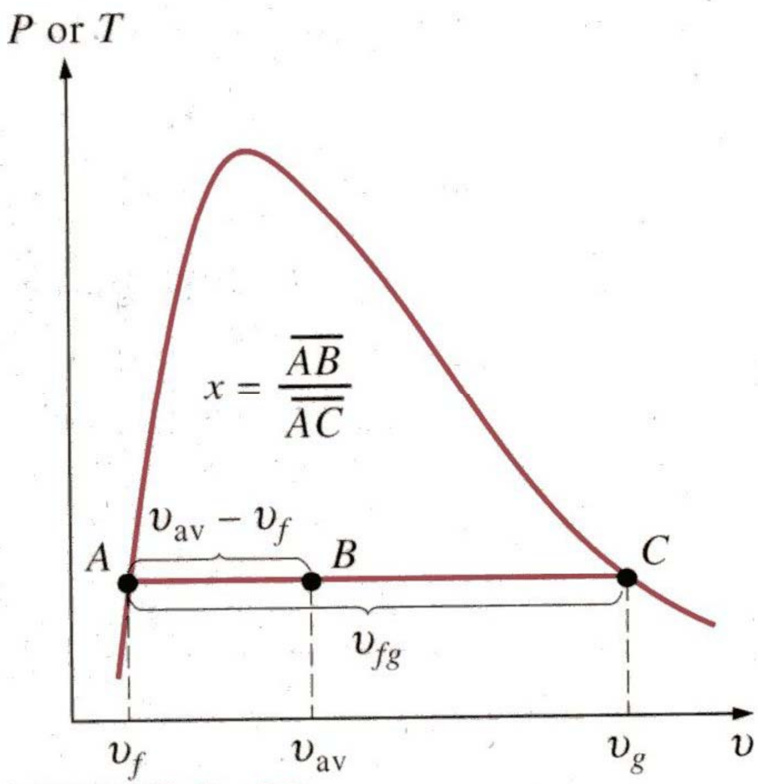

FIGURE 2–36

Quality is related to the horizontal distances on *P*-*v* and *T*-*v* diagrams.

$$v_f \leq v_{av} \leq v_g$$

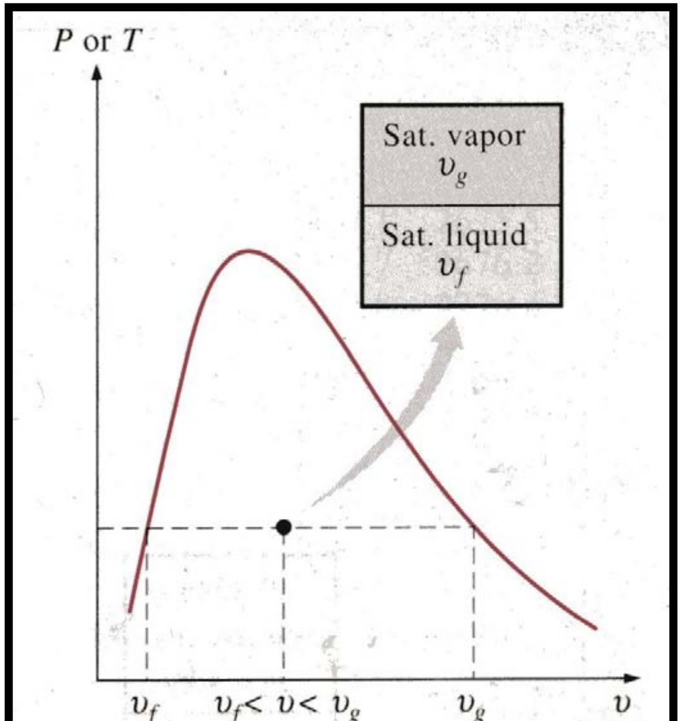

FIGURE 2–37

The v value of a saturated liquid–vapor mixture lies between the v_f and v_g values at the specified T or P.

Example 2-4

A rigid tank contains 10 kg of water at 90 °C. If 8 kg of the water is in the liquid form and the rest is in the vapor form, determine (a) the pressure in the tank (b) the volume of the tank.

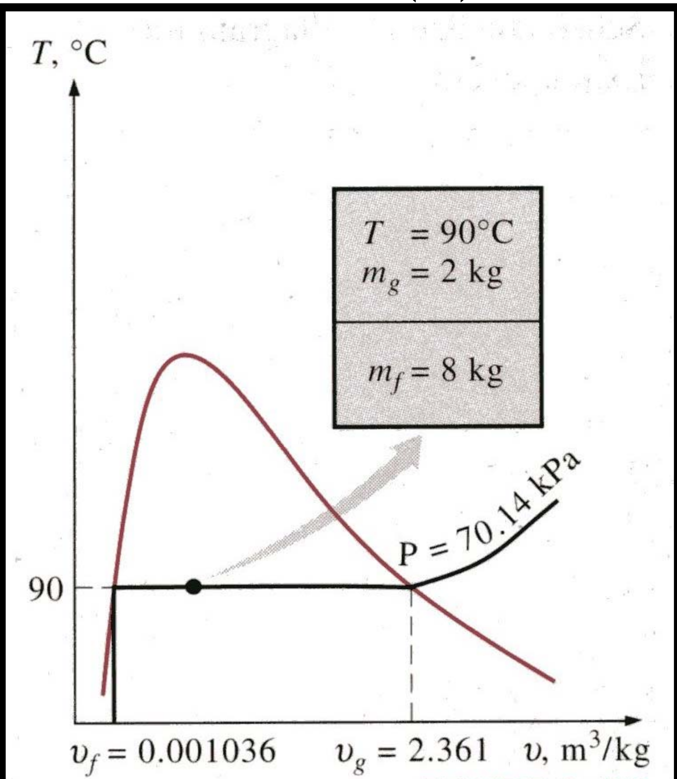

FIGURE 2–38
Schematic and T-v diagram for Example 2–4.

SOLUTION

(a) Saturation pressure from table A-4

$$P = P_{sat\,@\,90^{o}C} = 70.14\ \text{kPa}$$

(b) from table A-4

v_f = 0.001036 m^3 /kg, v_g = 2.361 m^3 /kg

$$V = V_f + V_g = m_f v_f + m_g v_g$$

$$= (8\text{kg})(0.00\ 1\text{m}^3/\text{kg}) + (2\text{kg})(2.36\ 1\text{m}^3/\text{kg})$$

$$= 4.73\text{m}^3$$

SOLUTION (ext)

Another way is to first determine the quality x

(b) Saturation pressure from table A-4

$$x = \frac{m_g}{m_t} = \frac{2\text{kg}}{10\text{kg}} = 0.2$$

Specific volume

$$v = v_f + xv_{fg}$$
$$= 0.001\text{m}^3/\text{kg} + (0.2)[(2.361 - 0.001)\text{m}^3/\text{kg}]$$
$$= 0.473\text{m}^3/\text{kg}$$

Volume of the tank

$$V = mv = (10\text{kg})(0.473\text{m}^3/\text{kg}) = 4.73\text{m}^3$$

Example 2-5

An 80-L vessel contains 4 kg of refrigerant-R134a at a pressure of 160 kPa. Determine (a) the temperture of refrigerant (b) the quality, (c) the enthalpy of the refrigerant, and (d) the volume occupied by the vapor phase.

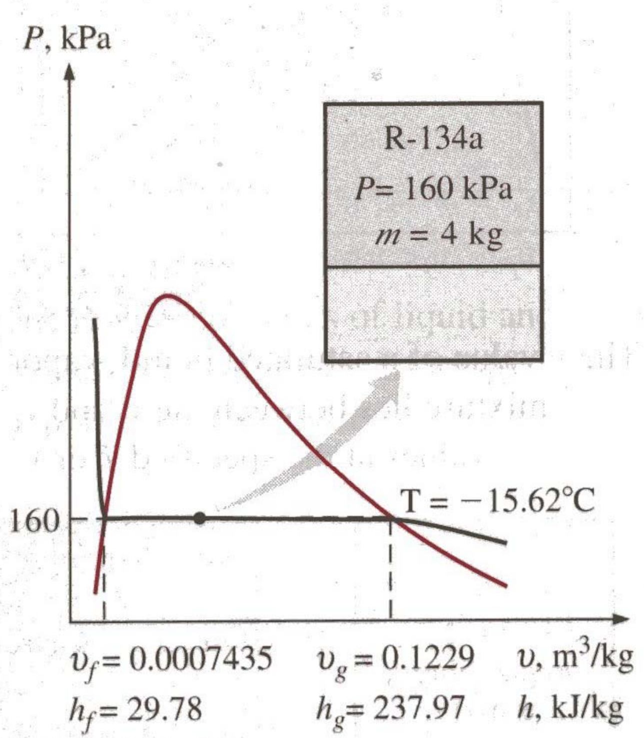

FIGURE 2-39
Schematic and P-v diagram for Example 2-5.

SOLUTION

(a)

$$v = \frac{V}{m} = \frac{0.080\ \text{m}^3}{4\ \text{kg}} = 0.02\ \text{m}^3/\text{kg}$$

At 160 kPa, from Table A-12

$v_f = 0.0007435\ \text{m}^3/\text{kg}$, $v_g = 0.1229\ \text{m}^3/\text{kg}$

$$T = T_{sat\ @160\ kPa} = -15.62\ ^{\circ}\text{C}$$

Example 2-5(Ext.)

(b)

$$x = \frac{v - v_f}{v_{fg}} = \frac{0.02 - 0.0007435}{0.1229 - 0.0007435} = 0.158$$

(c) At 160 kPa, from Table A-12 that h_f =29.78 kJ/kg, h_{fg} = 208.18 kJ/kg

$$h = h_f + xh_{fg}$$
$$= 29.78\text{kJ/kg} + (0.158)(20\ 8.18\text{kJ/kg})$$
$$= 62.7\text{kJ/kg}$$

(d) The mass of the vapor can be determined from Eq.2-3

$m_g = xm_t$ =(0.158)(4kg) = 0.6322 kg

$$V_g = m_g v_g = (0.632\text{kg})(0.1229\text{m}^3/\text{kg}) = 0.0777\text{m}^3\ (\text{or}77.7\text{L})$$

PROBLEMS

1. A gas is contained in a vertical, frictionless piston–cylinder device. The piston has a mass of 4 kg and cross sectional area of 35 cm^2 . A compressed spring above the piston exerts a force of 60 N on the piston. If the atmospheric pressure is 95 kPa, determine the pressure inside the cylinder. (123.4 kPa)

2 The average atmospheric pressure in Denver (elevation = 1610 m) is 83.4 kPa. Determine the temperature at which water in an uncovered pan will boil in Denver. (94.4°C)