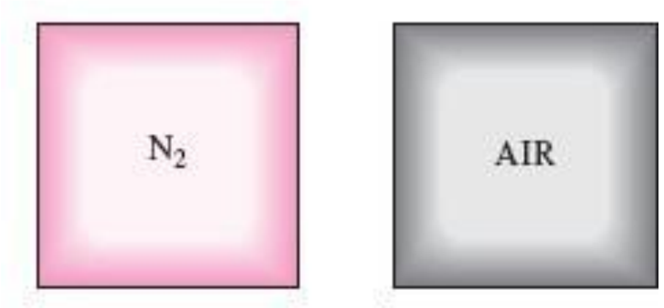
CHAPTER

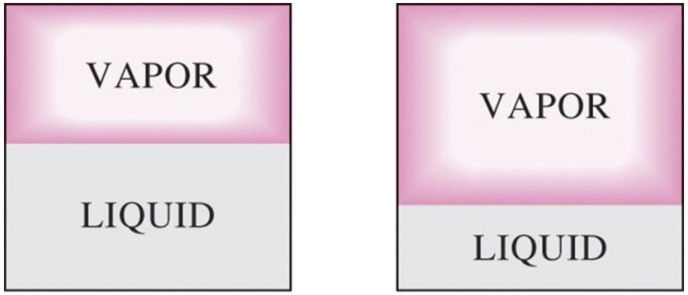
2

Properties of Pure Substances

What is Pure Substances?

- A substance that has a fixed chemical composition throughout is called a **pure substance.**
- A pure substance does not have to be of a single chemical element or compound, however. A mixture of various chemical elements or compounds also qualifies as a pure substance as long as the mixture is *homogeneous*.





(*a*) H_2O (*b*) AIR

- A mixture of liquid and water vapor is a pure substance, but a mixture of liquid and gaseous air is not.

Examples:

- Water (solid, liquid, and vapor phases)
- Mixture of liquid water and water vapor
- Carbon dioxide, CO_2
- Nitrogen, N_2
- Mixtures of gases, such as air, as long as there is no change of phase.

Phases of A Pure Substance

- The substances exist in different phases, e.g. at room temperature and pressure, copper is solid and mercury is a liquid.

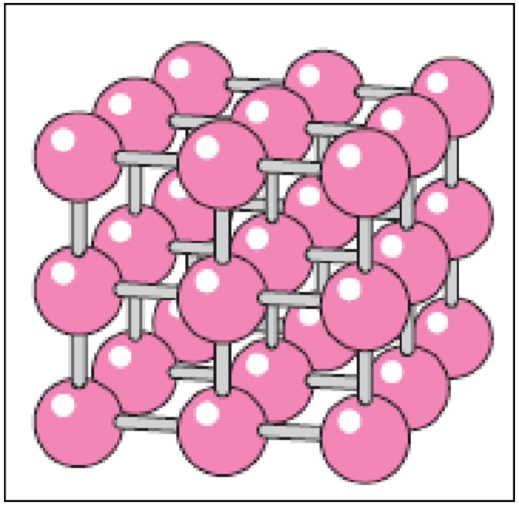
- It can exist in different phases under variations of condition.

- There are 3 Principal phases
  - *solid*
  - *Liquid*
  - *gas*

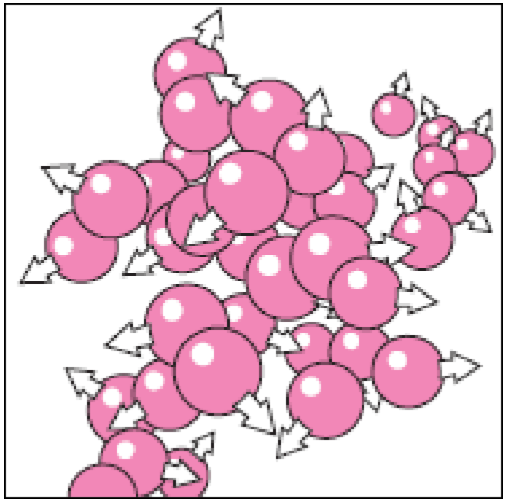
  Each with different molecular structures.

Phase-change Processes of Pure Substances

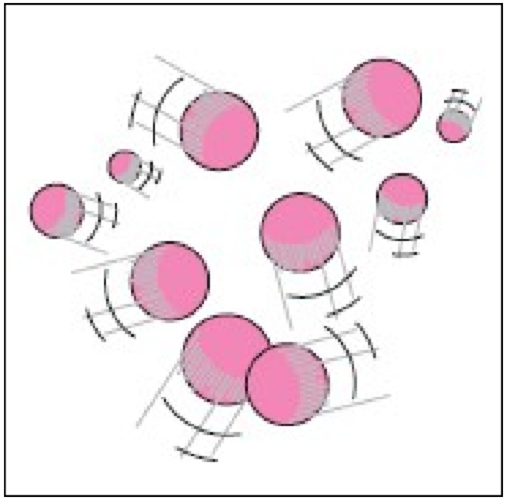
- There are many practical situations where two phases of a pure substances coexist in equilibrium.
- E.g. water exists as a mixture of liquid and vapor in the boiler and etc.
  - Solid: strong intermolecular bond
  - Liquid: intermediate intermolecular bonds
  - Gas: weak intermolecular bond



Solid

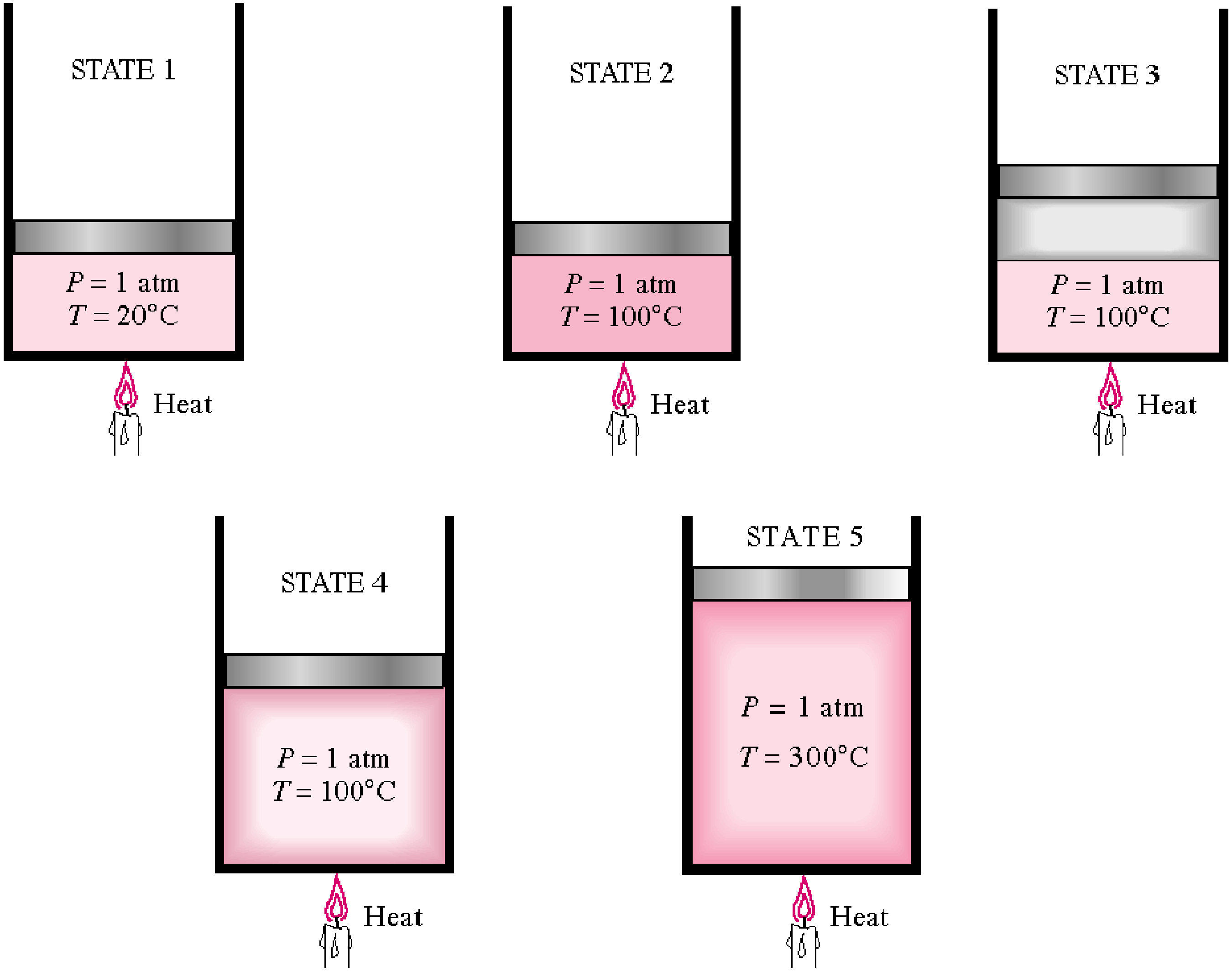


Liquid

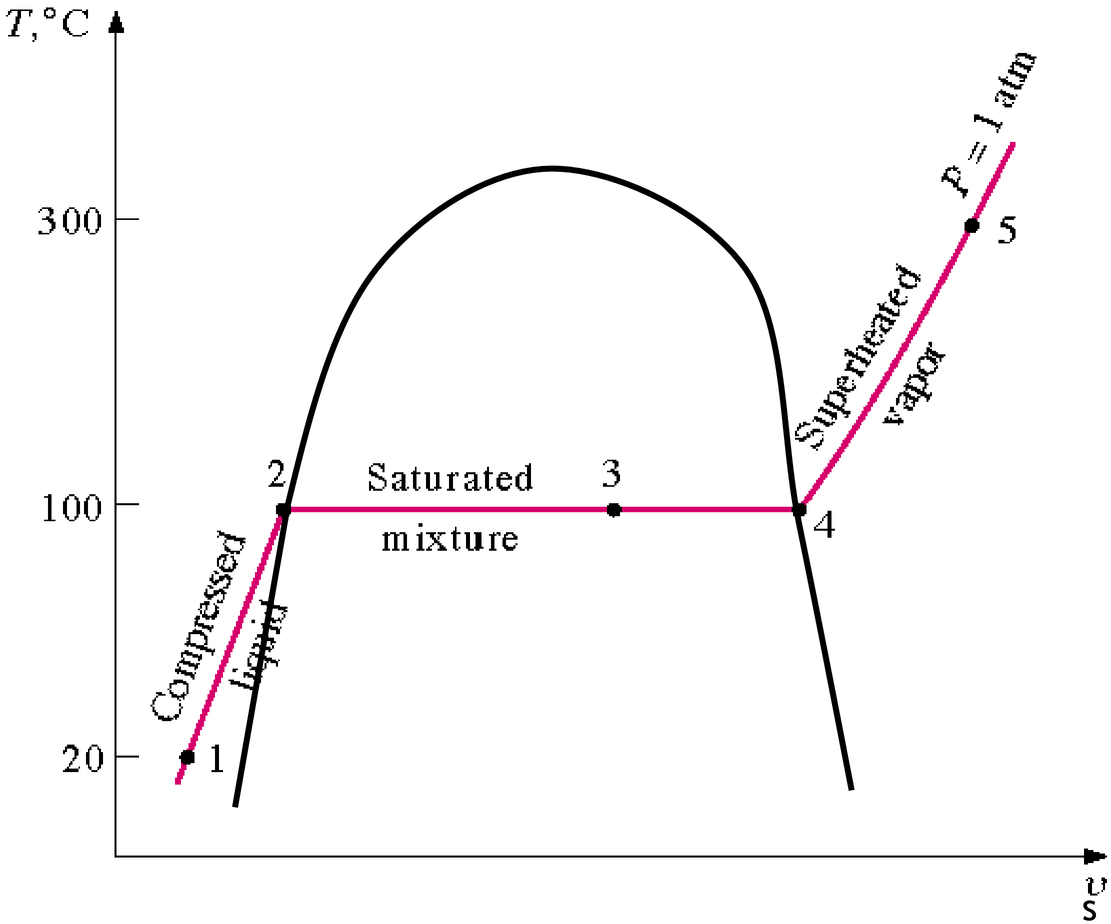


Gas

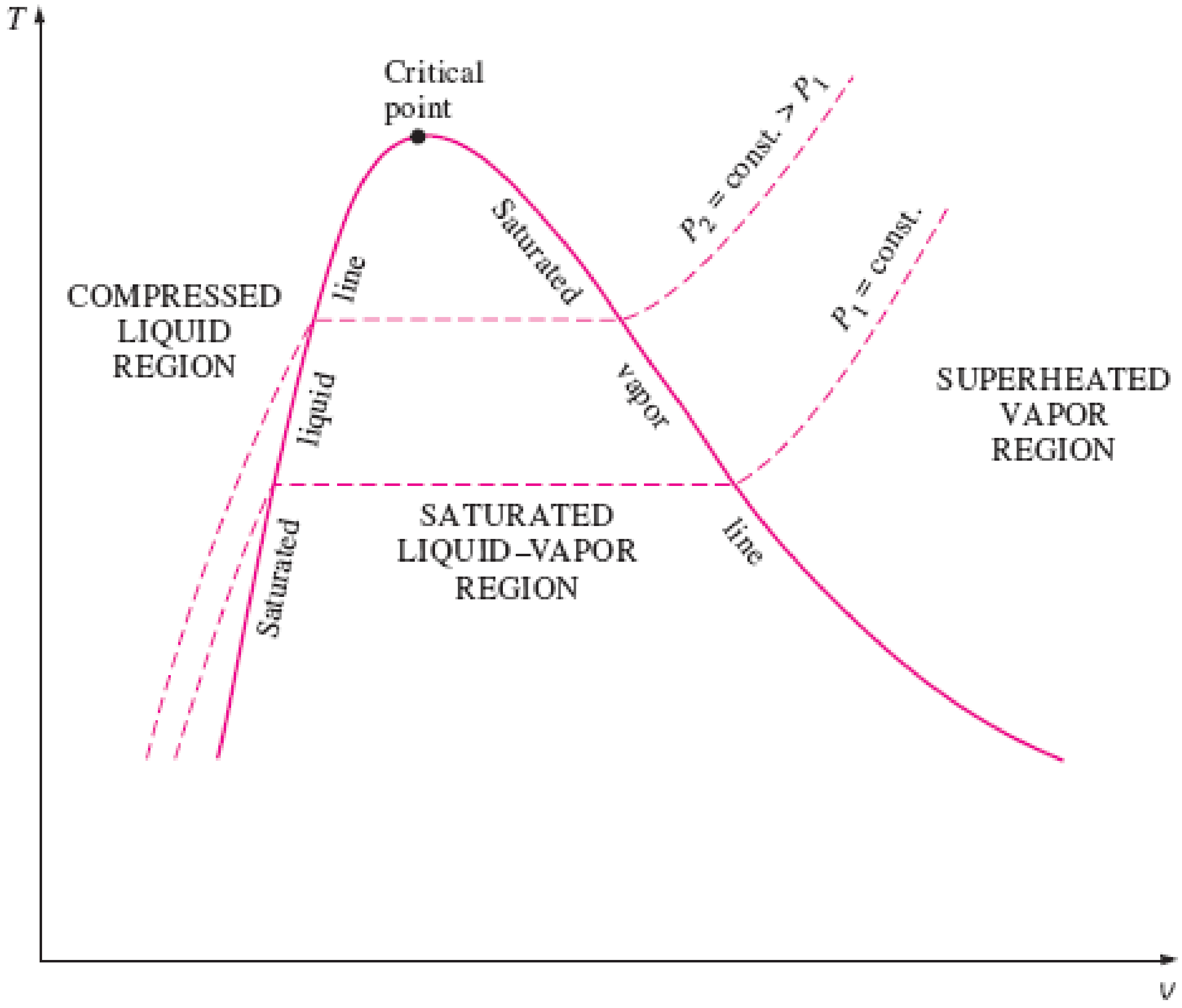
Phase-change Processes



This constant pressure heating process can be illustrated as:



Property Diagram



Saturation

- *Saturation* is defined as a condition in which a mixture of vapor and liquid can exist together at a given temperature and pressure.

- *Saturation pressure* is the pressure at which the liquid and vapor phases are in equilibrium at a given temperature

- For a pure substance there is a definite relationship between saturation pressure and saturation temperature. The higher the pressure, the higher the saturation temperature

The graphical representation of this relationship between temperature and pressure at saturated conditions is called the *vapor pressure curve*

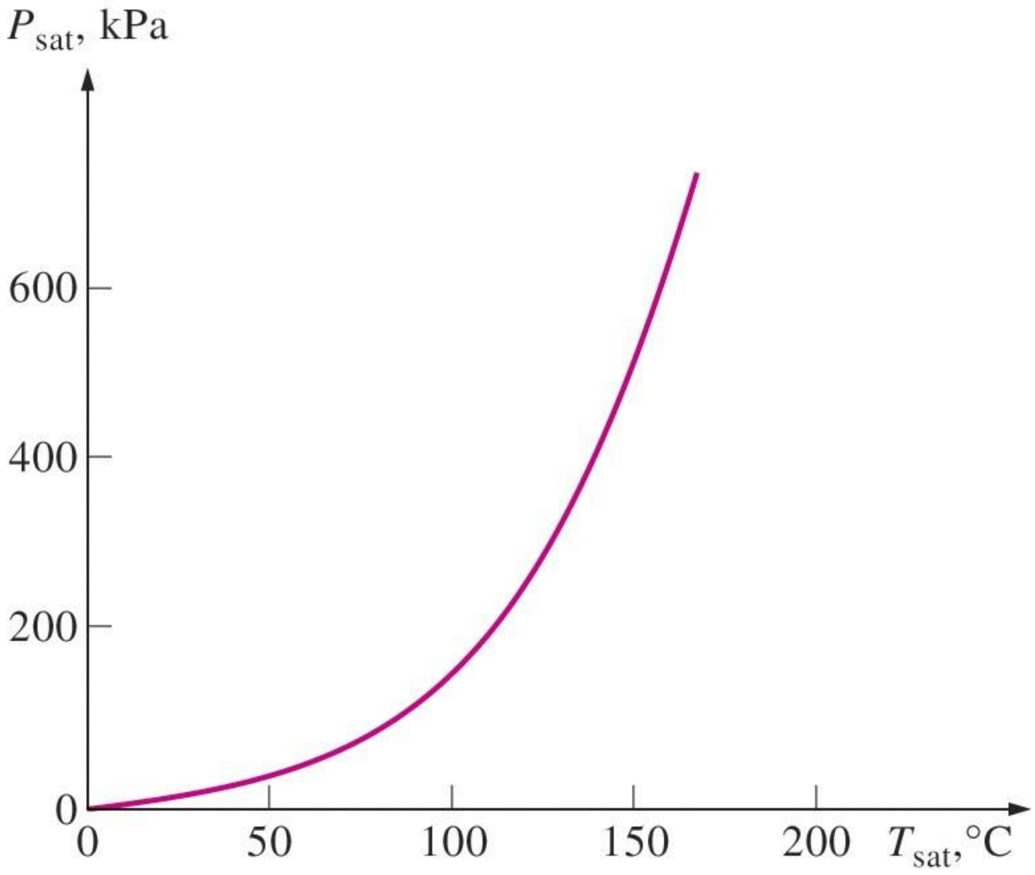


TABLE 3–1

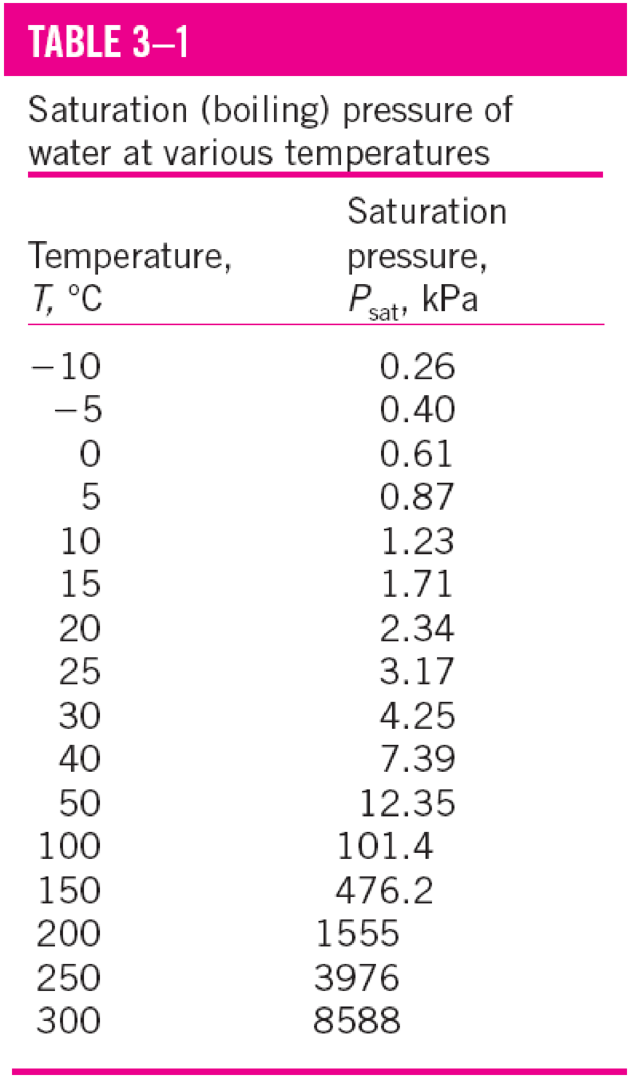
Saturation (boiling) pressure of water at various temperatures

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	7.39
50	12.35
100	101.4
150	476.2
200	1555
250	3976
300	8588

Saturated and Sub-cooled Liquids

- If a substance exists as a liquid at the saturation temperature and pressure, it is called a *saturated liquid*

- If the temperature of the liquid is lower than the saturation temperature for the existing pressure, it is called either a *subcooled liquid* or a *compressed liquid*



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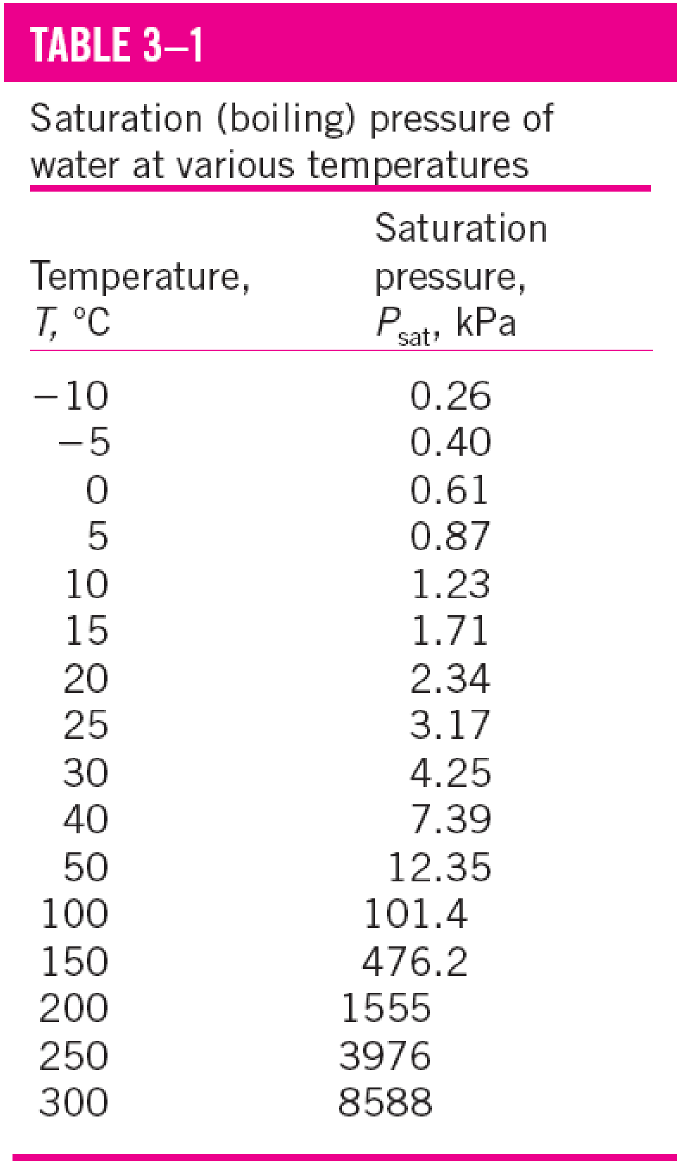
Saturated and Superheated Vapors



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40	7.39
50	12.35
100	101.4
150	476.2
200	1555
250	3976
300	8588

- If a substance exists entirely as vapor at saturation temperature, it is called *saturated vapor*.
- When the vapor is at a temperature greater than the saturation temperature, it is said to exist as *superheated vapor*.
- The pressure and temperature of superheated vapor are independent properties, since the temperature may increase while the pressure remains constant

Latent Heat

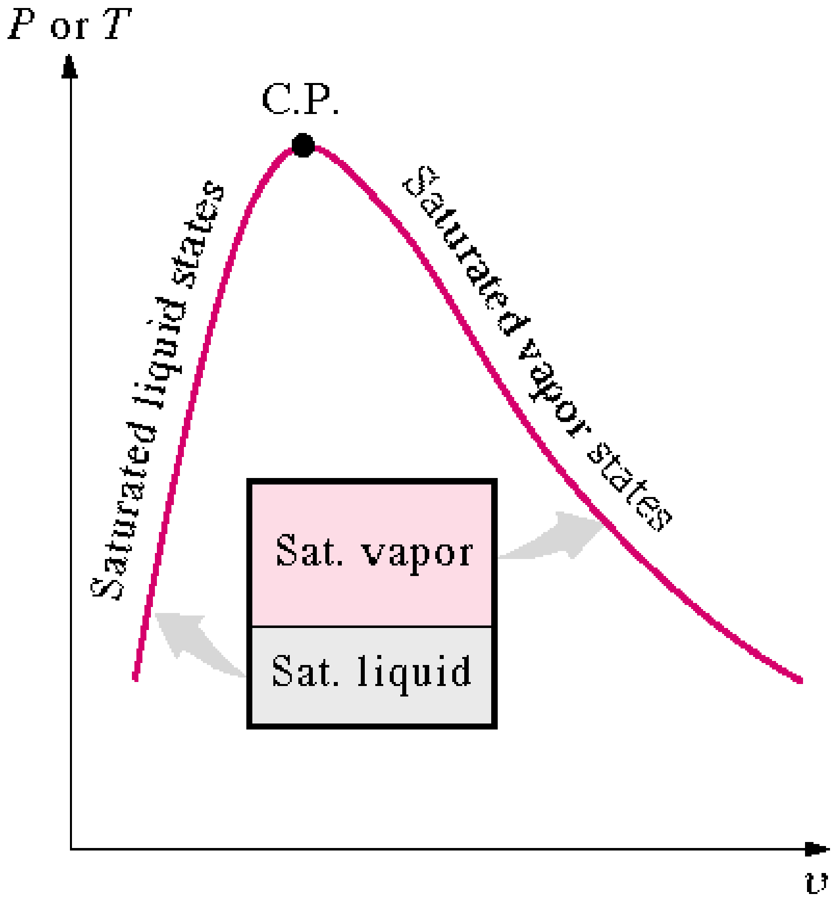
- **Latent heat**: The amount of energy absorbed or released during a phase-change process.
- **Latent heat of fusion**: The amount of energy absorbed during melting. It is equivalent to the amount of energy released during freezing.
- **Latent heat of vaporization**: The amount of energy absorbed during vaporization and it is equivalent to the energy released during condensation.
  - *At 1 atm pressure, the latent heat of fusion of water is 333.7 kJ/kg and the latent heat of vaporization is 2256.5 kJ/kg.*

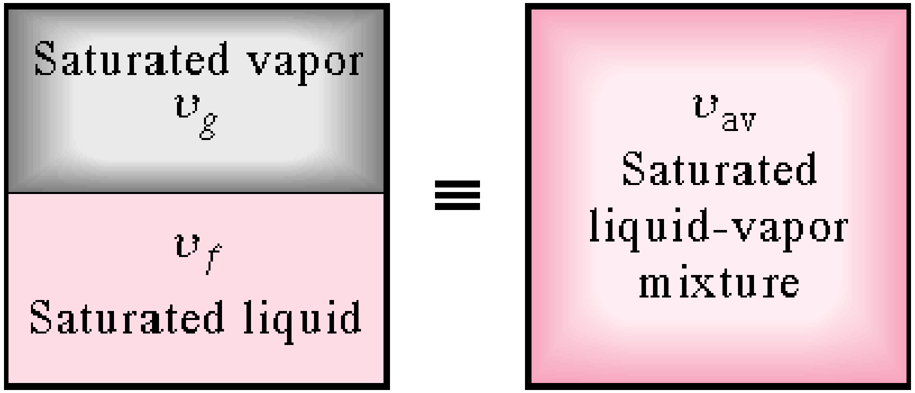
Quality

- When a substance exists as part liquid and part vapor at saturation conditions, its *quality* (x) is **defined** as the ratio of the mass of the vapor to the total mass of both vapor and liquid.
- The quality is zero for the saturated liquid and one for the saturated vapor ($0 \leq x \leq 1$)
- For example, if the mass of vapor is 0.2 g and the mass of the liquid is 0.8 g, then the quality is 0.2 or 20%.

$$x = \frac{mass_{saturated\ vapor}}{mass_{total}} = \frac{m_g}{m_f + m_g}$$

Quality





Mixture of liquid and vapor

Moisture Content

- The *moisture content* of a substance is the opposite of its quality. Moisture is defined as the ratio of the mass of the liquid to the total mass of both liquid and vapor

- Recall the definition of quality x

$$x = \frac{m_g}{m} = \frac{m_g}{m_f + m_g}$$

- Then

$$\frac{m_f}{m} = \frac{m - m_g}{m} = 1 - x$$

Moisture Content

- ♣ Take specific volume as an example. The specific volume of the saturated mixture becomes

$$v = (1 - x)v_f + xv_g$$

- ♣ The form that is most often used

$$v = v_f + x(v_g - v_f)$$

- ♣ Let *Y* be any extensive property and let *y* be the corresponding intensive property, *Y/m*, then

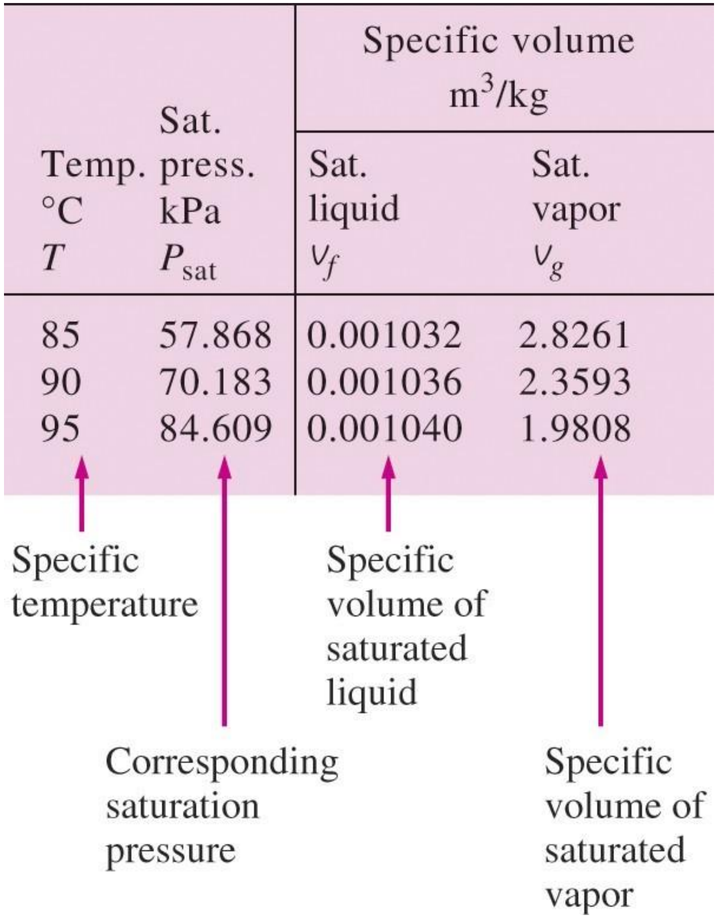
$$y = \frac{Y}{m} = y_f + x(y_g - y_f)$$

$$= y_f + x\, y_{fg}$$

$$where \quad y_{fg} = y_g - y_f$$

Property Table

- For example if the pressure and specific volume are specified, three questions are asked: For the given pressure,



Temp. °C T	Sat. press. kPa P_{sat}	Specific volume m^3/kg Sat. liquid v_f	Sat. vapor v_g
85	57.868	0.001032	2.8261
90	70.183	0.001036	2.3593
95	84.609	0.001040	1.9808

Specific temperature

Specific volume of saturated liquid

Corresponding saturation pressure

Specific volume of saturated vapor

Property Table

- If the answer to the first question is yes, the state is in the compressed liquid region, and the compressed liquid table is used to find the properties. (or using *saturation temperature table*)

$$v < v_f$$

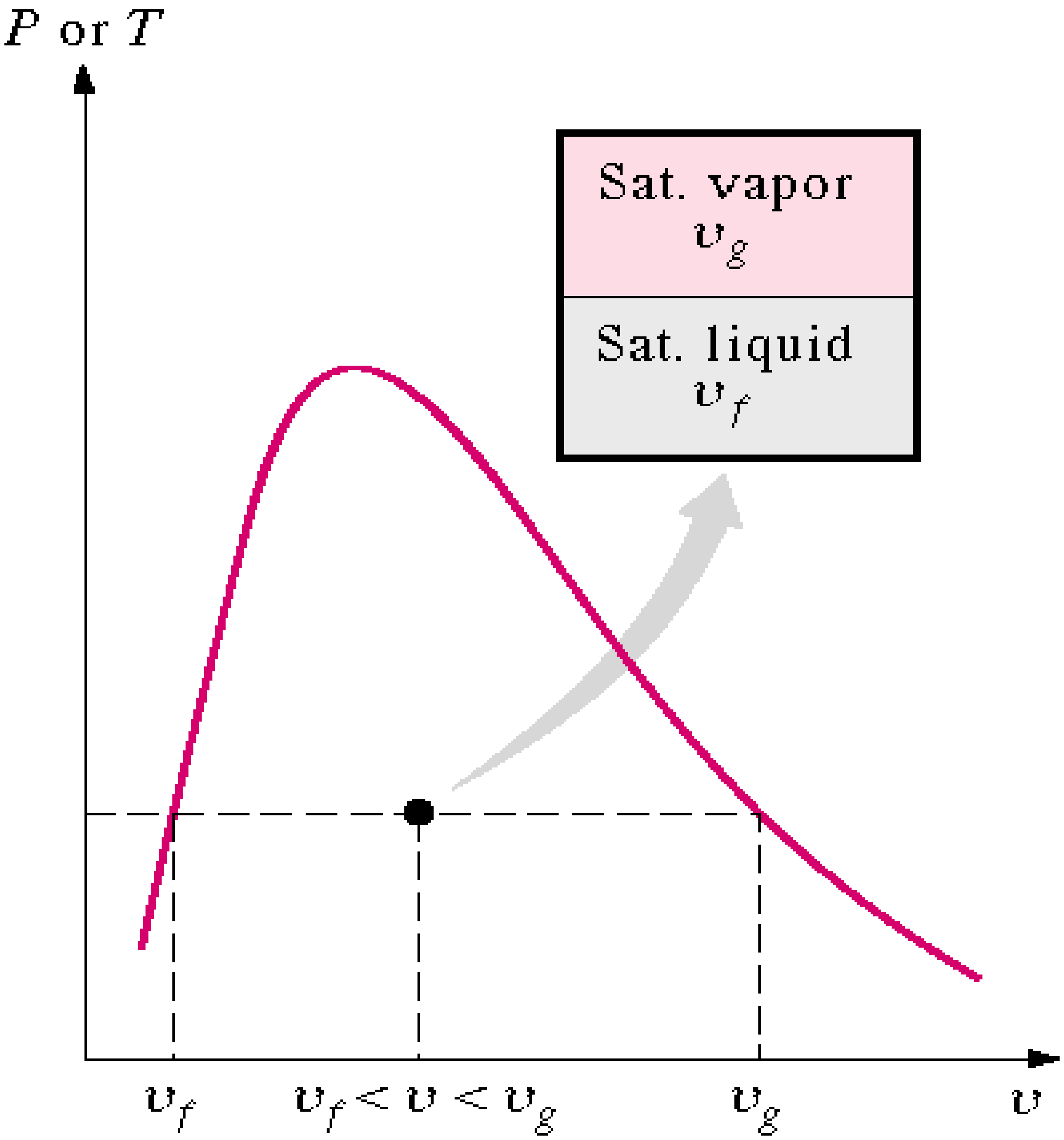
- If the answer to the second question is yes, the state is in the saturation region, and either the saturation temperature table or the saturation pressure table is used.

$$v_f < v < v_g$$

- If the answer to the third question is yes, the state is in the superheated region and the superheated table is used.

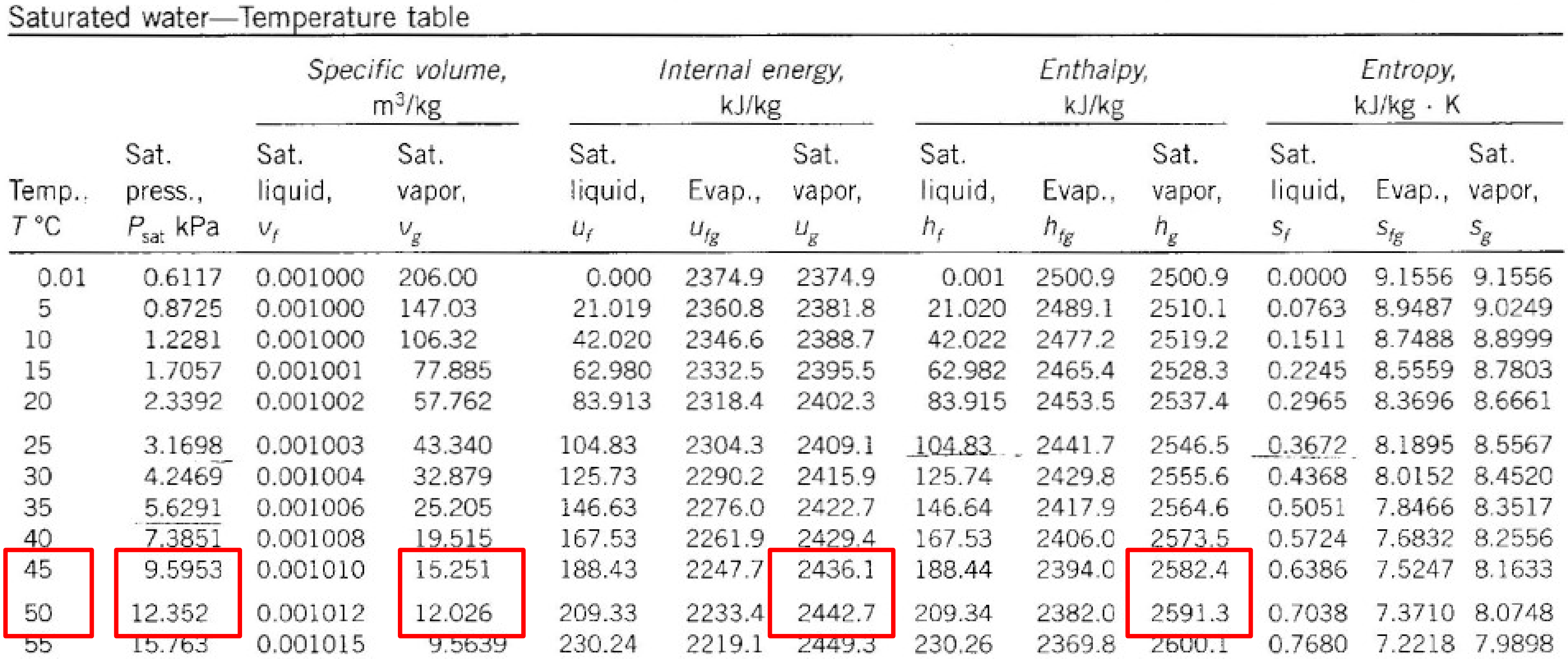
$$v_g < v$$

Property Table



Example 2.1

Determine the saturated pressure, specific volume, internal energy and enthalpy for saturated water vapor at 45°C and 50°C.

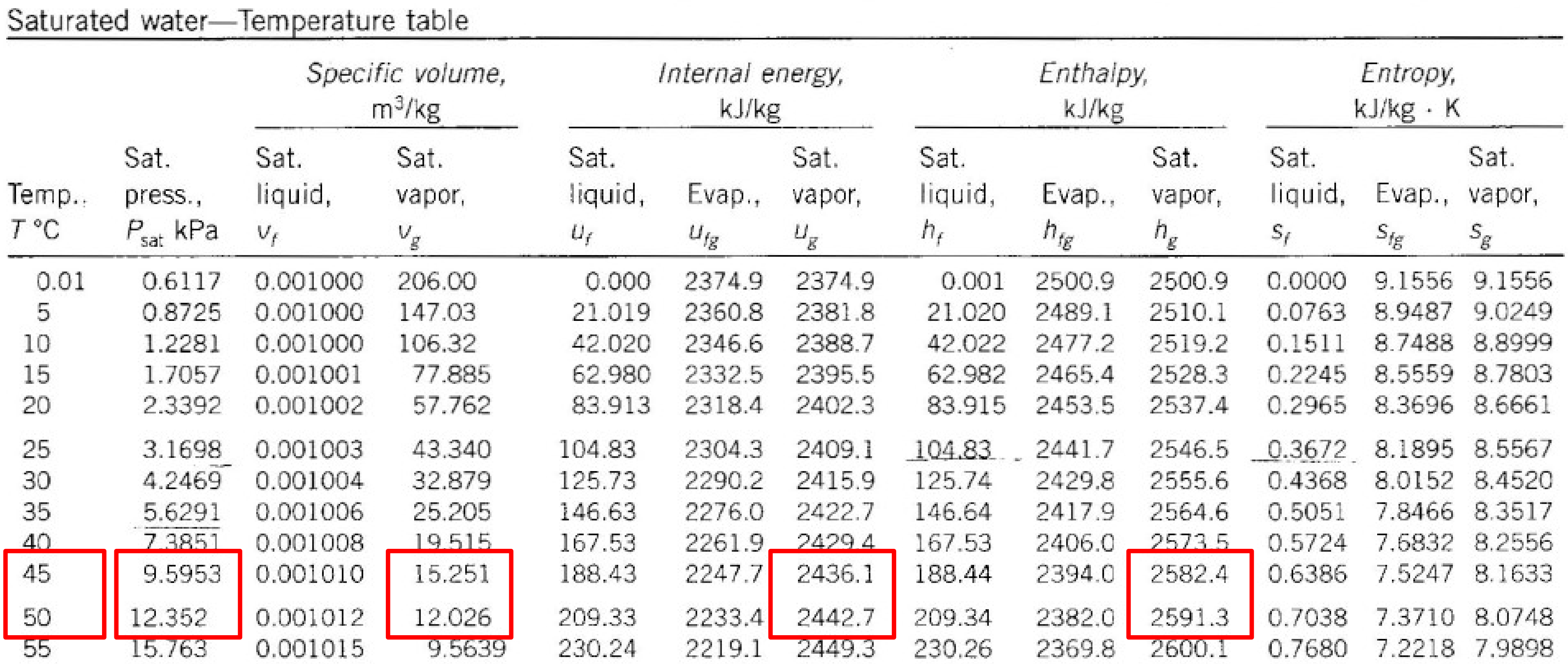


Saturated water—Temperature table

		Specific volume, m^3/kg		*Internal energy,* kJ/kg			*Enthalpy,* kJ/kg			*Entropy,* kJ/kg · K		
Temp., T °C	Sat. press., P_{sat} kPa	Sat. liquid, v_f	Sat. vapor, v_g	Sat. liquid, u_f	Evap., u_{fg}	Sat. vapor, u_g	Sat. liquid, h_f	Evap., h_{fg}	Sat. vapor, h_g	Sat. liquid, s_f	Evap., s_{fg}	Sat. vapor, s_g
0.01	0.6117	0.001000	206.00	0.000	2374.9	2374.9	0.001	2500.9	2500.9	0.0000	9.1556	9.1556
5	0.8725	0.001000	147.03	21.019	2360.8	2381.8	21.020	2489.1	2510.1	0.0763	8.9487	9.0249
10	1.2281	0.001000	106.32	42.020	2346.6	2388.7	42.022	2477.2	2519.2	0.1511	8.7488	8.8999
15	1.7057	0.001001	77.885	62.980	2332.5	2395.5	62.982	2465.4	2528.3	0.2245	8.5559	8.7803
20	2.3392	0.001002	57.762	83.913	2318.4	2402.3	83.915	2453.5	2537.4	0.2965	8.3696	8.6661
25	3.1698	0.001003	43.340	104.83	2304.3	2409.1	104.83	2441.7	2546.5	0.3672	8.1895	8.5567
30	4.2469	0.001004	32.879	125.73	2290.2	2415.9	125.74	2429.8	2555.6	0.4368	8.0152	8.4520
35	5.6291	0.001006	25.205	146.63	2276.0	2422.7	146.64	2417.9	2564.6	0.5051	7.8466	8.3517
40	7.3851	0.001008	19.515	167.53	2261.9	2429.4	167.53	2406.0	2573.5	0.5724	7.6832	8.2556
45	9.5953	0.001010	15.251	188.43	2247.7	2436.1	188.44	2394.0	2582.4	0.6386	7.5247	8.1633
50	12.352	0.001012	12.026	209.33	2233.4	2442.7	209.34	2382.0	2591.3	0.7038	7.3710	8.0748
55	15.763	0.001015	9.5639	230.24	2219.1	2449.3	230.26	2369.8	2600.1	0.7680	7.2218	7.9898

Example 2.2

Determine the saturated pressure, specific volume, internal energy and enthalpy for saturated water vapor at 47^{0} C .



Saturated water—Temperature table

		Specific volume, m^3/kg		Internal energy, kJ/kg			Enthalpy, kJ/kg			Entropy, kJ/kg · K		
Temp., T °C	Sat. press., P_{sat} kPa	Sat. liquid, v_f	Sat. vapor, v_g	Sat. liquid, u_f	Evap., u_{fg}	Sat. vapor, u_g	Sat. liquid, h_f	Evap., h_{fg}	Sat. vapor, h_g	Sat. liquid, s_f	Evap., s_{fg}	Sat. vapor, s_g
0.01	0.6117	0.001000	206.00	0.000	2374.9	2374.9	0.001	2500.9	2500.9	0.0000	9.1556	9.1556
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15	1.7057	0.001001	77.885	62.980	2332.5	2395.5	62.982	2465.4	2528.3	0.2245	8.5559	8.7803
20	2.3392	0.001002	57.762	83.913	2318.4	2402.3	83.915	2453.5	2537.4	0.2965	8.3696	8.6661
25	3.1698	0.001003	43.340	104.83	2304.3	2409.1	104.83	2441.7	2546.5	0.3672	8.1895	8.5567
30	4.2469	0.001004	32.879	125.73	2290.2	2415.9	125.74	2429.8	2555.6	0.4368	8.0152	8.4520
35	5.6291	0.001006	25.205	146.63	2276.0	2422.7	146.64	2417.9	2564.6	0.5051	7.8466	8.3517
40	7.3851	0.001008	19.515	167.53	2261.9	2429.4	167.53	2406.0	2573.5	0.5724	7.6832	8.2556
45	9.5953	0.001010	15.251	188.43	2247.7	2436.1	188.44	2394.0	2582.4	0.6386	7.5247	8.1633
50	12.352	0.001012	12.026	209.33	2233.4	2442.7	209.34	2382.0	2591.3	0.7038	7.3710	8.0748
55	15.763	0.001015	9.5639	230.24	2219.1	2449.3	230.26	2369.8	2600.1	0.7680	7.2218	7.9898

Solution:

- Extract data from steam table

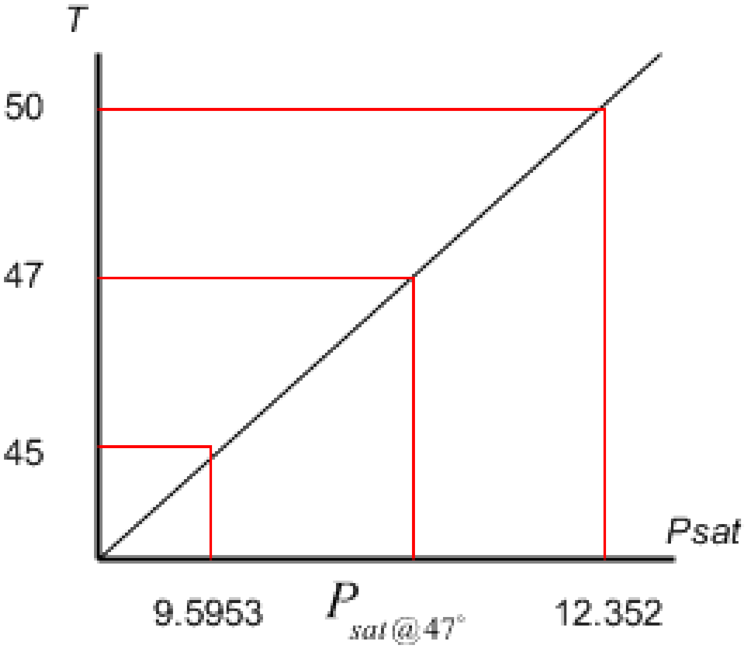
T	P_{sat}	v	u	h
45	9.5953	15.251	2436.1	2582.4
47	P_{sat}	v	u	h
50	12.352	12.026	2442.7	2591.3

- Interpolation for P_{sat}

$$\frac{P_{sat} - 9.5953}{12.352 - 9.5953} = \frac{47 - 45}{50 - 45}$$

$$P_{sat@47^{o}} = \underline{\underline{10.698\,kPa}}$$

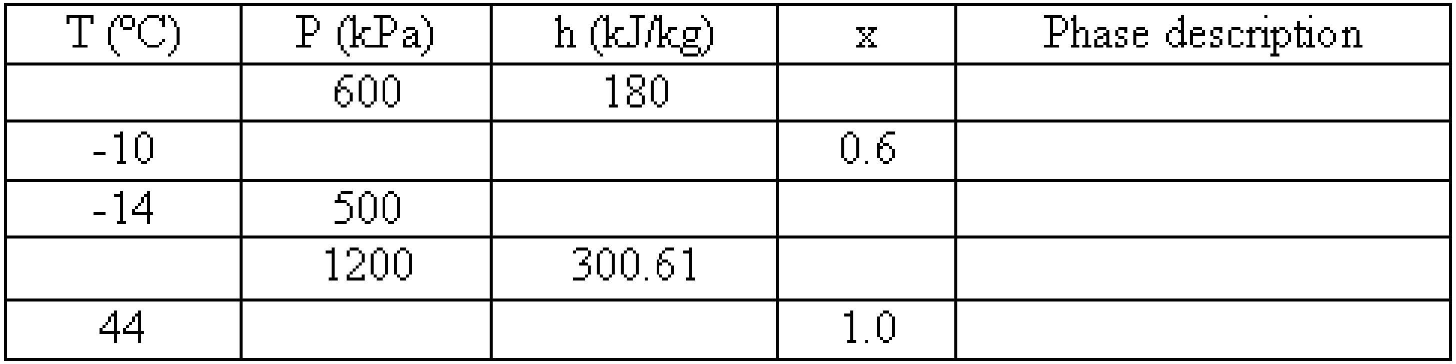
- Do the same principal to others!!!!



Interpolation Scheme for P_{sat}

Exercises

1. Fill in the blank using R-134a



T (°C)	P (kPa)	h (kJ/kg)	x	Phase description
	600	180		
-10			0.6	
-14	500			
	1200	300.61		
44			1.0	

2. Determine the saturated temperature, saturated pressure and enthalpy for water at specific volume of saturated vapor at 10.02 m^3/kg .

Example 2.3

Determine the enthalpy of 1.5 kg of water contained in a volume of 1.2 m³ at 200 kPa.

Solution:

- θ Specific volume for water

$$v = \frac{Volume}{mass} = \frac{1.2\,m^3}{1.5\,kg} = 0.8\,\frac{m^3}{kg}$$

- θ From table A-5:

$$v_f = 0.001061\, {}^{m^3}\!/_{kg}$$

$$v_g = 0.8858\, {}^{m^3}\!/_{kg}$$

Is $v < v_f$? No

Is $v_f < v < v_g$? Yes

Is $v_g < v$? No

- θ Find the quality

$$v = v_f + x(v_g - v_f)$$

$$x = \frac{v - v_f}{v_g - v_f}$$

$$= \frac{0.8 - 0.001061}{0.8858 - 0.001061}$$

$$= 0.903 \quad \text{(What does this mean?)}$$

- θ The enthalpy

$$h = h_f + x\,h_{fg}$$

$$= 504.7 + (0.903)(2201.6)$$

$$= 2492.7\,\frac{kJ}{kg}$$

Example 2.4

Determine the internal energy of refrigerant-134a at a temperature of 0°C and a quality of 60%.

Solution:

- From table A-5:

$$u_f = 51.63\,\frac{kJ}{kg}$$

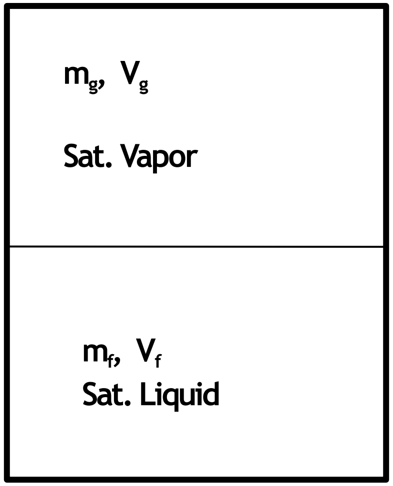
$$u_g = 230.16\,\frac{kJ}{kg}$$

- The internal energy of R 134a at given condition:

$$\begin{aligned} u &= u_f + x(u_g - u_f) \\ &= 51.63 + (0.6)(230.16 - 51.63) \\ &= 158.75\,\frac{kJ}{kg} \end{aligned}$$

Example 2.5

Consider the closed, rigid container of water as shown. The pressure is 700 kPa, the mass of the saturated liquid is 1.78 kg, and the mass of the saturated vapor is 0.22 kg. Heat is added to the water until the pressure increases to 8 MPa. Find the final temperature, enthalpy, and internal energy of the water



m_g, V_g

Sat. Vapor

m_f, V_f

Sat. Liquid

Solution:

- Theoretically:

$$v_2 = v_1$$

- The quality before pressure increased (***state 1***).

$$x_1 = \frac{m_{g1}}{m_{f1} + m_{g1}}$$

$$= \frac{0.22\,kg}{(1.78 + 0.22)\,kg} = 0.11$$

- Specific volume at ***state 1***

$$v_1 = v_{f1} + x_1 (v_{g1} - v_{f1})$$

$$= 0.001108 + (0.11)(0.2728 - 0.001108)$$

$$= 0.031 \frac{m^3}{kg}$$

State 2:

- Information :

$$P_2 = 8\ MPa \qquad v_2 = 0.031 \frac{m^3}{kg}$$

- From table A-5:

$$v_{f,2} = 0.001384 \frac{m^3}{kg}$$

$$v_{g,2} = 0.02352 \frac{m^3}{kg}$$

$v_{g\,2} < v_2$

- Since that it is in superheated region, use table A-6:

$$T_2 = 361.8^o\,C$$

$$h_2 = 3024 \frac{kJ}{kg}$$

$$u_2 = 2776 \frac{kJ}{kg}$$

Exercises

1. Four kg of water is placed in an enclosed volume of 1m^3. Heat is added until the temperature is 150°C. Find (a) the pressure, (b)the mass of vapor, and (c) the volume of the vapor.

2. A piston-cylinder device contains 0.1 m^3 of liquid water and 9.m^3 of water vapor in equilibrium at 800 kPa. Heat is transferred at constant pressure until the temperature reaches 350°C.
   (a)what is the initial temperature of the water,
   (b) determine the total mass of the water,
   (c)calculate the final volume, and
   (d)show the process on a P-v diagram with respect to saturation lines.

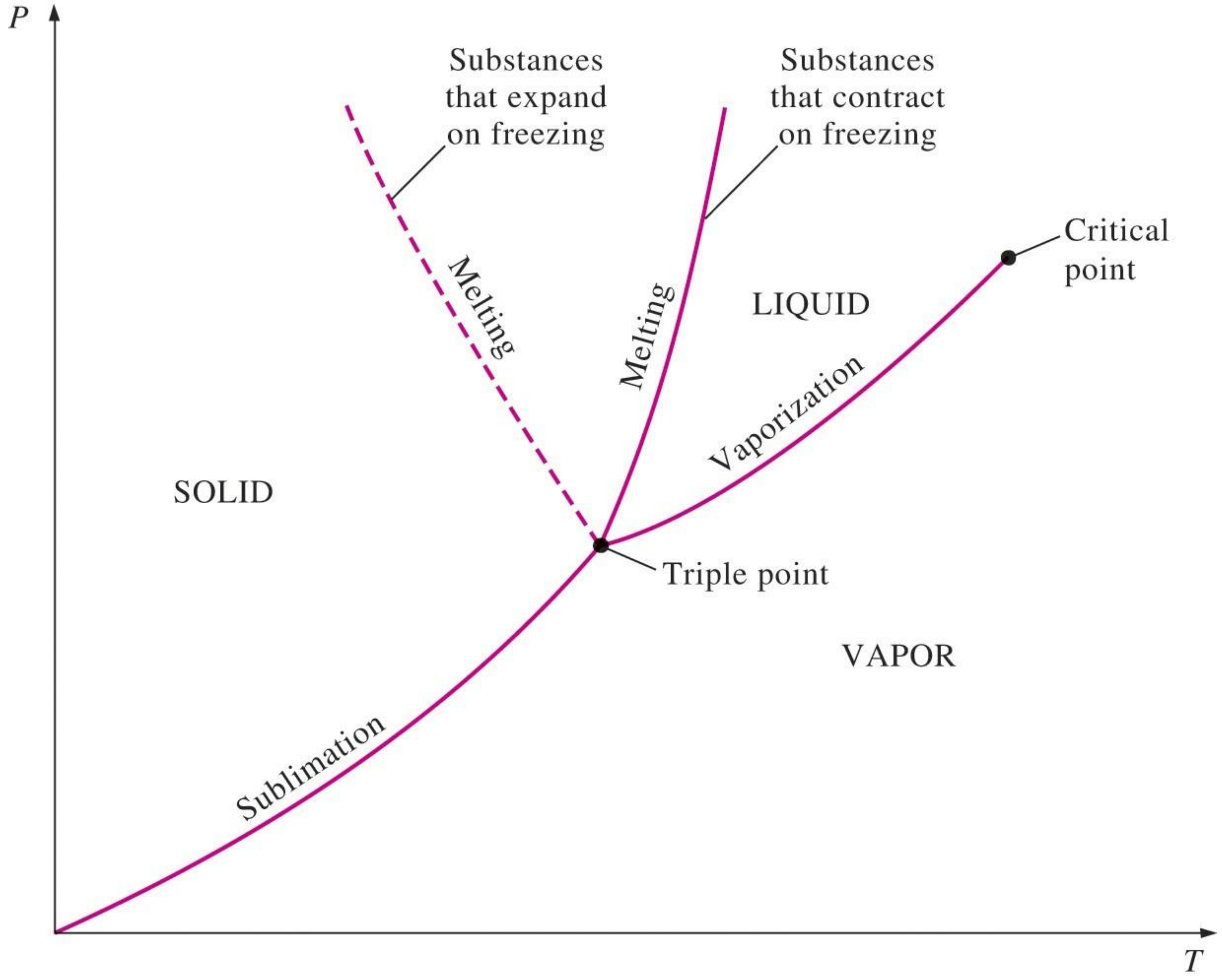
Exercises

3. For a specific volume of 0.2 m^3/kg, find the quality of steam if the absolute pressure is (a) 40 kPa and (b) 630 kPa. What is the temperature of each case?

4. Water is contained in a rigid vessel of 5 m^3 at a quality of 0.8 and a pressure of 2 MPa. If the a pressure is reduced to 400 kPa by cooling the vessel, find the final mass of vapor m_g and mass of liquid m_f.

Important Definition

- **Critical point** - the temperature and pressure above which there is no distinction between the liquid and vapor phases.
- **Triple point** - the temperature and pressure at which all three phases can exist in equilibrium.
- **Sublimation** - change of phase from solid to vapor.
- **Vaporization** - change of phase from liquid to vapor.
- **Condensation** - change of phase from vapor to liquid.
- **Fusion or melting** - change of phase from solid to liquid.


P
Substances that expand on freezing
Substances that contract on freezing
Melting
Melting
Critical point
LIQUID
Vaporization
SOLID
Triple point
VAPOR
Sublimation
T

Ideal Gas Law

- *Robert Boyle* formulates a well-known law that states the pressure of a gas expanding at constant temperature varies inversely to the volume, or

$$P_1V_1 = P_2V_2 = \text{constant}$$

- As the result of experimentation, *Charles* concluded that the pressure of a gas varies directly with temperature when the volume is held constant, and the volume varies directly with temperature when the pressure is held constant, or

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

- By combining the results of Charles' and Boyle's experiments, the following relationship can be obtained

$$\frac{Pv}{T} = \text{constant}$$

- The constant in the above equation is called *the ideal gas constant* and is designated by *R*; thus the ideal gas equation becomes

$$Pv = RT \quad or \quad PV = mRT$$

- In order to make the equation applicable to all ideal gas, a universal gas constant R_U is introduced

$$R = \frac{R_U}{M}$$

- For example the ideal gas constant for air, R_{air}

$$R_{air} = \frac{(R_U)_{air}}{(M)_{air}} = \frac{8.3144}{28.96} = 0.2871 kJ/kg.K$$

- The amount of energy needed to raise the temperature of a unit of mass of a substance by one degree is called the *specific heat at constant volume* C_v for a constant-volume process and the *specific heat at constant pressure* C_p for a constant pressure process. They are defined as

$$C_v = \left(\frac{\partial u}{\partial T}\right)_v \quad and \quad C_P = \left(\frac{\partial h}{\partial T}\right)_P$$

- Using the definition of enthalpy ($h = u + Pv$) and writing the differential of enthalpy, the relationship between the specific heats for ideal gases is

$$h = u + Pv$$

$$dh = du + RT$$

$$C_P\,dt = C_V dt + RdT$$

$$C_P = C_V + R$$

- The *specific heat ratio, k* is defined as

$$k = \frac{C_P}{C_v}$$

- For ideal gases u, h, C_v, and C_p are functions of temperature alone. The Δu and Δh of ideal gases can be expressed as

$$\Delta u = u_2 - u_1 = C_v (T_2 - T_1)$$

$$\Delta h = h_2 - h_1 = C_P (T_2 - T_1)$$

Example 2.6

An ideal gas is contained in a closed assembly with an initial pressure and temperature of 220 kPa and 70^0C respectively. If the volume of the system is increased 1.5 times and the temperature drops to 15^0C, determine the final pressure of the gas.

Solution:

given

$$\boxed{state 1}$$

$$P_1 = 220\, kPa$$

$$T_1 = 70 + 273K = 343\, K$$

$$\boxed{state 2}$$

$$T_2 = 15 + 273 = 288\, K$$

$$V_2 = 1.5 V_1$$

- From ideal-gas law:

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

$$P_2 = \left(\frac{V_1}{1.5 V_1}\right)\left(\frac{288}{343}\right)\left(220 \times 10^3\right)$$

$$= 123.15\, kPa$$

Example 2.7

A closed assembly contains 2 kg of air at an initial pressure and temperature of 140 kPa and 210^{0}C respectively. If the volume of the system is doubled and temperature drops to 37^{0}C, determine the final pressure of the air. Air can be modeled as an ideal gas.

Solution:

given

$\boxed{state 1}$

$P_1 = 140 kPa$

$T_1 = 210 + 273K = 483\,K$

$\boxed{state 2}$

$T_2 = 37 + 273 = 310K$

$V_2 = 2V_1$

- From ideal-gas law:

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$$

$$P_2 = \frac{V_1}{2V_1}\left(\frac{310}{483}\right)\left(140\times10^3\right)$$

$$= 44.93 kPa$$

Example 2.8

An automobile tire with a volume of 0.6 m^3 is inflated to a gage pressure of 200 kPa. Calculate the mass of air in the tire if the temperature is 20°C.

Solution:

given

$$\boxed{state1}$$

$$P = 200 + 100\, kPa$$

$$T = 20 + 273K = 293K$$

ϖ From ideal-gas law:

$$m = \frac{PV}{RT}$$

$$= \frac{300 \times 10^3 \frac{N}{m^3}\left(0.6m^2\right)}{287 \frac{Nm}{kg.K}\left(293K\right)}$$

$$= 2.14\, kg$$

Supplementary Problems

1. The pressure in an automobile tire depends on the temperature of the air in the tire. When the air temperature is 25°C, the pressure gage reads 210 kPa. If the volume of the tire is 0.025 m3, determine the pressure rise in the tire when the air temperature in the tire rises to 50°C. Also, determine the amount of air that must be bled off to restore pressure to its original value at this temperature. Assume the atmospheric pressure is 100 kPa.

   [*26 kPa, 0.007 kg*]

2. A 1-m^3 tank containing air at 25°C and 500 kPa is connected through a valve to another tank containing 5 kg of air at 35°C and 200 kPa. Now the valve is opened, and the entire system is allowed to reach thermal equilibrium with the surroundings, which are at 20°C. Determine the volume of the second tank and the final equilibrium pressure of air.

   [*2.21 m^3, 284.1 kPa*]

3. A 1 m^3 rigid tank has propane at 100 kPa, 300 K and connected by a valve to another tank of 0.5 m^3 with propane at 250 kPa, 400 K. The valve is opened and the two tanks come to a uniform state at 325 K. What is the final pressure?

[*139.9 kPa*]

4. A cylindrical gas tank 1 m long, inside diameter of 20 cm, is evacuated and then filled with carbon dioxide gas at 25°C. To what pressure should it be charged if there should be 1.2 kg of carbon dioxide?

[*2152 kPa*]