CHAPTER

3

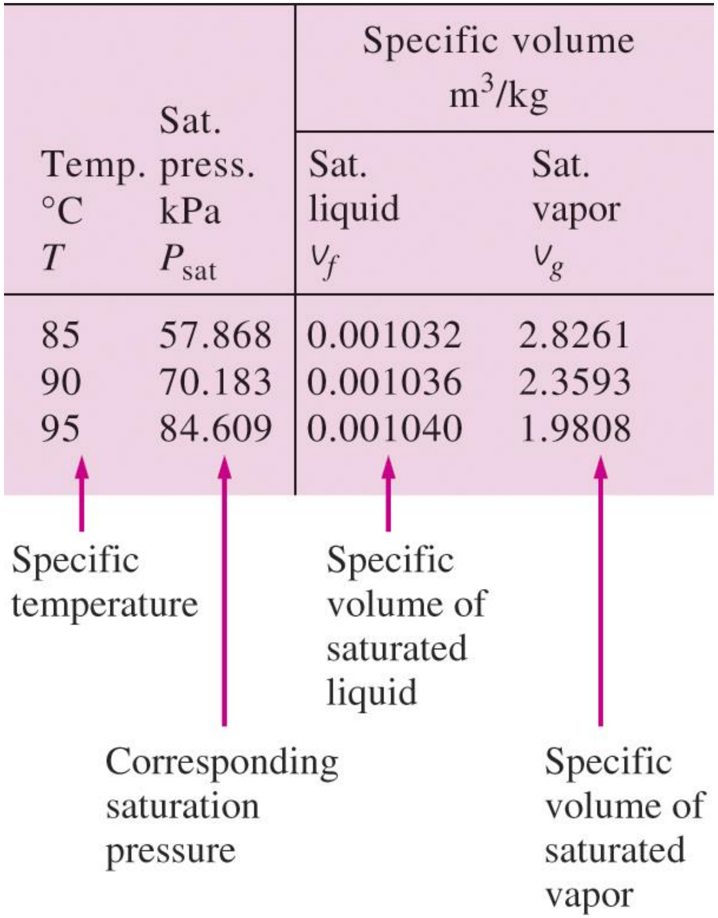
Thermodynamics

Petroleum
Engineering
Second year

Properties of Pure Substances

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

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*)

$$v < v_f$$

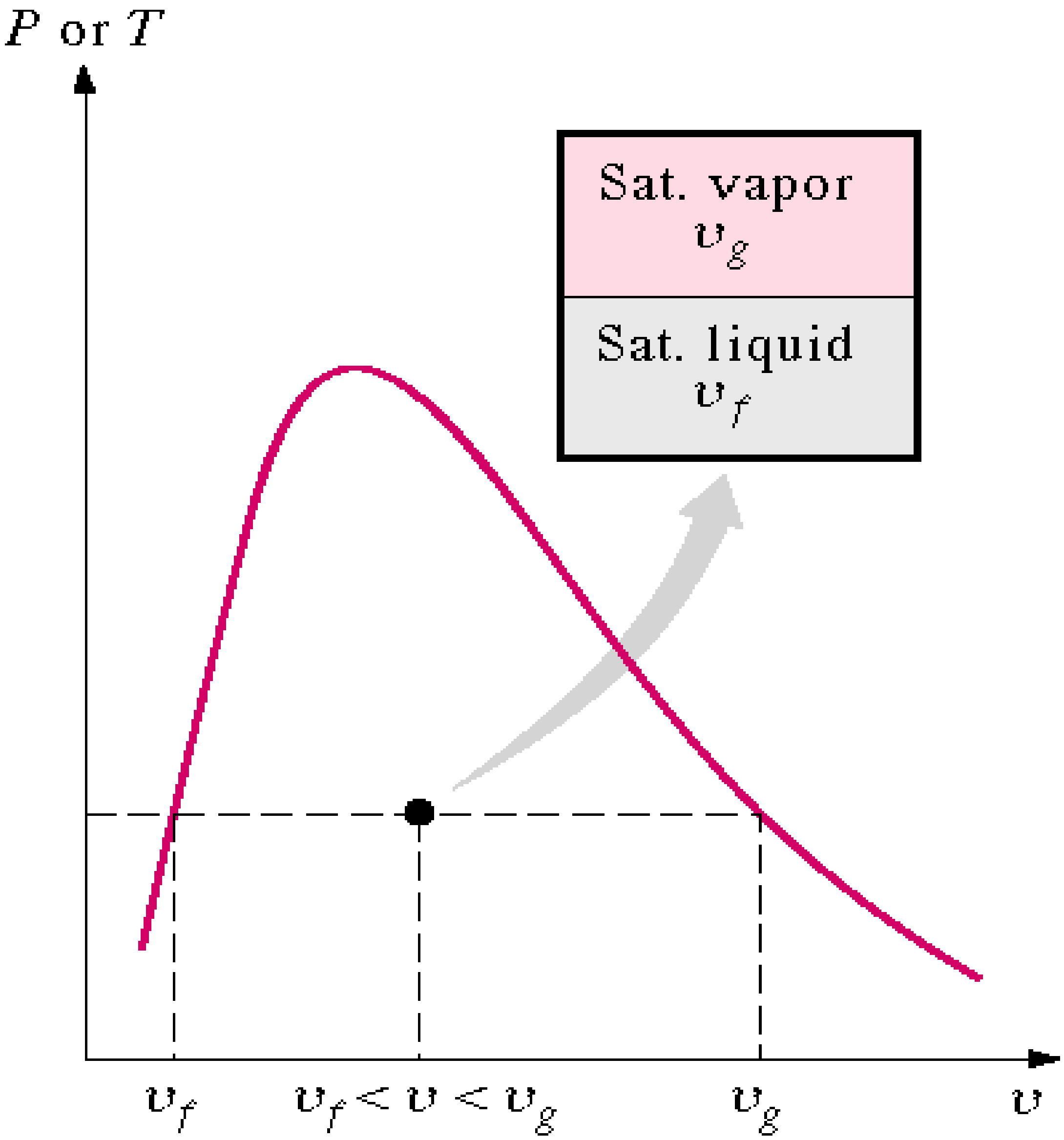
- If the answer to the second question is yes, the state is in the saturation region, and either the saturation temperature table or the saturation pressure table is used.

$$v_f < v < v_g$$

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

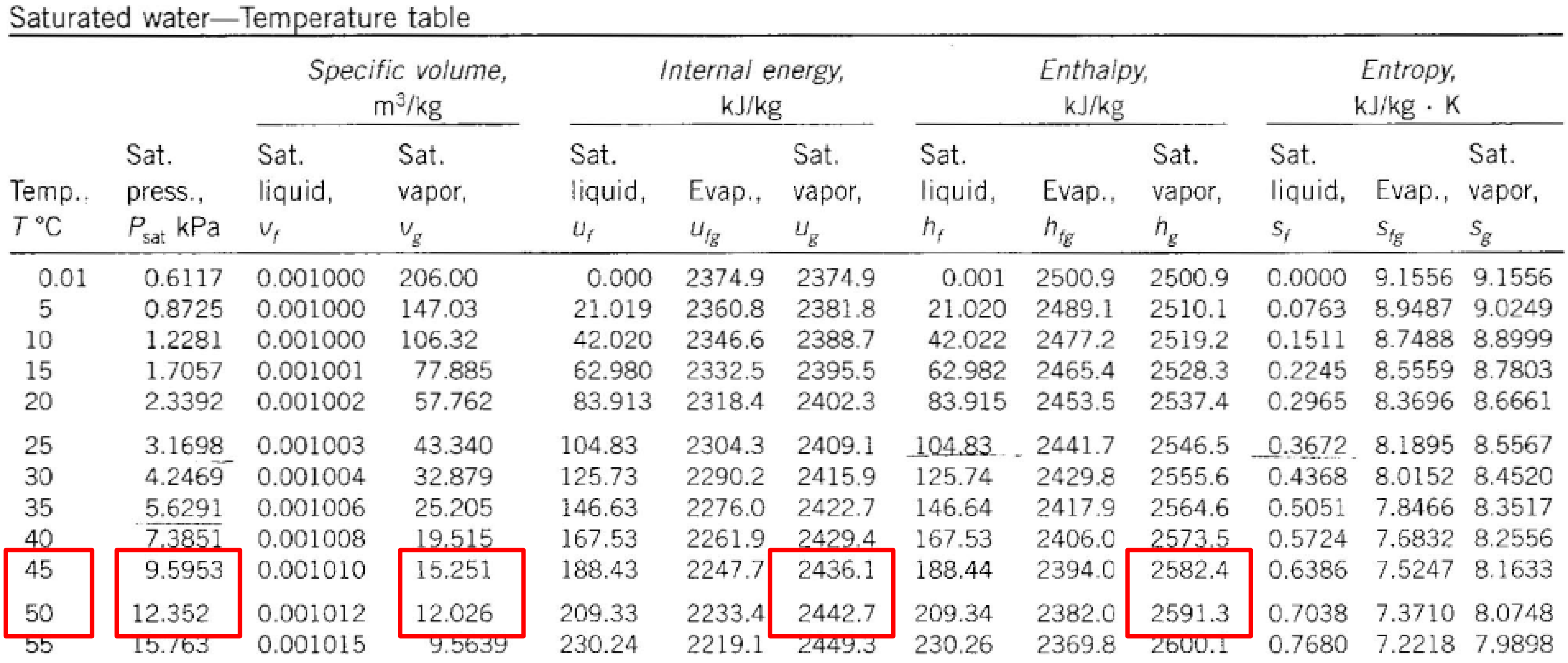
$$v_g < v$$

Property Table



Example 2.1

Determine the saturated pressure, specific volume, internal energy and enthalpy for saturated water vapor at 45^{o}C and 50^{o}C.

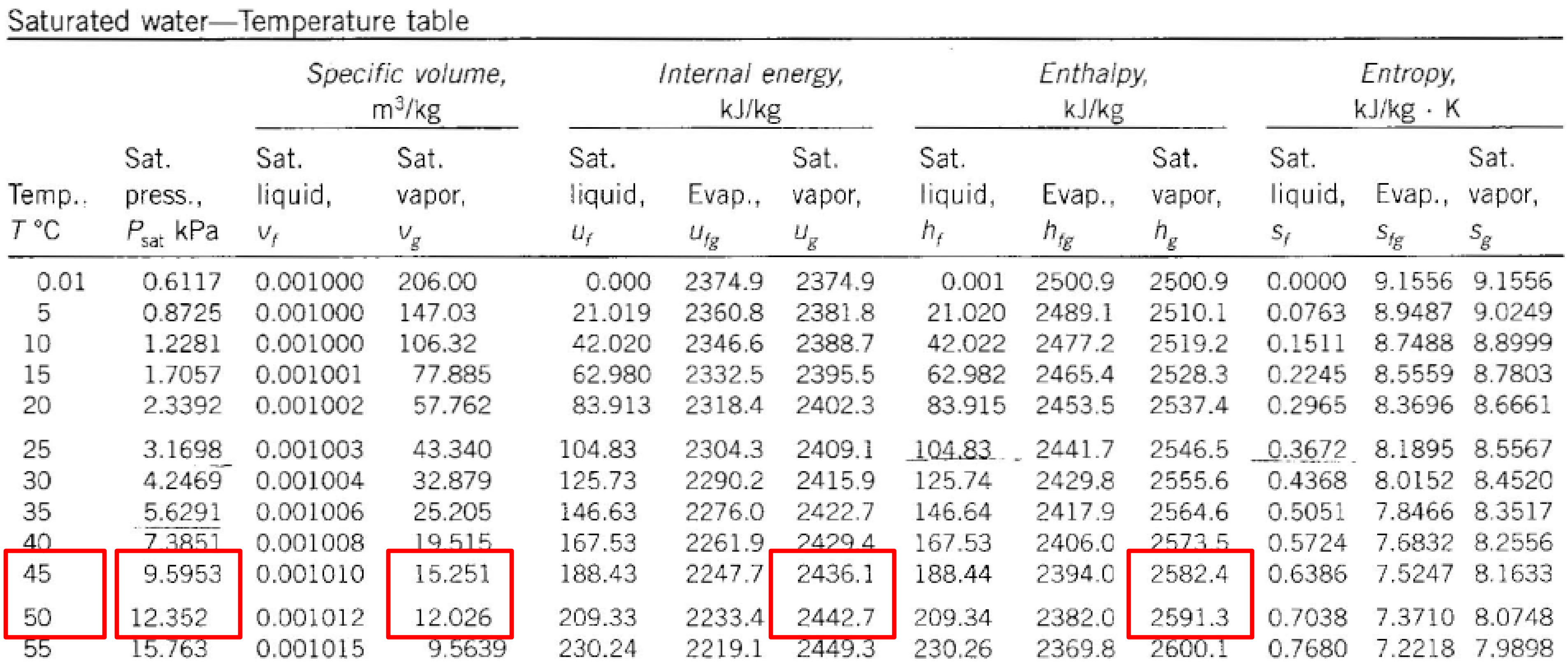


Saturated water—Temperature table

		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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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
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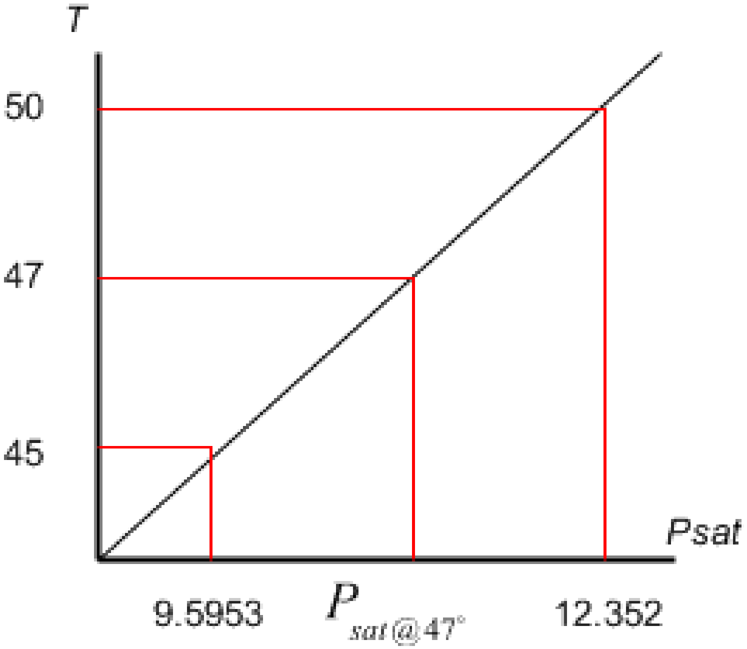
35	5.6291	0.001006	25.205	146.63	2276.0	2422.7	146.64	2417.9	2564.6	0.5051	7.8466	8.3517
40	7.3851	0.001008	19.515	167.53	2261.9	2429.4	167.53	2406.0	2573.5	0.5724	7.6832	8.2556
45	9.5953	0.001010	15.251	188.43	2247.7	2436.1	188.44	2394.0	2582.4	0.6386	7.5247	8.1633
50	12.352	0.001012	12.026	209.33	2233.4	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 Scheme for P_{sat}

- ☐ Interpolation for P_{sat}

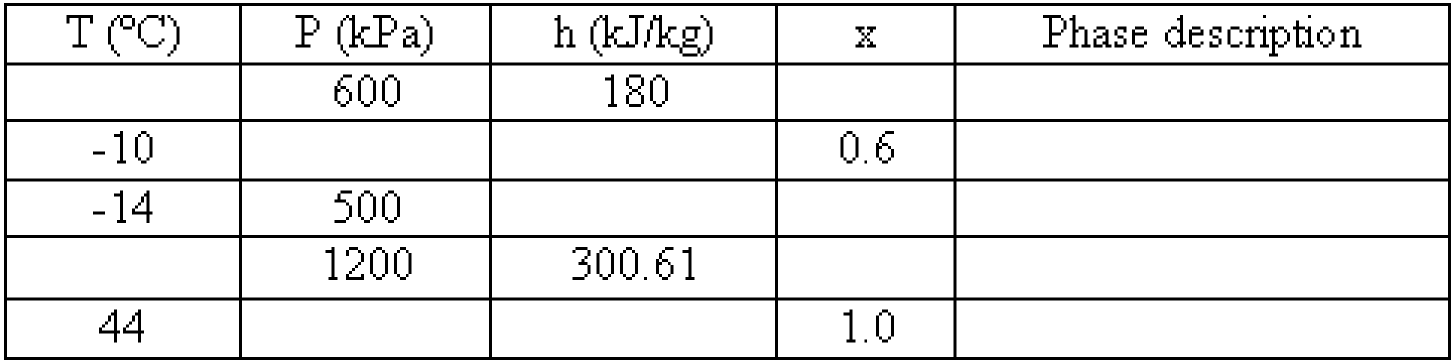
$$\frac{P_{sat} - 9.5953}{12.352 - 9.5953} = \frac{47 - 45}{50 - 45}$$

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

- ☐ Do the same principal to others!!!!

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 m^3 at 200 kPa.

Solution:

- ☐ Specific volume for water

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

- ☐ 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

- ☐ Find the quality

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

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

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

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

- ☐ 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:

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

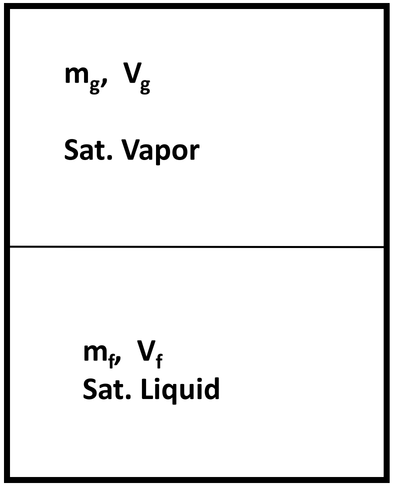
$$u_g = 230.16 \frac{kJ}{kg}$$

- 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



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 :

$$P_2 = 8\,MPa \quad v_2 = 0.031 \tfrac{m^3}{kg}$$

- From table A-5:

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

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

$v_{g2} < v_2$

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

$$T_2 = 361.8^o C$$

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

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

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 0.9 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.

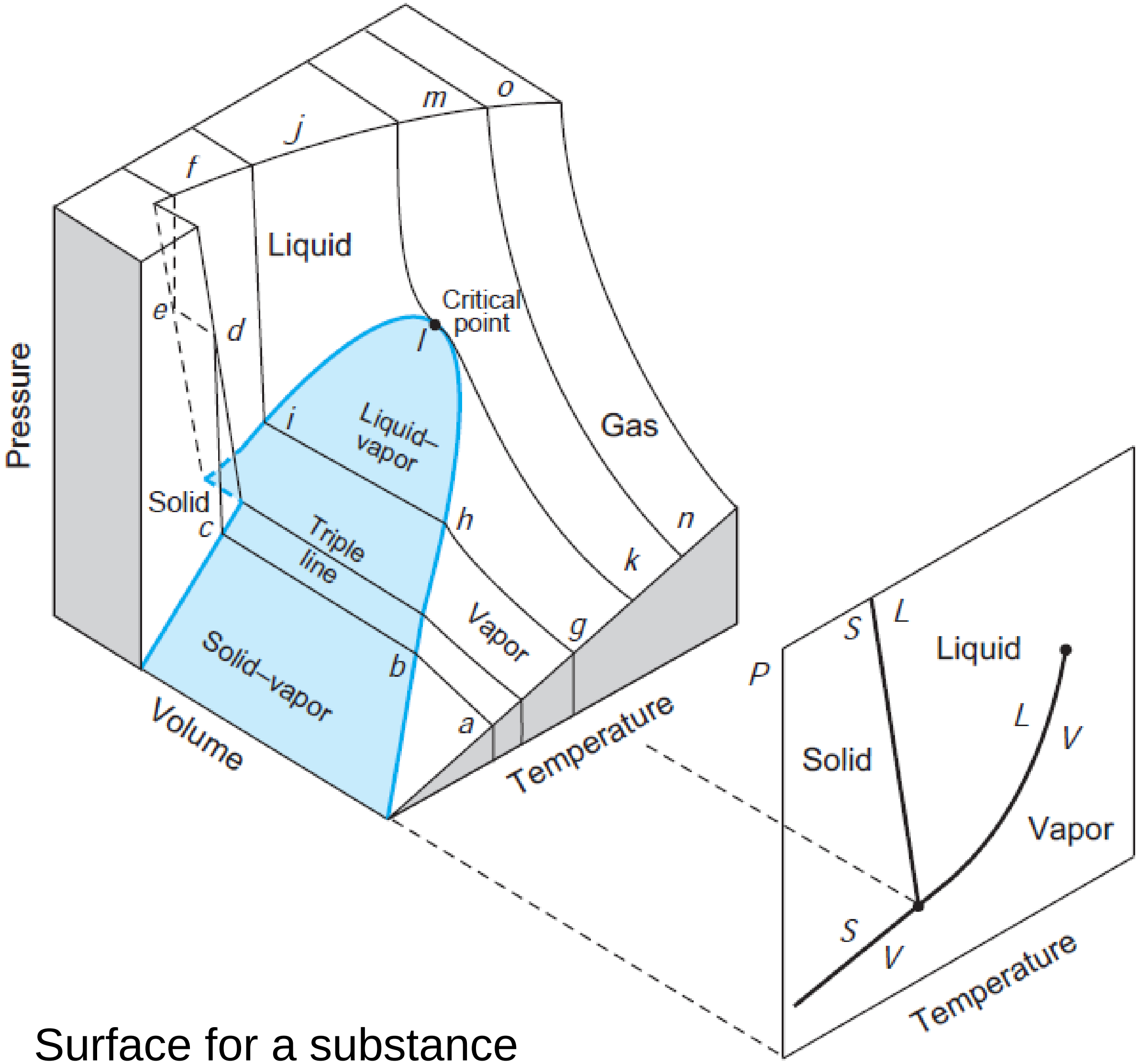
Exercises

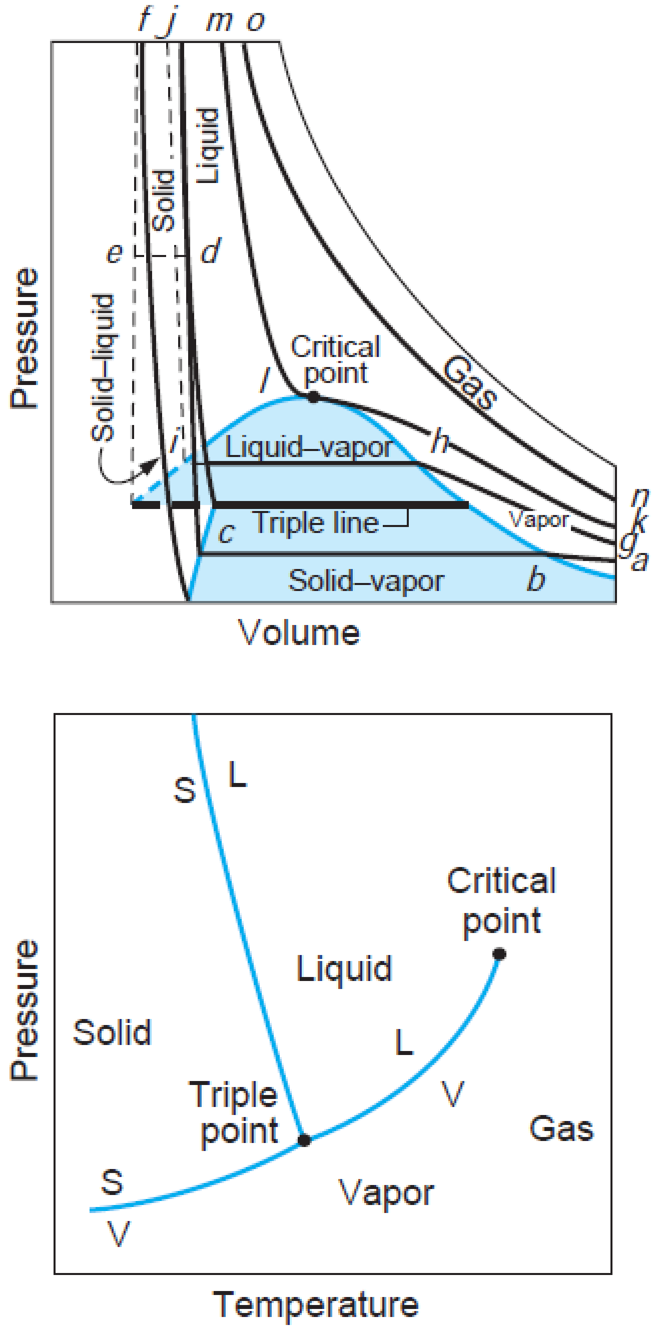
3. For a specific volume of 0.2 m^3/kg, find the quality of steam if the absolute pressure is (a) 40 kPa and (b) 630 kPa. What is the temperature of each case?

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.





Surface for a substance
that expands on freezing

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

$$\boxed{state\,1}$$

$$P_1 = 220\,kPa$$

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

$$\boxed{state\,2}$$

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

$$V_2 = 1.5V_1$$

❖ From ideal-gas law:

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

$$P_2 = \frac{V_1}{1.5V_1}\left(\frac{288}{343}\right)\left(220\times10^3\right)$$

$$= 123.15\,kPa$$

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

$$\boxed{state 1}$$

$$P_1 = 140\, kPa$$

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

$$\boxed{state\, 2}$$

$$T_2 = 37 + 273 = 310\, K$$

$$V_2 = 2V_1$$

❖ From ideal-gas law:

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

$$P_2 = \frac{V_1}{2V_1}\left(\frac{310}{483}\right)\left(140 \times 10^3\right)$$

$$= 44.93\, kPa$$

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

$$\boxed{state1}$$

$$P = 200 + 100\ kPa$$

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

- From ideal-gas law:

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

$$= \frac{300\times10^3 \frac{N}{m^3}\left(0.6m^2\right)}{287\frac{Nm}{kg.K}\left(293K\right)}$$

$$= 2.14\,kg$$

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*]