CHAPTER

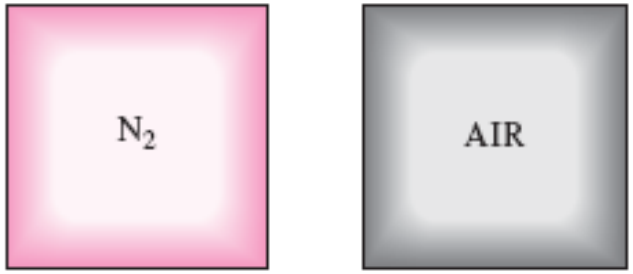
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MEng 2131
Thermodynamics I

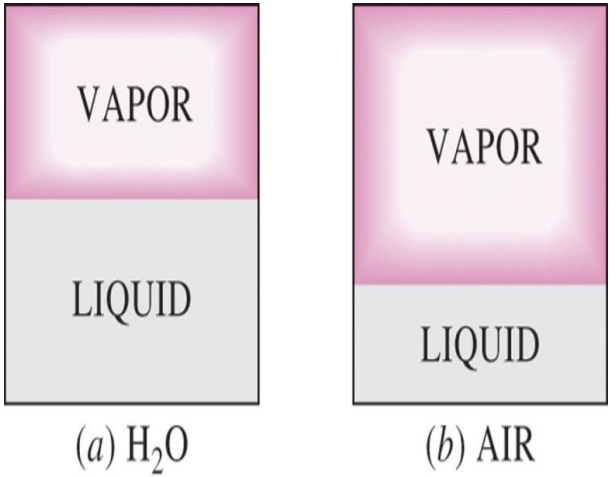
Properties of Pure Substances

What is Pure Substances?

❖ A substance that has a fixed chemical composition throughout is called a **pure substance.**



- Pure substance may exist in different phases, but the chemical compositions is the same.
  - water made up of two atoms of hydrogen and one atom oxygen. It will have the same composition when in ice, liquid and vapor forms.



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

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.

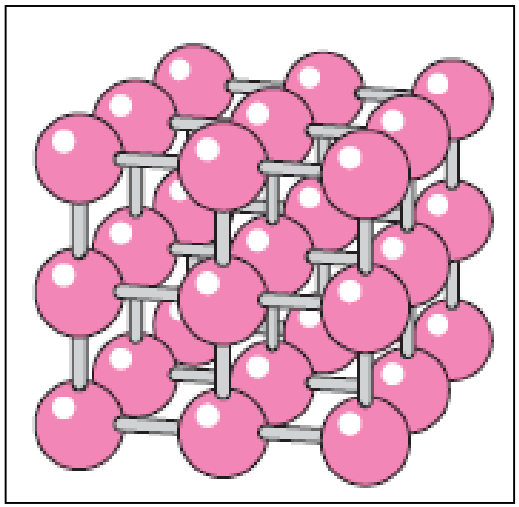
- It can exist in different phases under various condition.

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

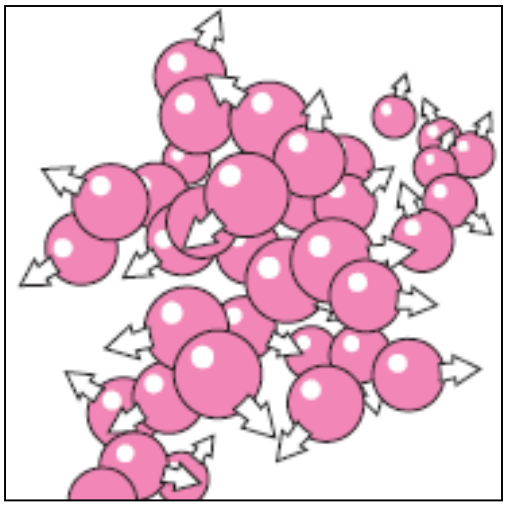
  Each with different molecular structures.

Phase-change Processes of Pure Substances

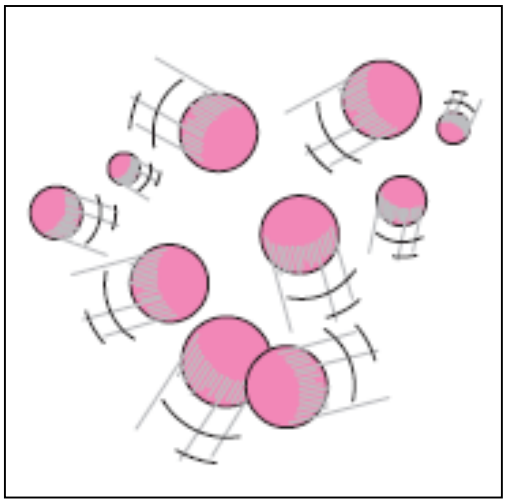
- There are many practical situations where two phases of a pure substances coexist in equilibrium.
- E.g. water exists as a mixture of liquid and vapor in the boiler and etc.
  - Solid: strong intermolecular bond
  - Liquid: intermediate intermolecular bonds
  - Gas: weak intermolecular bond



Solid

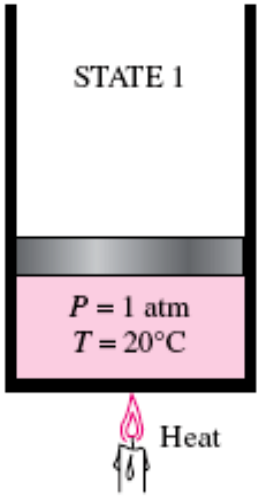


Liquid

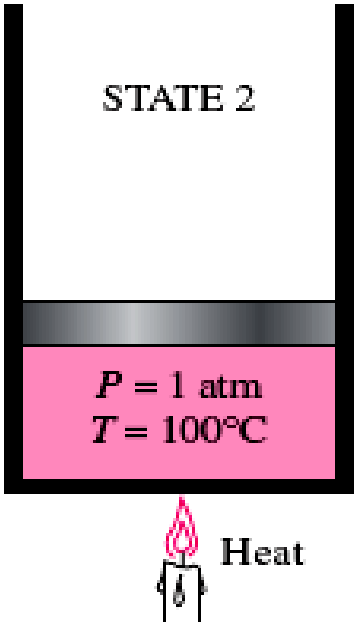


Gas

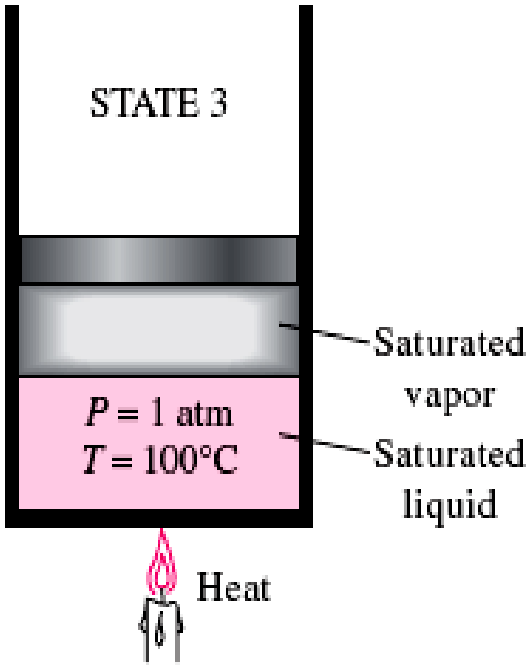
- Consider the piston-cylinder device containing liquid water at 20^{o}C and 1atm.



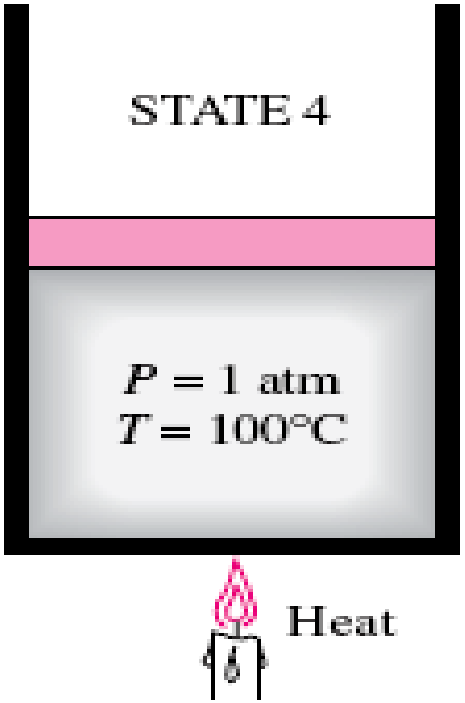
- Under these conditions, water exists in the liquid phase, and it is called a ***compressed liquid***, or a ***sub cooled liquid.***
- As the temperature rises, the liquid water expands slightly, and so its specific volume increases.



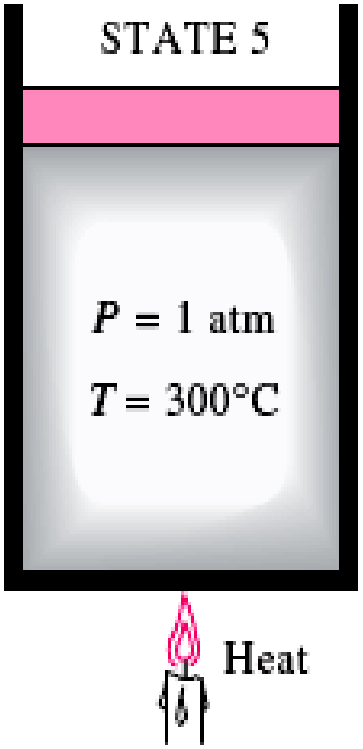
- At this point water still a liquid, but any heat addition will cause some of the liquid to vaporize.
- That is, a phase change process from liquid to vapor is about to take place.
- A liquid about to vaporize is called ***saturated liquid.***



- Once boiling starts, the ***temperature stops rising*** until the liquid is completely vaporized (it is a constant phase - change process at p-constant).
- During this process the only thing in change is volume.
- At this stage liquid and vapor phase coexist in equilibrium and it is called ***saturated liquid-vapor mixture***.

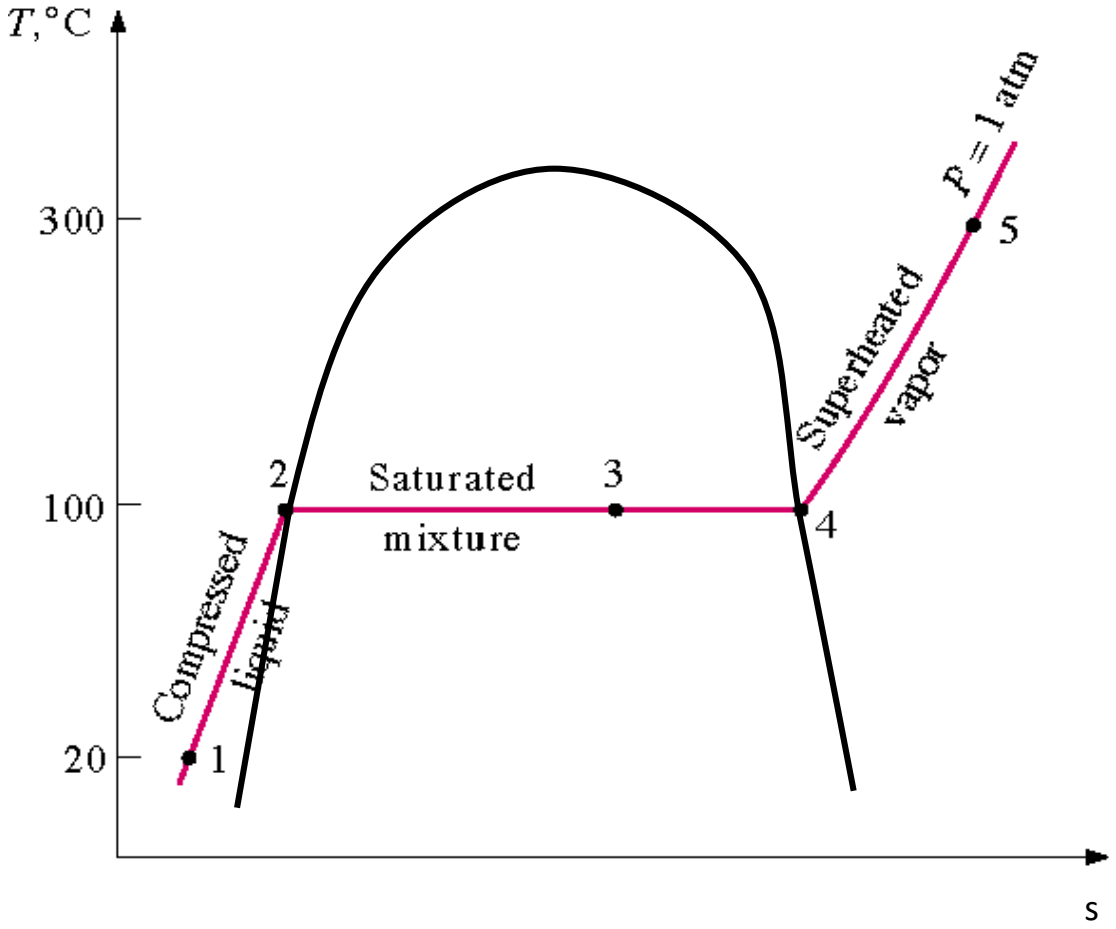


- At this point, the entire cylinder is filled with vapor that is on the borderline of the liquid phase.
- Any heat loss from this vapor will cause some of the vapor to condense (phase change from vapor to liquid).
- The vapor that is about to condense is called a ***saturated vapor.***

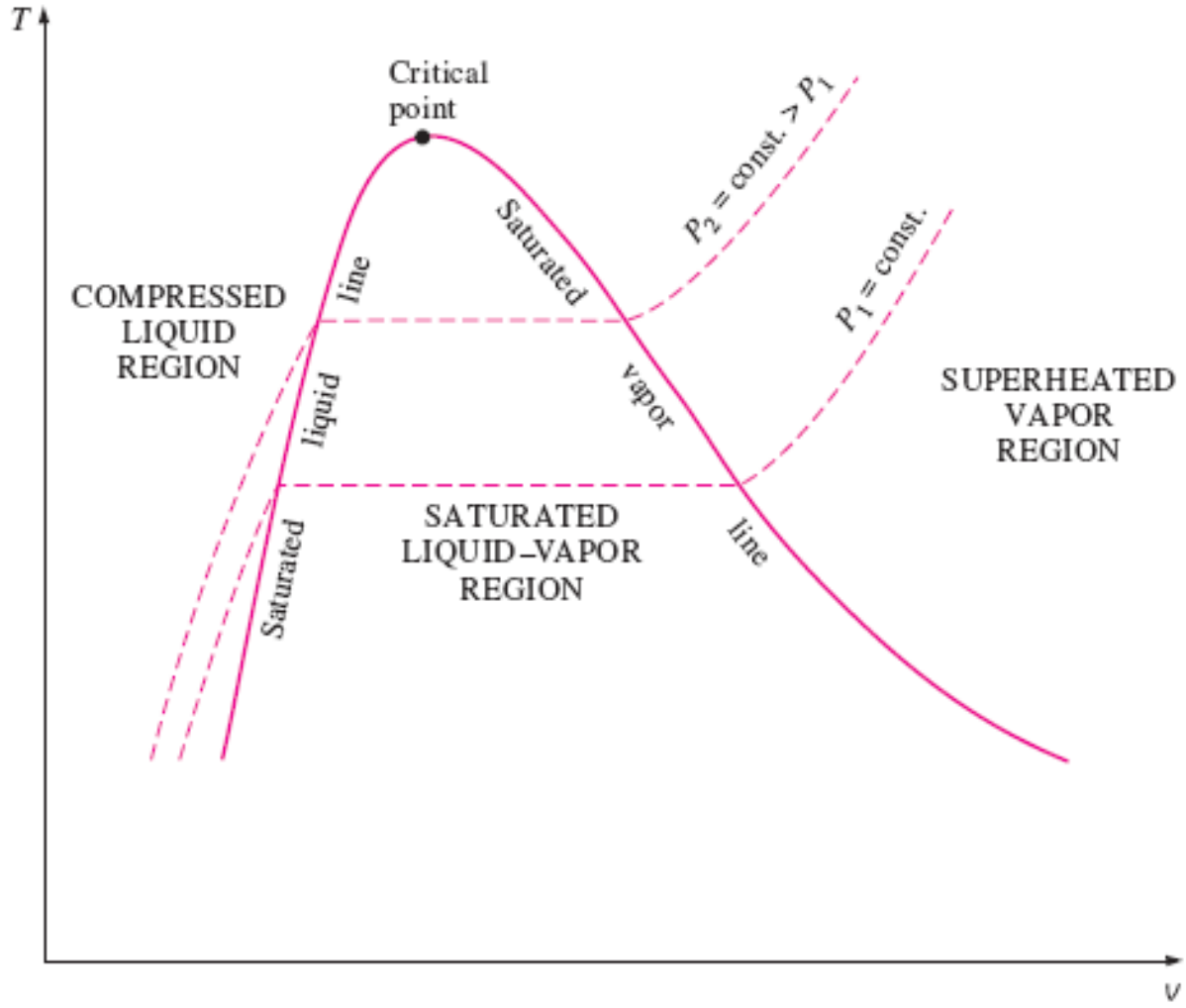


- At this stage the phase-change process is completed, we back to a single-phase region (vapor).
- Further transfer of heat will result in an increase in both the temperature and the specific volume.
- A vapor that is not about to condense (i.e. not a saturated vapor) is called a ***superheated vapor***.

This constant pressure heating process can be illustrated as:



Property Diagram



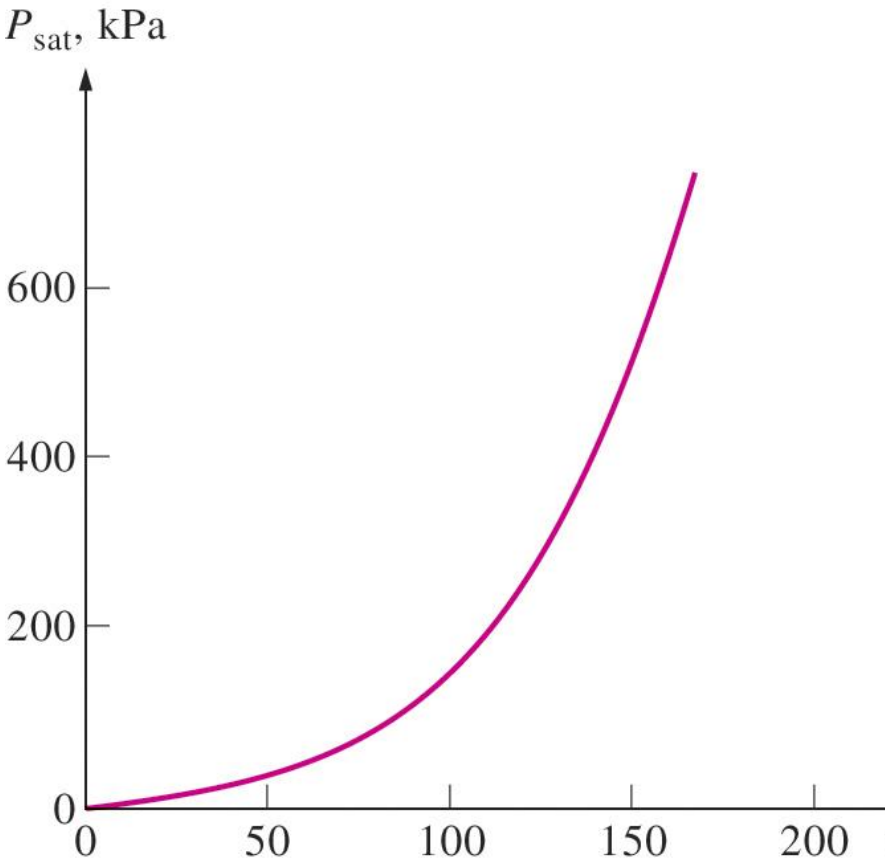
Saturation

- *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*

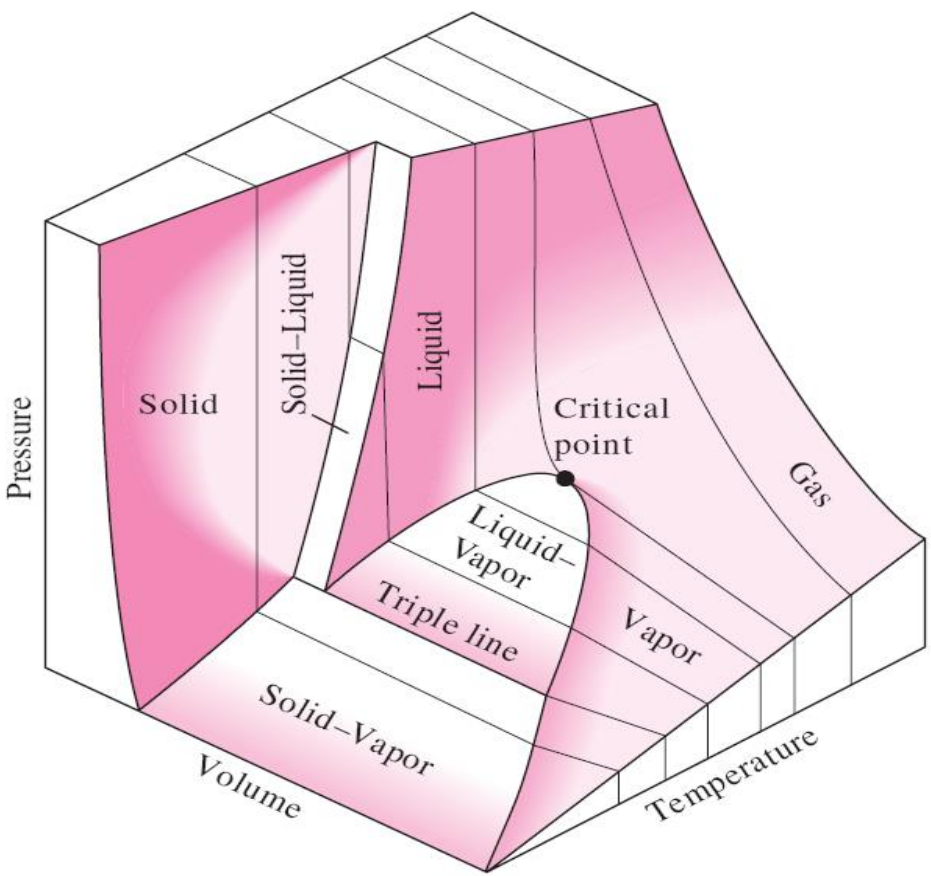


Temperature, T, °C	Saturation pressure, P_{sat}, kPa
−10	0.26
−5	0.40
0	0.61
5	0.87
10	1.23
15	1.71
20	2.34
25	3.17
30	4.25
40	7.39
50	12.35
100	101.4
150	476.2
200	1555
250	3976
300	8588

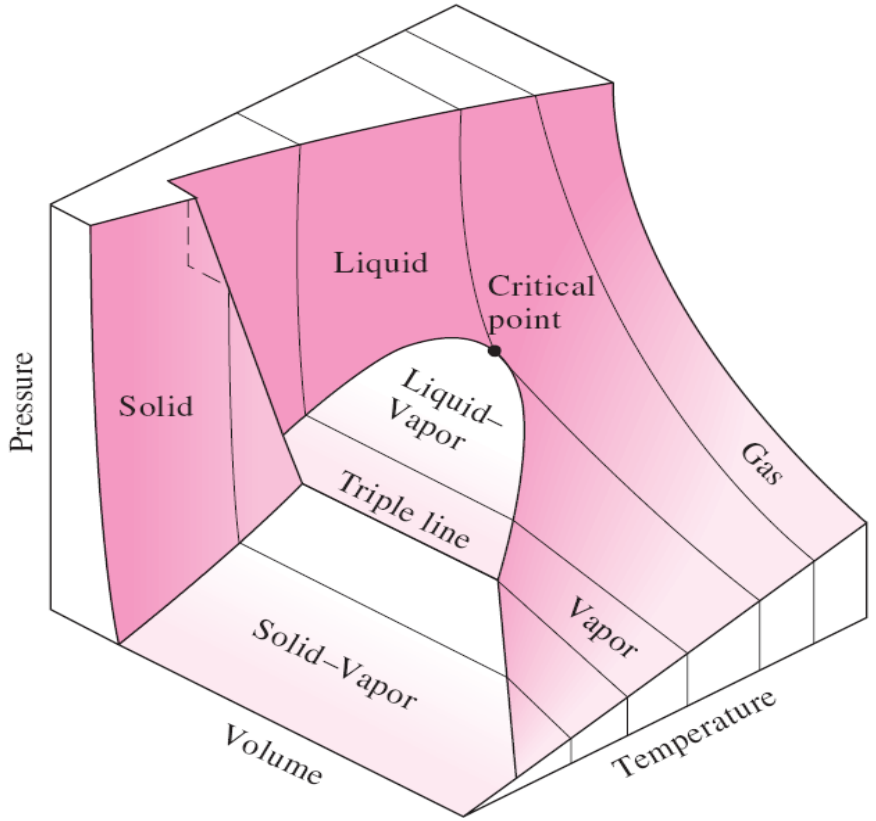
Latent Heat

- **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.*

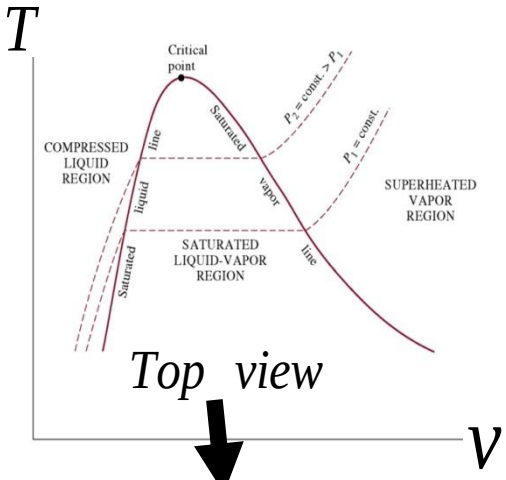
P-V-T diagram



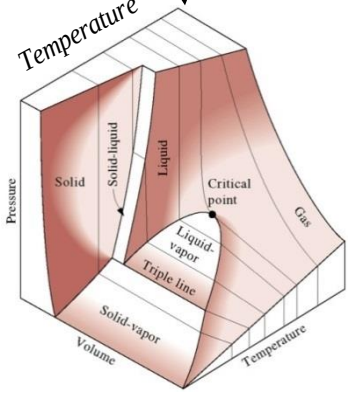
substance that *contracts on freezing.*



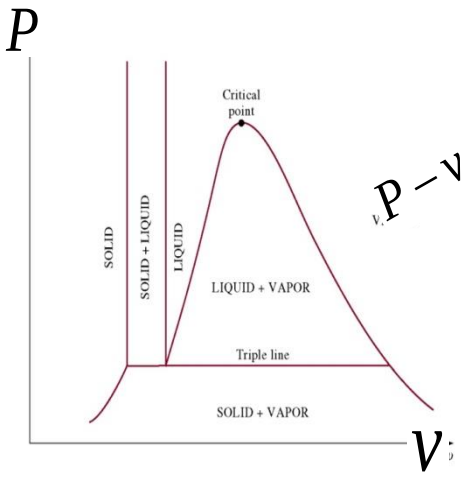
substance that *expands on freezing.*



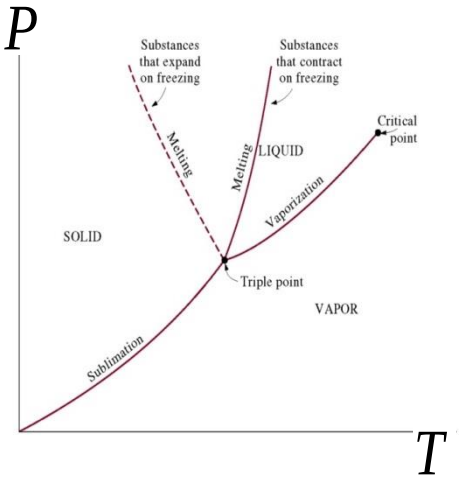
Top view



P – v view

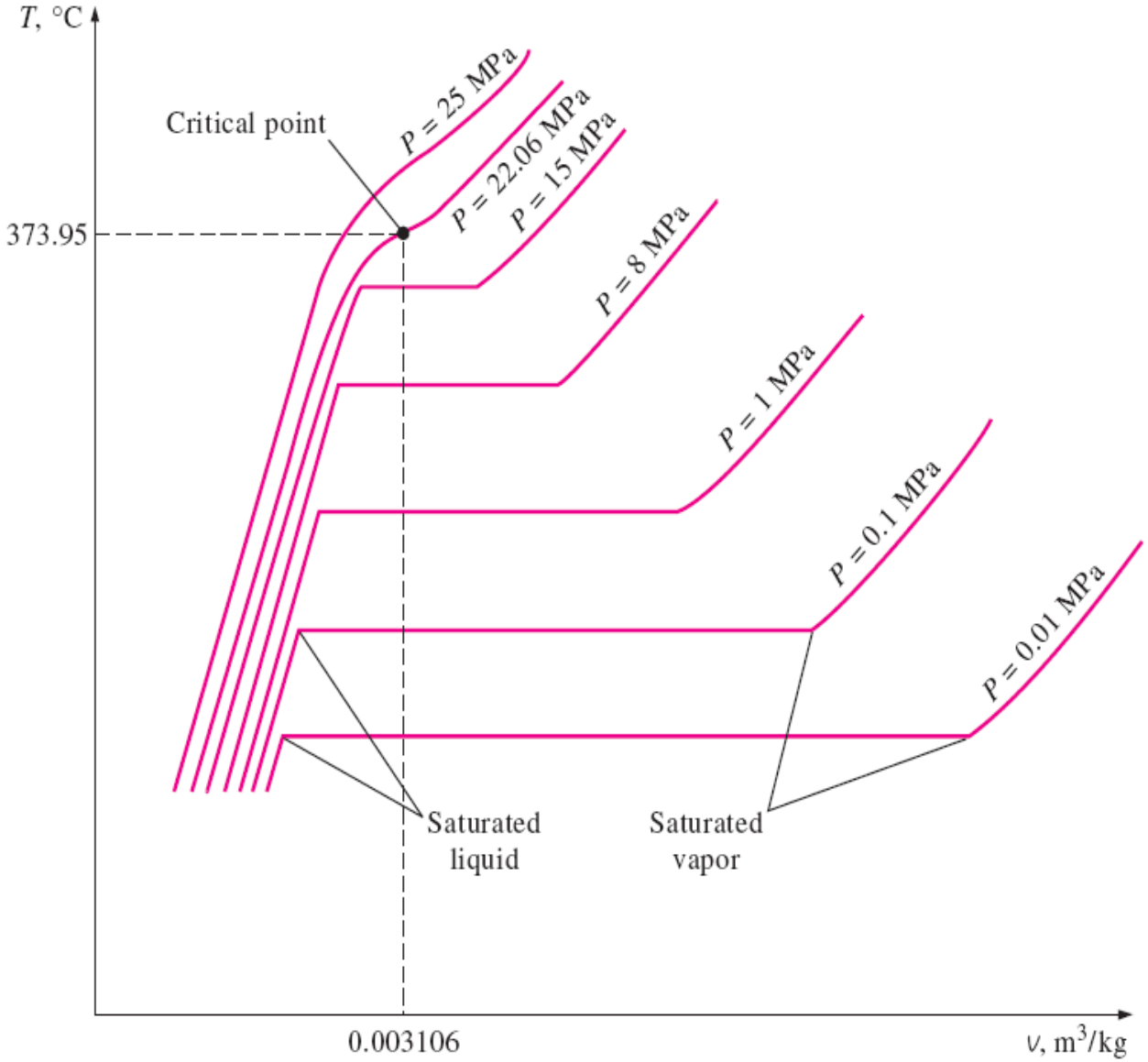


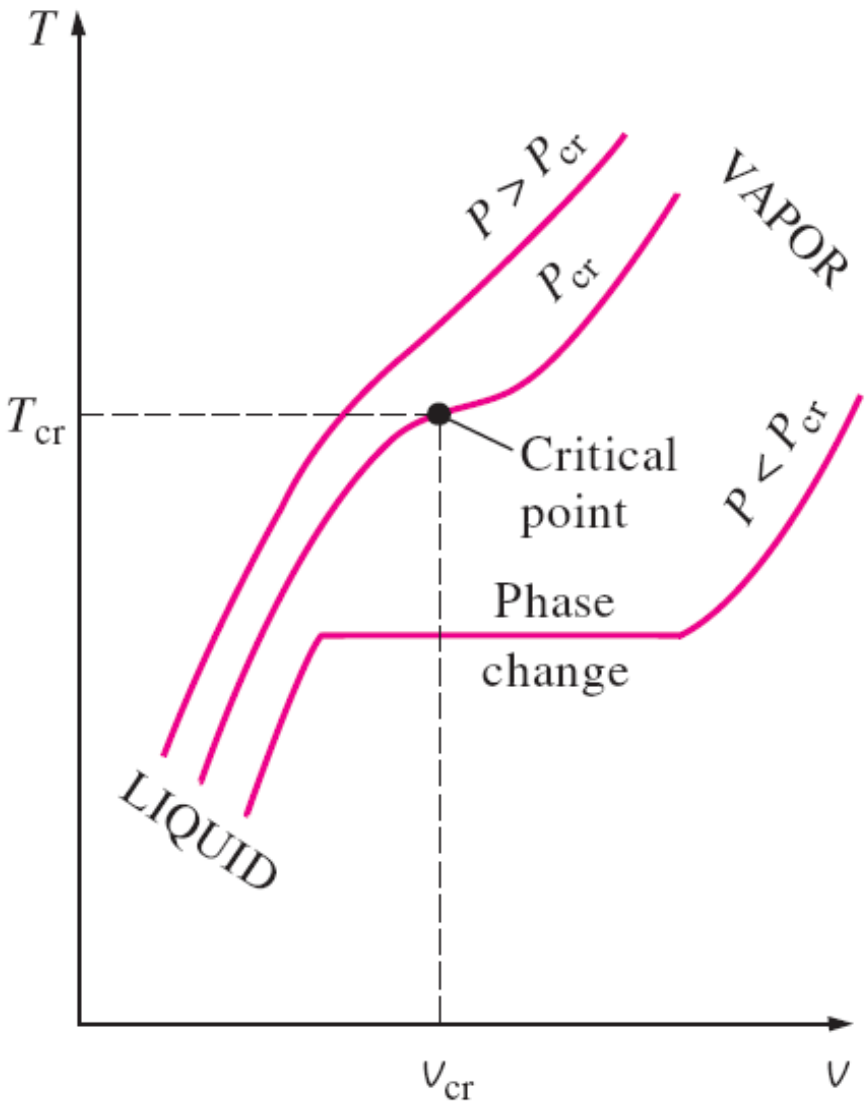
P – T view



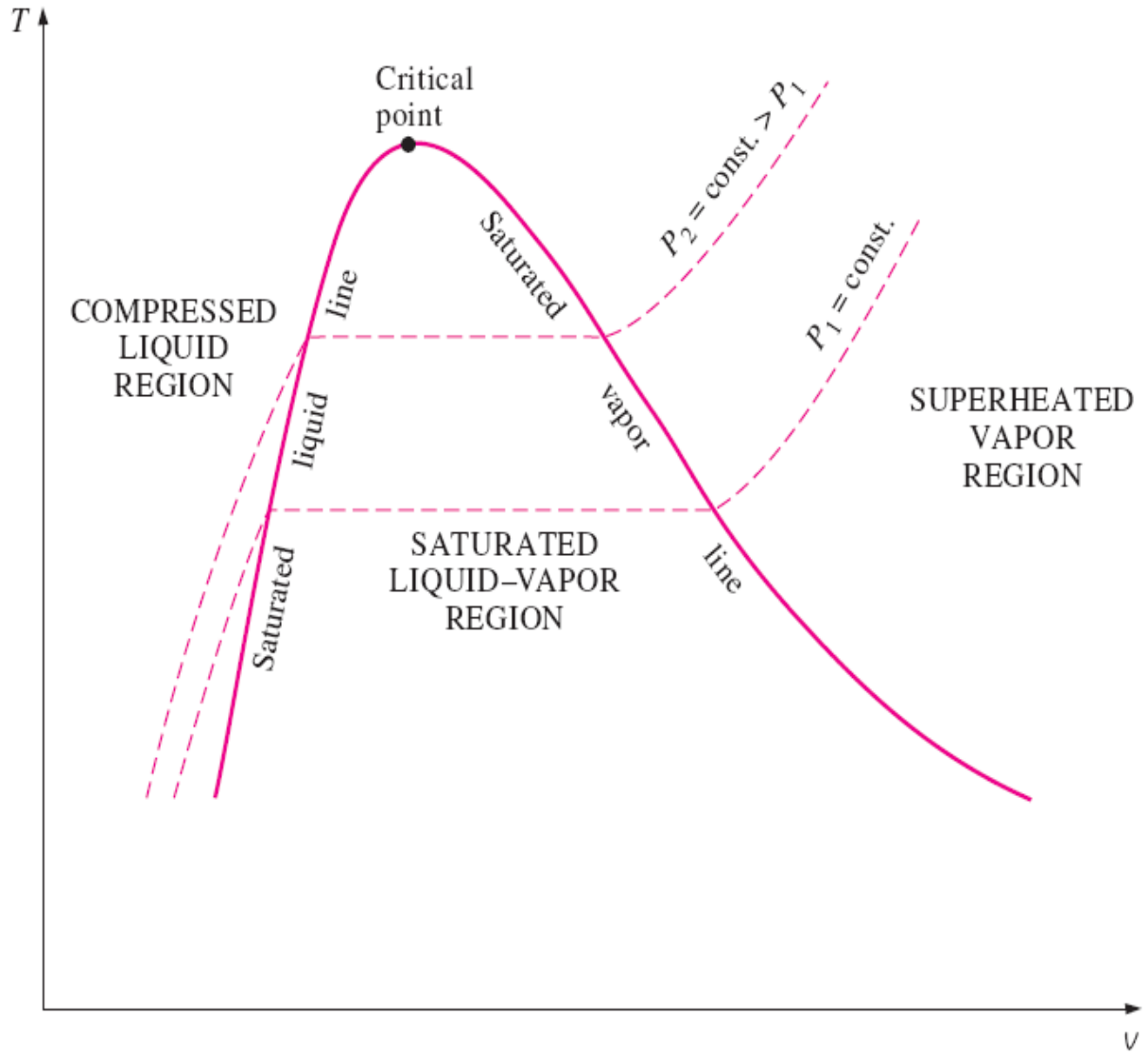
The T-V diagram

- Experimental result tells us, as the pressure is increased further, the saturation line of the process will continue to get shorter and it will become a point.
- This point is called the ***critical point*** of the substance and it may be defined as the point at which the saturated liquid saturated vapor states are identical.
- At pressures above the critical pressure, there is not a distinct phase-change process.
- We can never tell when the change has occurred.

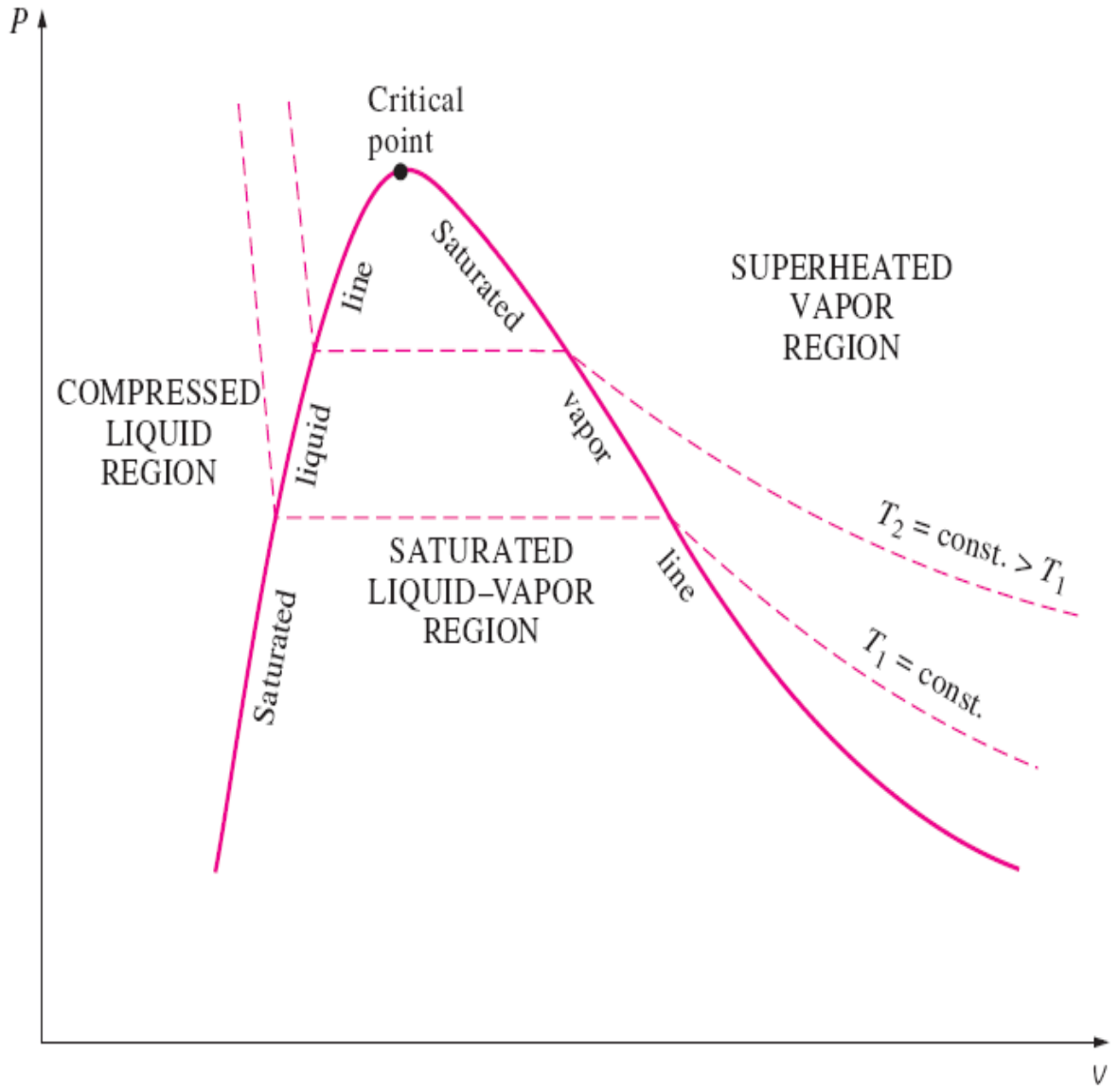

T, °C
Critical point
P = 25 MPa
P = 22.06 MPa
P = 15 MPa
373.95
P = 8 MPa
P = 1 MPa
P = 0.1 MPa
P = 0.01 MPa
Saturated liquid
Saturated vapor
0.003106
v, m³/kg


T
P > Pcr
Pcr
VAPOR
Tcr
Critical
point
P < Pcr
Phase
change
LIQUID
Vcr
V

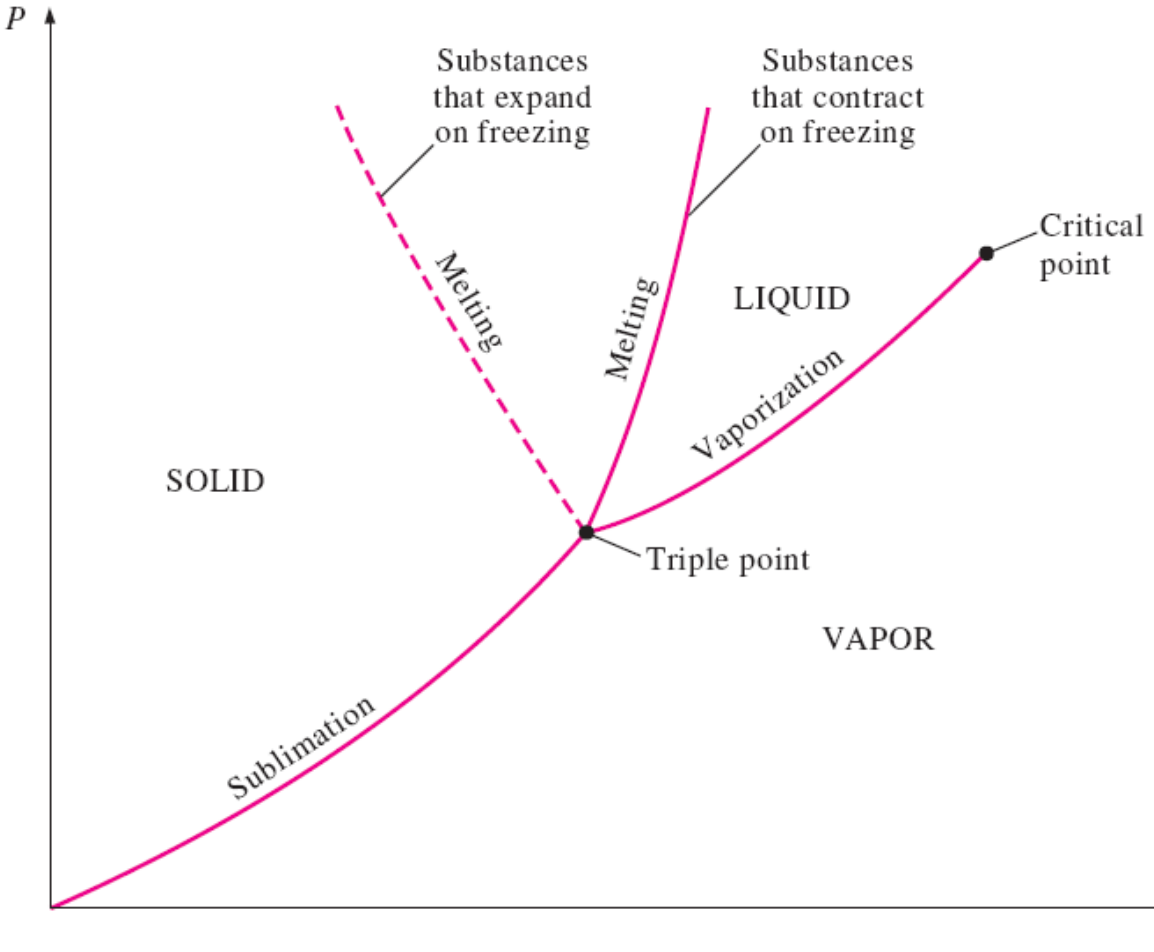
The T-V diagram



The P-V diagram



The P-T diagram



Thermodynamic Property Table

- Thermodynamic properties of substance are usually given in tabular form to facilitate calculation.
- Among them ***saturated, superheated*** and ***compressed liquid*** are the most frequently used properties.

TABLE A–4

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
60	19.947	0.001017	7.6670	251.16	2204.7	2455.9	251.18	2357.7	2608.8	0.8313	7.0769	7.9082
65	25.043	0.001020	6.1935	272.09	2190.3	2462.4	272.12	2345.4	2617.5	0.8937	6.9360	7.8296
70	31.202	0.001023	5.0396	293.04	2175.8	2468.9	293.07	2333.0	2626.1	0.9551	6.7989	7.7540
75	38.597	0.001026	4.1291	313.99	2161.3	2475.3	314.03	2320.6	2634.6	1.0158	6.6655	7.6812
80	47.416	0.001029	3.4053	334.97	2146.6	2481.6	335.02	2308.0	2643.0	1.0756	6.5355	7.6111
85	57.868	0.001032	2.8261	355.96	2131.9	2487.8	356.02	2295.3	2651.4	1.1346	6.4089	7.5435
90	70.183	0.001036	2.3593	376.97	2117.0	2494.0	377.04	2282.5	2659.6	1.1929	6.2853	7.4782
95	84.609	0.001040	1.9808	398.00	2102.0	2500.1	398.09	2269.6	2667.6	1.2504	6.1647	7.4151

Saturated liquid-vapor mixture

- During a vaporization process, a substance exists as part liquid and part vapor. ***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%.

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

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

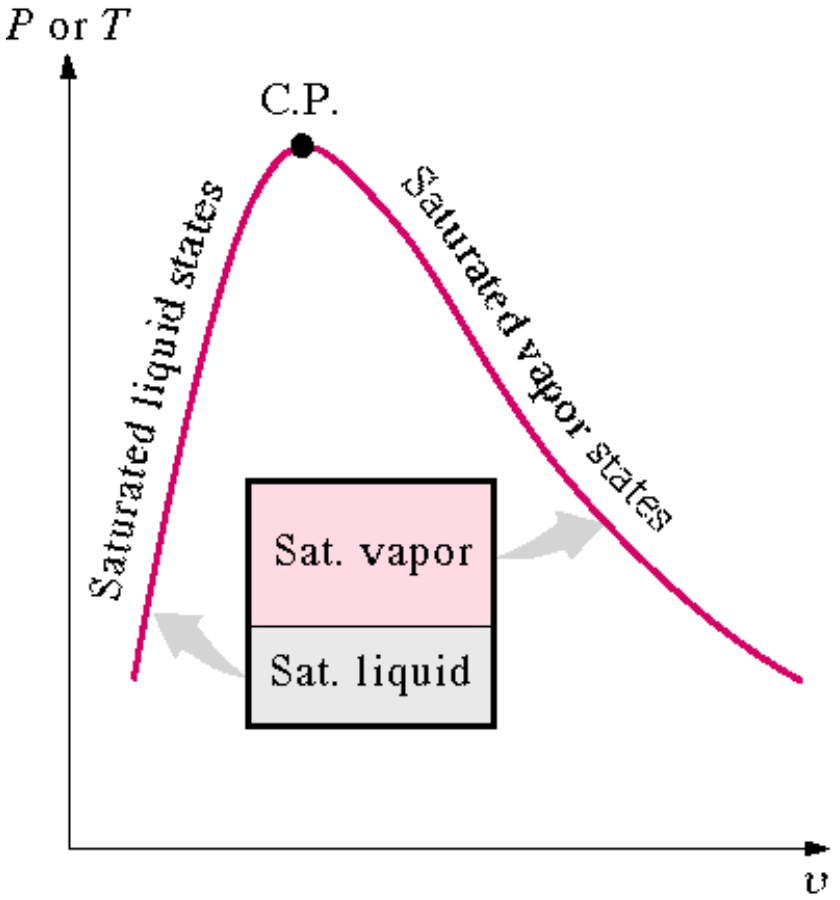
- Recall the definition of quality x

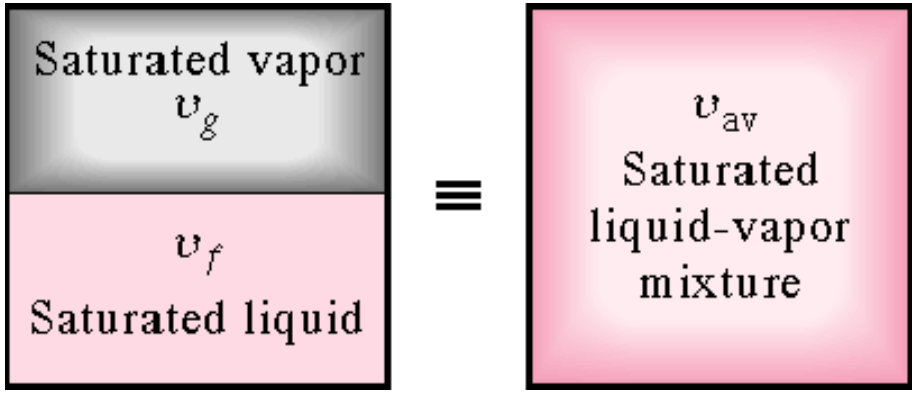
$$x = \frac{m_g}{m} = \frac{m_g}{m_f + m_g}$$

- Then

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

Quality





Mixture of liquid and vapor

- 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

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

$$u = u_f + xu_{fg}$$

$$h = h_f + xh_{fg}$$

$$s = s_f + xs_{fg}$$

Saturated Liquid and Saturated Vapor States

- The properties of saturated liquid and saturated vapor for water are listed in Thermodynamics tables.

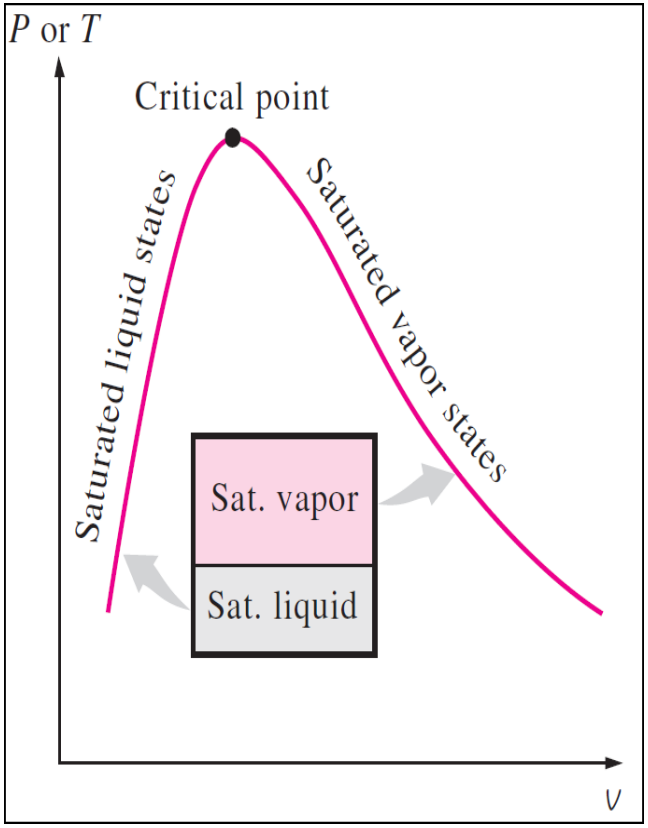
Temp. °C T	Sat. press. kPa P_{sat}	Specific volume m^3/kg Sat. liquid v_f	Sat. vapor v_g
85	57.868	0.001032	2.8261
90	70.183	0.001036	2.3593
95	84.609	0.001040	1.9808

Specific temperature

Corresponding saturation pressure

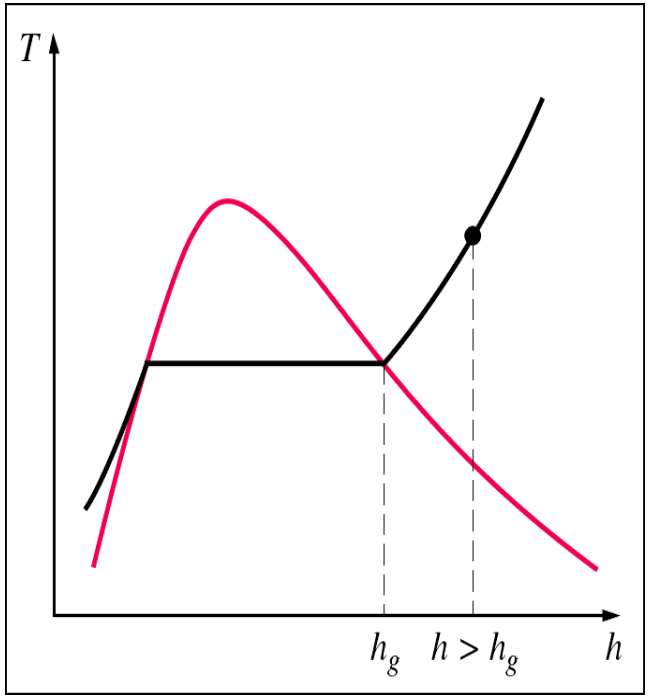
Specific volume of saturated liquid

Specific volume of saturated vapor



Superheated Vapor table

- In the region to the right of the saturated vapor line and at temperatures above the critical point temperature, a substance exists as superheated vapor.

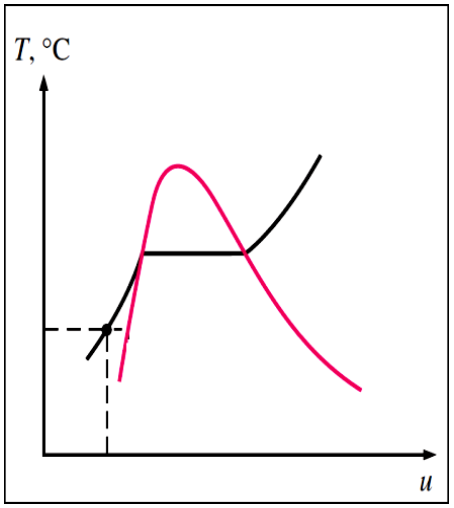


T °C	v m³/kg	u kJ/kg	h kJ/kg	s kJ/kg·K
	P = 0.05 MPa (81.32°C)			
Sat.	3.2403	2483.2	2645.2	7.5931
100	3.4187	2511.5	2682.4	7.6953
150	3.8897	2585.7	2780.2	7.9413
200	4.3562	2660.0	2877.8	8.1592
250	4.8206	2735.1	2976.2	8.3568
300	5.2841	2811.6	3075.8	8.5387
400	6.2094	2968.9	3279.3	8.8659
500	7.1338	3132.6	3489.3	9.1566
600	8.0577	3303.1	3706.0	9.4201
700	8.9813	3480.6	3929.7	9.6626
800	9.9047	3665.2	4160.4	9.8883
900	10.828	3856.8	4398.2	10.1000
1000	11.751	4055.2	4642.7	10.3000
1100	12.675	4259.9	4893.7	10.4897
1200	13.598	4470.8	5150.7	10.6704
1300	14.521	4687.3	5413.3	10.8429

- Compared to saturated vapor, superheated vapor is characterized by
  - Lower pressures ($P < P_{sat}$ at a given T)
  - Higher temperatures ($T > T_{sat}$ at a given P)
  - Higher specific volumes ($v > v_g$ at a given P or T)
  - Higher internal energies ($u > u_g$ at a given P or T)
  - Higher enthalpies ($h > h_g$ at a given P or T)

Compressed liquid table

- Compressed liquid tables are not as commonly available.
- In the absence of compressed liquid data, a general approximation is ***to treat compressed liquid as saturated liquid at the given temperature.***



In general, a compressed liquid is characterized by

- Higher pressures ($P > P_{sat}$ at a given T)
- Lower temperatures ($T < T_{sat}$ at a given P)
- Lower specific volumes ($v < v_f$ at a given P or T)
- Lower internal energies ($u < u_f$ at a given P or T)
- Lower enthalpies ($h < h_f$ at a given P or T)

How to Choose the Right Table

- Given the temperature or pressure and one other property from the group *v*, *u*, *h*, and *s*, the following procedure is used.
- For example if the pressure and specific volume are specified, three questions are asked: For the given pressure,

$$\text{Is } v < v_f \text{ ?}$$

$$\text{Is } v_f < v < v_g \text{ ?}$$

$$\text{Is } v_g < v \text{?}$$

  - If the answer to the first question is yes, the state is in the ***compressed liquid region.***
  - If the answer to the second question is yes, the state is in the ***saturation region.***
  - If the answer to the third question is yes, the state is in the ***superheated region***

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 47º 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

Solution:

- Extract data from steam table

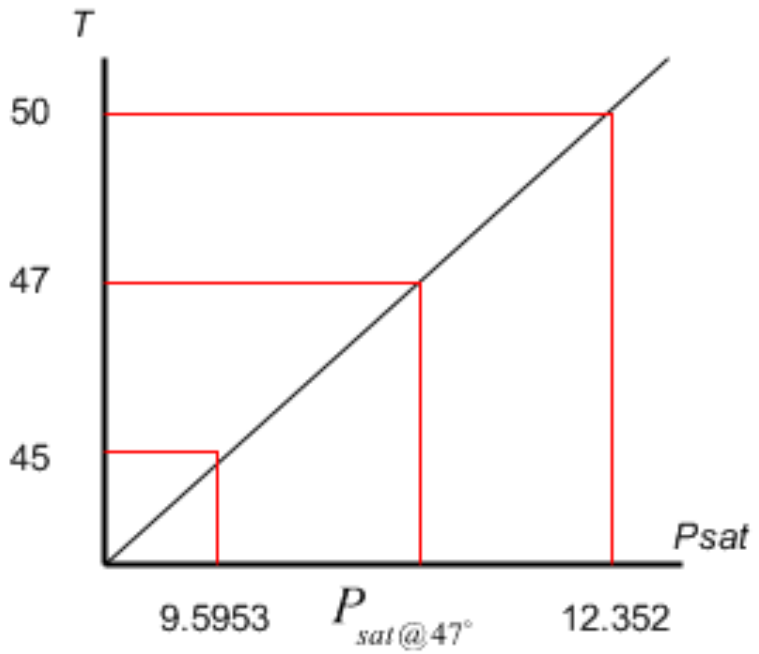
T	P_{sat}	*v*	*u*	*h*
45	9.5953	15.251	2436.1	2582.4
47	*Psat*	*v*	*u*	*h*
50	12.352	12.026	2442.7	2591.3

- 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 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 steam table @ 200 kPa :

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

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

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 :

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

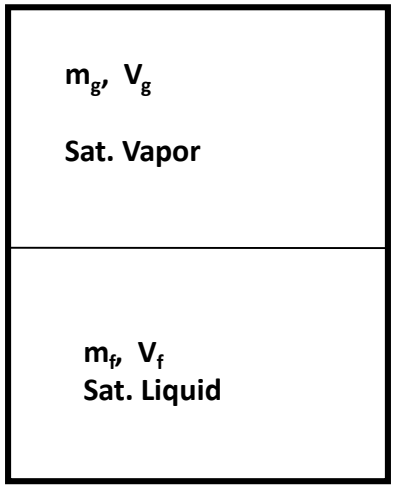
$$u_g = 230.16 \frac{kJ}{kg}$$

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

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

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 :

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

- From table A-5:

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

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

$v_{g2} < v_2$

- 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 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.

Equation of State

- The relationship among the state variables, temperature, pressure, and specific volume is called the ***equation of state***.
- There are several equations of state, some simple and others very complex.
- The simplest and best-known equation of state for substances in the gas phase is the ideal-gas equation of state.
- This equation predicts the P-v-T behavior of a gas quite accurately within some properly selected region.

- Based on our experience in chemistry and physics we recall that the combination of Boyle's and Charles' laws for gases at low pressure result in the equation of state for the ideal gas as

$$P = R\left(\frac{T}{v}\right) \quad Pv = RT \qquad PV = mRT = nMRT$$

- The constant of proportionality R is called the ***gas constant.***
- The gas constant R is different for each gas and is determined from

$$R = \frac{R_u}{M}(kJ/kg.K)$$

- Where R_u is the ***universal gas constant*** and M is the molar mass (also called *molecular weight*) of the gas. The constant R_u is the same for all substances, and its value is 8.314KJ/Kmol K

$$m = nM$$

- The ideal-gas equation of state can be written in several different forms

$$V = mv \rightarrow PV = mRT$$

$$mR = (MN)R = NR_u \rightarrow PV = NR_uT$$

$$V = N\bar{v} \rightarrow P\bar{v} = R_uT$$

- the properties of an ideal gas at two different states are related to each other by

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

- Air, nitrogen, oxygen, hydrogen, helium, argon etc can be treated as ideal gases.

- 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

$$h = u + Pv$$

$$dh = du + RdT$$

$$C_P dt = C_V dt + RdT$$

$$C_P = C_V + R$$

- 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

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

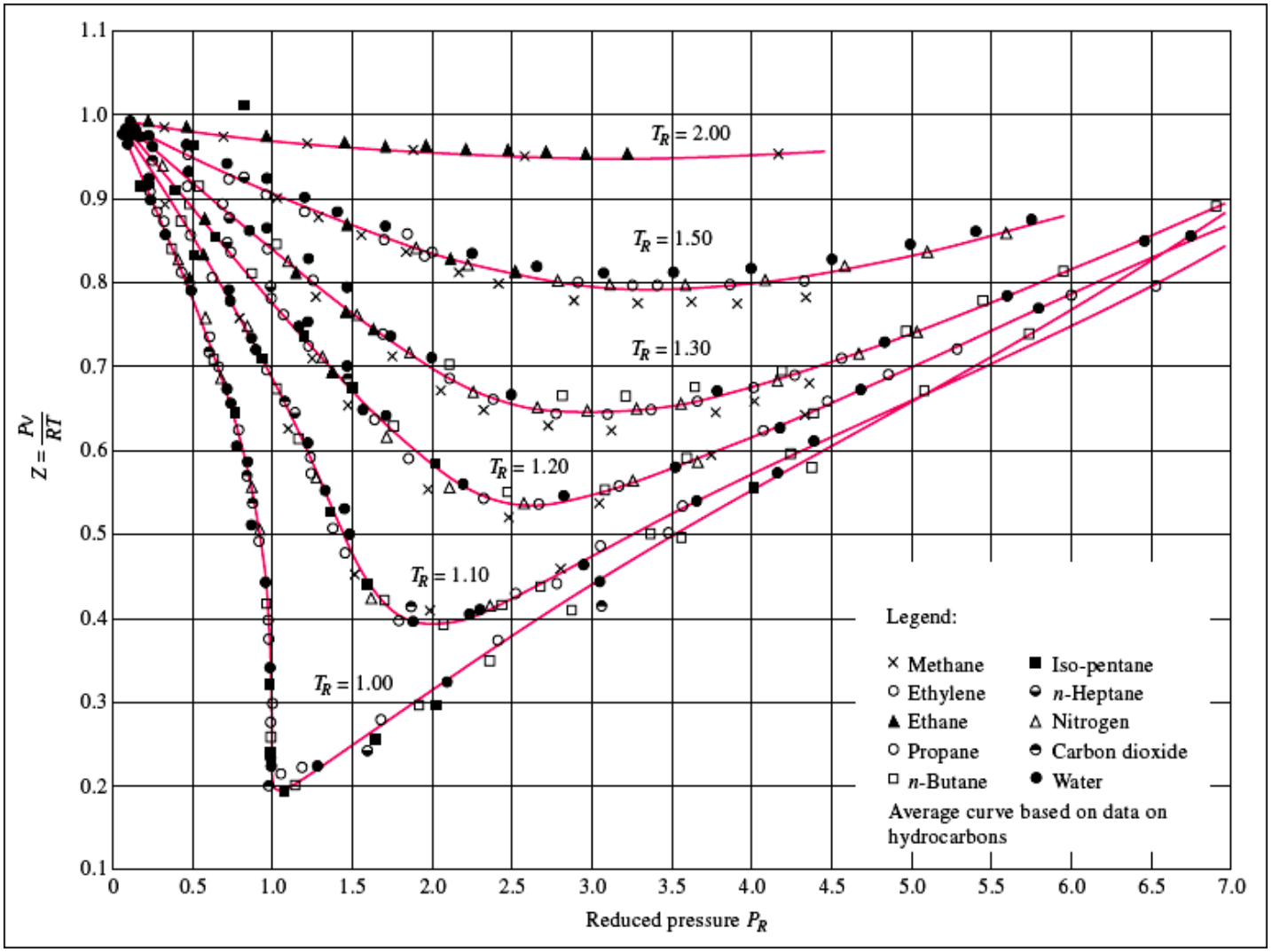
$$\Delta h = h_2 - h_1 = C_P(T_2 - T_1)$$

Compressibility factor (measure of deviation from ideal gas)

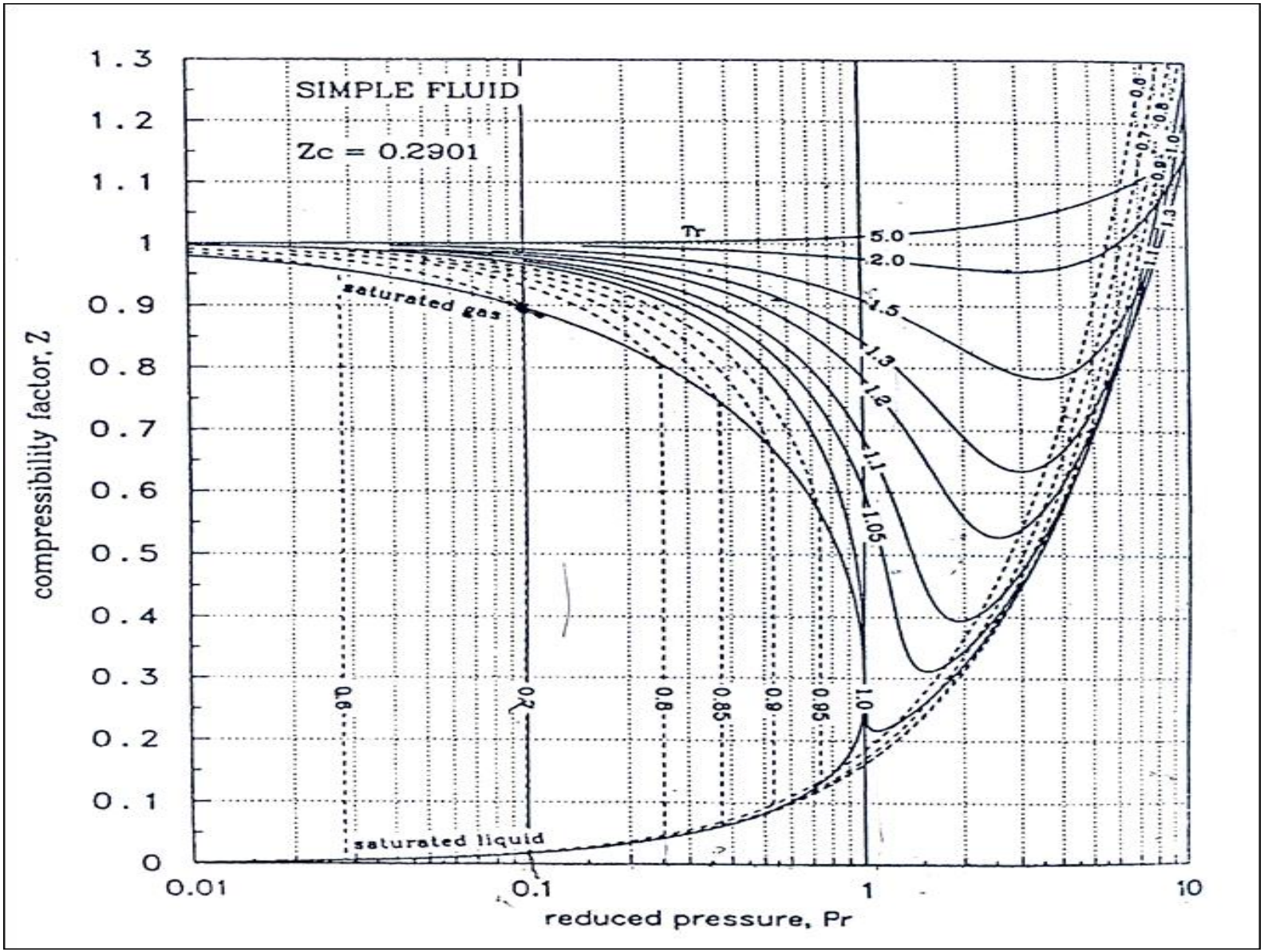
- The ideal-gas equation is very simple and thus very convenient to use.
- This deviation from ideal-gas behavior at a given temperature and pressure can accurately be accounted for by the introduction of a correction factor called the **compressibility factor *Z*** defined as

- For real gases Z can be greater than or less than unity.

$$PV = ZRT$$



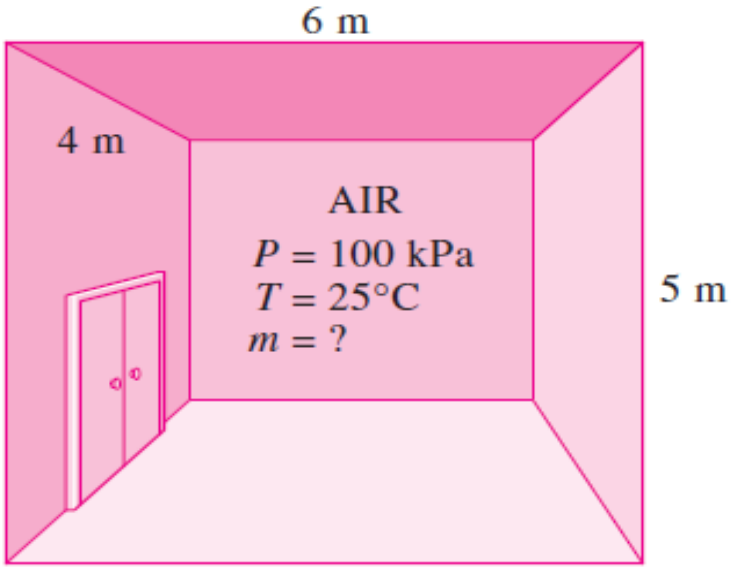
$$P_R = \frac{P}{P_{cr}} \qquad T_R = \frac{T}{T_{cr}}$$


SIMPLE FLUID
Zc = 0.2901
Tr
5.0
2.0
1.5
1.3
1.2
1.1
1.05
1.0
0.95
0.9
0.85
0.8
0.6
0.2
saturated gas
saturated liquid
compressibility factor, Z
reduced pressure, Pr
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0.01
0.1
1
10

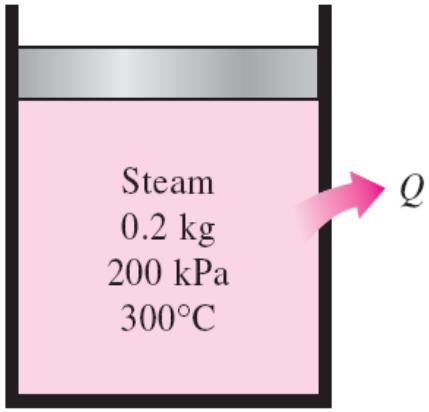
Example

1. Determine the mass of the air in a room whose dimensions are 4 m X 5 m X 6 m at 100 kPa and 25°C.

(R=0.287 kJ/kg. K)



2. A piston–cylinder device initially contains 0.2 kg of steam at 200 kPa and 300°C. Now, the steam is cooled at constant pressure until it is at 150°C. Determine the volume change of the cylinder during this process using the ideal gas equation and compare the result to the actual value.



3. 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:

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

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

$$= 123.15\,kPa$$

4. 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

$\boxed{state 1}$

$P = 200 + 100\ kPa$

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

❖ From ideal-gas law:

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

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

$$= 2.14\,kg$$

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*]