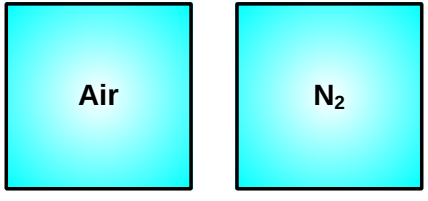
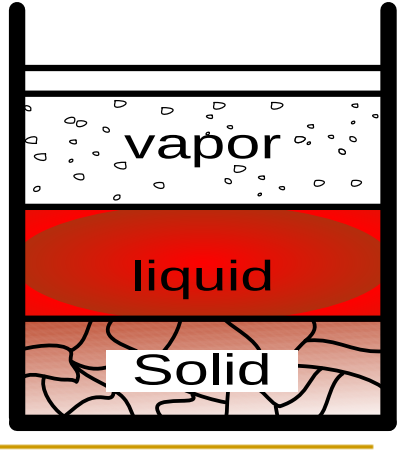
Properties of Pure Substance

Pure substance

- A substance that has a fixed chemical composition throughout is called a ***pure substance***.
- Pure substance may consists of more one element or compound
  - » Water
  - » Nitrogen
  - » Air
  - » Helium
  - » Carbon dioxide

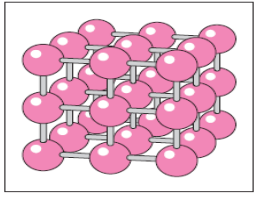


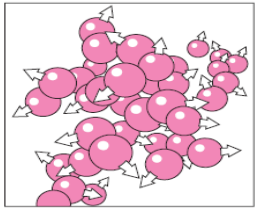
- Pure substance may exist in different phases, but the chemical compositions is the same.
  - water made up of two atoms of hydrogen and one atom oxygen. It will have the same composition when in ice, liquid and vapor forms.

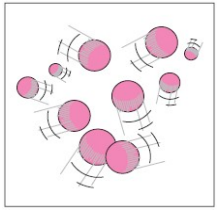


Phase of pure substances

- Under different conditions a substance may appear in different phases. The three principal phases are solid, liquid and gas.



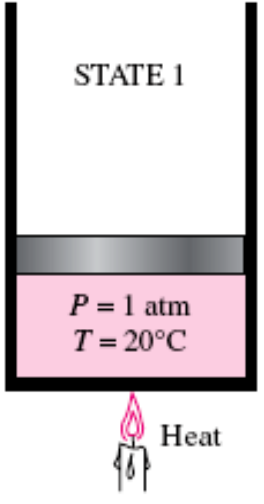




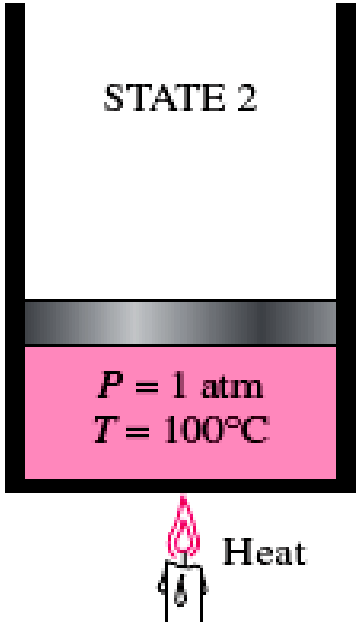
  - Considering water, it can be exist as
    - » Pure solid phase (ice)
    - » Pure liquid phase
    - » Pure vapor phase (steam)
  - It can also exist as an equilibrium mixture of different phase

Phase-change processes of pure substances

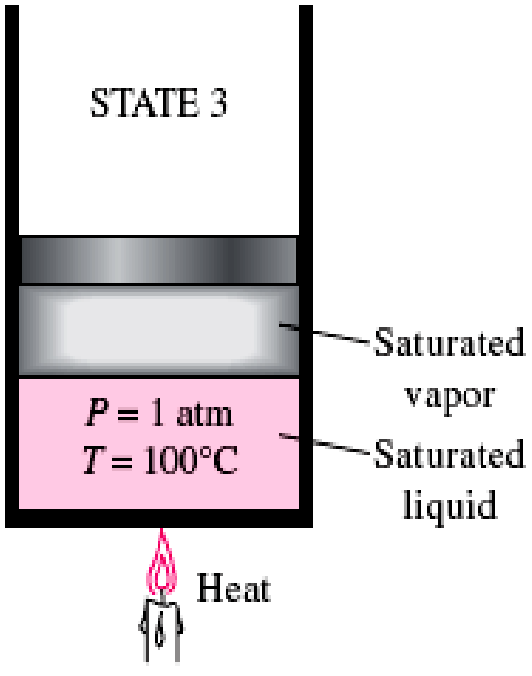
- Consider the piston-cylinder device containing liquid water 20^{o}C at and 1atm.



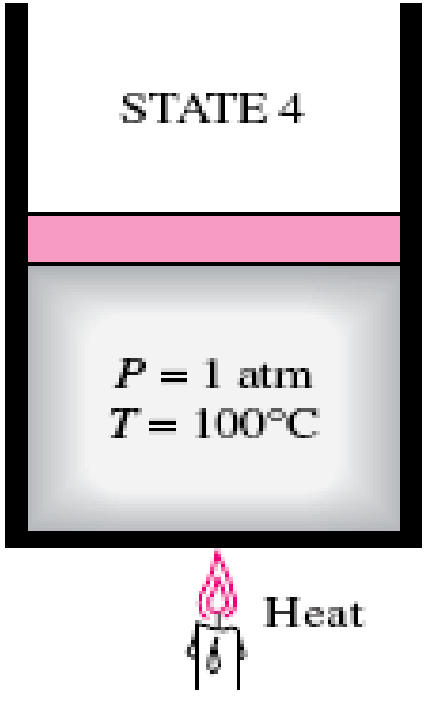
- Under these conditions, water exists in the liquid phase, and it is called a ***compressed liquid***, or a ***sub cooled liquid.***
- As the temperature rises, the liquid water expands slightly, and so its specific volume increases.



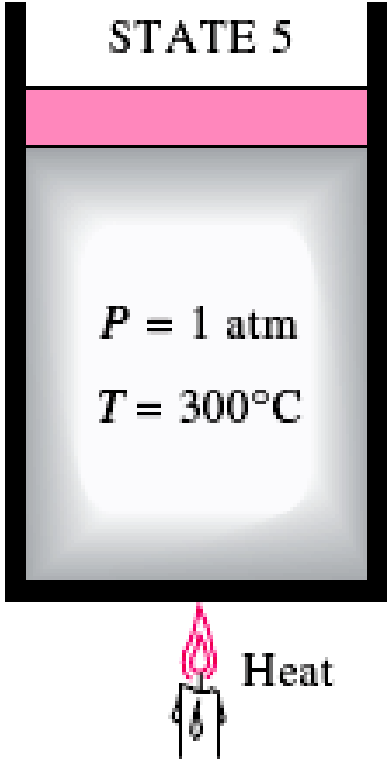
- At this point water still a liquid, but any heat addition will cause some of the liquid to vaporize.
- That is, a phase change process from liquid to vapor is about to take place.
- A liquid about to vaporize is called ***saturated liquid.***



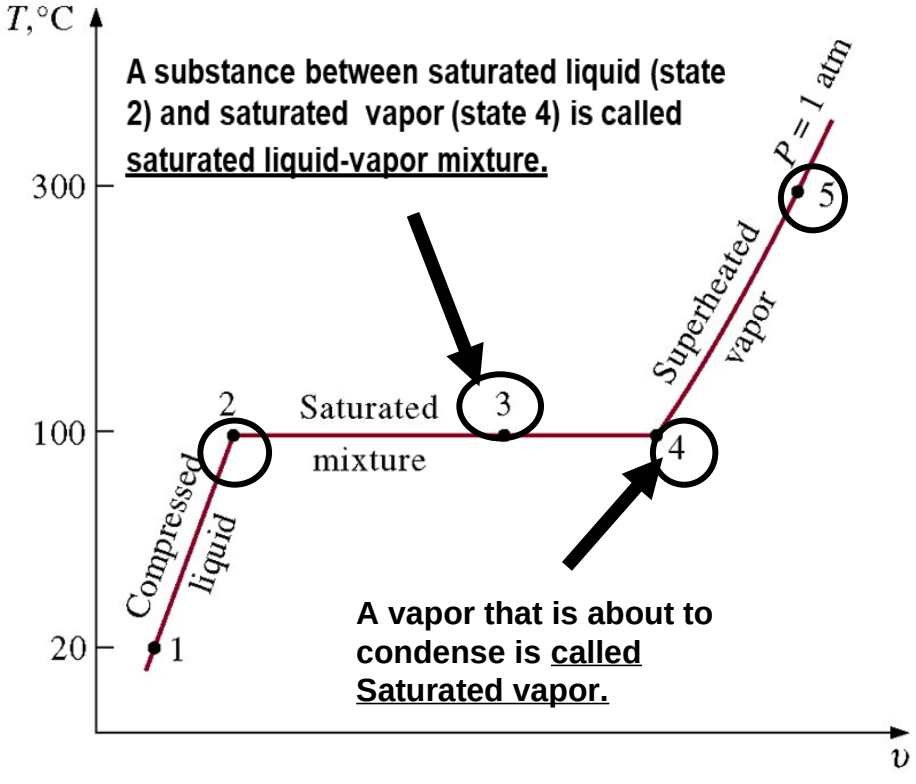
- Once boiling starts, the ***temperature stops rising*** until the liquid is completely vaporized (it is a constant phase - change process at p-constant).
- During this process the only thing is change in volume.
- At this stage liquid and vapor phase coexist in equilibrium and it is called ***saturated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


T, °C
300
100
20
A substance between saturated liquid (state 2) and saturated vapor (state 4) is called saturated liquid-vapor mixture.
P = 1 atm
5
Superheated vapor
2
Saturated mixture
3
4
Compressed liquid
1
A vapor that is about to condense is called Saturated vapor.
v

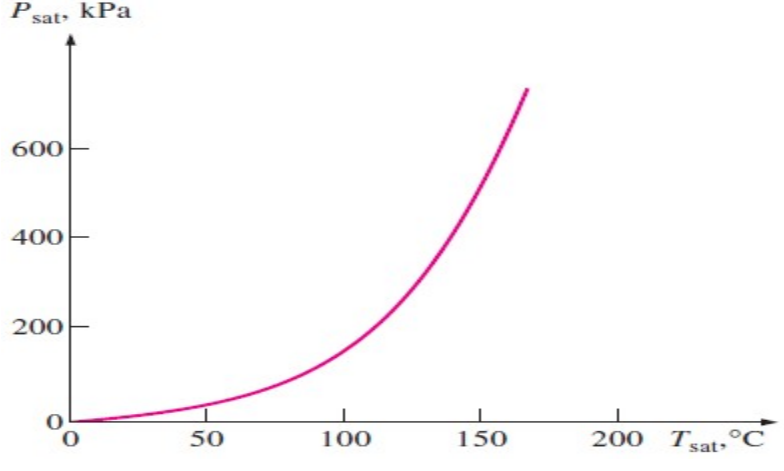
- At a given pressure, the temperature at which a pure substance changes phase is called the ***saturation temperature*** $T_{sat.}$
- At a given temperature, the pressure at which a pure substance changes phase is called the ***saturation pressure*** P_{sat}.
- At a pressure of 101.325 kPa, T_{sat} is 99.97°C.
- At a temperature of 99.97°C, P_{sat} is 101.325 kPa.

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

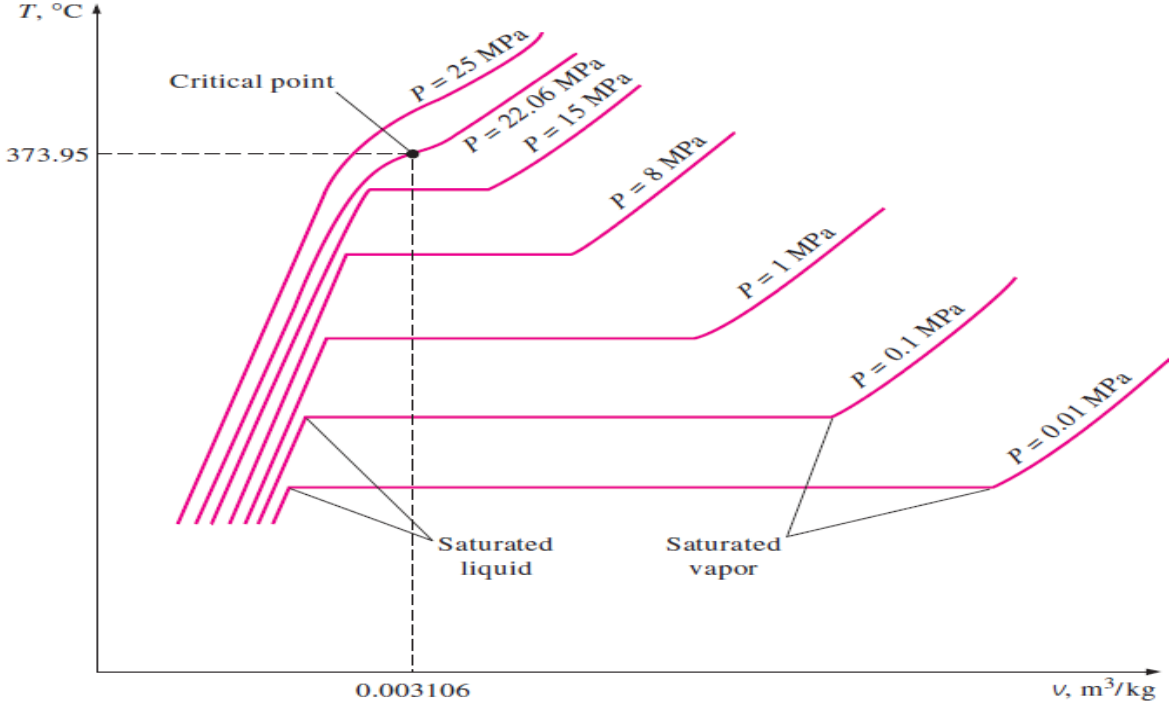
- The amount of energy absorbed or released during a phase-change process is called the ***latent heat.***
- The amount of energy absorbed during vaporization is called the ***latent heat of vaporization*** *a*nd it is equivalent to the energy released during condensation.
- The amount of energy absorbed during melting is called the ***latent heat of fusion*** and it is equivalent to the amount of energy released during freezing.

- The magnitude of the latent heats depend on the temperature or pressure at which the phase change occur.
- 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.
- During a phase-change process, pressure and temperature are obviously dependent properties $T_{sat} = f(P_{sat})$



Property diagrams for phase change processes

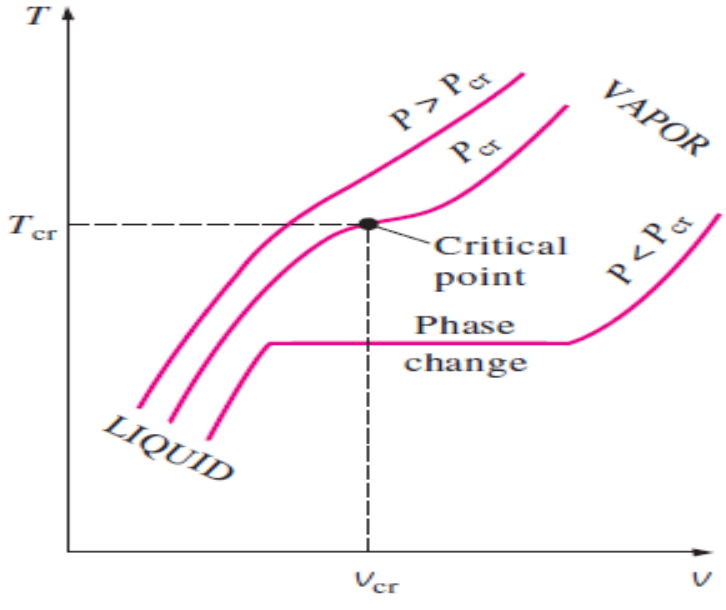
1, The *T*-*v* Diagram



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.
- At pressures above the critical pressure, there is not a distinct phase-change process.
- As the pressure is increased further, this saturation line continues to shrink.
- **Critical point** :- *the point at which the saturated liquid and saturated vapor states are identical.*

- The temperature, pressure, and specific volume of a substance at the critical point are called, *critical temperature* T_{cr}, *critical pressure* P_{cr}, and *critical specific volume* v_{cr}.



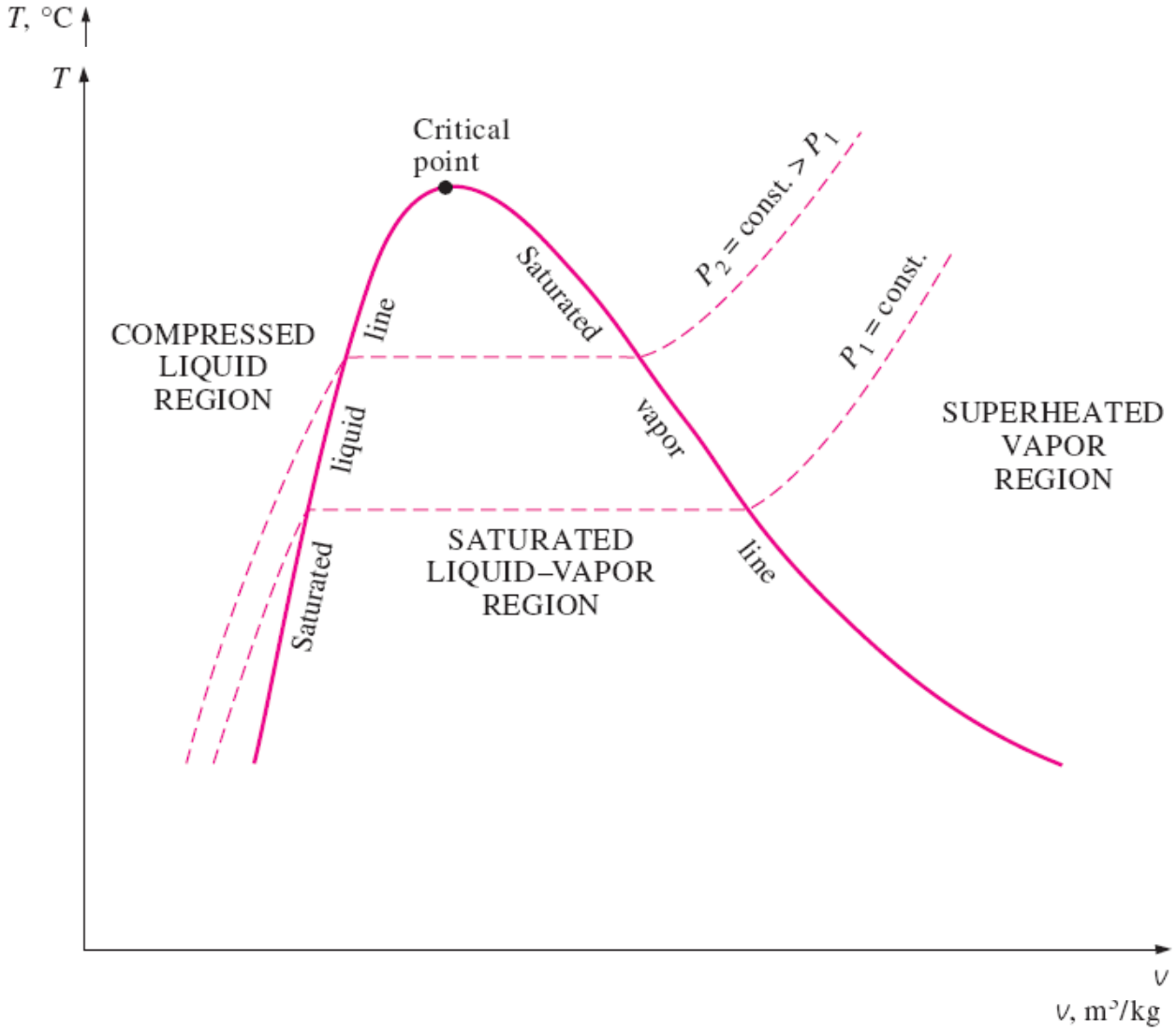
- For water are:-

  P_{cr} = 22.06 MPa,

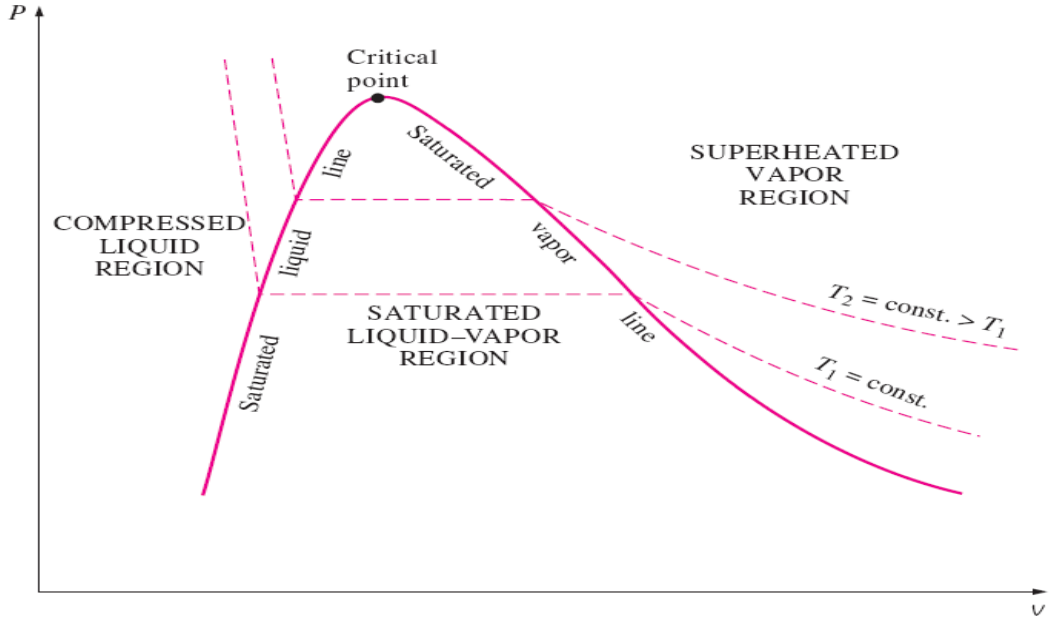
  T_{cr} = 373.95°C, and

  v_{cr} = 0.003106 m3/kg.

- At pressures above the critical pressure, there is not a distinct phase change process.


T, °C
T
Critical point
P_2 = const. > P_1
P_1 = const.
Saturated liquid line
Saturated vapor line
COMPRESSED LIQUID REGION
SATURATED LIQUID–VAPOR REGION
SUPERHEATED VAPOR REGION
v
v, m³/kg

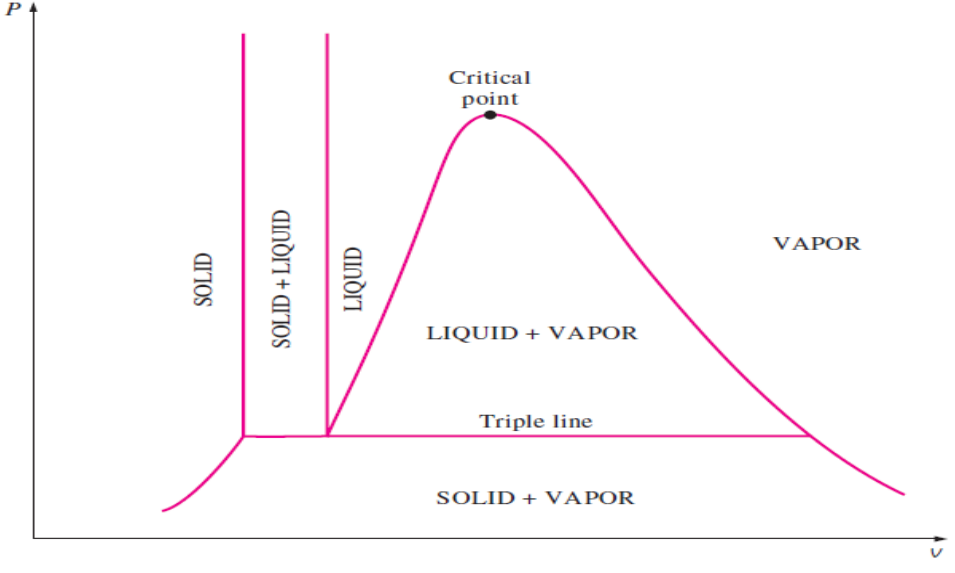
The P-V diagram



- As the pressure decreases, the volume of the water increases slightly. When the pressure reaches the saturation-pressure value at the specified temperature (0.4762 MPa), the water starts to boil.

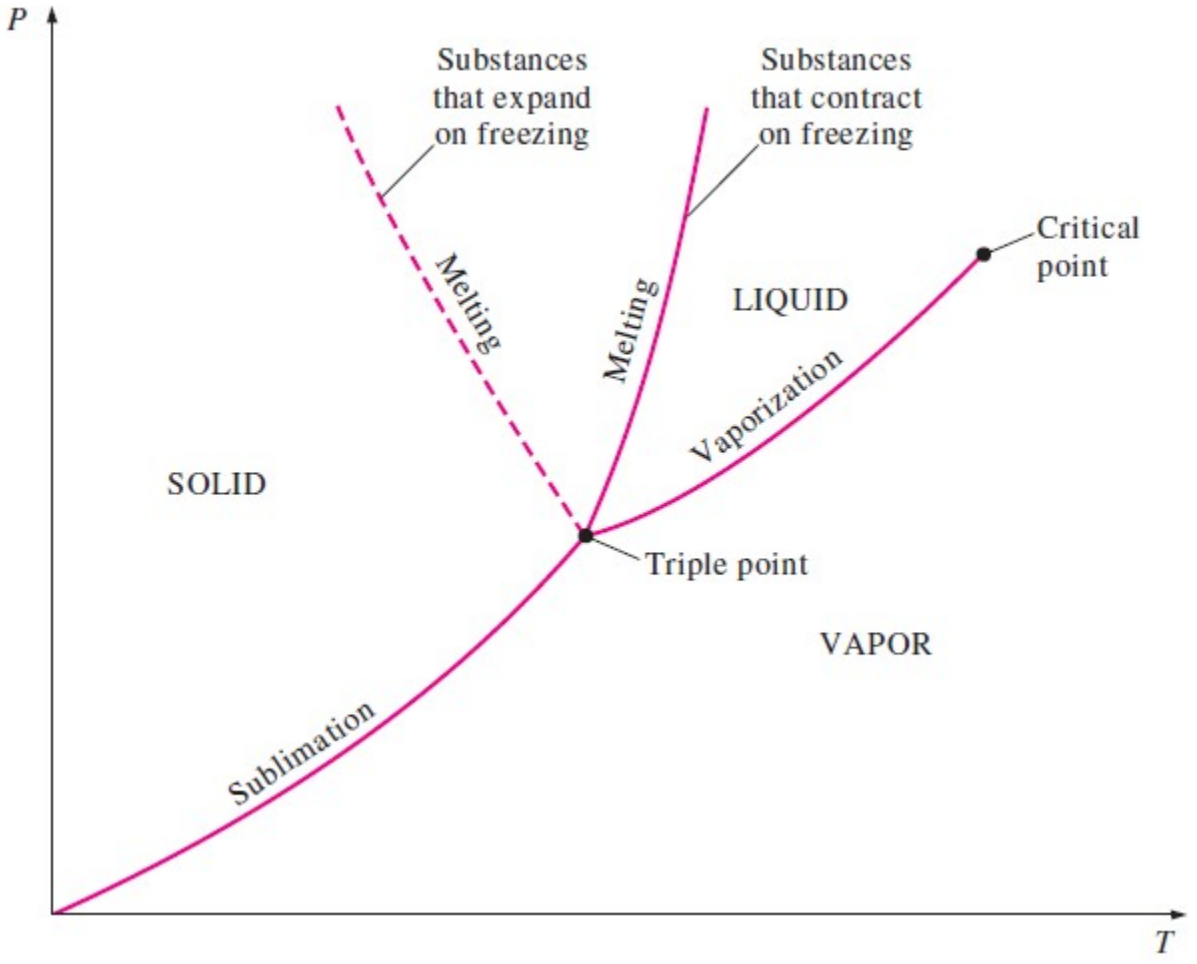
Extending the Diagrams to Include the Solid Phase

- These diagrams can easily be extended to include the solid phase as well as the solid–liquid and the solid–vapor saturation regions.
- Most substances contract during a solidification (i.e., freezing) process. Others, like water, expand as they freeze.



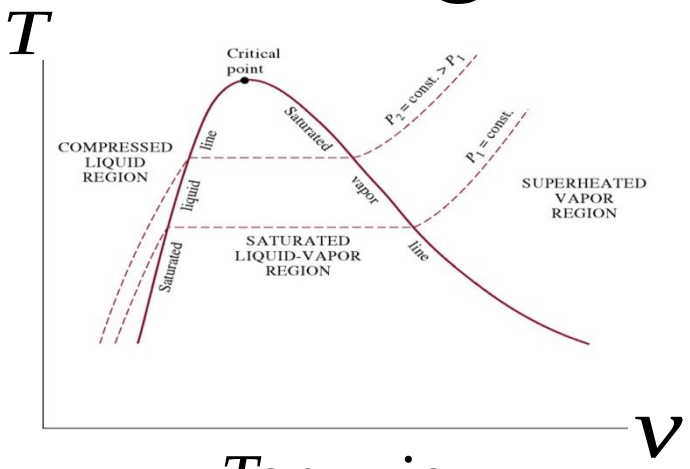
- The states on the triple line of a substance have the same pressure and temperature but different specific volumes.
- There are two ways a substance can pass from the solid to vapor phase: either
- it melts first into a liquid and subsequently evaporates, or
- it evaporates directly without melting first.
- At pressures below the triple point value, since a pure substance cannot exist in the liquid phase at those pressures. Passing from the solid phase directly into the vapor phase is called **sublimation.**

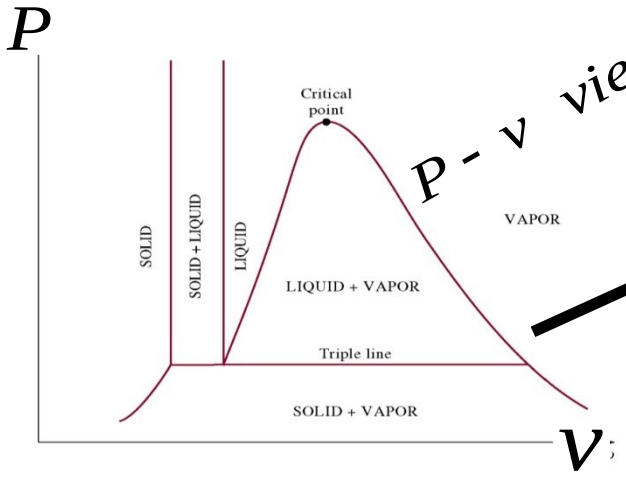
The P-T diagram



- All three phases are separated from each other by three lines.
- The sublimation line separates the solid and vapor regions, the vaporization line separates the liquid and vapor regions, and the melting (or fusion) line separates the solid and liquid regions.
- These three lines meet at the triple point, where all three phases coexist in equilibrium.
- The vaporization line ends at the critical point because no distinction can be made between liquid and vapor phases above the critical point.

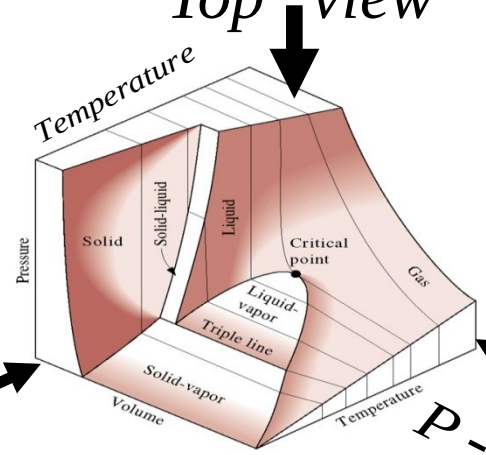
P-V-T diagram



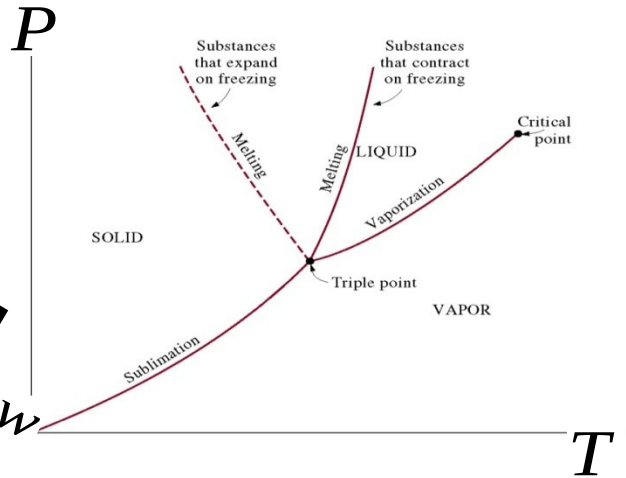


P - v view

Top view



P - T view



Thermodynamic tables

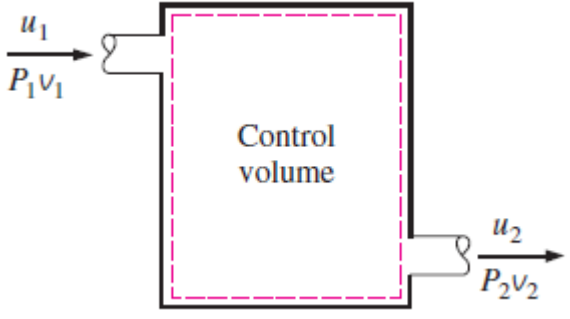
- Thermodynamic properties of substance are usually given in tabular form to facilitate calculation.
- Among them ***saturated, superheated steam*** and ***compressed liquid*** are the most frequently used properties.

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

Enthalpy—A Combination Property

- ***Internal energy U*** *of a system is the sum of all the microscopic forms of energy.*
- *Specific enthalpy:-* $h = u + Pv \quad (\text{kJ/kg})$ *or*
- the total enthalpy *H:-* $H = U + PV \quad (\text{kJ})$
- *u + Pv* as *heat content* and *total heat*.
- **Enthalpy** is sometimes known as "**the total heat content** in thermodynamics system"



Saturated liquid-vapor mixture

- During a vaporization process, a substance exists as part liquid and part vapor.
- To analyze this mixture properly, we need to know the **proportions** of the liquid and vapor phases in the mixture.
- ***Quality (x)*** as the ratio of the mass of vapor to the total mass of the mixture:

$$x = \frac{m_{vapor}}{m_{total}} \qquad m_{total} = m_{liquid} + m_{vapor} = m_f + m_g$$

$$x \equiv \frac{m_g}{m_f + m_g} = \frac{m_g}{m_{total}}$$

Its value is between 0 and 1

Saturated Liquid and Saturated Vapor States

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

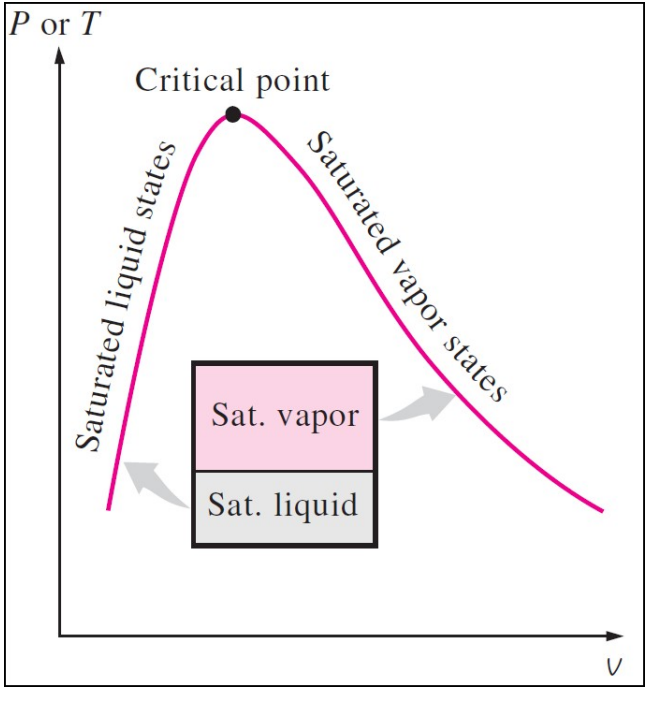
Temp. °C T	Sat. press. kPa P_{sat}	Specific volume m^3/kg Sat. liquid v_f	Sat. vapor v_g
85	57.868	0.001032	2.8261
90	70.183	0.001036	2.3593
95	84.609	0.001040	1.9808

Specific temperature

Corresponding saturation pressure

Specific volume of saturated liquid

Specific volume of saturated vapor



Saturated Liquid-Vapor Mixture

$$V = V_f + V_g$$

$$mv = m_f v_f + m_g v_g$$

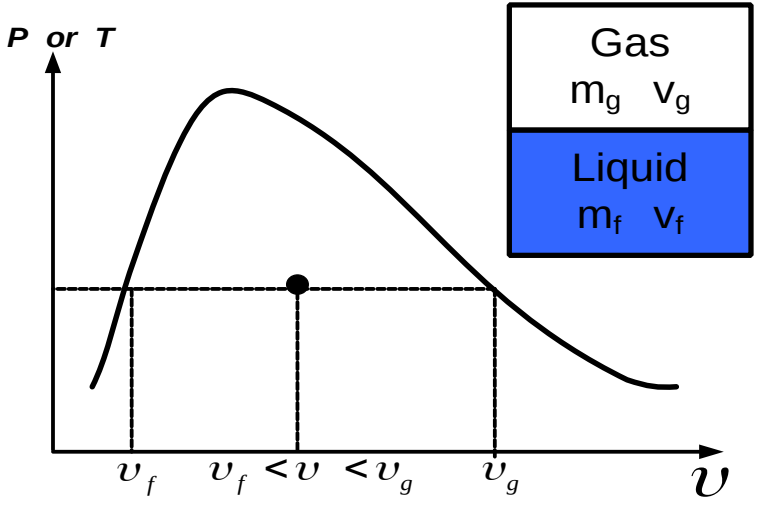
$$= (m - m_g) v_f + m_g v_g$$

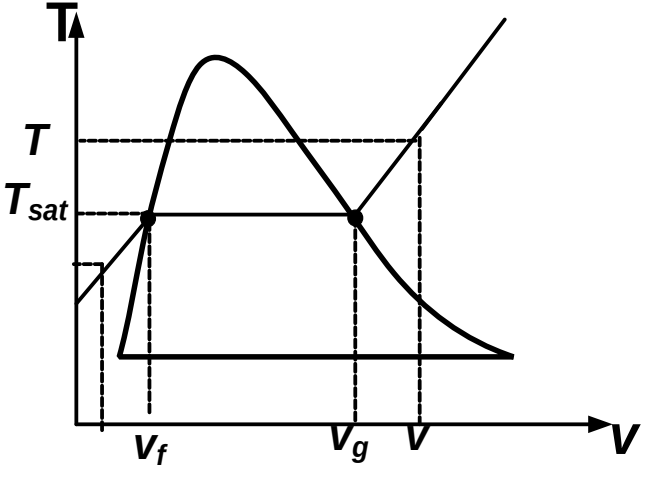
$$\therefore \quad v = (1 - x) v_f + x v_g$$

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

$$\Rightarrow \quad v = v_f + x v_{fg}$$

$$\text{where} \quad v_{fg} = v_g - v_f$$





$T = T_{sat}$ at given P

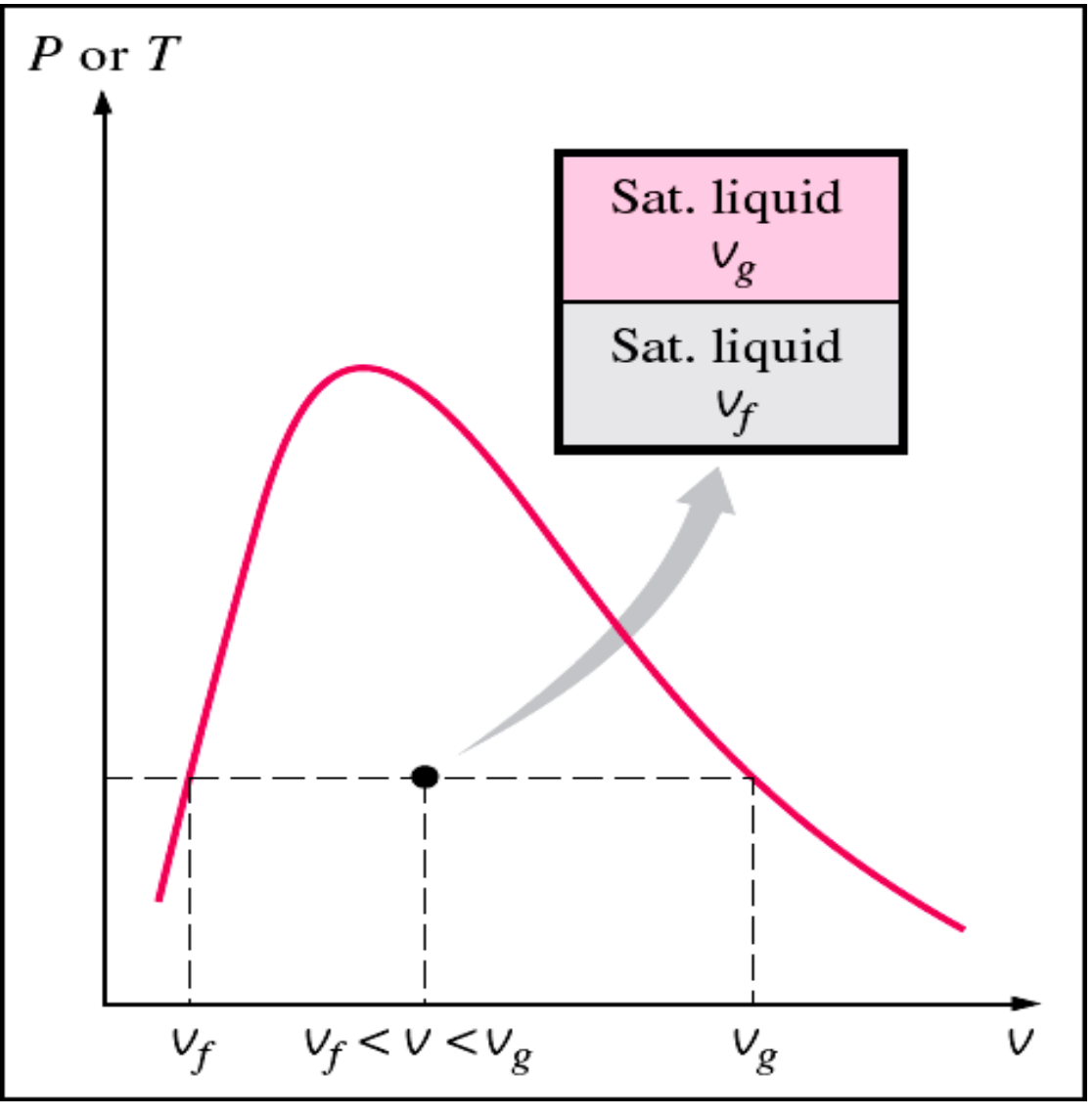
$P = P_{sat}$ at given T

$v_f < v < v_g$ at given P or T

$u_f < u < u_f$ at given P or T

$h_f < h < h_{\square\square}$ at given P or T

saturated mixture



$$V = V_f + V_g$$

$$V = mv$$

$$m_{tot} v_{avr} = m_f v_f + m_g v_g$$

$$m_f = m_{tot} - m_g$$

$$v_{avg} = v_f + x v_{fg}$$

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

$$u = u_f + x u_{fg}$$

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

$$s = s_f + x s_{fg}$$

Example 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. (Table A-4)

(Answers: 70.14 kPa, 0.0518 m^3)

Example 2-2

- A piston-cylinder device contains 2 m^3 of saturated water vapor at 50-kpa pressure. Determine the temperature of the vapor and the mass of the vapor inside the cylinder. (Table A-5)

(Answers: 81.32^oC, 0.613kg)

Example 2.3

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

(Answers: 70.183 kPa, 4.727 m^3)

Example 2.4

- An 80-L vessel contains 4 kg of refrigerant 134a at a pressure of 160 kPa. Determine a) the temperature of the refrigerant, b) the quality, c) the enthalpy of the refrigerant, and d) the volume occupied by the vapor phase.

(Answers: -15.60^{o}C, 0.157, 64.16 kJ/kg, 0.0776 m^{3})

Superheated steam 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.

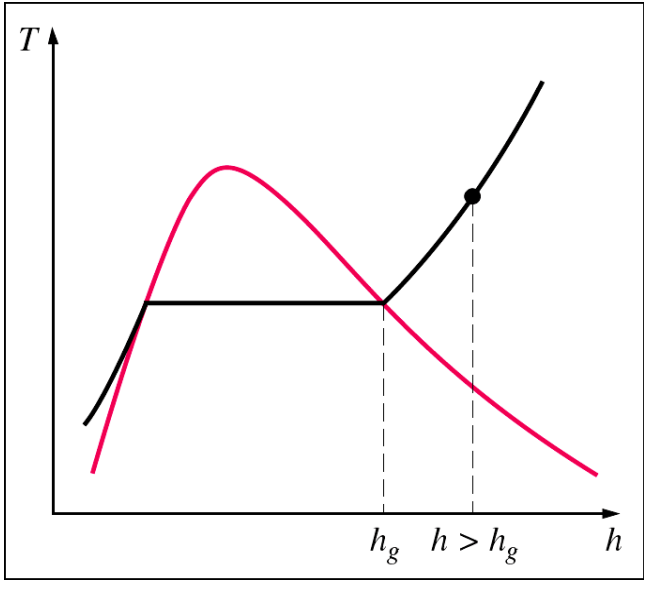


TABLE A–6

Superheated water

T °C	v m³/kg	u kJ/kg	h kJ/kg	s kJ/kg · K	v m³/kg	u kJ/kg	h kJ/kg	s kJ/kg · K
	P = 0.01 MPa (45.81°C)*				P = 0.05 MPa (81.33°C)			
Sat.†	14.674	2437.9	2584.7	8.1502	3.240	2483.9	2645.9	7.5939
50	14.869	2443.9	2592.6	8.1749				
100	17.196	2515.5	2687.5	8.4479	3.418	2511.6	2682.5	7.6947
150	19.512	2587.9	2783.0	8.6882	3.889	2585.6	2780.1	7.9401
200	21.825	2661.3	2879.5	8.9038	4.356	2659.9	2877.7	8.1580
250	24.136	2736.0	2977.3	9.1002	4.820	2735.0	2976.0	8.3556
300	26.445	2812.1	3076.5	9.2813	5.284	2811.3	3075.5	8.5373
400	31.063	2968.9	3279.6	9.6077	6.209	2968.5	3278.9	8.8642
500	35.679	3132.3	3489.1	9.8978	7.134	3132.0	3488.7	9.1546
600	40.295	3302.5	3705.4	10.1608	8.057	3302.2	3705.1	9.4178
700	44.911	3479.6	3928.7	10.4028	8.981	3479.4	3928.5	9.6599
800	49.526	3663.8	4159.0	10.6281	9.904	3663.6	4158.9	9.8852
900	54.141	3855.0	4396.4	10.8396	10.828	3854.9	4396.3	10.0967
1000	58.757	4053.0	4640.6	11.0393	11.751	4052.9	4640.5	10.2964
1100	63.372	4257.5	4891.2	11.2287	12.674	4257.4	4891.1	10.4859
1200	67.987	4467.9	5147.8	11.4091	13.597	4467.8	5147.7	10.6662
1300	72.602	4683.7	5409.7	11.5811	14.521	4683.6	5409.6	10.8382

- 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)

Linear Interpolation

A	B
100	5
130	Y
200	10

$$\frac{130 - 100}{200 - 100} = \frac{y - 5}{10 - 5}$$

•EXAMPLE 2.5

	T	P_{sat}
•X1=	140	y1= 361.53
•X =	143	y = ?
•X2=	145	y2= 415.68

$$\frac{y - y_1}{y_2 - y_1} = \frac{x - x_1}{x_2 - x_1}$$

$$y = y_1 + \frac{x - x_1}{x_2 - x_1} \times (y_2 - y_1)$$

$$P_{sat} := 0.3615 + \frac{143 - 140}{145 - 140} \cdot (0.4154 - 0.3615)$$

$$P_{sat} = 0.394 \quad kPa$$

Example 2-6

Superheated Vapor

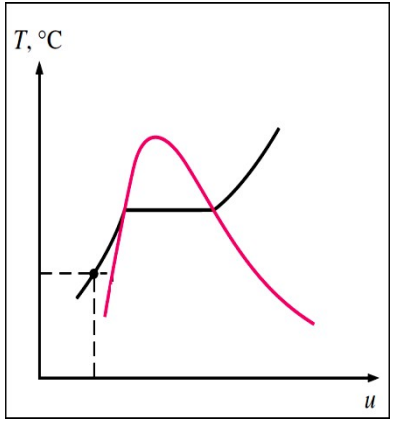
- Determine the temperature of water at a state of

  P = 0.5 MPa and h = 2890 kJ/kg

- (Answers: 216.4 ◦C)

Compressed liquid table

- Compressed liquid tables are not as commonly available this is because the compressed liquid properties depend on temperature much more strongly than they do on pressure.
- In the absence of compressed liquid data, a general approximation is ***to treat compressed liquid as saturated liquid at the given temperature.***

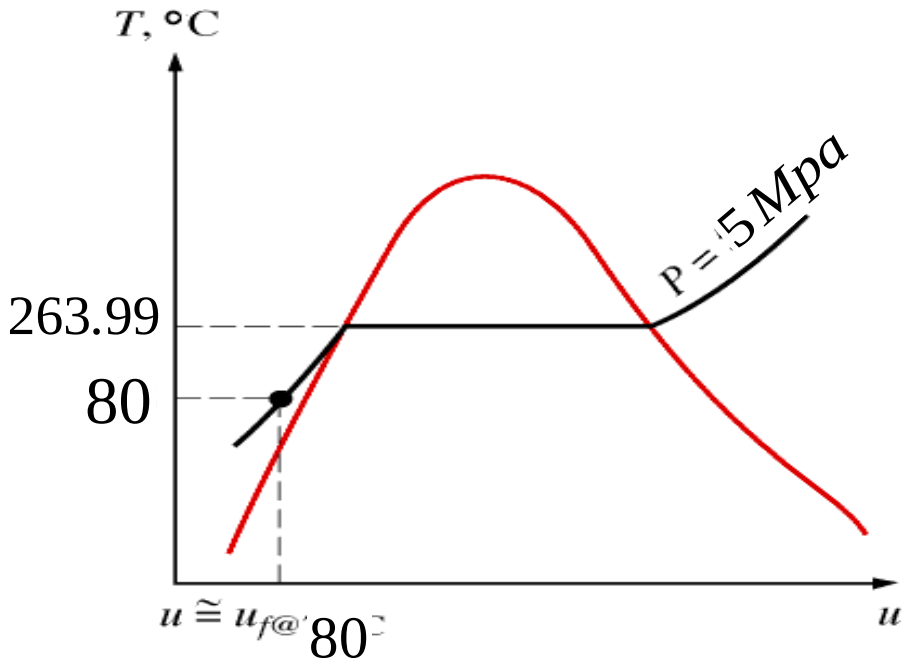


In general, a compressed liquid is characterized by

- 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)

Example 2-7:

- Determine the internal energy of compressed liquid water at 80°C and 5 MPa using (a) data from the compressed liquid table and (b) saturated liquid data. What is the error involved in the second case? (Answers: 333.72 kJ/kg, 334.86 kJ/kg, 0.34%)



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,

Is $v < v_f$?

Is $v_f < v < v_g$?

Is $v_g < v$?

  - 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***

Examples

1. Determine Phase(state) of water at each of the following points

a)	120°C, 100kPa	Super heated
b)	350kPa, 0.4992m^3/kg	Saturated L.V Mixture
c)	150°C, 0.4992m^3/kg	Super heated
d)	0.2MPa, 110°C	Compressed liquid

2. Plot the following process on P-v and P-T diagram.

a)	Super heated vapor is cooled at constant pressure until liquid just begins to form.
b)	A liquid – vapor mixture with a quality of 60% is heated at constant volume until its quality is 100%.
c)	A liquid – vapor mixture of water with a quality of 60% is heated at constant temperature of 200^{o}C until its volume is 4.67 times.

7. Determine the missing properties and the phase descriptions in the following table for

	T, °C	P, kPa	u, kJ/kg	x	Phase description
(*a*)		200		0.6	
(*b*)	125		1600		
(*c*)		1000	2950		
(*d*)	75	500			
(*e*)		850		0.0	

THE IDEAL-GAS EQUATION OF STATE

- Any equation that relates the pressure,temperature, and specific volume of a substance is called an **equation of state.**
- Property relations that involve other properties of a substance at equilibrium states are also referred to as equations of state.
- The simplest and best-known equation of state for substances in the gas phase is the **ideal-gas equation of state**.

P-v-T relation for ideal gases

- The vapor phase of a substance is called gas when it is above the critical temperature.
- Vapor implies a gas that is not far from a state of condensation.
- In 1802, Charles and Lussac experimentally determined the following (Ideal gas equation of state):

$$P = R\left(\frac{T}{v}\right)$$

or

$$Pv = RT$$

R is the Gas constant
R= Ru / M
Ru is universal gas constant
Ru = 8.314 KJ/Kmol . K
M is Molar Mass of the gas (molecular weight)

$$Pv = RT$$

$$PV = mRT \quad (v = V/m)$$

$$PV = NR_u T \quad (mR = NMR = NR_u)$$

$$P\bar{v} = R_u T \quad (\bar{v} = V/N)$$

- The properties of an ideal gas for a fixed mass at two different states are related to each other by:-

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

$$m_1 = m_2$$

$$\frac{P_1V_1}{RT_1} = \frac{P_2V_2}{RT_2} \text{ and } \frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$$

- An ideal gas is an imaginary substance that obeys the P-v-T relation.
- At low pressure and high temperature, the density of a gas decreases, and the gas behaves like an ideal gas.
- In the range of practical interest, many familiar gases such as air, nitrogen, oxygen, hydrogen, helium, Aragon, neon, krypton, and even heavier gases such as carbon dioxide can be treated as ideal gases with negligible error (often less than 1 %).

- Dense gases such as *water vapor* in steam power plants and *refrigerant vapor* in refrigerators, however, should not be treated as ideal gases.
- Instead, the property tables *should be* used for these substance

Is Water vapor an ideal gas?

At pressure below 10 KPa, water vapor can be treated as an ideal gas, regardless of its temperature, with negligible error (less than 0.1%).

At higher pressures, however, the ideal-gas assumption yields unacceptable errors.

In air-conditioning applications , where the pressure of the water vapor is very low (ideal gas relations can be used)

In steam power plant applications, they should not be used

