

PURE SUBSTANCES

Homogeneous
in composition

[Same proportion
of elements]

Steam	→ 2:1 (H_2O)
Water	→ 2:1 (H_2O)

$H_2 + \frac{1}{2} O_2$
Water

✓

$H_2 + O_2$
Water

X

Homogeneous in
chemical

Aggregation

[Same
formula]

Invariable in
chemical

aggregation

[Formula
does not
change
w.r.t.
time]

Two-property rule: State of a pure substance of given mass can be fixed by specifying two properties, provided i, system is in equilibrium
ii, no gravity, electricity, magnetism.

① For 1 kg of gaseous air, every time the pressure and temp. are caused to have these particular values, the volume will be same

② But for steam-water mixture, if the press. is 1 atm and temp. is 100°C, a no. of states could exist. Bcoz when water is at 1 atm changed into steam, the temp. remains at 100°C throughout the complete process. [In this case the two properties, pressure and temp. are not independent and ∴ count as one property]. → One property
→ State of steam water system at 1 atm press. would be fixed if the volume of the system were measured.

Two
property

Two property Rule:

$$Z = f(n, y)$$

if n and y is fixed, so is Z

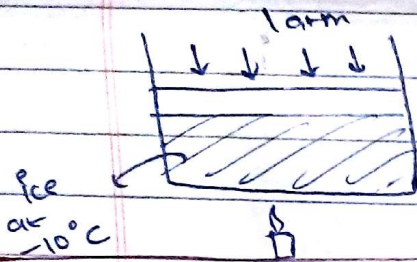
eg. $P = \frac{(a + bt)}{V}$

When ice melts, decrease in vol.

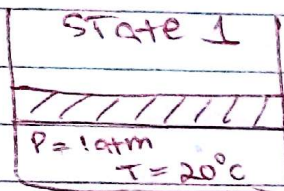
Pure Substance

→ constant chemical composition throughout its mass.

* P-V diag. for pure substance

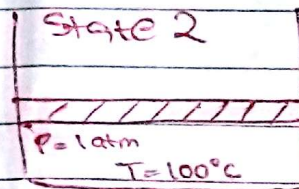


* Compressed liquid and Saturated liquid



Compressed liquid

↓
it is not about to vaporize

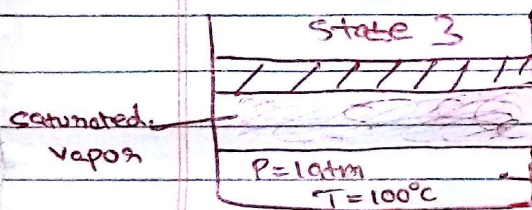


Saturated liquid

↓
about to vaporize

→ At this pt. water is still liquid but any heat addⁿ will cause some of liquid to vaporise

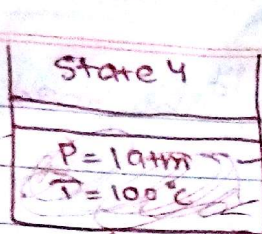
phase change process from liquid to vapour is about to take place



↑
increase in volume

→ Temp. will remain const. during the entire phase process if the press. is held const. until 1st drop is vaporised

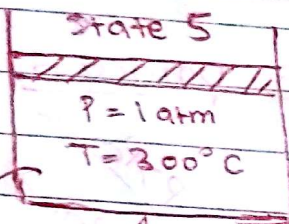
→ Saturated liquid-vapour mixture [liquid and vapour phase coexists in equilibrium]



Saturated Vapor

Any heat loss from this vapor causes some of vapor to condense about to condense

Further transfer of heat results in an increase in both the temp. and the specific volume.

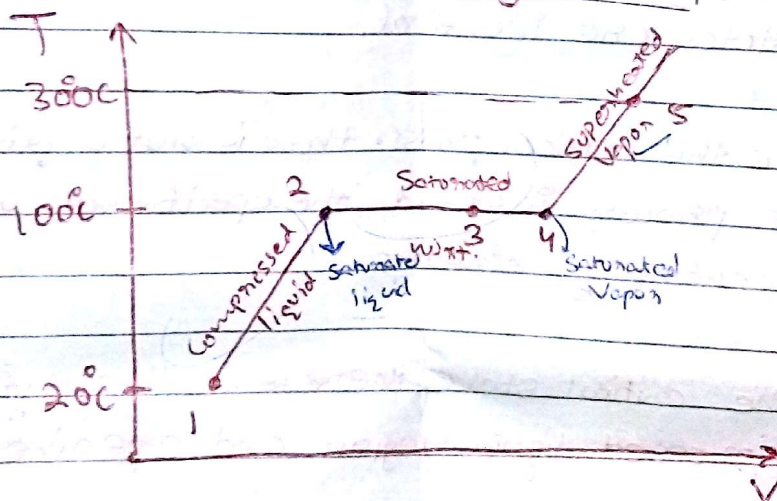


if we transfer some heat from vapor it will not condense as long as temp. remains above 100°C

Superheated Vapor

A vapor that is not about to condense is called a superheated vapor

Saturation temp - At a given press., the temp. at which pure substance changes phase is called saturation temp.
Saturation press. - At a given temp, the press. at



T-v
diag at
const.
press.

During phase change both temp. and press. remains const.

DATE: / / 201
Latent heat: The amount of ^{energy} ~~heat~~ absorbed or released during a phase change.

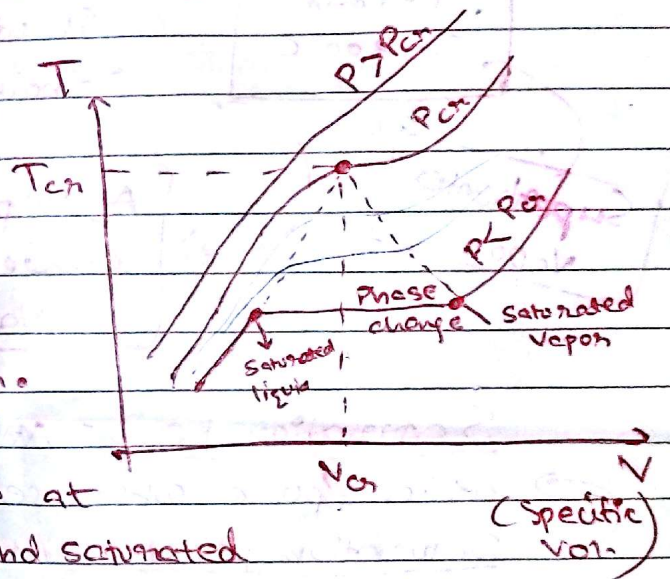
Latent heat of fusion
energy \downarrow absorb during melting

Latent heat of vaporisation
energy \downarrow absorb during vaporization

Property diag. for phase change process

i) T-v

→ The horizontal line that connects the saturated liquid and saturated vapor states becomes shorter as the press. is increased further.

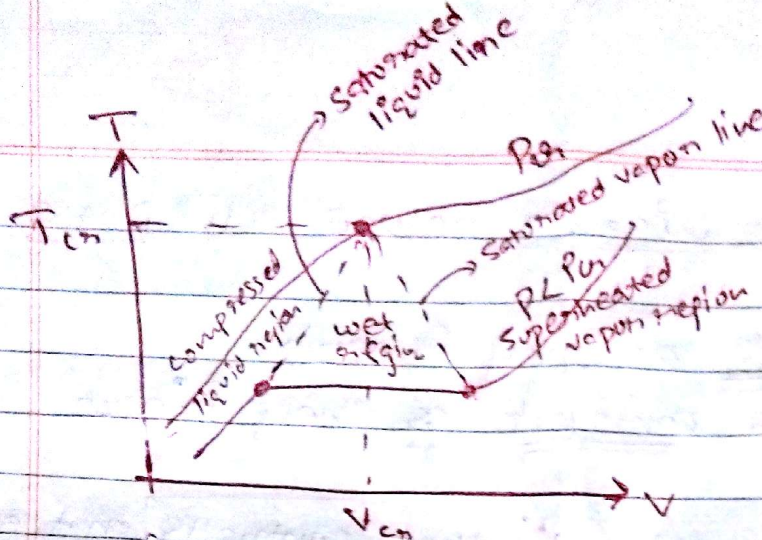


→ Critical pt. is defined as pt. at which saturated liquid and saturated vapor states are identical.

→ At press above the critical press. there is not a distinct phase-change process instead, the specific vol. of the substance continually increases.

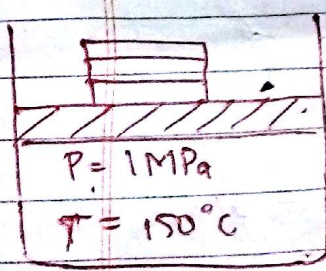
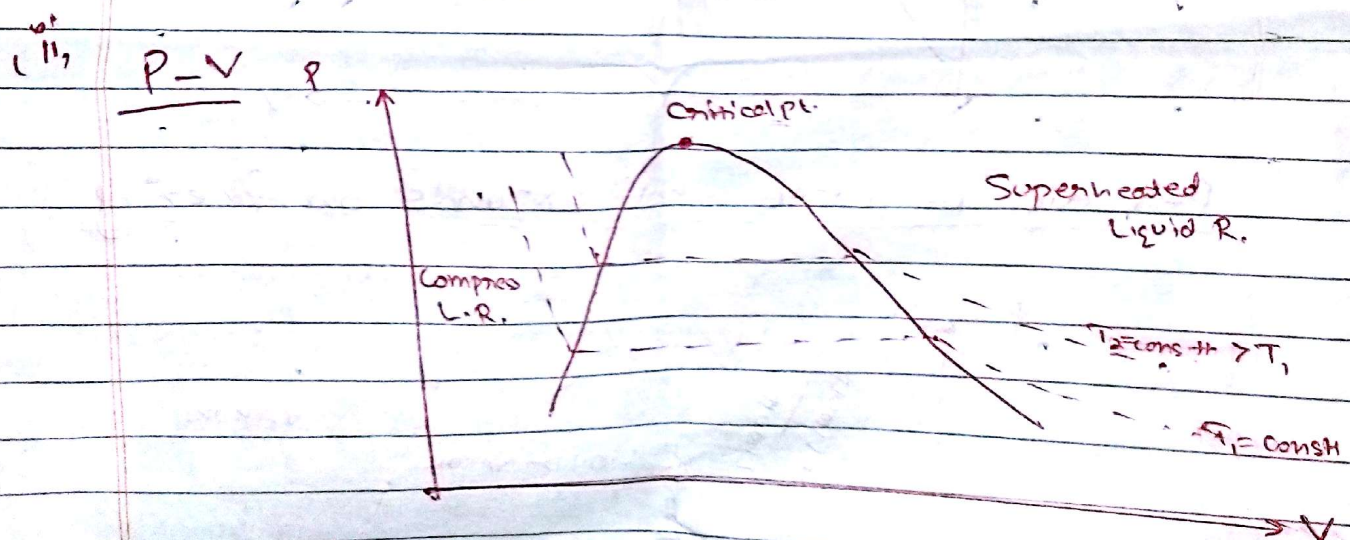
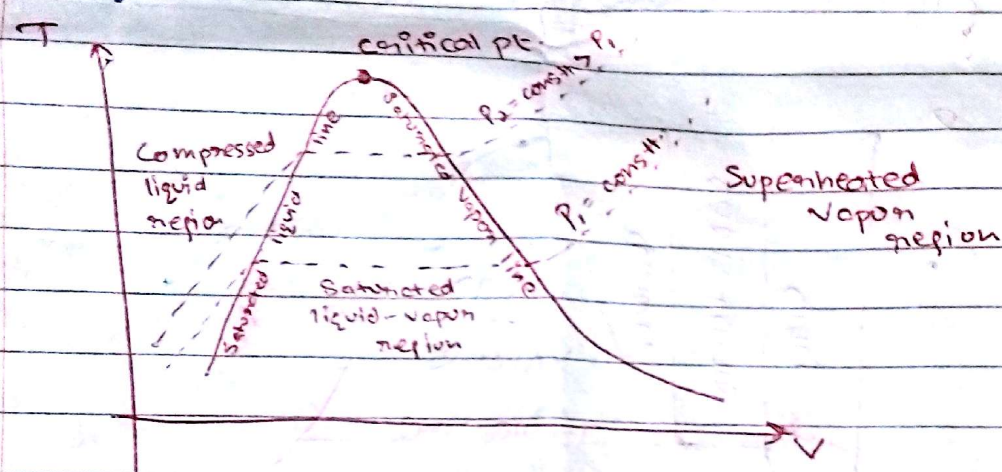
Above the critical state, there is no line that separates the compressed liquid region and superheated vapor region.

$T > T_c \rightarrow$ Superheated vapor region
 $T < T_c \rightarrow$ Compressed liquid region



$$\frac{1}{\rho} = \frac{v}{m}$$

Wet region or
Saturated liquid-vapor region



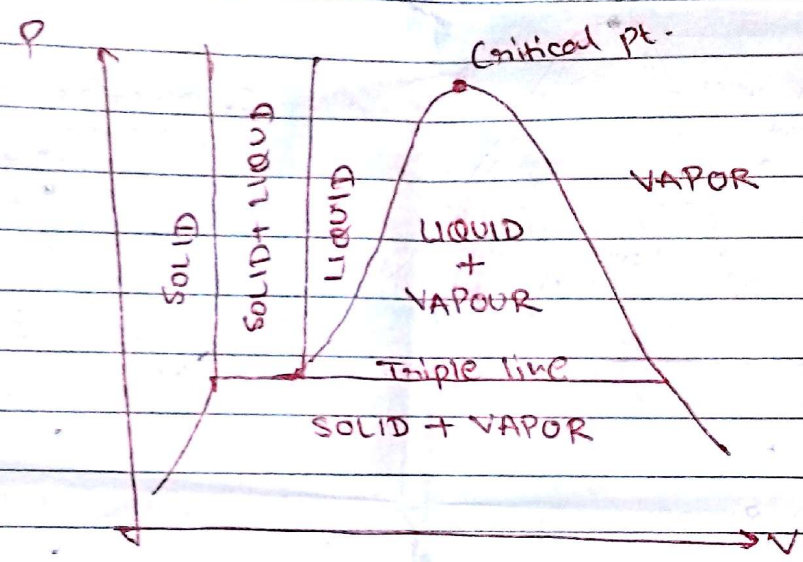
Consider a piston containing liquid water at 150°C . Water at this state exist as compressed liquid. Now the weights on top of piston are removed one by one so that the press. inside the cylinder decreases. Water is allowed to exchange heat with the surrounding so its temp. remains const.

iii)

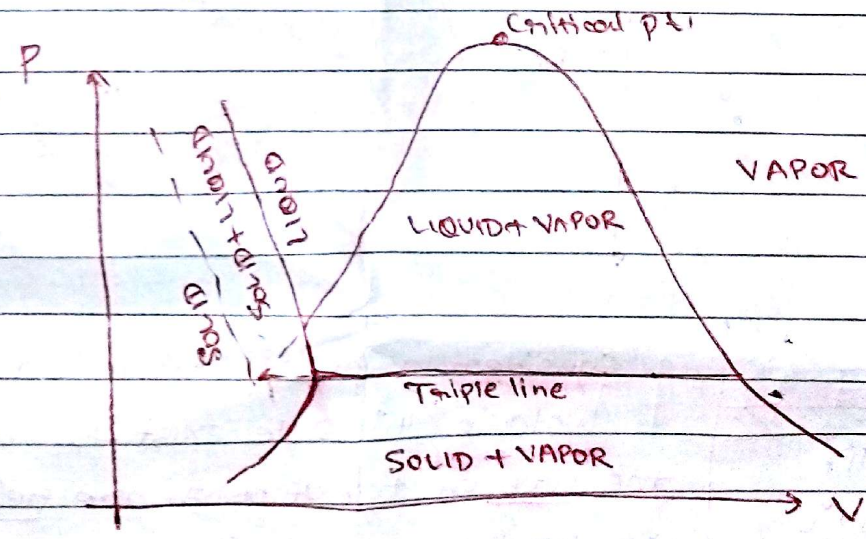
Extending the dig. to include solid phase.

Water expand as they freeze.
Most substances contract as they freeze

P-V dig. of a substance that contracts on freezing



P-V dig. of water that expands on freezing



~~Both~~
They differ only in solid-liquid saturation region

$$\frac{M_{\text{vapour}}}{M_{\text{mix}}} = \dots$$

$$h_g = u + \dots$$

* Triple point of water

temp. = 0.01°C and press. 611.2 N/m^2

* Steam Tables:

(1) Datum state: Internal energy shall be zero at some definite condition.

* The internal energy of saturated water at triple point ($t = 0.01^\circ\text{C}$) is arbitrarily chosen to zero

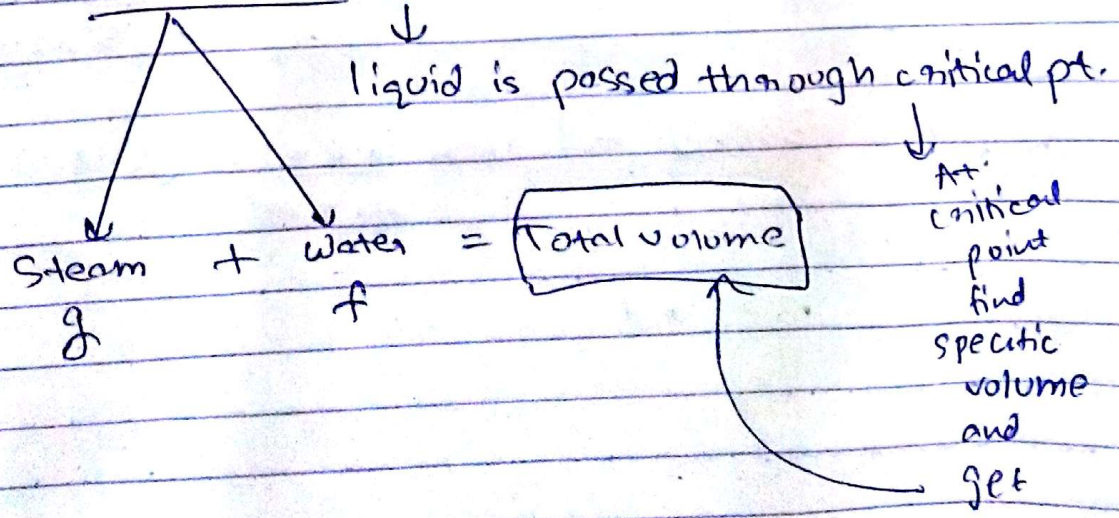
$$h = u + pv$$

→ For saturated liquid (f) [$h_f = u_f + pv_f$]
 enthalpy and internal energy are nearly equal. because of small value of pv_f .

→ u_{fg} and h_{fg} differ by term pv_{fg} → it is not negligible.

→ Critical point is at the bottom of the tables, ~~and~~ u_{fg} , v_{fg} and h_{fg} all tends to 0.

→ Wet steam is mentioned



① 2125

→ Net steam is mentioned

↓ liquid is passed through critical point

gk on

water

Total volume

$$m_T v = m_T v_{cr}$$

$$V_f + x V_{fg} = V$$

↓
At critical pt
find specific
volume
and

get

$$V_T = m_T v_{cr}$$

$$V_f + \frac{m_v}{m_T} V_{fg} = V$$

* Superheated steam: gives data for pure vapor.

h , v and s are contained in the body of table, for various values of pressure and temp.

Case 1:

→ Use interpolation when press. appears in table but temp. does not.

$$p_1 = 15 \text{ bar} \quad t = 429^\circ\text{C} \quad h = ??$$

$$p = 15 \text{ bar} \quad t = 400^\circ\text{C} \quad h = 3256.6 \text{ KJ/kg}$$

$$p = 15 \text{ bar} \quad t = 500^\circ\text{C} \quad h = 3472.8 \text{ KJ/kg}$$

$$h = \left(\frac{429 - 400}{500 - 400} \right) (3472.8 - 3256.6) + 3256.6$$
$$= 3319.3$$

→ Illustrating interpolation where neither the pressure nor the temp. appears in the table.

$$p = 16.8 \text{ bar} \quad t = 429^\circ\text{C} \quad h = ??$$

$$p = 15 \text{ bar} \quad t = 429^\circ\text{C} \quad h = 3319.3$$

$$p = 20 \text{ bar} \quad t = 429^\circ\text{C} \quad h = \text{use above method}$$
$$= 3312.9$$

$$h = 3319.3 - \cancel{16.8} \frac{16.8 - 15}{20 - 15} (3319.3 - 3312.9)$$

$$= 3316.7$$

Saturated Steam Temperature Table

$T, ^\circ\text{C}$	p, bar	$v_f, \text{m}^3/\text{kg}$	$v_g, \text{m}^3/\text{kg}$	$u_f, \text{kJ/kg}$	$u_g, \text{kJ/kg}$	$h_f, \text{kJ/kg}$	$h_g, \text{kJ/kg}$	$s_f, \text{kJ/kg}$	$s_g, \text{kJ/kg}$
0.01	0.0061	1.0002×10^{-3}	206.1	0.01	2376	0.01	2501	0.0	9.156
5.0	0.0087	1.0001×10^{-3}	147.1	21.00	2383	21.00	2511	0.0762	9.026
10.0	0.0123	1.0001×10^{-3}	106.4	42.01	2389	42.01	2520	0.151	8.901
15.0	0.0170	1.0007×10^{-3}	77.93	62.99	2396	62.99	2529	0.2245	8.781
20.0	0.0234	1.002×10^{-3}	57.79	83.94	2403	83.94	2538	0.2966	8.667
25.0	0.0317	1.0032×10^{-3}	43.36	104.9	2410	104.9	2547	0.3673	8.558
30.0	0.0425	1.0045×10^{-3}	32.90	125.8	2416	125.8	2556	0.4369	8.453
35.0	0.0563	1.0057×10^{-3}	25.22	146.7	2423	146.7	2565	0.5053	8.353
40.0	0.0738	1.0076×10^{-3}	19.52	167.5	2430	167.5	2574	0.5725	8.257
45.0	0.0959	1.010×10^{-3}	15.26	188.4	2437	188.4	2583	0.6386	8.165
50.0	0.1235	1.012×10^{-3}	12.03	209.3	2443	209.3	2592	0.7037	8.076
55.0	0.1576	1.015×10^{-3}	9.569	230.2	2450	230.2	2601	0.7679	7.991
60.0	0.1994	1.017×10^{-3}	7.671	251.1	2457	251.1	2610	0.8311	7.910
65.0	0.2503	1.020×10^{-3}	6.197	272.0	2463	272.0	2618	0.8934	7.831
70.0	0.3119	1.023×10^{-3}	5.042	293.0	2470	293.0	2627	0.9549	7.755
75.0	0.3858	1.026×10^{-3}	4.131	313.9	2476	313.9	2635	1.016	7.682
80.0	0.4739	1.029×10^{-3}	3.407	334.8	2482	334.9	2644	1.075	7.612
85.0	0.5783	1.033×10^{-3}	2.828	355.8	2488	355.9	2652	1.134	7.544
90.0	0.7013	1.036×10^{-3}	2.361	376.8	2494	376.9	2660	1.193	7.479
95.0	0.8455	1.039×10^{-3}	1.982	397.9	2501	398.0	2668	1.250	7.416
100.0	1.013	1.044×10^{-3}	1.673	418.9	2507	419.0	2676	1.307	7.355
110.0	1.433	1.052×10^{-3}	1.210	461.1	2518	461.3	2691	1.418	7.239
120.0	1.985	1.060×10^{-3}	0.892	503.5	2529	503.7	2706	1.528	7.130
130.0	2.701	1.069×10^{-3}	0.669	546.0	2540	546.3	2720	1.634	7.027
140.0	3.613	1.080×10^{-3}	0.509	588.7	2550	589.1	2734	1.739	6.930
150.0	4.758	1.091×10^{-3}	0.393	631.7	2559	632.2	2746	1.842	6.838
160.0	6.178	1.102×10^{-3}	0.307	674.9	2568	675.5	2758	1.943	6.750
170.0	7.916	1.114×10^{-3}	0.243	718.3	2576	719.2	2769	2.042	6.666
180.0	10.02	1.127×10^{-3}	0.194	762.1	2584	763.2	2778	2.140	6.586
190.0	12.54	1.141×10^{-3}	0.157	806.2	2589	807.6	2786	2.236	6.508
200.0	15.54	1.156×10^{-3}	0.127	850.6	2596	852.4	2793	2.331	6.432
210.0	19.06	1.172×10^{-3}	0.104	895.5	2600	897.8	2798	2.425	6.358
220.0	23.18	0.001190	0.086	940.8	2603	943.6	2802	2.518	6.286
230.0	27.95	0.001209	0.072	986.7	2603	990.1	2804	2.610	6.215
240.0	33.44	0.001229	0.060	1033	2603	1037.3	2804	2.702	6.144
250.0	39.73	0.001251	0.050	1080	2603	1085.3	2802	2.793	6.073
260.0	46.88	0.001275	0.042	1128	2600	1134.4	2797	2.884	6.002
270.0	54.98	0.001302	0.036	1177	2592	1184.5	2790	2.975	5.930
280.0	64.11	0.001332	0.030	1227	2587	1236.0	2780	3.067	5.857
290.0	74.36	0.001365	0.026	1279	2573	1289.0	2766	3.159	5.782
300.0	85.81	0.001403	0.022	1332	2560	1344.0	2749	3.253	5.704
320.0	112.7	0.001499	0.015	1445	2531	1461.5	2700	3.448	5.536
340.0	145.9	0.001638	0.011	1570	2462	1594.1	2622	3.659	5.336
360.0	185.5	0.00185	0.008	1719	2311	1764.8	2499	3.912	5.059

$Pa \times 10^{-5} = \text{bar}$ $\frac{200}{0.3656}$
 \uparrow Saturated temp.

Saturated Steam Pressure Table

\uparrow Saturated steam enthalpy

p, bar	T, °C	$v_f, m^3/kg$	$v_g, m^3/kg$	$u_f, kJ/kg$	$u_g, kJ/kg$	$h_f, kJ/kg$	$h_g, kJ/kg$	$s_f, kJ/kg$	$s_g, kJ/kg$
0.02	17.50	1.001×10^{-3}	67.00	73.48	2400	73.48	2534	0.261	8.724
0.04	28.96	1.004×10^{-3}	34.80	121.4	2415	121.4	2554	0.423	8.475
0.06	36.15	1.006×10^{-3}	23.75	151.5	2425	151.5	2567	0.521	8.331
0.08	41.50	1.008×10^{-3}	18.1	173.8	2432	173.8	2577	0.593	8.229
0.1	45.8	1.010×10^{-3}	14.68	191.8	2438	191.8	2585	0.649	8.150
0.2	60.07	1.017×10^{-3}	7.649	251.4	2457	251.4	2610	0.832	7.908
0.3	69.11	1.023×10^{-3}	5.229	289.2	2468	289.2	2625	0.944	7.769
0.4	75.87	1.026×10^{-3}	3.994	317.5	2477	317.6	2637	1.026	7.670
0.5	81.33	1.030×10^{-3}	3.240	340.4	2484	340.5	2646	1.091	7.594
0.6	85.94	1.033×10^{-3}	2.732	359.8	2490	359.9	2653	1.145	7.532
0.8	93.5	1.039×10^{-3}	2.087	391.6	2499	391.7	2666	1.233	7.435
1.0	99.62	1.043×10^{-3}	1.694	417.3	2506	417.4	2675	1.303	7.359
1.5	111.4	1.053×10^{-3}	1.159	466.9	2520	467.1	2694	1.434	7.223
2.0	120.2	1.061×10^{-3}	0.886	504.5	2530	504.7	2707	1.530	7.127
3.0	133.6	1.073×10^{-3}	0.606	561.1	2544	561.5	2725	1.672	6.992
4.0	143.6	1.084×10^{-3}	0.463	604.3	2554	604.8	2739	1.777	6.896
5.0	151.9	1.093×10^{-3}	0.375	639.7	2561	640.2	2749	1.861	6.821
6.0	158.9	1.101×10^{-3}	0.316	669.9	2567	670.6	2757	1.931	6.760
7.0	165.0	1.108×10^{-3}	0.273	696.4	2573	697.2	2764	1.992	6.708
8.0	170.4	1.115×10^{-3}	0.240	720.2	2577	721.1	2769	2.046	6.663
10.0	179.9	1.127×10^{-3}	0.194	761.7	2584	762.8	2778	2.139	6.586
20.0	212.4	1.177×10^{-3}	0.100	906.4	2600	908.8	2800	2.447	6.341
30.0	233.9	1.217×10^{-3}	0.067	1005	2604	1008	2804	2.646	6.187
40.0	250.4	1.252×10^{-3}	0.050	1082	2602	1087	2801	2.796	6.070
50.0	264.0	1.286×10^{-3}	0.039	1148	2597	1154	2794	2.920	5.973
60.0	275.6	1.319×10^{-3}	0.032	1205	2590	1213	2784	3.027	5.889
70.0	285.9	1.352×10^{-3}	0.027	1258	2580	1267	2772	3.121	5.813
80.0	295.1	1.384×10^{-3}	0.024	1306	2570	1317	2758	3.207	5.743
90.0	303.4	1.418×10^{-3}	0.021	1350	2558	1363	2742	3.286	5.677
100.0	311.1	1.453×10^{-3}	0.018	1393	2545	1408	2725	3.360	5.614
120.0	324.8	0.001527	0.014	1473	2513	1491	2685	3.496	5.492
140.0	336.8	0.001611	0.012	1549	2477	1571	2638	3.623	5.372
160.0	347.4	0.001711	0.009	1623	2432	1650	2581	3.746	5.246
180.0	357.0	0.001839	0.008	1699	2375	1732	2510	3.871	5.105
200.0	365.8	0.002036	0.006	1786	2295	1826	2411	4.013	4.931
220.9	374.1	0.003155	0.003155	2030	2030	2099	2099	4.430	4.430

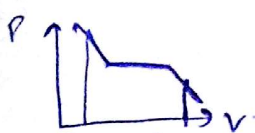
→ both temp. or press. is just sufficient to identify the state

→ Saturated liquid or the saturated vapor has only one independent variable.

→ v_{fg} , h_{fg} , s_{fg} refer to change in property during evaporation or condensation.

→ t_{sat} → Saturated temp. at which phase change occurs.

→ In a superheated vapour at a given pressure, the temp. have values greater than Saturation temp.



$$\frac{1163 \times 10^3}{10^3}$$

$$1 \times 10^3 \times 10$$



$$p_1 = 6 \text{ bar}$$

$$p_2 = 1 \text{ bar}$$

$$t_2 = 120^\circ\text{C}$$

h_g

$$h_1 =$$

$$h_1 = h_2$$

$$h_f + x h_{fg} = h_{g, 1 \text{ bar}}$$

$$= 2716.6$$

→ given temp > saturated temp.

→ the steam is superheated.

→ given enthalpy < saturated steam enthalpy after throttling

→ steam is wet

[if steam is wet

During adiabatic and irreversible process

→ initial and final equilibrium states 1 and 2 are joined by a dotted line.

During adiabatic and reversible process

→ State 2 lies just below State 1
i.e. ($S_1 = S_2$)

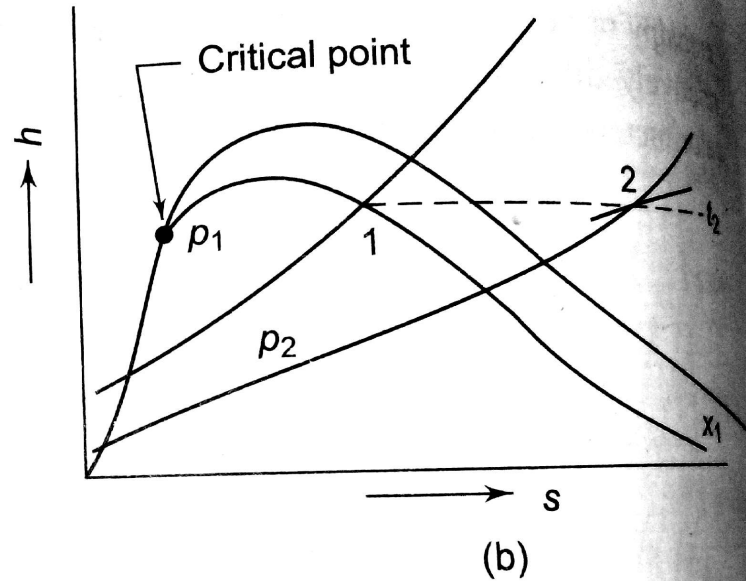
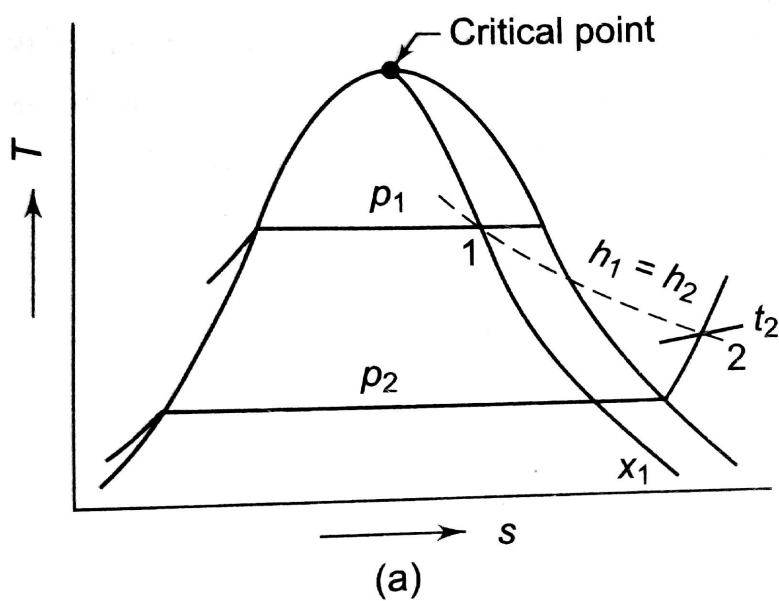


Fig. 9.24 Throttling Process on T-s and h-s Plot

intermediate states are non-equilibrium states not describable by thermodynamic coordinates. The initial state (wet) is given by p_1 and x_1 , and the final state by p_2 and t_2 (superheated). Now

since $h_1 = h_2$

$$\therefore W = h_1 - h_2$$

Work is done by steam at the expense of a fall in its enthalpy value. The process is reversible and adiabatic, so it is isentropic. The process is shown on the $T-s$ and $h-s$ diagram in Fig. 9.31.

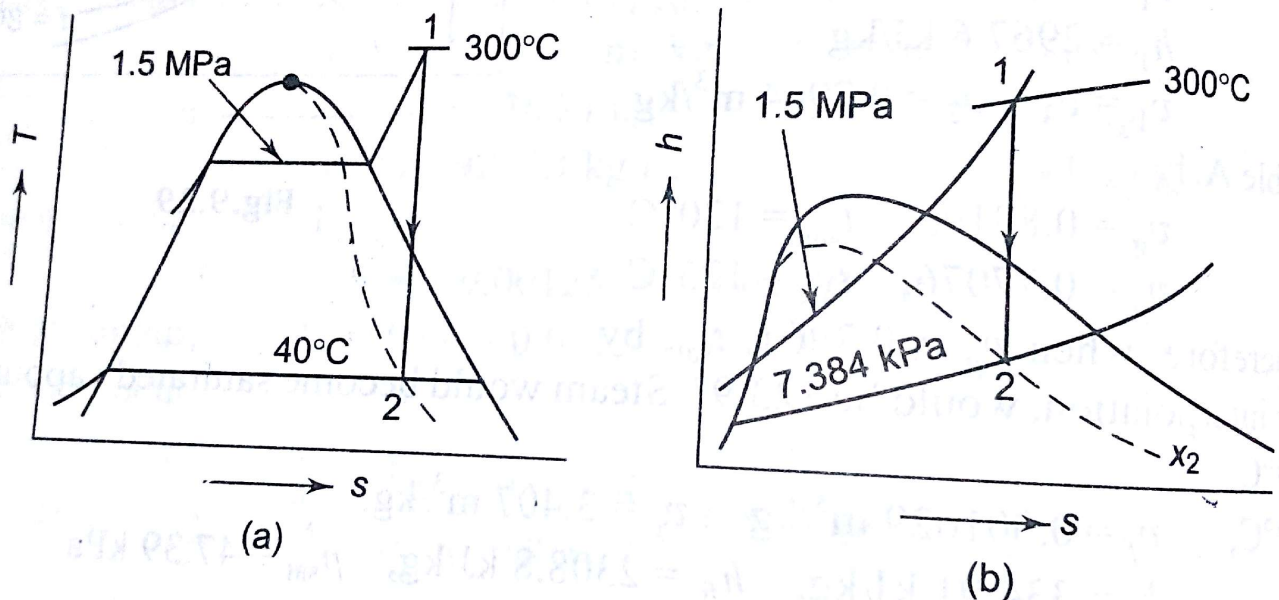


Fig. 9.31

From Table A.1(a), at 40°C

$$p_{\text{sat}} = 7.384 \text{ kPa,}$$

$$h_f = 167.57$$

$$s_f = 0.5725, \text{ and } s_{fg} = 7.6845 \text{ kJ/kg K}$$

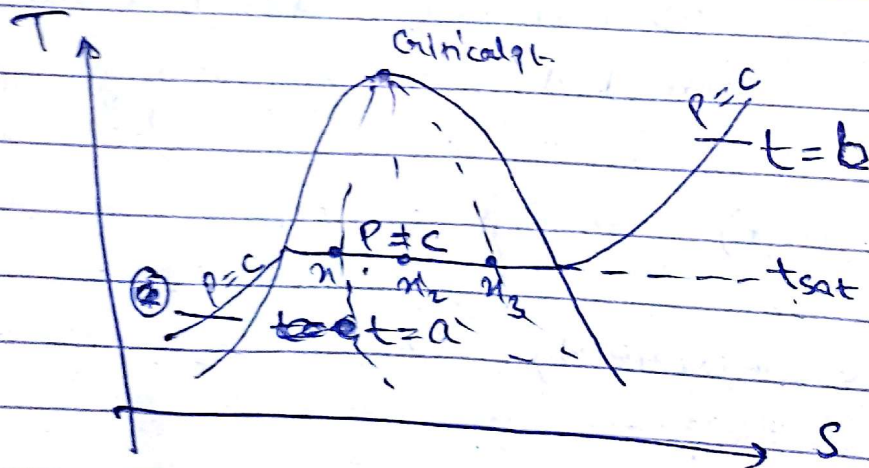
Soln

Dryness: mass fraction of vapour in the mixture

$$\frac{\text{mass of pure vapour phase}}{\text{mass of pure liquid phase}} = \frac{x}{1-x}$$

$$\frac{m_{\text{vapour}}}{m_{\text{total}}} = \frac{m_v}{m_v + m_l}$$

Remember: We always find dryness of wet region.



Every point in wet region has different dryness or quality.

$$x = \frac{m_{\text{vapour}}}{m_{\text{total}}}$$

THERMO ①

In the measurement of quality, the object is always to bring the state of the substance from the two-phase region to the single phase or superheated region, where both press. and temp. are independent, and measured to fix the state, either by adiabatic throttling or electric heating.

① Throttling calorimeter [irreversible]

→ The steady flow energy eqn gives the enthalpy after throttling as equal to enthalpy before throttling.

→ The initial and final equilibrium states 1 and 2 are joined by a dotted line as intermediate states are non-equilibrium

initial state (wet) p_1 x_1

final state (superheated) p_2 t_2

$$h_1 = h_2$$

$$h_{f p_1} + x_1 h_{fg p_1} = h_2$$

quality of wet steam ← $x_1 = \frac{h_2 - h_{f p_1}}{h_{fg p_1}}$

⇒ After throttling pressure ^(p_2) should be low enough to take the steam to the superheated region.

COMBINED SEPARATING AND THROTTLING CALORIMETER

→ When the steam is very wet and pressure after throttling is not low enough to take the steam to the superheated region, then a combined separating and throttling calorimeter is used for measurement of quality.

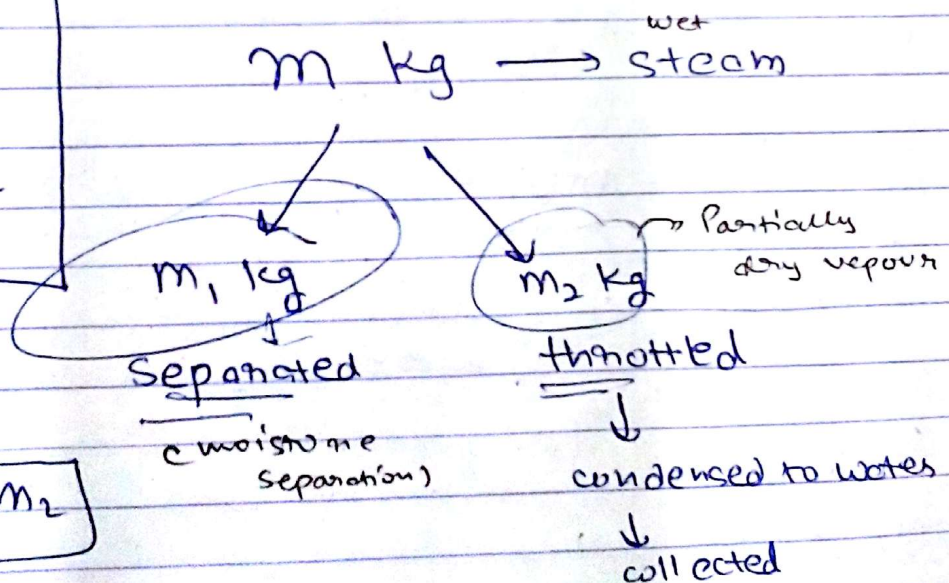
→ it involves first the moisture separation from the wet steam to obtain partially dry vapour which is then throttled.

x_2 → quality of steam after partial moisture separation

$$h_3 = h_2 = h_{fP_1} + x_2 h_{fgP_1}$$

At constant P_1 → moisture sep.

At P_2 → throttling to pressure P_2



$$m = m_1 + m_2$$

At state 2, $\text{mass of dry vapour} = x_2 m_2$

$$x_1 = \frac{\text{mass of dry vapour at state 1}}{\text{mass of liquid-vapour mix at state 1}}$$

Quality of steam at state 1

$$x_1 = \frac{x_2 m_2}{m_1 + m_2}$$

ELECTRIC CALORIMETER

→ The electrical energy input Q should be sufficient to take the steam to superheated region.

$$Q = \underset{\substack{\downarrow \\ \text{Volt}}}{V} \underset{\substack{\downarrow \\ \text{Ampere}}}{I} \times 10^{-3} \text{ kW}$$

Steady flow eqn gives

\dot{m}_a

$$\dot{m}_1 h_1 + Q = \dot{m}_1 h_2$$

$$\dot{m}_1 = \frac{m}{t}$$

$$h_1 + \frac{Q}{\dot{m}_1} = h_2$$

$$h_1 = h_{f,p_1} + x_1 h_{fg,p_1}$$

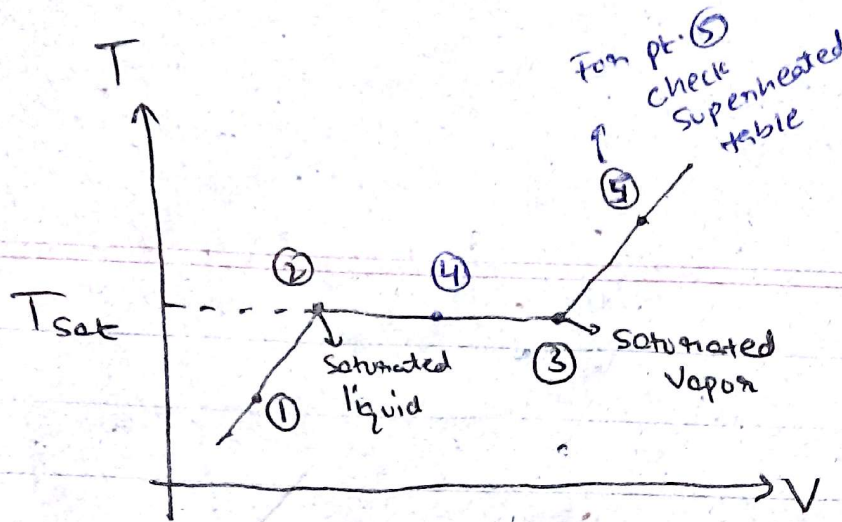
→ x_1 can be calculated from here

$$h_1 + \frac{Q}{\dot{m}} = h_2$$

$$h_1 = h_g +$$

$$V = m v$$

\downarrow Total volume \downarrow specific volume



At given

Press.

4. Suppose
= at
1 bar

Process
is taking
place

① At 9f At pt. ① ($T < T_{sat}$)

→ Check compressed liquid table

② Quality (x) is always found for wet steam
liquid + vapor

At pt. ② $x = 0\%$ [as there is no vapor
at this pt.]

$$v = v_f, h = h_f, s = s_f$$

At pt. ④ (in between) $x \neq 0\%$

Suppose: $x = 50\%$

then

$$v = v_f + x v_{fg}, h = h_f + x h_{fg}$$

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

At pt. ③ $x = 100\%$ [all liquid converted
to vapor]

$$v = v_g, s = s_g$$

$$h = h_g$$

9.1 Complete the following table of properties for 1 kg of water (liquid, vapour or mixture)

$$(t - t_{\text{sat}})$$

	p (bar)	t (°C)	v (m ³ /kg)	x (%)	Super- heat (°C)	h (kJ/kg)	s (kJ/kg K)
(a)	—	35	25.22	—	—	—	—
(b)	—	—	0.001044	—	—	419.04	—
(c)	—	212.42	—	90	—	—	—
(d)	1	—	—	—	—	—	6.104
(e)	10	320	—	—	—	—	—
(f)	5	—	0.4646	—	—	—	—
(g)	4	—	0.4400	—	—	—	—
(h)	—	500	—	—	—	3445.3	—
(i)	20	—	—	—	50	—	—
(j)	15	—	—	—	—	—	7.2690

A rigid vessel of volume 0.86 m^3 contains 1 kg of steam ^{$v+L$} at a pressure of 2 bar. Evaluate the specific volume, temperature, dryness fraction, internal energy, enthalpy, and entropy of steam.

The steam is heated to raise its temperature to 150°C . Show the process on a sketch of the $p-v$ diagram, and evaluate the pressure, increase in enthalpy, increase in internal energy, increase in entropy of steam, and the heat transferred. Evaluate also the pressure at which the steam becomes dry saturated.

Ans. (a) $0.86 \text{ m}^3/\text{kg}$, 120.23°C , 0.97, 2468.54 kJ/kg , 2640.54 kJ/kg , 6.9592 kJ/kg K

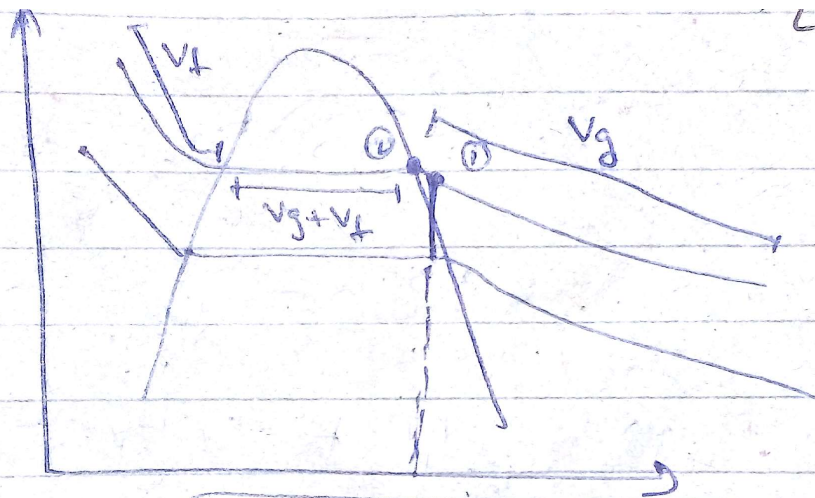
(b) 2.3 bar, 126 kJ/kg , 106.6 kJ/kg , 0.2598 kJ/kg K , 106.6 kJ/kg
 1 kg of water at 45°C is heated at a constant pressure of 10 bar until it becomes superheated vapour at 300°C . Find the change in volume, enthalpy, internal energy, entropy, and heat transferred.

dry saturated

→ Saturated Vapour

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

$$V_1 = V_2$$



$$V_g \text{ at pt-2} = V_g \text{ after pt-2}$$

Heat transfer in pure substances $U_2 - U_1$

At a given press. at ~~a~~ a time
U can find only one
property.

if it is at wetsteam, then check the
property of wetsteam.

and if this wetsteam is heated, the
given pressure changes,

So u have to find property
related to the new pressure.