THERMAL ENGINEERING-II

Keeping in view of the Pandemic COVID 19 , the regular classes have been stopped. Importance is being given to give handouts to the students and to conduct online classes. In a short time I have prepared this notes for benefit of the students and I hope, it will be interesting, as if two way of communication between you and me. All other chapters will be followed by.

LECTURE NOTES

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Syllabus

Chapter 3

Properties of Steam

i. Differentiate between gas & vapour
ii. Formation of steam
iii. Representation on P-V, T-S, H-S diagram
iv. Definition & properties of steam
v. Use of steam table & mollier chart for finding unknown properties
vi. Non flow and flow process of vapour
vii. P-V, T-S, H-S diagram
viii. Determine the change in properties & solve simple numericals

i. DIFFERENCE BETWEEN GAS &VAPOUR

GAS	VAPOUR
Gas is amixture of two or more substances predominantly all must be in same thermodynamic state (GAS).	Vapour is also a mixture of two or more substances, among them some substances are in liquid and rest are in gaseous phase (GAS+LIQUID).
Example - Air.	Example - Boiling water .
Molecular structure of constuitents are different.	Molecular structure of constituents are same.
Gas is a thermodynamic state of matter	Vapour is not a thermodynamic state of matter

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- Very nice way to start the topic, there must not be more interesting query to make a begin.
- The differences are quite few in number but diametrically apart from each other like North pole and South pole of the earth.
- So, how many states of matter are there from thermodynamics point of view?

ii. FORMATION OF STEAM

- Cylinder contains 1 kg of ice at -10^0 C under 1 atm pressure.
- **Process A-B, Heat is added**

  Temp.rises from -10^0 C to 0^0 C : Sensible heating

  Sp volume inceases but negligibly
- **Process B- C,** Heat addition is continuous
  - Ice begins to melt (Phase change begins) : Saturated solid : Latent heating
  - Sp volume increases
  - Temperature remains constant

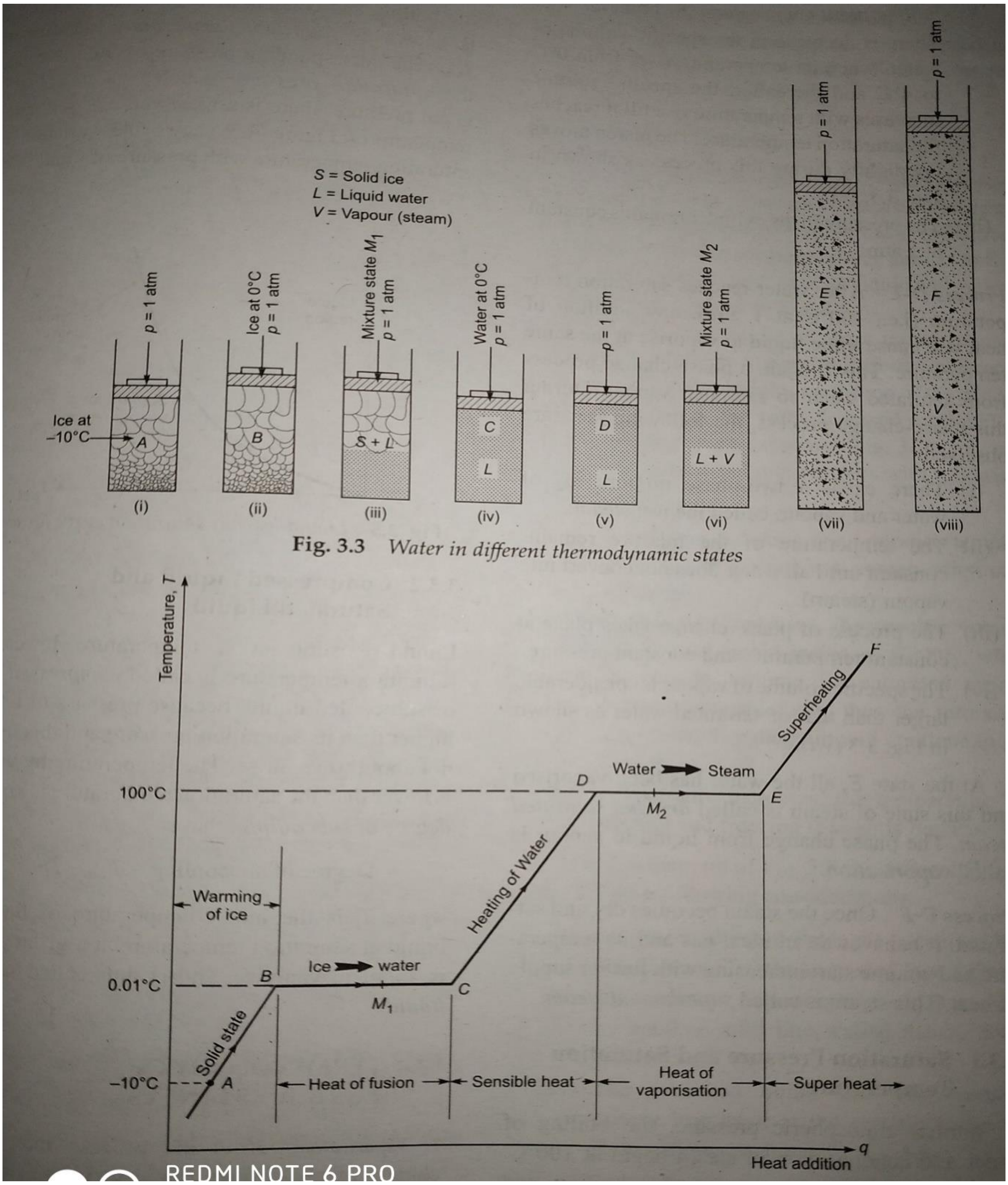


Figure 1 Heating curve of water under 1atm pressure. Courtesy: Thermal Engineering Mahesh M Rathore McGraw Hill Publications (India) Pvt Ltd.

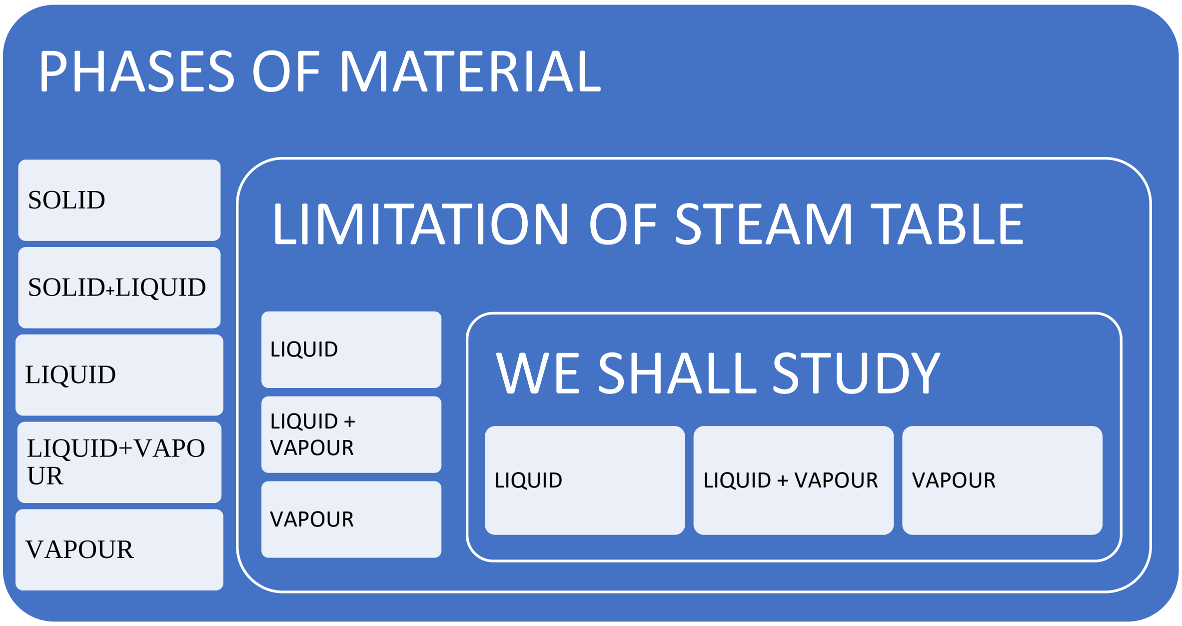
- **Process C-D,** Heat addition is continuous
  - All ice is converted into water
  - Temperature started to rise
  - From 0^0C to 4^0C sp volume deceases (negligibly) then rises
  - Same phenomenon coninues upto 100^0C : Sensible heating

- **Process D-E,** Heat addition is continuous
  - Formation of vapour begins (Phase change) : saturated liquid : Latent heating
  - Temperature remains constant
  - Sp.volume increases

- **Process E-F,** Heat addition is continuous
  - All water is converted into vapour : Saturated vapour
  - Sp volume increases rapidly
  - Temperature remains constant

iii. <u>REPRESENTATION ON 'P-v', 'T-S', 'h-s' THERMODYNAMIC PLOT</u>

- From the above heating curve we have seen various regions namely



- Now we shall learn how to represent thermodynamic properties like P (kPa), v ($\frac{m^3}{kg}$), T (K), h ($\frac{kJ}{kg}$), s ($\frac{kJ}{kg\ K}$) u ($\frac{kJ}{kg}$) on thermodynamic plot and read steam table. Units I have written by side so that you can acknowledge these properties.

- The most popular property diagram is T-v (Temp- Sp volume) and P-v (Pressure – Specific volume). All most all problems can be solved with the help of these two plots.

Temperature – Specific volume diagram

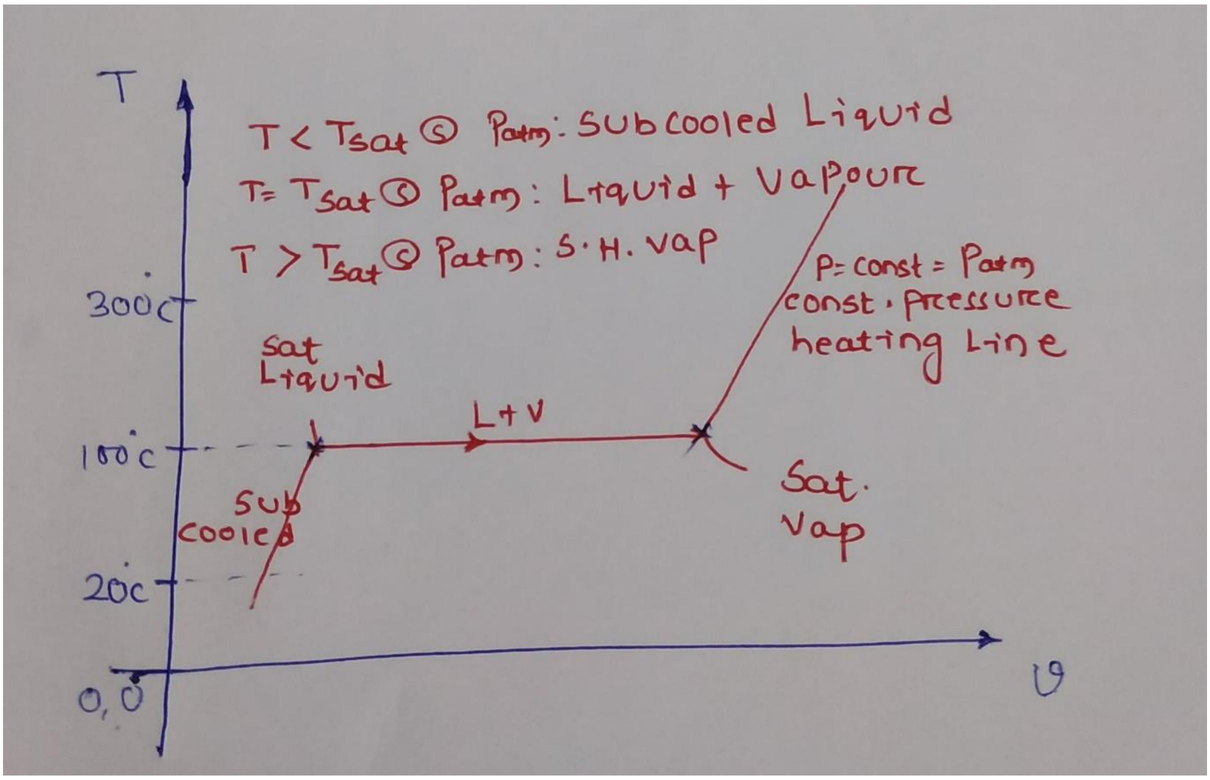


Figure 2 Temperature Specific volume diagram

- In a T- v plot Pressure is held constant. So the processes are either constant pressure heating or cooling curve

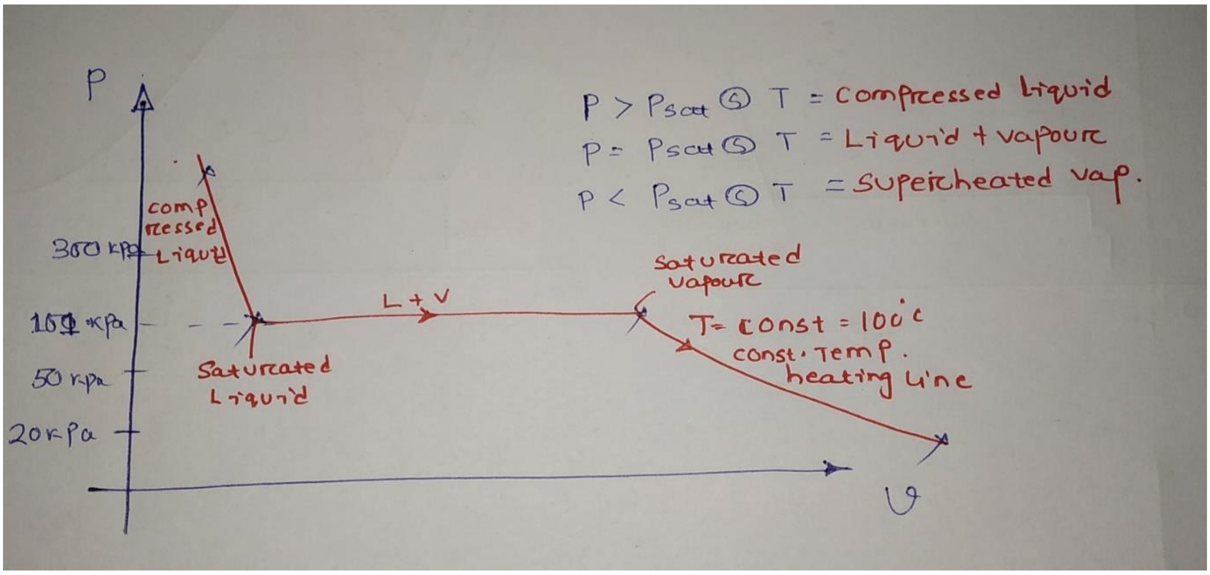


Figure 3 Pressure Specific volume diagram

- In a P- v plot Temperature is held constant. So the processes are either constant temperature heating or cooling curve
- Now the question comes what is the range of pressure limits as all we now in our mathematics class y = f(x)
- In thermodynamics class P α T and vice versa

$$P \propto T\,,\; T \propto P$$

Pressure (bar)	Temperature (^{0}C)	
0.00611	0.01	The first entry of steam table is called as triple point entry where all the 3 states of matter can be seen if we can maintain such a low pressure of 0.00611 bar and 0.01^0 C. The last entry of steam is Critical point entry at this state water directly flashes into vapour phase without liquid vapour region.
0.04	29	
1	99.63	
1.5	111.4	
2	120.2	
20	212.4	
30	233.9	
45	257.5	
50	264	
60	275.6	
70	285.9	
220.9	374.1	

- Now as you people know the range of pressures, if the locus of all saturated liquid point and saturated vapour points are joined a dome is created the sole objective to capture entire steam table in one figure

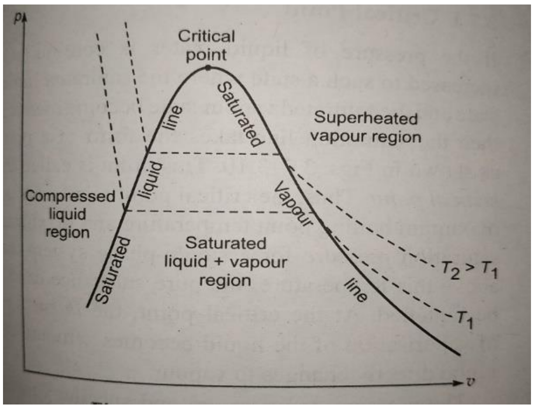


Figure 4: '3' regions of steam table is shown. Courtesy: Thermal Engineering Mahesh M Rathore McGraw Hill Publications (India) Pvt Ltd

- One important thing to note down the trend of constant temperature line in P-v plot.
- Apart from the properties P, v & T other properties which were in steam table (h, u & s) they are not covered in P-v & T-v plot. Never the less non flow processes can be taken care with help of P-v & T-v plot but not all the flow processes.
- This requirement gave birth more generic approach towards property plots like 'T-S' plot and 'h-s' plot

Temperature Entropy (T-s) diagram

- Most frequently used plot thermodynamic cycle like Rankine cycle
- As area under T-S plot is energy transfer or $\oint \delta Q = \oint \delta W$ very handy in calculating Net heat transfer, network transfer and cycle efficiency of power cycles of working fluid water.
- This plot has least implication in this chapter but you must know it here to apply in Power cycles.

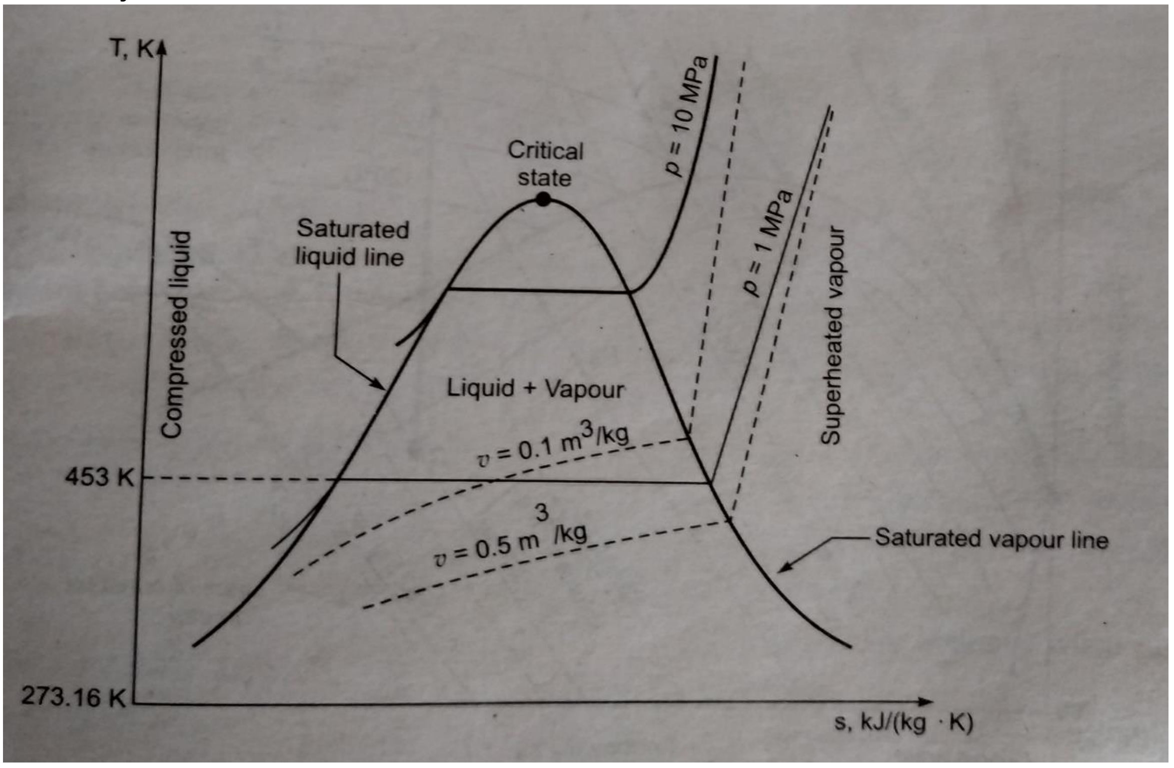


Figure 5 Temperature - Entropy plot. Courtesy: Thermal Engineering Mahesh M Rathore McGraw Hill Publications (India) Pvt Ltd

<u>Enthalpy Entropy (Mollier) diagram</u>

- ‘A picture is worth thousand words’ true is the phrase for mollier chart. Mollier chart covers entire all Steam table very useful in research of flow processes.

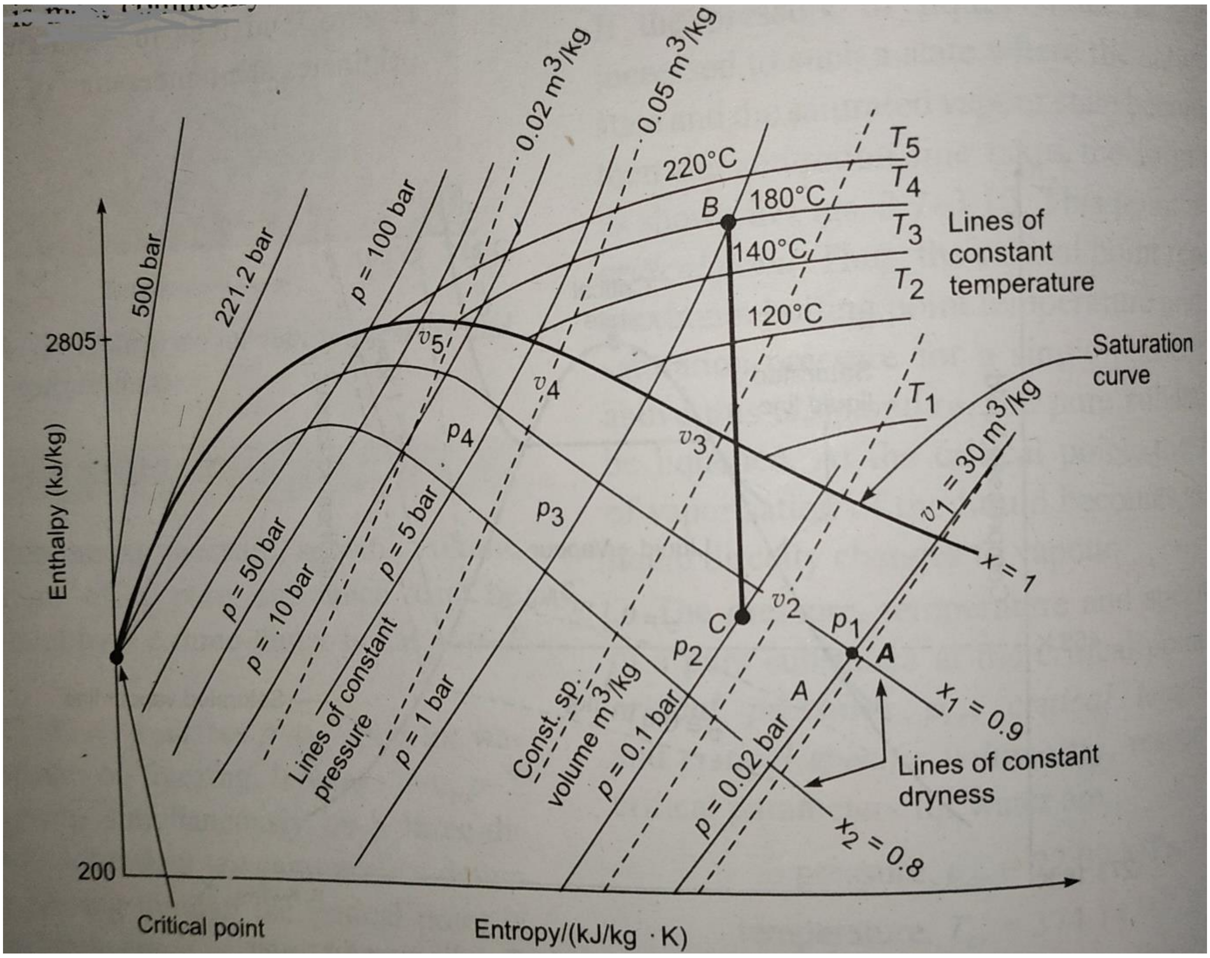


Figure 6 'h-s' chart for water

- Any two independent intensive properties in mollier chart are sufficient to completely identify the state and all other properties.

Constant Temp. line	• Straight and almost horizontal
Const. dryness fraction line	• Parallel to saturation lines
Const. Pressure line	• no change in shape in either region
Const. Volume line	• Similar to pressure line but more steeper

iv. DEFINITION & PROPERTIES OF STEAM

A pure substance may be a single element or combination/mixture of elements.

- A chemical compound which is a pure substance has same crystal structure through out all the phases.

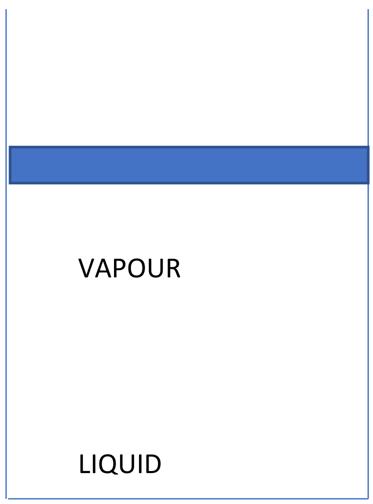
All elements are mostly pure substances

Eg. Nitrogen, carbon, Hydrogen, gold, Copper, oxygen.......

- But very few compounds are Pure Substances
- Eg. Water

Irrespective of elements a pure substance has fixed melting & boiling point.

B.P of H_2 = -252^0C, B.P of O2 = -183^0C, BP of H_2O = 100^0C under P_{atm}



If state of the substance is liquid vapour mixture to know the thermodynamic properties, we have to introduce another property

Figure 7 A cylinder piston arrangement contains liquid vapour mixture

- Though steam table gives data on saturated liquid line, saturated vapour line and superheated vapour region it does not give data in liquid vapour region. To calculate thermodynamic properties in this region we have to introduce one more thermodynamic property called as dryness fraction or quality of steam

- Suppose under P_{atm} a cylinder contains liquid & vapour mixture

  (Volume of mixture) = (Volume occupied by liquid) + (Volume occupied by vapour)

  $\approx V = V_f + V_g$

  $V = m_f v_f + m_g v_g$

  Now we will introduce $x = \frac{m_g}{m} = \frac{mass\ of\ the\ vapour\ part}{Total\ mass\ of\ the\ mixture}$

  X is called as dryness fraction or quality of steam.

  $\frac{V}{m} = \frac{m_f v_f}{m} + \frac{m_g v_g}{m}$

  $v = \frac{m - m_g}{m} v_f + \frac{m_g v_g}{m}$

  $v = [1 - \frac{m_g}{m}]v_f + \frac{m_g}{m} v_g$

  $v = [1 - x]v_f + xv_g$

  $v = v_f - xv_f + xv_g$

  $v = v_{f+} [xv_g - xv_f]$

  $v = v_f + x[v_g - v_f]$

  Where v_f = sp. Volume of saturated liquid, v_g = sp. Volume of saturated vapour and v = sp. Volume of the mixture

  Like wise all other properties can be found out if the state lies within Liquid vapour region

$$h = h_f + x[h_g - h_f]$$

$$s = s_f + x[s_g - s_f]$$

$$u = u_f + x[u_g - u_f]$$

v. USE OF STEAM TABLE & MOLLIER CHART FOR FINDING UNKNOWN PROPERTIES

➢ We will discuss this portion with some problems

1. Complete this table for H_2O

T, °C	P, kPa	h, kJ/kg	X	Phase description
	200		0.7	
140		1800		
	950			
80	500		0	
	800	3166.2		

2. Determine the volume change when 1 kg of saturated water is completely vaporized at a

pressure of 1 kPa, 100 kPa, and 10000 kPa.

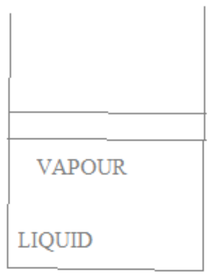
DATA GIVEN

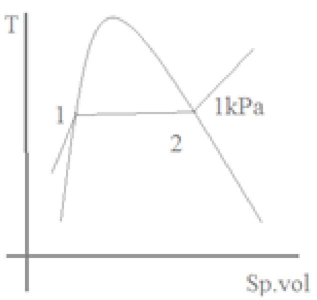
Mass = -------------kg

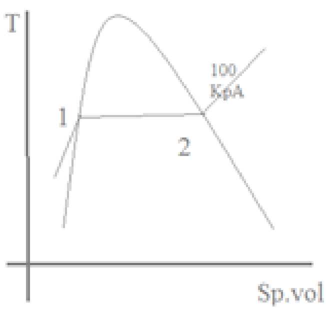
State 1: Saturated liquid

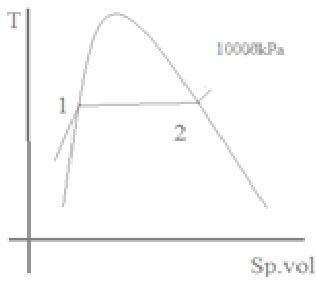
State 2: Saturated vapour

Closed system









TO FIND

Change in volume $V_2 – V_1$

ANALYSIS

v_f @ 1 kPa = --------------m^3/kg

v_g @ 1 kPa = ------------- m^3/kg

V_1= m× v_f @ 1 kPa = ------------ m^3

V_2 = m× v_g @ 1 kPa =------------- m^3

Calculate change in volume = $V_2 – V_1$ = ------- m^3 [Ans]

3. Calculate Specific enthalpy, specific volume and density of 1 kg of steam at a pressure of 2 MPa, having a dryness fraction of 0.85

DATA GIVEN

m = -----------kg

P = 2 MPa = 20 bar = ---------kPa

X= ----------

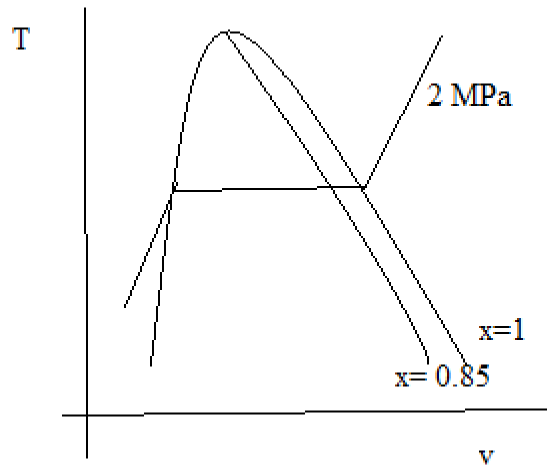
Closed system

TO FIND

Sp. Enthalpy (h) = ------kJ/kg

Sp. Volume (v) = ----------m^3/kg

Density (ρ) = -----------kg/m3



ANALYSIS

Two intensive independent properties are required to completely specify state of the substance on thermodynamic co-ordinate.

We have got three properties here

Identify the state ------------------------

From steam table find out

v_f @ 20 bar = --------------m^3/kg

v_g @ 20 bar = ------------- m^3/kg

h_f @ 20 bar = --------------kJ/kg

h_g @ 20 bar = ------------- kJ /kg

$$v_{20\ bar\ and\ x\ 0.85} = v_f + x[v_g - v_f]@20\ bar$$

v= ----------------- m^3/kg [Ans]

$\rho = \frac{1}{v} = ------ \frac{kg}{m^3}$ [Ans]

Like wise

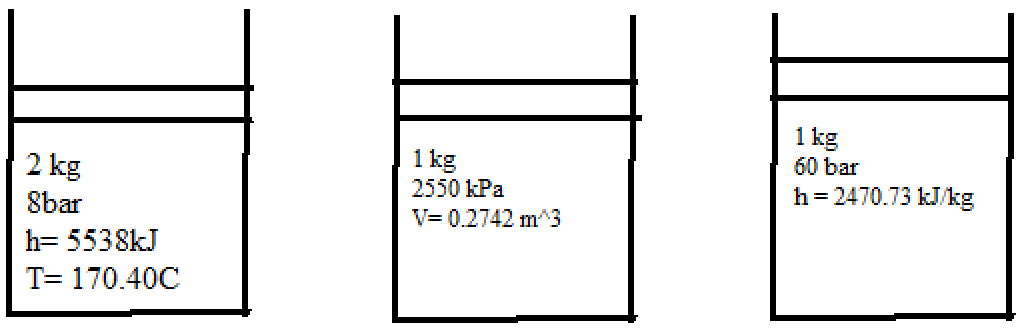
$$h_{20\ bar\ and\ x\ 0.85} = h_f + x[h_g - h_f]@20\ bar$$

h = ------------------kJ/kg [Ans]

4. Identify the type of steam in the following three cases using steam table and giving necessary calculations supporting your claim

   a. 2 kg steam at 8 bar enthalpy 5538 kJ at a temperature of 170.4^{0}C
   b. 1 kg steam at 2550 kPa occupies a volume of 0.2742m^3 find temperature of steam.
   c. 1 kg steam at 60 bar enthalpy 2470.73 kJ/kg.

Data given



It is always praise worthy and make our job very easier if we represent the data given in diagrammatic form

Closed system

To find

Identify and name State of the steam in 1

Temp of steam in state 2

Identify and name State of the steam in 3

Analysis

For fig 1

Specific enthalpy = h =H/m = -------------kJ/kg

T = 170.4^0C

Find out from steamtable P_{sat} @ 170.4^0C

Now 3 cases arises

If P < P_{sat} @ 170.4^0C State is in compressed liquid region Not within the scope of steam table	If P = P_{sat} @ 170.4^0C State is in Liquid Vapour region T = T_{sat} @ 170.4^0C	If P > P_{sat} @ 170.4^0C State is in Superheated vapour region

Tick out which ever is correct for your case.

For fig 2

Specific volume of steam = v = V/m= --------------m^3/kg

Pressure in the system = P = 2550 kPa

Now find out from steam table

v_f @ 2550 kPa = --------------- m^3/kg

v_g @ 2550 kPa = --------------- m^3/kg

Now 3 cases may be possible

v < v_f @ 2550 kPa is in State is in compressed liquid region	v_f @ 2550 kPa < v < v_g @ 2550 kPa State is in Liquid Vapour region	v > vg @ 2550 kPa State is in Superheated vapour region. If this is the outcome then our work is prolonged little bit but interesting. Go to superheated steam table of 2550 kPa now search in the column of specific volume in ascending order from the first entry where ever you will get v stick there. The corresponding Temp is your answer.

5. Explain why rice cooks faster in a pressure cooker than in conventional cooking

Now this question may seem to be an odd man out. It is a descriptive question try on yourself. However I may provide you some hint

List how many factors influence

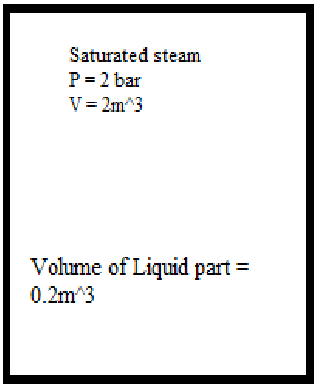
Cooking of rice	Conventional	Pressure cooker
	Pressure on container ---------------	Pressure inside cooker = $P_{atm} + \frac{W_{whistle}}{c.s\ area\ on\ which\ whistle\ is\ resting}$ = ---------------
	T_{sat} @ P_{atm} = ---------	T_{sat} @ P_{cooker} = ----------
	Remark---------------- ------------------------- -------------------------	Remark---------------------------------------

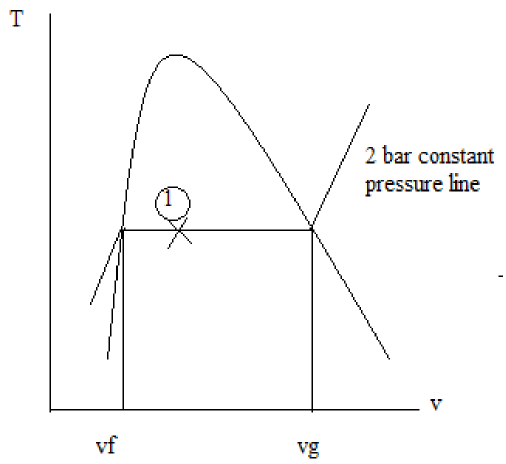
NONFLOW PROCESSES OF VAPOUR

- We will here also consider some problems to understand Nonflow and flow process.

6. A rigid tank of volume $2m^3$ is filled with saturated steam at 2 bar. It contains $0.2m^3$ of moisture and rest is vapour. Calculate mass of moisture, mass of vapour and quality of steam.

DATA GIVEN





Closed system

TO FIND

M_{fluid} =?

M_{vapour} = ?

X =?

ANALYSIS

$V = V_{liquid} + V_{vapour}$

$V_{vapour} = \cdots \ldots \ldots \ldots \ldots .(m^3)$

From steam table find

v_f @ 2 bar =---------(m^3/kg)

v_g@ 2 bar =---------(m^3/kg)

$m_{vapour} = V_{vapour}(m^3) \times \frac{1}{v_g}(\frac{kg}{m^3})$ = -------------kg [Ans]

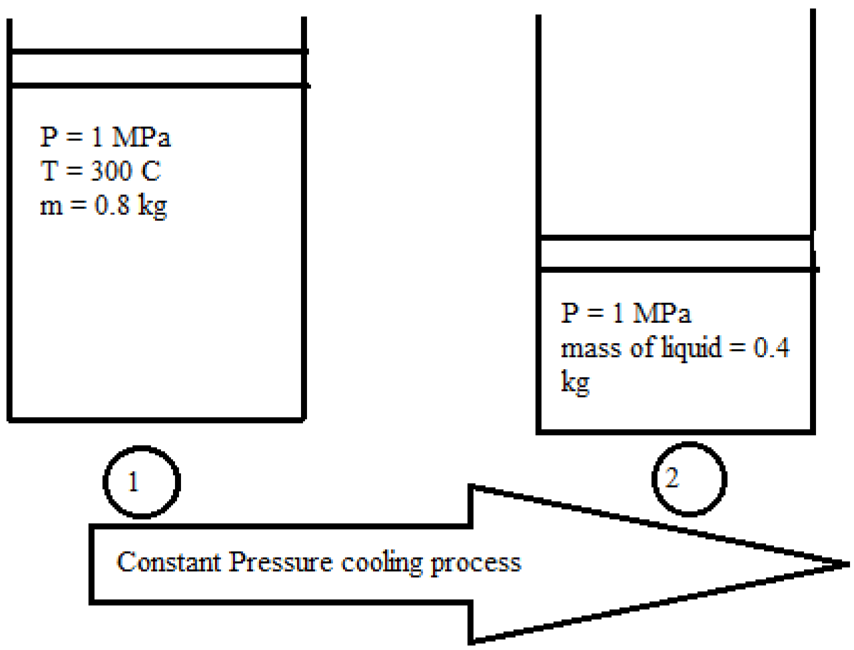
$m_{liquid} = V_{liquid}(m^3) \times \frac{1}{v_f}(\frac{kg}{m^3})$ = -------------kg [Ans]

$x = \frac{mass\ of\ vapour}{Total\ mass\ of\ mixture} = \frac{m_g}{m_g+m_f}$ =--------------------- [Ans]

7. A piston cylinder device contains 0.8 kg of steam at 300^{0}C and 1 MPa. Steam is cooled at constant pressure until one half of the mass condenses.

    Show the process on T-v diagram
    Find the final temperature
    Determine the volume change

DATA GIVEN



TO FIND

T- v plot

Temp at state 2 = T_2 = ?

Change in volume = $V_2 - V_1$ = ?

ANALYSIS

P_1 = 1 MPa

Find from steam table

T_{sat}@ 1 MPa = ----------

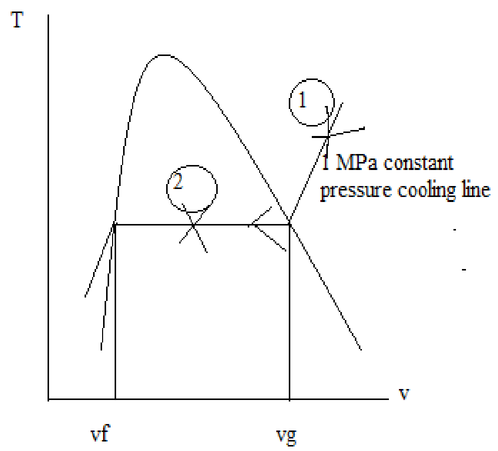
Now here comes three probabilities

If T1 < T_{sat}@ 1 MPa State is in compressed liquid region	If $T_1 = T_{sat}$@ 1 MPa State is in Liquid Vapour region	If $T_1 = T_{sat}$@ 1 MPa State is in superheated vapour region Refer to superheated steam table of 1 MPa and find T_1 Corresponding v, h, s and u can be found from that corresponding entry.

V_1 = m------(kg) × vg@ 1 MPa and 300^0 C of superheat (m^3/kg)------- = --------(m^3)

X = m_{vapour}/ m total = $\frac{m_{vapour}}{m_{total}} = - =$ -------------

Now you can plot T- v diagram



$T_2 = T_{sat}$ @ 1 Mpa = -------------- (Ans)

From steam table find

v_f @ 1 MPa =---------(m^3/kg)

v_g@ 1 MPa =---------(m^3/kg)

$V_2 = V_{liquid\ 2} + V_{vapour\ 2}$

V_2 = {m_{liquid} × [v_f + x (v_g - v_f) @ 1 MPa](m^3)} +{ m_{vapour} × v_g@ 1 MPa (m^3)}

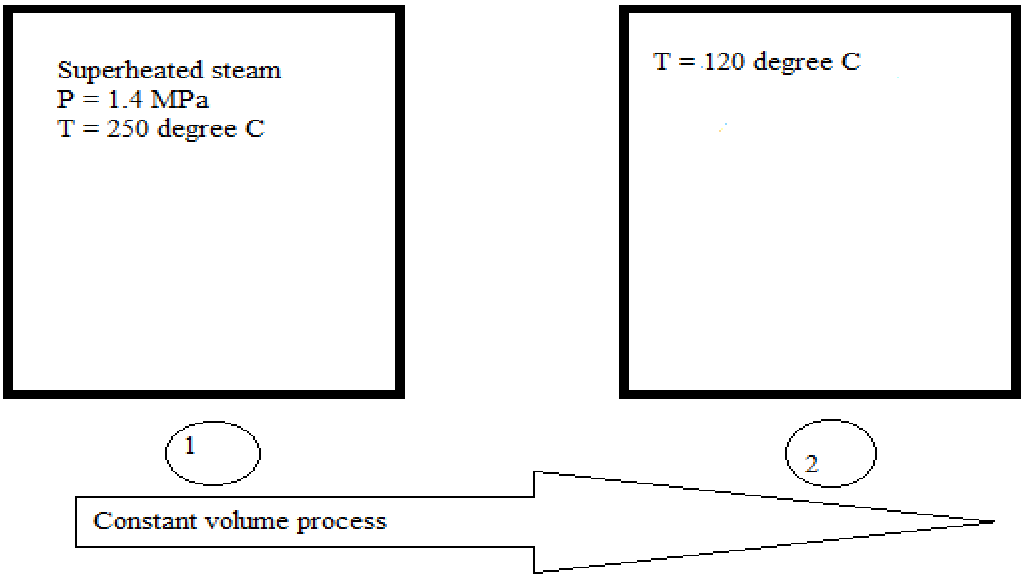
V_2 = ------------------------(m^3) + ------------------------(m^3)

V_2=-----------------(m^3)

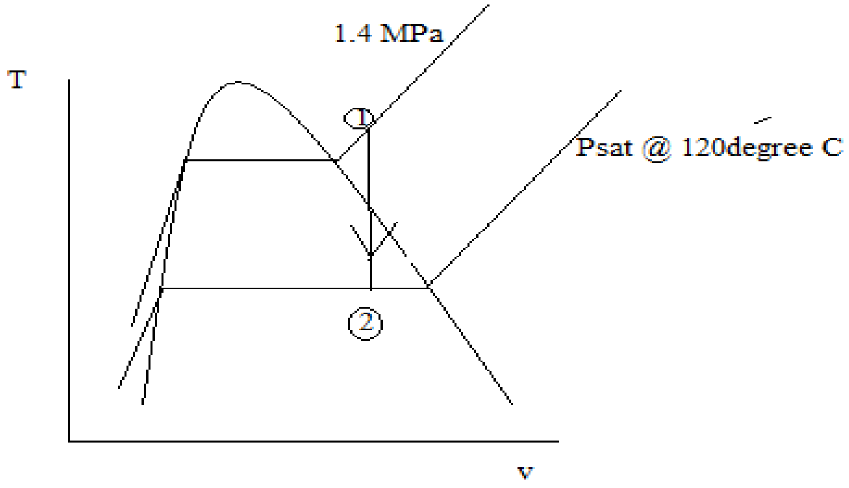
Change in volume = V_2 – V1 = ______________ - _________________(m^3)

8. Superheated water vapour at 1.4 MPa and 250^{0}C is allowed to cool at constant volume until temperature drops to 120^{0}C. At the final state, determine
   - The Pressure
   - The quality
   - Enthalpy
   - Show the process on T-v plot

DATA GIVEN



Closed system exhibiting constant volume thermodynamic process



TO FIND

Pressure at state 2 = P_2

Quality of steam at state 2 = x_2

Enthalpy of steam at state 2 = h_2

Thermodynamic process on T-v plot

ANALYSIS

At state 1 Pressure and temperature are given so state can be identified.

Only you check the saturation entries of steam at 1.4 MPa from steam table

Tsat @ 1.4 MPa = -----------------^{0}C

vf @ 1.4 MPa = ---------------------(m^3/kg)

vg @ 1.4 MPa =---------------------(m^3/kg)

hf @ 1.4 MPa = ---------------------(kJ/kg)

hg @ 1.4 MPa = ---------------------(kJ/kg)

From the superheated steam table of 1.4MPa

By method of inspection find where lies temperature 250^{0}C

v_1 = v at 1.4 MPa and 250^{0}C degree of superheat = ---------(m^3/kg)

since the rigid container is exhibiting a constant volume process $v_1 = v_2$

Now by checking v_2 find out in which region the state 2 will come

Find out from steam table

v_f @ 120^{0}C = ---------------------(m^3/kg)

v_g @ 120^{0}C = ---------------------(m^3/kg)

$v_2 = v_f + [x \times (v_g - v_f)]$ @ 120^{0}C

$x = ----$

Now calculate

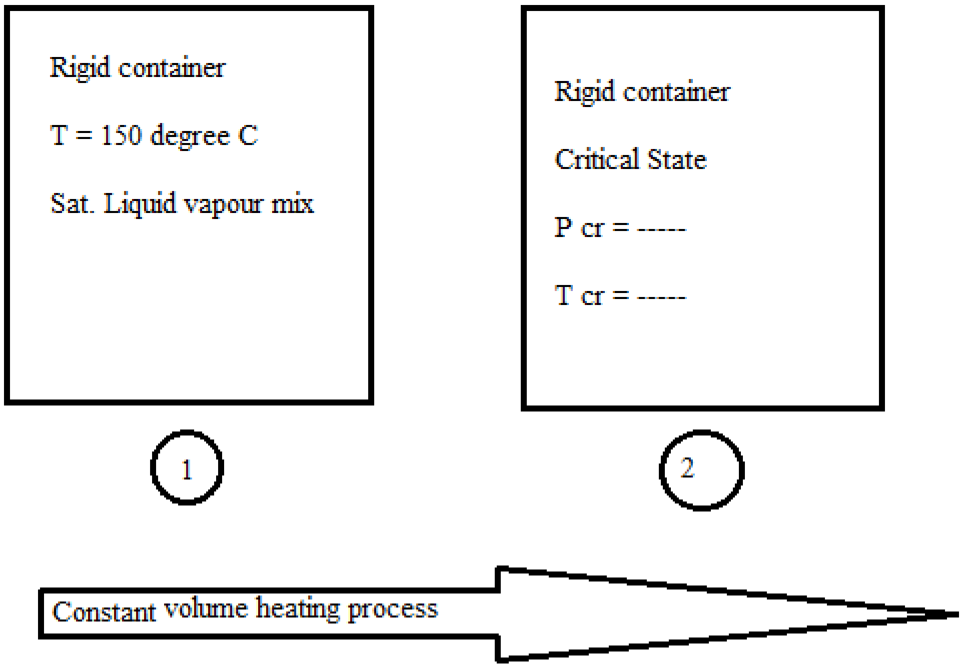
$h_2 = h_f + [x \times (h_g - h_f)]$ @ 120^0C

h_2 = --------------- (kJ/kg) [Ans]

$P_2 = P_{sat}$ @ 120^0C= --------------- [Ans]

9. A 0.3 m^3 rigid vessel initially contains saturated liquid vapour mixture of water at 150^0C. The water is now heated until it reaches the critical state. Determine mass of liquid water and volume occupied by liquid at initial state

DATA GIVEN



Volume of rigid container = 0.3m3
Closed system exhibiting a thermodynamic process

TO FIND
Mass of liquid water at state 1 = $m_{liquid1}$ = ?
Mass of vapour at state 1 = $m_{vapour1}$ = ?

ANALYSIS
Find out from steam table
P_{sat} @ 150^0C

v_f @ 150^0C = --------------------(m3/kg)

v_g @ 150^0C = --------------------(m3/kg)

h_f @ 150^0C = --------------------(kJ/kg)

h_g @ 150^0C = --------------------(kJ/kg)

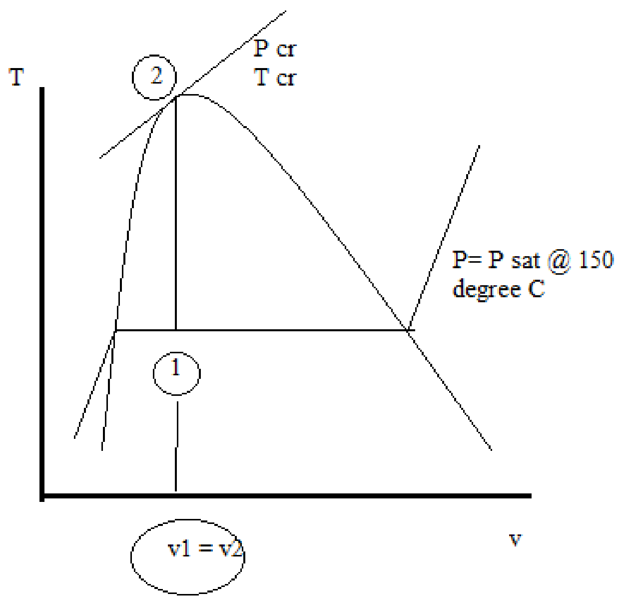
Since state 1 lies in the L-V region Pressure & temperature are not sufficient to identify the state since both ‘P’ & ‘T’ are dependent properties in the liquid vapour region.

So we will change our approach little bit we will start from state 2 since it is well defined

Find from the steam table
P_{cr} = ------------
T_{cr} = ------------ ^0C
v @ P_{cr} = ------m^3/kg
h @ P_{cr} = -------kJ/kg

$v_2 = v_{cr} = v_1$ since constant volume process

$v_1 = v_f + [x \times (v_g - v_f)]@\,150^0C$
From here determine x = -------------
Ok
Now since, $x = \frac{m_g}{m}$
But two unknowns and one equation it cannot help us



Since it is a closed system the mass is conserved at state 1 and state 2
Mass at state 2 can be determined

$$m_2 = m = \; V_2(m^3) \times v_{Pcritical}\left(\frac{m^3}{kg}\right) = --------(kg)$$

$$So\ total\ massof\ the\ mixture\ is\ m = -------\ kg$$

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

$m_g = x \times m = -------$ (Ans)

$$volume\ of\ vapour\ part\ in\ state\ 1 = v_g @\ 150^0C \times m_g = ------$$

Now volume of the liquid part in state 1

$V_{liquid} = V - V_g\ @\ state\ 1$

$$m_{liquid} = V_{liquid}\,(m^3) \times \frac{1}{v_{f\ @\ 150^0}C} = ----$$

m_{liquid} = ----------------kg [Ans]

10. 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
    c. and the volume of the vapor

Try on your own

FLOW PROCESSES OF VAPOUR

11. Steam at 0.75 bar and 150^{0}C is condensed in a condenser reversibly. Find the heat removed and change in entropy. Sketch the process on T-S plot

12. Steam flows steadily through an adiabatic turbine. The inlet condition of steam are 10 MPa, 450^{0}C and 80 m/s. The exit conditions are 10 kPa, 92% quality and 50 m/s.. The mass flow rate of steam is 12 kg/sec. Determine

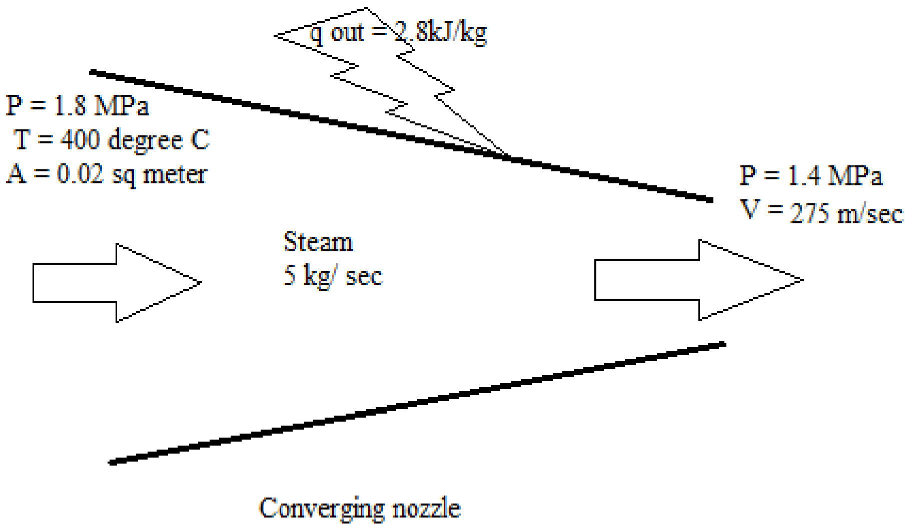
    Change in Kinetic energy
    Power output

    Turbine inlet area

13. Steam at 1.8 MPa and 400^{0}C steadily enters a nozzle whose inlet area is 0.02 m^2. The mass flow rate of steam through nozzle is 5 kg/sec. Steam leaves nozzle at 1.4 MPa with a velocity of 275 m/sec. Heat loss in the nozzle per unit mass of steam are estimated to be 2.8 kJ/kg. Determine

    The inlet velocity
    Exit temperature of steam

DATA GIVEN



Control volume (Steam turbine) exhibiting an isentropic expansion

All the data given are shown diagrammatically

TO FIND

Inlet velocity of steam V_{in} ?

Exit temperature of steam T_{exit} ?

ANALYSIS

Inlet state is identified

Referring to the superheated steam table at P_1 = 1.8 MPa and T_1 = 400^0C

v_1 = --------------(m^3/kg)

h_1 = ---------------(kJ/kg)

from continuity equation $\dot{m} = \rho\ (kg/m3)A(m2)V(m/sec)$

inlet velocity can be calculated as $V_1 = \frac{\dot{m}}{\rho\ A}$ (m/sec)

Steady flow energy equation for any C.V can be written as

$$\dot{Q} - \dot{W} = \dot{m}\ [(h_2 - h_1) + \left(g(Z_2 - Z_1)\right) + (\frac{V_2^2 - V_1^2}{2})]$$

For a nozzle it reduces to

$$\dot{Q} = \dot{m}\ [(h_2 - h_1) + \frac{V_2^2 - V_1^2}{2})]$$

Upon putting all the data and solving for the unknown you can find out

h_2 = ------------- J/kg

Now two properties are known at state 2

P = 1.4 MPa and h_2 = ------------- J/kg

Check in the steam table

hf @ 1.4 MPa = -------------kj/kg

hg @ 1.4 MPa = ------------kJ/kg

Now 3 cases my arise

$h_2 < h_f$ @ 1.4 MPa State is in compressed liquid region	h_f @ 1.4 MPa $< h <$ h_g @ 1.4 MPa State is in Liquid Vapour region	h> hg @ 1.4 MPa State is in Superheated vapour region. Go to superheated steam table of 1.4 MPa now search in the column of enthalpy in ascending order from the first entry where ever you will get h_2 stick there. The corresponding Temp is your answer.

14. Saturated liquid vapour mixture of water, called wet steam in a steam line at 2000 kPa is throttled to 100 kPa and 120^0 C. What is the quality in steam line