UNIT - IV - PROPERTIES OF PURE SUBSTANCES

Steam - formation and its thermodynamic properties - p-V, p-T, T-V, T-S, h-s diagrams. PVT - surface. Determination of dryness fraction. Calculation of workdone and heat transfer in non flow and flow processes using Steam table and Mollier chart.

Course objective :-

Teach the various properties of steam through steam tables and Mollier chart.

Course outcome :-

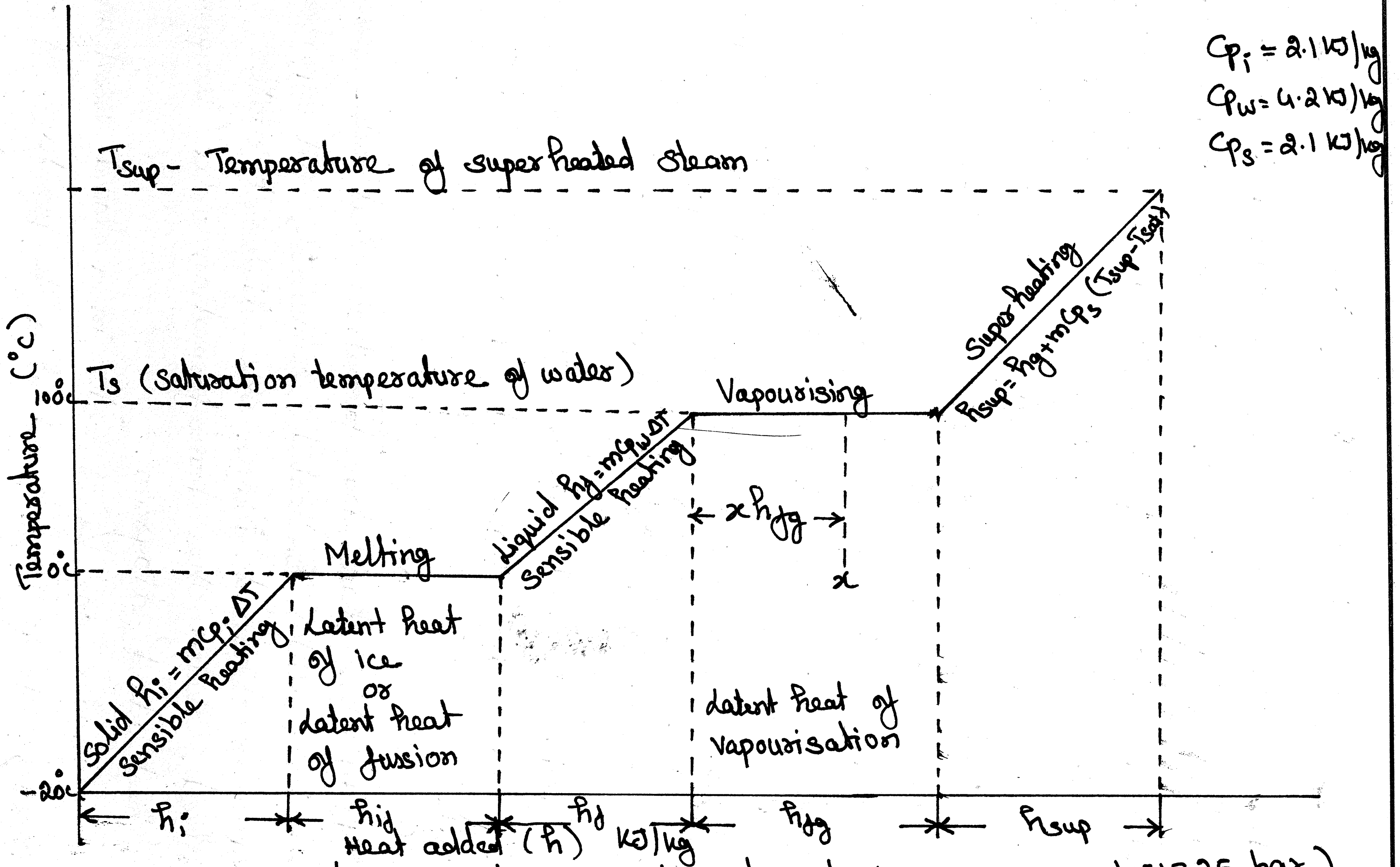
Apply the second law of thermodynamics in evaluating the various properties of steam through steam tables and Mollier chart.

01. Explain steam formation with relevent sketch and label all salient points and explain every point in detail.

or

Explain the phase transformation that takes place when ice (solid) is heated continuously till superheated steam is obtained. Name the different states involved. Sketch the transformation on a 'temperature' vs 'heat added' diagram.

Consider one kg of water in a closed vessel under a pressure of p (N/m²) at at a temperature of $-20°C$ If the water is gradually heated when the pressure



Formation of steam (under atmospheric pressure 1.01325 bar) remains constant, the following changes will occur.

a) The temperature of the ice will increase till it reaches the freezing temperature of water ie $0^\circ c$. It is shown by the line 1-2 in fig.

b) When more heat is added after the point-2, the Ice starts melting. At the same time there is no change in temperature till the whole of the ice has been melted and converted into water. This process is represented by a line 2-3 in fig. The heat added during this process (period) is called latent heat of fussion of ice or latent heat of ice.

c) On further heating, the water reaches its boiling point or saturation point.4. At a given pressure, the temperature at which a pure substance starts boiling is called the saturation temperature T_{sat}. Similarly, at a given temperature, the pressure at which a pure substance starts boiling is called the saturation pressure P_{sat}. Both saturation temperature and pressure are the functions of each other. At atmospheric pressure, the boiling point of water is $100^\circ c$. The amount of heat added during heating of water from $0^\circ c$ to saturation temperature of 100°c is known as sensible heat of water. It is denoted by h_f.

$$h_f = mC_{p_w}(T_2 - T_1)$$

d) On further heating beyond 4, the water will gradually ~~heated~~ converted into steam, when the temperature remains constant. At this stage the steam will have some water particles suspended in it. This steam is called wet steam. The same process continues till all water particles are converted, and it becomes dry steam. The line 4-5 in fig represents this process.

e) The amount of heat added during heating of water from boiling point to dry saturated stage is called latent heat of vapourisation or enthalpy of vapourization or latent heat of steam. It is denoted by h_{fg}.

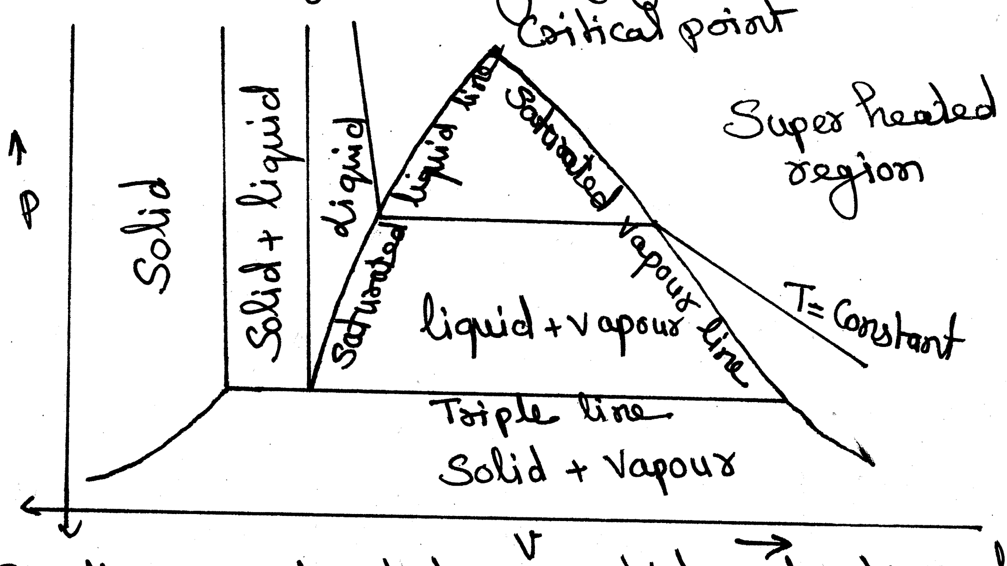
f) When the dry steam is further heated, the temperature rises again. This process is called 'super heating' and the steam obtained is called super-heated steam. The heat supplied during this process is called superheat enthalpy or heat of superheat. It is denoted by 'h_{sup}"

$$h_{sup} = h_g + C_p(T_{sup} - T_{sat})$$

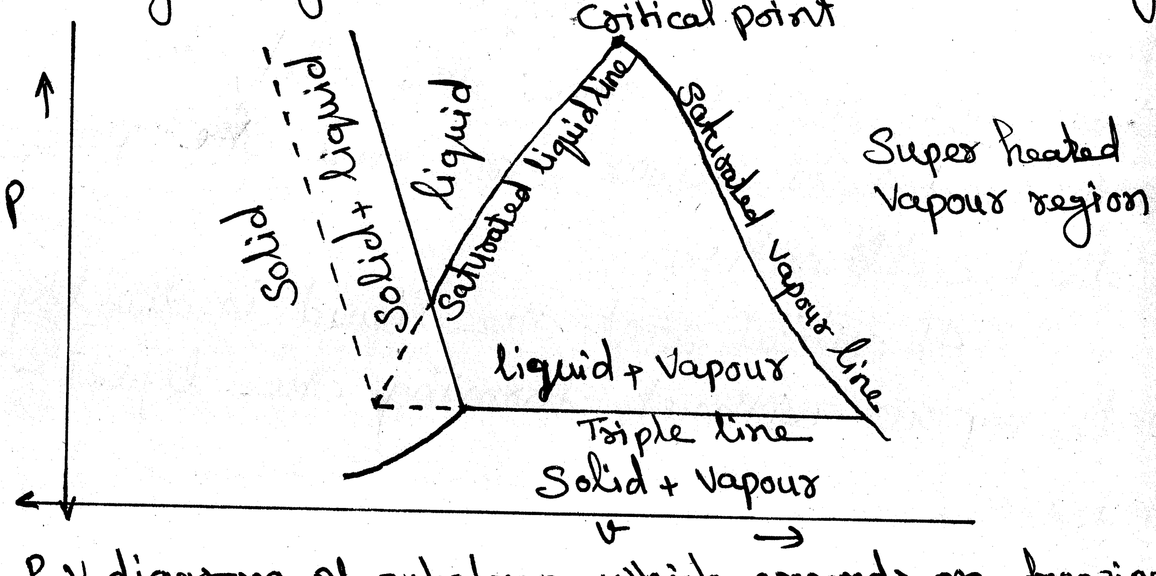
2. Draw P-V, P-T, T-V, T-S diagram of pure substance and explain various regions of the diagram in detail.

a) P-V- diagram :-

In this diagram the speeific volume is taken in x-axis and pressure is taken in Y axis. The state changes of a puresubstance when it is slowly heated at various constant pressures are shown in the following figures.



P-V diagram of substance which contracts on freezing



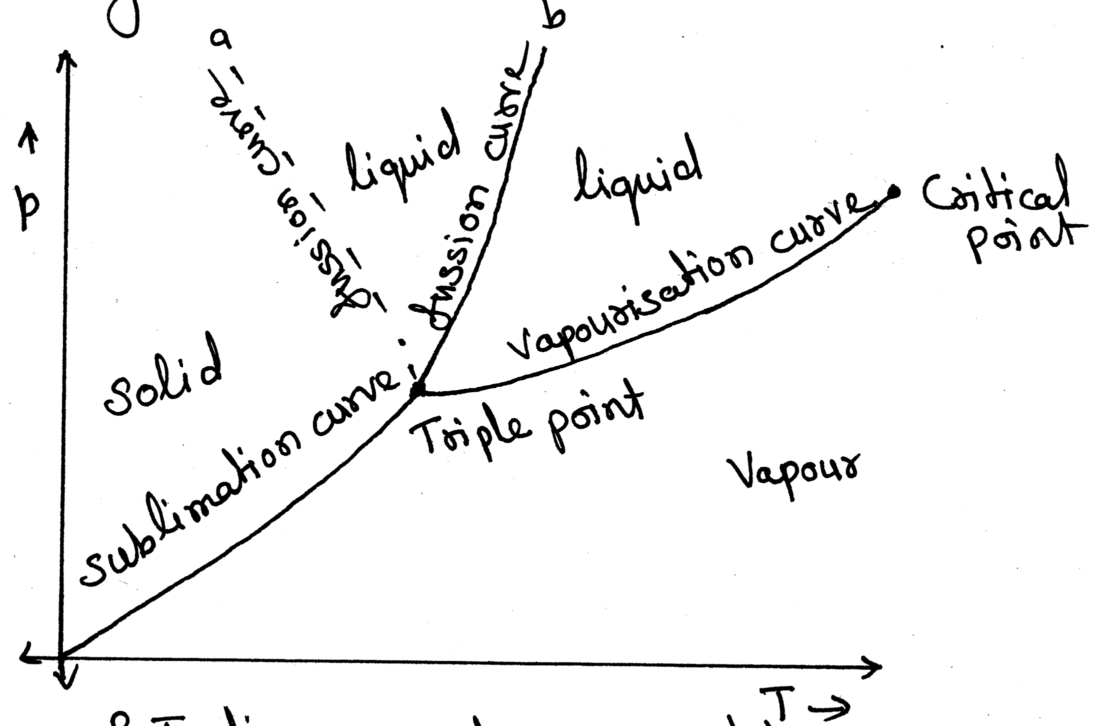
P-V diagram of substance which expands on freezing

Most of the substance contract during a solidification or freezing process. Some substance such as water expand on freezing. These two figures differ only in the solid - liquid saturation region. The point at which the saturated liquid curve meets the saturated vapour curve is known as critical point. The corresponding temperature, pressure are called critical temperature and critical pressure. For water the critical temperature is 374.15°c and critical pressure is 22.12 MPa. As the pressure increases, the latent heat of vapourization decreases and becomes zero at the critical point.

The triple point line represents the state at which solid, liquid and vapour phase exist in equillibrium. For water, the triple point temperature is 0.01°c and the triple point pressure is 0.6113 KPa. No substance can exist in liquid phase at a pressure below the triple point pressure. Below the triple point pressure the solid state is directly converted into vapour phase and the process is called sublimation.

At critical point the liquid is directly converted into vapour without forming the liquid - vapour mixture.

b) P-T-diagram :-



P-T diagram of a pure substance

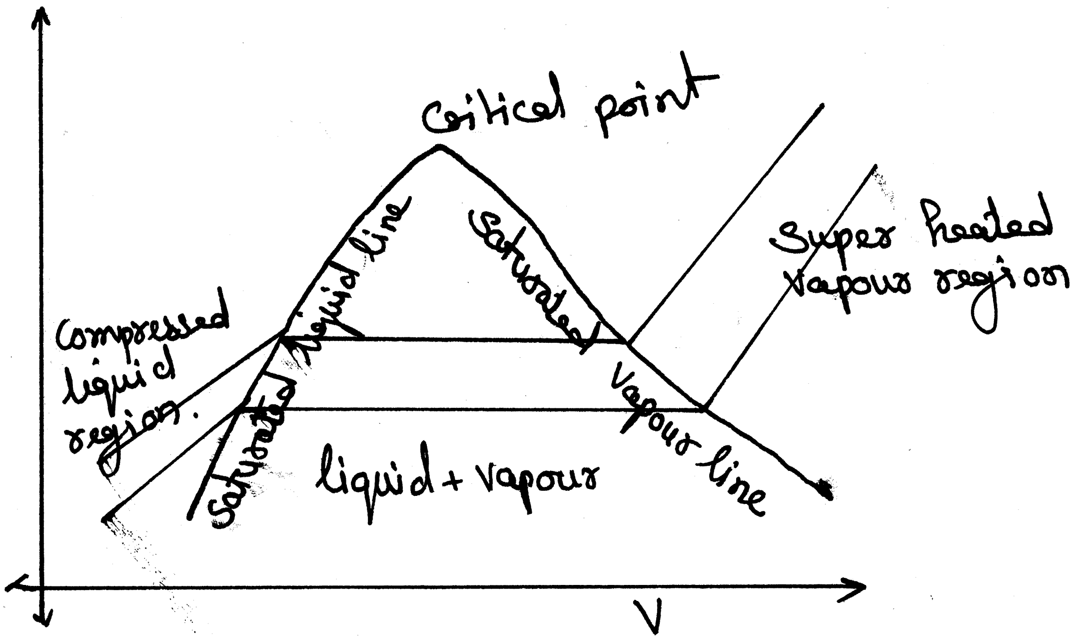
a - fussion curve for pure substance which expands on freezing.

b - fussion curve for pure substance which contracts on freezing.

Solid - liquid → melting or fussion
liquid - solid → freezing
liquid - vapour → Vapourization
Vapour - liquid → condensation.
Solid - vapour → sublimation
Vapour - solid → deposition or desublimation.

The slope of sublimation and vapourization curve for all substance are positive. The slope of fussion curve is positive for the substance which contracts on freezing and negative for the substance which expands (water) on freezing.

c) T-V - diagram.



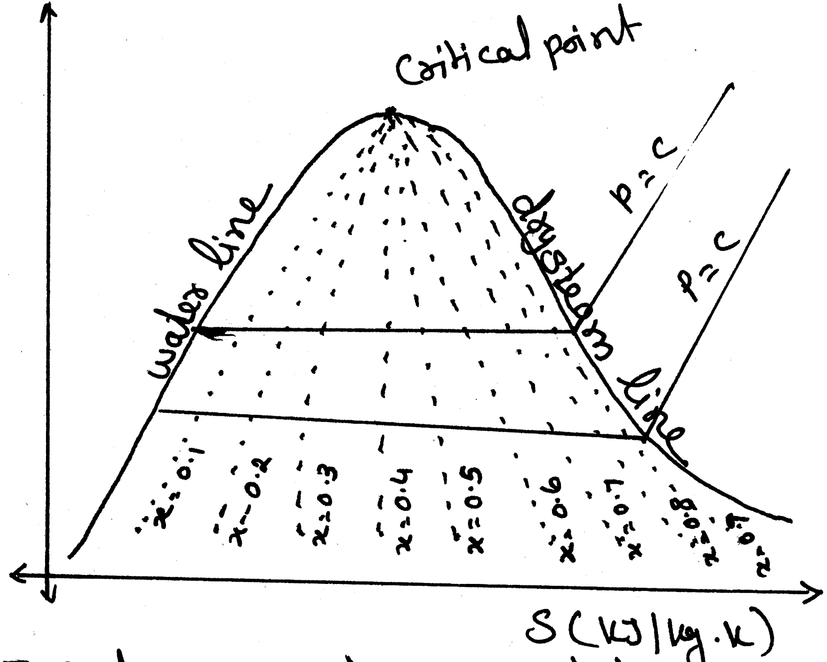
T-V diagram of a pure substance

The general shape of T-V diagram of a pure substance is similar to P-V -diagram but the constant pressure lines have an upward trend. The region in which the actual temperature is less than saturation temperature corresponding to that pressure is called sub cooled or under cooled region.

Degree of sub cooling = $T_{sat} - T_{act}$.

The region in which the actual pressure is less than saturation pressure corresponding to that temperature is called as compressed liquid region.

d) T-S diagram



T-S diagram of pure substance

T-S is the plot of saturation temperature of water and steam corresponding to the various absolute pressures against the entropies at that saturation temperatures. The left side of the water line the water exist as liquid The right side of the dry steam line the water exist as super heated steam. In between the water line and dry saturated steam line water exist as wet steam. Therefor the dryness fraction lines (constant quality lines) are represented in these regions as shown in figure. The value of various quantities are directly read from the diagram.

An iso thermal process is represented by a horizontal line and a reversible adiabatic process is represented by a vertical line. In this diagram constant volume lines are plotted in the wet region and constant pressure lines are plotted in the super heated region.

3. Briefly explain the 'dryness fraction and wetness fraction of steam.

Dryness fraction:-

It is defined as the ratio of the mass of the dry steam actually present to the mass of the total steam. It is denoted by 'x'.

$$\text{Dryness fraction } x = \frac{m_g}{m_f + m_g}$$

where

m_g - mass of dry steam in kg.

m_f - mass of water vapour in suspension.

This term is applicable only for wet steam.

For dry steam, $m_f = 0 \Rightarrow x = 1$

The dryness fraction when it is expressed in percentage (ie $100x$) is called quality of steam.

Wetness fraction:-

It is defined as the ratio of the mass of water vapour in suspension to the total steam.

$$\text{Wetness fraction} = \frac{m_f}{m_f + m_g}$$

$$= \frac{m_f}{m_f + m_g} + 1 - 1$$

$$= 1 - \left[1 - \frac{m_f}{m_f + m_g}\right]$$

$$= 1 - \frac{\cancel{m_f} + m_g - \cancel{m_f}}{m_f + m_g} = 1 - \frac{m_g}{m_f + m_g}$$

Wetness fraction $= 1-x$

The wetness fraction expressed in percentage $(1-x)100$ is called priming.

4. A vessel of volume 0.04 m^3 contains a mixture of saturated water and steam at a temperature of 250°c. The mass of the liquid present is 9 kg. Find the pressure, mass, specific volume, enthalpy, entropy and internal energy of the mixture.

Given data :-

$V = 0.04\,m^3$
$T = 250^\circ C$
$m_f = 9\,kg$

To find :-

$P_{mix}, m_{mix}, V_{mix}, h_{mix}, S_{mix}, U_{mix}$

Sol :-

From saturated water table of temperature scale, corresponding to 250°c.

$v_f = 0.001251\ m^3/kg$
$v_g = 0.050037\ m^3/kg$
$\boxed{p = 39.776\ bar = 3977.6\ kPa}$
$h_f = 1085.8\ kJ/kg$
$h_{fg} = 1714.6\ kJ/kg$
$s_f = 2.794\ kJ/kg.K$
$s_{fg} = 3.277\ kJ/kg.K$

Total Volume $V = V_f + V_s$

$$= m_f . v_f + m_s . v_s$$

$$V_f = m_f . v_f = 9 \times 0.001251$$

$$= 0.0113\ m^3$$

$$V = V_f + V_s$$

$$0.04 = 0.0113 + V_s$$

$$V_s = 0.04 - 0.0113 = 0.0287\ m^3$$

$$V_s = m_s . v_s$$

$$0.0287 = m_s \times 0.050037$$

$$m_s = 0.574\ kg$$

Total mass of mixture $m_{mix} = m_f + m_s$

$$= 9 + 0.574$$

$$\boxed{m_{mix} = 9.574\ kg}$$

Total specific volume of mixture

$$V_{mix} = m_{mix} \times v_{mix}$$

$$0.04 = 9.574 \times v_{mix}$$

$$\boxed{v_{mix} = 4.18 \times 10^{-3}\ m^3/kg}$$

W.K.T

$$v_{mix} = v_f + x\, v_{fg}$$

$$4.18 \times 10^{-3} = 0.001251 \times x\,(0.050037 - 0.001251)$$

$$x = \frac{4.18 \times 10^{-3} - 0.001251}{(0.050037 - 0.001251)}$$

$$x = 0.06$$

Enthalpy of mixture $h_{mix} = h_f + x h_{fg}$

$= 1085.8 + 0.06 \times 1714.6$

$\boxed{h_{mix} = 1188.67 \text{ kJ/kg}}$

Entropy of the mixture $s_{mix} = s_f + x s_{fg}$

$= 2.794 + 0.06 \times 3.277$

$\boxed{s_{mix} = 2.99 \text{ kJ/kg.K}}$

Internal energy of mixture

W.K.T $\quad h = u + pv \Rightarrow u = h - pv$

$u_{mix} = h_{mix} - P_{mix} \cdot V_{mix}$

$= 1188.67 - 3977.6 \times 0.00418$

$\boxed{u_{mix} = 1172.05 \text{ kJ/kg}}$

5. A rigid tank of 0.03 m³ capacity contains wet vapour at 80 kPa. If the wet vapour mass is 12 kg, calculate the heat added and quality of the mixture when the pressure inside the tank reaches 7 MPa.

Given data :-

$V_1 = V_2 = 0.03 \text{ m}^3$ (rigid tank)

Constant volume process.

$P_1 = 80 \text{ kPa} = 0.8 \text{ bar}$

$m = 12 \text{ kg}$

$P_2 = 7 \text{ MPa} = 7000 \text{ kPa} = 70 \text{ bar}$

To find :-

Q, quality of steam at the end of process.

Sol :-

$V_{mix} = m_{mix} \times v_{mix}$

$0.03 = 12 \times v_{mix}$

$v_{mix} = 0.0025 \; m^3/kg.$

From saturated water table of pressure scale, corresponding to 0.8 bar.

$v_f = 0.001039 \; m^3/kg$

$v_g = 2.0869 \; m^3/kg$

$h_f = 391.7 \; kJ/kg.$

$h_{fg} = 2274.21 \; kJ/kg.$

W.K.T

$v_{mix_1} = v_f + x v_{fg}$

$0.0025 = 0.001039 \times x (2.0869 - 0.001039)$

$$x = \frac{0.0025 - 0.001039}{(2.0869 - 0.001039)}$$

$x = 0.0007$

$h_1 = h_{f_1} + x h_{fg_1}$

$= 391.7 + 0.0007 \times 2274.21$

$h_1 = 393.29 \; kJ/kg.$

At the end of the process (constant volume)

$V_1 = V_2 = 0.0025 \; m^3/kg$

From saturated water table of pressure scale, corresponding to 70 bar,

$$V_{f_2} = 0.0010351 \text{ m}^3/\text{kg}$$
$$V_{g_2} = 0.027368 \text{ m}^3/\text{kg}$$
$$h_{f_2} = 1267.4 \text{ kJ/kg}$$
$$h_{fg_2} = 1506 \text{ kJ/kg}.$$

Since $V_{g_2} > V_2$ the steam is in wet region.

$$V_2 = V_{f_2} + x V_{fg_2}$$
$$0.0025 = 0.0010351 + x\,(0.027368 - 0.0010351)$$
$$x = \frac{0.0025 - 0.0010351}{(0.027368 - 0.0010351)}$$
$$\boxed{x = 0.056}$$
$$h_2 = h_{f_2} + x\, h_{fg_2}$$
$$= 1267.4 + 0.056 \times 1506$$
$$h_{f_2} = 1351.74 \text{ kJ/kg}.$$

Acc. to first law of thermodynamics

$$Q = \Delta U + W$$

for constant volume process $W = p\,dv = p(v_2 - v_1)$

$W = 0 \quad \because v_1 = v_2$

$$Q = \Delta U \qquad \because H = U + PV$$
$$Q = U_2 - U_1 \qquad U = H - PV$$
$$Q = (H_2 - P_2V_2) - (H_1 - P_1V_1)$$
$$= (H_2 - H_1) - (P_2V_2 - P_1V_1)$$
$$= (H_2 - H_1) - V(P_2 - P_1) \qquad \because V_1 = V_2$$

$$Q = m\left[(h_2 - h_1) - V(P_2 - P_1)\right]$$

$$= 12\left[(1351.74 - 393.29) - 0.0025(1000-80)\right]$$

$$= 11293.8\ \text{kJ}$$

$$\boxed{Q = 11.29\ \text{MJ}}$$

6. 10 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, change in enthalpy, change in internal energy and change in entropy.

Given data :-

$m = 10$ kg

$T_1 = 45^\circ C$

Process: constant pressure process.

$P_1 = P_2 = 10$ bar $= 1000$ kPa

$T_2 = 300^\circ C$

To find :-

ΔV, Δh, ΔS and ΔU

Sol:-

From saturated water table of temperature scale, corresponding to 45°C,

$v_{f_1} = 0.001010\ m^3/kg$

$h_{f_1} = 188.4\ kJ/kg$

$S_{f_1} = 0.638\ kJ/kg.K$

From saturated water table of pressure scale, Corresponding to 10 bar, $T_{sat} = 179.9°C$

Since $T_2 > T_{sat}$, the steam is in super heated region.

From superheated enthalpy, super heated entropy and super heated specific volume tables, corresponding to 10 bar and 300°C.

$h_2 = 3052.1$ KJ/kg

$s_2 = 7.125$ KJ/kg.K

$v_2 = 0.258$ m^3/kg.

change in volume $\Delta V = m(v_2 - v_1)$

$$\Delta V = 10(0.258 - 0.001010)$$

$$\boxed{\Delta V = 2.57 \; m^3}$$

change in entropy $\Delta S = m(s_2 - s_1)$

$$= 10(7.125 - 0.638)$$

$$\boxed{\Delta S = 64.87 \text{ KJ/K}}$$

change in enthalpy $\Delta H = m(h_2 - h_1)$

$$= 10(3052.1 - 188.4)$$

$$\boxed{\Delta H = 2863.7 \text{ KJ}}$$

change in internal energy $\Delta U = m(u_2 - u_1)$

$$= m[(h_2 - P_2 v_2) - (h_1 - P_1 v_1)]$$

$$= m[(h_2 - h_1) - (P_2 v_2 - P_1 v_1)]$$

$$Q = m\left[(h_2 - h_1) - P(V_2 - V_1)\right] \quad \because P_1 = P_2$$

$$= 10\left[(3052.1 - 188.4) - 1000(0.258 - 0.001010)\right]$$

$$\boxed{Q = 26067.1 \text{kJ}}$$

7. 1 kg of steam initially dry saturated at 1.1 MPa expands in a cylinder following the law $PV^{1.13} = C$. The pressure at the end of the expansion is 0.1 MPa. Determine the i) final volume, ii) final dryness fraction iii) Work done iv) change in internal energy and v) heat transferred.

Given data :-

$m = 1$ kg

$P_1 = 1.1$ MPa $= 1100$ kP $= 11$ bar

$P_2 = 0.1$ MPa $= 100$ kP $= 1$ bar

$PV^{1.13} = C$ (Polytropic process)

To find :-

V_2, x, W, ΔU and Q

Sol :-

From saturated water table of pressure scale,

at 11 bar

$V_{g_1} = 0.17739$ m³/kg

$h_{g_1} = 2779.7$ kJ/kg.

For polytropic process $PV^n = C$

$$P_1V_1^n = P_2V_2^n \Rightarrow \left(\frac{V_2}{V_1}\right)^n = \left(\frac{P_1}{P_2}\right)$$

$$\left(\frac{V_2}{V_1}\right) = \left(\frac{P_1}{P_2}\right)^{1/n} \Rightarrow V_2 = V_1\left(\frac{P_1}{P_2}\right)^{1/n}$$

$$V_2 = 0.17739 \times \left(\frac{1.1}{0.1}\right)^{1/1.13}$$

$$\boxed{V_2 = 1.122 \ m^3/kg}$$

From saturated water table of pressure scale, corresponding to 1 bar.

$$V_{f_2} = 0.001043 \ m^3/kg$$

$$V_{g_2} = 1.6938 \ m^3/kg$$

$$h_{f_2} = 417.5 \ kJ/kg$$

$$h_{fg_2} = 2257.9 \ kJ/kg$$

W.K.T

$$V_2 = V_{f_2} + x V_{fg_2}$$

$$1.122 = 0.001043 + x(1.6938 - 0.001043)$$

$$x = \frac{1.122 - 0.001043}{(1.6938 - 0.001043)}$$

$$\boxed{x = 0.662}$$

$$h_2 = h_{f_2} + x h_{fg_2}$$

$$= 417.5 + 0.662 \times 2257.9$$

$$h_2 = 1912.23 \ kJ/kg$$

For polytropic process

Workdone $W = \frac{P_1V_1 - P_2V_2}{n-1}$

$= \frac{1100 \times 0.17739 - 100 \times 1.122}{1.13 - 1}$

$\boxed{W = 637.9 \text{ kJ}}$

Change in internal energy

$\Delta U = m(u_2 - u_1)$

$= 1\left[(h_2 - P_2V_2) - (h_1 - P_1V_1)\right]$

$= 1\left[(h_2 - h_1) - (P_2V_2 - P_1V_1)\right]$

$= \left[(1912.13 - 2779.7) - (100 \times 1.122 - 1100 \times 0.17739)\right]$

$\Delta U = -784.64 \text{ kJ}$ (– Sign indicates energy loss to sur)

Heat transfer $Q = \Delta U + W$

$Q = 784.64 + 637.9$

$\boxed{Q = 1422.54 \text{ kJ}}$

8. A pressure cooker contains 1.5 kg of saturated steam at 5 bar. Find the quantity of heat which must be rejected so as to reduce the quality to 60% dry. Determine the pressure and temperature of the steam at the new state.

Given data :-

mass of steam in cooker = 1.5 kg

Pressure of the steam = 5 bar = 500 kPa

Initial dryness fraction $x_1 = 1$

Final dryness fraction $x_2 = 0.6$

To find :-

Q_R , P_2 , T_2

Sol :-

From saturated water table of pressure scale, at 5 bar,

$T_{sat} = 151.8^\circ c$

$V_g = 0.375 \ m^3/kg$

$h_g = 2747.5 \ kJ/kg.$

Thus the volume of the pressure cooker

$V = m_s \times V_s$

$= 1.5 \times 0\,375$

$V = 0.5625 \ m^3$

Internal energy of steam at initial condition

$U_1 = mu_1 = m(h_1 - P_1 v_1)$

$= 1.5 \, (2747.5 - 500 \times 0.375)$

$U_1 = 3840 \ kJ$

At final condition

$V_1 = V_2$ (constant volume)

$V_2 = m_g . x V_{g2}$

$$0.5625 = 1.5 \times 0.6 \times V_{g_2}$$

$$V_{g_2} = \frac{0.5625}{1.5 \times 0.6} = 0.625\ m^3/kg$$

From steam table corresponding to 0.625 m^3/kg (pressure scale)

$$\boxed{P_2 = 2.9\ bar = 290\ KPa}$$

$$\boxed{T_{sat} = 132.4^\circ C}$$

$$h_{f_2} = 556.5\ kJ/kg$$

$$h_{fg_2} = 2166.6\ kJ/kg.$$

Internal energy at final condition

$$U_2 = m u_2 = m\left[h_2 - P_2 V_2\right]$$

$$= m\left[(h_{f_2} + x h_{fg_2}) - P_2 \times x V_{g_2}\right]$$

$$= 1.5\left[(556.5 + 0.6 \times 2166.6) - 290 \times 0.6 \times 0.625\right]$$

$$= 1.5\,(1856.46 - 108.75)$$

$$U_2 = 2621.625\ kJ$$

The amount of heat rejected

$$Q_R = \Delta U = U_2 - U_1$$

$$= 2621.625 - 3840$$

$$\boxed{Q_R = -1218.375\ kJ}$$

The negative sign indicates the heat loss from the system.

9. Two streams of steam, one at 2 MPa, 300°C and the other at 2 MPa, 400°C mix in a steady flow adiabatic process. The rates of flow of the two streams are 3 kg/min and 2 kg/min respectively. Evaluate the final temperature of the emerging steam if there is no pressure drop due to the mixing process. What would be the rate of increase in the entropy of the universe? This steam with negligible velocity now expands adiabatically in a nozzle to a pressure of 1 kPa. Determine the exit velocity of the stream and exit area of the nozzle.

Given data :-

$P_1 = 2\,MPa = 2000\,kPa = 20\,bar$

$T_1 = 300^\circ C$

$P_2 = 2\,MPa = 2000\,kPa = 20\,bar$

$T_2 = 400^\circ C$

$m_1 = 3\,kg/min$

$m_2 = 2\,kg/min$

$P_3 = 2\,MPa = 2000\,kPa = 20\,bar$

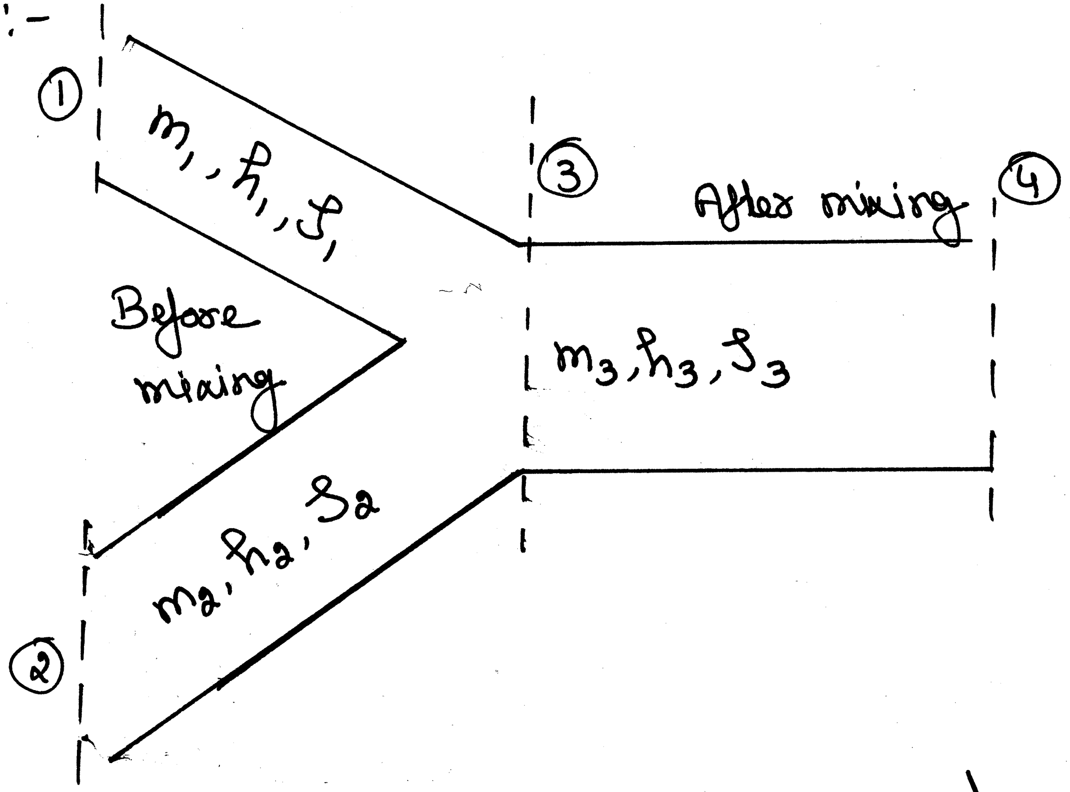
$m_3 = m_1 + m_2 = 5\,kg/min = m_4$

$P_4 = 1\,kPa = 0.01\,bar$

To find :-

T_3, S_3, C_4 and A_4

Sol :-



From saturated water table of pressure scale,

at 20 bar - $T_{sat} = 212.4°C$

Since $T_1 > T_{sat}$, the state of the steam is in super heated region.

Corresponding to 20 bar at 300°C from super heated enthalpy, super heated entropy and super heated specific volume tables

$h_1 = 3025$ kJ/kg

$s_1 = 6.77$ kJ/kg.K

$v_1 = 0.1255$ m^3/kg.

$|||^{ly}$ at 20 bar and 400°C

$h_2 = 3248.7$ kJ/kg

$s_2 = 7.13$ kJ/kg.K

$v_2 = 0.1511$ m^3/kg

Enthalpy after mixing

$$m_1h_1 + m_2h_2 = m_3h_3 = (m_1+m_2)h_3$$

$$h_3 = \frac{m_1h_1 + m_2h_2}{(m_1+m_2)} = \frac{3\times3025 + 2\times3248.7}{3+2}$$

$$h_3 = 3114.48 \text{ kJ/kg}.$$

From super heated enthalpy table, corresponding to $h_3 = 3114.48$ kJ/kg at 20 bar, the super heated temperature,

$$\frac{350-300}{350-x} = \frac{3138.6-3025}{3138.6-3114.48} = \frac{113.6}{24.12} = 4.709$$

$$\frac{50}{350-x} = 4.709 \quad \Rightarrow \frac{50}{4.709} = 350-x$$

$$10.616 = 350-x$$

$$x = 339.38^\circ C$$

$$\boxed{T_3 = 339.38^\circ C}$$

|||ly entropy after mixing

$$s_3 = \frac{m_1s_1 + m_2s_2}{m_1+m_2} = \frac{3\times6.77 + 2\times7.13}{5}$$

$$\boxed{s_3 = 6.914 \text{ kJ/kg.K}}$$

From saturated water table of pressure scale, at 0.01 bar

$$v_{f_4} = 0.001 \text{ m}^3/\text{kg}$$

$$v_{g_4} = 129.21 \text{ m}^3/\text{kg}$$

$$h_{f_4} = 29.3 \text{ kJ/kg}$$

$h_{fg_4} = 2485.1$ kJ/kg

$s_{f_4} = 0.106$ kJ/kg.k

$s_{fg_4} = 8.871$ kJ/kg.k

W.K.T the flow in the nozzle is adiabatic (isentropic)

$$S_3 = S_4 = 6.914 \text{ kJ/kg.k}$$

$$S_4 = S_{f_4} + x S_{fg_4}$$

$$6.914 = 0.106 + x\, 8.87$$

$$x = \frac{6.914 - 0.106}{8.87} = 0.767$$

Enthalpy at the exit of the nozzle

$$h_4 = h_{f_4} + x h_{fg_4}$$

$$= 29.3 + 0.767 \times 2485.1$$

$$h_4 = 1935.37 \text{ kJ/kg.k}$$

Specifiv volume at exit of nozzle

$$v_4 = v_{f_4} + x v_{fg_4}$$

$$= 0.001 + 0.767\,(129.21 - 0.001)$$

$$v_4 = 99.1 \text{ m}^3/\text{kg}$$

From SFEE of nozzle

Velocity of steam at exit $C_4 = \sqrt{2000\,(h_3 - h_4)}$

$$C_4 = \sqrt{2000\,(3114.48 - 1935.37)}$$

$$\boxed{C_4 = 1535.65 \text{ m/s}}$$

Exit area of nozzle $A_4 = \frac{m_4 v_4}{C_4}$

$$A_4 = \frac{\frac{5}{60} \times 99.1}{1535.65} = 0.005378 \text{ m}^2$$

$$\boxed{A_4 = 0.005378 \text{ m}^2}$$

10. Steam flows through a small turbine at the rate of 500 kg/hr entering at 15 bar, 300°c and leaving at 0.1 bar with 4% moisture. The steam enters at 80 m/s at a point 2 m above the discharge and leaves at 40 m/s. Compute the shaft power assuming that the device is adiabatic but considering kinetic and potential energy changes. Calculate the areas of the inlet and discharge tubes.

Given data :-

$\dot{m} = 500 \text{ kg/hr} = \frac{500}{3600} = 0.1388 \text{ kg/s}$

$P_1 = 15 \text{ bar} = 1500 \text{ kPa}$

$T_1 = 300°c$

$P_2 = 0.1 \text{bar} = 10 \text{ kPa}$

$\text{moisture} = 4\% \Rightarrow x = \frac{100-4}{100} = 0.96$

$C_1 = 80 \text{ m/s}$

$Z_1 = 2 \text{ m}$

$V_2 = 40 \text{ m/s}$

To find :-

W, A_1 and A_2

Sol :-

From saturated water tabe of pressure scale,

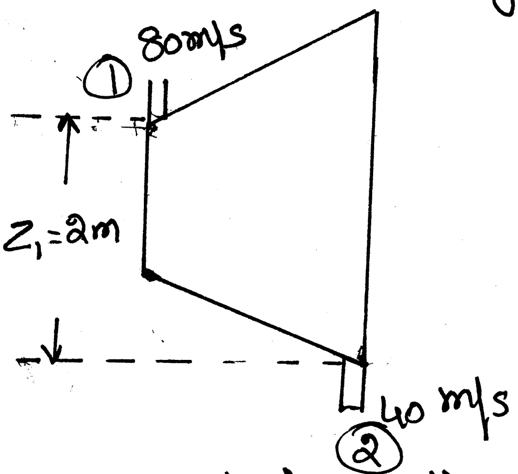
at 15 bar $T_{sat} = 198.3°c$

Since $T_1 > T_{sat}$ the steam lies in super heated region.

From super heated enthalpy table corresponding to 15 bar and 300°C,

$h_1 = 3038.9$ kJ/kg

$v_1 = 0.1697$ m^3/kg



At the exit of the turbine the pressure $p_2 = 0.1$ bar

From saturated water table of pressure scale,

at 0.1 bar

$h_{f_2} = 191.8$ kJ/kg $\quad V_{g_2} = 14.675$ m^3/kg

$h_{fg_2} = 2392.8$ kJ/kg $\quad V_{f_2} = 0.001010$ m^3/kg

$$h_2 = h_{f_2} + x\, h_{fg_2}$$

$$= 191.8 + 0.96 \times 2392.8$$

$$h_2 = 2489 \text{ kJ/kg}$$

Shaft power $W = \dot{m}\left[(h_1 - h_2) + \frac{C_1^2 - C_2^2}{2000} + \frac{g(z_1 - z_2)}{1000}\right]$

$$= 0.1388\left[(3038.9 - 2489) + \frac{80^2 - 40^2}{2000} + \frac{9.81\,(2)}{1000}\right]$$

$$= 0.1388\left[549.9 + 2.4 + 0.01962\right]$$

$$\boxed{W = 76.66 \text{ KW}}$$

$$V_2 = V_{f_2} + x\, V_{fg_2}$$

$V_2 = 0.001010 + 0.96\,(14.675 - 0.001010)$

$V_2 = 14.088\ m^3/kg$

Area at inlet $A_1 = \frac{m_1 v_1}{C_1} = \frac{0.1388 \times 0.1697}{80}$

$$\boxed{A_1 = 2.94 \times 10^{-4}\ m^2}$$

Area at exit $A_2 = \frac{m_2 v_2}{C_2} = \frac{0.1388 \times 14.088}{40}$

$$\boxed{A_2 = 0.0488\ m^2}$$

---

11. 3 kg of steam at 18 bar occupies a volume of 0.2550 m^3. During a constant volume process, the heat rejected is 1320 KJ. Determine the final internal energy, initial dryness and work done.

Given data :-

$V = 0.2550\ m^3$

$m = 3\ kg$

$P_1 = 18\ bar = 1800\ kPa$

$Q_R = 1320\ KJ$

To find :-

U_2, x_1, W

Sol :-

Specific volume $v = \frac{V}{m} = \frac{0.2550}{3} = 0.085\ m^3/kg$

From saturated water table of pressure scale, at 18 bar

$h_{f_1} = 884.5\ KJ/kg$ $\qquad v_{g_1} = 0.11033\ m^3/kg$

$h_{fg_1} = 1910.3\ KJ/kg$

$v_{f_1} = 0.001168\ m^3/kg$

Since $v_1 < v_{g_1}$, the steam lies in wet region.

$$v = v_{f_1} + x v_{fg_1}$$

$$0.085 = 0.001168 + x(0.11033 - 0.001168)$$

$$x = \frac{0.085 - 0.001168}{(0.11033 - 0.001168)}$$

$$\boxed{x = 0.768}$$

$$h_1 = h_{f_1} + x h_{fg_1}$$

$$= 884.5 + 0.768 \times 1910.3$$

$$h_1 = 2351.61 \text{ kJ/kg}$$

For constant volume process

$v_1 = v_2$ and $\boxed{W = 0}$

Acc. first law of thermodynamics

$$Q = \Delta U + W$$

$$Q = \Delta U \qquad \because W = 0$$

$$Q = U_2 - U_1$$

$$-1320 = m\left[u_2 - (h_1 - p_1 v_1)\right]$$

$$-1320 = 3\left[u_2 - (2351.61 - 1800 \times 0.085)\right]$$

$$\frac{-1320}{3} = u_2 - 2198.61$$

$$u_2 = 2198.61 - 440$$

$$\boxed{u_2 = 1758.61 \text{ kJ/kg}}$$

12. Steam initially at 1.5 MPa, 300°C expands reversible adiabatic process in a steam turbine to 40°C. Determine the ideal workoutput of the turbine per kg of steam.

Given data :-

$P_1 = 1.5\text{ MPa} = 1500\text{ kPa} = 15\text{ bar}$

$T_1 = 300^\circ C$

$T_2 = 40^\circ C$

To find :-

W

Sol :-

From saturated water table of pressure scale, at 15 bar $T_{sat} = 198.3^\circ C$

Since $T_1 > T_{sat}$, the steam is in super heated region.

From super heated enthalpy and super heated entropy tables, corresponding to 15 bar and 300°C.

$h_1 = 3038.9\text{ kJ/kg}$

$s_1 = 6.921\text{ kJ/kg.K}$

From saturated water table of temperature scale, corresponding to 40°C.

$h_{f_2} = 167.5\text{ kJ/kg}$ $\quad s_{g_2} = 8.258\text{ kJ/kg.K}$

$h_{fg_2} = 2406.9\text{ kJ/kg}$

$s_{f_2} = 0.572\text{ kJ/kg.K}$

$s_{fg_2} = 7.686\text{ kJ/kg.K}$

W.K.T for reversible adiabatic process (isentropic)

$$S_1 = S_2 = 6.921 \text{ kJ/kg.k}$$

Since $S_2 < S_{g_2}$, the steam is in wet region after expansion in the turbine.

$$S_2 = S_{f_2} + x S_{fg_2}$$

$$6.921 = 0.572 + x\, 7.686$$

$$x = \frac{6.921 - 0.572}{7.686}$$

$$x = 0.826$$

Enthalpy at exit,

$$h_2 = h_{f_2} + x h_{fg_2}$$

$$= 167.5 + 0.826 \times 2406.9$$

$$h_2 = 2155.6 \text{ kJ/kg}$$

Work output for turbine

$$W = h_1 - h_2$$

$$= 3038.9 - 2155.6$$

$$\boxed{W = 883.3 \text{ kJ/kg}}$$

---

13. A large insulated vessel is divided into two chambers, one containing 5 kg of dry saturated steam at 0.2 MPa and the other 10 kg of steam, 0.8 quality at 0.5 MPa. If the partition between the chambers is removed and the steam is mixed thoroughly and allowed to settle, find the final pressure, steam quality and entropy change in the process.

Given data :-

$m_1 = 5$ kg

$p_1 = 0.2$ MPa $= 200$ kPa $= 2$ bar

$m_2 = 10$ kg

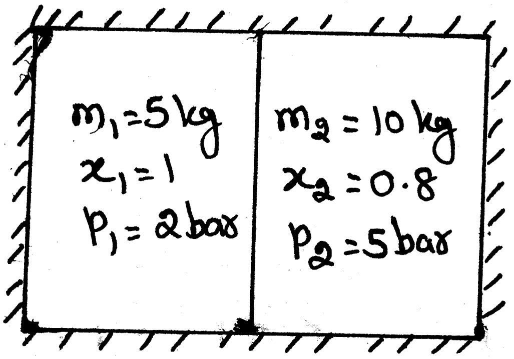
$x_2 = 0.8$

$P_2 = 0.5$ MPa $= 500$ kPa $= 5$ bar

To find :-

P_3, x_3, ΔS

Sol :-



mass of steam after mixing $m_3 = m_1 + m_2 = 5 + 10$

$m_3 = 15$ kg

From saturated water table of pressure scale at 2 bar (dry saturated)

$h_{g_1} = 2706.3$ kJ/kg

$s_{g_1} = 7.127$ kJ/kg.K

$V_{g_1} = 0.8854$ m^3/kg

|||ly for 5 bar

$h_{f_2} = 640.1$ kJ/kg

$h_{fg_2} = 2107.4$ kJ/kg

$s_{f_2} = 1.86$ kJ/kg.K

$s_{fg_2} = 4.959$ kJ/kg.K

$v_{f_2} = 0.001093 \ m^3/kg$

$v_{g_2} = 0.37466 \ m^3/kg$

$h_2 = h_{f_2} + x h_{fg_2}$

$= 640.1 + 0.8 \times 2107.4$

$h_2 = 2326.02 \ kJ/kg$

$s_2 = s_{f_2} + x s_{fg_2}$

$= 1.86 + 0.8 \times 4.959$

$s_2 = 5.83 \ kJ/kg.k$

$v_2 = v_{f_2} + x v_{fg_2}$

$= 0.001093 + 0.8 \times (0.37466 - 0.001093)$

$v_2 = 0.3 \ m^3/kg$

Volume after mixing

$$v_3 = \frac{m_1 v_1 + m_2 v_2}{(m_1 + m_2)} = \frac{5 \times 0.8854 + 10 \times 0.3}{15}$$

$v_3 = 0.495 \ m^3/kg$

$$h_3 = \frac{m_1 h_1 + m_2 h_2}{(m_1 + m_2)} = \frac{5 \times 2706.3 + 10 \times 2326.02}{15}$$

$h_3 = 2452.78 \ kJ/kg$

$$s_3 = \frac{m s_1 + m_2 s_2}{(m_1 + m_2)} = \frac{5 \times 7.127 + 10 \times 5.83}{15}$$

$s_3 = 6.3 \ kJ/kg.k$

Corresponding to $h_3 = 2452.78 \ kJ/kg$ and $v_3 = 0.495 \ m^3/kg$ from mollier diagram, read dryness fraction and pressure values.

$\boxed{x_3 = 0.862}$

$\boxed{P_3 = 3.3 \ bar}$

change in entropy ΔS = Entropy after mixing − Entropy before mixing

$$\Delta S = m_3 s_3 - (m_1 s_1 + m_2 s_2)$$

$$= 15 \times 6.3 - (5 \times 7.127 + 10 \times 5.83)$$

$$\boxed{\Delta S = 0.565 \text{ kJ/kg.k}}$$

14. Describe with neat sketch, the methods used in determing the dryness fraction of steam.

The dryness fraction of steam can be measured by using the following calorimeters.

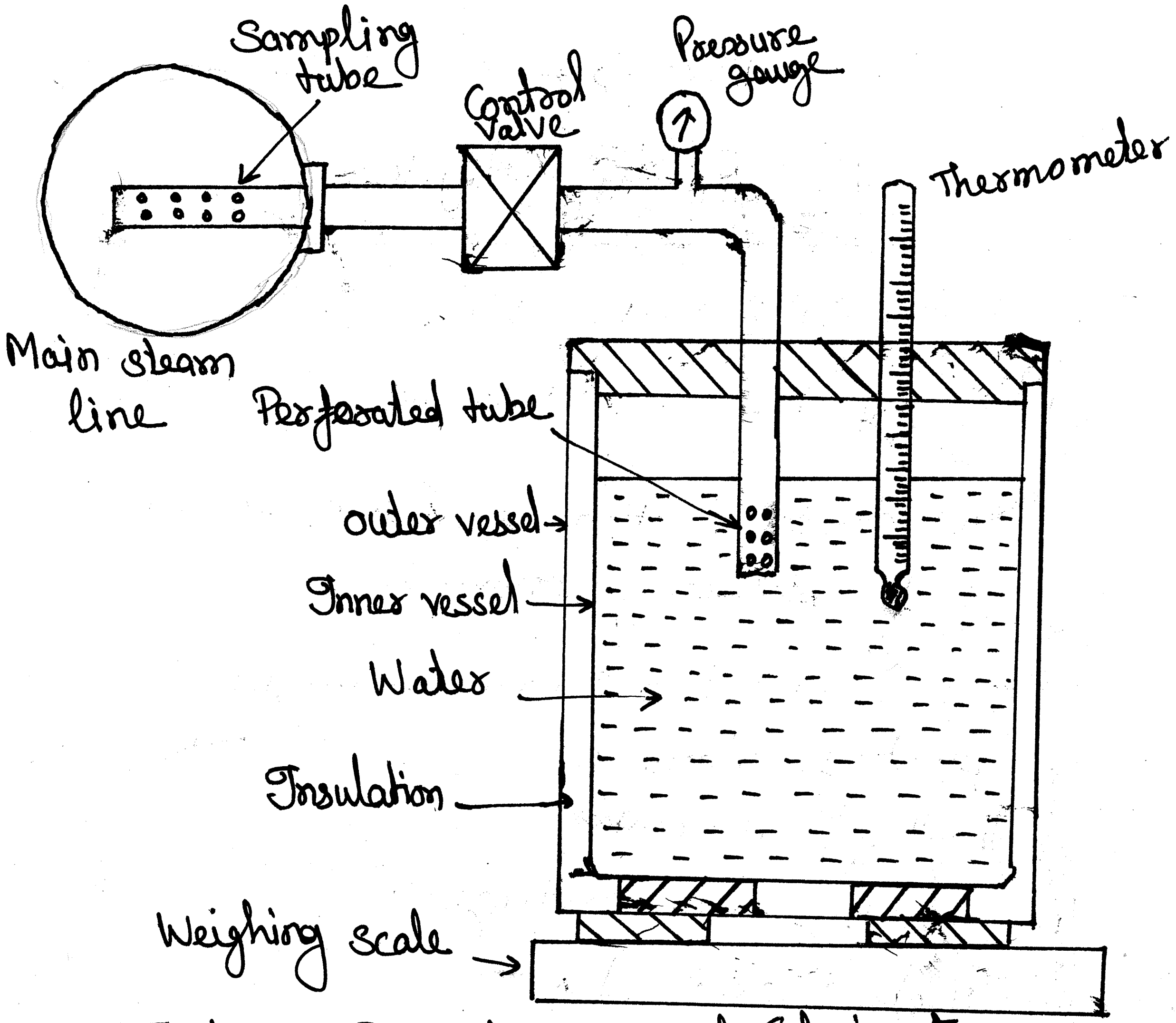
1. Tank or Bucket or Barrel Calorimeter.
2. Sperating calorimeter
3. Throttling calorimeter
4. Seperating and throttling calorimeter
5. Electric calorimeter

1. Tank or Bucket or Barrel Calorimeter :-

The dryness fraction of steam can be found with the help of tank calorimeter as follows.

A known mass of steam is passed through a known mass of water and steam is completly condensed. The heat lost by the steam is equated to heat gained by the water.

The following figure shows the arrangement of this calorimeter.



Tank or Bucket or Barrel Calorimeter.

The steam is passed through the sampling tube into the bucket calorimeter containing a known mass of water.

The weights of calorimeter with water before mixing with the steam and after mixing with the steam are obtained by weighing.

The temperature of water before and after mixing the steam are measured by mercury thermometer. The pressure of steam passed through the sampling tube is measured with the help of pressure gauge.

The heat lost by the steam = The heat gained by the water.

$$m_s . x h_{fg} + m_s . C_{p_s} (T_s - T_2) = m_w . C_{p_w} (T_2 - T_1) + m_c . C_{p_c} . (T_2 - T_1)$$

where

m_s - mass of the steam. (kg)
x - dryness fraction of the steam
h_{fg} - latent heat of steam (kJ)
C_{p_s} - Specific heat capacity of steam (kJ/kg.k)
T_s - Saturation ~~temperature~~ (k)
T_2 - temperature of water after mixing. (k)
T_1 - temperature of water before mixing. (k)
m_w - mass of water (kg)
C_{p_w} - Specific heat capacity of water (kJ/kg.k)
m_c - mass of calorimeter (kg)
C_{p_c} - Specific heat capacity of calorimeter (kJ/kg.k)

By solving the above equation we can find the value of dryness fraction.

Limitations :-

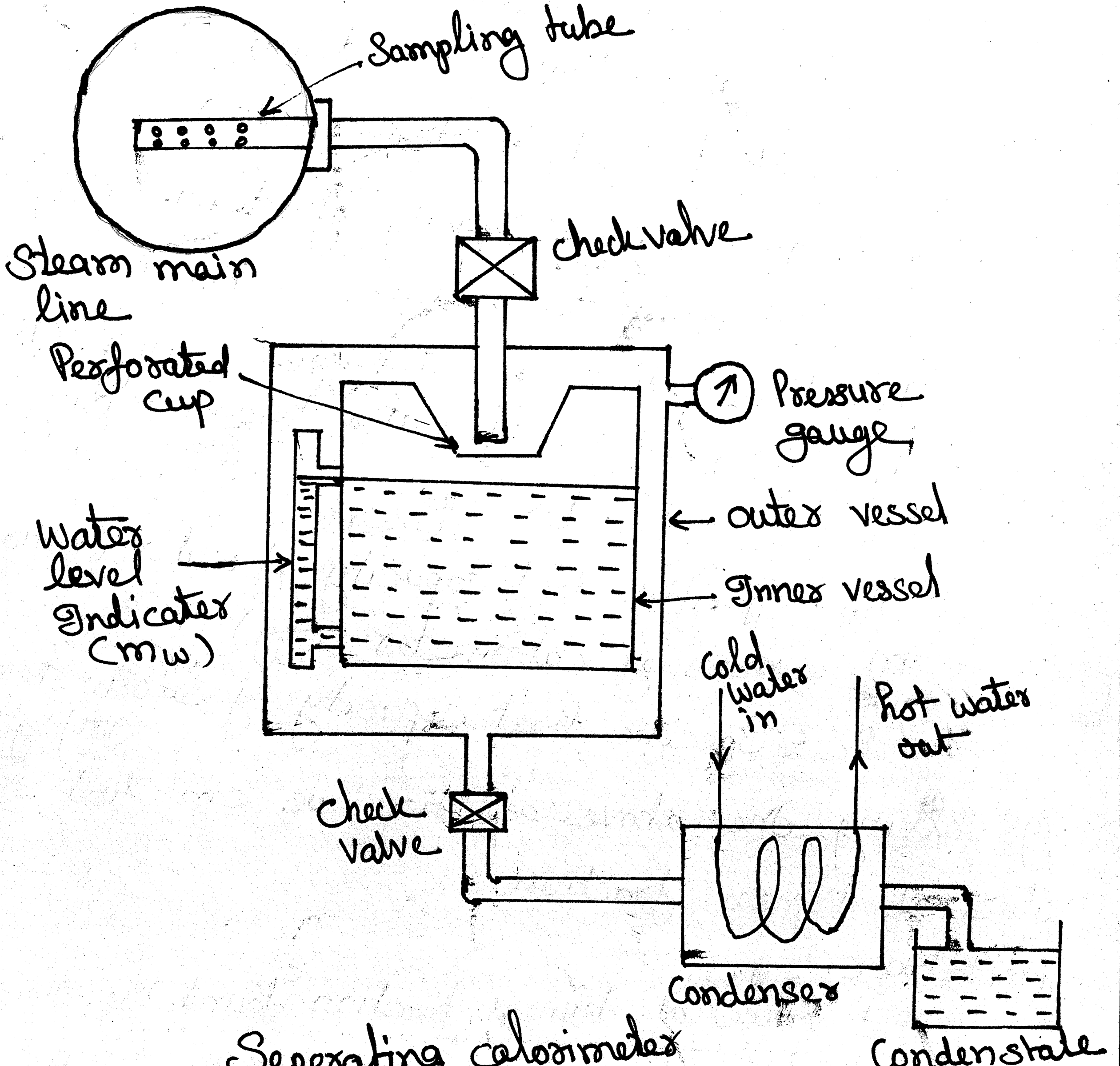
1. The value of dryness fraction found by this method involves some inaccuracy since

losses due to convection and radiation are not taken into account.

The calculated value of dryness fraction neglecting losses is always less than the actual value of dryness.

2. Seperating Calorimeter:-

This calorimeter is used to measure the dryness fraction of steam which is more wet.



Seperating calorimeter

The steam is passed through the sampling tube to the seperating calorimeter. The incoming steam will strike the perforated cup of the calorimeter where due to inertia of steam the heavier water particles in the wetsteam will settle at the perforated cup area and the water will be collected in the inner vessel. The increase in water level can be measured by the water level indicator. The remaing drysteam will pass around the inner vessel and they are allowed to go through a condenser where it losses the heat to the incoming cold water and the condensated water is collected seperately. The pressure of the steam is measured by the pressure gauge provided in the calorimeter.

The dryness fraction is measured by

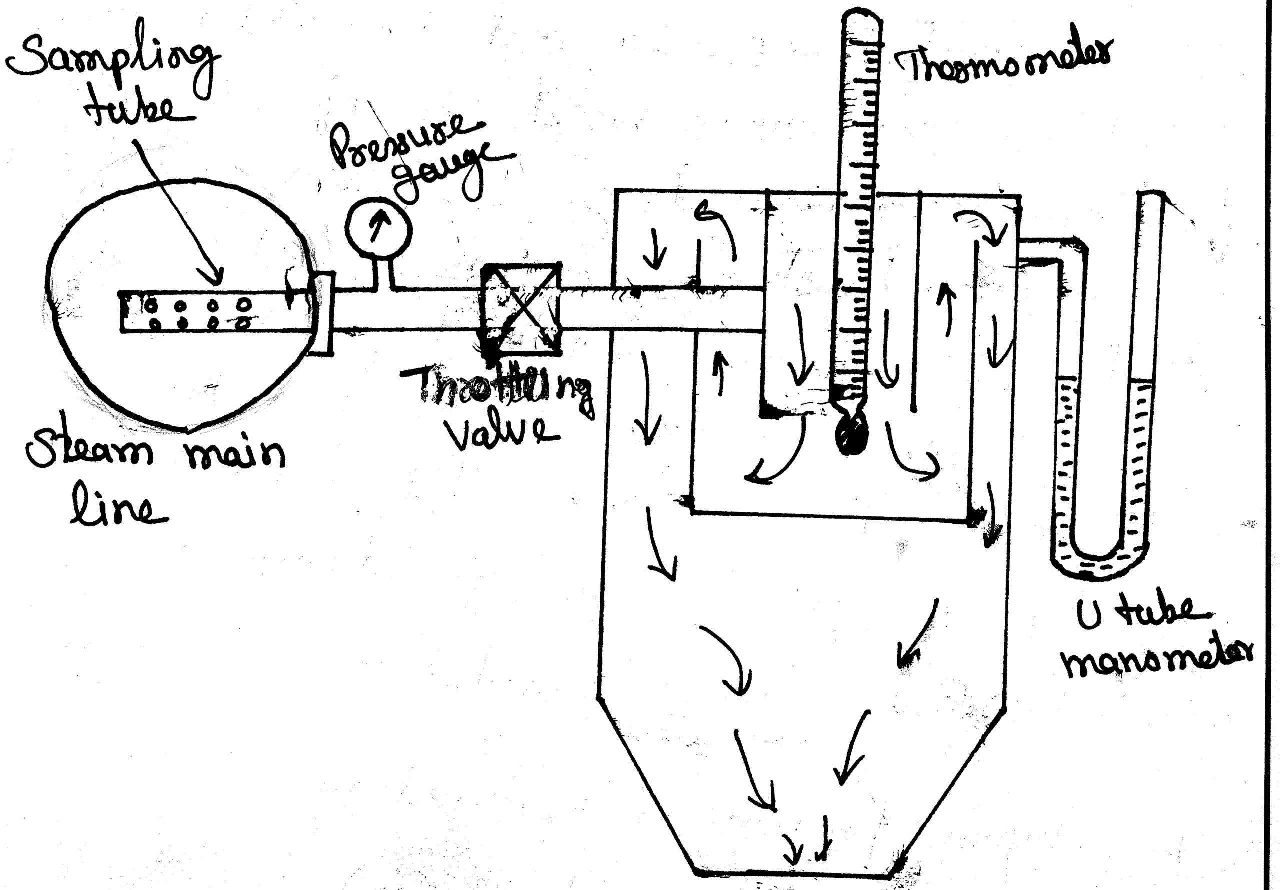
$$x = \frac{\text{mass of steam } (m_s)}{\text{mass of steam } (m_s) + \text{mass of water } (m_w)}$$

Limitations:-

In this method the steam leaving the vessel may carry some water particles along with the steam. So the dryness fraction measured is actually less than what is found out.

3. Throttling calorimeter:-

The dryness fraction of wet steam can be determined by using a throttling calorimeter which is illustrated diagrammatically as follows.



Throttling calorimeter

The steam to be sampled is taken from the pipe by means of suitable positioned and dimensioned sampling tube. It passes into an insulated container and is throttled through an orifice to atmospheric pressure. During the throttling process the enthalpy of the steam remains constant. The throttling process is shown on a h-s diagram by the line

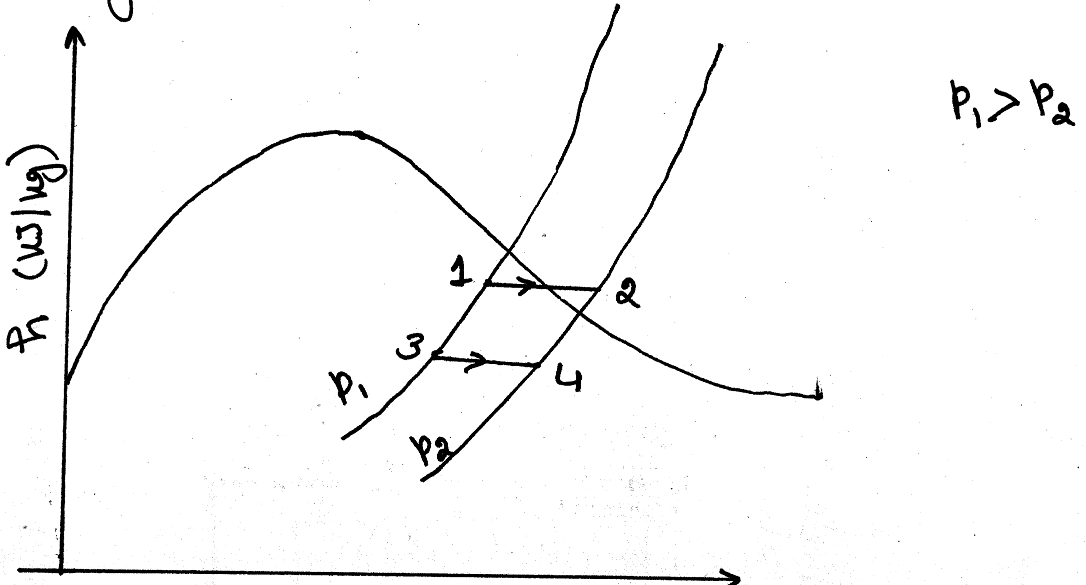
1-2. If steam initially wet is throttled through a sufficiently large pressure drop, then the steam at state 2 will becomes super heated. State 2 can then be defined by the measured pressure and temperature.

For an isenthalpic process $h_1 = h_2$

$h_1 = h_{f_1} + x h_{fg_1}$ at pressure p_1.

$h_2 = h_g + m C_{p_s} (T_{sup} - T_{sat})$

Hence the dryness fraction is determined and state 1 is defined.

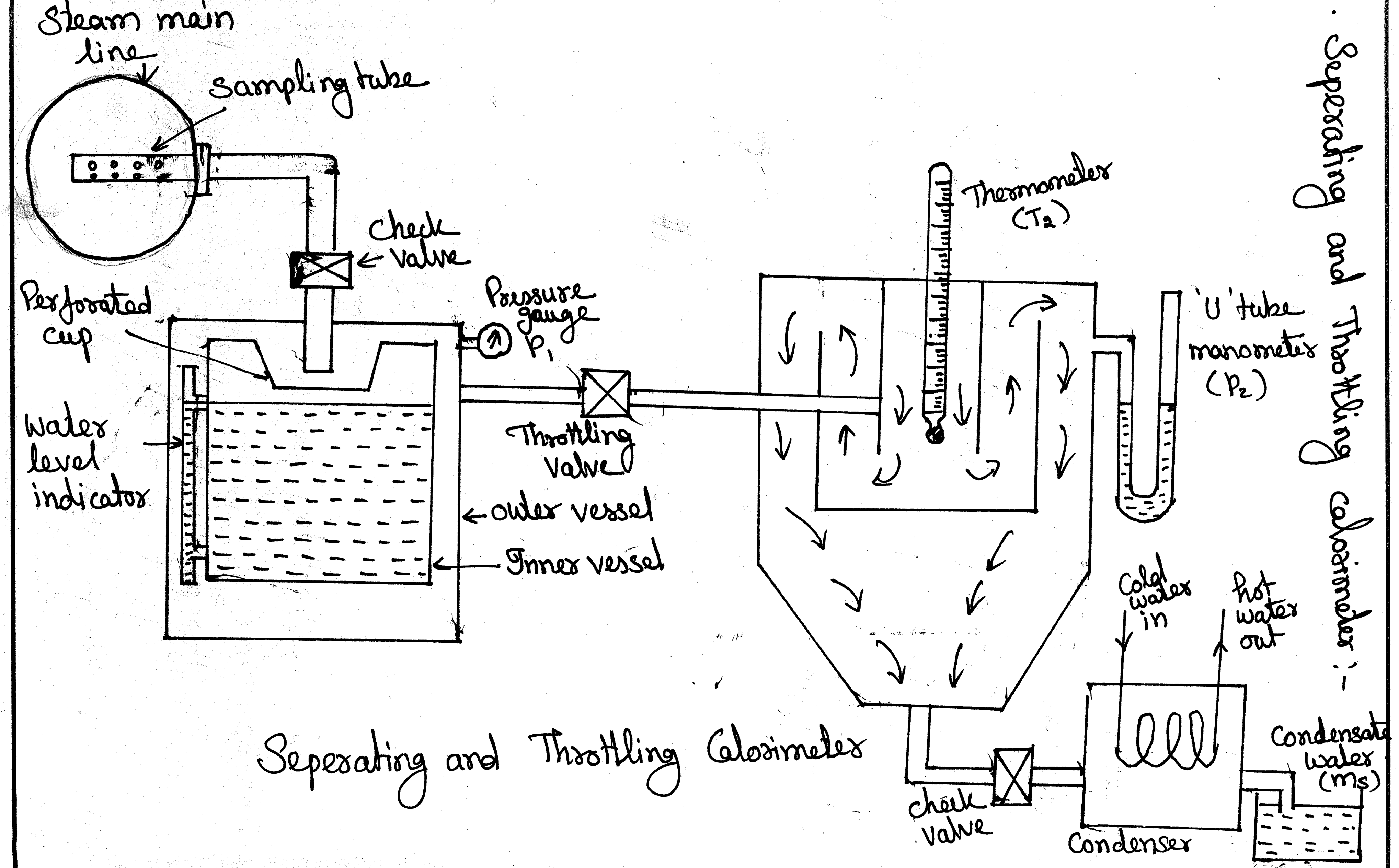


Throttling process.

Limitations:-

In this process the steam having more wet, the dryness fraction cannot be determined. Since after throttling process it still remains in the wet region.

4. Seperating and Throttling calorimeter :-



Seperating and Throttling Calorimeter

If the steam whose dryness fraction is to be determined is very wet than throttling to atmospheric pressure may not be sufficient to ensure superheated steam at exit. In this case it is necessary to dry the steam partially, before throttling. This is done by passing the steam sample from the main through a seperating calorimeter. The steam is made to change direction suddenly, and the water, being denser than the dry steam is seperated out. The quantity of water which is seperated out (m_w) is measured at the seperator, the steam remaining, which now has a higher dryness fraction, is passed through the throttling calorimeter. With combained seperating and throttling calorimeter, it is necessary to condense the steam after throttling and measure the amount of condensate (m_s). If a throttling calorimeter only is sufficient, there is no need to measure condensate, the pressure and temperature measurements at exit being sufficient. Dryness fraction at 2 is x_2, therefore, the mass of dry steam leaving the seperating calorimeter is equal to $x_2 m_s$ and this must be the mass of dry vapour in the sample drawn from the main at state 1.

Hence fraction in main, $x_1 = \frac{\text{Mass of dry vapour}}{\text{Total mass}}$

$$x_1 = \frac{x_2 . m_s}{m_s + m_w}$$

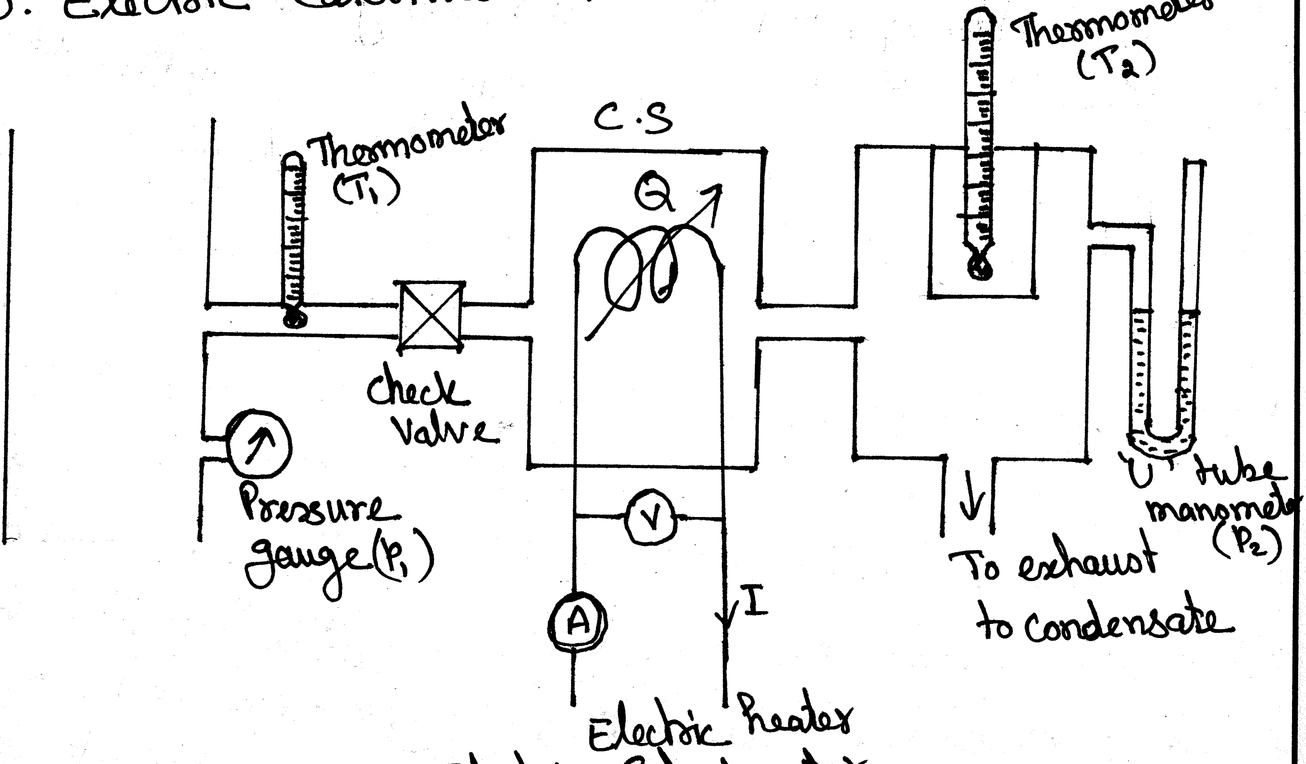
The dryness fraction x_2, can be determined as follows.

$$h_3 = h_2 = h_{f_2} + x_2 h_{fg_2} \text{ at } p_2 .$$

$$h_3 = h_{g_3} + C_{p_3}(T_{sup} - T_{sat}) \text{ at Pressure } P_3$$

The values of h_{f_2} and h_{fg_2} are read from steam tables at pressure p_2. The pressure in the seperator is small so that p_1 is approximately equal to p_2.

5. Electric Calorimeter :-



Electric Calorimeter

An electric calorimeter can be used to measure the dryness fraction of the steam. Here a portion of steam is led into the sampling tube. The pressure (P_1) and the temperature (T_1) of the steam are measured. Then the steam is sent to a electric heater, where the wet steam is converted into superheated steam by the electric coil. The heat

The heat supplied (Q) is calculated by $VI \times 10^{-3}$ kW. The pressure and temperature of super heated steam is measured at the final stage. The steam is then led into the atmosphere.

To calculate the dryness fraction the energy balance is applied at electric heater.

$$m h_1 + Q = m h_2$$

where $h_1 = h_{f_1} + x h_{fg_1}$ at pressure P_1

$Q = VI \times 10^{-3}$ kW

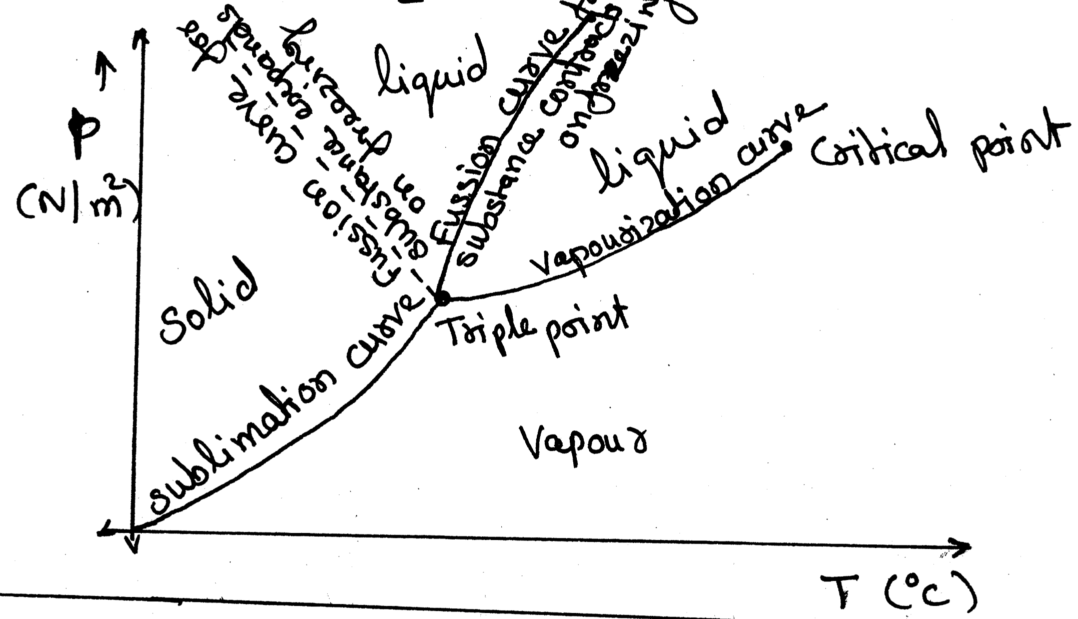
$h_2 = h_{g_2} + C_{P_S}(T_{sup} - T_{sat})$ at pressure P_2.

Thus the dryness fraction of the steam can be determined.

Unit - IV PROPERTIES OF PURE SUBSTACES

TWO MARK QUESTIONS AND ANSWERS

1. Draw a P-T (pressure - Temperature) diagram for a pure substance [June - 14]



2. State the phase rule for pure substance [May - 16]

The number of independent variables associated with a multi-component, multiphase system is given by the phase rule. It is also called as Gibb's phase rule. It is expressed by the equation as

$$n = C - \varphi + 2$$

where

n - number of independent variables or degree of freedom.

C - number of components

φ - number of phase present in the equillibrium.

3. Difference between Saturated liquid and compressed liquid [Dec-17]

A liquid which is about to vapourize is called as saturated liquid. A small amount of heat addition will cause the liquid to vapourize.

A liquid which is below the saturation temperature ~~or~~ saturation pressure are called as sub-cooled liquid or compressed liquid.

---

4. Define dryness and wetness fraction. [May-18]

Dryness fraction :-

It is defined as the ratio of the mass of steam actually present to the total mass of mixture of steam.

$$\text{Dryness fraction } x = \frac{\text{mass of steam}}{\text{Total mass of mixture}} = \frac{m_s}{m_f + m_s}$$

Wetness fraction :-

It is defined as the ratio of the mass of the water particle present to the total mass of the mixture of steam.

$$\text{Wetness fraction} = \frac{\text{Mass of water particle}}{\text{Total mass of mixture}} = \frac{m_f}{m_f + m_s}$$

---

5. What are compressed solids and compressed liquids? [May-19, May-17]

If a solid lies in the region, below the Saturation temperature of solid then it is Called compressed solids.

If a liquid lies in the region below the saturation temperature or saturation pressure of the liquid, then it is called sub cooled liquid or compressed liquid or unsaturated liquid.

6. Is iced water pure substance? why? [Dec-19, Dec-16]

Iced water is a pure substance. It is a mixture of both solid and liquid phase but it is having uniform chemical composition through out the mixture.

7. What is critical condition of steam [Dec-18]

At critical condition of steam the liquid and vapour phases are indistingushable. ie the liquid is directly converted into vapour.

For steam Critical pressure is 22.12 MPa

Critical temperature is 647.14K

8. A vessel of 2 m³ contains wet steam of quality 0.8 at 210°C. Determine the mass of the liquid and vapour present in the vessel. [Dec-19, Dec-16]

Given data:-

$V = 2\,m^3$ $T = 210°C$

$x = 0.8$

To find:-

$m_f = ?$

$m_s = ?$

from saturated water table (~~pr~~ temperature scale) at 210°c

$$v_f = 0.001172 \ m^3/kg \ , \ v_g = 0.104240 \ m^3/kg$$

Specific volume of wet steam $v_{wet} = x v_g$

$$v_{wet} = 0.8 \times 0.104240 = 0.083392 \ m^3/kg$$

mass of wet steam $m_s = \frac{V}{v_s} = \frac{2}{0.083392} = 23.98 kg$

dryness fraction $x = \frac{m_s}{m_s + m_f} = \frac{1}{1 + \frac{m_f}{m_s}} = 0.8$

$$1 + \frac{m_f}{m_s} = \frac{1}{0.8} = 1.25 \Rightarrow \frac{m_f}{m_s} = 1.25 - 1 = 0.25$$

$$m_f = 0.25 m_s = 0.25 \times 23.98 \ kg = 5.995 \ kg$$

Ans:-

$m_s = 23.98 \ kg$

$m_f = 5.995 \ kg$

---

9. What is triple point? For a pure substance how many degree of freedom are there at triple point? [Dec-19, Dec-16]

Triple point :-

Triple point is a state at which all three phases ie solid, liquid and vapour coexist in equillibrium.

Degree of freedom $n = C - \varphi + 2$

where

n - degree of freedom

C - no. of components

φ - no. of phase

For puresubstance no. of components $C = 1$

~~At~~ triple point no. of phase $\phi = 3$

$$n = 1 - 3 + 2 = 0$$

$$\boxed{n = 0}$$

At triple point the degree of freedom is zero.

10. List the advantages of super heated steam. [May-19]

1. Super heated steam has more heat energy and more work can be obtained using it.
2. Thermal efficiency increases as the temperature of super heated steam is high.

11. Write short note on Mollier chart. [May-19]

An enthalpy - entropy (H-S) chart also knowns as mollier diagram, plots the total heat against the entropy. The specific enthalpy, specific entropy, specific volume and dryness fraction can be directly obtained from the chart for a particular pressure and temperature.

12. What is latent heat of evapourization [Dec-19]

The amount of heat added during heating of water from boiling point to dry saturated state is called as latenent heat of vaporisation or enthalpy of vaporisation or latent heat of steam.

13. What is critical condition in phase change in thermodynamics? [May-21]

It represents the highest pressure and temperature at which the liquid and vapour phases co-exeist in equillibrium. At the critical point the liquid and vapour phases are indistinguishable ie, liquid is directly converted into vapour.

14. What is pure substance? Give example

Pure substance is a substance which has a fixed chemical composition throughout its mass. It may be single or compound or a mixture of various elements. As long as it has a uniform chemical composition and homogeneous we can call it as pure substance.

Example :- Water, carbon dioxide, air.

8/12/22