



The Pressure-Volume Diagram:-

$ABC D \equiv$ Isothermal Line

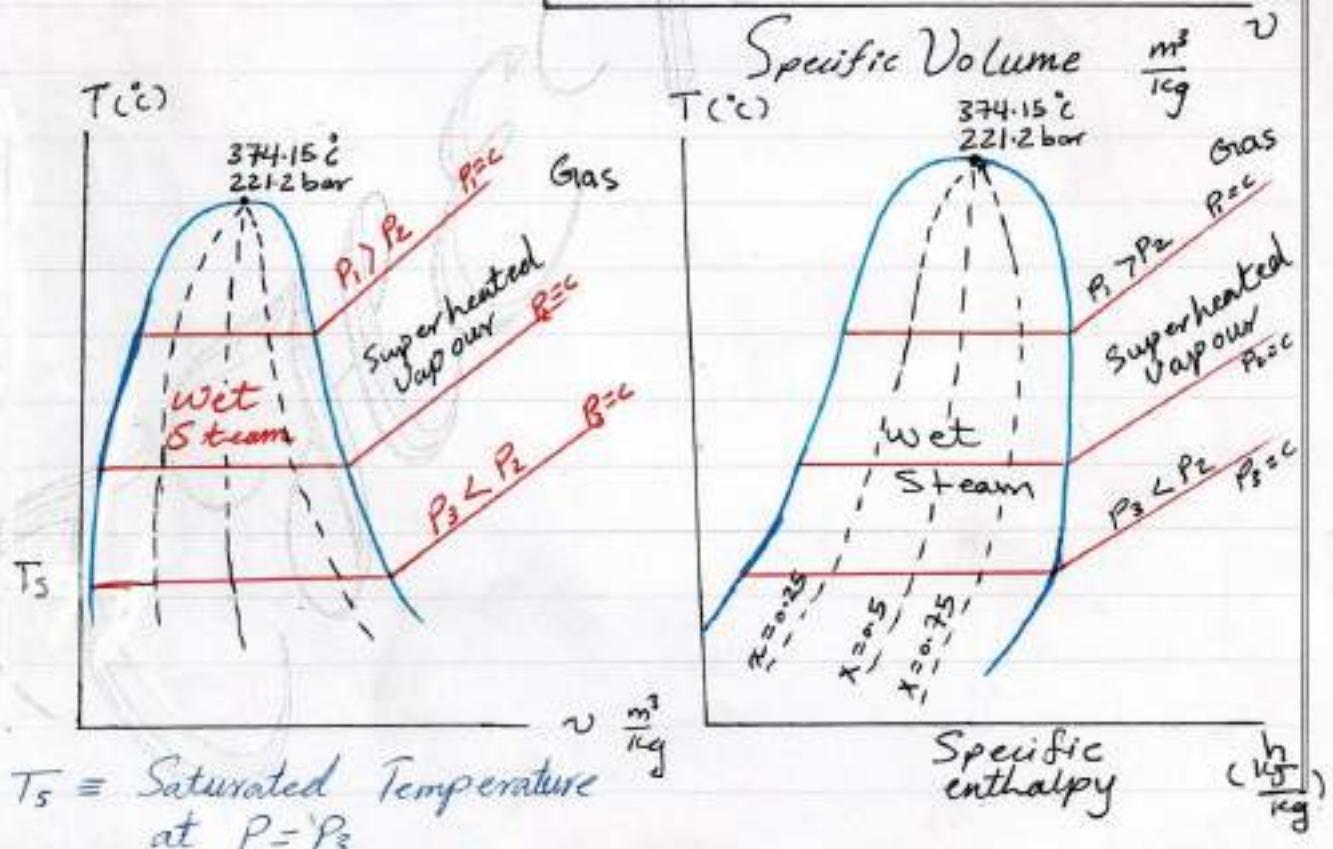
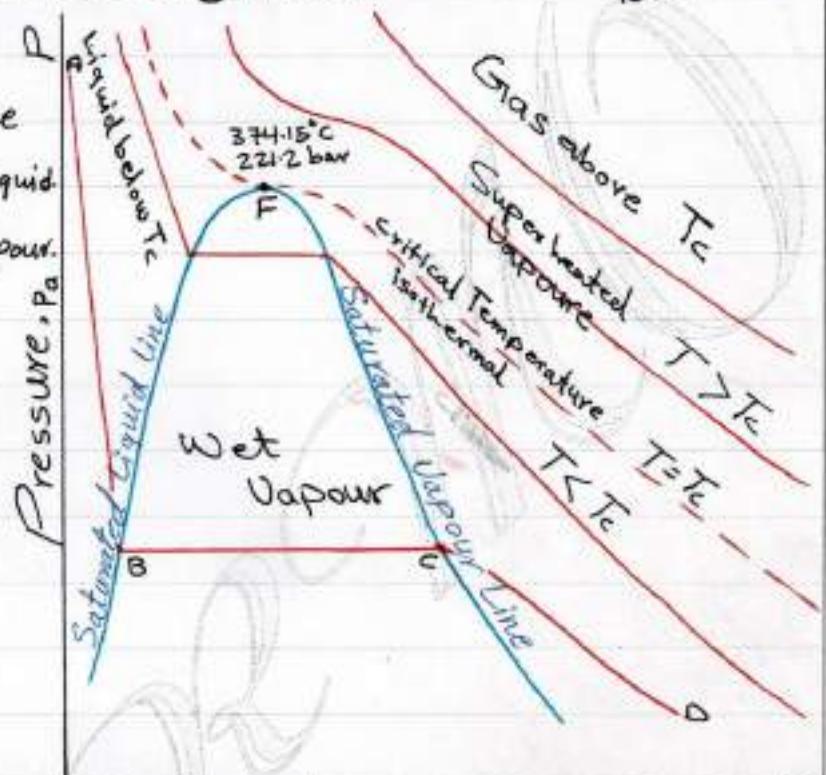
Point $B \equiv$ Saturated liquid

" $C \equiv$ " Vapour.

" $F \equiv$ Critical point

Note:

Area under curve (or line) represent the magnitude of work.





* Reversible and Irreversible Processes :

1. Closed System (Reversible)

a. Constant volume process (Isometric process)

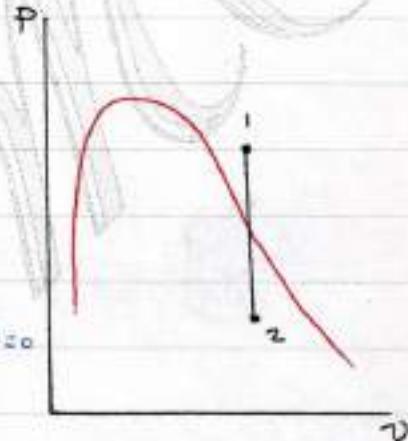
From non-flow Energy Equation:

$$Q = W + \Delta U$$

Per unit mass

$$q = w + \Delta u \quad , \quad u = c \Rightarrow w = 0$$

$$\therefore q = u_2 - u_1 \quad , \quad h = u + Pv$$



$$\therefore q = (u_2 - u_1) - v(P_2 - P_1)$$

heat
added or rejected

Ex: A vessel having a volume of 5 m^3 contains 0.05 m^3 of Saturated Liquid water and 4.95 m^3 of Saturated water vapour at 0.1 MPa . Heat is transferred until the vessel is fitted with saturated vapour. Determine the heat transfer for this process.

Sol: condition (1) wet Steam

$$\text{at } 0.1\text{ MPa} \quad v_f = 1.0432 \times 10^{-3} \text{ m}^3/\text{kg}$$

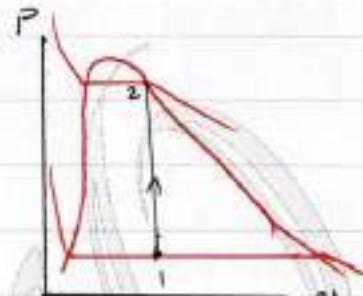
$$v_g = 1.694 \text{ m}^3/\text{kg}$$



$$m_L = V_L / \nu_f = 0.05 / 1.043 \times 10^{-3} = 47.93 \text{ kg}$$

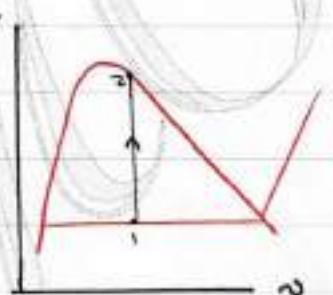
$$m_g = V_g / \nu_g = 4.95 / 1.694 = 2.92 \text{ kg}$$

$$m_t = m_L + m_g = 47.93 + 2.92 = 50.85 \text{ kg}$$



$$x = m_g / m_t = 2.92 / 50.85 = 0.0574$$

$$\begin{aligned} Q &= W + \Delta U , \quad V = C \quad \therefore W = 0 \\ &= U_2 - U_1 = m(U_2 - U_1) \end{aligned}$$



$$U_1 = U_f + x U_{fg} = 417.36 + 0.0574 \times 2088.7 = 521.8 \frac{\text{kJ}}{\text{kg}}$$

$$U_1 = \frac{V}{m} = \frac{5}{50.85} = 0.09833 \text{ m}^3 / \text{kg} \quad , \quad U_1 = U_2 = 0.09833 = U_g$$

from Steam tables:

$$\text{By Interpolation, } U_2 = 2600.465 \frac{\text{kg}}{\text{kg}} \quad \frac{U_g}{0.09963} \quad \frac{U_g}{2600.26}$$

$$\begin{aligned} \therefore Q &= 50.85(2600.465 - 521.8) \\ &= 105700.1 \text{ kJ} \quad (0.09833) \quad U_2 \\ & \qquad \qquad \qquad 0.08875 \quad 2601.98 \end{aligned}$$

when (C_v) is given:

$$Q = m C_v (T_2 - T_1)$$

for Sensible Heat
 (for gas)



Ex: A closed vessel of 0.6 m^3 capacity contains dry Saturated Steam at 360 kNm^{-2} . The vessel is cooled until the pressure is reduced to 200 kNm^{-2} . Calculate:
 a. the mass of Steam in the vessel,
 b. the final dryness of the Steam.
 c. the amount of heat transferred during the cooling process.

Sol:

a. At 360 kNm^{-2} , $v_g = 0.510 \text{ m}^3/\text{kg}$

\therefore mass of Steam in vessel $= \frac{0.6}{0.51} = 1.18 \text{ kg}$

b. $V = c$, $v_2 = v_g = 0.510 \text{ m}^3/\text{kg}$, $v_f \approx 0$

$v_2 = x v_g$, at $P = 200 \text{ kNm}^{-2}$ $v_g = 0.885 \text{ m}^3/\text{kg}$

$0.510 = x \cdot 0.885 \Rightarrow x = 0.510 / 0.885 = 0.576$

c. $Q = m(u_2 - u_1)$, $V = c \Rightarrow w = 0$

$u_1 = u_g$ at $P = 360 \text{ kNm}^{-2}$

from Steam tables, $u_g = 2549.87$ (By Interpolation)

$u_2 = u_f + x u_{fg}$

from Steam tables, $u_f = 504.47 \text{ J/g/kg}$, $u_{fg} = 2025.02 \text{ J/g}$

$u_2 = 504.47 + 0.576 * 2025.02$

$= 1670.88 \text{ J/g/kg}$

$\therefore Q = 1.18 * (1670.88 - 2549.87)$

$= -1037.2 \text{ kJ}$

100



b. Constant Pressure Process (Isobaric Process)

from NFEF

$$Q = W + \Delta U$$

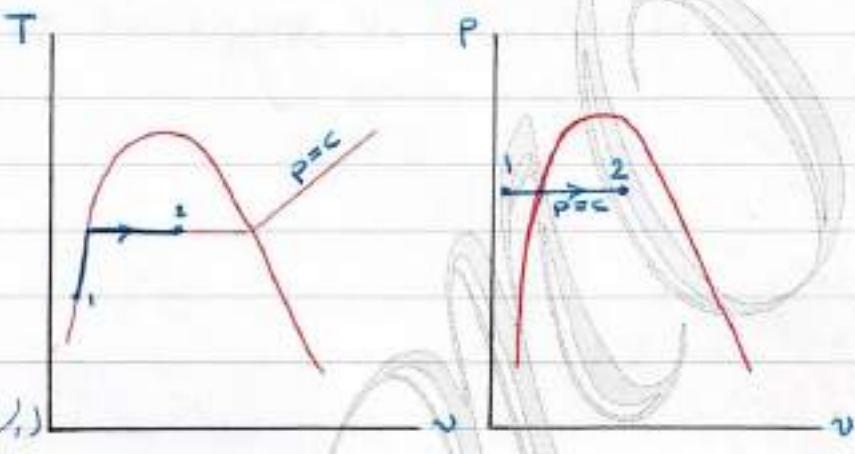
$$W = SpdV$$

$$= P(V_2 - V_1)$$

$$Q = (P_2 V_2 - P_1 V_1) + (U_2 - U_1)$$

$$= H_2 - H_1 \Rightarrow$$

$$Q = m(h_2 - h_1)$$



When C_p is given (for Sensible Heat) (for gas)

$$Q = m C_p(T_2 - T_1)$$

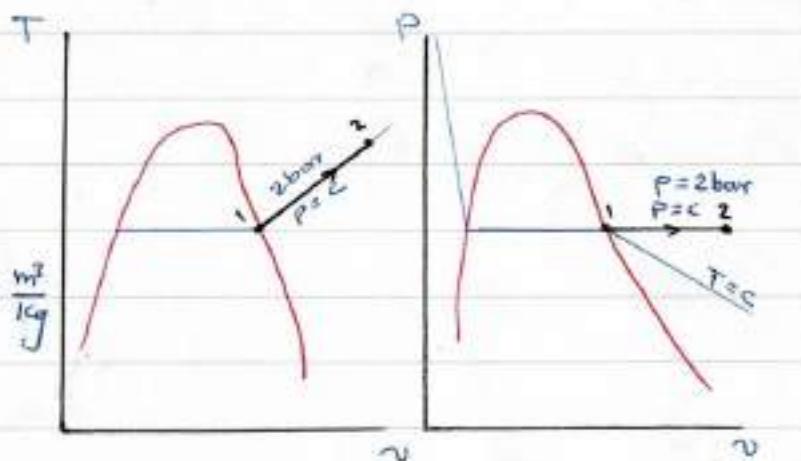
Ex: 0.05 kg of a dry Saturated Steam is heated at a constant pressure of 2 bar until the volume occupied is 0.0658 m³. Calculate the heat supplied and the work done.

Sol:

$$h_1 = h_g \text{ at } 2 \text{ bar}$$

$$= 2707 \text{ kJ/kg}$$

$$V_2 = \frac{V}{m} = \frac{0.0658}{0.05} = 1.316 \frac{\text{m}^3}{\text{kg}}$$





the Steam is Superheated, from Steam tables
 at 2 bar & $1.316 \frac{m^3}{kg}$ $\Rightarrow h_2 = 3072 \text{ kJ/kg}$

$$Q = h_2 - h_1 = m(h_2 - h_1) = 0.05(3072 - 2707)$$

\therefore Heat Applied = 18.25 kJ/kg

$$W = p(v_2 - v_1), \quad v_1 = v_g \text{ at } 2 \text{ bar} = 0.8856 \frac{m^3}{kg}$$

$$v_2 = 1.316 \frac{m^3}{kg}$$

$$W = 2 \times 10^5 (1.316 - 0.8856)$$

$$W = m \cdot W = 0.05 \times 2 \times 10^5 \times 0.4304$$

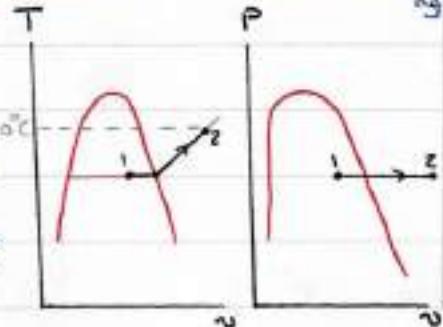
$$= 4304 \text{ J} = 4.304 \text{ kJ}$$

Ex 10 Steam at 4 MPa and dryness fraction 0.95 receives heat at constant pressure until its temperature becomes 350°C . Determine the heat received by the Steam per unit mass.

Sol 10 At $p = 4 \text{ MPa}$ and $x = 0.95$ dry, $h_1 = h_f + xh_{fg}$
 $h_1 = 1087.4 + 0.95 \times 1712.9 = 2714.7 \text{ kJ/kg}$

At $p = 4 \text{ MPa}$, from Steam tables $T_{sat} = 250.3^\circ\text{C}$
 $\therefore T > T_{sat} \Rightarrow$ Superheated Steam $\therefore h_2 = 3095 \frac{\text{kJ}}{\text{kg}}$

$$\begin{aligned} \text{Heat received} &= h_2 - h_1 \\ &= 3095 - 2714.7 \\ &= 380.3 \text{ kJ/kg} \end{aligned}$$





Ex 80 A cylinder fitted with a piston has a volume of 0.1 m^3 and contains 0.5 kg of Steam at 0.4 MPa . Heat is transfer to the steam until the temperature is 300°C . While the pressure remains constant. Determine the heat transfer and work done.

Sol 80

$$Q = W + \Delta U = m(h_2 - h_1)$$

$$V_1 = V/m = 0.1/0.5 = 0.2 \text{ m}^3/\text{kg}$$

$$\text{at } 0.4 \text{ MPa} \quad V_g = 0.4625 \text{ m}^3/\text{kg}$$

Since $V < V_g \Rightarrow$ wet Steam

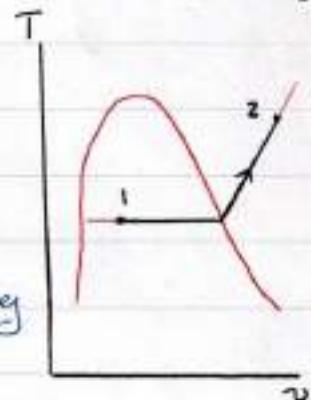
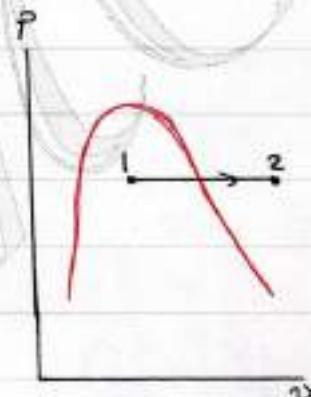
$$V = V_f + x V_{fg}$$

$$0.2 = 1.0836 \times 10^3 + x(0.4625 - 1.0836 \times 10^3)$$

$$x = 0.431$$

$$\therefore u_1 = u_f + x u_{fg} = 604.31 + 0.431 \times 1949.3 \\ = 1444.6 \text{ J/kg}$$

$$h_1 = 604.74 + 0.431 \times 2132.8 = 1524.6 \text{ J/kg}$$



Point 2, $P = 0.4 \text{ MPa}$ - from Steam tables

$T_2 = 143.63^\circ\text{C}$, since $T_2 > T_{sat} \Rightarrow$ Superheated
 from Superheated Steam tables, $u_2 = 2804.8 \text{ J/kg}$

$$h_2 = 3066.8 \text{ J/kg}$$

$$Q = 0.5(3066.8 - 1524.6) = 771.1 \text{ J}$$

$$W = Q - \Delta U = 771.1 - 0.5(2804.8 - 1444.6) \\ = 91 \text{ J}$$



c. Constant Temperature process (Isothermal Process)

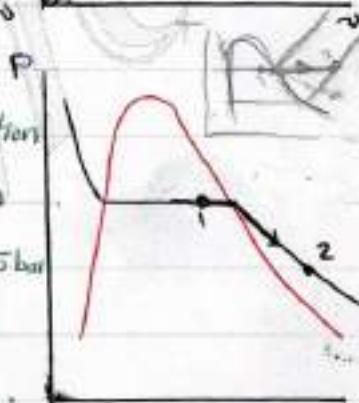
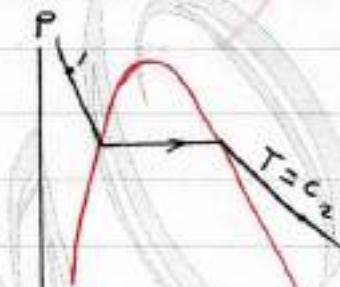
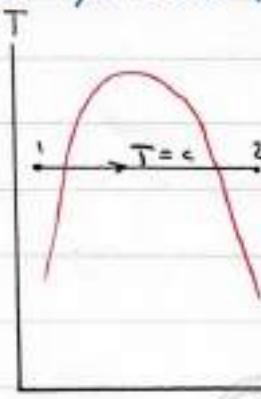
$$Q = W + \Delta U$$

$$W = P V \ln \frac{V_2}{V_1}$$

$$\Delta U = U_2 - U_1$$

$$Q = H_2 - H_1$$

$$W = Q - \Delta U$$



Ex-10: Steam at 7 bar and dryness fraction

- q expands in a cylinder behind a piston isothermally and reversibly to a pressure of 1.5 bar
- Calculate the change of internal energy and the change of enthalpy per kg of Steam.

The heat supplied during the process is found to be $400 \frac{\text{kJ}}{\text{kg}}$. Calculate the work done per kg of Steam.

Sol: $U_1 = U_f + x U_{fg}$ (at 7 bar) $\Rightarrow T_{sat} = 165^\circ\text{C}$
 $= 2385.3 \frac{\text{kJ}}{\text{kg}}$

from Steam tables (Superheated) at 1.5 bar at 165°C

$$U_2 = 2602.8 \frac{\text{kJ}}{\text{kg}} \rightarrow h_2 = 2803 \frac{\text{kJ}}{\text{kg}}$$

$$\therefore \Delta U = U_2 - U_1 = 2602.8 - 2385.3 = 217.5 \frac{\text{kJ}}{\text{kg}}$$

$$h_1 = h_f + x h_{fg} = 697 + 0.9 * 2067 = 2557.3 \frac{\text{kJ}}{\text{kg}}$$

$$\therefore \Delta h = h_2 - h_1 = 2803 - 2557.3 = 245.7 \frac{\text{kJ}}{\text{kg}}$$

$$Q = \Delta U + W \Rightarrow \therefore W = Q - \Delta U$$

$$= 400 - 217.5 = 182.5 \frac{\text{kJ}}{\text{kg}}$$



d. The hyperbolic Process $PV=C$

$$P_1 V_1 = P_2 V_2$$

$$\text{Work done} = W = PV \ln \frac{V_2}{V_1} \quad \text{for any mass}$$

$$W = Pv \ln \frac{V_2}{V_1} \quad \text{for unit mass}$$

the NFEE.

$$q = \Delta U + W$$

$$= (h_2 - u_1) + Pv \ln \frac{V_2}{V_1}$$

$$= (h_2 - PvV_2) - (h_1 - PvV_1) + Pv \ln \frac{V_2}{V_1}, \quad PvV_1 = PvV_2$$

$$= (h_2 - h_1) + Pv \ln \frac{V_2}{V_1}$$

$$\therefore Q = (H_2 - H_1) + PV \ln \frac{V_2}{V_1}$$

Ex: A quantity of dry saturated steam occupies 0.2634 m^3 at 1.5 MPa. Determine the final condition of the steam if it is compressed until the volume is halved:

a. If the compression is carried out in an isothermal manner:

b. \rightarrow follows the law $PV=C$.

SOL 80

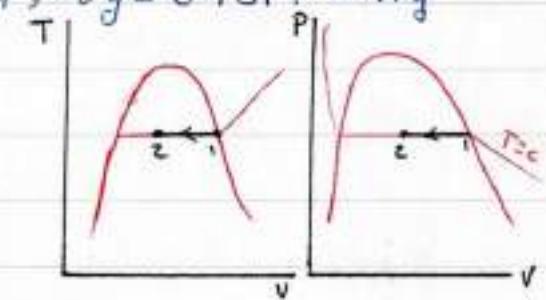
a. from Steam tables at 15 MPa, $v_g = 0.1317 \text{ m}^3/\text{kg}$

$$m = \frac{V}{v} = \frac{0.2634}{0.1317} = 2 \text{ kg}$$

When the volume is halved.

$$V_2 = \frac{V_1}{2} = \frac{0.1317}{2} = 0.0659 \text{ m}^3/\text{kg}$$

$$x = \frac{0.0659}{0.1317} = 0.5$$





In this case the steam is operating in the evaporation region, since the temperature remains constant.

$$h_2 = h_f + x h_{fg} \quad \text{from Steam tables at } P=15 \text{ MPa}$$

$$h_f = 844.7 \text{ kJ/kg}, h_{fg} = 1945.2 \text{ kJ/kg}$$

$$h_2 = 844.7 + 0.5 * 1945.2 = 1817.3 \text{ kJ/kg}$$

$$H_2 = m \cdot h_2 = 2 * 1817.3 = 3634.6 \text{ kJ}$$

$$\text{Heat loss} = 0.5 h_{fg} = 0.5 * 1945.2 = 972.6 \text{ kJ/kg}$$

for 2 kg, Heat loss = $2 * 972.6 = 1945.2 \text{ kJ}$

- b. If the compression is according to the law $PV=C$,
 then $P_1 V_1 = P_2 V_2$

$$\therefore P_2 = P_1 \cdot \frac{V_1}{V_2} = 1.5 * 2 = 3 \text{ MPa}$$

Specific volume after compression, $V_2 = \frac{V_1}{2} = \frac{V_g}{2} = 0.0659 \text{ m}^3/\text{kg}$
 from Steam tables,

$$\text{at } P_2 = 3 \text{ MPa}, V_g = 0.0666 \text{ m}^3/\text{kg}, h_f = 1008.4 \text{ kJ/kg}$$

$$V_2 < V_g \Rightarrow \text{Wet Steam} \quad h_{fg} = 1793.9 \text{ kJ/kg}$$

$$x = \frac{V_2}{V_g} = \frac{0.0659}{0.0666} = 0.989$$

$$h_2 = h_f + x h_{fg} = 1008.4 + 0.989 * 1793.9 = 2782.6 \text{ kJ/kg}$$

$$H_2 = m \cdot h_2 = 2 * 2782.6 = 5565.2 \text{ kJ}$$



Ex: 1 kg of water at 30 bar, 300°C. expand reversibly to 0.75 bar. Calculate the heat flow and the work done when the process is hyperbolic.

Sol:

$$\text{at } P = 30 \text{ bar}, T_s = 233.9^\circ\text{C}, T_i = 300^\circ\text{C}$$

since $T_i > T_{sat} \Rightarrow$ Superheated Steam
 from Steam tables at 30 bar & 300°C

$$v_1 = 0.08119 \text{ m}^3/\text{kg}, u_1 = 2750.1 \text{ kJ/kg}$$

$$P_1 v_1 = P_2 v_2 \Rightarrow v_2 = \frac{P_1}{P_2} \cdot v_1 = \frac{30}{0.75} * 0.08119 \\ = 3.243 \text{ m}^3/\text{kg}$$

$$\text{at } P = 0.75 \text{ bar}, v_g = 2.21711 \text{ m}^3/\text{kg}$$

$\therefore v_2 > v_g \Rightarrow$ Superheated Steam
 at 0.75 bar & 3.243 from Superheated Steam tables

$$h_2 = 2986.3 \text{ kJ/kg}, u_2 = 2742.9 \text{ kJ/kg}$$

$$W = P_1 v_1 \ln \frac{v_2}{v_1} = 30 * 10^5 * 0.08119 \ln \frac{3.243}{0.08119} \\ = 897.9 \text{ kJ/kg}$$

$$W = m \cdot W = 1 * 897.9 = 897.9 \text{ kJ}$$

$$\Delta U = m(u_2 - u_1) = 1 * (2742.9 - 2750.1) \\ = -7.21 \text{ kJ}$$

$$Q = W + \Delta U = 897.9 - 7.21 \\ = 890.68 \text{ kJ}$$



e. The Polytropic Process $PV^n = C$

Here the steam is assumed to be expanded or compressed according to the law $PV^n = C$.

$$Q = W + \Delta U \quad , \quad W = \frac{P_1 V_1 - P_2 V_2}{n-1}$$

$$\dot{Q} = W + \Delta U$$

$$\begin{aligned} \Delta U &= U_2 - U_1 = (h_2 - P_2 V_2) - (h_1 - P_1 V_1) \\ &= (h_2 - h_1) - (P_2 V_2 - P_1 V_1) \end{aligned}$$

$$\dot{Q} = \frac{P_1 V_1 - P_2 V_2}{n-1} + (h_2 - h_1) - (P_2 V_2 - P_1 V_1)$$

$$= (h_2 - h_1) + \frac{P_1 V_1 - P_2 V_2}{n-1} + (P_1 V_1 - P_2 V_2)$$

$$= (h_2 - h_1) + (P_1 V_1 - P_2 V_2)(1 + n-1/n-1)$$

$$= (h_2 - h_1) + n \cdot \frac{P_1 V_1 - P_2 V_2}{n-1}$$

$$\therefore \boxed{\dot{Q} = (h_2 - h_1) + n \cdot W} \quad \text{---*}$$

$$Q = (H_2 - H_1) + n \cdot W$$



Ex 80 A quantity of Steam at a pressure of 2.1 MPa and 0.9 dry occupies a volume of 0.2562 m³. It is expanded according to the law $PV^{1.25} = C$, to a pressure of 0.7 MPa. Determine :

- the mass of Steam present,
- the external work done .
- the change of internal energy,
- the heat exchange between the Steam and surroundings.

Sol:

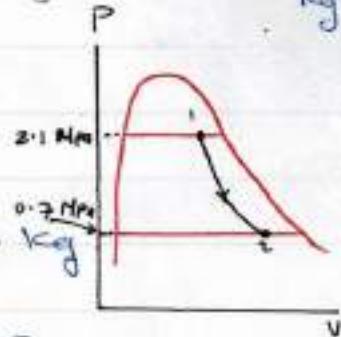
a. $v_1 = v_f + x_1 v_{fg}$, from Steam tables at 2.1 MPa

$$v_f = 1.181 \times 10^{-3}, v_g = 0.0949 \frac{m^3}{kg}$$

$$\therefore v_1 = 1.181 \times 10^{-3} + 0.9(0.0949 - 1.181 \times 10^{-3})$$

$$= 0.0856 \text{ m}^3/\text{kg}$$

$$v = V/m \Rightarrow m = \frac{V}{v} = \frac{0.2562}{0.0856} = 3 \text{ kg}$$



b. $A = W + \Delta U$, $W = P_1 V_1 - P_2 V_2 / m - 1$

$$P_1 V_2^{1.25} = P_2 V_1^{1.25} \Rightarrow V_2 = (P_1/P_2)^{1/1.25} * V_1$$

$$= (2.1/0.7)^{1/1.25} * 0.0856$$

$$= 0.206 \text{ m}^3/\text{kg}$$

$$W = \frac{2.1 \times 10^3 \times 0.0856 - 0.7 \times 10^3 \times 0.206}{1.25 - 1} = 143.36 \text{ J/g/kg}$$

$$W = m \cdot W = 3 * 143.36 = 430 \text{ J/kg}$$



c:

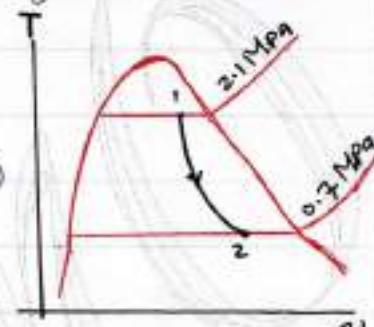
at $P = 0.7 \text{ MPa}$, $v_g = 0.273 \text{ m}^3/\text{kg}$, $v_f = 0.206$

$v_g > v_f \Rightarrow \text{wet Steam}$

$$v_2 = v_f + x v_{fg}$$

$$0.206 = 1.108 \times 10^{-3} + x_2(0.273 - 1.108 \times 10^{-3})$$

$$x_2 = 0.753$$



$$\therefore u_1 = u_f + x_1 u_{fg} = 917.5 + 0.9(2598.2 - 917.5) \\ = 2430 \text{ J/kg}$$

$$u_2 = u_f + x_2 u_{fg} = 696.3 + 0.753(2571.1 - 696.3) \\ = 2108 \text{ J/kg}$$

$$\Delta U = m(u_2 - u_1) = 3 * (2108 - 2430) = -966 \text{ J}$$

d.

$$Q = W + \Delta U = 430 - 966 = -536 \text{ J} \quad (\text{loss to the Surrounding})$$

Ex 10 In a steam engine the steam at the beginning of the expansion process is at 7 bar, dryness fraction 0.95, and the expansion follows the law $Pv^n = c$, down to a pressure of 0.34 bar. Calculate the work done per kg of steam during the expansion, and the heat flow per kg of steam to or from the cylinder walls during the expansion.

100

Sol: At 7 bar, $v_g = 0.2728 \text{ m}^3/\text{kg}$, $v_f \approx 0$
 $\therefore v_1 = x_1 v_g = 0.95 \times 0.2728 = 0.259 \text{ m}^3/\text{kg}$

$$\frac{P_1}{P_2} = \left(\frac{v_2}{v_1}\right)^n \Rightarrow v_2 = v_1 \left(\frac{P_1}{P_2}\right)^{\frac{1}{n}} = 0.259 \left(\frac{7}{0.34}\right)^{\frac{1}{1.1}}$$

$$\therefore v_2 = 4.05 \text{ m}^3/\text{kg}$$

$$W = \frac{P_1 v_1 - P_2 v_2}{n-1} = \frac{7 \times 10^5 \times 0.259 - 0.34 \times 10^5 \times 4.05}{1.1 - 1}$$

$$\therefore W = 436 \text{ kJ/kg}$$

At 0.34 bar, $v_g = 4.649 \text{ m}^3/\text{kg}$,
 $v_2 < v_g \Rightarrow$ Wet Steam
 $x_2 = \frac{v_2}{v_g} = \frac{4.05}{4.649} = 0.873$

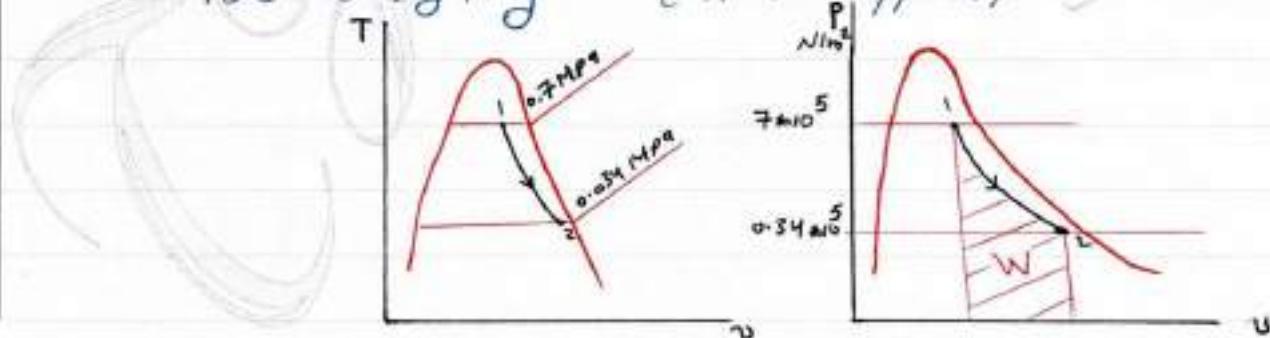
$$u_1 = u_f + x_1 u_{fg} = 696 + 0.95(2573 - 696) = 2476.8 \text{ kJ/kg}$$

$$u_2 = u_f + x_2 u_{fg} = 302 + 0.873(2472 - 302) = 2196.4 \text{ kJ/kg}$$

$$Q = \Delta U + W$$

$$= (2196.4 - 2476.8) + 436$$

$$= 155.6 \text{ kJ/kg} \quad (\text{Heat Supplied})$$





f. Adiabatic Process :

An adiabatic process is one in which no heat is transferred to or from the fluid during the process.

from NFEE,

$$Q = W + \Delta U \quad , \quad Q = 0$$

$$W = -\Delta U$$

$$W = U_1 - U_2$$

Per 1 kg, $W = u_1 - u_2$

Ex: 1 kg of Steam at 100 bar and 375°C expands reversibly in a perfectly insulated cylinder behind a piston until the pressure is 38 bar and the steam is then dry saturated. Calculate the work done by the system.

Sol:

$$Q = W + \Delta U \quad , \quad Q = 0 \quad (\text{perfectly insulated})$$

$$\therefore W = u_1 - u_2$$

at 100 bar, $t_s = 311^\circ\text{C}$, since $t > t_s \Rightarrow$ Superheated

$$\therefore u_1 = 2621.78 \text{ kJ/kg} \quad , \quad u_2 = u_g = 2608 \text{ kJ/kg}$$

$$W = m \cdot w$$

$$= m(u_2 - u_1)$$

$$= 1 \cdot (2608 - 2621.78)$$

$$= 13 \text{ kJ/kg}$$



Ex: 10 Determine the volume occupied by 2kg of Steam at 0.85 MPa and dryness fraction of 0.95.

If this Steam is expanded reversibly and adiabatically to 0.17 MPa, the law of expansion is $(PV^{1.13} = c)$. Determine the final dryness fraction and the change in internal energy during expansion.

Sol: 10

$$V_1 = V_f + x_1(v_g - v_f) \quad , \text{at } 0.85 \text{ MPa} \& x_1 = 0.95$$

$$= 1/18 \cdot 10^{-3} + 0.95(0.227) = 0.2167 \text{ m}^3/\text{kg}$$

$$V_1 = \frac{V}{m} \Rightarrow V_1 = V * m = 0.2167 * 2 = 0.4335 \text{ m}^3$$

$$P_1 V_1^{1.13} = P_2 V_2^{1.13} \Rightarrow V_2 = (0.85/0.17)^{1/1.13} * 0.2167$$

$$= 0.9 \text{ m}^3/\text{kg}$$

$$Q = W + \Delta U \Rightarrow Q = 0$$

$$W = m(U_2 - U_1) \quad \text{or} \quad U_2 - U_1 = -(P(V_1 - P_2 V_2)) / n - 1$$

$$U_1 = U_f + x_1 u_{fg} = 731.1 + 0.95(2577.1 - 731.1) = 2484.8 \text{ kJ/kg}$$

at $P_2 = 0.17 \text{ MPa}$, $v_g = 1.0312 \text{ m}^3/\text{kg}$, $V_2 = 0.9 \text{ m}^3/\text{kg}$
 $\Rightarrow V_2 < v_g \Rightarrow \text{wet steam}$

$$V_2 = V_f + x_2 v_{fg}$$

$$0.9 = 1.056 \cdot 10^{-3} + x_2 * (1.0312 - 1.056 \cdot 10^{-3}) \Rightarrow x_2 = 0.8717$$

$$U_2 = U_f + x_2 u_{fg} = 483.02 + 0.8717 * 2040.9$$

$$= 2262.1 \text{ kJ/kg}$$

$$W = 2 * (2484.8 - 2262.1)$$

$$= 445.26 \text{ kJ}$$



2. Irreversible Process ::

1. A diabatic mixing:

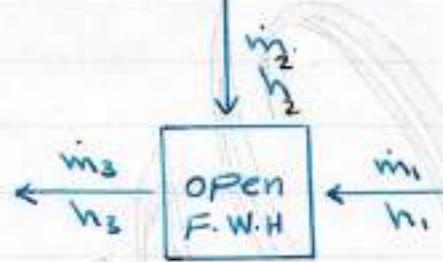
from flow equation

$$H_1 + H_2 = H_3$$

$$\dot{m}_1 h_1 + \dot{m}_2 h_2 = \dot{m}_3 h_3$$

$$\dot{m}_1 h_1 + \dot{m}_2 h_2 = (\dot{m}_1 + \dot{m}_2) h_3$$

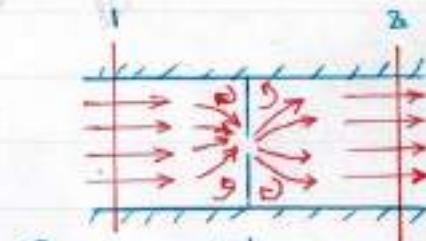
$$\dot{m}_1 \cdot C_p \cdot T_1 + \dot{m}_2 \cdot C_p \cdot T_2 = (\dot{m}_1 + \dot{m}_2) \cdot C_p s \cdot T_3$$



open feedwater heater

2. Throttling:

$$h_1 + \frac{C_1^2}{2} + q = h_2 + \frac{C_2^2}{2} + w$$



$$q = 0, w = 0,$$

$$h_1 + \frac{C_1^2}{2} = h_2 + \frac{C_2^2}, \quad C_1^2 - C_2^2/2 \approx 0$$

$$h_1 = h_2 \Rightarrow C_p T_1 = C_p T_2$$

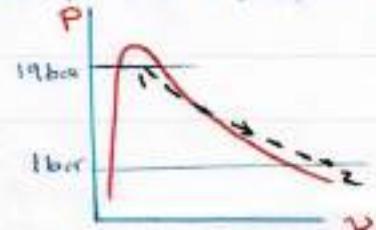
Ex: Steam at 19 bar is throttled to 1 bar and the temperature after throttling is found to be 150 °C. Calculate the initial dryness fraction of the steam.

Sol: from Steam tables, at 1 bar & 150 °C, $h_2 = 2777$

$$h_2 = h_1 = h_f + x h_{fg} \Rightarrow$$

$$2777 = 897 + x_1 * 1901$$

$$\therefore x = 0.989$$

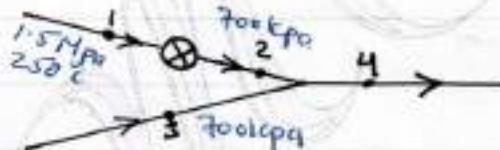




Ex: Steam at 1.5 MPa and 250°C flowing at 1.5 kg/s is throttled to 700 kPa and then mixed with a steam at 700 kPa also 0.97 dryness fraction with a flow rate of 3.6 kg/s. find the condition of resulting steam.

Sol:

at 1.5 MPa from Steam tables, $t_s = 198.32^\circ\text{C}$



Since $t_1 > t_s \Rightarrow$ Superheated Steam at point 1 from Superheated Steam tables. $h_1 = 2925 \text{ J/g/kg} = h_2$

$$m_2 h_2 + m_3 h_3 = m_4 h_4$$

$$h_3 = h_{f3} + x_3 h_{fg3} \quad \text{at } P = 700 \text{ kPa}, h_f = 697 \text{ J/g/kg}$$

$$h_{fg} = 2067 \text{ J/g/kg}$$

$$h_3 = 697 + 0.97 \times 2067 = 2702 \text{ J/g/kg}$$

$$h_4 = \frac{m_2 h_2 + m_3 h_3}{m_2 + m_3} = \frac{1.5 \times 2925 + 3.6 \times 2702}{1.5 + 3.6} = 2767.6 \text{ J/g/kg}$$

at 700 kPa, $h_g = 2763.5 \text{ J/g/kg}$, $T_s = 164.97^\circ\text{C}$

since $h_4 > h_g \Rightarrow$ Superheated Steam from Superheated Steam tables, $T_4 = 166.64^\circ\text{C}$

\therefore Degree of Superheat = $(t - t_s)$

$$= 166.64 - 164.92$$

$$= 1.67^\circ\text{C}$$



Ex: 0

Steam at 0.6 MPa, 200°C enters an insulated nozzle with a velocity of 50 m/s. It leaves at 0.15 MPa and velocity of 600 m/s. Determine the final temperature of steam if it is superheated and quality if it is wet.

Sol: 0 From SFEE

$$\int z_1 + \frac{1}{2} C_1^2 + h_1 + q = \int z_2 + \frac{1}{2} C_2^2 + h_2 + w$$

$$z_1 \approx z_2, q = 0 \text{ (insulated)}, w = 0 \text{ (for nozzle)}$$



$$\therefore h_2 = h_1 + \frac{1}{2} (C_1^2 - C_2^2) * 10^3$$

at 0.6 MPa $\rightarrow t_s = 158.8^\circ\text{C}$, since $T_s > T_s$ \therefore Superheated from Superheated Steam tables at 0.6 MPa & 200°C

$$h_1 = 2850.1 \text{ kJ/kg}$$

$$h_2 = 2850.1 + \frac{1}{2} (50^2 - 600^2) * 10^3 = 2671.4 \text{ kJ/kg}$$

at 0.15 MPa $h_g = 2693.6 \text{ kJ/kg}$ (from Steam tables)

Since $h_2 < h_g \Rightarrow$ wet Steam

$$h_2 = h_f + x_2 h_{fg}, \text{ at } p = 0.15 \text{ MPa from Steam table}$$

$$h_f = 467.1 \text{ kJ/kg}, h_{fg} = 2226.5 \frac{\text{kg}}{\text{kg}}$$

$$\therefore 2671.4 = 467.1 + x_2 * 2226.5$$

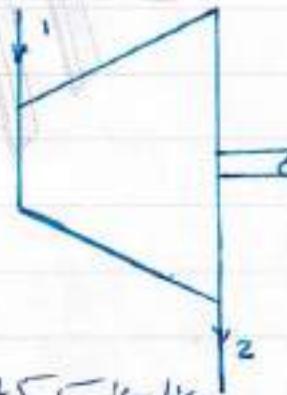
$$x_2 = 0.99$$



Ex-50 The mass flow rate of steam turbine is 1.5 kg/s and the heat transfer from the turbine is 8.5 kW. The following data are known for steam entering and leaving turbine. Find the power output of turbine.

	P(Mpa)	t (°C)	x	C(m/s)	Z(m)
input	2	350	-	50	6
output	0.1	-	100%	200	3

Sol-50 $gZ_1 + h_1 + \frac{1}{2} C_1^2 + Q = gZ_2 + h_2 + \frac{1}{2} C_2^2 + W$
 $W = g(Z_1 - Z_2) * 10^{-3} + (h_1 - h_2) + \frac{1}{2}(C_1^2 - C_2^2) * 10^{-3} + \frac{Q}{m}$



from Superheated Steam tables at
 2 MPa & 350°C , $h_1 = 3137 \text{ kJ/kg}$
 at $P = 0.1 \text{ MPa}$ & dry $\rightarrow h_2 = h_g = 2675.5 \text{ kJ/kg}$

$$W = 9.8(6-3)*10^{-3} + (3137 - 2675.5) + \frac{1}{2}(50^2 - 200^2)*10^{-3} + \frac{(-8.5)}{1.5}$$

$$= 437.11 \text{ kJ/kg}$$

$$\text{Power} = \dot{m} \cdot W = 1.5 * 437.11$$

$$= 656 \text{ kW}$$

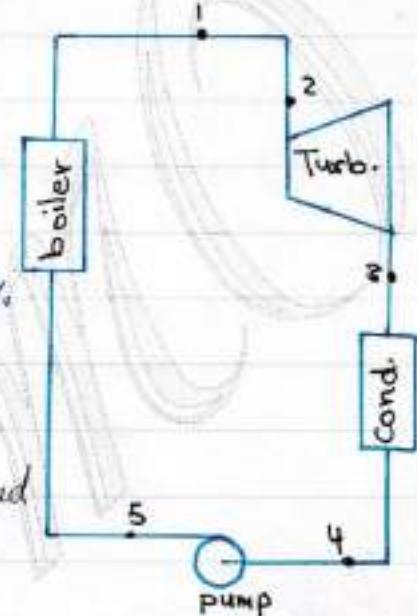


Ex: Consider the simple power plant, as shown. the following data are :

	P	t (°C)	x
Leaving boiler	2 MPa	300	-
entering turbine	1.9 MPa	290	-
leaving turbine	15 kPa	-	90%
leaving condenser	14 kPa	45	-

Pump work = 4 kJ/kg , Find :

- a. heat transfer between boiler and turbine
- b. turbine work
- c. heat transfer in condenser
- d. heat transfer in boiler



Sol: a. pipe 1→2

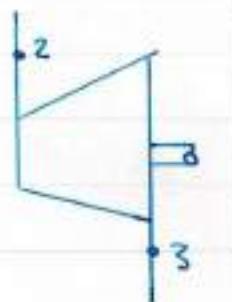
$$gz_1 + \frac{1}{2} C_1^2 + h_1 + q = gz_2 + \frac{1}{2} C_2^2 + h_2 + w \quad \text{--- (1)} \\ z_1 \approx z_2 \Rightarrow C_1 = C_2 \Rightarrow w = 0 \quad \text{--- (2)} \\ \therefore q = h_2 - h_1 \quad \text{--- (3)}$$

from Superheated Steam, at 2 MPa & 300°C , $h_1 = 302.5 \text{ kJ/kg}$
 " " " " , at 1.9 MPa & 290°C , $h_2 = 3002.5 \text{ kJ/kg}$

$$\therefore q = 3002.5 - 302.5 = -21 \text{ kJ/kg}$$

b. Turbine 2→3

$$gz_2 + \frac{1}{2} C_2^2 + h_2 + q = gz_3 + \frac{1}{2} C_3^2 + h_3 + w \\ z_2 \approx z_3 \Rightarrow C_2 = C_3 \Rightarrow q = 0$$





$$w = h_2 - h_3$$

$$h_3 = h_f + x h_{fg} \quad , \text{ at } 15 \text{ kPa} , h_f = 226.1 \text{ kJ/kg}$$

$$h_{fg} = 2373.1 \text{ kJ/kg}$$

$$h_3 = 226 + 0.9 * 2373.1 = 2361.8 \text{ kJ/kg}$$

$$\therefore w_t = 3002.5 - 2361.8 = 640.7 \text{ kJ/kg}$$

C. Condenser 3 → 4

$$gZ_3 + \frac{1}{2} C_3^2 + h_3 + q = gZ_4 + \frac{1}{2} C_4^2 + h_4 + w$$

$$Z_3 \approx Z_4 , C_3 = C_4 \Rightarrow w = 0$$

$$\therefore q = h_4 - h_3$$

$$\text{at } P = 14 \text{ kPa} \quad t_s = 52.5^\circ\text{C} , t_4 = 45^\circ\text{C}$$

$\therefore t_4 < t_s \Rightarrow$ Subcooled liquid

from Steam table at $t_s = 45^\circ\text{C}$, $h_4 = 188.5 \text{ kJ/kg}$

$$q = 188.5 - 2361.8 = -2173.3 \text{ kJ/kg}$$

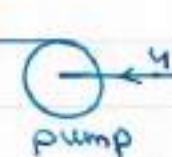


d. Pump 4 → 5

~~$$gZ_4 + \frac{1}{2} C_4^2 + h_4 + w = gZ_5 + \frac{1}{2} C_5^2 + h_5 + w$$~~

$$w = h_4 - h_5 \Rightarrow -4 = 188.5 - h_5$$

$$\therefore h_5 = 192.5 \text{ kJ/kg}$$



e. Boiler 5 → 1

~~$$gZ_B + \frac{1}{2} C_5^2 + h_5 + q = gZ_1 + \frac{1}{2} C_1^2 + h_1 + w$$~~

$$\therefore q = h_1 - h_5 = 3023 - 192.5$$

$$= 2831 \text{ kJ/kg}$$





Measurement of Dryness Fraction of Steam.

1. Barrel Calorimeter

P = pressure of the steam,

t = temperature of steam

formation at pressure P (from S.T.)

h_{fg} = latent heat of steam at pressure

P (from steam tables)

m_c = Mass of the calorimeter

C_c = Specific heat of the calorimeter

m_s = Mass of the steam condensed

m_w = Mass of cold water in the

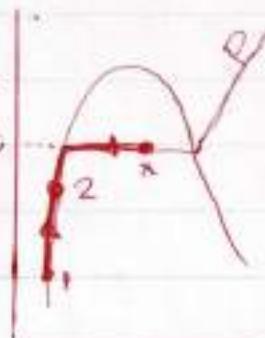
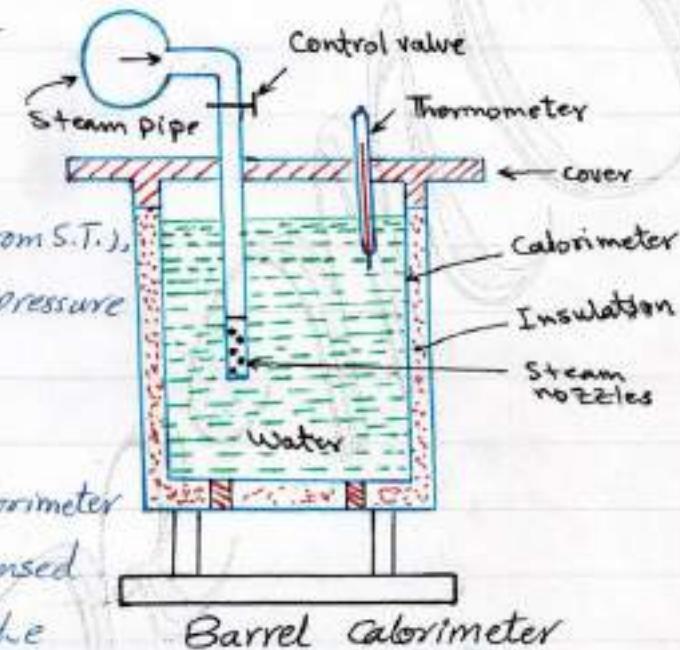
Calorimeter

t_1 = Initial temperature of water and calorimeter.

t_2 = Final " " " " " . t

C_w = Specific heat of water ($4.2 \text{ Jg}^{-1}\text{kg}^{-1}\text{K}$)

x = Dryness fraction of steam sample.



According to the law of conservation, the heat lost by steam is equal to the heat gained by water and calorimeter. Heat lost = $m_s [x h_{fg} + C_w (t - t_2)]$

$$\text{Heat gained} = (m_w C_w + m_c C_c)(t_2 - t_1)$$

$$\therefore m_s [x h_{fg} + C_w (t - t_2)] = (m_w C_w + m_c C_c)(t_2 - t_1)$$

from this equation, the dryness fraction (x) may be determined.



Ex: 0 In a laboratory experiment on wet Steam by a barrel calorimeter, the following observations were recorded:

Mass of copper calorimeter	= 1 kg = m_c
Mass of calorimeter + water	= 3.8 kg = $m_c + m_w$
Mass of calorimeter + water + Steam	= 4 kg = $m_c + m_w + m_s$
Initial temperature of water	= 10 °C
Final temperature of water	= 50 °C
Steam pressure	= 5.5 bar

If the Specific heat of Copper is 0.406 kJ/kg·K.
 Determine the dryness fraction of steam.

Sol: 0 $m_w = 3.8 - m_c = 3.8 - 1 = 2.8 \text{ kg}$

$$m_s = 4 - (m_c + m_w) = 4 - (3.8) = 0.2 \text{ kg}$$

from Steam tables at $P = 5.5 \text{ bar} \Rightarrow t_s = 155.5^\circ\text{C}$

$$h_{fg} = 2095.5 \frac{\text{kJ}}{\text{kg}}$$

$$\begin{aligned} \text{Heat lost by Steam} &= m_s [x h_{fg} + C_w(t_2 - t_1)] \\ &= 0.2 [x \cdot 2095.5 + 4.2(155.5 - 50)] \\ &= 419.1x + 88.6 \text{ kJ} \quad \dots \text{①} \end{aligned}$$

Heat gained by water and calorimeter

$$= (m_w C_w + m_c C_c)(t_2 - t_1)$$

$$= (2.8 \cdot 4.2 + 1 \cdot 0.406)(50 - 10) = 486.6 \text{ kJ}$$

Equating eqs ① and ②

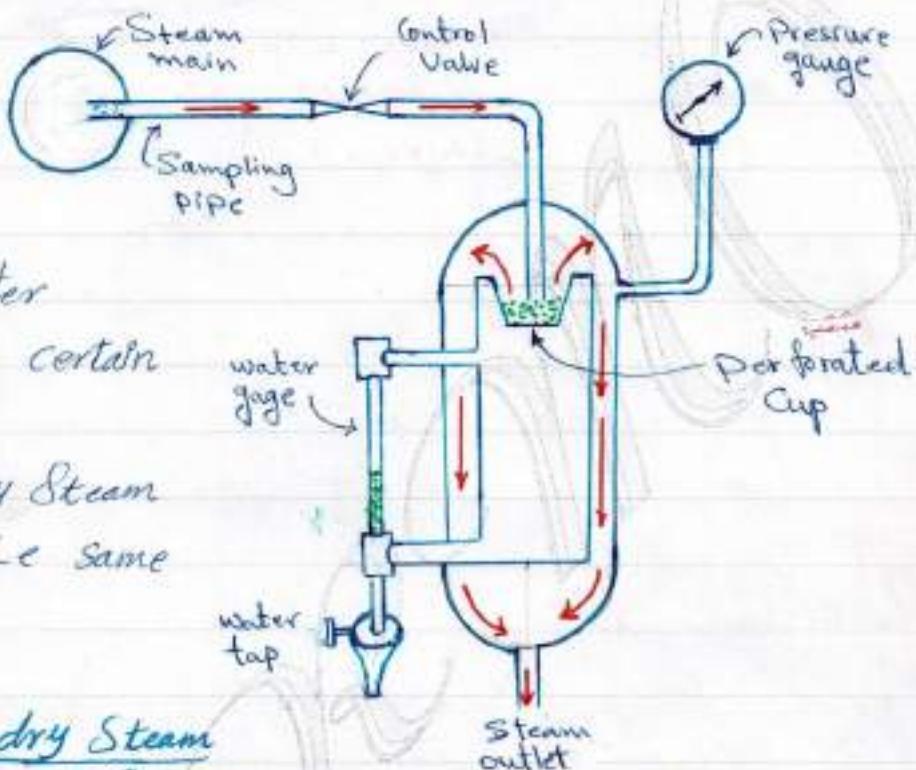
--- ②

$$419.1x + 88.6 = 486.6$$

$$\therefore x = 0.95$$



2. Separating Calorimeter :



m = Mass of water collected in a certain time

M = Mass of dry steam passing in the same time.

$$x = \frac{\text{Mass of dry Steam}}{\text{Mass of wet Steam}}$$

$$x = \frac{M}{M+m}$$

Separating calorimeter

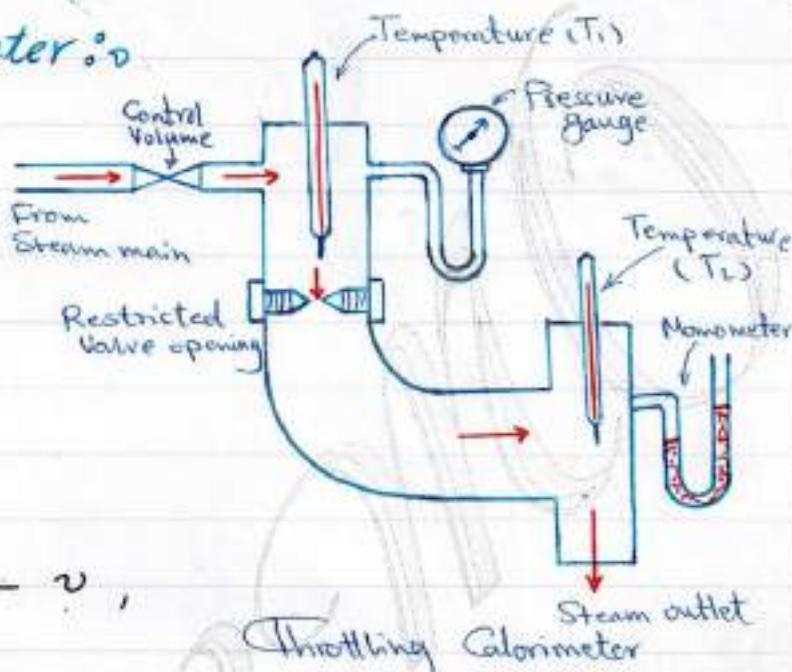
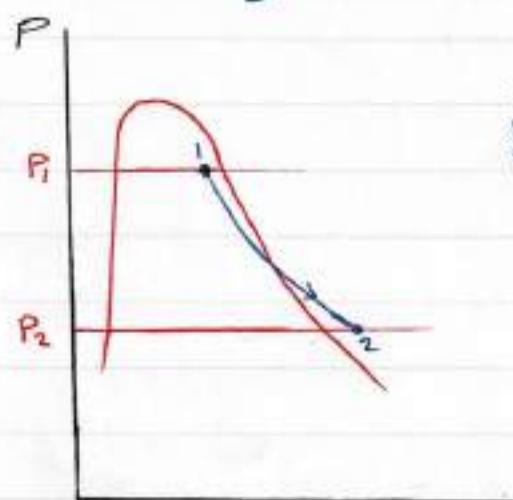
Ex: In a laboratory experiment, a sample of wet steam is allowed to pass through a separating calorimeter. At some instant, the water collected in the chamber was 0.1 kg whereas the condensed steam was found to be 1.25 kg. Determine the dryness fraction of steam entering the calorimeter.

Sol: $m = 0.1 \text{ kg} = M = 1.25 \text{ kg}$

$$x = \frac{M}{M+m} = \frac{1.25}{1.25+0.1} = 0.926$$



3. Throttling Calorimeter:



the Steam in point (2) after throttling in superheated state and at a lower pressure than (P₁).

$$\text{Total heat before throttling} = \text{Total heat after throttling}$$

$$h_1 = h_2$$

or

$$h_{f_1} + x h_{fg_1} = h_{g_2} + C_p(t_{sup} - t_2)$$

$\underbrace{at P_1}_{at P_2} \quad \underbrace{at P_2}_{at P_2}$

Ex:- In a throttling calorimeter, the steam is admitted at a pressure of 10 bar. If it is discharged at atmospheric pressure and 110°C after throttling, determine the dryness fraction of steam. Assume specific heat of steam as 2.2 kJ/kg·K.



Sol: $P_1 = 10 \text{ bar}, P_2 = 1.013 \text{ bar}, t_{\text{sup}} = 110^\circ\text{C}, C_p = 2.2 \text{ kJ/kg.K}$

from Steam tables at 10 bar, $h_f = 762.6 \text{ kJ/kg}$

$$h_{fg} = 2013.6 \text{ kJ/kg}$$

from Steam tables at 1.013 bar, $t_2 = 100^\circ\text{C}, h_g = 2676.5 \text{ kJ/kg}$

$$h_f + x h_{fg} = h_g + C_p(t_{\text{sup}} - t_2)$$

$$762.6 + x \cdot 2013.6 = 2676 + 2.2(110 - 100)$$

$$x = 0.961$$

4. Combined Separating and Throttling Calorimeter :

A very successful method of measuring the dryness fraction of steam is by a combined separating and throttling calorimeter.

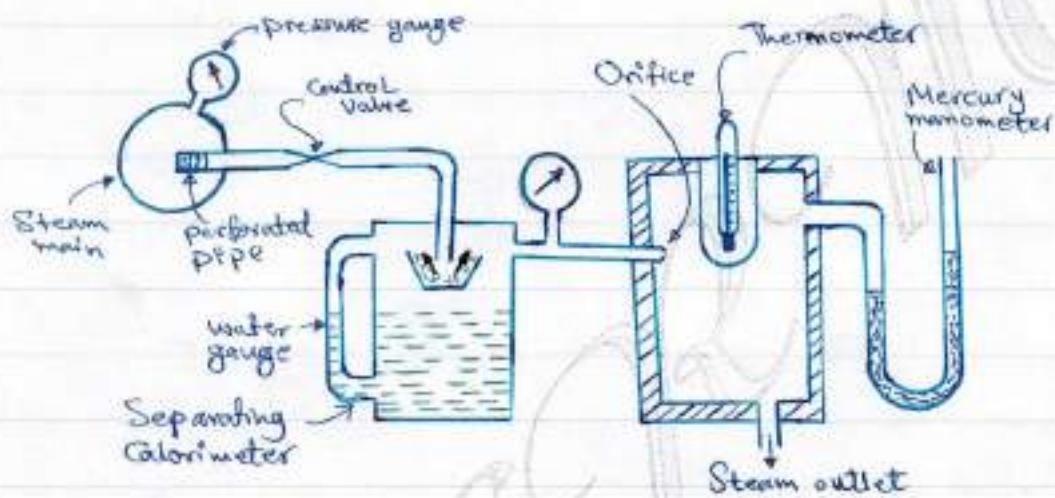
In this calorimeter the wet steam is first collected in a perforated collecting pipe and then passed through a separating calorimeter. A part of water is removed by separating calorimeter owing to quick change of direction of flow. The resulting semi-dry steam is throttled into a throttling calorimeter. This method ensures that the steam will be superheated after throttling. This instrument is well insulated to prevent any loss of heat.



x_1 = Dryness fraction of Steam considering separating calorimeter.
 x_2 = Dryness fraction of Steam entering the throttling .

Now the actual dryness fraction of Steam in the Steam main,

$$x = x_1 * x_2$$



„Combined Separating and throttling calorimeter“

Note: It is not possible to obtain results with this instrument if the final condition of Steam is wet. The final condition of Steam must be just dry or superheated.



Ex: In a laboratory experiment, the following observations were recorded to find the dryness fraction of Steam by combined separating and throttling calorimeter:

$$\text{Total quantity of Steam passed} = 36 \text{ kg} = m_s + m_w$$

$$\text{Water drained from Separating} = 1.8 \text{ kg} = m_w$$

$$\text{Steam pressure before throttling} = 12 \text{ bar} = P_1$$

$$\text{Temperature of Steam after throttling} = 110^\circ\text{C} = t_{\text{sup}}$$

$$\text{Pressure after throttling} = 1.013 \text{ bar} = P_2$$

$$\text{Specific heat of Steam} = 2.1 \text{ kJ/kg.K}$$

Determine the dryness fraction of Steam before inlet to the calorimeter

Sol: $m_s = ?$

We know that mass of dry Steam

$$m_s = (m_s + m_w) - m_w = 36 - 1.8 = 34.2 \text{ kg}$$

$$x_1 = m_s / (m_s + m_w) = 34.2 / 36 = 0.95$$

from Steam tables, corresponding to $P_1 = 12 \text{ bar}$

$$h_f_1 = 798.4 \text{ kJ/kg}, h_{fg} = 1984.3 \text{ kJ/kg}$$

at $P_2 = 1.013 \text{ bar}$

$$h_g_2 = 2676 \text{ kJ/kg}, t_2 = 100^\circ\text{C}$$

$$h_f_1 + x_1 h_{fg_1} = h_g_2 + C_p(t_{\text{sup}} - t_2)$$

$$798.4 + x_1 * 1984.3 = 2676 + 2.1(110 - 100)$$

$$x_1 = 0.957 \Rightarrow x = x_1 + x_2 = 0.95 + 0.957 = 0.909$$



(Sheet No. 5)

Q1: Steam at a pressure of 28 kPa is passed into a condenser and it leaves as condensate at a temperature of 59°C. Cooling water circulates through the condenser at the rate of 45 kg/min. It enters at 15°C and leaves at 30°C. If the steam flow rate is 1.25 kg/min, determine the dryness fraction of steam as it enters the condenser.

Q2: 1 kg of saturated steam at 10 bar undergoes a non-flow constant volume process until the pressure becomes 3.5 bar. Determine :

- the final condition of steam.
- the change in internal energy.
- the change in specific enthalpy
- the heat energy transferred.

Ans. [0.37, -1273 kJ/kg, -1500 kJ/kg, -1273 kJ]

Q3: A sample of steam at 1.4 MPa is taken from a boiler and passed through a throttling calorimeter where after throttling to 0.11 MPa, its temperature is observed to be 110°C. Determine the dryness fraction of the steam leaving the boiler.

Ans. [0.95]



Q4: 0.5 kg of water at 7 bar and 15°C is contained in a cylinder 0.3 m diameter by friction-less piston. Heat energy is supplied until the temperature of cylinder contents becomes 204°C, the pressure of the contents remains at 7 bar.

- Determine:
- the heat energy supplied
 - the distance moved by the piston.
 - the work energy,
 - the change in internal energy.

Ans. [1395.81 kJ/kg, 2.14 m, 1051 kJ, 1290.81 kJ]

Q5: 0.075 m³ of dry saturated steam at 8 bar and contained in a cylinder by friction-less piston if the steam undergoes hyperbolic equation to a pressure of 4 bar. Determine the work energy, the change in internal energy and the heat energy transferred.

Ans. [41.51 kJ, 0.6241 kJ, 40.51 kJ]

Q6: A quantity of dry saturated steam occupies 0.2634 m³ at 1.5 MPa. Determine the final condition of the steam if it is compressed until the volume is halved.

- if the compression is carried out in an isothermal manner, then find the heat rejected.
- if the compression follows the law $PV = C$.

Ans. [a. 0.5, 972.61 kJ/kg, b. 0.989]