

MECHANICAL ENGINEERING

ELEMENTS OF MECH. ENGG.



Basic elements

Thermodynamics

System :-

Thermodynamic system is defined as prescribed region or space of finite quantity of matter surrounded by an envelope which is called boundary (may be real / imaginary)

Surrounding :-

The matter in space external to system that may be influenced by changes in the system is called surrounding or environment.

Boundary

Diathermic

Adiabatic

Adiabatic :-

The walls or boundaries which do not allow exchange of energy in the form of heat transfer to take place across the boundaries are called adiabatic boundaries.

Diathermic :-

Walls that do allow heat interaction across them are called diathermic walls or boundaries.

Types of System :-

1) open

2) closed

3) isolated

Closed :-

mass same

A system is called closed system if the mass within the boundary of system remains constant & only the energy in the form of heat & work

can exchange with its environment. Physical nature, chemical composition of mass may change. Chemical rxn may occur if more than one component is present in system.

Bomb calorimeter (used to determine calorific value of fuel)

Open System :-

In open system, there is mass exchange with surrounding along with the transfer of energy in form of heat & work.

- e.g. (i) Water wheel (or Water Turbine)
(ii) used in hydroelectric power plants
(iii) Gas turbine
(iv) Boiler
(v) IC Engine

Isolated system :-

If neither mass or energy transfers with other system or surrounding is called isolated system.

Thermal flask.

Adiabatic Systems :-

There exist walls/boundaries which do not allow heat transfer to take place across them. Can exchange energy in form of work only.

Homogeneous Systems :-

These represent quantity of matter that is uniform throughout in physical nature and chemical composition.

2 phase system:- Consisting gas and liquid.
 3 phase system:- Consisting all three phases.

System consisting of single phase is known as Homogeneous system.

Heterogeneous System:-

System whose mass content is not uniform throughout and it consist of more than one phase.

e.g. weight steam

Every system has certain characteristic by which its physical condition can be described

e.g. pressure, volume, colour, chemical composition such are called properties of system.

When all the properties of system the system is said to exist at definite state.

Any change or operation in which one or more of the properties of the system changes it is called change of state and succession of states passes through during a change of state it is called path of the change of state.

When the path is completely defined the change of state is called a process.

e.g. Constant Volume process, Constant pressure process

Thermodynamic Cycle:-

A series of state changes so that final state is identical to initial state.



Thermodynamic property in a state func.

Intensive Property-
which do not depend on mass of system:

e.g. Viscosity, Temp., Pressure.

Extensive Property-

which depends on the mass of system.

e.g. Enthalpy

$$P = P_1 + P_2 + P_3$$

Thermodynamic equilibrium-

when no change in any macroscopic property is observed. If the system is isolated from its surrounding

3 types equilibrium $\begin{matrix} \xrightarrow{\text{Mechanical}} \\ \xrightarrow{\text{Thermal}} \\ \xrightarrow{\text{Chemical}} \end{matrix}$

In the absence of external as well as internal unbalanced force

Thermal Equilibrium-

When the system existing in mechanical and chemical eqm is separated from surrounding by diathermic walls and if there is no spontaneous change in any property of system, the system is said to be in state of thermal eqm.

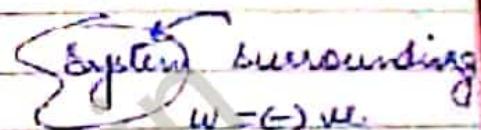
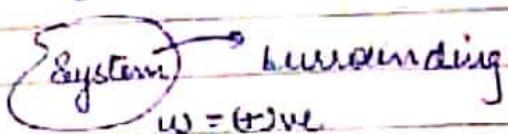
Zeroth law of thermodynamics-

When two bodies at different temp. are brought in contact with each other after sometime they attain common temp., then they are said to be in thermal eqm. When a body A is in thermal eqm with body B & B with C, then they are in thermal eqm with each other.

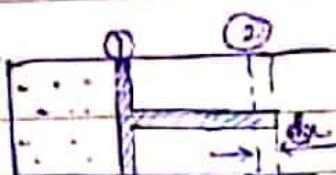
A	B
C	

Work -

In thermodynamics, work transfer is considered to be occurring b/w the system & surroundings : i.e. work is said to be done by system if the sole effect on things external to system can be reduced to the rising of a weight.



PdV / Displacement work -



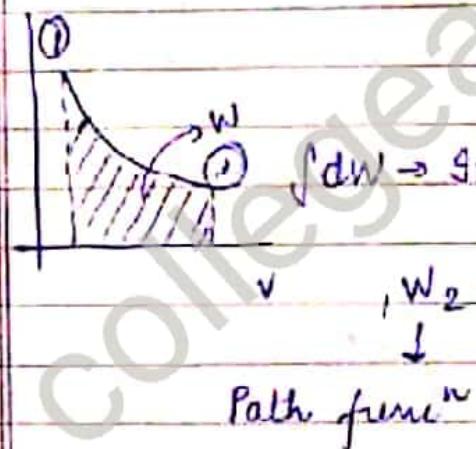
$$F = \rho A$$

$$\Delta W = F \times \text{Distance}$$

$$= F \times \Delta x$$

$$\Delta W = P \times A \times \Delta x$$

$$\Delta W = P \times dV$$



$$\int dW = V_2 - V_1$$

Exact differential

$\int dW \rightarrow$ Inexact differential $\rightarrow \int dW \neq W_2 - W_1$

$$W_2 = \int_1^2 P dV = P(V_2 - V_1)$$

Path func

i) Constant Pressure Process -

$$W_2 = \int_1^2 P dV = P(V_2 - V_1)$$

ii) Constant Volume Process -

$$W_2 = \int_1^2 P dV = 0$$

iii) Constant temp. Process ($PV = C$) -

$$PV = P_1 V_1 = C$$

$$W_2 = \int_1^2 P dV = \int_{V_1}^{V_2} \frac{P_1 V_1}{V} dV = P_1 V_1 \ln \frac{V_2}{V_1}$$

4) Polytropic Process -

$n = \text{Polytropic} -$

$n=0$

$n=1$

$n=2$

$n=\infty$

$$W_2 = \int_1^2 P dV$$

$$PV^n = P_1 V_1^n = P_2 V_2^n = C$$

$$P = \frac{P_1 V_1^n}{V^n}$$

$$W_2 = \int \frac{P_1 V_1^n}{V^n} dV = P_1 V_1^n \left[\frac{V^{1-n}}{1-n} \right] = P_1 V_1^n \left[\frac{V^{1-n}}{1-n} \right]$$

Heat -

Heat is defined as the energy which is associated with the random motion of atoms & molecules. It is a form of energy that is transferred without transfer of mass across the boundary of system because of temp. diff. b/w system & its surroundings.

It is a Path funcⁿ.

unit - Joule

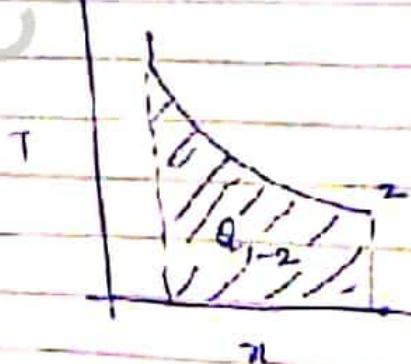
$$\int dQ_{1-2} = \int T dV$$

$$dQ = T dV$$

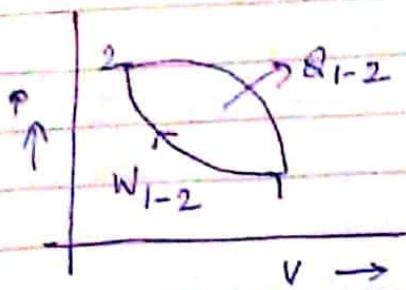
$$dV = \int \frac{dQ}{T}$$

$$\Delta S = \int \frac{dQ}{T}$$

Entropy



I Law of Thermodynamics -



Wcycle = Δ cycle

$$\Sigma W \propto \Sigma Q$$

$$\oint W = \oint Q$$

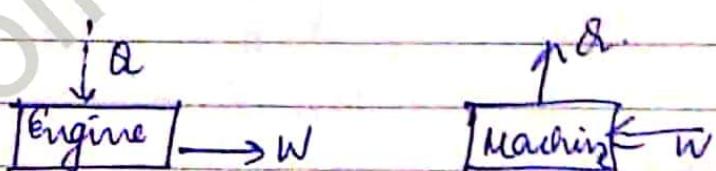
Energy can neither be created nor destroyed. It can be converted from one form to another. Heat & work are mutually convertible. When a system undergoes a thermodynamic cycle, the net heat supplied to system from surroundings is equal to the net work done by the system on its surroundings.

Total energy of an isolated system in all its forms remains constant.

No machine can produce energy without corresponding expenditure of energy.

Perpetual Motion \leftrightarrow Machine of Ist kind -

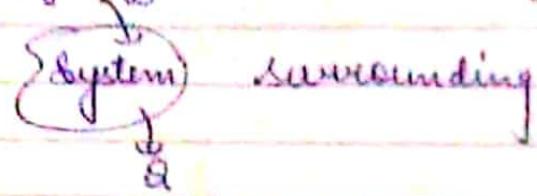
(CPMM - L)



There can be no machine * which would continuously supply mechanical work without some other form of energy disappearing simultaneously. Such a machine is hypothetical & impossible.

* No machine is there which would continuously consume work without some other form of energy appearing simultaneously.

Energy stored - a property of system

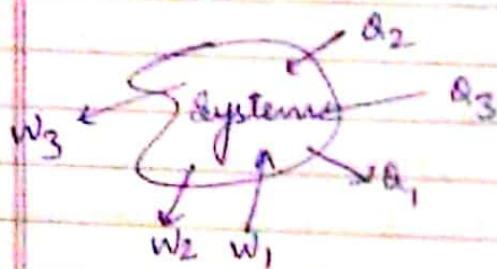


$$Q-W = \Delta E$$

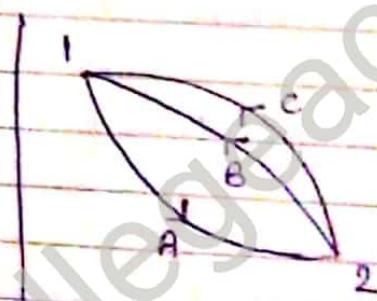
Internal Energy

$$Q = \Delta E + W$$

Energy eqⁿ for closed system



$$Q_2 + Q_3 - Q_1 = \Delta E + W_2 + W_1 - W_1$$



Along path A & B

$$\Delta Q_A = \Delta E_A + W_A$$

$$\Delta Q_B = \Delta E_B + W_B$$

A & B forms a cycle

$$(\sum W)_{\text{cycle}} = (\sum Q)_{\text{cycle}}$$

$$W_A + W_B = \Delta Q_A + \Delta Q_B$$

$$\Delta Q_A - W_A = \Delta W_B - \Delta Q_B$$

$$\Delta E_A = -\Delta E_B$$

$$\Delta E_A + \Delta E_B = 0$$

Along path A & C

$$\Delta E_A = -\Delta E_C$$

$$-\Delta E_B = -\Delta E_C$$

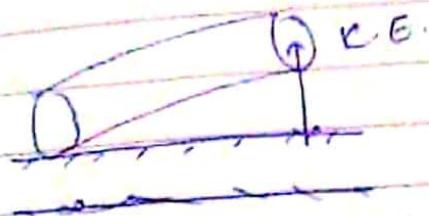
$$\Delta E_B = \Delta E_C$$

Internal Energy -

denoted by U

denoted by U

Total internal energy of substance = $U + \frac{1}{2}mv^2 +$
 Electrical + Magnetic + chemical



$$\therefore Q = \Delta E + W$$

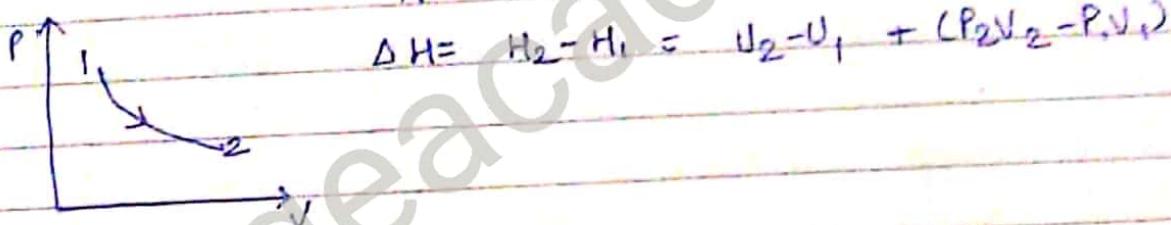
$$\Rightarrow Q = U + W$$

$$Q = \Delta U + P \int dV$$

Enthalpy:-

Enthalpy is total energy of substance due to molecular K.E. as well as pressurization.

$$H = U + PV$$



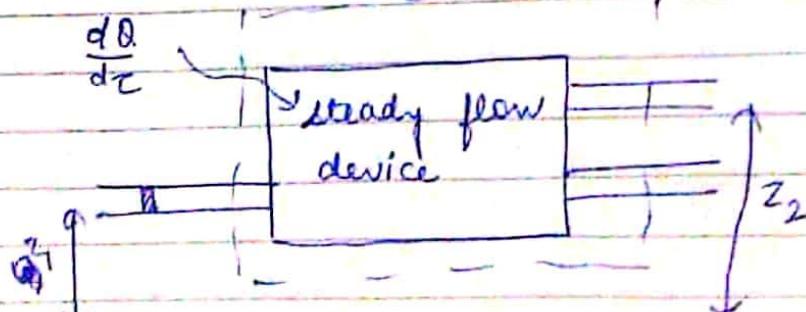
Energy Eqn for closed systems (Non-flow process) -

Controlled Volume:-

A certain fixed region in space is called controlled volume through which the moving substance flows & surface of controlled volume is called controlled surface.

Steady flow:-

Steady flow means the rate of flow of mass & energy across the controlled surface are constant.



A_1, A_2 = Area of
 (m²) cross-section

w_1, w_2 = Mass flow
 rate (kg/s)

$$\frac{dm}{dt}$$

P_1, P_2 = Absolute pres.
 on inlet & outlet (kN/m²)

v_1, v_2 = specific volume of inlet, outlet m^3/kg .
 u_1, u_2 = specific internal energy, J/kg .
 v_1, v_2 = velocity, m/s

g, c_2

z_1, z_2 = elevation (m)

$\frac{dQ}{dt}$ = Net rate of heat transfer (J/s)

$\frac{dW_x}{dt}$

= Net rate of work transferred by system
(J/s)

t = time (in sec.)

and

Mass Balance: $w_1 = w_2 \equiv w = \frac{dm}{dt}$

- Energy Balance:

Energy required to push an fluid element of 1 kg.

$$P \frac{\cancel{V/A}}{\cancel{t}} = PV$$

Unit: Nm (or J)

Total work transfer

$$W = W_x - P_1 V_1 + P_2 V_2$$

in rate form

$$\frac{dW}{dt} = \frac{dW_x}{dt} - P_1 V_1 \frac{dm_1}{dt} + P_2 V_2 \frac{dm_2}{dt}$$

(V = Mass = Mass \times sp. volume),
Density

$$w_1 e_1 + \frac{dQ}{dt} = w_2 e_2 + \frac{dW}{dt}$$

$$w_1 e_1 + P_1 V_1 \frac{dm_1}{dt} + \frac{dQ}{dt} = w_2 e_2 + P_2 V_2 \frac{dm_2}{dt} + \frac{dW_x}{dt}$$
$$- P_1 V_1 \frac{dm_1}{dt} + P_2 V_2 \frac{dm_2}{dt}$$

$$w_1 e_1 + P_1 V_1 \frac{dm_1}{dt} + \frac{dQ}{dt} = w_2 e_2 + P_2 V_2 \frac{dm_2}{dt} + \frac{1}{2} V_2^2 \frac{dm_2}{dt}$$

$$\frac{dm}{dt} \left(U_1 + \frac{C_1^2}{2} + z_1 \right) + P_1 V_1 \frac{dm_1}{dt} + \frac{dQ}{dt} = \frac{dm}{dt} \left(U_2 + \frac{C_2^2}{2} + z_2 \right) + P_2 V_2 \frac{dm_2}{dt} + \frac{dW_x}{dt}$$

$$H = U + PV$$

~~Energy~~
Energy per unit time $\int (H_1 + \frac{C_1^2}{2} + z_1) + \frac{dQ}{dt} = (H_2 + \frac{C_2^2}{2} + z_2) + \frac{dW_x}{dt}$

~~Energy~~
Energy per unit mass $\int (H_1 + \frac{C_1^2}{2} + z_1) + \frac{dQ}{dm} = (H_2 + \frac{C_2^2}{2} + z_2) + \frac{dW_x}{dm}$

$$(H_1 + \frac{C_1^2}{2} + z_1) + Q = (H_2 + \frac{C_2^2}{2} + z_2) + W$$

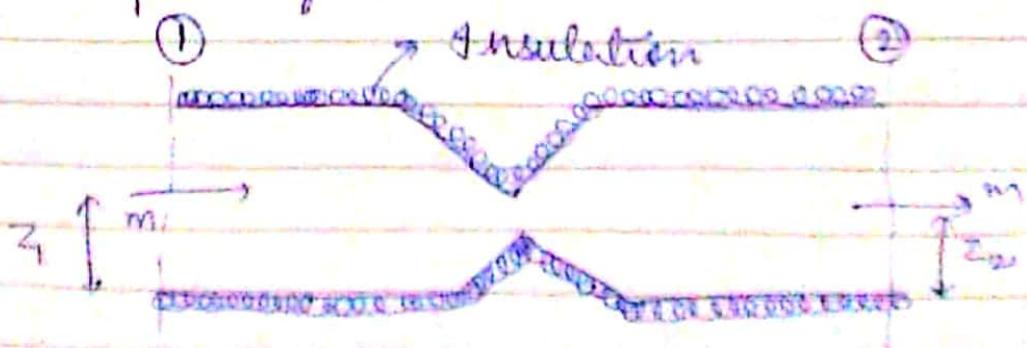
$$Q - W = (H_2 - H_1) + \frac{1}{2} (C_2^2 - C_1^2) + (z_2 - z_1)$$

$$Q - W = H_2 - H_1$$

Steady flow Energy Equation (Nozzles & Diffusers)

Nozzle is a device which increases the velocity or K.E. of a fluid at the expense of its pressure drop.
(P.L., K.E.)

Whereas diffuser increases the pressure of fluid at the expense of K.E.



$$h_1 + \frac{c_1^2}{2} + z_1 + \frac{dQ}{dm} = h_2 + \frac{c_2^2}{2} + z_2 + \frac{dW_L}{dm}$$

$$h_1 + \frac{c_1^2}{2} = h_2 + \frac{c_2^2}$$

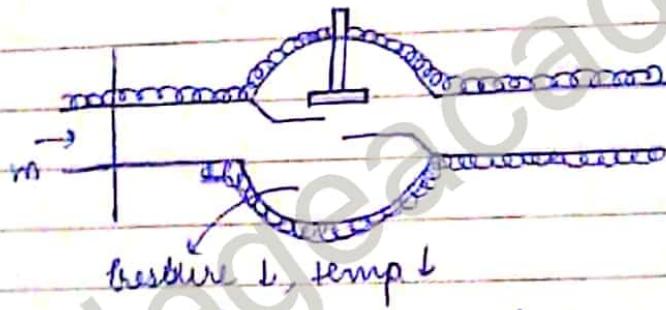
$$h_1 = h_2 + \frac{c_2^2}{2}$$

$$c_1 \ll c_2$$

$$c_2 = c_1 = \sqrt{2(h_1 - h_2)}$$

$$z_2 - z_1 = 0$$

SFEE for a Throttling device



Pressure ↓, temp ↓

when a fluid flows through a constricted passage or an orifice or porous plug.

$$\frac{dQ}{dm} = 0, \quad \frac{dW_L}{dm} = 0$$

Change in K.E.

$$h_1 + \frac{c_1^2}{2} + 0 = h_2 + \frac{c_2^2}{2} + 0$$

$$\frac{c_2^2 - c_1^2}{2} = 0, \quad h_1 = h_2$$

In case of any throttling process, enthalpy before throttling are equal to enthalpy after throttling

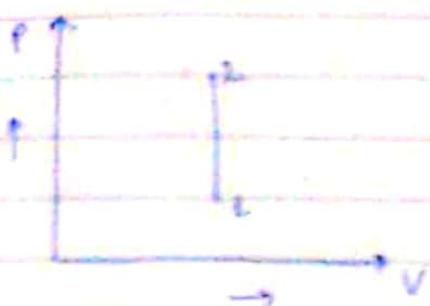
$$(h_1 = h_2)$$

Throttling is used in Refrigeration & air conditioning

Thermodynamic Processes

(i) Constant Volume Process-

(i) Relation b/w P, V, T -



Applying gas eq, with (1) & (2)

$$P_1 V_1 = M R T_1 \quad \text{and} \quad T_1$$

$$P_2 V_2 = M R T_2 \quad \text{and} \quad T_2$$

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

$$\therefore V_1 = V_2$$

$$\frac{P_1}{T_1} = \frac{P_2}{T_2} \quad \text{or} \quad \frac{P_1}{P_2} = \frac{T_1}{T_2}$$

(ii) Work done -

$$W_{\text{cv}} = \int F dV = P(V_2 - V_1) = 0$$

(iii) Change in Internal Energy -

$$\Delta U = m C_v (T_2 - T_1) \quad \text{Joules}$$

C_v = Specific heat at const. vol

specific heat at constant vol. of a sub. is defined as the rate of change of internal energy w.r.t. temp. when the volume is held constant.

$$C_v = \left(\frac{\partial U}{\partial T} \right)_V$$

$$\int dU = \int C_v dT$$

$$\Delta U_{\text{cv}} = C_v (T_2 - T_1) \quad \text{Joules/kg}$$

$$\Delta U = m C_v (T_2 - T_1) \quad \text{Joules}$$

(iv) Heat Transfer -

Apply 1 law -

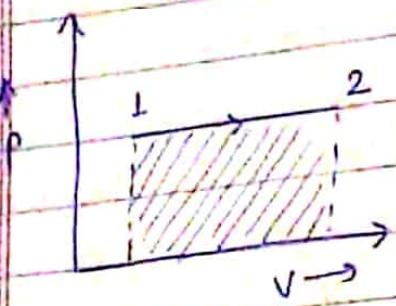
$$Q = \Delta U + W$$

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

2) Constant Pressure Process -

(i) Relation b/w P, V, T -

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



$$\boxed{\frac{V_1}{V_2} = \frac{T_1}{T_2}}$$

(ii) Work done during process -

$$W = P \int_{V_1}^{V_2} dV = P(V_2 - V_1) = mR(T_2 - T_1)$$

(iii) Change in Internal energy -

$$\Delta U = mC_p(T_2 - T_1) \quad \Delta U = mC_v(T_2 - T_1)$$

(iv) Heat Transfer -

$$Q = W + \Delta U$$

$$Q = mR(T_2 - T_1) + mC_v(T_2 - T_1)$$

$$R = C_p - C_v$$

$$Q = (m(C_p - C_v) + mC_v)(T_2 - T_1)$$

$$Q = mC_p(T_2 - T_1)$$

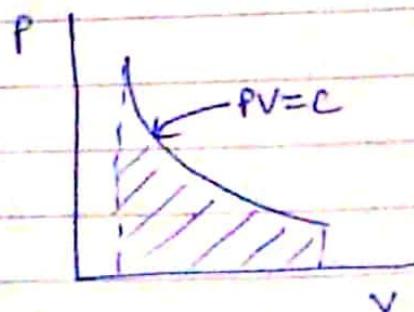
$R \neq 0$

3) Constant temp. / Isothermal Process -

(i) Relation b/w P, V, T -

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

$$\boxed{P_1 V_1 = P_2 V_2}$$



(ii) Work done -

$$W = \int_{V_1}^{V_2} P dV$$

$$\text{Since, } P_1 V_1 = P_2 V_2 = PV \Rightarrow P = \frac{P_1 V_1}{V}$$

$$W = \int_1^2 \frac{P_i V_i}{V} dV \Rightarrow W = P_i V_i \log \frac{V_2}{V_1} = P_1 V_1 \log \frac{P_1}{P_2}$$

(iii) change in Internal energy -

$$\Delta U = m C_V (T_2 - T_1) = 0$$

(iv) Enthalpy -

$$\Delta H = m C_p (T_2 - T_1) = 0$$

(v) Heat Transfer -

$$Q = W + \Delta U$$

$$Q = P_i V_i \log \frac{P_1}{P_2} + 0$$

$$Q = m R T_1 \log \frac{P_1}{P_2}$$

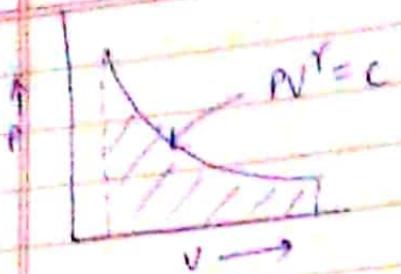
4) Reversible Adiabatic Process -

A gas is said to have undergone a reversible adiabatic process, when there is no interchange of heat b/w the gas & its surroundings during the process. So, an adiabatic expansion can take place in an engine cylinder if no transfer of heat take place through the walls of an engine cylinder. In this way, work is done by the gas during expansion. Since, work is done without transfer of heat to the gas, the internal energy of the gas decreases.

Ideal adiabatic process should follow the conditions:-

- 1) No heat is added or rejected during process
- 2) No friction
- 3) Work is either developed or absorbed during process

i) Relation b/w P_1, V_1, T_1



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

$$\frac{P_1}{P_2} = \frac{V_2}{V_1} \times \frac{T_1}{T_2} = \left(\frac{V_2}{V_1}\right)^Y$$

$$[T_1 V_1^{Y-1} = T_2 V_2^{Y-1}]$$

$$\frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{Y-1} = \left(\frac{P_2}{P_1}\right)^{\frac{Y-1}{Y}}$$

$$Y = \frac{C_P}{C_V}$$

ii) Work done -

$$W = \int P dV$$

$$P V^Y = P_1 V_1^Y = P_2 V_2^Y = C$$

$$P = \frac{P_1 V_1^Y}{V^Y}$$

$$W_{1 \rightarrow 2} = \int \frac{P_1 V_1^Y}{V^Y} dV = P_1 V_1^Y \left[\frac{V_2^{1-Y} - V_1^{1-Y}}{1-Y} \right]$$

$$= \frac{P_2 V_2^Y}{P_1 V_1^Y} \cdot \frac{P_2 V_2 - P_1 V_1}{1-Y}$$

$$W = \frac{P_1 V_1 - P_2 V_2}{Y-1} \rightarrow \underline{m R (T_1 - T_2)}$$

$$\frac{C_P - C_V}{C_V} = \frac{R}{C_V}$$

$$\therefore Y-1 = \frac{R}{C_V}$$

$$Y-1 = \frac{R}{C_V}$$

$$C_V = \frac{R}{Y-1}$$

$$W = m C_V (T_1 - T_2)$$

(iii) Change in Internal Energy -

$$\Delta U = mC_V(T_2 - T_1)$$

$$\Delta U = -mC_V(T_1 - T_2)$$

$$\Delta H = mC_P(T_2 - T_1)$$

(iv) Heat Transfer

$$Q = \Delta U + W$$

$$Q = -mC_V(T_1 - T_2) + mC_V(T_2 - T_1)$$

$$Q = (T_2 - T_1) [mC_V + \cancel{mC_V}] \quad Q = 0$$

5) Polytropic Process

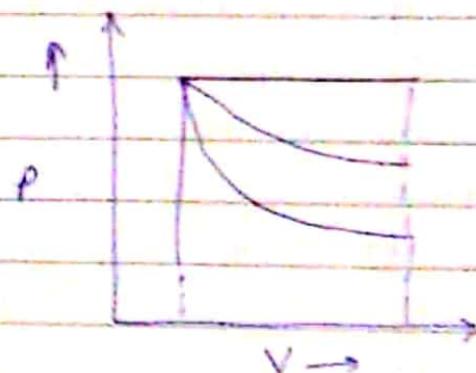
Polytropic process is also known as general law for expansion & compression of gases. So, the term polytropic can be used for any process that can be described by the eqⁿ $PV^n = C$, where 'n' is a constant during any one process, but having any value from 0 to ∞ .

(i) Relation -

$$PV^n = P_1V_1^n = P_2V_2^n = \text{constant}$$

$$T_1V_1^{n-1} = T_2V_2^{n-1}$$

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} = \left(\frac{V_1}{V_2}\right)^{n-1}$$



(ii) Work -

$$W = \frac{P_2V_2 - P_1V_1}{1-n} = \frac{mR(T_2 - T_1)}{1-n}$$

$$n = \frac{\log\left(\frac{P_2}{P_1}\right)}{\log\left(\frac{V_1}{V_2}\right)}$$

6) Throttling Process-

$$h_1 = h_2$$

$$W=0, Q=0$$

$$\Delta U=0$$

7) Irreversible Process-

All the natural processes takes place simultaneously at finite speed and through finite discontinuities b/w system & its environment & are said to be irreversible & processes can be said irreversible as a result of the degradation of energy by the factors fricⁿ, turbulence, diffusion, inelasticity, electrical resistance.

PROPERTIES OF STEAM

- A pure substance is one having constant chemical composition throughout its mass. Eg:- Atmospheric air, steam-water mixture.
- Phase:- It is the homogeneous part of the system. It is essentially chemical and physical state of aggregation of molecules of which substance is made of.
- Vapourization:- It is the process that involves changes from liquid phase to vapour phase.

Vapourization

Evaporation

The process of vapourization only from the surface of liquid. The molecules having greater velocity or K.E., break away from the liquid surface and escape to surrounding atoms and intensity of this escaping increases with rise in temperature of liquid.

Boiling

When heat is added to a liquid, it boils and vapour get generated both from the free surface of liquid and inside the liquid. Therefore, it refers to the process of vapour formation that takes in the whole mass of the liquid.

Saturated & Super Saturated Steam :-

Steam is called saturated when molecules escaping from liquid surface become equal to the molecules returning to the liquid.

Saturated steam has the maximum

density at given temperature and will be in thermal equilibrium with the liquid, so temperature of saturated steam vapour and liquid in contact with it is called Saturation Point or Boiling Point.

Liquid at its BP

at a specified pressure is called the saturated liquid and such a liquid will be in thermal equilibrium with its own vapour at specified temperature and pressure.

→ Wet Saturated Steam :-

when the saturated vapour contains particles of liquid evenly distributed over the entire mass of vapour.

→ Dryness Fraction :-

It is the ratio of mass of dry saturated vapour and mass of mixture in a mixture of dry and wet vapour.

$$\therefore D.F. = \frac{\text{Mass of dry saturated vapour}}{\text{Mass of mixture}}$$

When expressed in

% it is called Quality
of steam

$$D.F. = \frac{m_g}{m_g + m_f}$$

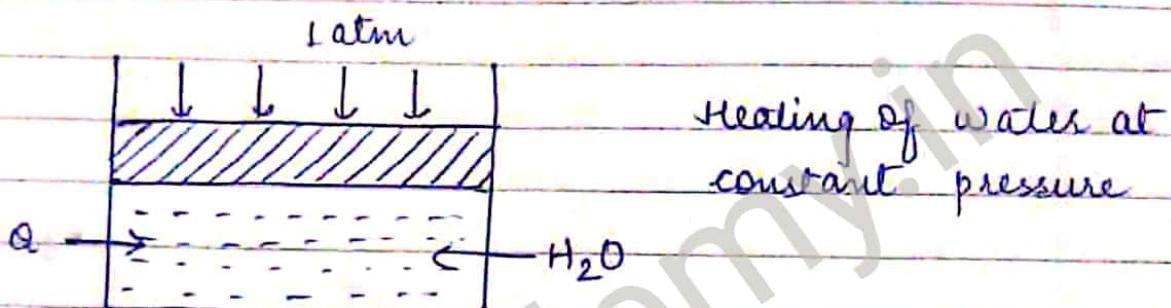
Mass of water particles
which is in suspension
with saturated vapour

→ Steam Generation :-

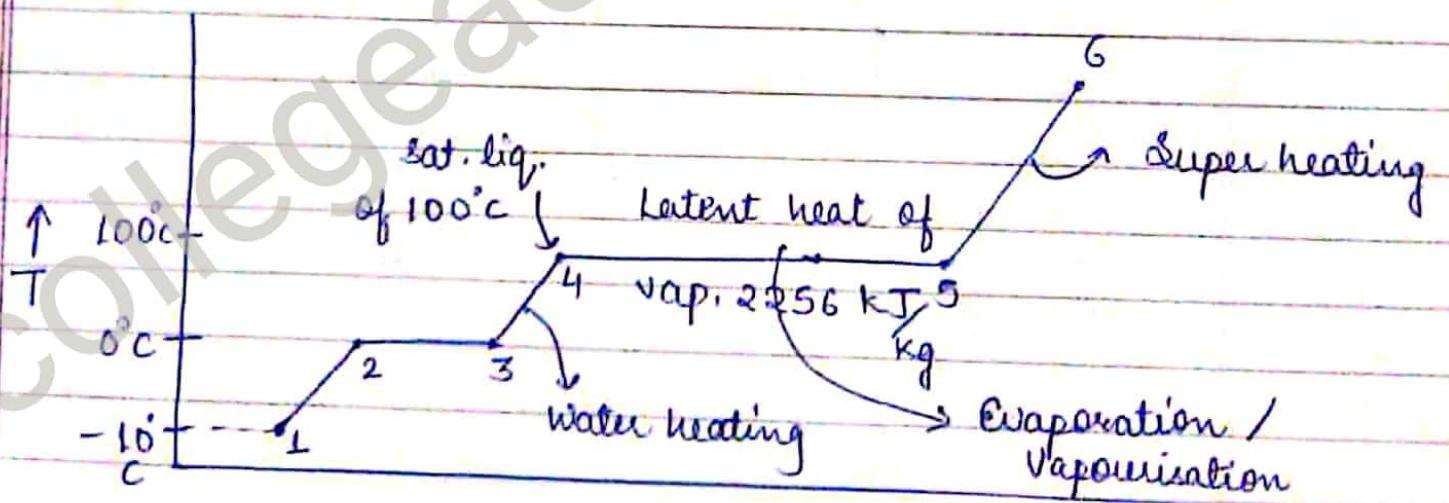
(Constant pressure & constant temperature phenomenon)

Process of steam generation can be divided into 3 stages :-

- (1) Heating of water to B.P,
- (2) Evaporation of boiling water and its conversion into dry saturated steam.
- (3) Transformation of dry saturated steam into superheated steam.



→ Heat v/s Temperature diagram :-



4 → Sat. liq. of 100°C

5 → Dry steam (sat.) of 100°C

6 → Super sat. steam

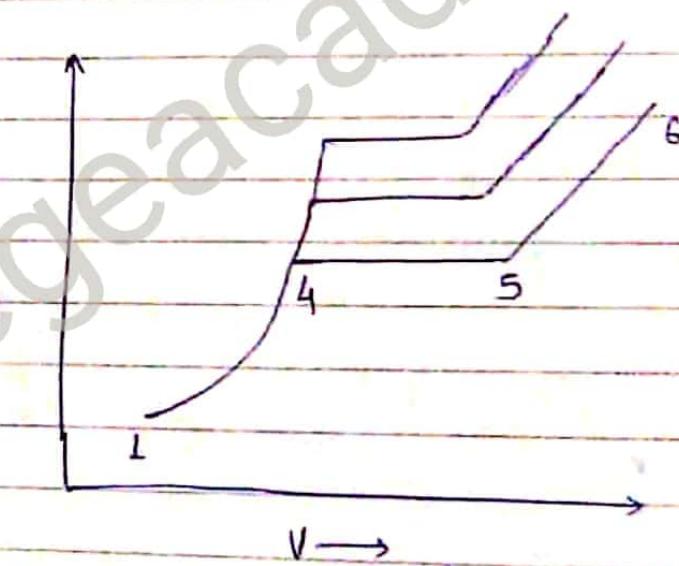
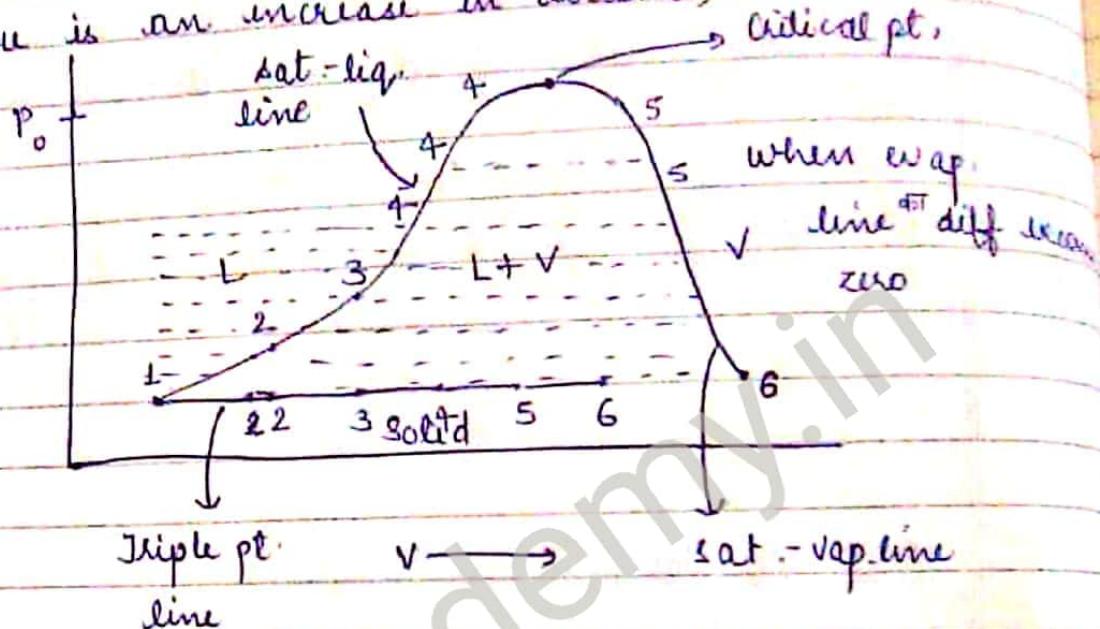
* All else → Sensible heating

There is no limit for Super heating

→ Steam generation is an isobaric and isothermal Phenomena :-

(But there is an increase in volume)

At every pressure there's ↑
steam generation



Horizontal distance b/w saturated liq. line and dry saturated vapour line becomes less and less with increase of pressure and temperature. So, the point at which this distance become zero is called critical point.

At critical Point :-

- (1) The liquid is directly & fully converted into dry vapour without phase of evaporation. (Latent heat = 0)
- (2) The liquid & vapour are indistinguishable.

(3) The properties of saturated liquid & saturated vapour are identical so above the critical point liquid upon heating suddenly flashes into vapour or vapour upon cooling suddenly condenses into liquid.

$$P_c = 221.2 \text{ bar}$$

$$T_c = 374.15^\circ\text{C}$$

$$V_c = 0.00317 \text{ m}^3/\text{kg.}$$

→ Triple Point:-

It is a line on P-V diagram where all the 3 phases (s, l, g) exist in equilibrium. So, at pressure below the triple pt. line substance cannot exist in the liquid phase and the substance when heated transforms from solid to vapour (sublimation) by absorbing the latent heat of sublimation from the surrounding.

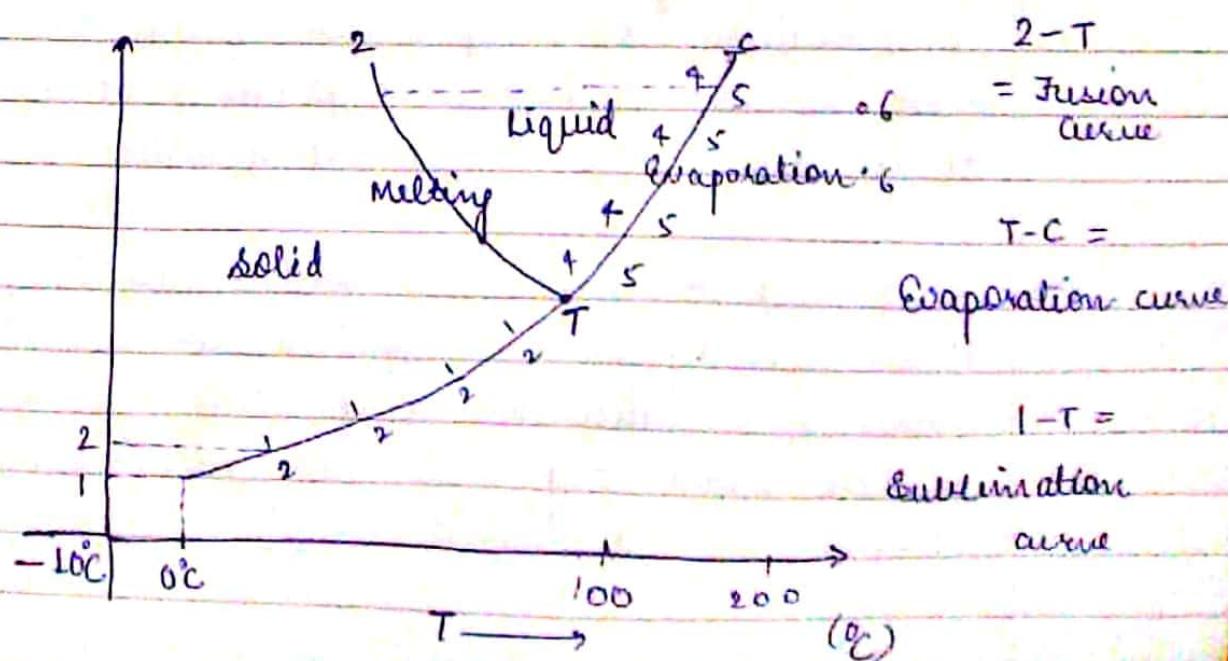
→ Solid-Liquid Vapour Equilibrium Diagram

OR

Phase Equilibrium Diagram

OR

P-T Curve :-



Evaporation line ends at critical point C where there is no change in liquid and vapour state, this point is called critical point.

Sub-curve, fusion/vapourisation curve and evaporation curve meet at point T called Triple Point at which all the solid, liquid and vapour phases exist at equilibrium at a definite pressure and Temperature.

→ Triple Pt. for water \Rightarrow

$$= 4.58 \text{ mm of Hg}$$

$$= 0.611 \text{ kPa}$$

$$= 0.01^\circ\text{C}$$

$$= 273.16 \text{ K}$$

→ Triple Pt. of $\text{CO}_2 \Rightarrow$

$$= 3085 \text{ mm Hg}$$

$$= 5 \text{ atm}$$

$$= 216.55 \text{ K}$$

→ Properties of Steam :-

(1) Sensible heat of steam (h_f) :-

It is quantity of heat required to rise the temperature of 1 kg water from 0°C from heating water p.t. or saturation temperature at a given pressure. It is also called Total Heat of Water.

(2) Latent Heat of Evaporation/Vaporization ($h_{fg} = L$) :-

It is quantity of heat required to convert 1 kg. of water at saturation temperature for a given pressure into dry and saturated steam at that temperature and pressure.

(3) Total heat / enthalpy of wet steam ($h_{\text{wet}} = h_f + x h_{fg}$) :-
Sensible Dryness fraction

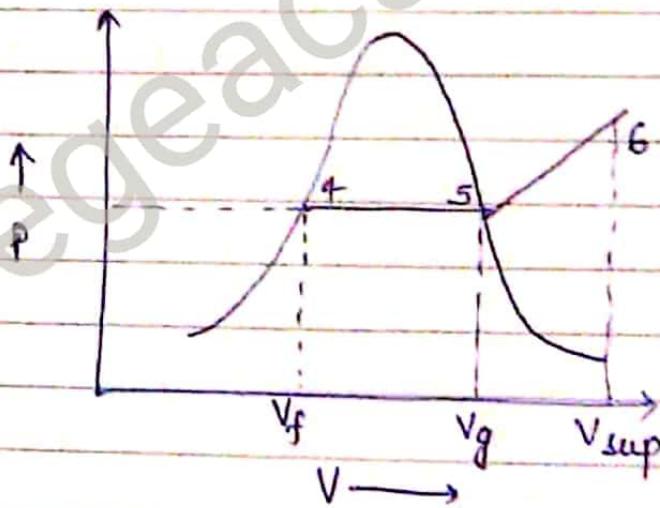
It is quantity of heat required to convert 1 kg. of water at 0°C into wet steam at constant pressure.

(4) Total enthalpy of dry saturated steam (h_g) :-

It is quantity of heat required to convert 1 kg. water at 0°C into dry steam at constant pressure.

$$h_g = h_f + h_{fg}$$

(5) Total enthalpy of superheated steam (h_{sup}) :-



$$h_{\text{sup}} = \underbrace{h_f + h_{fg}}_{\text{Dry Enthalpy}} + m_s c_{ps} (T_{\text{sup}} - T_{\text{sat}})$$

↳ $T_{\text{sup}} - T_{\text{sat}} = \text{Degree of Superheat}$

↳ $c_{ps} = \text{Specific heat of superheated steam at constant pressure}$
= 2.0 to 2.1 KJ / kg K

Page
specific volume of steam-

It is the volume occupied by 1 kg of steam at a given pressure and temperature (m^3/kg).

Density of steam-

It is the mass of steam per unit volume of steam at a given pressure and temperature (kg/m^3).

$$\begin{aligned}\text{specific volume of dry steam} &= \frac{V_g}{\text{mass}} \\ &= V_g / \text{wt}\end{aligned}$$

specific volume of dry steam-

It is the volume occupied by 1 kg of steam. It decreases with increasing pressure.

specific volume of wet steam-

Volume of dry portion of steam

+ Volume of water in suspension

x = Dryness fraction of weight steam

1 kg. of wet steam

x kg. dry part

$(1-x)$ kg. water in suspension

$$V_w = xV_g + (1-x)V_f$$

$$x = \frac{V_w - V_f}{V_g - V_f}$$

$$V_f \ll \ll 1$$

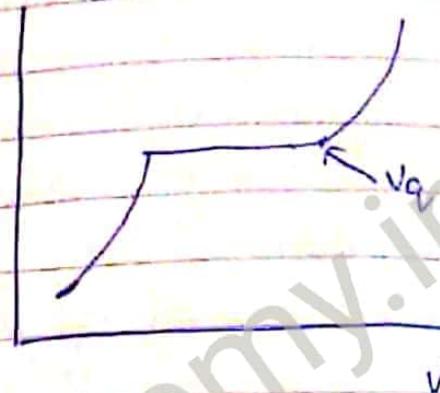
$$x \geq 80$$

$$p < 30 \text{ bar}$$

Supersaturated steam -
Dry and saturated steam behaves like a perfect gas
(Charles Law)

$$\frac{V_g}{T_{sol}} = \frac{V_{sup}}{T_{sup}}$$

$$V_{sup} = V_g \cdot \frac{T_{sup}}{T_{sol}}$$



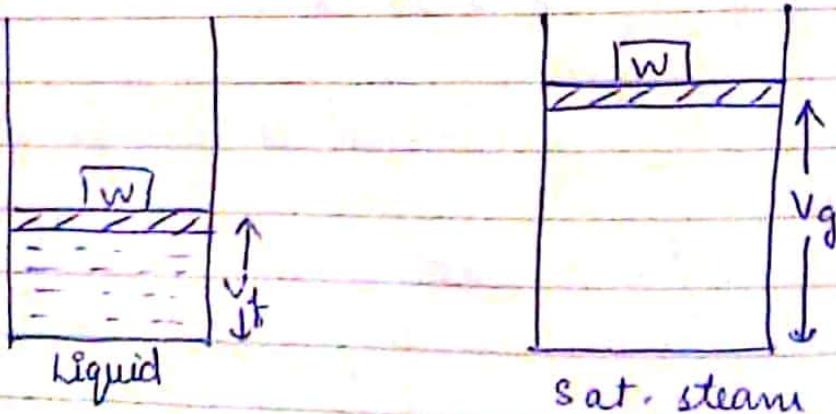
Internal energy of steam -

consider the formation of 1 kg. steam of dry steam at pressure P from water at 0°C.

Heat given for formation of 1 kg. steam (dry)

$$h_g = h_f + h_{fg}$$

When water evaporates to form steam & its volume increases from V_f to V_g at constant pressure



Work is done by steam in increasing its volume
it means work is done by steam in lifting the wt. through a vertical height. This work is called external work of evaporation.

The actual heat energy above the freezing pt. of water stored in the steam. This is known as internal energy of steam & work of evaporation is utilised in doing external work & does not store in the steam.



$$W = \int_{f}^g PdV = P(V_g - V_f) Nq$$

$$W = P(V_g - V_f) \quad V_f < V_g$$

$$U = h_g - PV$$

$$U = h_g - PV_g$$

$$\boxed{U = h_g - PV_g}$$

$$\text{Wet steam: } U_{\text{wet}} = (h_f + n h_{fg}) - p \cdot x \cdot V_g$$

$$\text{Dry steam: } V_g = h_f + h_{fg} - p \cdot V_g$$

$$\text{Supersaturated steam: } U_{\text{sup}} = h_f + h_{fg} + C_p(T_{\text{sup}} - T_{\text{sat}}) - PV_{\text{sup}}$$

Entropy -

Capacity or utility of available energy is decided by the term entropy which is a measure of quality of energy. Any thermal energy always flows from higher temp. to lower temp. Entropy is always calculated as the temp. difference before and after energy changes from higher to lower temperature.

$$p = m C_v (T - 0)$$

$$ds = \frac{dQ}{T_1} = C_v \frac{dT}{T}$$

$$S_2 - S_1 = C_v \int_{T_1}^{T_2} \frac{dT}{T}$$

Entropy of steam -

1) Entropy of water (s_f) -

$$ds = \frac{dQ}{T_1} = C_p \frac{dT}{T}$$

$$dQ = m C_p (T - 0)$$

Integrate b/w initial and final states

$$S_2 - S_1 = C_p \ln \frac{T_2}{T_1}$$

$$S_2 - S_1 = C_p \ln \frac{T_2}{273}$$

T_s = saturation Temp.

2) ^{Entropy} Entropy of ~~to~~ evaporation -

$$S_{fg} = \frac{h_{fg}}{T_s} = \text{dry + sat. steam}$$

$$S_{fg} = \frac{x h_{fg}}{T_s} = \text{for wet steam}$$

S = Entropy of water + Entropy change during evapora-

$$= S_f + \frac{x h_{fg}}{T_s}$$

$$= S_f + x S_{fg}$$

3) Entropy of dry steam -

$$S = S_f + \frac{h_{fg}}{T_s}$$

$$= S_f + S_{fg}$$

$$S = S_g - S_f$$

4) Entropy of Superheated steam

$$\int ds = \frac{\text{Heat of superheated steam}}{T} = \frac{dQ}{T} = \int C_p \frac{dT}{T}$$

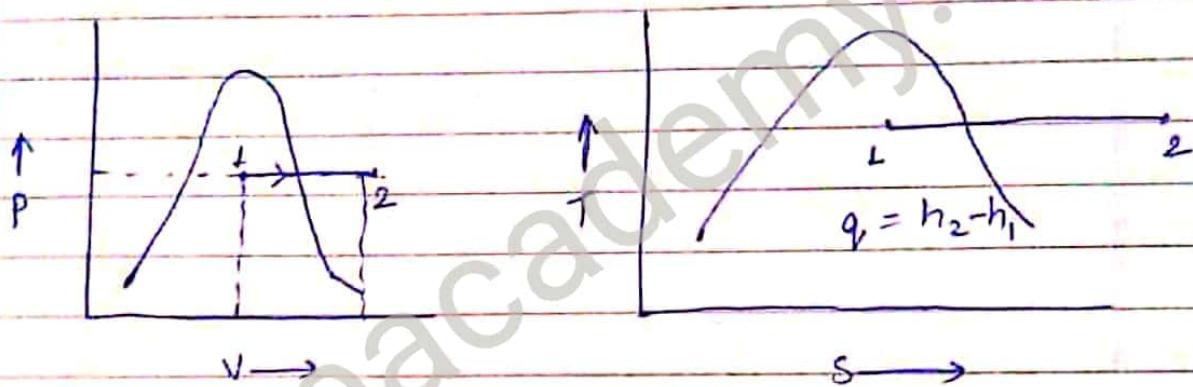
$$\int ds = s_2 - s_1 = C_p \cdot \ln g_e \frac{T_{sup}}{T_{sat}}$$

Total entropy =

$$s_{sup} = s_f + s_g + s_{vap} = s_f + s_{fg} + C_p \ln \frac{T_{sup}}{T_{sat}}$$

Vapour Process

Constant Pressure Process -



W.D. during constant pressure heating for 1 kg. of steam, $W = \int P dV = P(V_2 - V_1)$

$$V_1 = n_1 \cdot V_{fg1} = n V_g$$

$$h_1 = h_{f1} + x h_{fg1}$$

$$V_{sup2} = V_{g2} \cdot \frac{T_{sup2}}{T_{sat2}}$$

$$\begin{aligned} \text{Change in internal energy} : \Delta U &= U_2 - U_1 \\ &= (h_2 - p_2 V_2) - (h_1 - p_1 V_1) \end{aligned}$$

$$= (h_2 - h_1) - p(V_2 - V_1)$$

Heat Transfer, $\alpha = \Delta U + W$

$$= (h_2 - h_1) - p(V_2 - V_1) + p_2 V_2 - p_1 V_1$$

$$\alpha = h_2 - h_1 = \Delta h$$

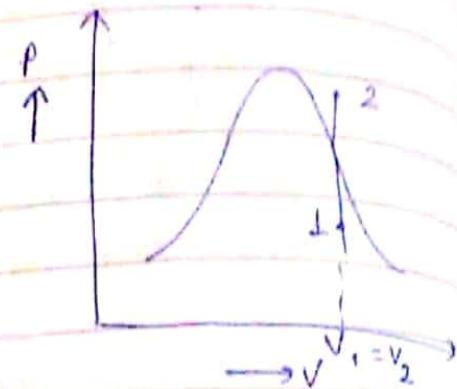
Constant volume vapour process
 Let the initial state of steam is 1. and final state is at 2.

1 - wet region

2 - superheated region

$$V_1 = V_2$$

$$V_1 = (1-x)V_f + xV_g$$



$$V_2 = V_{sup2} = V_g 2 \cdot \frac{T_{sup2}}{T_{sat2}}$$

$$V_{sup2} = (1-x)V_f + xV_g$$

$$x = \frac{V_{sup} - V_f}{V_g - V_f}$$

$$W_D = p \int_V^2 dV = p(V_2 - V_1)$$

$$= p \times 0$$

$$= 0$$

Acc to 1st law

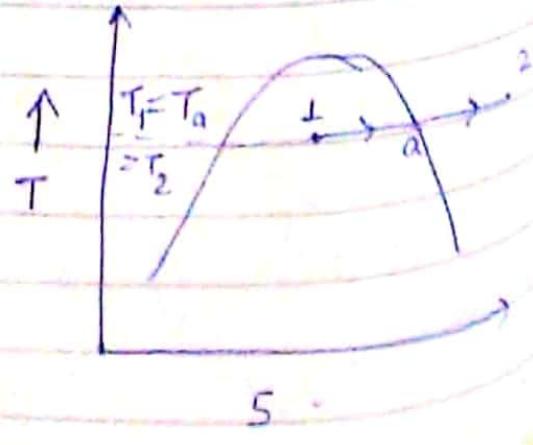
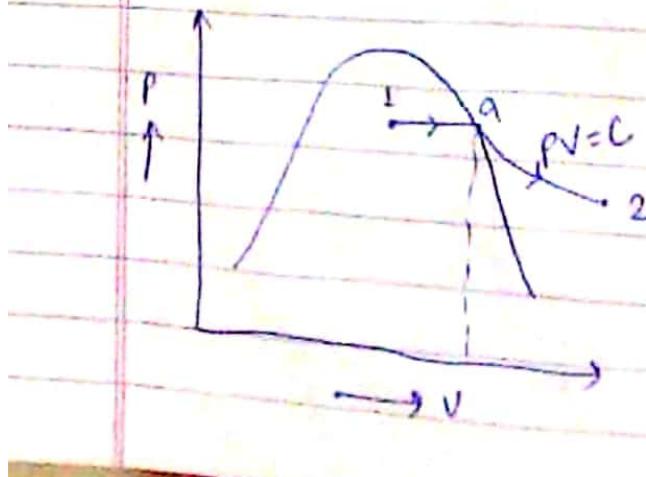
$$Q = W + \Delta U$$

$$= 0 + (U_2 - U_1)$$

$$Q = U_2 - U_1$$

$$= (h_2 - p_2 V_2) - (h_1 - p_1 V_1)$$

Constant Temperature Vapour Process



$$\begin{aligned} p_1 &= p_a \\ T_1 &= T_a \end{aligned} \quad \left. \begin{array}{l} \text{wet region} \end{array} \right\}$$

In superheated region,

a-2, Hyperbolic

$$p_a V_a = p_2 V_2$$

① Process 1-a :-

Heating of steam as constant temp.

$$W_{1-a} = p(V_a - V_1)$$

$$p_1 = p_a = p$$

$$V_a - V_1 = (h_a - h_1) - p(V_a - V_1) + p(V_a - V_1)$$

$$\Delta_{1-a} = h_a - h_1$$

$$Q = \Delta U + W$$

$$\Delta_{1-a} = (h_a - h_1) - p(V_a - V_1) + p(V_a - V_1)$$

$$\Delta_{1-a} = h_a - h_1$$

② Process a-2 in superheated region :-

Follows Boyle's law

$$pV = C$$

$$p_a V_a = p_2 V_{sup}$$

$$V_{sup} = \frac{p_a}{p_2} \cdot V_a$$

Charles' Law -

$$\frac{-V_2}{T_2} = \frac{V_a}{T_a}$$

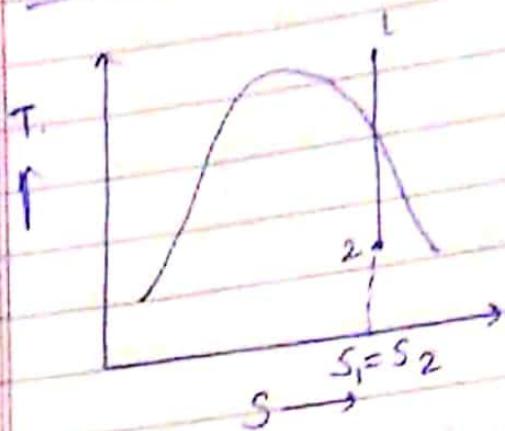
$$V_{sup2} = V_a \cdot \frac{T_2}{T_a}$$

Reversible adiabatic vapour process -

1 kg. of steam

$$S_1 = S_2$$

$$S_1 + x_1 S_{fg1} = S_2 + x_2 S_{fg2}$$



If superheated

$$S_{g1} + C_p \log_e \frac{T_{\text{sup},1}}{T_{\text{sat},1}} = S_{f2+}$$

$$x_2 S_{fg2}$$

$$x_2 = \frac{S_{g2} + C_p \log_e \frac{T_{\text{sup},2}}{T_{\text{sat},2}}}{S_{fg2}}$$

Change in Int. energy

$$\Delta U = U_2 - U_1 \\ = (h_2 - p_2 v_2 x_2) - (h_1 - p_1 v_1 x_1)$$

$$\Delta U = 0$$

Apply I law

$$Q = W + \Delta H$$

$$0 = W_{1-2} + \Delta H$$

$$W_{1-2} = -\Delta H$$

$$= -(U_2 - U_1)$$

$$W_{1-2} = U_1 - U_2$$

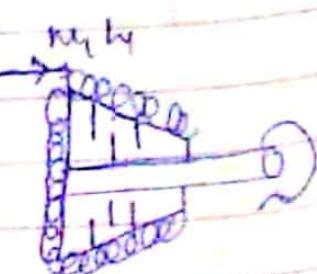
Energy Eqn -

$$h_1 + Q = h_2 + W$$

$$h_1 - W + Q = h_2$$

$$Q = 0$$

$$W = h_1 - h_2$$



Polytropic vapour process -

Consider a mass of steam undergoing a polytropic process from stage 1 to 2.

$$p_1 V_1^n = p_2 V_2^n$$

$$p_1 (x_1 v g_1)^n = p_2 (x_2 v g_2)^n$$

$$x_2 = \frac{x_1 v g_1}{v g_2} \left(\frac{p_1}{p_2} \right)^{1/n}$$

$$p_1 V_1^n = p_2 (V_{sup2})^n$$

$$V_{sup} = x_1 N g_1 \left(\frac{p_1}{p_2} \right)^{1/n}$$

$$\frac{V_{sup2}}{T_{sup2}} = \frac{v g_L}{T_{sat}}$$

$$W = p_1 V_1 - p_2 V_2$$

~~+ n - 1~~

$$\Delta U = U_2 - U_1$$

$$= (h_2 - p_2 v_2) - (h_1 - p_1 v_1)$$

$$\Omega = \Delta U + W$$

Throttling -

$$h_1 = h_2$$

$$W = 0$$

$$\Omega = 0$$

Measurement Of dryness fraction of steam -

- ① Bucket / Barrel calorimeter
- ② Separating calorimeter
- ③ Throttling calorimeter
- ④ Separating & Throttling
- ⑤ Electrical calorimeter

Q. Calculate the dryness fraction of steam which has 1.25 kg H₂O in suspension with 40 kg of steam.

$$\text{Def: } \eta = \frac{m_{\text{dry steam}}}{m_{\text{dry steam}} + m_{\text{water}}} = \frac{m_s}{m_s + m_f}$$

$$= \frac{40}{40 + 1.25} = \frac{40}{41.25} = 0.97$$

Q. A spherical shell of 30 cm radius attains saturated steam & water at 300°C. Calculate the mass of each if their volumes are equal.

Let -

$$V = \frac{4}{3} \pi r^3 = \frac{4}{3} \pi \times (30)^3 = \frac{108000 \times \pi}{3} = 36000 \pi$$

$$= 113047.34 \text{ cm}^3$$

60 cm

$$= 0.11304 \text{ m}^3$$

(From $\frac{r}{4}$ of $\frac{\pi}{3}$ cm^3 and m^3)
Table (mother) corresponding to 300°C temp., specific volume of saturated liq. / water $v_f = 0.001404 \text{ m}^3/\text{kg}$ and specific volume of sat. vapour $v_g = 0.0217 \text{ m}^3/\text{kg}$

Vol. of saturated liquid & vapour are equal.

$$\text{Vol. of sat. liquid } v_f = \frac{0.11304}{2} = 0.0565 \text{ m}^3$$

$$\text{Vol. of sat. vapour } v_g = \frac{0.11304}{2} = 0.0565 \text{ m}^3$$

Mass of liquid, $m_f = \text{Vol.} \times \text{density}$

$$= \frac{\text{Vol.}}{\text{f. wt}} = \frac{0.0565 \text{ m}^3}{0.001404 \text{ m}^3/\text{kg}}$$

$$= 40.256 \text{ kg}$$

$$\text{Mass of vapour, } m_g = \frac{0.0175}{0.0217} = 2.604 \text{ kg}$$

Q1. A tank contains 100 kg. of liquid water and 5 kg of water vapour under saturation conditions at 20°C if the specific volume of sat. vapour at that temp. is taken as 57.79 m³/kg. Calculate volume of the tank & moisture content of the mixture.

Sol:-

$$100 \text{ kg. - } H_2O, 5 \text{ kg. - } \cancel{\text{sat.}} \text{ vapour}$$

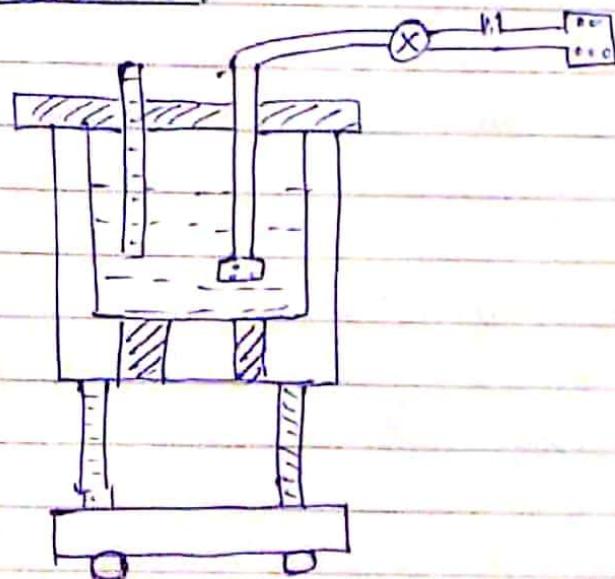
$$V_f = 0.02339, V_g = 0.001002$$

$$V_f = 0.001002, V_g = 57.79$$

$$\text{dryness fraction} = \frac{5}{5+100} = \frac{5}{105}$$

$$\text{Req.} = \text{moisture content} = \frac{100}{105} = 0.002$$

Bucket calorimeter



$$\begin{aligned}
 (m_{cws} - m_{cw}) &= m_s \\
 \Rightarrow m_s (\chi h_{fg} + c_{pw} (t_s - t_{aws})) &= (m_{cw} - m_c) c_{pw} (t_{aws} \\
 &\quad + m_c c_p (t_{aws} - t_{aw})) \\
 \Rightarrow m_s [\chi h_{fg} + c_{pw} (t_s - t_{aws})] &= (t_{aws} - t_{aw}) [m_{cw} - m_c] \\
 &\quad (c_{pw} + \frac{m_c}{m_s} c_p)
 \end{aligned}$$

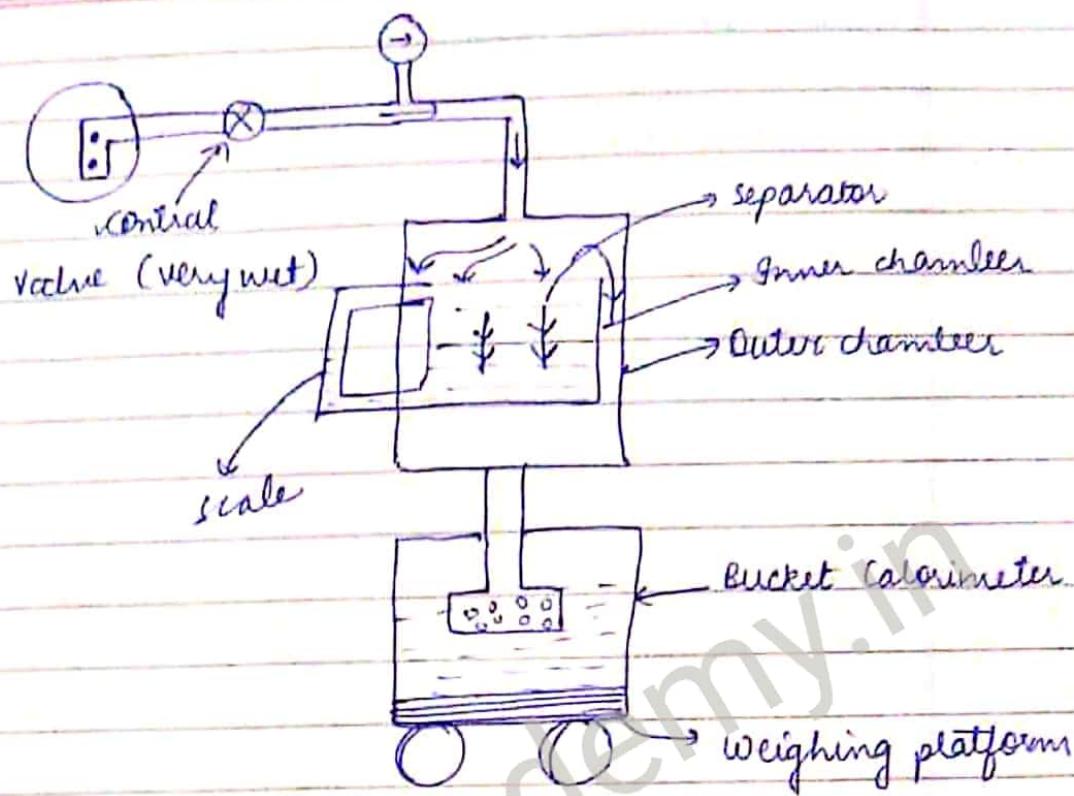
$$\Rightarrow m_s [\chi h_{fg} + c_{pw} (t_s - t_{aws})] = (t_{aws} - t_{aw}) [m_w c_{pw} + m_c c_p]$$

from here we can find out degree of freedom

Separating Calorimeter -

Used to measure probable value of χ of steam if steam is very wet.

dryness



The steam whose dryness fraction is to measured is passed through perforated tube that is put into a main steam pipe.

Moisture is separated mechanically from steam passing through the separator. The water particles due to inertia of the water droplets is passed through the perforation and steam undergoes sudden several dirⁿ of motion when it strikes the waffle plates of the separator. This outgoing steam is then condensed in a bucket calorimeter.

m_w = Mass of water separator.

m_s = Mass of steam condensed in bucket calorimeter.

m_1 = Mass of bucket with water before steam mixing

m_2 = Mass of bucket with water after steam mixing.

$x = \text{dryness fraction}$

$$x_L = \frac{m_S}{m_S + m_W}$$

Q. A sample of steam at 5 bar having an enthalpy of 2350 kJ/kg. calculate specific volume, internal energy and entropy of this sample of steam.

Sol:- At 5 bar, Enthalpy from steam table (page No.-7)

$$h_g = 2748.7 \text{ kJ/kg} \quad (\text{By Mehta \& Mathur, Steam \& other tables})$$

$$h_f = 640.2 \text{ kJ/kg}, \quad h_{fg} = 2108.5, \quad v_g = 0.375 \text{ m}^3/\text{kg}$$

$$\text{Given enthalpy of sample} = 2350 \text{ kJ/kg}$$

\therefore This steam is wet.

Dryness fraction is to be calculated/ worked out.

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

$$2350 = 640.2 + x \times 2108.5$$

$$x = \frac{2350 - 640.2}{2108.5} = 0.81$$

$$\text{Specific volume of wet steam} = x v_g$$

$$= 0.81 \times 0.375$$

$$= 0.304 \text{ m}^3/\text{kg}$$

Internal Energy

$$U = h - PV$$

$$\text{External work of evaporation, } PV = 5 \times 0.304 = 1.5205$$

$$= 1.520 \times 10^5 \text{ Nm}^2$$

$$(1 \text{ bar} = 10^5 \text{ N/m}^2)$$

$$= 152.05 \text{ kJ/kg}$$

$$U = 2350 - 152.05 = 2197.95 \text{ kJ/kg.}$$

Entropy

$$S_{wet} = S_f + x S_{fg}$$

$$= 1.861 + \frac{0.81}{0.304} \times 4.961$$

$$= 5.879 \text{ kJ/kg K}$$

Q-2) Calculate specific volume, internal energy, entropy of steam at 15 bar pressure and 220°C, the volume of water can be neglected. Specific heat of superheated steam = 2.2 kJ/kg

Sol:-

At 15 bar,

$$v_g = 0.132 \text{ m}^3/\text{kg}, h_f = 844.9 \text{ kJ/kg}$$

$$h_{fg} = 1947.3 \text{ kJ/kg}, s_f = 2.315 \text{ kJ/kg K}$$

$$s_{fg} = 4.130 \text{ kJ/kg K}, T_{sat} = 198.3^\circ\text{C}$$

Total Enthalpy / total heat of 1 kg. of steam (superheated)

$$h_{sup} = h_f + h_{fg} + (p_s (T_{sup} - T_{sat}))$$

$$= 844.9 + 1947.3 + 2.2 [220 - 198.3]$$

$$= 844.9 + 1947.3 + 2.2 \times 21.7$$

$$= 2839.94 \text{ kJ/kg}$$

Charles Law

$$\frac{V_{sup_2}}{T_{sup_2}} = \frac{V_g}{T_{sat_2}}$$

$$V_{sup_2} = \frac{0.132 \times (220 + 273)}{(198.3 + 273)}$$

$$= \frac{0.132 \times 493}{471.3} = 0.138$$

Internal Energy

$$U = h_{sup} - PV$$

$$= 2839.94 - 15 \times 0.138 \times 100$$

$$\text{kJ/kg}$$

Entropy

$$S_{\text{sup}} = S_f + S_{fg} + C_p s \log \frac{T_{\text{sup}}}{T_{\text{sat}}}$$

$$= 2.315 + 4.130 + 2.2 \log \left(\frac{220+273}{19.8 \cdot 198.3 + 273} \right)$$

$$= 6.445 + 2.2 \times 0.1038$$

Q-③ A pressure cooker contains 2 kg. of steam at 5 bar pressure and 0.9 dryness fraction. Find quantity of steam which must be transferred so that quality of steam becomes 60% dry. Find quantity of heat which must be transferred in above case. Calculate pressure & temp. of steam that exist in the cooker after heat rejection.

Q-④ A rigid tank of 1 m^3 volume contains dry sat. steam at 0.2 MPa. Due to poor insulation, there is heat transfer to surroundings & pressure drops of 0.1 MPa after some time. Calculate for the final condⁿ of steam & amount of heat transfer.

Q-⑤ Wet steam at 20 bar pressure & 0.9 dryness fraction is heated reversibly at const. pressure to a temp. 300°C. Calculate work done, heat supplied & changes in int. energy & entropy.

Q-⑥ Dry sat. steam initially at a pressure of 600 kPa contained in a thermally insulated cylinder fitted with a frictionless piston as the piston moves slowly, the steam expand to a pressure 60 kPa. Calculate WD by steam.

Q. (1) Steam at 10 bar & 250°C expands polytropically to a pressure 1 bar. Polytropic exponent 1.2. Calculate i) vol. & temperature after expansion, heat interact., change in entropy.

Q. (2) In a steam turbine, 3 kg/s of steam expand isothermally from initial pressure 20 bar & 350°C to a final temp. 85°C . i) calculate the quality of steam at end of process.
ii) steady flow work done.

Q. (3) Steam at 9 bar, 0.93 dry contained in a vessel of 0.9 m^3 volume. The delivery valve is opened & steam is blown off until the pressure reduces to 4 bar. Delivery valve is then closed & vessel is cooled until the pressure is 3 bar. Assume enthalpy remains constant during blowing of period, calculate
i) mass of steam blown off
ii) Quality of steam in vessel after cooling.

Q. (4) In a combined separating & throttling calorimeter following data observed

pressure in steam main pipe = 14 bar

after throttling = $13.2 \text{ cm of } \text{Hg}$ (mercury)
mass of steam collected in the separator
 $= 0.8 \text{ kg / min.}$

discharge from throttling calorimeter = 10 kg / min

Temp. of steam after throttling = 115°C .

Barometer reading = 76 cm Hg
Calculate

- dryness fraction of steam in the steam main pipe
- velocity of flow in steam main pipe if diameter is 12 cm. & flow of steam 130 kg/min .

- iii) Mass of water required to condense the steam after throttling calorimeter if the temp. rise in the cooling water is 12°C .
- a. (i) 3kg of steam at 10bar & 250°C undergoes const. pressure process, the resulting steam is wet having dryness frac" 0.6, Calc. wd, change in enthalpy, heat transfer assuming non-flow process.

Glossimeter

Dryness factor measurement apparatus

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