

The behaviour of matter can be studied in two views, they are .

Macroscopic view:-

- A certain quantity of matter is considered
- Neglecting the events occurring in molecular level.
- Effects are viewed as a whole and perceived by human senses.
- Ex: The change in pressure can be sensed by human beings and is measured by a pressure gauge.

Microscopic view:-

- The matter is viewed in its molecular level.
- The change of physical and chemical properties are accounted due to the change in rate of collision between the molecules.
- Entire (molecular) behaviour is integrated to know about the behaviour of the matter.
- Also called as statistical thermodynamics.
- Ex: All the properties can be viewed from this aspect .

Thermodynamics:-

- Science dealing with the energy transfer of a substance and its effect on the physical properties of the substance .

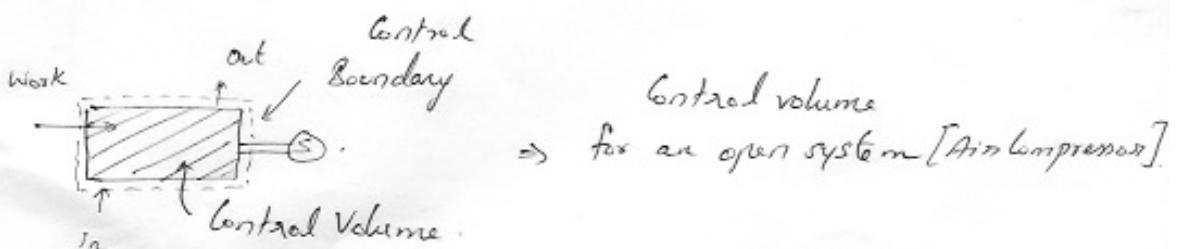
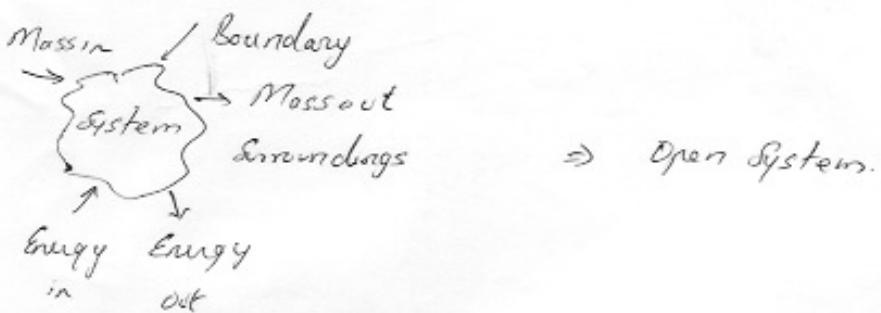
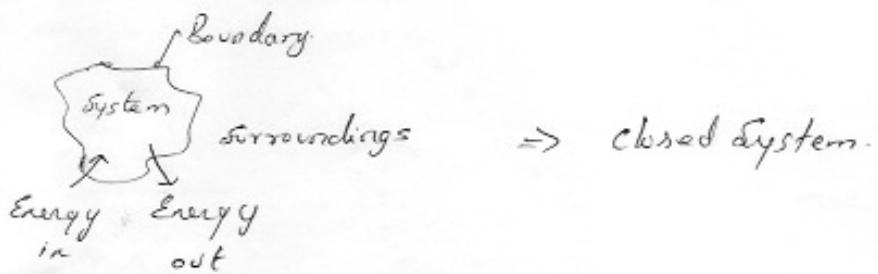
- A quantity of matter on a specified region upon which the attention is made.
- Rest of the things other than the system constitute surroundings.
- System and surroundings are separated by system boundary.
- [System + Surrounding] \Rightarrow Universe.

Types of thermodynamic systems:

- Closed system:-
 - ① No mass transfer but energy transfer is available.
 - ② Energy is transferred from the system or to the system.
 - ③ Ex:- A system consisting of matter.
 - ④ Volume can change in a fixed boundary.
- Open system:-
 - ① Mass transfer and energy transfer are experienced.
 - ② Energy transfer is bidirectional.
 - ③ Ex:- All engineering devices like engines & compressors are open systems.
 - ④ A system consisting of a specified region.
 - ⑤ For an open system the masses are focused within certain boundary and volume called as control surface

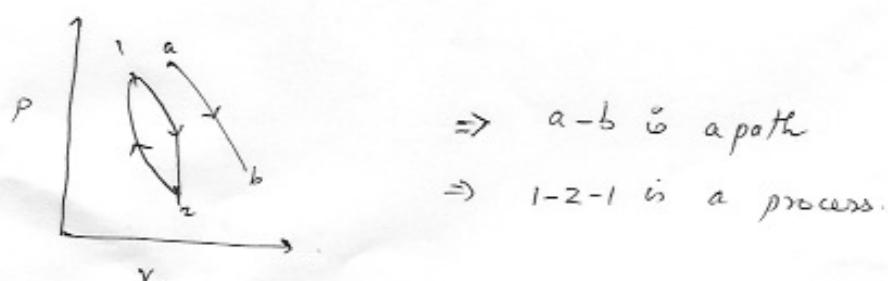
- Isolated system:

- No energy transfer and no mass transfer
- No interaction between system and surroundings.



Properties:-

- The characteristics that describe the physical condition of a system is called as its properties.
- Ex: Pressure, Temperature.
- If all the properties concerned has a definite values, then the system exist in a definite state.
- Any operation done in a system changes the properties of the system is said to have a change in state.
- The succession of states obtained during a state change is called as the path.
- A specified path is called as a process. [A constant pr. ex: process].
- When along an operation the initial and final conditions are the same then it is called as a thermodynamic process.



Homogeneous & heterogeneous systems :-

- Substance can exist in 2 phases solid, liquid, gaseous.
- System consisting of a single phase is homogeneous system.
- System consisting of a combination of phases is called

- Ex: Water placed in a container, [Water + Steam] in a heated boiler. [Air + Water]

Intensive properties:

- The properties that are independent of mass in a system.
- Ex: Pressure, Temperature, Density.
- The Extensive Properties.
- The properties that are dependent of mass in a system.
- Ex: Volume, Mass, Energy.

Note:

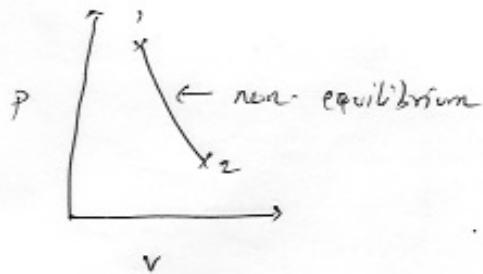
- Extensive properties \Rightarrow Intensive properties
Unit mass
- Ex: Specific volume, specific energy.

Thermodynamic Equilibrium:

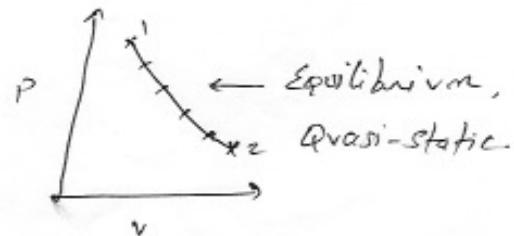
- Thermodynamic Equilibrium is satisfied when the mechanical, chemical and thermal equilibrium are satisfied.
- Mechanical Equilibrium - No unbalanced forces.
- Chemical Equilibrium - No mass transfer or chemical reaction.
- Thermal Equilibrium - No temperature difference.
- If the above conditions aren't satisfied, the system will undergo changes [mechanical, chemical, thermal] to restore equilibrium.
- In investigations, all systems are assumed to be in equilibrium.

Quasi-static Process:

- Gas in a cylinder is balanced by a piston upon which weights are placed. $[P_1, V_1, T_1]$
- If the weights are removed the piston is pushed up by the pressure experienced to a new position. $[P_2, V_2, T_2]$
- The path along $1 \rightarrow 2$ can't be traced as the process is ~~very~~ ~~one~~ fast.
- If the same operation is done from $1 \rightarrow 2$ by removing parts of the entire weight, it is possible to trace the points of equilibrium from $1 \rightarrow 2$.
- This process is called as quasi-static process or process that is traced with a number of equilibrium points.
- It is also called as a reversible process.



Weight removed as
a whole



Weight removed as
parts.

Pure substance:

- Has same chemical composition throughout its mass and the relative constituents' proportion is available constant.
- Ex: Air, [Water + steam], [Air + Water].
- Any 2 properties of a pure substance is known, it is possible to find the other properties using thermodynamic relations and is called as a two property rule.

Units & Dimensions:

- Force \Rightarrow Push or a pull (or) $m \times a \Rightarrow$ Newton.

- Pressure \Rightarrow Force per unit area $\Rightarrow N/m^2$.

④ Note: $1N/m^2 = 1 \text{ Pascal}$.

$10^5 \text{ Pascal} = 1 \text{ bar}$.

1 atmosphere = 1.01 bar.

- ① Gauge pressure is the relative pressure of the system with the surroundings.

② Absolute pressure is the relative pressure of the system with respect to vacuum.

③ $P_g = \rho g z \text{ N/m}^2$.

where P_g - Gauge pressure.

z - Datum

ρ - Density

g - Acceleration due to gravity.

④ Pressure is measured by manometers, transducers for engineering applications.

- Specific volume $\Rightarrow \frac{\text{The volume occupied by the system}}{\text{unit mass of the system}}, \text{m}^3/\text{kg}$
- Density $\Rightarrow \frac{\text{Mass}}{\text{volume}}, \text{kg/m}^3$.
- Energy \Rightarrow capacity to do work, Nm (or) joules.
 (i) $1 \text{Nm} = 1 \text{joule}$.
- Power \Rightarrow Rate of doing work, Watts.
 (ii) $1 \text{Watt} = 1 \text{J/s} = 1 \cdot \text{Nm/s}$

Problem:-

- Gas pipeline, 1 limb to pipeline, 1 limb to atmosphere, Difference in heights of Hg column is 562 mm, Atm. pressure is 761 mm of Hg & ρ of Hg is $13,640 \text{ kg/m}^3$. Find pressure of the pipeline.

Soln:

$$P = P_0 + \rho g z$$

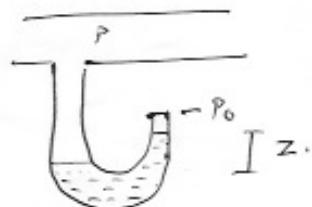
$$\text{But, } P_0 = \rho g z_0.$$

$$\Rightarrow P = \rho g z_0 + \rho g z.$$

$$= [(13640) \times (9.8 \text{ m/s}^2) \times (0.761)] + [(13640) \times (9.8) \times (0.562)]$$

$$= 177 \times 10^3 \text{ N/m}^2$$

$P = 1.7 \text{ bar}$



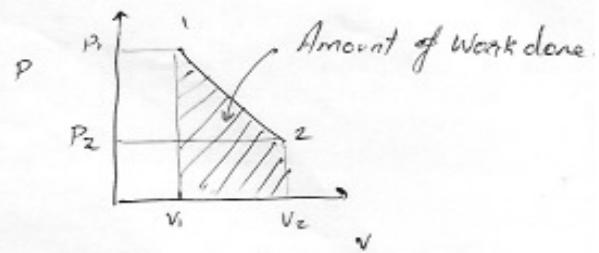
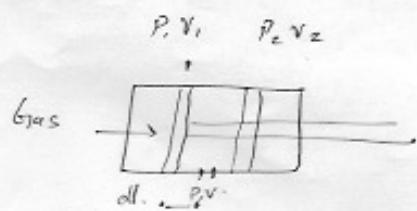
Zeroth law of thermodynamics:-

- A is in thermal equilibrium with B and separately with C, implies B and C are in thermal equilibrium with each other.
- When two bodies of different temperatures are brought together, the temperature of both the bodies changes until they reach a common temperature constituting a thermal equilibrium.
- Mechanics - Force.
- Dynamics - Velocity.
- Thermodynamics - Temperature.
- The measure of heat is obtained by a device called as thermometer.
- Usually a mercury quantity is enclosed in a evacuated capillary tube. The change in mercury level indicates the change in temperature.

Work:

- It is the product of force involved and the displacement.
- In thermodynamics, work transfer is happening between the system and surroundings through energy interactions.
- If work is done by a system, it attains a positive value and if work is done on a system, it attains a negative value.

Expression for work done:



- States 1, 2 are assumed to be in thermal equilibrium.
- Intermediate points are also in thermal equilibrium.

$$dW = F \cdot dL = P_a \cdot dL \quad [\text{as } P = \frac{F}{a}].$$

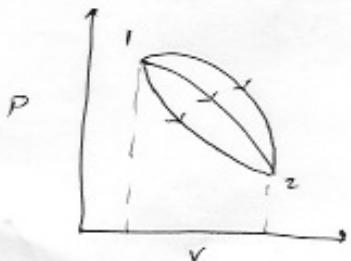
$$\Rightarrow dW = P_a \cdot dL.$$

$$\Rightarrow dW = PV \quad [\text{as } a \cdot dL = V].$$

$$W_{1 \rightarrow 2} = \int_{V_1}^{V_2} P \cdot dV.$$

- Provided the process is quasi-static.
- Work transfer is a path function and is understood from the graph.

Path and Point Functions:-



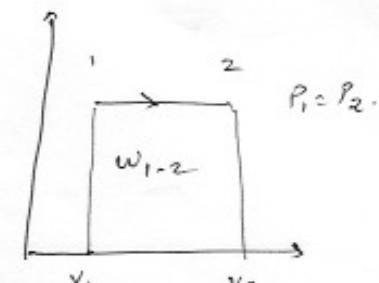
- The area under each path differs and hence the work transfer.
- So work transfer is path dependent.

- Whereas the properties like P, V are point functions at 1, 2.

Work done for various processes:-

- Constant Pressure:-

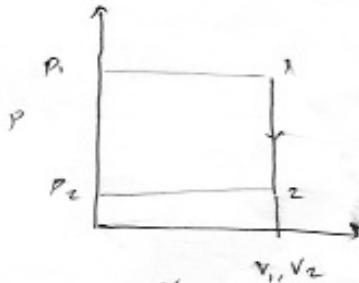
$$W_{1-2} = \int_{V_1}^{V_2} P \cdot dV = \int_{V_1}^{V_2} P \cdot dV$$



$$W_{1-2} = \int_{V_1}^{V_2} P \cdot dV = P(V_2 - V_1)$$

- Constant Volume:-

$$W_{1-2} = \int_{V_1}^{V_2} P \cdot dV = 0 \quad [\text{as } V_1, V_2 \text{ are same}]$$



- PV = c :-

$$W_{1-2} = \int_{V_1}^{V_2} P \cdot dV$$

$$= P_1 V_1 \int_{V_1}^{V_2} \frac{dV}{V}$$

[as $PV = P_1 V_1 = c$].

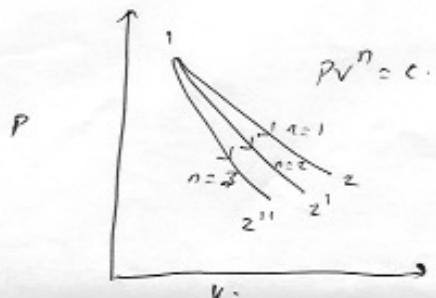
$$\Rightarrow P = \frac{P_1 V_1}{V}$$

$$W_{1-2} = P_1 V_1 \ln \frac{V_2}{V_1} \quad \text{or} \quad P_1 V_1 \ln \frac{P_1}{P_2}$$

- $PV^n = c$:-

$$P_1 V_1^n = P V^n = c$$

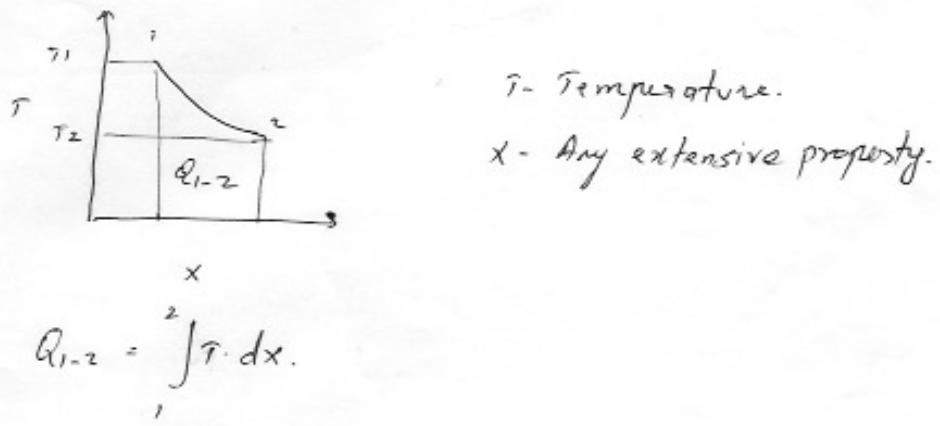
$$\Rightarrow W_{1-2} = \frac{P_1 V_1 - P_2 V_2}{n-1}$$



Heat transfer:

[only]

- Heat transfer is effected by temperature difference across a system boundary.
- Heat flow into a system is taken positive and outward from a system is taken negative.
- Work & heat transfer are boundary functions.
- Unlike work, heat transfer is a path function as shown in graph.

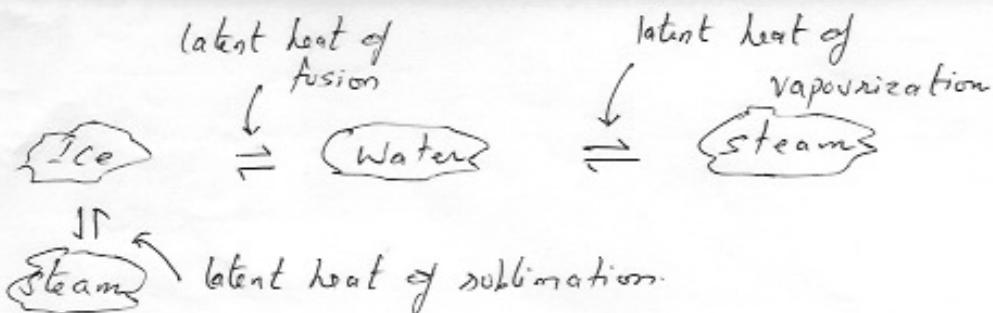


Specific heat

- The amount of heat required to raise unit temperature of a unit mass. Denoted by c , q_p , c_v .
- where $c = \frac{Q}{m \cdot \Delta T}$ ($J/kg \cdot K$)
- mass \times specific heat = heat capacity of the system.

Latent heat:

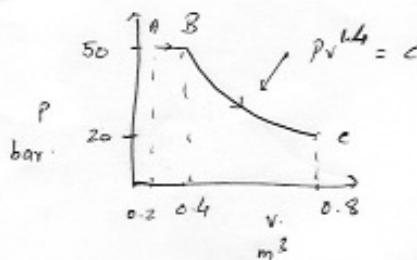
- The amount of heat required to change the phase of unit mass at constant pressure at constant temperature.



- l_{fv} is not affected by pressure but l_{lv} is affected.

Problem:-

- Find total Workdone: [Expansion]



Soln:-

$$\text{Total } W = W_{A-B} + W_{B-C}$$

$$= \int_A^B p \cdot dv + \int_B^C p \cdot dv \quad [1 \text{ bar} = 10^5 \text{ N/m}^2]$$

$$= P [V_B - V_A] + \left[\frac{P_1 V_1 - P_2 V_2}{n-1} \right]$$

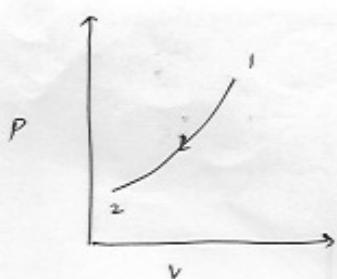
$$= P [V_B - V_A] + \left[\frac{P_B V_B - P_C V_B}{n-1} \right]$$

$$= 50 \times 10^5 [0.4 - 0.2] + \left[\frac{(50 \times 10^5) \times 0.4 - (20 \times 10^5) \times 0.8}{1.4-1} \right]$$

$$= (1 \times 10^6) + \left[\frac{2 \times 10^6 - 1.6 \times 10^6}{0.4} \right]$$

$$= (1 \times 10^6) + (1 \times 10^6)$$

$$= 2 \times 10^6 \text{ N.m.}$$



Given:

$$m_1 = 1.5 \text{ kg} , \rho_1 = 1.16 \text{ kg/m}^3$$

$$P_1 = 0.1 \text{ MPa}$$

$$P_2 = 0.7 \text{ MPa}$$

$$PV = \text{constant}$$

[Compression]:

Find:

Work done.

Soln:-

$$W = P_1 V_1 \ln \frac{V_2}{V_1} = P_1 V_1 \ln \frac{P_1}{P_2}$$

$$\Rightarrow P_1 V_1 \ln \frac{P_1}{P_2} = (10^5 \times V_1) \ln \left(\frac{10^5}{7 \times 10^5} \right)$$

$$\Rightarrow 0.1 \times 10^6 \text{ Pa} - 0.7 \times 10^6 \text{ Pa}$$

$$\Rightarrow \rho = \frac{m}{V}$$

$$= 1 \times 10^5 \text{ Pa} - 7 \times 10^5 \text{ Pa}$$

$$\Rightarrow V = \frac{m}{\rho} = \frac{1.5}{1.16} = 1.29 \text{ m}^3$$

$$= 1 \times 10^5 \text{ N/m}^2 - 7 \times 10^5 \text{ N/m}^2$$

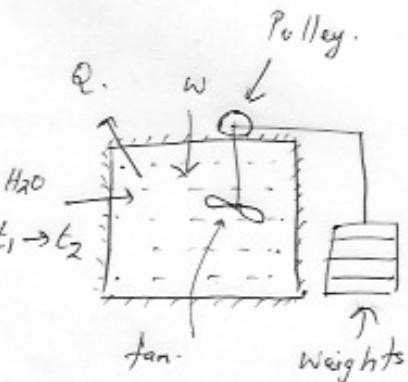
$$\Rightarrow (10^5 \times 1.29) \cdot \ln \left(\frac{1}{7} \right)$$

$$= 1.29 \times 10^5 \cdot \ln (0.14)$$

$$\approx 251.6 \text{ KN-m (or) } \text{KJ}$$

First law of Thermodynamics:-

- Types of Energy
 - ① Transit - Work and heat
 - ② Stored - P.E + K.E + I.E.
- Closed system: (cyclic process)
 - Work input is given to a closed system containing water in a vessel.
 - Input is given by weight connected to a paddle wheel.
 - As the input is given the water gets heated up from t_1 to t_2 . The container is insulated.
 - Consequently after the work input, insulation is removed and the heat transfer takes place from system to the surroundings till reaching thermal equilibrium.
 - It is found that in this cycle process,
- $\oint dw = \oint dQ$
- , where J is Joule's constant
for a cyclic process.
- Closed system: (state change)
 - Q amount of heat is transferred to a system, that produces W amount of work.
 - The difference in this energy transition is the stored energy or the total stored energy.



$$\Rightarrow Q - W = \Delta E.$$

$$\Rightarrow Q = \Delta E + W \quad \text{for a change of state}$$

$$- \Delta E = P.E + K.E + \Delta U$$

Where, ΔE - Total Energy

$P.E$ - Potential energy due to datum

$K.E$ - Kinetic energy due to motion of mass

ΔU - Internal energy due to microscopic properties

- In absence of motion and gravity, means v and $h \Rightarrow 0$,

$$\Delta E = \Delta U.$$

- From above eqn,

$$Q = \Delta U + W \quad (\text{or}) \quad Q = \Delta U + \int P dV$$

- For an isolated system $dQ=0$, $dW=0$, $dE=0$.

Perpetual Motion Machine of First kind:

- A machine that produces work continuously without consuming equivalent amount of heat violates the law of conservation of energy [First law] is called as PMM-I.

- First law states that energy can neither be created nor destroyed and is transferred from one form to another.

Limitations of the first law:

- The energy transfer in a closed system is not direction specific i.e., from a hot body to cold body or vice-versa.
- Second law indicates the quality of energy transfer and its directions.

Problem :-

Given:

Gas is compressed from

0.3 m^3 , 0.105 MPa to
 0.15 m^3 , 0.105 MPa .

$$Q = 37.6 \text{ kJ}$$

Find ΔU .

Soln:-

$$Q = \Delta U + W \rightarrow ①$$

$$\Rightarrow W = \int_{V_1}^{V_2} P \cdot dV = P [V_2 - V_1] = -15.75 \text{ kJ}$$

$$① \Rightarrow -37.6 = (U_2 - U_1) - 15.75$$

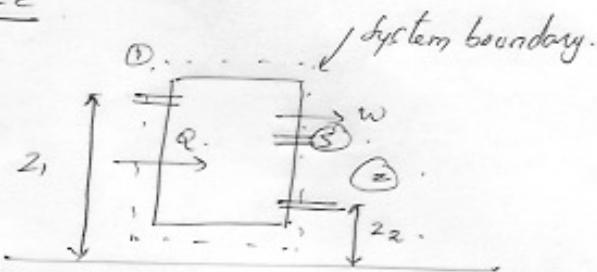
$$(or) (U_2 - U_1) = \boxed{-21.85 \text{ kJ}}$$

ΔU decreases by 21.85 kJ

Steady flow

→ It is a flow, in which the physical properties doesn't vary with respect to time for each & every state point.

S.F.E.E



→ Mass flow rate & energy flow rate are constant in a steady flow.

$$\left. \begin{array}{l} \text{Total energy} \\ \text{of a system} \end{array} \right\} = P.E + K.E + I.E + F.E$$

$$P.E = mgz_1$$

$$K.E = \frac{1}{2} m v^2$$

$$I.E = m u_1$$

$$F.E = m(p_1 v_1)$$

→ [Total input energy = Total output energy] from law of energy conservation,

$$\Rightarrow Q + m g z_1 + \frac{1}{2} m v_1^2 + m u_1 + m(p_1 v_1) = \\ W + m g z_2 + \frac{1}{2} m v_2^2 + m u_2 + m(p_2 v_2).$$

(or)

$$\boxed{m \left[g z_1 + \frac{v_1^2}{2} + u_1 + (p_1 v_1) \right] + Q = m \left[g z_2 + \frac{v_2^2}{2} + u_2 + (p_2 v_2) \right] + W}$$

where,

m - mass of fluid.

g - acceleration due to gravity.

z - datum or height from ground.

v - velocity

e - specific internal energy.

P - Pressure

v^* - specific volume

Q - heat supplied

W - Work done.

→ Mass balance:

Mass flow rate entering = Mass flow rate leaving.

$$\Rightarrow \textcircled{w_1} = w_2.$$

(or)
$$\frac{\rho_1 v_1}{\rho_2} = \frac{A_2 v_2}{A_1}$$
 is equation of continuity. $\frac{1 \text{ m/s}}{m^3/\text{kg}} = \text{kg/s}$.

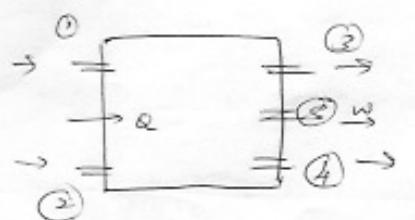
Where,

v_1, v_2 - velocity.

w_1, w_2 = mass flow rates.

A - Gross sectional area.

Example:



Mass balance $\Rightarrow w_1 + w_2 = w_3 + w_4$.

Energy balance:-

- Internal energy + Flow energy = enthalpy.

$$\Rightarrow u + p_1 v_1 = h_1 \quad \left. \begin{array}{l} \\ \end{array} \right\}$$

$$u_2 + p_2 v_2 = h_2 \quad \left. \begin{array}{l} \\ \end{array} \right\}$$

$$\Rightarrow m \left[g_{21} + \frac{v_1^2}{2} + h_1 \right] + q = m \left[g_{21} + \frac{v_2^2}{2} + h_2 \right] + w.$$

Applications:-

Nozzle:- Diffuser:-

$$Q=0, z_1=z_2, w=0.$$

Nozzle \rightarrow \uparrow Velocity
 \downarrow Pressure

$$\Rightarrow \rho \left[\frac{v_1^2}{2} + h_1 \right] = \rho \left[\frac{v_2^2}{2} + h_2 \right]$$

Diffuser \rightarrow \downarrow Velocity
 \uparrow Pressure

$$h_1 + \frac{v_1^2}{2} = h_2 + \frac{v_2^2}{2}.$$

Aircraft engine

$$v_1 \text{ is negligible} \Rightarrow h_1 = h_2 + \frac{v_2^2}{2}.$$

$$\Rightarrow v_2 = \sqrt{2(h_1 - h_2)} \text{ m/s}$$

Throttling device:-

$$Q=0, z_1=z_2, w=0.$$

$$\Rightarrow h_1 + \frac{v_1^2}{2} = h_2 + \frac{v_2^2}{2}.$$

Throttling device \rightarrow Pressure drop.

$$\text{if } v_1 = v_2 \Rightarrow h_1 = h_2$$

[Refrigeration].

→ Turbine & Compressor:

→ Turbine gives power output and hence W is positive.

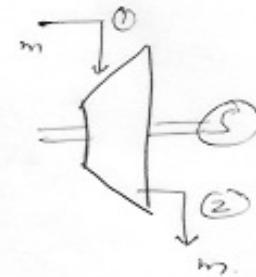
⇒ $v_1 + v_2$ are neglected as velocity is nearly the same,

$z_1 + z_2$ are equal.

Q is neglected.

$$\Rightarrow h_1 = h_2 + \frac{w}{m} \text{ (con)} \quad \boxed{\frac{w}{m} = (h_1 - h_2)}$$

Work done depends upon the enthalpy.



→ Compressor takes in work input and W is negative.

⇒ v_1, v_2, z_1, z_2 are neglected for the same above reason.

$$\Rightarrow h_1 = h_2 - \frac{w}{m} \text{ (con)} \quad \boxed{\frac{w}{m} = (h_2 - h_1)}$$

If Q is considered,

$$\boxed{h_1 - \frac{Q}{m} = h_2 + \frac{w}{m}} \text{ rarely.}$$

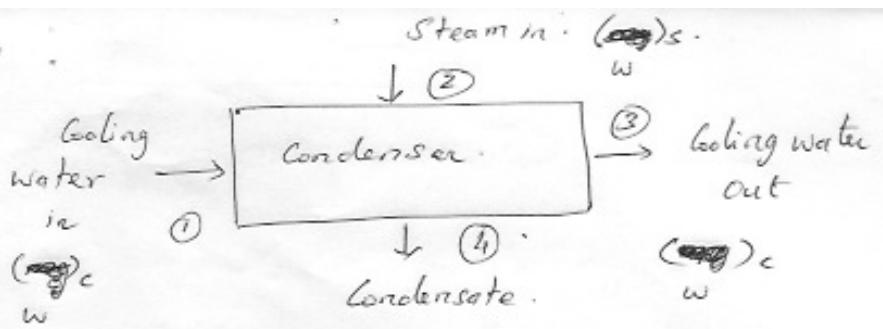
→ Heat Exchanger:

→ Exchanges heat between two fluids. Ex: steam condenser.

⇒ v_1, v_2 is zero, z_1, z_2 is zero, w is zero, Q is zero.

$$\Rightarrow \cancel{(c_v)_1} h_1 + \cancel{(c_v)_2} h_2 = \cancel{(c_v)_3} h_3 + \cancel{(c_v)_4} h_4.$$

$$\Rightarrow \cancel{(c_v)_2} (h_2 - h_1) = \cancel{(c_v)_3} (h_3 - h_4).$$



Throttling \rightarrow constant enthalpy
 when $gZ_1 = gZ_2$ the \therefore

$$\frac{V_1^2}{2} + h_1 + \textcircled{Q} \xrightarrow{\text{no work}} \frac{V_2^2}{2} + h_2 + \textcircled{W}$$

$$\frac{V_1^2}{2} + h_1 = \frac{V_2^2}{2} + h_2$$

$$V_1 \ll V_2 \quad \text{so} \quad V_1 = 0$$

~~$$V_2 > \sqrt{2(h_1 - h_2)}$$~~

Throttling devices used to reduce pressure.

Eg: Refrigerator.

$$\frac{V_1^2}{2} + h_1 = \frac{V_2^2}{2} + h_2$$

$$h_1 = h_2$$

Compressor:

$$m = 0.5 \text{ kg/s}$$

$$V_f = m/s$$

$$P_1 = 100 \text{ kPa}$$

$$V_1 = 0.95 \text{ m}^3/\text{kg}$$

$$V_2 = 5 \text{ m/s}$$

$$P_2 = 700 \text{ kPa}$$

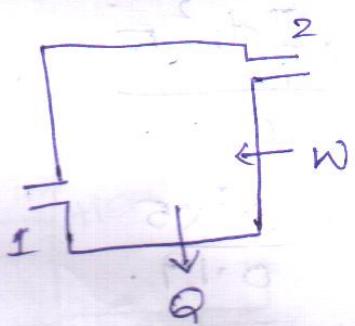
$$V_2 = 0.19 \text{ m}^3/\text{kg}$$

$$u_2 = (u_1 + q) \text{ kJ/kg} \quad u_2 - u_1 = q$$

$$q = 58 \text{ kW}$$

$$-u_f = q$$

$$u_{fg} = -$$



$$m[gz_1 + \frac{v_1^2}{2} + u_1 + P_1 v_1] + Q = m(gz_2 + \frac{v_2^2}{2} + u_2 + P_2 v_2) + W$$

$$\left(\frac{v_1^2}{2} + u_1 + P_1 v_1 \right) + Q = \left(\frac{v_2^2}{2} + u_2 + P_2 v_2 \right) + W.$$

$$\begin{aligned} & \left(\frac{49}{2} + -90 + u_2 + 100(0.95) \right) + 58 \\ &= \left(\frac{25}{2} + (u_1 + 90) + 700(0.19) \right) \\ & \quad + W. \end{aligned}$$

$$\begin{aligned} & \left(\frac{49}{2} + -90 + u_2 + 950 \right) + 58 \\ &= \left(\frac{25}{2} + u_1 + 90 + 133 \right) + W \end{aligned}$$

$$\begin{aligned} & \frac{700 \times 0.19}{6300} \times W \left(\frac{v_1^2}{2} - \frac{v_2^2}{2} + u_1 - u_2 + P_1 v_1 - P_2 v_2 \right) \\ &+ Q \\ & \frac{700 \times 0.19}{6300} \times W \left(\frac{49}{2} - \frac{25}{2} + u_1 - u_2 - 90 + 950 - 133 \right) \\ &+ 58 \\ &= W \end{aligned}$$

$$W = 116.275$$

$$0.5(24.5 - 12.5 - 90 + 950 - 133) + 58 = W.$$

$$0.5(12.5 - 133) + 58 = W$$

$W = 116 \text{ k-watt}$

$$V_1 = \frac{V_2}{\sqrt{\frac{P_1}{P_2}}}$$

$$\frac{\frac{\pi d_1^2}{4} \times 7}{0.95} = \frac{\frac{\pi d_2^2}{4} \times 5}{0.19}$$

$$\frac{d_1^2 \times 7}{0.95} = \frac{d_2^2 \times 5}{0.19}$$

$$\frac{d_1^2 \times 7}{d_2^2 \times 5} = \frac{0.95}{0.19}$$

$$\frac{d_1^2}{d_2^2} \times \frac{7}{5} = \frac{5 \times 5}{0.19}$$

$$\frac{d_1^2}{d_2^2} = 3.57$$

$$\frac{d_1}{d_2} = \underline{1.88}$$

Q. $P_1 = 600 \text{ kPa}$ $P_2 = 100 \text{ kPa}$

$V_1 = 16 \text{ m/s}$ $V_2 = 270 \text{ m/s}$

$Z_1 = 32 \text{ m.}$ $Z_2 = 0$

$\rho_1 = 0.37 \text{ kg/m}^3$ $\rho_2 = 0.62 \text{ kg/m}^3$

$Q = 9 \text{ kJ/kg}$, heat loss $W = 135 \text{ kJ}$

$(u_1 - u_2) > \text{change in internal energy}$

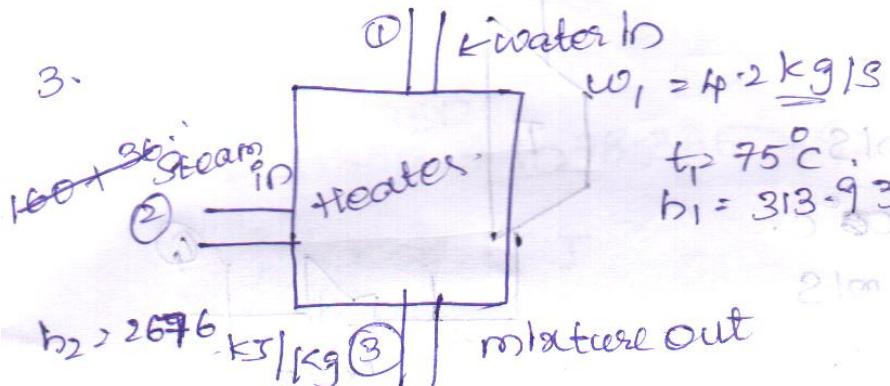
$$(u_1 - u_2 + P_1 V_1 - P_2 V_2 + \frac{V_1^2}{2} - \frac{V_2^2}{2} + g Z_1 - g Z_2)$$

$$u_1 - u_2 = -P_1 V_1 + P_2 V_2 - \frac{V_1^2}{2} + \frac{V_2^2}{2} - g Z_1 + g Z_2 + Q - W = 0$$

$$= -600(0.37) + 100(0.62) - (16)^2 + (270)^2 + 9.8(32)$$

$$\begin{aligned}
 & -222 + 62 - 128 + 36450 + 313.6 + 9-135 \\
 & \Rightarrow 36484.5 \text{ kJ/kg} \\
 & \Rightarrow 20.16 \text{ kJ/kg}
 \end{aligned}$$

convert to $^{\circ}\text{C}$



$$h_2 = 2676 \text{ kJ/kg}$$

$$t_2 = 100^{\circ}\text{C}$$

$$t_3 = 100^{\circ}\text{C}$$

$$b_3 = 419 \text{ kJ/kg}$$

$$w_2 = ?$$

$$w_1 + w_2 = w_3$$

By mass balance

$$w_1 b_1 + w_2 b_2 = w_3 b_3$$

$$4.2 \times 313.93 + w_2 2676 = w_3 419$$

$$(w_1 + w_2) 419$$

$$1318.5 + w_2 2676 - (4.2 + w_2) 419$$

$$1318.5 + w_2 (2676 - 419) = 1759.8 - 419 w_2$$

$$-441.3 + w_2 (2676 - 419) = 0$$

$$-441.3 + 2257 w_2 = 0$$

$$2257 w_2 = 441.3$$

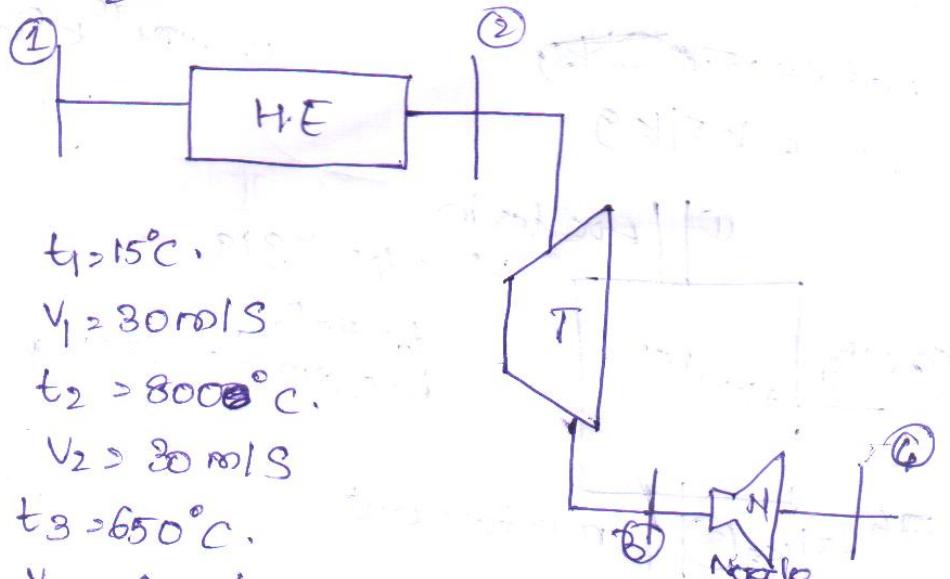
$$w_2 = 0.195 \text{ kg/s}$$

$$Q_{\text{out}} = 20.16 \times 0.195 \times 36000$$

$$72576 \text{ W}$$

$$72.576 \text{ kW}$$

Q2/F12:



$$t_1 = 15^\circ\text{C}$$

$$V_1 = 30 \text{ m/s}$$

$$t_2 = 800^\circ\text{C}$$

$$V_2 = 30 \text{ m/s}$$

$$t_3 = 650^\circ\text{C}$$

$$V_3 = 60 \text{ m/s}$$

$$t_4 = 500^\circ\text{C}$$

$$w = 0 \text{ kg}$$

$$h = c_p t$$

$$c_p = 1.005 \text{ kJ/kg}\cdot\text{K}$$

$$V_4 = \sqrt{2(1.005 \times 923 - 1005 \times 773)} \\ = 549.090$$

$$\frac{V_3^2}{2} + h_3 = \frac{V_4^2}{2} + h_4$$

$$\frac{(60)^2}{2} + 1.005 \times 650 = \frac{V_4^2}{2} + 1.005 \times 50$$

$$\frac{3600}{2} +$$

$$2453.25 =$$

$$\frac{V_4^2}{2} + 502.5$$

$$V_4 = 62.46$$

$$= 552 \text{ m/s}$$

$$Q_{1-2} = w(h_1 - h_2)$$

$$= 2(1.005 \times 15^\circ - 1.005 \times 800^\circ)$$

$$= 2(289.44 - 1078.365)$$

$$= 1599.85 \text{ kJ}$$

Turbine Work:

$$2 \left(\frac{(30)^2}{2} + 1.005 \times 1073 \right) = 2$$

$$2 \left(\frac{(30)^2}{2} - \frac{(60)^2}{2} + 1.005 \times 1073 - 1.005 \times 923 \right) = \underline{\underline{w_t}}$$

$$2 \left(\frac{1350}{2} + 1078.365 - 927.615 \right) = 3002.5 \text{ J}$$

$$2 \left(450 - 1800 + 1078.3 - 927.615 \right)$$

$$\underline{\underline{1078.3 - 927.615}} = \underline{\underline{298.675}}$$

$$w_t = 298.675 \Rightarrow \underline{\underline{298 \text{ kJ}}}$$

Non flow:-

$$P_1 = 0.105 \text{ MPa}$$

$$V_1 = 0.3 \text{ m}^3$$

$$P_2 = 0.105 \text{ MPa}$$

$$V_2 = 0.15 \text{ m}^3$$

$$Q_{1-2} = -37.6 \text{ kJ}$$

To find :-

$$G = \Delta u + w$$

$$Q_{1-2} = u_2 - u_1 + 0.105 \left[0.15 - 0.3 \right]$$

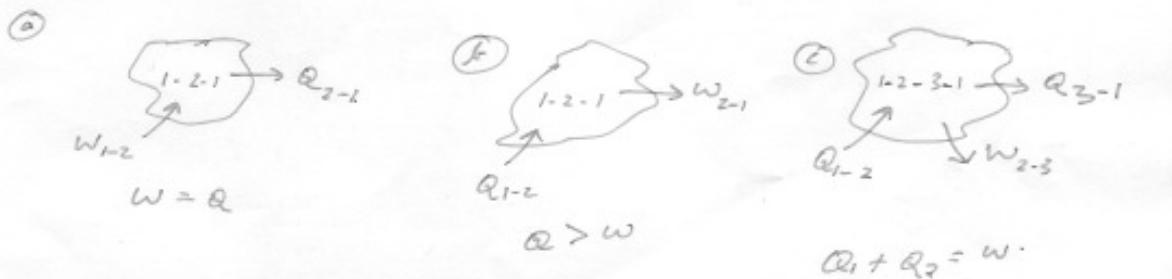
$$-37.6 \times 10^6 \text{ } u_2 - u_1 + 0.105 \times [-0.15]$$

$$-37.6 + 0.01575 \times 10^6 = u_2 - u_1$$

$$u_2 - u_1 = -21850 =$$

Chapter - 2 0 law of thermodynamics.

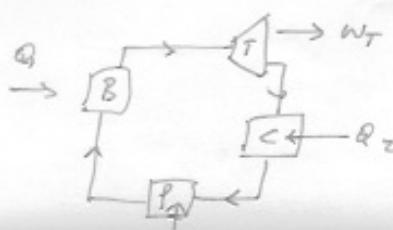
- By Joule's experiment work can be converted completely to heat
- But heat can't be completely converted into work and there exists heat rejection.
- Work - High grade energy.
Heat - Low grade energy.
- Heat flows from a higher temperature body to a lower temperature body and the potential is required to extract work.



- Said by Carnot, low grade energy can't be completely converted to high grade energy in a cycle.

Cyclic heat engine:

- System which executes a heat engine cycle is called cyclic heat engine.
- Heat engine produces mechanical work at the expense of heat.
- Example: steam boiler.



- Net heat transfer is $Q_1 - Q_2$

Net Work transfer is $W_T - W_P$.

- By 1st law of thermodynamics,

$$\Sigma Q = \Sigma W.$$

$$\Rightarrow Q_{net} = W_{net}$$

$$\Rightarrow \boxed{Q_1 - Q_2 = W_T - W_P}$$

- γ of the heat engine is expressed as,

$$\gamma_e = \frac{\text{Net Work output}}{\text{Total heat supplied}} = \frac{W_{net}}{Q_1 - Q_2}$$

$$\Rightarrow \frac{W_T - W_P}{Q_1} = \gamma_e$$

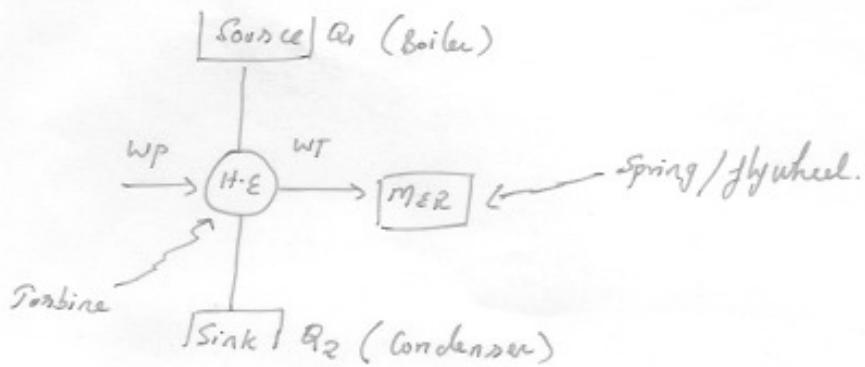
$$\Rightarrow \gamma_e = \frac{Q_1 - Q_2}{Q_1} \Rightarrow \boxed{\gamma_e = 1 - \frac{Q_2}{Q_1}}$$

- Max. W_{net} at given Q_1 determines the cycle efficiency.

Energy reservoirs:

- A large body of infinite heat capacity in rejecting and absorbing heat.
- From the example, Boiler is a source reservoir and Condenser is a sink reservoir.
- Process is assumed to be quasi-static.

- The work output from turbine can be stored as ~~energy~~ spring) and on K.E (flywheel) for further use.



- MER is the mechanical energy reservoir to store work.

Kelvin-Plank Statement:

It is impossible for a heat engine to produce net work output in a cycle if it exchanges heat only with bodies of same temperature

- ⇒ Q_1 and Q_2 can't be same to produce work.
- ⇒ Q_2 can't be maintained zero and heat rejection is a must to do work.
- ⇒ Also $Q \neq W$, hence η_{th} is less than unity.

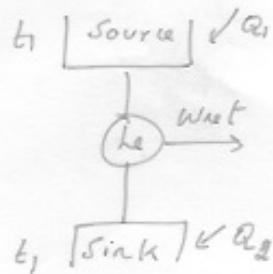
PMM-2:

If a machine gives net work output exchanging heat from only one reservoir [means $Q_2 = 0$] violates Kelvin-Plank's statement and such a machine is PMM-2.

Note:

- Energy reservoirs of finite heat capacities can't give

- First law explains conservation of energy.
- Second law explains the method of utilizing energy.



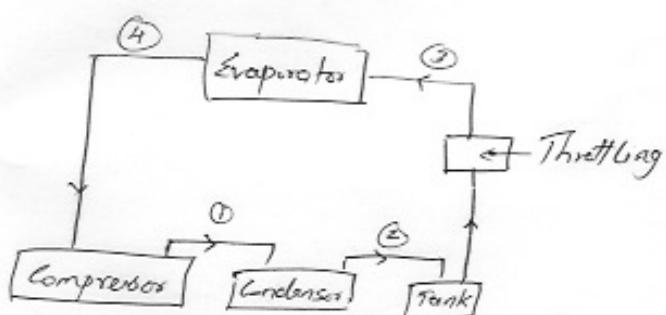
[Carnot machine]

as temperature of Source/Sink is same.

Claudius statement

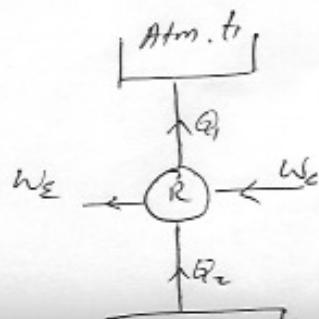
- It is impossible to construct a device in a cycle, to transfer heat from a cold body to a hot body without external workdone.
- Refrigerator and heat pump works on this statement.

Refrigerator



- 1 - high pressure, temp.
- 2 - high pressure, low temp.
- 3 - low pressure, low temp.
- 4 - high temp, low pressure

- Refrigerant is used in the cycle to remove latent heat from the evaporator.

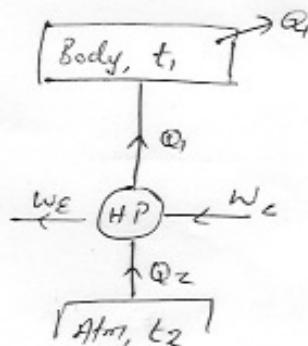


• heat from body is released to atmosphere

$$(C.O.P)_x = \frac{\text{Desired effect}}{W_{net}} = \frac{Q_1}{Q_1 - Q_2} \rightarrow (1)$$

- Heat pump

- Supplies heat into the body (system) when atmosphere is at low temperature.



$$- (C.O.P)_{HP} = \frac{\text{Desired effect}}{W_{net}} = \frac{Q_1}{Q_1 - Q_2} \rightarrow (2)$$

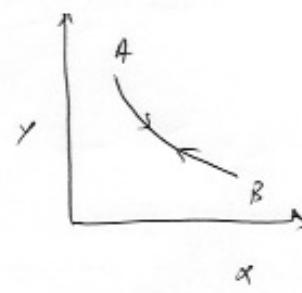
From (1) & (2).

$$(C.O.P)_{HP} = (C.O.P)_x + 1$$

- C.O.P is greater than unity and is ∞ , as $w \neq 0$.

Reversible process:

- It is an ideal process.
- Quasi-static
- Infinitesimally slow
- Maintaining equilibrium points
- Reverse process follows the same path



Irreversible process

- It is a natural process.
- Process is spontaneous.
- Causes for irreversibility are,
 - (i) Lack of equilibrium (ii) Dissipative effects.
 - Ex: - Mechanical,
 - Thermal, *in equilibrium*
 - chemical.
- Because of these factors the reverse of the process is not possible along the same path.

Temperature a function of heat transfer:

- Change in temperature affects change in heat transfer through some proportionality.

$$Q_1, Q_2, \dots = F(T_1, T_2, \dots)$$

(or)

$$\gamma_{th} = \frac{Q_1 - Q_2}{Q_1} = \frac{T_1 - T_2}{T_1}$$

$$(COP)_r = \frac{Q_2}{Q_1 - Q_2} = \frac{T_2}{T_1 - T_2}$$

$$(COP)_{hp} = \frac{Q_1}{Q_2 - Q_1} = \frac{T_1}{T_1 - T_2}$$

Carnot's theorem:

- A reversible engine has the highest efficiency operating between a constant temperature source and constant temperature sink.

- Processes

① Isothermal process.

- $(t_1 - t_2)$ constant
- Q_1 enters
- V increases.

② Adiabatic process.

- t_1 to t_2 . (decreases)

$$\Delta Q = 0$$

- W is done
- V decreases.

③ Isothermal process.

- $(t_2 - t_3)$ constant

- Q_2 leaves.

- V decreases.

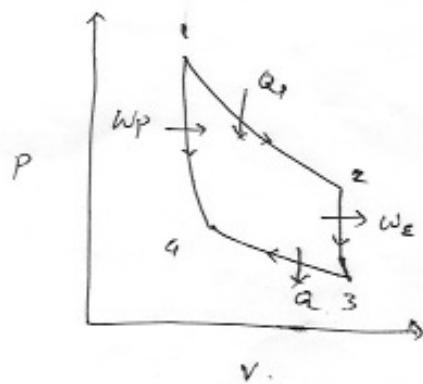
④ Adiabatic process

- t_3 to t_4 (increases).

$$\Delta Q = 0$$

- W is done.

- V increases



In summation,

$$Q_1 - Q_2 = \Delta Q = (W_{1-2} + W_{2-3}) - (W_{3-4} + W_{4-1}) = \Delta W.$$

$\Rightarrow \boxed{\Delta Q = \Delta W}$

Problems:-

Given:-

Heat engine.

$$\text{Source temp} = 800^\circ\text{C} + 273 = 1073\text{K} \quad (\tau_1)$$

$$\text{Sink temp} = 30^\circ\text{C} + 273 = 303\text{K.} \quad (\tau_2)$$

$$W_{net} = 1\text{KW}$$

To find:-

η_{he} and heat rejected.

Soln:

$$\eta_{he} = \frac{\tau_1 - \tau_2}{\tau_1} = \frac{1073 - 303}{1073}$$

$$\boxed{\eta_{he} = 0.718 \text{ or } 71.8\%}$$

Also,

$$\eta_{he} = \frac{W_{net}}{Q_s}$$

$$\Rightarrow Q_s = \frac{W_{net}}{\eta_{he}} = \frac{1}{0.718}$$

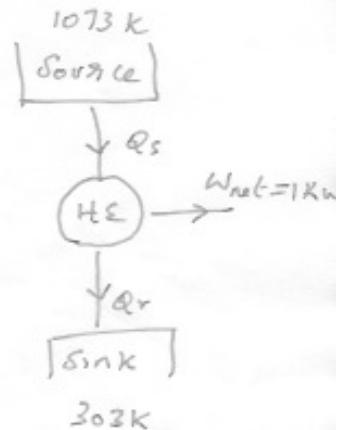
$$\Rightarrow \boxed{Q_s = 1.392\text{ KW}}$$

Also,

$$W_{net} = Q_s - Q_r$$

$$Q_r = Q_s - W_{net}$$

$$\Rightarrow \boxed{Q_r = 0.392\text{ KW}}$$



2 Given:-

Refrigerator.

$$\text{Source temp.} = 30^\circ\text{C} + 273 = 303\text{ K. } (T_1)$$

$$\text{Sink temp.} = -15^\circ\text{C} + 273 = 258\text{ K. } (T_2)$$

$$\text{Heat rejection} = 1.75 \text{ kJ/s} = 1.75 \text{ kW.}$$

To find:-

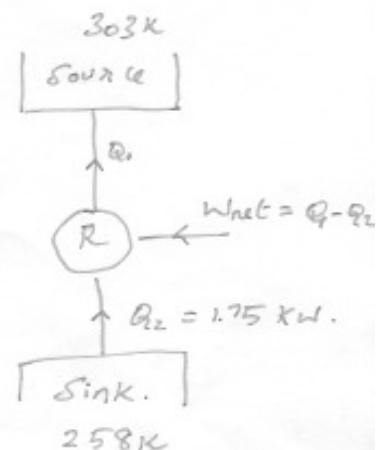
Net.

Soln:-

$$\frac{Q_2}{T_2} = \frac{Q_1}{T_1}$$

$$Q_1 = \frac{Q_2 \times T_1}{T_2} = \frac{1.75 \times 303}{258}$$

$$Q_1 = 2.055 \text{ kW}$$



Also,

$$W_{net} = Q_1 - Q_2 = 2.055 - 1.75$$

$$W_{net} = 0.305 \text{ kW}$$

4. Given:-

Heat engine coupled with refrigerator.

$$\text{Source temp. (h.e)} = 600^\circ\text{C} + 273 = 873\text{K} \quad (T_1)$$

$$\text{Sink temp. (h.e)} = 40^\circ\text{C} + 273 = 313\text{K} \quad (T_2)$$

$$\text{Source temp. (r)} = 40^\circ\text{C} + 273 = 313\text{K} \quad (T_2)$$

$$\text{Sink temp. (r)} = -20^\circ\text{C} + 273 = 253\text{K} \quad (T_3)$$

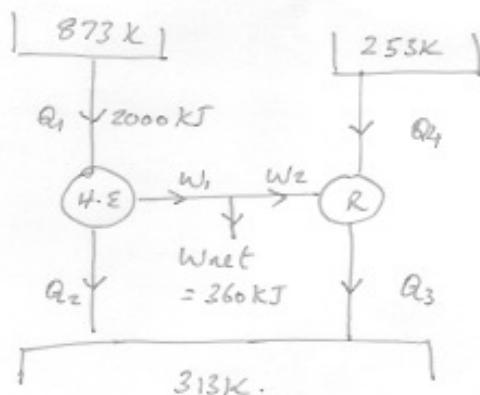
heat supplied to h.e = 2000 kJ, Q_1

Combined W_{net} (h.e & r) = 360 kJ

To Find :-

Heat rejection to 40°C reservoir. $(Q_2 + Q_3)$.

Soln:-



$$\eta_{h.e} = \frac{T_1 - T_2}{T_1} = \frac{873 - 313}{873} = [0.641]$$

Also,

$$\eta_e = \frac{W_{net}}{Q_s} \Rightarrow (W_{net})_{h.e} = Q_s \times \eta_{h.e.} = 2000 \times 0.641$$

$$\Rightarrow \eta_{h.e} \times Q_s \Rightarrow (W_{net})_{h.e} = [1282.9 \text{ kJ}] \rightarrow ①$$

$$(C.O.P)_n = \frac{\text{Desired effect}}{(W_{net})_n} = \frac{Q_4}{(W_{net})_n}$$

$$(C.O.P)_n = \frac{T_3}{T_2 - T_3} = \frac{253}{313 - 253} = [4.21]$$

$$\Rightarrow Q_4 = (C.O.P)_n \times (W_{net})_n$$

But, $W_1 \neq W_2 = 360 \text{ kJ}$

(or) $(W_{net})_{h.e} - (W_{net})_n = 360 \text{ kJ}$

$$(W_{net})_n = (W_{net})_{h.e} - 360 \text{ kJ}$$

$$\begin{aligned} (W_{net})_n &= 1282.9 - 360 && (\text{from } ①) \\ &= [922.9 \text{ kJ}] \end{aligned}$$

$$\Rightarrow Q_4 = 4.21 \times 922.9 = [3885.4 \text{ kJ}]$$

$$Q_3 \Rightarrow (W_{net})_n = Q_3 - Q_4.$$

$$Q_3 \Rightarrow (W_{net})_n + Q_4 = 922.9 + 3885.4$$

$$Q_3 = [4808.30 \text{ kJ}]$$

$$(W_{net})_{h.e} = Q_1 - Q_2$$

$$\Rightarrow Q_2 = Q_1 - (W_{net})_{h.e}.$$

$$= 2000 - 1282.9$$

$$Q_2 = [717.1 \text{ kJ}]$$

So,

heat rejected to 40°C reservoir is,

$$Q_2 + Q_3 = 717.1 + 4808.30 = \boxed{5525.4 \text{ KJ}}$$

→ If actual $\gamma_{h.e}$ and C.O.P₂ are 40% of original values,

$$\gamma_{h.e} = 0.256$$

$$- (W_{net})_{h.e} = 513.6 \text{ KJ}$$

$$- (W_{net})_2 = 153.6 \text{ KJ}$$

$$- (C.O.P)_2 = 1.69$$

$$- Q_4 = 259.6 \text{ KJ}$$

$$- Q_3 = 259.6 + 153.6 = 413.2 \text{ KJ}$$

$$- Q_2 = 1486.4 \text{ KJ}$$

$$- (Q_2 + Q_3) = 1899.6 \text{ KJ}.$$

Entropy:-

- Randomness / Disorderliness of a system in molecular level.
- Disorderliness exhibits increased entropy.
- Examples:-

① Melting of ice at room temperature.

- Ⓛ Entropy is gained by ice and lost by room.
- Ⓛ Temperature increase favours increase of entropy.
- Ⓛ Temperature decrease favours decrease of entropy.

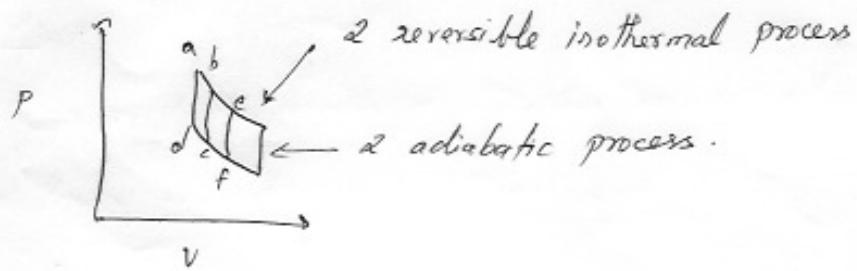
② Heat engine.

- Ⓛ Total heat available isn't converted to equivalent work.
- Ⓛ Friction and other losses produces change in entropy of the system.
- Ⓛ More entropy \Rightarrow less available work.

③ Refrigerator.

- Ⓛ Evaporator has reduced entropy than the atmosphere as the heat is removed from evaporator and rejected to atmosphere.
- In general the entropy of the universe is increasing for all the processes [thermal, mechanical] taking place.
- It may lead to highest entropy \Rightarrow all objects of same temperature, no heat transfer and no work transfer.

Clausius theorem



Consider the strip abcd,

Q_1 heat is supplied at T_1 and Q_2 heat is rejected at T_2 .

$$\Rightarrow \frac{dQ_1}{T_1} = - \frac{dQ_2}{T_2}$$

$$\Rightarrow \frac{dQ_1}{T_1} + \frac{dQ_2}{T_2} = 0$$

Consider path (strip) bcfc,

Q_3 heat is supplied at T_3 and Q_4 heat is rejected at T_4 .

$$\Rightarrow \frac{dQ_3}{T_3} = - \frac{dQ_4}{T_4}$$

$$\Rightarrow \frac{dQ_3}{T_3} + \frac{dQ_4}{T_4} = 0$$

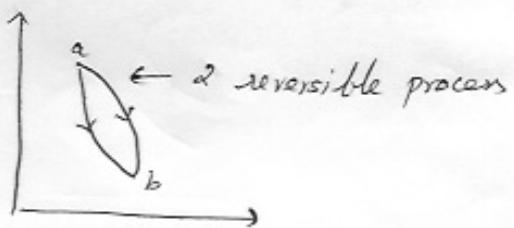
Summating,

$$\frac{dQ_1}{T_1} + \frac{dQ_2}{T_2} + \frac{dQ_3}{T_3} + \frac{dQ_4}{T_4} + \dots = 0$$

(or)

$$\boxed{\oint \frac{dQ}{T} = 0}$$

Entropy change:



$$\int_a^b \frac{dQ}{T} = S_b - S_a$$

$$\Rightarrow \frac{dQ}{T} = dS.$$

Where S is entropy with unit J/K .

S is extensive property.

$\frac{S}{m}$ is specific entropy with unit $J/kg\cdot K$.

Clausius inequality:

- Explains the possible ways to reversibility/irreversibility of a cycle

$\oint \frac{dQ}{T} = 0$, reversible process [no loss]

$\oint \frac{dQ}{T} < 0$, irreversible process [losses]

$\oint \frac{dQ}{T} > 0$, impossible violating Kelvin-Planck II law.

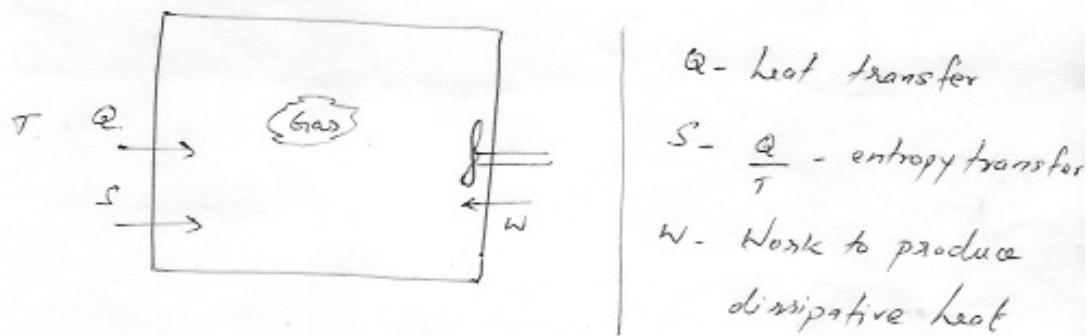
If $dS > \frac{dQ}{T}$, the process is irreversible

$dS = \frac{dQ}{T}$, the process is reversible

- dS for an isolated system ≥ 0 means it has an increasing attitude.
 - $dS > 0$ if it follows a irreversible path.
 - $dS = 0$ if it follows a reversible path.

Entropy generation in a closed system:-

- Entropy of a closed system increases by always:
 - ① Heat transfer \rightarrow entropy transfer
 - ② Dissipative effects / frictional heat \rightarrow entropy generation.

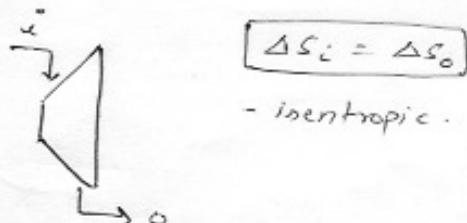


Now,

$$\Delta S_{\text{System}} = \Delta S_{\text{transfer}} + \Delta S_{\text{generation.}}$$

Example:

- Isentropic expansion in a turbine.



- A reversible adiabatic process is isentropic.
- An isentropic process need not be adiabatic or reversible.

- If the process is isentropic and adiabatic the process is irreversible. [due to frictional losses].

$$\Rightarrow \Delta S = S_o - S_i^o = \int_i^o \frac{dq}{T}$$

$$\Rightarrow S_o - S_i^o = \int_i^o \frac{dq}{T} = S_{\text{generation}}$$

where,

$\Delta S, S_o - S_i^o \rightarrow$ entropy change

$\frac{dq}{T} \rightarrow$ entropy transfer.

SI, $S_{\text{gen}} \Rightarrow$ entropy generation due to Work interaction

$S_{\text{gen}} > 0$, process is irreversible

$S_{\text{gen}} = 0$, process is reversible.

- The value of (magnitude) $S_{\text{generation}}$ gives the possibility for irreversibility of the process.
- If $S_{\text{generation}}$ is more, irreversibility is more.

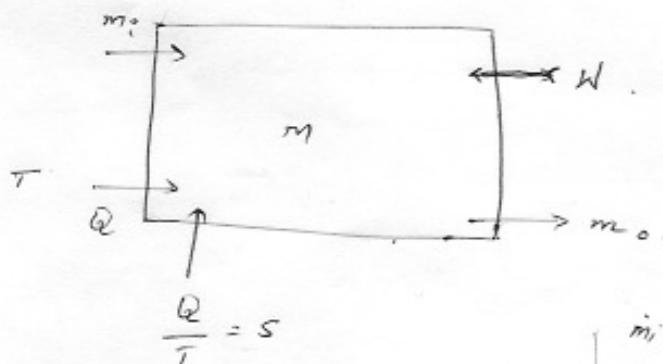
Entropy generation in an open system:

- 3 transfers are possible in an open system.

(1) Mass

(2) Energy ^{heat}
Work.

(3) Entropy



Mass transfer rate:

$$\dot{m}_i - \dot{m}_o = \frac{dm}{dt}$$

m_i - inlet mass flow rate.
 m_o - outlet mass flow rate.

W - Work transfer.

$\frac{Q}{T}$ - Entropy transfer

Net mass transfer rate = rate of mass accumulation.

Energy transfer rate:

$$\left[m_i \left[h + \frac{V^2}{2} + gz \right] \right]_i - \left[m_o \left[h + \frac{V^2}{2} + gz \right] \right]_o + Q - W = \frac{\partial E}{\partial t}$$

from steady flow energy equation

Net energy transfer rate = Rate of energy accumulation.

Entropy transfer rate:

$$m_i s_i - m_o s_o + \frac{Q}{T} \leq \frac{\partial S}{\partial t}$$

$$\left[m_i \Delta s + \frac{Q}{T} \leq \frac{\partial S}{\partial t} \right]$$

out of

$$\frac{\partial S}{\partial T} = \frac{\partial S}{\partial T} - m \cdot \Delta S = \frac{Q}{T}$$

$$S_{\text{gen}} = \frac{\partial S}{\partial T} - m \cdot \Delta S - \frac{Q}{T}$$

2f,

$S_{\text{gen}} > 0$, process is irreversible.

$S_{\text{gen}} = 0$, process is reversible.

Third law of thermodynamics:

- "The entropy of a crystal is zero at absolute zero."
- Absolute zero is 0K or, -273°C .
- As the temperature reduces to -273°C , the entropy reaches to a minimum or zero value.

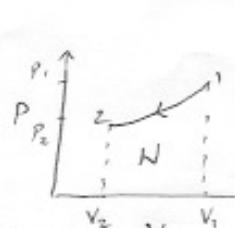
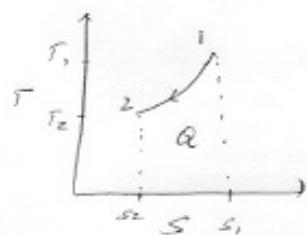
Property diagrams involving entropy:-

Two important property diagrams involving entropy are T-S and h-s diagram.

T-S

When Temperature and Entropy are plotted on a graphical scale, it is possible to find the heat transfer. Heat transfer is evaluated as the area under the curve.

Irreversible process can be denoted by dotted curves.



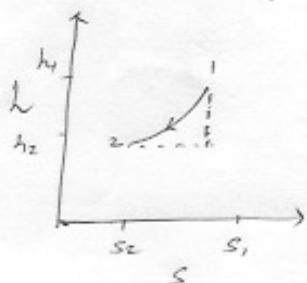
{ P-V diagram is useful to find Work transfer

{ ④ Horizontal lines are isothermal lines
④ Vertical lines are reversible adiabatic

{ T-S diagram is useful to find

h-s

When enthalpy and entropy are plotted on a graphical scale, it is helpful to find work interaction and the possibility of irreversibility of a process.



- vertical lines visualize work interaction
- horizontal lines visualize based on the possibility of irreversibility.

-- Thus these graphs are helpful to study the properties graphically.

Available Energy:

The useful amount of heat that can be converted to work is the available energy and the heat that is rejected without any purpose is called unavailable energy.

Thermodynamic relations:

Maxwell's relation:

We know that,

$$\left. \begin{array}{l} h = u + Pv \\ f = u - TS \\ g = h - TS \end{array} \right\} \quad \begin{array}{l} \text{where } f - \text{Helmholtz energy} \\ g - \text{gibbs free energy} \end{array}$$

From I law,

$$Q = W + \Delta U.$$

$$\Rightarrow \boxed{dQ = P \cdot dV + dU.}$$

From II law,

$$\boxed{T \cdot dS = P \cdot dV + dU} \quad (3)$$

$$\text{or } \boxed{dU = T \cdot dS - P \cdot dV} \quad (4)$$

$$(1) \Rightarrow dh = du + d(PV)$$

$$\Rightarrow dh = du + P \cdot dV + V \cdot dP.$$

$$\text{Subs } du \Rightarrow dh = T \cdot dS - P \cdot dV + P \cdot dV + V \cdot dP$$

$$\boxed{dh = T \cdot dS + V \cdot dP} \quad (5)$$

$$(1) \Rightarrow df = du - d(TS)$$

$$df = T \cdot dS - P \cdot dV - T \cdot dS - S \cdot dT$$

$$\boxed{df = -P \cdot dV - S \cdot dT} \quad (6)$$

$$\Rightarrow dg = dh - d(Ts)$$

$$dg = T.ds + v.dp - T.ds - s.dT.$$

$$\boxed{dg = V.dp - S.dT} \quad \textcircled{7}$$

Equations 4, 5, 6, 7 (property equations) p, v, T are only measured and hence they can be treated as variables.

$$u(s, v), h(s, p), f(T, v), g(T, p).$$

Let $z = (x, y)$, z can be any extensive property.

$$dz = \underbrace{\left(\frac{\partial z}{\partial x}\right)_y \cdot dx}_{M} + \underbrace{\left(\frac{\partial z}{\partial y}\right)_x \cdot dy}_{N}; \text{ Partially differentiating}$$

$$\Rightarrow \boxed{dz = M \cdot dx + N \cdot dy} \quad \textcircled{8}$$

2^{nd} derivative of a p.d.e will be symmetrical on variable side

$$\therefore \boxed{\left(\frac{\partial M}{\partial y}\right)_x = \left(\frac{\partial N}{\partial x}\right)_y} \quad \textcircled{9}$$

Comparing $\textcircled{7}$ & $\textcircled{8}$.

$$M = T, x = s, N = -P, y = v$$

$$\boxed{\left(\frac{\partial T}{\partial v}\right)_s = -\left(\frac{\partial P}{\partial s}\right)_v} \quad \textcircled{10}$$

Comparing $\textcircled{8}$ & $\textcircled{10}$

$$M = T, x = s, N = v, y = P$$

$$\boxed{\left(\frac{\partial T}{\partial v}\right)_s = \left(\frac{\partial v}{\partial s}\right)_P} \quad \textcircled{11}$$

Comparing ⑥ & ⑧,

$$M = -S, \quad x = T, \quad N = -P, \quad y = v$$

$$\left[\left(\frac{\partial S}{\partial V} \right)_T = \left(\frac{\partial P}{\partial T} \right)_V \right] ⑫$$

Comparing ⑦ & ⑧,

$$M = -S, \quad x = T, \quad N = v, \quad y = P$$

$$\left[\left(\frac{-\partial S}{\partial P} \right)_T = \left(\frac{\partial v}{\partial T} \right)_P \right] ⑬$$

Eqs. ⑩, ⑪, ⑫, ⑬ are the Maxwell's equations that are useful to tabulate the properties of fluids from experimental values.

Toule-Thomson coefficient :-

Consider a throttling process in which the pressure and temperature reduces to a greater extent and enthalpy remains constant. The degree of reduction in temperature for a given pressure range can be evaluated as a number called as Toule-Thomson coefficient denoted by letter ' μ '.

$$\left[\mu = \left[\frac{\partial T}{\partial P} \right]_h \right] \rightarrow ⑭$$

μ expressed in terms of p, v, T and C_p as given,

$$dh = C_p \cdot dT + \left[v - T \left(\frac{\partial v}{\partial T} \right)_p \right] \cdot dp$$

Putting tends $dh = 0$.

$$\Rightarrow [C_p \cdot dT]_h = \left\{ \left[T \left(\frac{\partial v}{\partial T} \right)_p - v \right] \cdot dp \right\}_h$$

$$\left[\frac{\partial T}{\partial p} \right]_V = \left[\frac{T \left(\frac{\partial v}{\partial T} \right)_p - v}{C_p} \right] = \mu, \text{ from } @$$

↓ @.

But,

$$\left(\frac{\partial v}{\partial T} \right)_p = v \cdot \beta. \rightarrow (b)$$

Subs (b) in (c)

$$\Rightarrow \boxed{\mu = \frac{v}{C_p} [T \cdot \beta - 1]}$$

is an expression to find the value of coefficient.

Note :-

β is the coefficient of expansion of gases. It is the increase in volume per unit volume of a gas. Change in volume and temperature are expressed as,

$$\boxed{\beta = \frac{1}{v} \int \frac{\partial v}{\partial T} dt} \quad [\text{constant pressure}]$$

Clausius - Clapeyron equation :

- It is helpful to evaluate the change in enthalpy, entropy, specific volume for a given saturation pressure and temperature during phase transformations.
- Consider the evaporation process in which there is no change in temperature and pressure; but change in enthalpy, entropy and specific volume is noted { (increases) $h, s, v \}$.

Consider \rightarrow Maxwell's relation,

$$\left[\frac{\partial P}{\partial T} \right]_S = \left[\frac{\partial S}{\partial V} \right]_T$$

During evaporation the phase change from liquid to gas.

$$\left[\frac{\partial P}{\partial T} \right]_{sat} = \frac{s_g - s_f}{v_g - v_f} = \frac{s_{fg}}{v_{fg}}$$

$$\text{Also, } s_g - s_f = s_{fg} = \frac{h_{fg}}{T_s}$$

$$v_g - v_f = v_{fg}$$

(or)

$$\left[\frac{\partial P}{\partial T} \right]_{sat} = \frac{s_{fg}}{v_{fg}} = \frac{h_{fg}}{T_s \cdot v_{fg}}$$

is known as Clausius - Clapeyron equation for evaporation at constant

- This equation can also be used for melting and sublimation processes.
- Interpreting the slope ($\frac{\partial p}{\partial T}$) with vapour pressure curve, the values of h_{fg} , v_g , v_f can be found for a given temperature.
- If the limits are replaced with 1 and 2.

$$\left[\frac{\partial p}{\partial T} \right]_{sat} = \left[\frac{(h_2 - h_1)}{T \cdot (v_2 - v_1)} \right]$$

If v_2 is very greater than v_1 , it can be eliminated,

$$\boxed{\left[\frac{\partial p}{\partial T} \right]_{sat} = \left[\frac{h_2 - h_1}{T \cdot v_2} \right].}$$

If the gas behaves ideally v_2 is replaced with $\frac{RT}{P}$

$$\left[\frac{\partial p}{\partial T} \right]_{sat} = \left[\frac{h_2 - h_1}{T \cdot \frac{RT}{P}} \right]$$

$$(or) \left[\frac{\partial p}{\partial T} \right]_{sat} = \left\{ \frac{h_2 - h_1}{R} \left[\frac{P}{T^2} \right]_{sat} \right\}$$

Dalton's law of Partial pressure:

- The total pressure of a mixture of ideal gases is equal to the sum of the partial pressures.
- Consider a homogeneous mixture of an ideal gases at P, V, T .
Let n_1 moles of A_1 , n_2 moles of A_2 ... etc are present.
From the law,

$$PV = (n_1 + n_2 + \dots) RT$$

$$\Rightarrow P = \frac{n_1 RT}{V} + \frac{n_2 RT}{V} + \dots$$

where, $\frac{n_1 RT}{V} = P_1$; $\frac{n_2 RT}{V} = P_2$; ...

P_1 & P_2 are the pressures of gases A_1, A_2, \dots

→ Properties of pure substances:

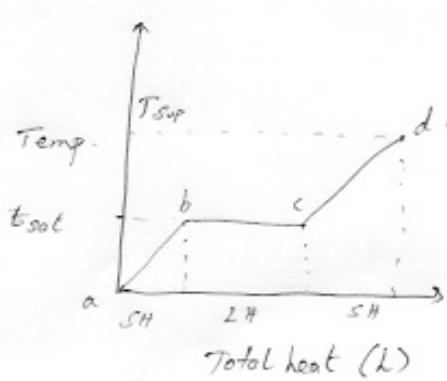
- A substance having the same chemical composition throughout its mass is called as pure substance. [Macroscopic]
- Steam is a pure substance irrespective of the phases.

→ Steam formation:

- Consider a process to heat water at 0°C to 240°C .
- The processes involved are,

- ① $0^{\circ}\text{C} - 0^{\circ}\text{C} \Rightarrow$ solid - liquid.
- ② $0^{\circ}\text{C} - 100^{\circ}\text{C} \Rightarrow$ liquid - liquid
- ③ $100^{\circ}\text{C} - 100^{\circ}\text{C} \Rightarrow$ liquid - liquid + gas - gas
- ④ $100^{\circ}\text{C} - 240^{\circ}\text{C} \Rightarrow$ gas

- Graphically,



$a-b \Rightarrow$ specific heat

$b-c \Rightarrow$ latent heat of vaporisation

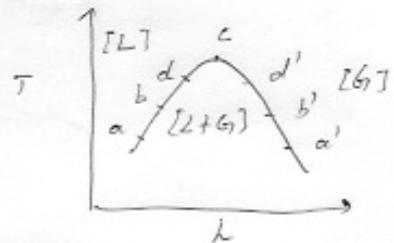
$c-d \Rightarrow$ heat of superheat

- For various values of pressure, the boiling point and saturation temperature and latent heat also varies.

- Pressure increases \Rightarrow Boiling point increases.
Saturation temperature increases
latent heat decreases.

- As these values are plotted and joined by ~~smooth~~ curve, a dome shape is obtained.

- Graphically,



Phases.

L - [Liquid]

L+G - [Liquid + gas]

G - [Gas]

- Points a,b,d for different pressures mention the liquid state of water, corresponding a',b',d' mention the vapour state of water in the graph.
- Point c is the critical point where water at liquid phase converts directly into vapour without any latent heat.
- Left part of the curve denotes saturated liquid line and right part of the curve denotes saturated vapour line.

⇒ Dryness of steam :- (x)

- Water on the saturated ^{liquid} vapour line has zero dryness

- Water on the saturated vapour line has 100% dryness

- At the intermediate region the dryness varies from 0.05-99.5 %.

$$- x = \frac{m_g}{m_l + m_g}$$

where, m_g - mass of gaseous substance
 m_l - mass of liquid substance

→ Specific properties of steam:

- The vital properties involved to analyse a process are,
 - ① enthalpy,
 - ② entropy,
 - ③ Temperature,
 - ④ Pressure,
 - ⑤ Specific volume.
 - ⑥ Internal Energy.
- Enthalpy :- (h).

It is the total heat content of the process. Enthalpy at a point can be given as,

$$h = h_f + x \cdot h_{fg}$$

$$h = h_f$$
 or saturated liquid line as $x = 0$.

$$h = h_g$$
 or saturated vapour line as $x = 1$ and $h_f = 0$.

where,
 h_f - enthalpy of fluid
 x - dryness fraction
 h_{fg} - enthalpy of vaporisation.

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

- Entropy :- (s)

This property is involved to find the amount of heat transfer and the degree of irreversibility.

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

$$s = s_f$$
 for saturated liquid line

$$s = s_g$$
 for saturated vapour line.

where,

$$s_{fg} = s_g - s_f$$

→ Superheated region:

- Dryness fraction 'x' disappears at superheated region and the formulas changes to, as at

$$\left. \begin{aligned} h_{\text{sup}} &= h_g + c_p (T_{\text{sup}} - T_{\text{sat}}) \\ s_{\text{sup}} &= s_g + c_p (T_{\text{sup}} - T_{\text{sat}}). \end{aligned} \right\} \begin{array}{l} \text{this temperatures} \\ \text{the steam behaves} \\ \text{like a perfect gas.} \end{array}$$

where, T_{sup} is the superheated temperature.

T_{sat} is the saturation temperature.

- Internal energy:

$$u = h + pv$$

$$\Rightarrow u = (h_f + x \cdot h_{fg}) + p \cdot (xv_g - v_f)$$

⇒ If $x=1$,

$$\Rightarrow u = h_g - p v_g$$

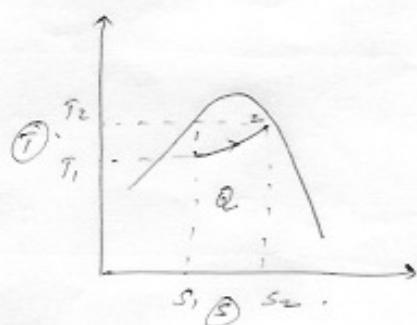
⇒ If super heated,

$$u_{\text{sup}} = [h_f + h_{fg} + c_p (T_{\text{sup}} - T_{\text{sat}})] - p \cdot v_{\text{sup}}$$

$$v_{\text{sup}} = v_{\text{sat}} \left[\frac{T_{\text{sup}}}{T_{\text{sat}}} \right]$$

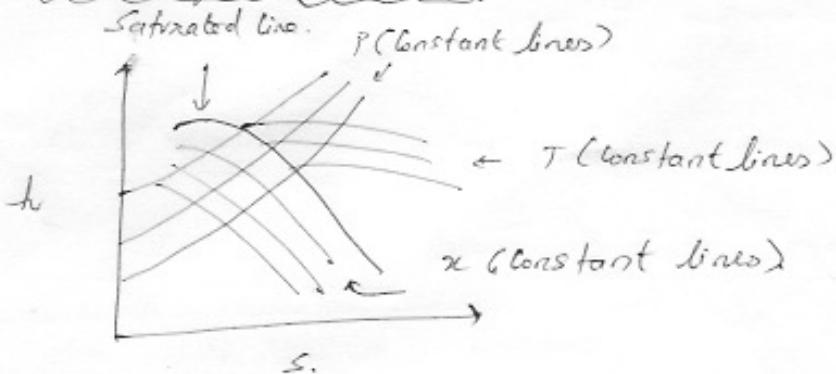
→ Property diagrams:

- T-S diagram



- Helpful to find the heat transfer in a process.
[Area under the curve].

- h-s diagram [Mollier]



- Mollier plot is useful to find the enthalpy values to get heat supplied, find dryness fraction, study isentropic processes.

→ Various processes involved by steam transformation

- Constant volume heating:- [$v=c$]

Ex: Boiling Water in a closed vessel.

- Constant pressure heating:- [$p=c$]

Ex: Heating Water in a Boiler

- Isothermal process:- [$T=c$]

Ex: Latent heat of vaporisation.

- Hyperbolic process: [$T_1 = c$]

Also isothermal process and exists at superheated region. [Ex: Boiling/heating steam above 100°C]
- Isoentropic process: [$s_1 = s_2$]

Ex: Expansion in a steam turbine.
- Throttling process: [$h_1 = h_2$]

Ex: TXV valve in a refrigerator.

Problem :-

1. $P = 1 \text{ MPa}$.

Find;

$$T_{sat}, v_{fg}, s_{fg}, h_{fg}.$$

Soln:

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

From steam tables,

$$v_{fg} = [0.193] \text{ m}^3/\text{kg}; s_{fg} = [4.44] \text{ kJ/kg.K}; h_{fg} = [2015.3] \text{ kJ/kg}$$

$$\text{Also, } v_{fg} = v_g - v_f.$$

$$s_{fg} = s_g - s_f.$$

$$h_{fg} = h_g - h_f.$$

2. Dry saturated steam of 12 bar is sent to turbine. Exit condition is 0.1 bar.

Find γ :-

Soln:-

$$\gamma = \frac{h_2 - h_3}{h_2 - h_{f3}} = \frac{\text{Work done}}{\text{Heat supplied.}}$$

$$h_2 = h_{f2} + x_2 h_{fg2}$$

$$h_2 = 798.4 + (1) 1984.3$$

$$h_2 = 2782.7 \text{ kJ/kg}$$

$$s_2 = s_{f2} + x_2 s_{fg2}$$

$$s_2 = s_{g2} = 6.519$$

$\rightarrow x_2 = 1$ because inlet

$$s_2, s_{g2} = s_3 = s_{f3} + x_3 s_{fg3} \quad \text{is dry saturated.}$$

$$6.519 = 0.649 + (x_3) \cdot 7.502$$

$\rightarrow s_2 = s_3$ because expansion
is isentropic.

$$h_3 = h_{f3} + x_3 h_{fg3}$$

$$h_3 = 191.8 + (0.783) \times 2393$$

$$h_3 = 2065.5 \text{ kJ/kg}$$

$$\gamma = \frac{2782.7 - 2065.5}{2782.7 - 191.8}$$

$$\gamma = 27\%$$

3. Initial condition 10 bar and $x = 0.9$, $\epsilon = 1$.
 Final condition 0.2 bar.

Find γ :-

$$\gamma = \frac{h_2 - h_3}{h_2 - hf_3} = \boxed{23.6\%}$$

$P_2 = 10 \text{ bar}$
$x_2 = 0.9$
$P_3 = 0.2 \text{ bar}$

$$\gamma = \frac{h_2 - h_3}{h_2 - hf_3} = \boxed{24.7\%}$$

$P_2 = 10 \text{ bar}$
$x_2 = 1$
$P_3 = 0.2 \text{ bar}$

γ increases with increase in dryness of steam.

4. $P_2 = 15 \text{ bar}$, $T_2 = 350^\circ\text{C}$.

$$P_3 = 0.06 \text{ bar}$$

Find γ .

Soln:

$$\gamma = \frac{h_2 - h_3}{h_2 - hf_3} \quad [P_2 = 15 \text{ bar} \text{ and } T_2 = 350^\circ\text{C}, \text{ steam table}]$$

$$\boxed{h_2 = 3148.7 \text{ kJ/kg}}$$

~~[$s_2 = s_3 + x_3 \cdot s'_{f3}$]~~

$$s_2 = s_3 = sf_3 + x_3 \cdot s'_{f3} \quad \cancel{[s_2 = s_3 + x_3 \cdot s'_{f3}]}$$

$$\Rightarrow 7.104 = sf_3 + x_3 \cdot s'_{f3}$$

$$\Rightarrow \boxed{x_3 = 0.843}$$

$$\Rightarrow \boxed{h_3 = 2188 \text{ kJ/kg}}$$

$$\gamma = \frac{3148.7 - 2188}{3148.7} = \boxed{32\%}$$