

# Chapter - 1 Concepts & Terminology

Thermodynamics → It is defined as the branch of Science which deals with heat energy transfer and its effect on physical property of the substance.

OR.

It may be defined as the science which deals with the conversion of heat into mechanical work or energy by using a suitable medium.

Heat → Heat is a form of energy. OR. heat is a state of temperature.

Unit → Joule - In SI.

Calorie - In CGS

Property → In thermodynamics, a physical property is any property that is measurable, and whose value describes a state of physical system.

## Thermodynamic System:

System → A system is defined as any quantity of matter or a region in space having certain volume upon which our attention is concerned in analysis of problem.

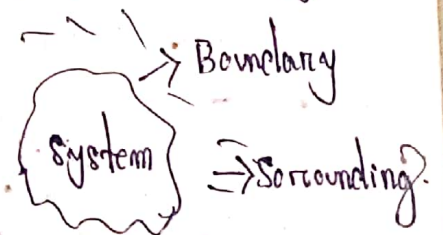
Surrounding → Anything external to the system constitute as surrounding.

Boundary → System is separated from the surrounding by system boundary.

→ Boundary may be fixed or movable.

System are classified into three types —

- i) open system
- ii) closed system
- iii) isolated system.



i) open system → Both mass and energy cross the boundary.

ii) it is also called constant volume.

iii) it is also known as flow system.

Eg → Turbine, pump, Air Compressor.

ii) closed system →

i) Mass within the boundary remains constant only energy interaction bet<sup>n</sup> system and surrounding.

ii) it is also known as non-flow system.

Eg. Tea kettle, cylinder piston arrangement.

Isolated System — An isolated system is one in which there is no interaction between system and surrounding.  
Eg. Universe, thermoflask etc.

### Macroscopic & Microscopic approach:

Macroscopic approach → It is used in regard to larger units which is visible in naked eye.

i) Certain quantity of matter is considered without taking into consideration the events occurring at molecular level.

ii) otherwise it is concerned with overall behaviour of matter.

iii) This type of study is also known as classical thermodynamics.

Microscopic approach →

i) Matter is considered to be composed of tiny particles called molecules and study of each particles having certain position, velocity, and energy at a given instant.

ii) It is also called statistical thermodynamics.

### Concept of Continuum:

The system is regarded as continuum if the system is assumed to contain continuous distribution of matter.

→ From the continuum point of view, the matter is seen as being distributed through space and treats the substance as being continuous disregarding the action of individual molecules.

→ There are no voids and values of action of many molecules & atoms.

Notes → Molecule → A group of atoms bonded together, representing the smallest fundamental unit of chemical compound that can take part in a chemical reaction.

### Thermodynamic property:

Property → A thermodynamic property refers to the characteristic by which the physical change of condition state of a system can be described such as  $p$ ,  $V$ ,  $T$ , etc.

Pressure → It is defined as Force per unit area.

Unit → In SI — Pascal (Pa) =  $\text{N/m}^2$ .

$$1 \text{ Bar} = 10^5 \text{ N/m}^2 = 100 \text{ kPa.}$$

$$1 \text{ ATM} = 760 \text{ mm of Hg} \text{ or } 1.013 \text{ bar} \text{ or } 101.325 \text{ kPa.}$$

Temperature  $\rightarrow$  It is a thermal state of a body which determines the hotness or coldness of a body.

$\rightarrow$  The temp of a body is proportional to the stored molecular energy.

Unit  $\rightarrow$  Degree Celsius or Kelvin.

### Intensive and Extensive property: —

Intensive property  $\rightarrow$  The property which are independent of mass of the system are known as intensive properties.

$\rightarrow$  Its value remains the same whether one considers the whole system or only a part of it.

Eg. Prc, temp, sp vol<sup>m</sup>, sp energy, sp density.

Extensive property  $\rightarrow$  The property depends upon mass of the system are known as extensive property.

Eg. Vol<sup>m</sup>, Energy, enthalpy, entropy.

Notes State  $\rightarrow$  The condition of physical existence of a system at any instant of time is called state.

### Thermodynamic Processes: —

When the property of a system changes, there is a change in state and the system is said to have undergone a thermodynamic process.

Commonly used processes are —

- i) Isochoric process — The process which takes place at constant Vol<sup>m</sup> is said to be isochoric process.
- ii) Isobaric process — Process takes place at const prc.
- iii) Isothermal process — Process takes place at const temp.
- iv) Adiabatic process — Process in which no heat transfer bet<sup>n</sup> the system and surrounding.

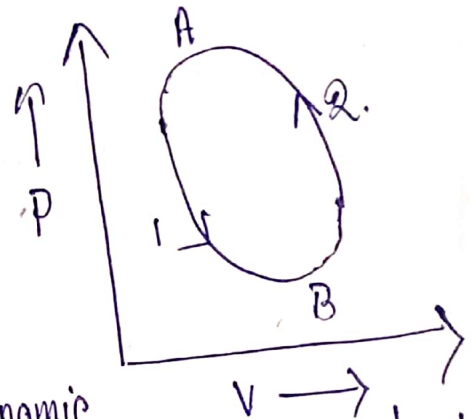
Reversible adiabatic process is known as isentropic process.

The other processes are polytropic, throttling, free expansion, and hyperbolic process.

### Thermodynamic cycle: —

When a process is performed in such a way that the final state is identical with the initial state. It is then known as thermodynamic cycle or cyclic process.

A-1-B and A-2-B represents process.  
whereas A-1-B-2-A represents a thermodynamic cycle.



### Thermodynamic Equilibrium: —

A system is said to be in thermodynamic equilibrium when no change in any macroscopic property is registered, if the system is isolated from its surrounding.

Thermodynamics mainly studies the properties of physical system are found in equilibrium state.

A system will be said to be in thermodynamic equilibrium if the following three conditions of equilibrium is satisfied.

- 1) Mechanical equilibrium.
- 2) Chemical "
- 3) Thermal "

### 1) Mechanical equilibrium: —

When there is no unbalanced force on any part of the system or in-between the system and surrounding then the system is said to be in mechanical equilibrium.

Eg. If the pressure is not uniform throughout the system then internal changes in the state of the system will take place until the mechanical equilibrium is reached.

(3)

Chemical Equilibrium:— when there is no chemical reaction or transfer of matter from one part of the system to another. Such as diffusion or solution, then the system is said to exist in a state of chemical equilibrium.

Thermal Equilibrium:— when there is no temp difference bet<sup>n</sup> the parts of the system or bet<sup>n</sup> the system and surrounding it is then said to be in thermal equilibrium.

Reversible process:—

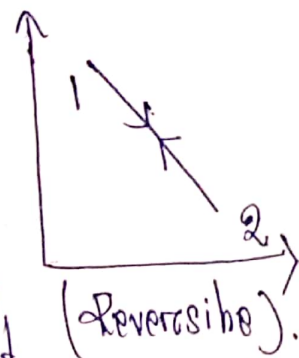
A process in which act is reversed in dir<sup>n</sup> and the system retraces the same continuous series of equilibrium state it is said to be reversible process.

→ It carried out with absolute slowness so that the system will be always in equilibrium.

→ In actual practice reversible process can't be attain, but it can be approximated as closely as possible.

Irreversible process:—

A process in which the system passes through a sequence non-equilibrium state i.e. the property such as vol<sup>m</sup>, pr<sup>e</sup>, temp is not uniform throughout the system is known as irreversible process.



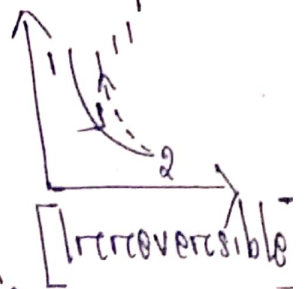
Quasi-static process:—

→ The word quasi means almost.

→ This process is a succession of equilibrium states and infinite slowness is the characteristic feature of quasi-static process.

→ It is also called as reversible process.

→ The basic difference is not all the point but almost major points is in equilibrium condition.



## Energy & Work transfer

## Chapter - 2

A closed system interacts with the surrounding by energy transfer and this energy transfer takes place in two ways.

- i) Work transfer
- ii) Heat transfer.

Notes: —

**Work** — In thermodynamics work is quantity of energy transfer from one system to another. Unit - Joule

Heat & Work are the main mode of energy transfer and there are certain similarities and differences both heat & Work.

- The heat & Work are boundary phenomena. they observe at the boundary of the system.
- When a system undergoes a change in state, heat transfer or work done may occur.
- Heat & Work are path function and depends upon the process.
- Work is said to be high grade energy and heat, low grade energy.

Work transfer —

The action of a force on a moving body is identified as work.

- For work transfer the system has to be such selected that its boundary just move.
- There can't be work transfer in a closed system without moving the system boundary.

Eg. In a cylinder piston arrangement the top of the system is moving system boundary and the work is transferred by the movement of piston.

Work done by the system is considered as positive and work done on the system is taken as negative.

Work done = Force  $\times$  displacement. Unit - N-m or J

The rate at which work is done upon by the system is known as power.

Unit  $\rightarrow$  J/s or watt.

PdV work or displacement work: —

Let us consider a gas in cylinder.

Initial  $p$  or  $P_1$   
 Volume  $- V_1$

$P_1$	$P_2$
$V_1$	$V_2$
1	2.

$\rightarrow$  The system in thermal equilibrium.

$\rightarrow$  The piston is the system boundary which moves due gas  $p$  or.

$\rightarrow$  Let the piston move out to a new final position 2 which is also in thermodynamic equilibrium specified by  $P_2$  and volume  $V_2$ . when the piston moves an infinitesimal distance  $dx$  it a be the area of the piston.

$\rightarrow$  The Force Acting on the piston will be

$$F = P \times a.$$

$\rightarrow$  The amount of work done by gas on the piston will be

$$dW = F \cdot dI = P \times a \times dx = P dV.$$

where  $dV = a \times dx$ .

$\rightarrow$  when the piston moves out by position 1 to 2 then the amount of work done by the system will be

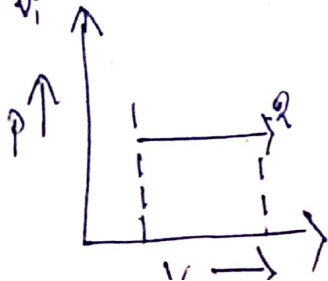
$$W_{1-2} = \int_{V_1}^{V_2} P dV.$$

$\rightarrow$  The above eqn represents the displacement work.

$\rightarrow$  Displacement work applied to different thermodynamic process.

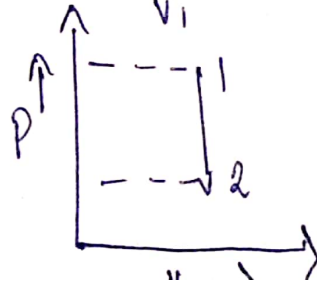
1. Isobaric process: —

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



2. Isochoric process —

$$W_{1-2} = \int_{V_1}^{V_2} P dV = 0$$



3. Isothermal process —  
In this process  $PV = \text{Constant}$ .

$$PV = P_1 V_1 = C$$

$$P = P_1 V_1 / V$$

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

$$W_{1-2} = P_1 V_1 \int_{V_1}^{V_2} \frac{dV}{V}$$

$$= P_1 V_1 \left[ \log V \right]_{V_1}^{V_2} = \frac{P_1 V_1}{P_1} \ln \frac{P_2 V_2}{P_1 V_1}$$

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

### Heat transfer: —

Heat is defined as the form of energy that is transferred across a boundary by virtue of which temp diff betn the system and the surroundings.

→ If the heat flows into the system or the system receives heat then heat transfer  $Q$  is taken as +ve, and if heat is rejected from the system then  $Q$  is taken as -ve.

The heat transfer takes place by three different modes —

i) Conduction → The transfer of heat betn two bodies in direct contact is called conduction.

→ In this heat transfer process transfer of heat from one particle to another in the dirn of fall of temp.

→ In solid particles it occurs.

ii) Convection → The process of heat transfer from one particle to another by convection currents i.e. transfer of heat betn the wall and fluid system in motion.

→ In this case, the particles of the body move relative to each other.

4. polytropic process —  
The process in which expansion and contraction takes place according to the law  $PV^n = C$ .

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

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

$$= \int_{V_1}^{V_2} \left[ \frac{P_1 V_1^n}{V^n} \right] dV$$

$$= P_1 V_1^n \left[ \frac{V^{n+1}}{-n+1} \right]_{V_1}^{V_2}$$

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

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



Radiation: - Heat transfer bet<sup>m</sup> two bodies separated by empty space or gases through electromagnetic waves in re-radiation.

Sensible heat -> The heat req<sup>d</sup> to change from liq state to vapour state or boiling point is called sensible heat.

-> It is the amount of heat absorbed by 1kg of water when heated at const prc, from the freezing point 0°C to the temp of formation of steam.

Latent heat -> It is the amount of heat absorbed to evaporate 1kg of water at boiling point without change of temp.

Specific heat -> The amount of heat req<sup>d</sup> to raise the temp of unit mass of a substance through one degree is called sp. heat

Unit -> kJ/kg.k

Mathematically heat req<sup>d</sup> to raise the temp of a body is -

Q = m . C [T<sub>2</sub> - T<sub>1</sub>] In kJ.

where m = Mass of substance in kg.

C = sp heat in kJ/kg.k

T<sub>1</sub> = Initial temp in degree or kelvin.

T<sub>2</sub> = Final " " " "

Specific heat at const Vol<sup>m</sup> [C<sub>v</sub>] -

It is defined as amount of heat req<sup>d</sup> to raise the temp of a unit mass of a gas by one degree at const Vol<sup>m</sup>.

Specific heat at const prc [C<sub>p</sub>] -

It is defined as amount of heat req<sup>d</sup> to raise the temp of a unit mass of a gas by one degree at const prc.

Energy: - The energy is defined as the capacity to do work.

-> In broad sense energy is classified as stored energy and transient energy.

The energy that remains within the system boundary is called stored energy. Eg. potential, kinetic, & internal energy.

The energy which crosses the system boundary is known as energy in transition.

Ex. Heat, work, electricity.

### Different forms of stored energy —

1. Potential Energy — The energy possessed by a body by virtue of its position or state of rest is known as potential energy.

$$PE = w \times h = mgh.$$

$w$  = wt of the body in N.  
 $m$  = mass of the body in kg.  
 $g$  = Acceleration due to gravity.  
 $h$  = height in metre.

2. Kinetic energy: —

The energy possessed by a body by virtue of its motion.

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

$v$  = vel of the body.

3. Internal energy: —

The energy possessed by a body or a system by virtue of its molecular arrangement and motion of molecules.

→ The change in temp causes the change in internal energy.

→ denoted by "U".

→ The sum of the above three energies is the total energy of the system.

$$E = P.E + K.E + U$$

but when the system is stationary and the effect of gravity is neglected then  $P.E = 0$  &  $K.E = 0$ .

Thus  $E = U$ .

i.e. the total energy is equal to the total energy of a system.

# Chapter 3 First law of thermodynamics

Introduction: — Heat & Work are different forms of the same entity called energy.

- Energy is always conserved;
- Energy may enter a system as heat and leave as work and vice-versa.

Energy has two forms —

- i) transit energy
- ii) stored energy.

The internal energy is the stored energy. whenever heat & work enters a system, stored energy increases and when heat & work leaves the system stored energy decreases.

## First law of thermodynamics:

Whenever heat is absorbed by a system it goes to increase its internal energy plus to do some external work. [pdv work]

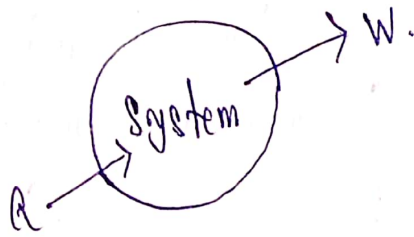
$$Q = \Delta E + W$$

where  $Q$  is the energy entering a system.

$\Delta E$  increases in internal energy.  
 $W$  producing some external work.

$$\delta Q = dE + p dV$$

Sometimes more than two energy transfers, so it becomes —

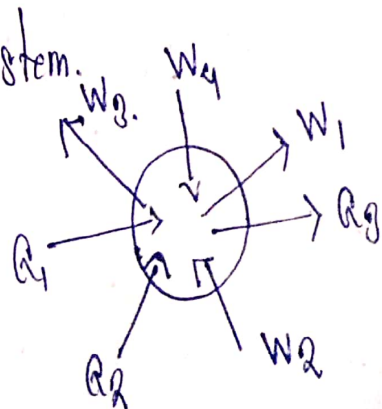


$$Q_1 + Q_2 - Q_3 = \Delta E + W_1 - W_2 + W_3 - W_4$$

Sign Convention: —

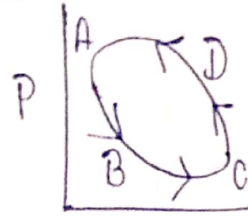
It will be "+Q" if that heat goes into the system and "-Q" if heat goes out of the system.

+W → when it is done by the system.  
 -W → is done on the system.



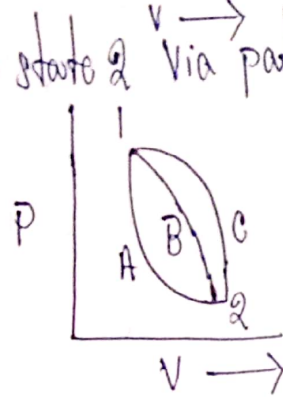
Cyclic process: — For a cyclic process, the work done is the area enclosed by the PV Curve.

clockwise = +W.  
anticlockwise = -W.



Energy as a System property: —

Let a system changes from state 1 to state 2 via path A, path B and path C. which as follows —  
Applying 1st law of thermodynamics to path A.



$$Q_A = \Delta E_A + W_A$$

For path B  $Q_B = \Delta E_B + W_B$

If process A & B form a complete cycle —

$$\Delta Q = \Delta W$$

$$(Q_A + Q_B) = \Delta E_A + \Delta E_B + (W_A + W_B)$$

$$\Delta Q = \Delta E_A + \Delta E_B + \Delta W$$

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

Similarly  $\Delta E_B = \Delta E_C$

So it is independent of path hence a property extensive or in nature.

Different forms of stored energy: —

Energy can be stored in a system by two modes —

i) Macroscopic mode    ii) Microscopic mode.

i) Macroscopic mode: — In this mode, the mode is stored energy in two forms.

$$E_{KE} = \frac{1}{2}mv^2$$

$$E_{PE} = mgz$$

ii) Microscopic mode — This mode of stored energy refers to energy stored in molecular and atomic structure.

Hence it is called molecular Internal energy. Or simply Internal Energy. ⑦

1. Translational KE
2. Rotational KE.
3. Vibration K.E.
4. Electronic energy.
5. Chemical energy.
6. Nuclear energy.

$$L = L_{\text{translational}} + L_{\text{rotational}} + L_{\text{vib}} + L_{\text{Ele}} + L_{\text{chem}} + L_{\text{Nucl.}}$$

Total energy: —

$$E = E_{KE} + E_{PE} + U$$

In absence of motion, gravity  $E_{KE}, E_{PE} = 0$ .

So  $E = U$

$$Q = \Delta U + \int p \, dv$$

First law for a closed system undergoing a cyclic process —

Enthalpy Concept → Enthalpy is a state property of a system.  
→ It is denoted by H.

$$H = U + PV$$

→ It is a point function.

→ Intensive property.

→ sp enthalpy is given by  $h = U + \frac{1}{m} PV$   
 $= U + PV.$

First law for a steady flow process: —

Steady flow → A flow process is one in which a fluid enters the system and then leaves the system after work interaction.

The mass flow rate and energy flow rate across the system boundary are constant.

Notes →

Flow work → Whenever a certain amount of mass enters a system, an amount of work is req. to push the mass into the system and out of it to maintain the continuity of flow. i.e. flow work =  $PV$ .

Control Vol<sup>m</sup>: — For Computation of mass and energy rates during a flow process, it is convenient to focus attention upon a certain fixed region in space called Control Vol<sup>m</sup>.

Control Surface —

The boundary line defining Control Vol<sup>m</sup> is called Control Surface.

Stored energy of a system in a flow process: —

During a steady state flow, there is neither any accumulation of mass nor energy.

$$(\text{Mass Flow rate})_{in} = (\text{Mass Flow rate})_{out}$$

$$\sum \text{Energy}_{in} = \text{Energy}_{out}$$

Now the total energy of a fluid at any section of the Control Vol<sup>m</sup>.

$$E = U + \frac{1}{2} (mv^2) + mgz$$

$$e = U + \frac{1}{2} v^2 + gz$$

As all energy is conserved

$$\sum \text{Energy}_{in} + \text{Heat Flux} = \sum \text{Energy}_{out} + \text{Work output}$$

$$U_1 + \frac{1}{2} mv_1^2 + mgz_1 + P_1V_1 + Q = U_2 + \frac{1}{2} mv_2^2 + mgz_2 + P_2V_2 + W$$

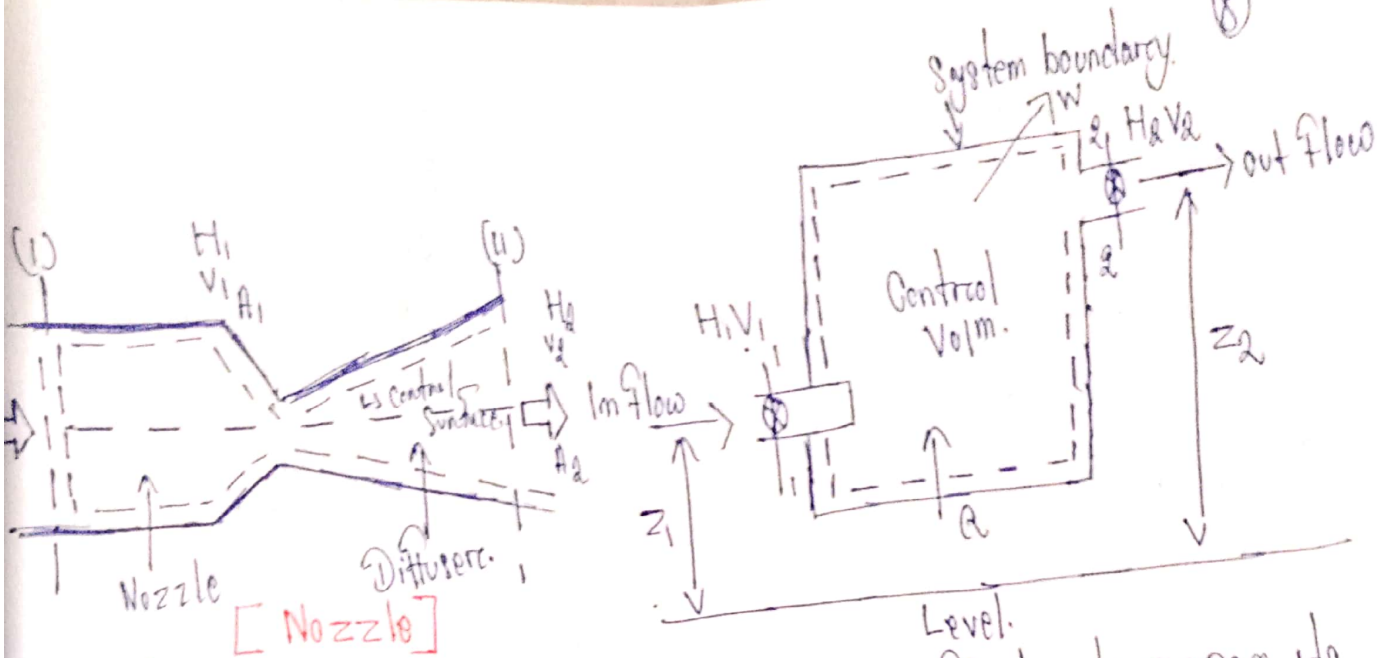
$$\left[ h_1 + \frac{1}{2} mv_1^2 + mgz_1 + R \right] + \left[ h_2 + \frac{1}{2} mv_2^2 + mgz_2 + W \right]$$

On the basis of per unit mass rate of flow: —

$$h_1 + \frac{v_1^2}{2} + gz_1 + R/m$$

$$h_2 + \frac{v_2^2}{2} + gz_2 + W/m$$

$$h_1 + \frac{v_1^2}{2} + gz_1 + R = h_2 + \frac{v_2^2}{2} + gz_2 + W$$



**Nozzle:** — It is a device used to throttle a fluid where upon its pre energy is converted into K.E.  
 → The enthalpy of fluid decreases as the vel of the fluid increases coz of higher fluid vel at the nozzle outlet.  
 → A nozzle is harnesses to gain a high thrust in rocket and jet engines and drive impulse type steam and gas turbine.

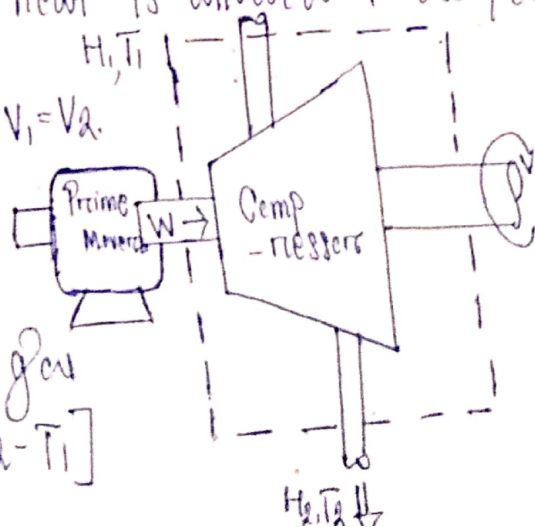
**Compressor:** — A compressor compresses air or gas by harnessing external work fed from a prime mover.  
 → The increase in gas pr is accompanied by the temp rise.  
 → If the compressor is perfectly insulated and the compression is adiabatic then it req minor work output to increase the gas pr.  
 → All the generated heat of compression is expanded to compresses the gas as no heat is allowed to escape.

So  $Q = 0$ .  
 Mass flow route of the gas =  $M \times v_1 = v_2$ .  
 $z_1 = z_2$ .

$$h_1 = h_2 + C - W_c$$

-ve sign refers work done on gas

$$W_c = M C (h_2 - h_1) = M C_p [T_2 - T_1]$$



Eg. An air Compressor air from 0.1 MPa/300k to 1MP. The Compressor Casing is well insulated. yet there is a heat loss to the surrounding to the extent of 5% of the Compressor Work. determine air temp at outlet and power input given

$$V_1 = 40 \text{ m/s}, \quad V_2 = 100 \text{ m/s}, \quad A_1 = 100 \text{ cm}^2, \quad A_2 = 20 \text{ cm}^2, \quad C_p = 10^3 \text{ J/kg}^\circ\text{K}$$

Solution  $\rightarrow$

$$P_2 V_2 = RT_2$$

$$T_2 = P_2 V_2 / R.$$

$$V_2 \rightarrow \text{SP Vol}^m.$$

We have  $m_1 = m_2$ .

$$\frac{a_1 V_1}{V_1} = \frac{a_2 V_2}{V_2}$$

$$P_1 V_1 = RT_1$$

$$V_1 = \frac{RT_1}{P_1} = \frac{287 \times 300}{0.1 \times 10^6} = 0.861 \text{ m}^3 \text{ kg}^{-1}.$$

$$V_2 = \frac{a_2 V_2}{a_1 V_1} \times V_1 = \left(\frac{20}{100}\right) \left(\frac{100}{40}\right) \times 0.861 = 0.4305 \text{ m}^3 \text{ kg}^{-1}$$

$$T_2 = P_2 V_2 / R.$$

$$= \frac{1 \times 10^6 \times 0.4305}{287} = 1500 \text{ K}.$$

$$z_1 = z_2.$$

$$R = 5\% \text{ } W_c.$$

- R as rejected  
- W work done on the system.

$$H_1 + \frac{1}{2} m v_1^2 + C - R = H_2 + \frac{1}{2} m v_2^2 + (W_c)$$

$$-0.5 W_c + W_c = M [h_2 - h_1] + m [v_2^2 - v_1^2]$$

$$0.95 W_c = 0.4646 \times C_p [C T_2 - T_1] + \frac{1}{2} C [v_2^2 - v_1^2]$$

$$m = \frac{A_1 V_1}{V_1}$$

$$= 0.4646 \times [10^3 (1500 - 300) + \frac{1}{2} C (100^2 - 40^2)] \quad (A_n = 500 \text{ cm}^2)$$



## Nozzle: —

There is no work output =  $W=0$ .

No heat influx or escape  $Q=0$

For a horizontal disposition  $z_1 = z_2$ .

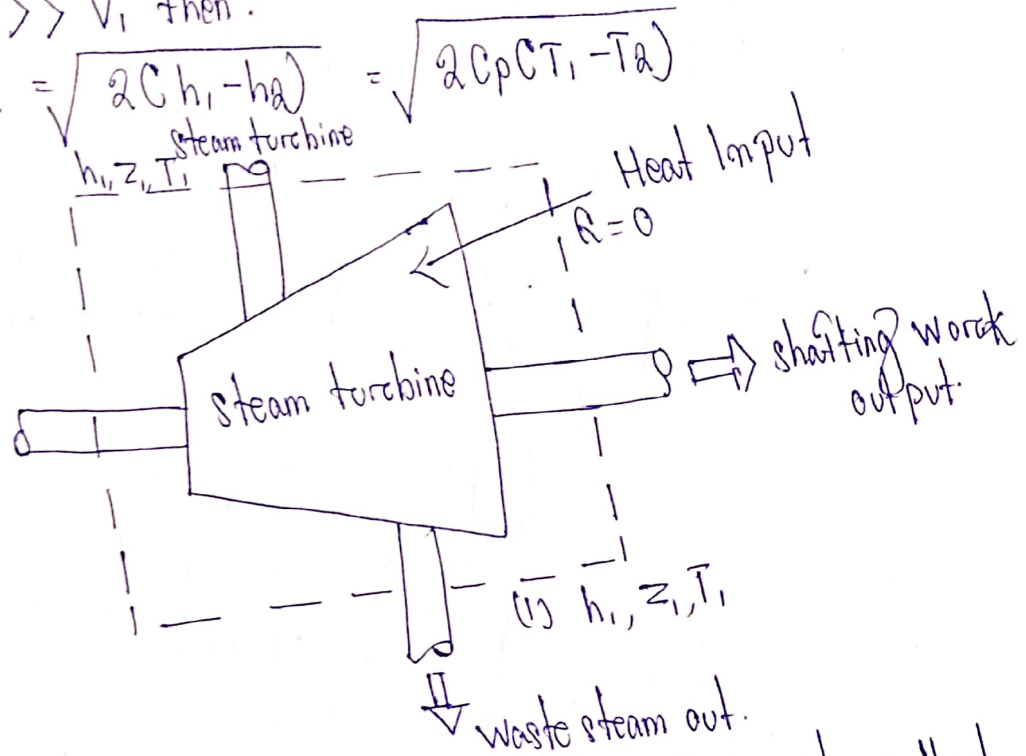
And so the SFEE applied to the nozzle boils down to

$$h_1 + \frac{1}{2}(v_1)^2 = h_2 + \frac{1}{2}(v_2)^2$$

If  $v_2 \gg v_1$  then.

$$v_2 = \sqrt{2C(h_1 - h_2)} = \sqrt{2Cp(T_1 - T_2)}$$

Turbine —



→ A steam turbine receives a superheated, high pressure steam that experiences it.

→ Enthalpy drop as the system passes over the turbine blades.

→ This enthalpy drop is converted into kinetic energy of rotation of blades mounted on the turbine drum.

→ The turbine is well insulated which gives rise to the maximum work output.

→ The turbine is well insulated.

$Q=0$ .

Steam vel at the turbine input = The steam vel at the output

i.e.  $v_1 = v_2$ .

the turbine is position horizontally.  $z_1 = z_2$

Applying SFEE to the Control Vol<sup>m</sup> —

$$h_1 = h_2 + W.$$

$$W = h_1 - h_2 = C_p [T_1 - T_2]$$

$$W = m \cdot C_p [T_1 - T_2]$$

Perpetual motion machine: —

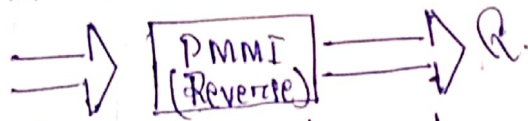
It is a hypothetical machine that will continuously churn out work but without absorbing heat from its surrounding.

$$Q = 0.$$



But such a machine is not feasible from a practical point of view. For it violates law of conservation of energy.

$$W = 0.$$



The reverse of perpetual machine is also not true, → It is a hypothetical machine which is not feasible, as it violates the 1st law of thermodynamics.

Notes: —

1st law of thermodynamics: — when a closed system undergoes a thermodynamic cycle, the net heat transfer is equal to the net work transfer.

# Second law of thermodynamics Chapter 4

## Limitation of 1st law:

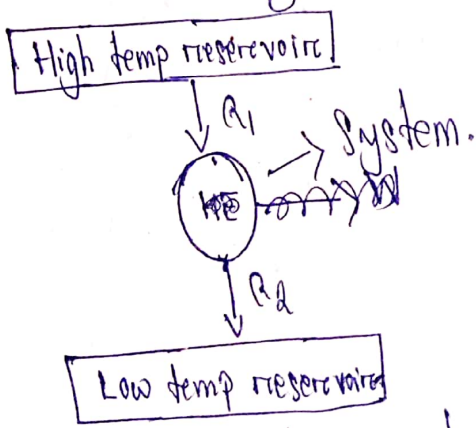
- There are two basic limitations of 1st law of thermodynamics.
- 1) 1st law doesn't differentiate bet<sup>n</sup> heat & work —  
It assumes complete inter-converibility of the two. Through work being a high grade energy can be fully converted into heat but heat can't be completely converted to work.
  - 2) It doesn't permit us to know the dir<sup>n</sup> of energy transfer. We can't ascertain whether heat will flow from a higher temp body to lower temp body.

## Thermal Reservoir:

A thermal reservoir is a heat source or heat sink that remains at a const temp. regardless of energy interaction. Otherwise a thermal energy reservoir [TER] is a large system body of infinite heat capacity which is capable of absorbing or rejecting a finite amount of heat without any changes in its thermodynamic co-ordinates.

The high temp reservoir ( $T_H$ ) that supplies heat is a source. Sink - low temp reservoir to which heat is rejected.

Ex. Ocean water and atm air are two good example.



## Concept of heat engine:

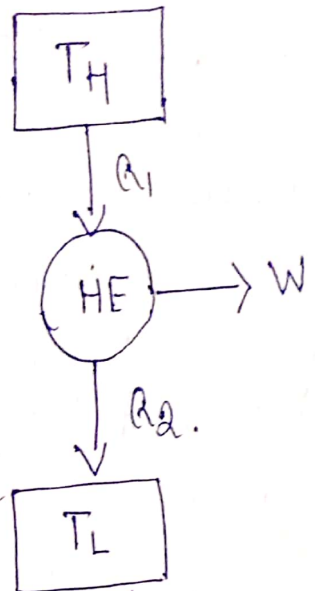
A heat engine is a device that can operate continuously to produce work rejecting heat from a high temp  $T_H$  and.

rejecting non-converted heat to a low temp sink.

$$\text{Effect} = \frac{\text{Output}}{\text{Input}} = \frac{W}{Q_1}$$

but  $W = Q_1 - Q_2$  in a cycle.

$$\eta_{\text{thermal}} = \frac{Q_1 - Q_2}{Q_1} = 1 - \frac{Q_2}{Q_1}$$



### Heat pump:

A heat pump is a reversed heat engine.

→ It receives heat from a low temp reservoir and rejects it to high temp reservoir. For which an external work which is supplied to the pump.

→ The efficiency of a heat pump cycle is usually called the Co. of performance (C.O.P.).

→ It is the desired effect upon the external work supplied for obtaining that desired effect.

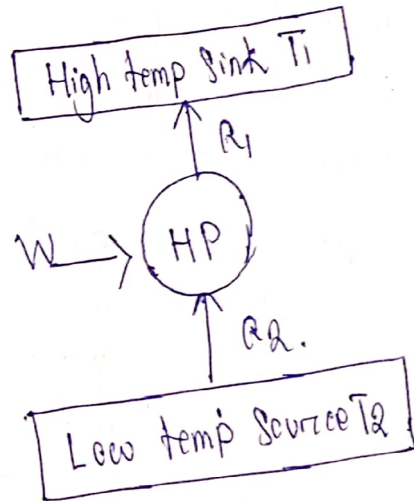
$$\text{COP} = \frac{\text{Desired effect}}{\text{Work input}}$$

$$\text{COP}_{\text{HP}} = Q_1 / W$$

$$\text{Again } \sum_{\text{cycle}} Q = \sum_{\text{cycle}} W$$

$$Q_1 - Q_2 = W$$

$$\text{COP}_{\text{HP}} = \frac{Q_1}{Q_1 - Q_2}$$



Refrigerators: — A refrigerator is similar to heat pump.

→ It operates as a reversed heat engine.

→ Its duty is to extract heat as much as possible from the cold body and deliver the same to high temp body.

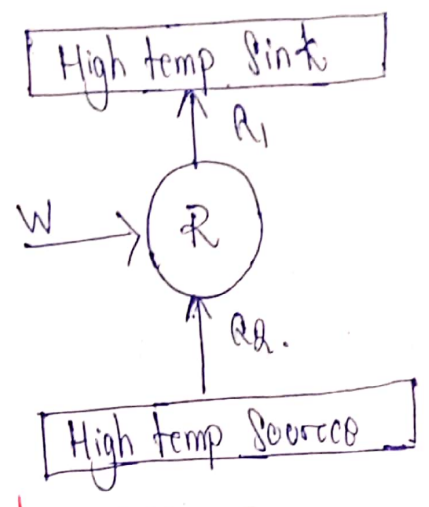
The desired effect of a refrigerator is to remove  $Q_2$  heat infiltrating into the cold space. By using the external work it rejects  $Q_1$  heat to the high temp reservoir. (11)

$$(CoP)_{ref} = \frac{Q_2}{W}$$

Again  $\sum Q = \sum W$   
 cycle cycle

$$Q_1 - Q_2 = W$$

$$CoP_{ref} = \frac{Q_2}{Q_1 - Q_2}$$



**Statement of 2nd law of thermodynamics: —**

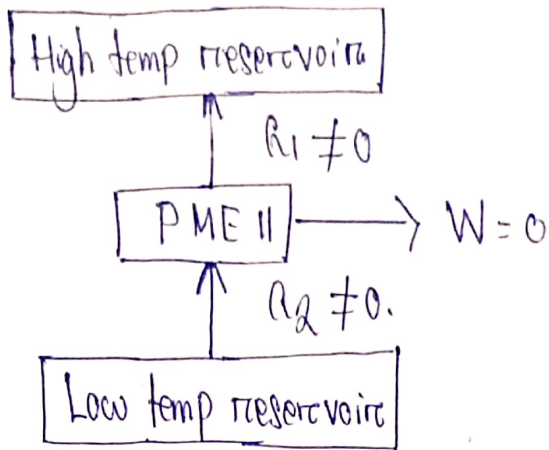
Clausius statement: — It is impossible to construct a device that will produce no effect other than the transfer of heat from a low temp body to high temp body while operating in a cycle.

Kelvin plank statement — No heat engine, operating in cycle, can convert heat into work.  
 → It is impossible to build a heat engine that can register 100% efficiency.

Notes: — kelvin plank statement is of relevance to a heat engine. The C-statement relates more directly to a reversed heat engine.

**Perpetual motion machine II: —**

It is a hypothetical machine that will continuously pump out from a low temp reservoir to a high temp reservoir at  $(T_1)$  without taking up any input work from surrounding.



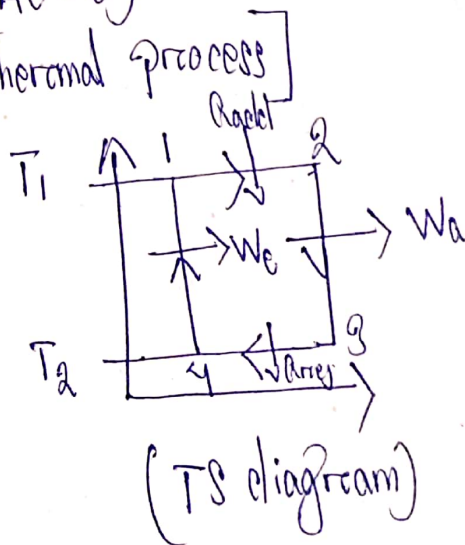
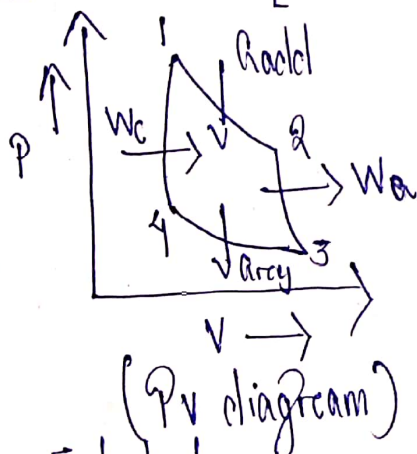
Carnot cycle: —

- Carnot cycle is a hypothetical cycle developed by a French military engineer, Nicholas Sadi Carnot.
- It is meant for a heat engine or reversed heat engine.
- All the processes involved in this cycle are reversible, thereby ensuring the best possible device that one could construct.
- This cycle comprises four reversible processes.

Process 1-2: — Reversible isothermal heat addition. Heat ( $Q_{add}$ ) flows from a high temp reservoir to the working fluid which is at a constant temp but only infinitesimally below that of the source.

$$Q_{add} = \Delta U + W_{1-2} \quad (\Delta U = 0)$$

$$Q_{add} = W_{1-2} \quad [\text{as Isothermal process}]$$



Process 2-3 [adiabatic expansion]

The working fluid expands through a turbine or expander adiabatically producing a net positive work output.

Here  $Q = 0$

$$0 = \Delta U_{2-3} + W_{2-3}$$

Process 3-4 (Isothermal heat rejection).

Heat is rejected by the fluid to sink both are at a const temp. but differ only by an infinitesimal amount.

$\Delta U = 0$ , Isothermal process.

$$-Q_{rej} = -W_{3-4}$$

-  $Q$  = Heat has been rejected by the system.

-  $W$  = Work has been done on the system.

Process 4-1 (Reversible adiabatic compression)

The temp of the working fluid is raised back to the temp level to high temp through adiabatic compression. i.e.  $Q = 0$ .

$$0 = \Delta U_{4-1} + -W_{4-1}$$

$$\Delta U_{4-1} = W_{4-1}$$

As the two isothermal and two adiabatic complete the cycle —

$$\text{So } \sum_{\text{cycle}} Q_{net} = \sum_{\text{cycle}} W_{net}$$

$$\text{or } Q_{add} + (-Q_{rej}) = W_{1-2} + W_{2-3} - [W_{3-4} + W_{4-1}]$$

$$Q_{add} - Q_{rej} = W_e - W_c$$

So the efficiency

$$\eta = \frac{\text{Net Work output}}{\text{Net heat input}} = \frac{W_e - W_c}{Q_{add}} = \frac{Q_{add} - Q_{rej}}{Q_{add}} = 1 - \frac{Q_{rej}}{Q_{add}}$$

Alt.: — Refer to the T-S diagram

Net Work done  $W_{net} = \text{Area } 1-2-3-4$ .

$$= \text{Side } 1-4 \times \text{Side } 1-2$$

$$= T_1 - T_2 \times S_2 - S_1$$

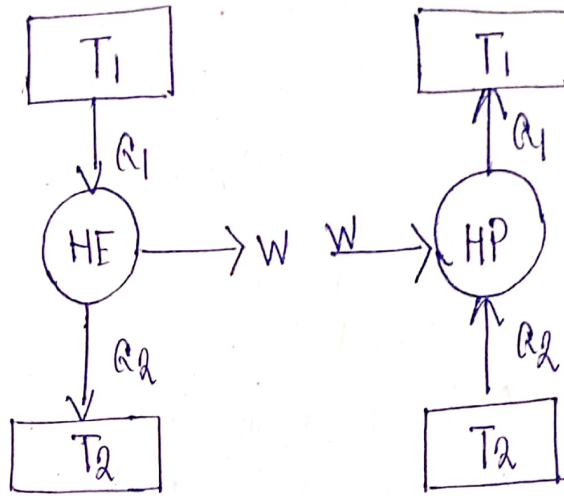
$$Q_{add} = T_1 [S_2 - S_1]$$

$$\text{Efficiency } \eta = \frac{W_{net}}{Q_{add}} = \frac{(T_1 - T_2) \Delta S}{T_1 \Delta S} = 1 - \frac{T_2}{T_1}$$

Application of 2nd law of heat engine, heat pump, refrigerator and determination of COP and efficiencies: —

Clausius statement: — According to 2nd law without work input heat can't flow from low temp to high temp.

Case of heat engine: —



Kelvin Planck statement: —

No heat engine operating in a cycle can convert entire heat into work. In this engine —

$$Q_1 = Q_2 + W$$

that means,  $Q_2$  is rejected along with  $W$  output —

$$Q_1 \neq W$$

In a heat pump —

$$W + Q_2 = Q_1$$

$$W = 0, Q_2 = Q_1$$

which is impossible  $W \neq 0$ .

In a refrigerator: —

$$(COP)_{HP} = \frac{D.E}{\text{Work Input}}$$

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

as  $\frac{Q_1}{T_1} = \frac{Q_2}{T_2}$  [According to Carnot's theory]

$$(COP)_{ref} = \frac{D.E}{\text{Work}_{ref}} = \frac{Q_2}{Q_1 - Q_2} = \frac{T_2}{T_1 - T_2}$$

$$1 + (COP)_{ref} = 1 + \frac{T_2}{T_1 - T_2} = \frac{T_1 - T_2 + T_2}{T_1 - T_2}$$

Notes: —

If installed backward your household air conditioner will function as a heat pump, cooling the surrounding but heating the room.

$$1 + (COP)_{ref} = (COP)_{HP}$$



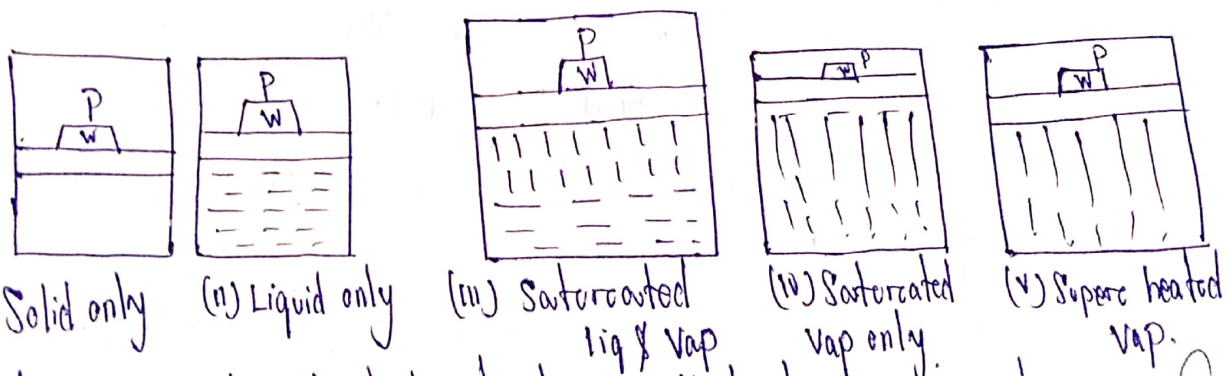
Pure substance: — Substances whose chemical composition is uniform throughout the mass.

It should have the following properties: —

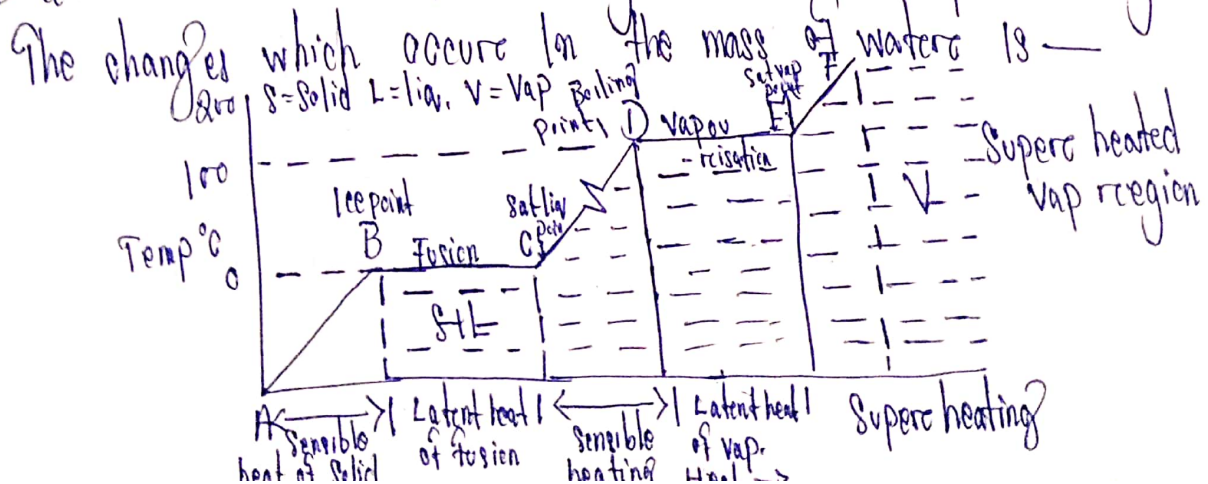
- i) Homogeneous in composition.
  - ii) Homogeneous in chemical aggregation.
  - iii) Invariable in chemical aggregation.
- 1) Homogeneous in composition: — Composition of each part of the system is same.
- 2) Homogeneous in chemical aggregation — Chemical elements must be combined chemically in the same way in all parts of the system.
- 3) Invariable in chemical aggregation — The state of chemical combination of the system doesn't change with time.

Phase change of pure substance: —

Let the cylinder and piston machine contains a unit mass of ice at  $-10^{\circ}\text{C}$  under pressure "P" exerted by a weight W placed on the free frictionless piston.



Let the ice be heated slowly so that its temp is always uniform



Process A-B - Sensible heating of ice.

- On heating the temp of ice increases from  $-10^{\circ}\text{C}$  to  $100^{\circ}\text{C}$ .
- The vol<sup>m</sup> of ice also increases the point 'B' is called as ice point or freezing point of water. ( $0^{\circ}\text{C}$ ).

Process B-C [Fusion] -

- On the heating ice melts into water at a const temp  $0^{\circ}\text{C}$ .
- The heat added during the process is called as latent heat of Fusion or latent heat of ice.
- The vol<sup>m</sup> of water decreases in comparison with ice at  $0^{\circ}\text{C}$ . This is a peculiar characteristic of water.
- but all other pure substances increase their vol<sup>m</sup> during the process
- The process in opposite dir<sup>n</sup> [C-B] is called Solidification.

Process C-D [Sensible heating of water]

- On heating the temp of water increases from  $0^{\circ}\text{C}$  to  $100^{\circ}\text{C}$ .
- The vol<sup>m</sup> of water increases due to thermal expansion.

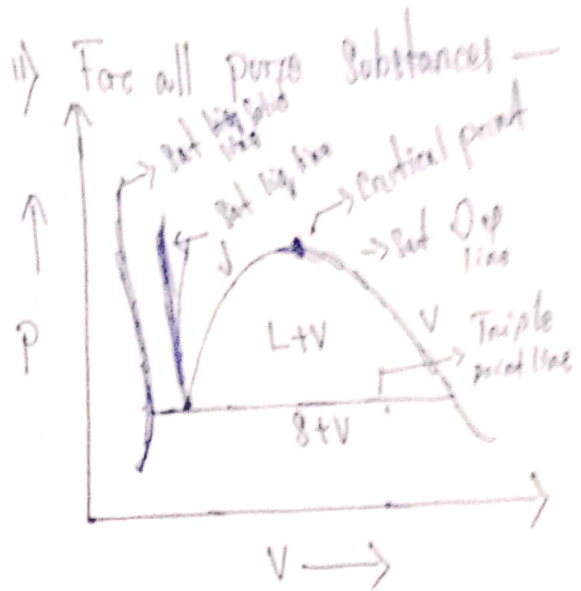
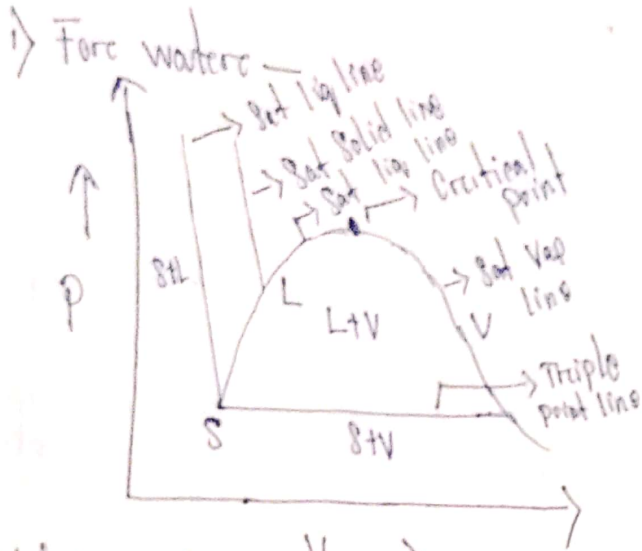
Process D-E [Vapourisation]

- On heating the water starts boiling to vap at const temp of  $100^{\circ}\text{C}$ .
- The heat added during the process is called latent heat of vap.
- The vol<sup>m</sup> of the mix of water and vap increases.
- The vap at state 5 is dry saturated.
- The process in opposite dir<sup>n</sup> [E-D] is called Condensation.

Process E-F [Superheating]

- On heating the sat vap at E gets superheated & temp of the vap increases to say  $200^{\circ}\text{C}$ .
- The vol<sup>m</sup> of the vap also increases to height extent.
- The rise in temp during the process is called degree of Superheat.
- The heat added during this process is called as heat of Superheat.

P-V diagram:



Solid liq mixture region [S+L]:

The space bet<sup>n</sup> saturated solid line and Sat liq line w.r.t the solidification is called Solid liq mixture region.

Solid region (S):

The space left to the Sat solid line is called solid region.

Liq. region (L) → The space bet<sup>n</sup> a saturated liq line is called liq region.

Liq Vap mixture region [L+V]: → The space bet<sup>n</sup> Sat liq line w.r.t vapourisation and Sat Vap line is called liq vap mixture region.

Triple point line → It is a line on P-V diagram, where all these phases exist in equilibrium.

Solid vap mixture region (S+V) → The space below the triple point line is called Solid Vap mixture region.

Critical point →

→ The point at which the sat liq line & Sat vap line meet each other is known as Critical point.

→ Above the Critical point, the liq on heating suddenly converted into vap or the vap on cooling suddenly converted into liq.

→ The prc. temp, & vol<sup>m</sup> w.r.t critical point are known as Critical prc. Critical temp, Critical vol<sup>m</sup>.

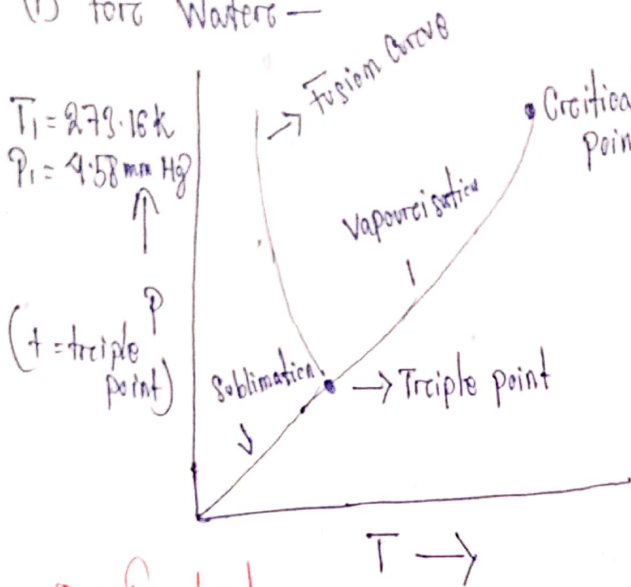
Forc Waters →  $P_c = 221.2 \text{ bar}$ ,  $T_c = 374.15$ ,  $V_c = 0.00317 \text{ m}^3/\text{kg}$ .

Sat temp → The temp at which a pure liq [at a given prc] changes into vap.

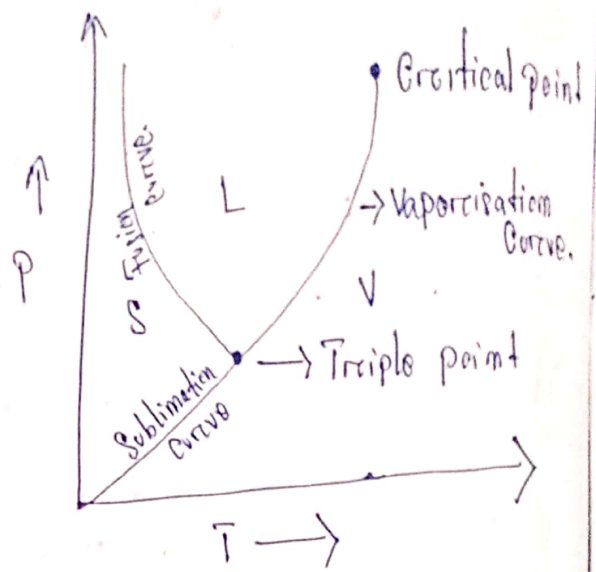
Saturated pressure  $\rightarrow$  At a given temp a pure liq changes into pro. that Critical pro is called saturated pro.

P-T diagram  $\rightarrow$

(1) For Water  $\rightarrow$



(2) For pure substance  $\rightarrow$



Specific heat  $\rightarrow$

$\rightarrow$  It is defined as the amount of heat req. to raise the temp of a unit mass of substance through unit degree.

$\rightarrow C = \frac{Q}{m \cdot \Delta t}$  Unit  $\text{J/kg} \cdot \text{K}$ . where  $M = \text{Mass of substance}$   
 $\Delta t = \text{Rise or fall of temp.}$

$\rightarrow$  sp heat at const pro is called  $C_p$ .

$\rightarrow$  sp heat at const vol<sup>m</sup> is called  $C_v$ .

$\rightarrow$  it doesn't depend upon path.

Quality of dryness fraction  $\rightarrow$  It is defined as the ratio of mass of dry steam actually present to the total mass of the vap which contains it.

Dryness fraction =  $\frac{\text{dry steam mass}}{\text{Total mass of vap}}$

$x = \frac{m_g}{m_g + m_f} = \frac{m_g}{M}$  where  $M = \text{Total mass} = (m_g + m_f)$   
 $m_g \rightarrow \text{Mass of dry vap.}$   
 $m_f \rightarrow \text{Mass of liq particle.}$

Wetness fraction =  $\frac{\text{Mass of liq particle present}}{\text{Total mass of steam}}$   $(1-x) = \text{wetness fraction.}$

For dry saturated vap quality = 100%.  $x = 1$ .

(1)  $V = V_f + V_g$

$V_f = \text{Vol}^m \text{ of liq particle present.}$

$V_g = \text{Vol}^m \text{ of vap present.}$

$V = V_f + x V_{fg}$
$S = S_f + x S_{fg}$
$U = U_f + x U_{fg}$

$v_{fg} = v_g - v_f$

$s_{fg} = s_g - s_f$

$h_{fg} = h_g - h_f$

Head of Superheat  $h_s = C_p [T_{sup} - T_{sat}]$

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

Steam table: — The properties of water are arranged in the steam table as the function of temp & pres.

If temp given — then it is a case of Superheat.

$$V = V_1 + \frac{V_2 - V_1}{T_2 - T_1} \times \text{given } T.$$

$$h = h_1 + \frac{h_2 - h_1}{T_2 - T_1} \times \text{given } T.$$

$$S = S_1 + \frac{S_2 - S_1}{T_2 - T_1} \times \text{given } T.$$

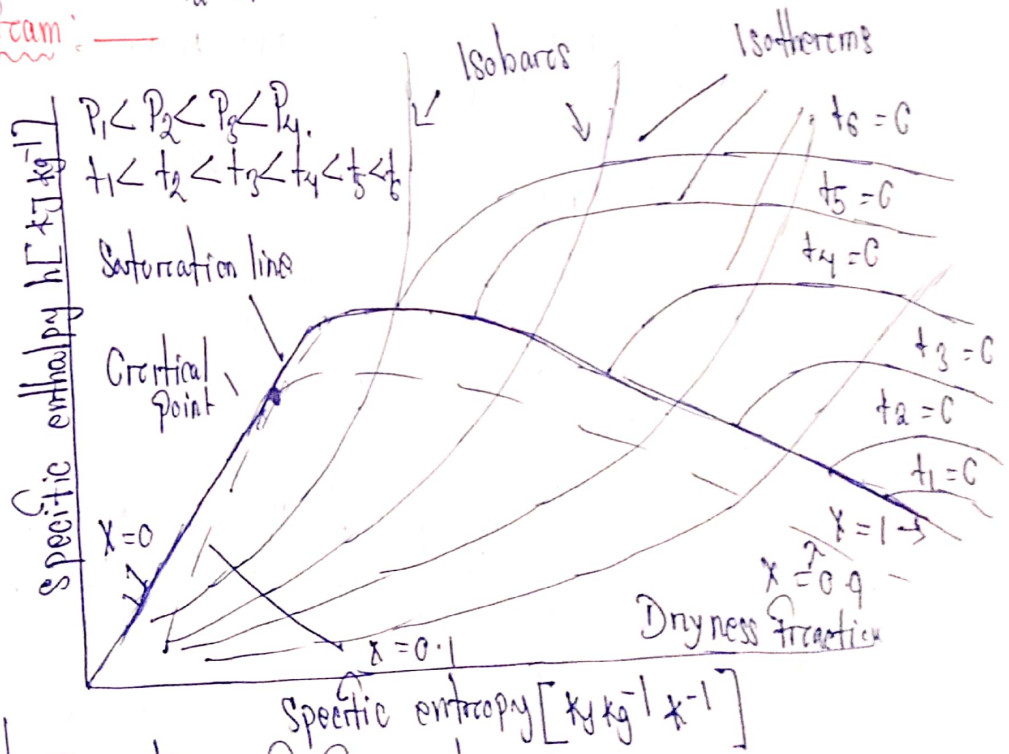
If given Vol<sup>m</sup> → steam table Vol<sup>m</sup> it is a case of Superheat

$$T = T_1 + \frac{T_2 - T_1}{V_2 - V_1} \times \text{given } T.$$

$$h = h_1 + \frac{h_2 - h_1}{V_2 - V_1} \times \text{given } T.$$

$$S = S_1 + \frac{S_2 - S_1}{V_2 - V_1} \times \text{given } T.$$

Mollier diagram:



Const pres line =  $P_1, P_2 \dots$  etc.  
 " temp " =  $t_1, t_2 \dots$  etc.

# Ideal gases & Real gases

Boyle's law → The Vol<sup>m</sup> of the given mass of gas is inversely proportional to its abs. pres at const temp.

$$V \propto \frac{1}{P} \text{ at Const Temp. } \boxed{PV = \text{Constant}}$$

Charles law → The Vol<sup>m</sup> of a given mass of a gas is directly proportional to its absolute temp at const pres.

$$V \propto T \text{ [at Const Pres.]} = \boxed{\frac{V}{T} = \text{Constant}}$$

Ideal gas Law: — From Boyle's law  $PV = C$ .

Charles law  $V/T = C$

Combining both the law  $\frac{PV}{T} = C$  i.e.  $PV \propto T$   
 $PV = RT$

This eq<sup>n</sup> is called characteristic gas eq<sup>n</sup> or ideal gas eq<sup>n</sup> —

$R$  = characteristic gas constant.

$$= 0.287 \text{ kJ/kg-K [for atm air]}$$

Universal gas constant ( $R_u$ ): —

In general  $PV = mRT$ .

$m$  = mass of gas. but  $m = nM$ .

$n$  = No of kg moles.

$M$  = Molecular mass of the gas.

$$PV = nMT$$

$$= n(MR)T = nR_u T$$

$R_u$  = Universal gas constant. =  $M \cdot R$ .

$M \cdot R$  = Constant of all gases.

$$\boxed{R_u = 8.314 \text{ kJ/kg}}$$

Avogadro's law: — it states that the equal Vol<sup>m</sup> of different ideal gases at the same temp & pres contains equal no of molecules.

$$\eta = \frac{m_1}{M_1} = \frac{m_2}{M_2} = \frac{m_3}{M_3}$$

but  $M = PV$ .

$$\eta = \frac{P_1}{M_1} = \frac{P_2}{M_2} = \frac{P_3}{M_3}$$

Sp Vol<sup>m</sup> molecular weight = Molar Volume

$$\boxed{V \cdot M = \bar{V}}$$

$S_1$  = Mass density =  $1/V$ .

$V$  = sp. Vol<sup>m</sup>.

$$\eta = \frac{1}{M_1 V_1} = \frac{1}{M_2 V_2} = \frac{1}{M_3 V_3}$$

$$M_1 V_1 = M_2 V_2 = M_3 V_3 = C$$

Dalton's law: — The  $P$  of a mixture of gases is equal to the sum of the partial  $P$  of the constituents. (18)

→ The partial  $P$  of each constituent is that  $P$  which the gas would exert if it occupied alone at that given vol $^m$  occupied by the mixture at the same temp.

$$P = P_A + P_B$$

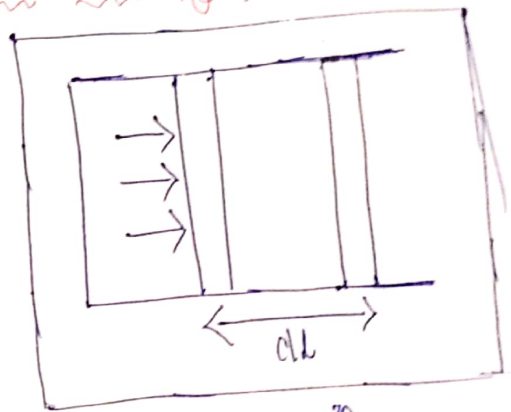
→ It is found the Dalton's law is more accurately by gas mixture at low  $P$ .

$$P = P_A + P_B + \dots + P_n = \sum P_i$$

$P_i$  = Partial  $P$  of the constituent.

Workdone in moving the boundaries of a closed system: —

Consider a gas contained in a piston cylinder arrangement.  $P$  exerted by the gas is  $P$  on the cross-sectional area of piston  $A$ .



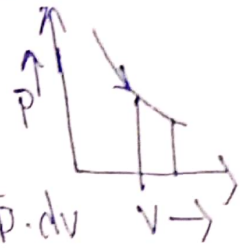
Let the piston move a distance  $dL$ .

$$\begin{aligned} \text{Workdone} &= \text{Force} \times \text{displacement} \\ &= (P \cdot A) \times dL \quad (P = F/A) \\ &= P \cdot dV \quad (A \cdot dL = dV) \end{aligned}$$

Suppose, gas expands from 1 to 2 then  $W \cdot D = \int_{V_1}^{V_2} P \cdot dV$

Workdone by the system is +ve.

" " " " " -ve.



Constant Vol $^m$  Process: —

$$W \cdot D = P \cdot dV = 0$$

$$dW = 0$$

$$dQ = MC_v \cdot dT \quad [\text{Heat supplied}]$$

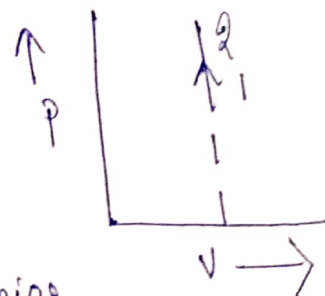
According to 1st law of thermodynamics

$$dQ - dW = dU$$

$$MC_v \cdot dT = 0 = dU$$

$$\Delta U = MC_v [T_2 - T_1]$$

Isochoric process



## Constant pressure process — Isobaric process

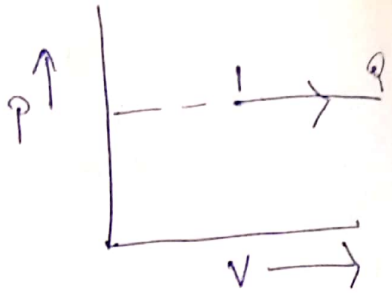
$$dw = \int_1^2 p dv = p [v_2 - v_1] = p_2 v_2 - p_1 v_1$$

$$= MR [T_2 - T_1]$$

$$dq = \int_1^2 m c_p dT = m \cdot c_p [T_2 - T_1]$$

$$du = m \cdot c_p (T_2 - T_1) - m \cdot R (T_2 - T_1) = m \cdot c_v [T_2 - T_1]$$

$$\boxed{c_p - c_v = R}$$



## Constant temp process — Isothermal process

$$Pv = C$$

$$P = C/v$$

$$dw = \int_{v_1}^{v_2} P \cdot dv = \int_{v_1}^{v_2} \frac{C}{v} dv = C [\ln v] \Big|_{v_1}^{v_2}$$

$$= C [\ln v_2 - \ln v_1] = C \ln \left[ \frac{v_2}{v_1} \right] = p_1 v_1 \ln \left[ \frac{v_2}{v_1} \right] = p_2 v_2 \ln \left[ \frac{v_2}{v_1} \right]$$

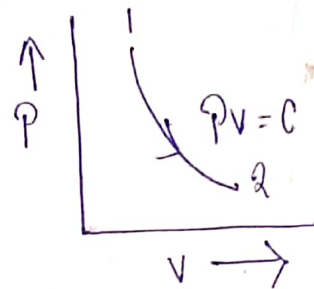
$$= m \cdot R \cdot T \ln \left[ \frac{v_2}{v_1} \right]$$

$$du = m \cdot c_v [T_2 - T_1] = 0$$

$$T_2 = T_1$$

$$Q - W = \Delta U = U_2 - U_1$$

$$\boxed{Q = W}$$



## Isentropic process: —

No heat transfer bet<sup>n</sup> the system & the surroundings.

Constant pressure process (Isobaric process)

$$Pv^\lambda = C$$

$$dw = \int_1^2 P \cdot dv = C \int_{v_1}^{v_2} \frac{dv}{v^\lambda} = C \left[ \frac{v^{-\lambda+1}}{-\lambda+1} \right]_{v_1}^{v_2}$$

$$= \frac{C}{1-\lambda} [P_2 v_2^\lambda v_2^{1-\lambda} - P_1 v_1^\lambda v_1^{1-\lambda}]$$

$$= \frac{P_1 v_1 - P_2 v_2}{\lambda - 1} [C = \gamma \cdot v_1^\lambda = P_2 v_2^\lambda]$$

$$Q = 0$$

$$\boxed{\Delta U = W}$$

