

THERMODYNAMICS-I

Chapter-01

Fundamental Concepts

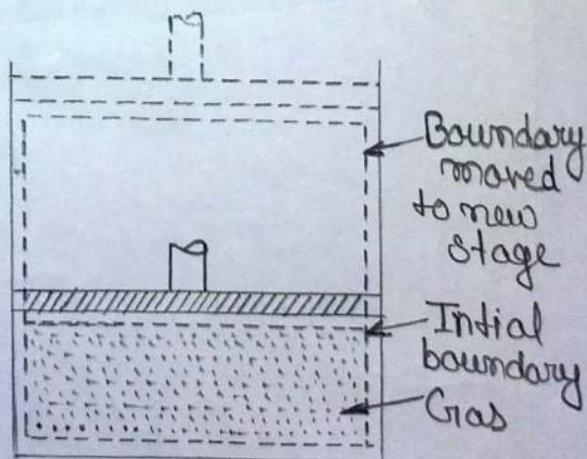
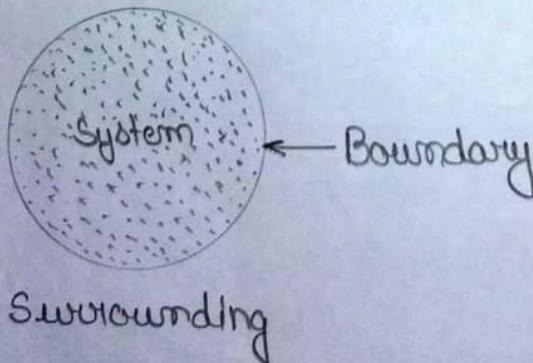
Thermodynamic state and system, boundary, surrounding, universe, thermodynamic systems - closed, open, isolated, adiabatic, homogeneous and heterogeneous, macroscopic and microscopic, properties of system - intensive and extensive, thermodynamic equilibrium, quasi-static process, reversible and irreversible processes, Zeroth law of thermodynamics, definition of properties like pressure, volume, temperature, enthalpy and internal energy.

Thermodynamics :- Thermodynamics may be defined as the field of science dealing with energy in the form of heat and work and their conversion into each other.

System :- A thermodynamic system is defined as a quantity of matter at a prescribed region in space upon which attention is focused for study.

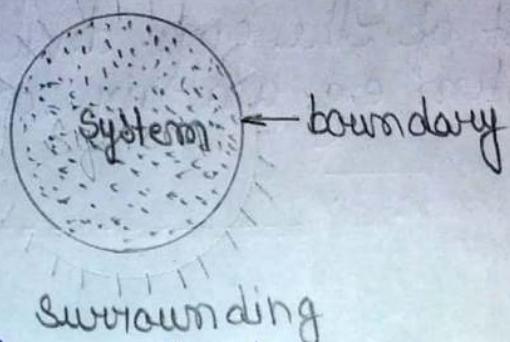
State :- The condition of a system at any instant of time described by its physical properties is known as state of the system.

Boundary :- It is kind of envelope which separates the system from surroundings. The boundary may be real or imaginary. It may be fixed or moving. Piston moving in a cylinder containing gas is an example of moving boundary.



Moving Boundary

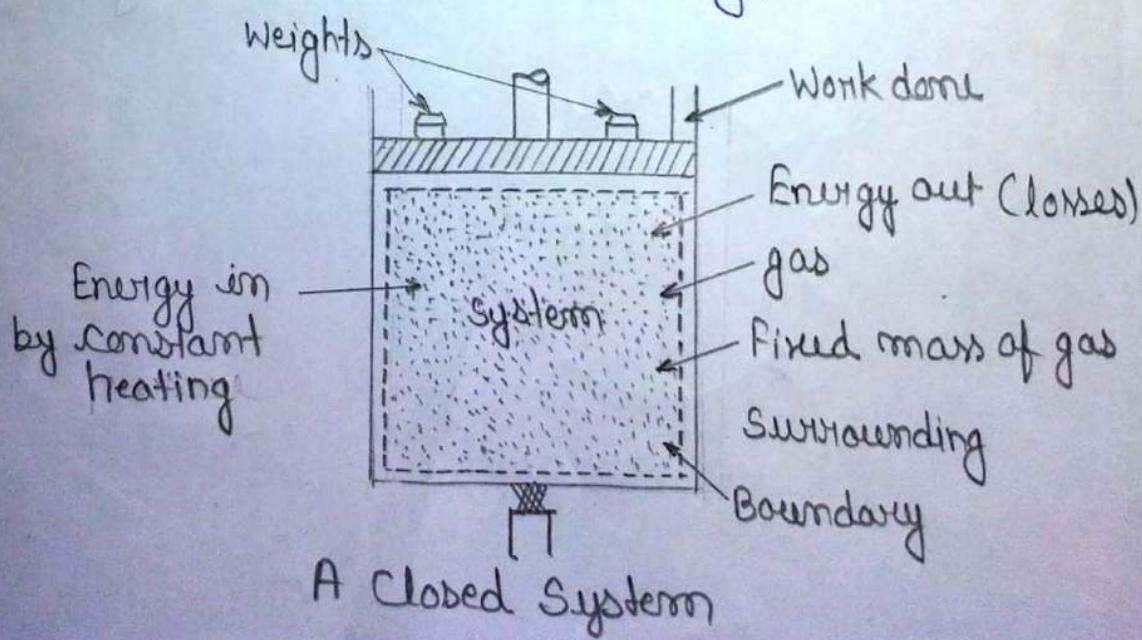
Surroundings:- Everything external to the system is called as surrounding or the environment.



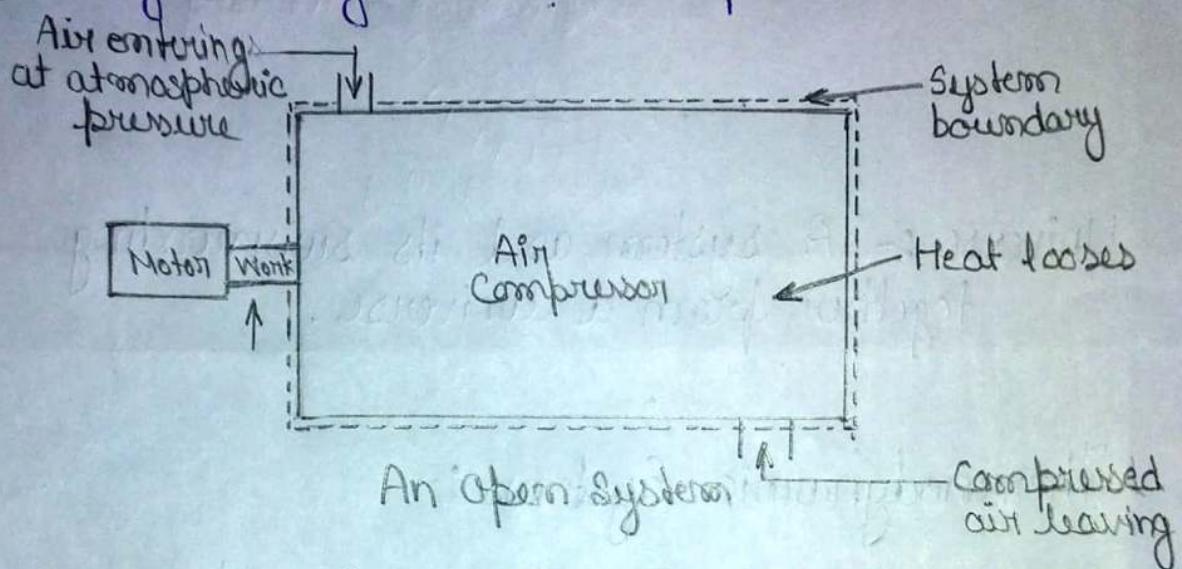
Universe :- A system and its surrounding together form a universe.

Thermodynamic Systems :-

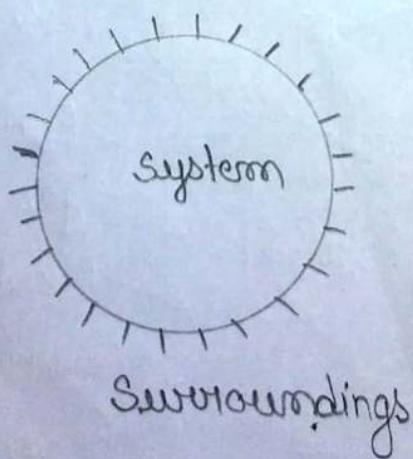
(a) Closed system :- If there is no transfer of mass across the system boundary (i.e between system and surroundings), it is called closed system. Example of closed system is motor-car battery, Bomb calorimeter.



(b) Open System: In an open system, there is an exchange of mass across the system boundary. There may be energy transfer also. Most of the engg. device are generally open system e.g. an air compressor.



(c) Isolated System :- In an isolated system, there is no transfer of mass and energy to and from the system. It is a system of fixed mass and no heat or work energy can cross the system boundary.



Adiabatic :- It is relating to or denoting a process or condition in which heat does not enter or leave the system concerned.

Homogeneous System :- A system which consists of a single phase is known as homogeneous system.

Heterogeneous System :- A system consisting of more than one phase is called heterogeneous system.

Intensive :- The properties which do not depend upon the mass of the system are known as intensive properties e.g. temperature, density etc.

Extensive :- The properties which depend upon mass or size of the system are known as extensive properties e.g. energy, entropy, volume etc.

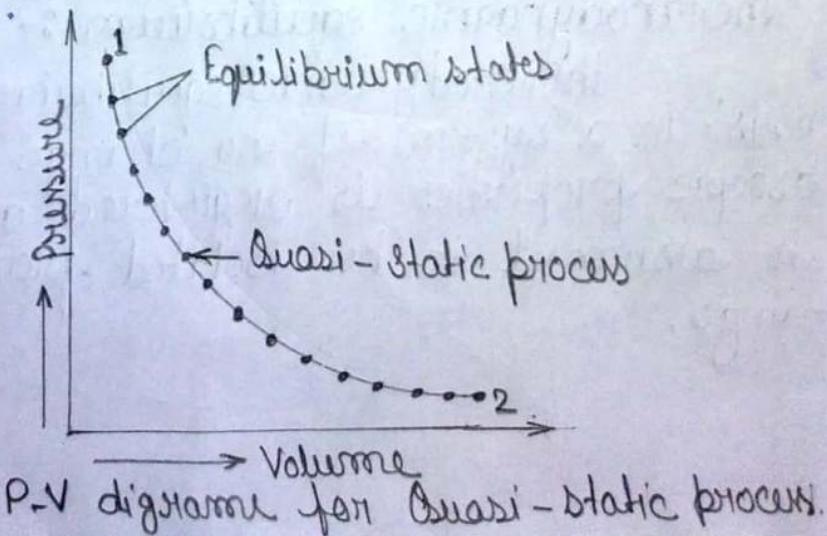
Thermodynamic equilibrium :- A state of thermodynamic equilibrium is said to exist in a system if no change in any macroscopic properties is registered and the system is assumed to be isolated from its surroundings.

(a) Mechanical Equilibrium :- In the absence of any unbalance force within the system and also between the system and surroundings, the system is said to be in a state of mech. equilibrium.

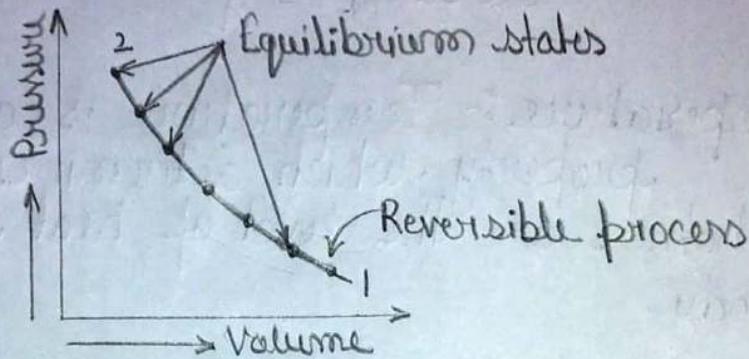
(b) Chemical Equilibrium :- If there is no chemical reaction of matter with in system or between the system and surrounding, the system is said to be in a state of chemical equilibrium.

(c) Thermal Equilibrium :- It is the condition or state in which the temperature of the system is uniform is called as thermal equilibrium.

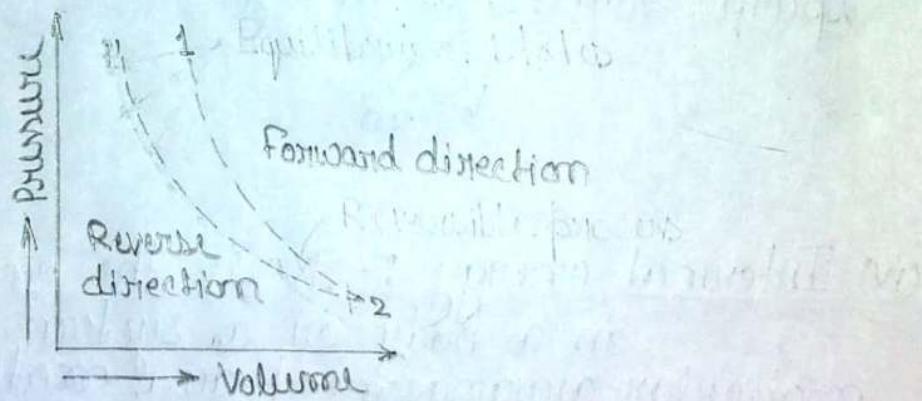
Quasi - Static Process :- When the process is carried out in such a manner that at every instant, the system deviation from the thermodynamic equilibrium is very small, then the process is known as quasi-static process. A quasi-static process is also called a reversible process.



Reversible processes :- A process which can be reversed in direction and the system retraces the same path and the same equilibrium states is known as reversible process.



Irreversible process :- A process is said to be irreversible process cannot come back to the original state, if made to proceed in reverse direction.



Zeroth law of thermodynamics :- This law states that if a body A is in thermal equilibrium with a body B and also separately with a body C, then bodies B and C will be in thermal equilibrium with each other.

(i) Pressure :- Pressure may be defined as the normal force exerted by a system against unit area of the surface.

$$\text{Pressure, } P = \frac{F}{A}$$

(ii) Temperature :- Temperature is an intensive property which determines the degree of hotness or the level of heat intensity of a body.

(iii) Specific Volume :- It is reciprocal of mass density. The specific volume of a system is the volume occupied by the unit mass of the system. It is denoted by v . S.I. unit of specific volume is m^3/kg .

$$v = \frac{V}{m}$$

(iv) Internal energy :- It is the energy stored in a body or a system due to its molecular arrangement and motion of molecules. If certain amount of heat is supplied to a gas, a part of it is converted into mech. energy and remaining gas stored in the gas itself. This energy is used for raising the temp. of gas and is called internal energy of gas. It is generally denoted by U . It is the function of temperature.

Internal energy is given by

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

(v) Enthalpy :- The sum of internal energy and pressure volume product is known as enthalpy. In other words, the total heat energy contained in a gas is known as enthalpy.

$$\text{i.e } H = U + PV$$

$$\text{for unit mass, } h = u + Pv$$

Chapter-02 Law of Perfect gases

Definition of gases, explanation of perfect gas laws - Boyle's law, Charles' law, Avogadro's law, Regnault's law, Universal gas constant, characteristics gas constants and its derivation.

Specific heat at constant pressure, specific heat at constant volume of gas, derivation of an expression for specific heat with characteristics, Simple numerical problem on gas equation.

Perfect Gas :- A perfect gas or ideal gas may be defined as a state of a substance, whose evaporation from its liquid state is complete. A perfect gas strictly obey all the gas laws under all conditions of temperature and pressure. In actual practice, no gas is perfect gas, but some real gases like CO_2 , nitrogen, hydrogen, air etc. may be regarded as perfect gases within certain temp. and pressure limits.

Laws of perfect gases

(i) **Boyle's law :-** This law states, "The absolute pressure of a given mass of a perfect gas varies inversely as its volume, provided the temperature remains constant." Mathematically,

$$P \propto \frac{1}{V}$$

or, $PV = \text{Constant}$

The more useful form of the above eqⁿ is

$$P_1 V_1 = P_2 V_2 = P_3 V_3 = \dots = \text{Constant.}$$

(ii) **Charles's Law :-** This law was formulated by a Frenchman Jacques A.C. Charles. This law may be stated in the following two ways:

(a) "The volume of a given mass of a perfect gas varies directly as its absolute temperature,

provided the pressure remains constant."

Mathematically,

$$V \propto T \text{ or } \frac{V}{T} = \text{Constant.}$$

$$\frac{V_1}{T_1} = \frac{V_2}{T_2} = \frac{V_3}{T_3} = \text{Constant}$$

(b) "All perfect gases change in volume by $\frac{1}{273}$ th of its original volume at 0°C for every 1°C change in temperature, when the pressure remains constant."

$$\begin{aligned} V_1 &= V_0 + \frac{1}{273} V_0 \times t \\ &= V_0 \left(\frac{273+t}{273} \right) = V_0 \times \frac{T}{T_0} \end{aligned}$$

$$\frac{V_1}{T} = \frac{V_0}{T_0}$$

(iii) Avogadro's Law :- This law states, "Equal volume of all gases will have equal no. of molecules, under identical conditions of temperature and pressure.

According to this law, 1m^3 of hydrogen will contain the same number of molecules as 1m^3 of oxygen when temp. and pressure is same. We know that molecular mass of hydrogen is 2 and that of oxygen is 32. As 1m^3 of these two gases have equal number of molecules, therefore, mass of one molecule of oxygen will be $\frac{32}{2} = 16$ times the mass of hydrogen molecule.

At normal temp. and pressure (N.T.P) i.e., at 0°C and 1.01325 bar, the density of oxygen is 14.29 kg/m^3 .

∴ Specific volume of oxygen at N.T.P,

$$V = \frac{1}{1.429} \text{ m}^3 / \text{kg.}$$

Volume of 32 kg (or 1 kg-mol) of oxygen at N.T.P
 $= \frac{1}{1.429} \times 32 = 22.4 \text{ m}^3$

In this way, it can be proved that volume of 1 kg mol of any gas at N.T.P is 22.4 m^3 .

Regnault's law :- This law states, the two specific heat C_p (specific heat at constant pressure) and C_v (specific heat at constant volume) of a gas do not change with the change of temperature and pressure.

As the specific heat of gas vary with the temp; therefore, Regnault's law gives the approximate result only.

Universal gas Constant :- The universal gas constant or molar constant (generally denoted by R_u) of a gas is the product of the gas constant and the molecular mass of gas.

Mathematically,

$$R_u = MR$$

M = Molecular mass of gas in kg/mole

R = Gas constant

$$R_u = M_1 R_1 = M_2 R_2 = M_3 R_3 = \underline{\quad}$$

$$P_V = MRT \text{ (For 1 kg mole)}$$

$$P_v = R_u T$$

$$R = \frac{P_v}{T} = \frac{10135 \times 22.413}{273} = 8314.3 \text{ J/kg mole/K}$$

Specific heat at constant pressure (C_p) :- It is the amount of heat required to raise the temperature of a unit mass of a gas through one degree, when its pressure is kept constant.

If m kg of a gas is heated from temp. T_1 to temp. T_2 at constant pressure, then amount of heat supplied to gas is given by

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

The value of C_p for air in S.I. unit is 1 kJ/Kg K .

Specific heat at constant Volume (C_v) :- It is the amount of heat required to raise the temperature of a unit mass of a gas through one degree, when its volume is kept constant.

If m kg of a gas is heated at constant vol. from temp. T_1 to temp T_2 , then amount of heat supplied to gas is given by

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

The value of C_p is always greater than C_v and, therefore, their ratio of C_p and C_v will be greater than one.

$$\gamma = \frac{C_p}{C_v} > 1$$

The value of γ for air is 1.4.

Relationship between specific heat C_p and C_v

Let us consider m kg of a gas enclosed in a container and is being heated at constant pressure.

T_1 = Initial temp. of the gas,

T_2 = Final temp. of the gas,

V_1 = Initial volume of gas,

V_2 = Final volume of gas,

C_p = Specific heat at constant pressure,

C_v = Specific heat at constant volume,

P = Absolute constant pressure,

We know that heat supplied to the gas at constant pressure,

$$Q = mC_p(T_2 - T_1) \quad \text{---(i)}$$

$$Q = W + dU \quad \text{---(ii)}$$

$$W = P(V_2 - V_1) \quad \text{---(iii)}$$

$$dU = mC_v(T_2 - T_1) \quad \text{---(iv)}$$

$$Q = P(V_2 - V_1) + mC_v(T_2 - T_1) \quad \text{---(v)}$$

Using characteristic gas equation, we have

$$PV_1 = mRT_1$$

$$PV_2 = mRT_2$$

$$P(V_2 - V_1) = mR(T_2 - T_1) \quad \text{---(vi)}$$

Putting the value of $P(V_2 - V_1)$ from equation (vi) in equation (v), we get

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

Now putting the value of θ from equation (i) in above equation, we get.

$$m C_p (T_2 - T_1) = mR (T_2 - T_1) + mC_v (T_2 - T_1)$$

$$C_p = R + C_v$$

$$C_p - C_v = R$$

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

$$C_p = C_v + R$$

Dividing both sides by C_v , we get

$$\frac{C_p}{C_v} = 1 + \frac{R}{C_v}$$

$$Y = 1 + \frac{R}{C_v}$$

Let M = Molecular mass of the gas,
and R_u = Universal gas constant,
Then, from equation, we get

$$R = \frac{R_u}{M}$$

The equation becomes

$$C_p - C_v = \frac{R_u}{M}$$

Simple numerical problem on gas eqn.

1 Find the mass of a gas occupying 5.5 m^3 at 7 bar abs. and 200°C . Take gas constant $R = 287\text{ J/kg K}$.

Soln Given $V = 5.5\text{ m}^3$, $P = 7\text{ bar abs} = 7 \times 10^5 \text{ N/m}^2$,
 $R = 287\text{ J/kg K}$, $T = 200^\circ\text{C} = 473\text{ K}$.

Let m is the mass of the air.

We know that characteristics gas equation is given by

$$PV = mRT$$

$$m = \frac{PV}{RT}$$

$$m = \frac{7 \times 10^5 \times 5.5}{287 \times 473}$$

$$m = 28.36 \text{ kg. Ans.}$$

Thermodynamics Processes

Types of Thermodynamic processes - isochoric, isobaric, isothermal, adiabatic, isentropic, polytropic and throttling processes, equation representing the processes.

Derivation of work done, change in internal energy, change in entropy, state of heat transfer for the above processes.

Types of thermodynamic processes

The important thermodynamic processes are :-

1 Constant volume process (Isochoric process) :-

The main characteristic of this process is that the displacement work is eliminated. The boundary of the system is rigid, but paddle may may be there.

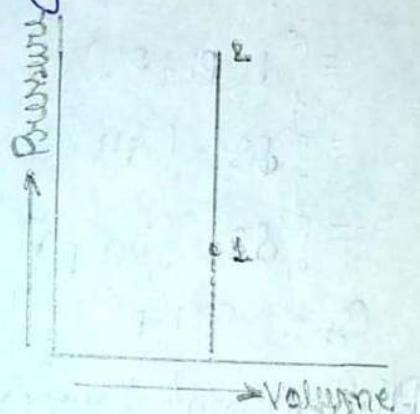
From first law of thermodynamics,

$$\text{Q}_{1-2} - W_{1-2} = U_2 - U_1$$

$$W_{1-2} = \int_1^2 P dV = U_2 - U_1$$

$$\text{Q}_{1-2} = U_2 - U_1$$

$$\text{Q}_{1-2} = m c_v (T_2 - T_1)$$



Constant volume process

Thus during a constant volume process, the heat transfer equals the change in internal energy of the system.

2. Constant Pressure Process :- In constant pressure process, the system is subjected to constant hydrostatic pressure at its boundaries. The fluid is free to expand and the change in system boundary causes displacement work against the constant pressure due to weight.

If the work is carried out quasi-statically

$$\int_1^2 \delta W = \int_1^2 P dV$$

Then, from first law of thermodynamics

$$\int_1^2 \delta Q - \int_1^2 \delta W = \int_1^2 dU$$

$$\int_1^2 \delta Q = \int_1^2 dW + \int_1^2 dU$$

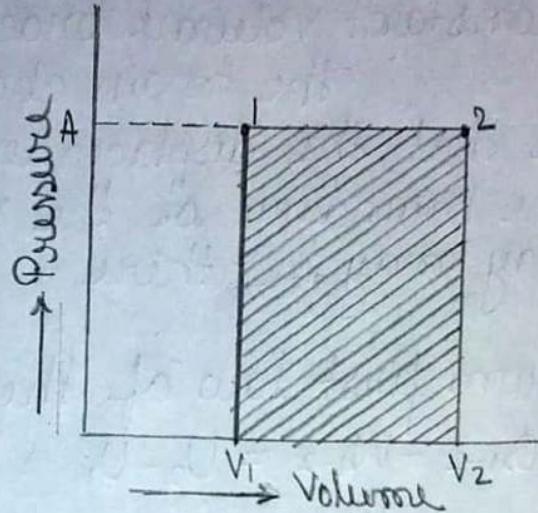
$$= \int_1^2 P dV + \int_1^2 dU$$

$$= \int_1^2 d(U + PV)$$

$$= \int_1^2 \delta Q = \int_1^2 dH$$

$$= \int_1^2 \delta Q = \int_{T_1}^{T_2} C_p dT$$

$$Q_{1-2} = m C_p (T_2 - T_1)$$



Constant pressure process

3 Isothermal process :- In this, the system has movable boundary. Therefore displacement work is present, but the system temp. is maintained constant by contact of the system with a constant temp. reservoir. During the expansion the volume will increase to maintain the temperature constant.

$$\delta Q - dW = dU$$

$$dU = m C_v dT$$

$$dT = 0$$

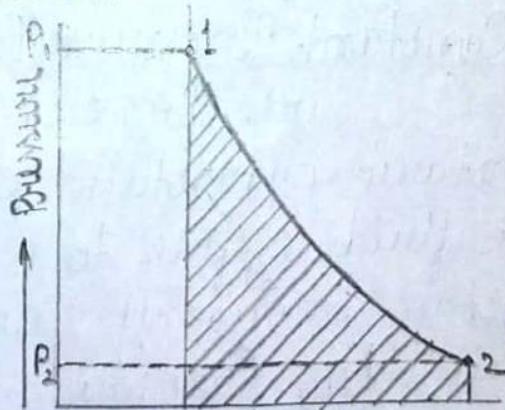
$$dU = 0$$

$$\delta Q - \delta W = 0$$

$$\delta Q = \delta W$$

$$\int_1^2 \delta W = \int_1^2 P dV$$

$$W_{1-2} = \int_1^2 P dV = \int_1^2 \frac{PV}{V} dV = \int_1^2 PV \log_e\left(\frac{V_2}{V_1}\right), Q_{1-2} = m R T_1 \log\left(\frac{V_2}{V_1}\right)$$



4. Adiabatic Process :- The process during which work is done and no heat is transferred across the system boundary is known as adiabatic process.

5. Isentropic process :- This is produced during reversible adiabatic process, entropy remains constant, so that process is also known as isentropic process.

6. Polytropic process :- It is found that in actual practice many processes approximate to a reversible process of the form $PV^n = \text{constant}$, where n is called polytropic Index. Both vapours and perfect gases follow this type of process closely. Work done during the process from state 1 to state 2 by system.

$$\int_1^2 dW = \int_1^2 PdV = \int_1^2 \frac{P_1 V_1^n}{V^n} dV$$

$$W_{1-2} = P_1 V_1^n \left[\frac{V_2^{-n+1} - V_1^{-n+1}}{-n+1} \right]$$

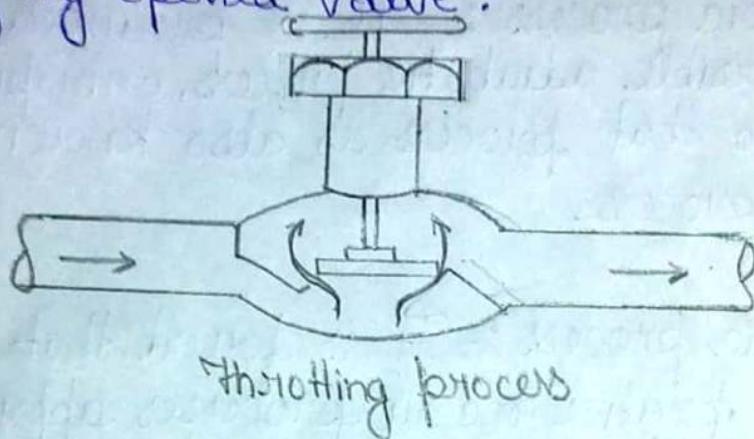
$$W_{1-2} = \frac{P_1 V_1^n V_2^{-n+1} - P_1 V_1^n V_1^{-n+1}}{-n+1}$$

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

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

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

7. Throttling Process :- Throttling process is an irreversible steady flow expansion process in which a perfect gas is expanded through an orifice of very minute dimensions or slightly opened valve.



Throttling process

$$Q_{1-2} = 0 \text{ and } W_{1-2} = 0$$

$$H_1 = H_2$$

Chapter - 04

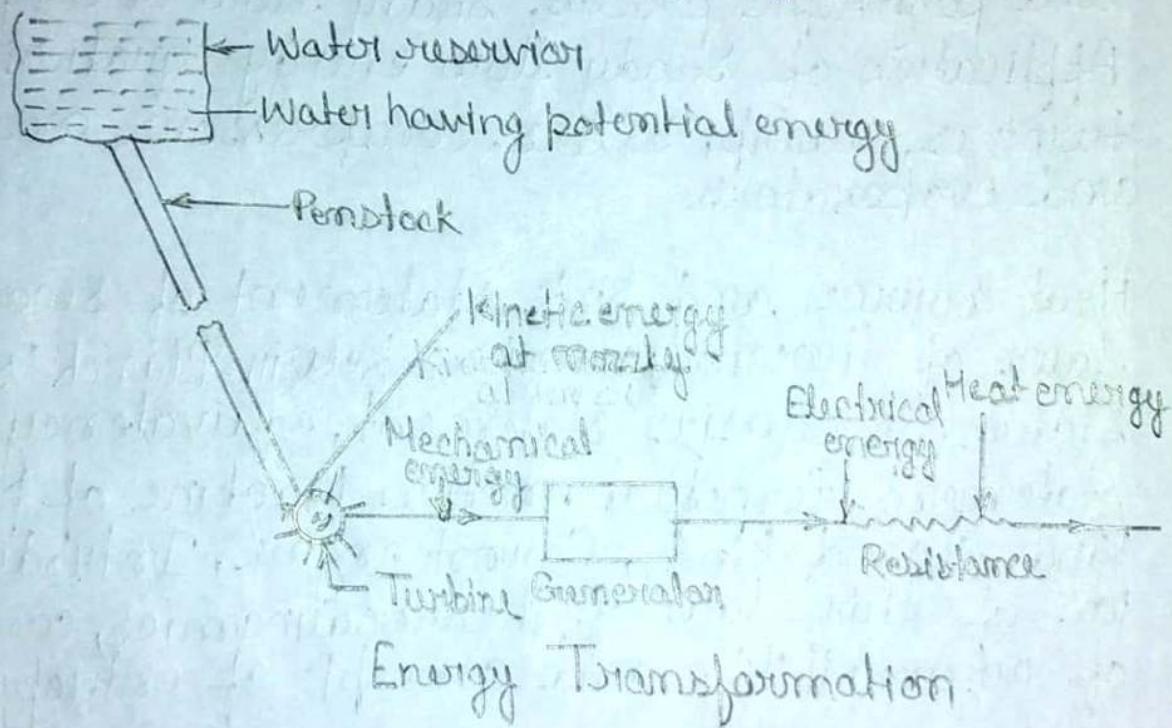
Laws of Thermodynamics

Laws of conservation of energy, first law of thermodynamics (Joule's experiment) and its limitations, Application of first law of thermodynamics to non-flow system - constant volume, Constant pressure, Adiabatic and polytropic process, steady flow energy eqn, Application of steady flow energy equation for turbines, pump, boilers, compressors, nozzles, and evaporators.

Heat source and sink, statement of second laws of thermodynamics: Kelvin Planck's statement, Clausius statement, equivalency of statement, Perpetual motion Machine of first kind, Second kind, Carnot engine, Introduction of third law of thermodynamics, concept of irreversibility and concept of entropy.

Law of conservation of energy :- This law states, "The energy can neither be created nor be destroyed, though it can be transformed from one form to any other form, in which the energy can exist." It implies that the total energy possessed by a system remain constant. Some example of conservation of energy are as follow :

- (i) Conversion of electrical energy into heat energy by flowing the current through a resistance.



First law of Thermodynamics (Joule experiment)

A process is cyclic if the initial and final states of the system are identical. J.P. Joule, a scientist, through various experiments gave an

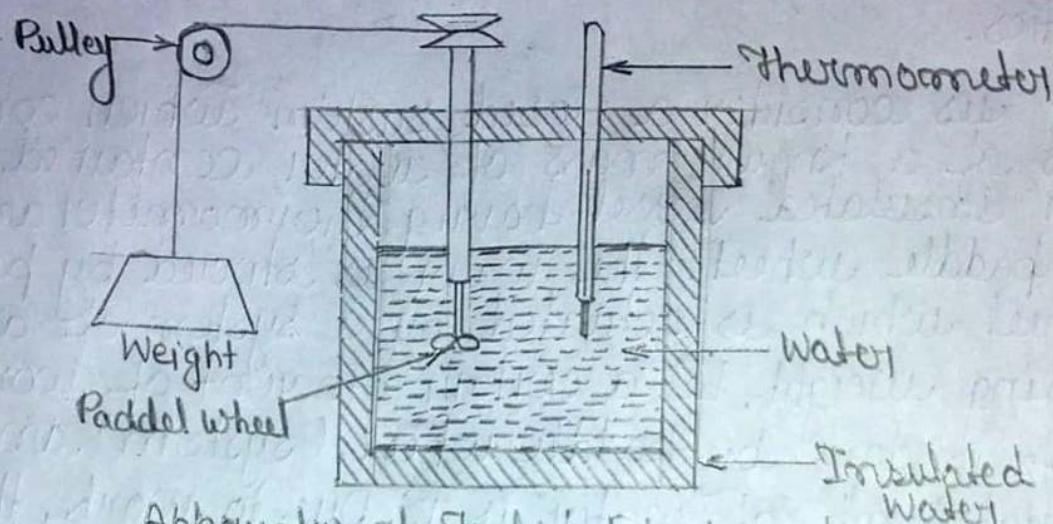
important result that heat and mechanical work are equivalent and interconvertible quantities.

Let us consider a closed system which consists of a known mass of water contained in an insulated vessel having thermometer and a paddle wheel. The water is stirred by paddle wheel which is actuated by a system of a falling weight. Let a certain amount of work W_{1-2} is done by paddle wheel (system). and initial temp. of water is T_1 . Due to work, the temp. of water rises to T_2 . The process 1-2 undergone by the system. Let the insulation of vessel is removed and now the system will start transferring heat to the surrounding till the system returns to the temp T_1 . The amount of heat transfer Q_{2-1} can be calculated. Thus the system undergoes a cycle, which consists work input W_{1-2} to the system and heat output Q_{2-1} from the system. It has been found that work W_{1-2} is always proportional to the heat Q_{2-1} and the constant of proportionality is called the Joule's equivalent of heat. If the cycle involves many more heat and work quantities, the same results will be found.

Limitation of first law of thermodynamics :-

- The temp. of liquid contained in a vessel rises when it is churned by paddle work.

(ii) Fuel burns with air to form the product of combustion.

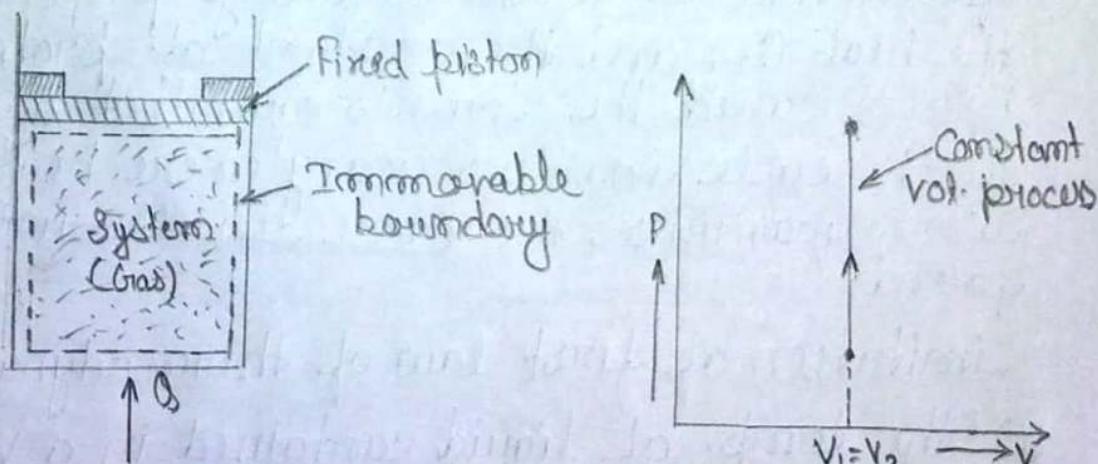


Apparatus of Joule's Experiment

Application of first law of thermodynamics to non-flow processes or closed systems.

1 Constant Volume Process (Isochoric process):

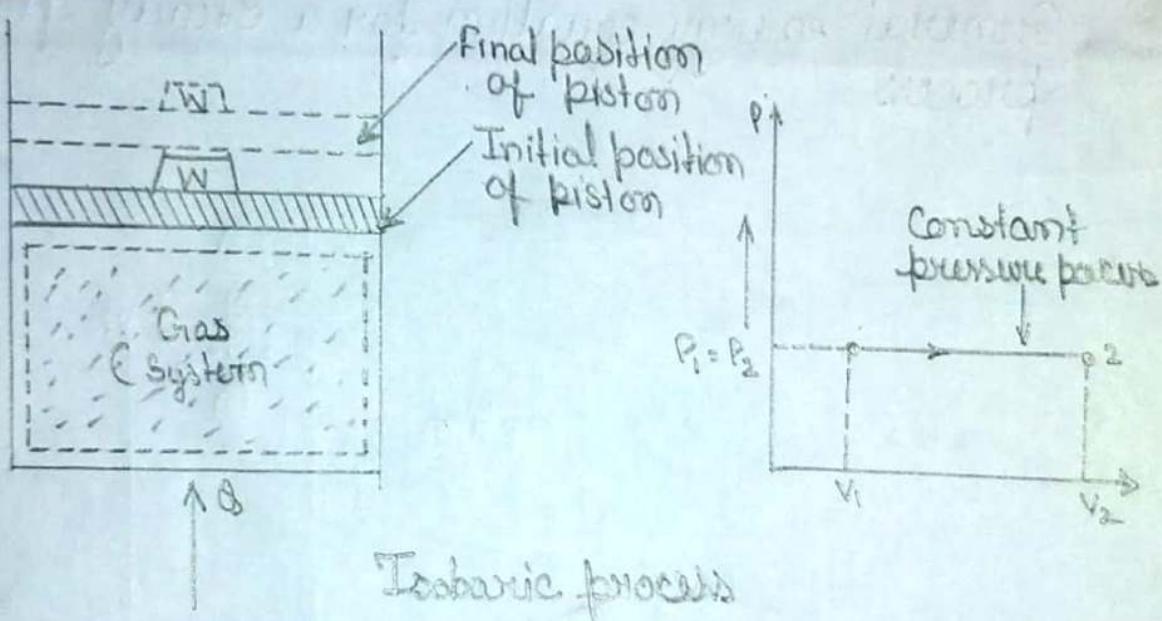
When a gas is heated at a constant volume, its temperature and pressure will increase. As the boundary of the system is immovable therefore, no work can be done on or by the system.



Isochoric Process

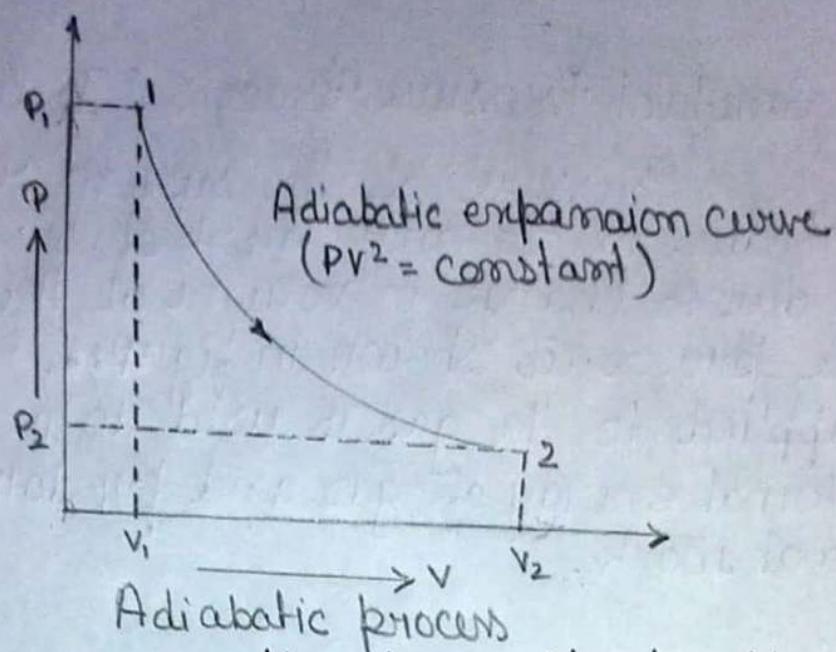
2. Constant Pressure Process (Isobaric Process):

Pressure of the system remains constant due to the movement of system boundary i.e due to change in volume of the system. The process is shown in figure. The heat supplied to the gas is used to increase the internal energy of gas and for doing some external work.

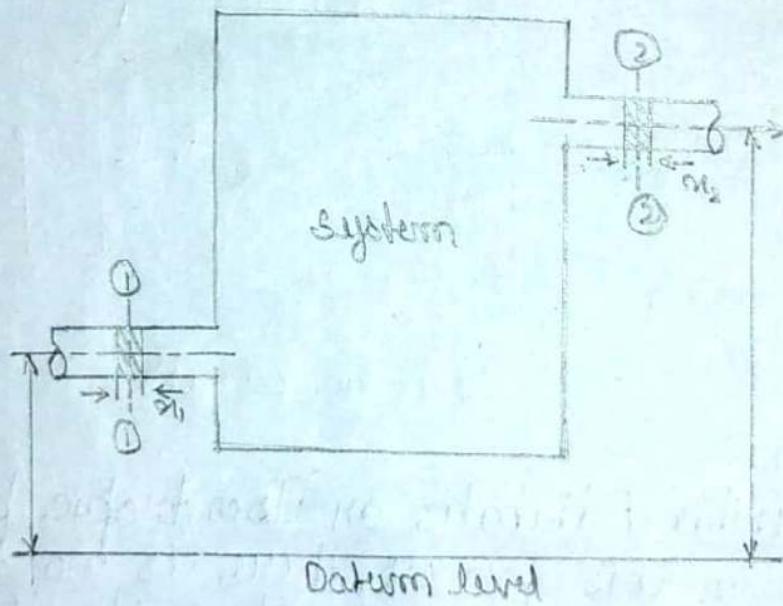


3. Reversible Adiabatic or Isentropic process:-

In this process, there is no transfer of heat to or from the system. In this case, entropy of the system remain constant.



General energy equation for a Steady flow process



Steady flow process

P_1, P_2 = Pressure of working substance at inlet and outlet of system,

z_1, z_2 = Datum height at inlet and outlet,

c_1, c_2 = Velocity of working substance at inlet and outlet,

- Q = Heat supplied to the system,
 W = Work delivered by the system,
 V_1, V_2 = Volume of working substance entering and leaving the system,
 U_1, U_2 = Internal energy of working substance at inlet and outlet.
 m = mass of working substance.

$$E_{\text{entering}} = U_1 + \frac{mc_1^2}{2} + mz_1g + P_1V_1 + Q$$

$$E_{\text{outlet}} = U_2 + \frac{mc_2^2}{2} + mz_2g + P_2V_2 + W$$

$$E_{\text{entering}} = E_{\text{outlet}}$$

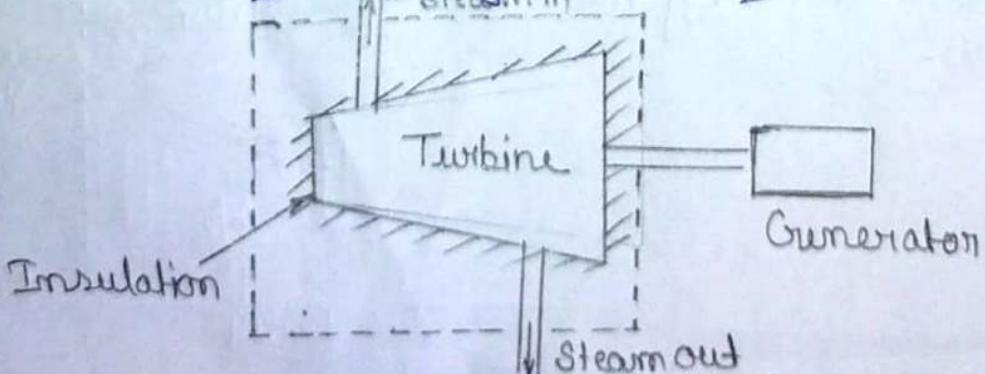
$$\therefore U_1 + \frac{mc_1^2}{2} + mz_1g + P_1V_1 + Q = U_2 + \frac{mc_2^2}{2} + mz_2g + P_2V_2 + W$$



Application of Steady flow equation :-

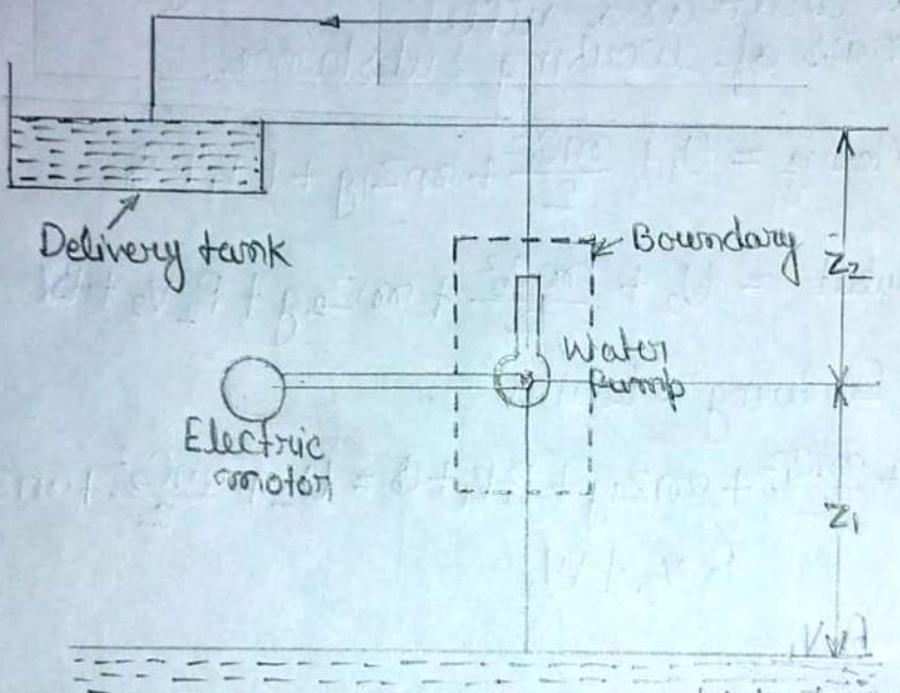
1. Turbine :- A turbine is a device which converts the energy of working sub. (gas or steam) into mechanical work.

$$H_1 + \frac{mc_1^2}{2} + mz_1g = H_2 + \frac{mc_2^2}{2} + mz_2g + W$$

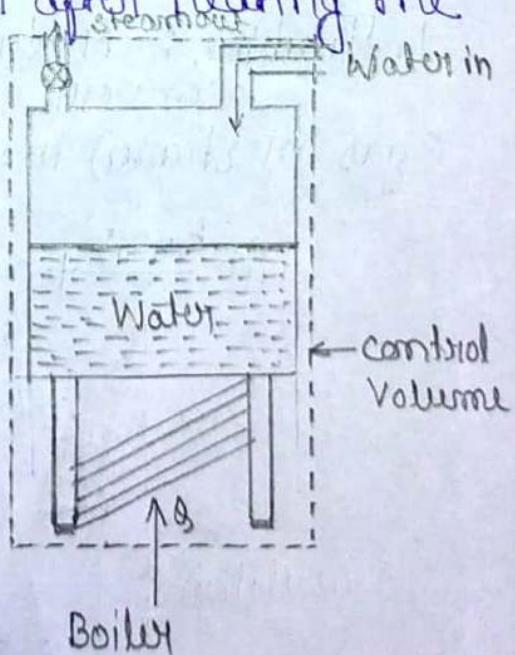


2. Pump :- A pump is a device which lifts the water from lower level and delivers it to higher level.

$$\frac{mc^2}{2} + m z_1 g + P_1 V_1 = \frac{mc^2}{2} + m z_2 g + P_2 V_2 - W$$



3. Boiler :- A boiler is a device which is used to generate the steam after heating the water. In this system, there is no change in kinetic and potential energy. Also, there is no work done by the system.



4. Compressor :- Compressor is used to increase the pressure of air. There are mainly two type of compressor :

(a) Rotary Compressor :- In this case, the compressor is insulated, so that no transfer of heat take place ($Q=0$) and also, the work is done on the system. From energy equation.

$$H_1 + \frac{mc_1^2}{2} + mZ_1g = H_2 + \frac{mc_2^2}{2} + mZ_2g + W$$

(b) Reciprocating compressor :- In case of reciprocating compressor, the rate of flow is low as compared to rotary compressor, so there is large area in contact with the surroundings. Amount of heat transfer is appreciable and cannot be ignored.

$$H_1 - Q = H_2 - W \quad (\text{K.E and P.E are negligible})$$

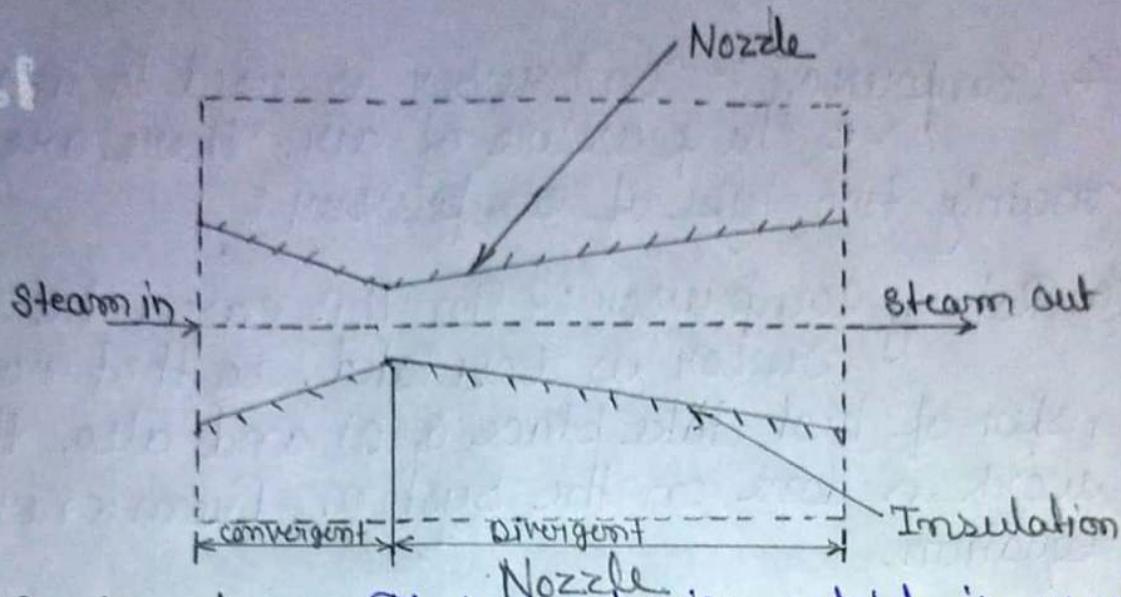
$$W = Q + (H_2 - H_1)$$

5 Nozzle :- A nozzle is a device which is used to increase the velocity of working sub. at the cost of pressure drop.

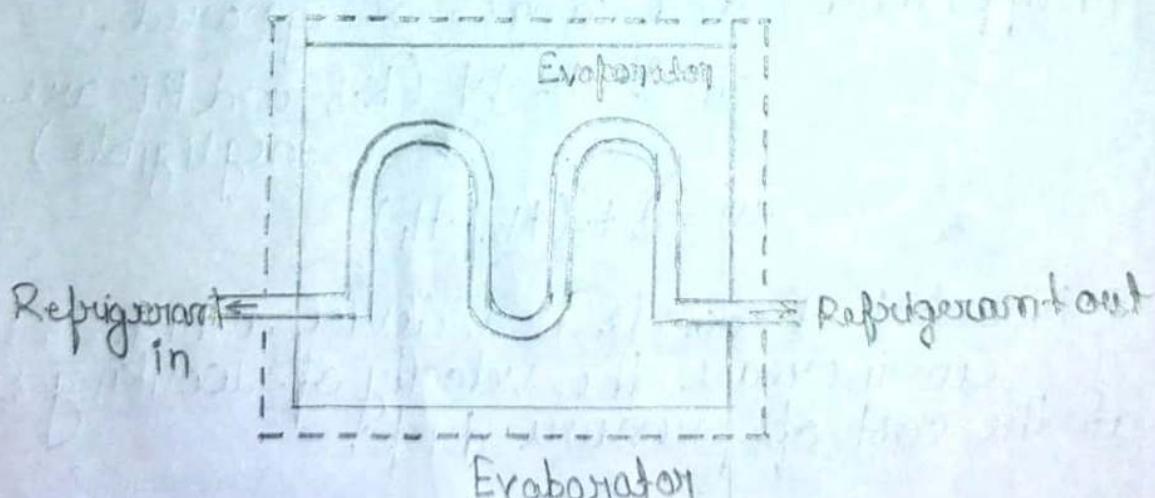
from general energy equation

$$H_1 - H_2 = \frac{mc^2}{2}$$

$$c = \sqrt{\frac{2(H_1 - H_2)}{m}}$$



6. Evaporator :- It is a device which is used in refrigeration system. In this system, kinetic energy and potential energy can be neglected. Also there is no work done by the system.

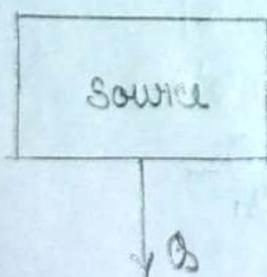
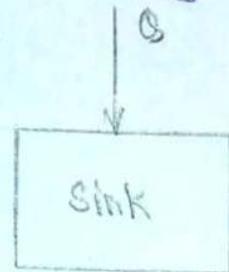


$$H_1 + Q = H_2$$

$$Q = H_2 - H_1$$

Heat source and Heat sink

A thermal (heat) reservoir is that part of environment which can exchange heat energy with a system. It has large heat capacity and its temperature is not affected by the quantity of heat transferred to or from it. Due to this, the temperature of heat reservoir remains constant. The reservoir which is at high temp. and supplies heat is known as heat source e.g. a combustion chamber, furnace etc. The reservoir which is at low temp. and which heat is transferred is called heat sink e.g. atmospheric air, river etc.

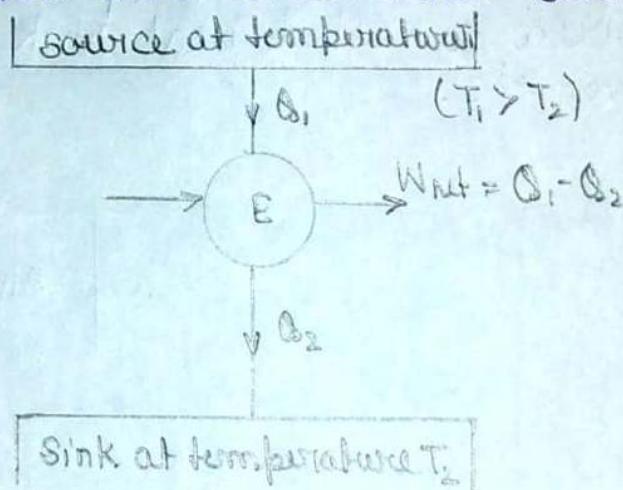


↓
↳ Heat source and sink

Second Law of Thermodynamics

1 Kelvin-Planck Statement: According to Kelvin statement, "It is impossible to construct an engine working on a cyclic process, whose sole purpose is to convert heat energy from a single thermal reservoir into an equivalent amount of work"

As per this law, there will be a degradation of energy in this process of producing mechanical work from the heat supplied, so this law is sometimes known as law of degradation of energy. Heat engine should have at least two reservoirs of heat, one at higher temp. (source) and other at low temp. (sink). Let us assume that heat energy (Q_1) at temp. T_1 is supplied to heat engine from source and heat source and heat energy (Q_2) at temp. T_2 is rejected to the sink. Then the remaining or net energy ($Q_1 - Q_2$) will be converted into mechanical work (W_{net}).



Heat Engine

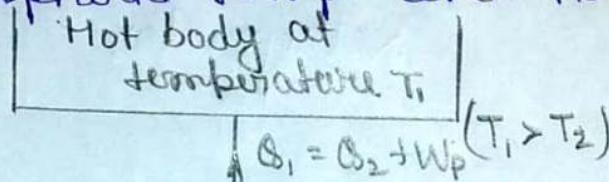
$$\eta_{th} = \frac{W_{net}}{\text{Total heat supplied}} = \frac{Q_1 - Q_2}{Q_1}$$

$$\eta_{th} = 1 - \frac{Q_2}{Q_1}$$

2. Clausius statement: According to Clausius statement "It is impossible to construct a device operating in a cycle which can transfer heat from a body at a lower temp. to a body at a higher temperature without the help of an external agency."

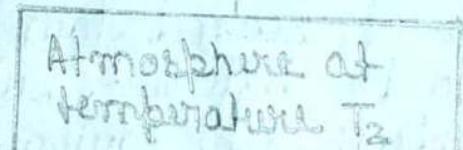
Therefore, heat cannot flow of itself from a body at a lower temp. of a body at a higher temp. The application of this law are found in a refrigerator and heat pump.

Heat pump :- It is a device operating in a cyclic process which maintains the temp. of a hot body at a temp. higher than the temperature of surrounding. Heat pump operates between atmospheric temp. and hot body temp.



$W_p \rightarrow P \leftarrow \text{Heat Pump}$

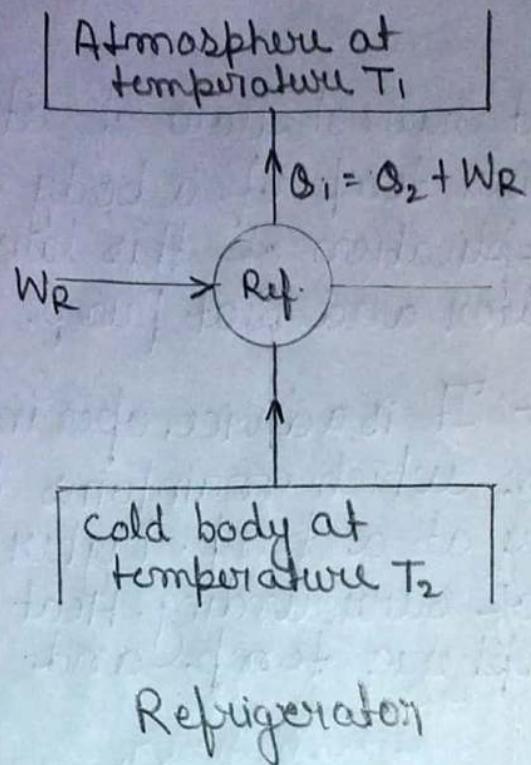
$\uparrow Q_2$



$\uparrow Q_1$

$$(C.D.P)_{H.P} = \frac{Q_1}{W_p} = \frac{Q_1}{Q_1 - Q_2}$$

Refrigerator :- A refrigerator is a device operating in a cycle which maintains a body at a temp. lower than the temp. of the surroundings. A refrigerator works between the cold body temp. and the atmospheric temperature.

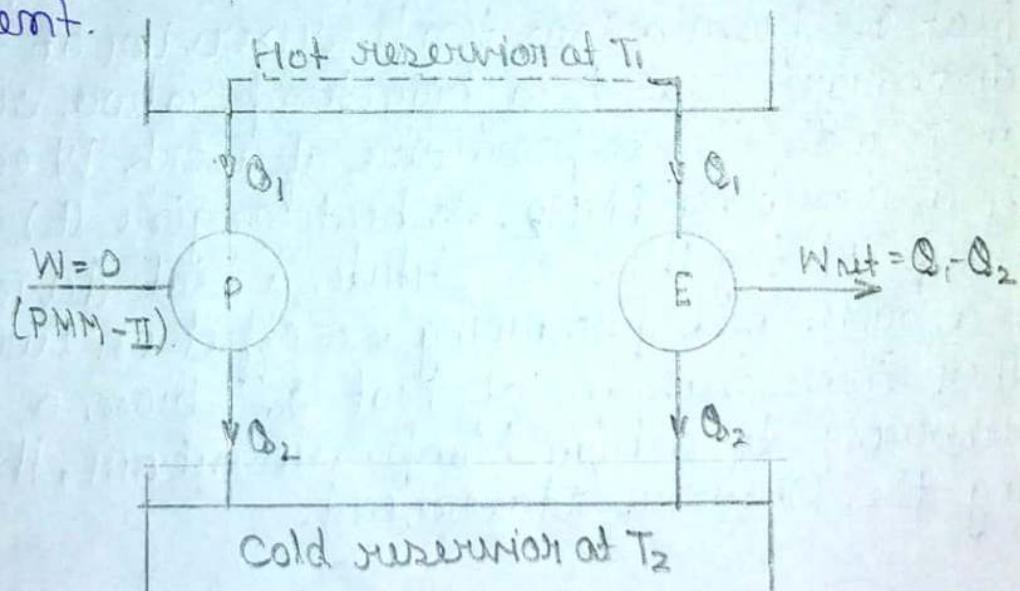


Equivalence of Kelvin Planck and Clausius Statements.

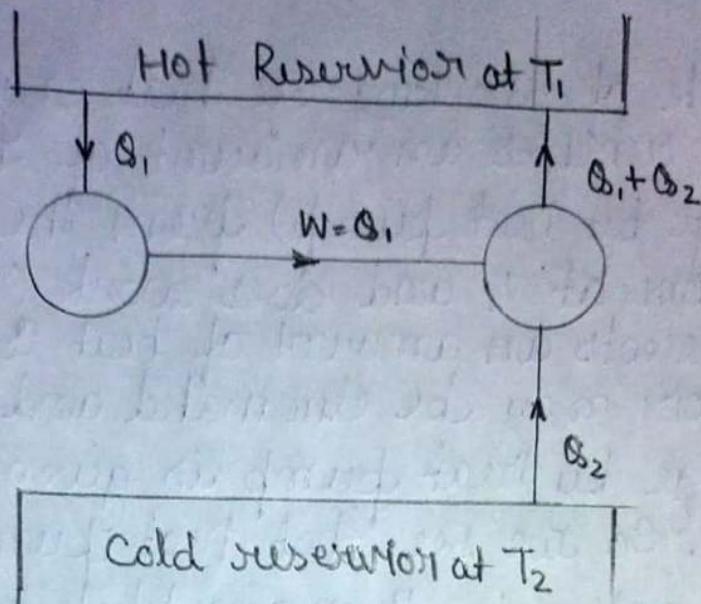
Both statements of second law of thermodynamics appear to be different, but both are equivalent in all respects. The equivalence these statements can be proved if it can be shown that violation of one statement implies the violation of second statement and vice-versa.

1. Let us, first, consider a heat pump which transfers heat from a low temperature reservoir (T_2) to a high temp reservoir (T_1) without any expenditure of work, thus violating Clausius statement. Now, let us assume a cyclic heat engine E operating between the same heat reservoir, producing W_{net} in one cycle.

The rate of working of heat engine is such that it receives an amount of heat Q_1 (as discharge by heat pump) from the high temp. reservoir at T_1 and does work ($W_{net} = Q_1 - Q_2$) and rejects an amount of heat Q_2 to low temp. reservoir may be eliminated and the heat Q_1 discharge by heat pump is given to the heat engine. So we see that heat pump and heat engine acting together constitute a heat engine operating in cycles and producing net work while exchanging heat only with one body at a single fixed temp. This violates the Kelvin-Planck statement.



- Let us consider a system. In this system, a heat engine having 100% efficiency (i.e PMH-II) is violating the Kelvin-Planck statement as it converts the heat energy (Q_1) from a single high temperature reservoir at T_1 in equivalent amount of work (i.e. $W = Q_1$).



Let assume a cyclic heat pump (P) extracting heat Q_2 from a low temp. reservoir at T_2 and discharging heat to a high temperature reservoir at T_1 with the expenditure of work W equal to Q_1 delivered by PMN_2 . So heat engine (E) and heat pump (P) together constitute a heat device working in a cycle and producing no effect on surroundings other than transfer of heat Q_2 from a low temp. reservoir to a high temp. reservoir, thus violating the Clausius Statement.

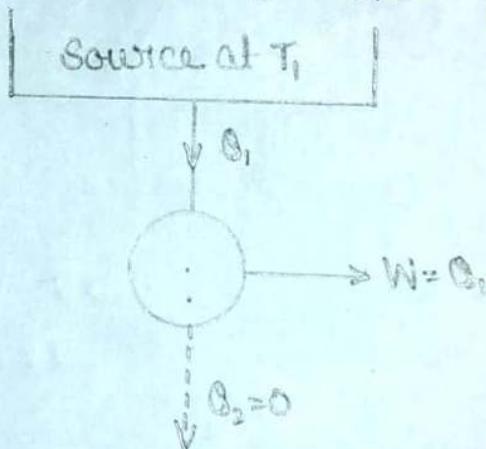
Perpetual motion machine of first kind (PMM1) And Second Kind (PMM2)

(i) Perpetual motion machine of first kind (PMM1) :- A machine which violates the first law of thermodynamics is known as PMM1

It is also define a machine which produces without consuming an equivalent amount of energy from other source. Such a machine is impossible to obtain in actual practice because no machine can produce energy at its own.

Perpetual motion machine of second kind (PMM2):

A device which converts whole of the heat energy into mechanical work is known as PMM2. This machine is 100% efficient machine and is impossible to be obtain in actual practice.



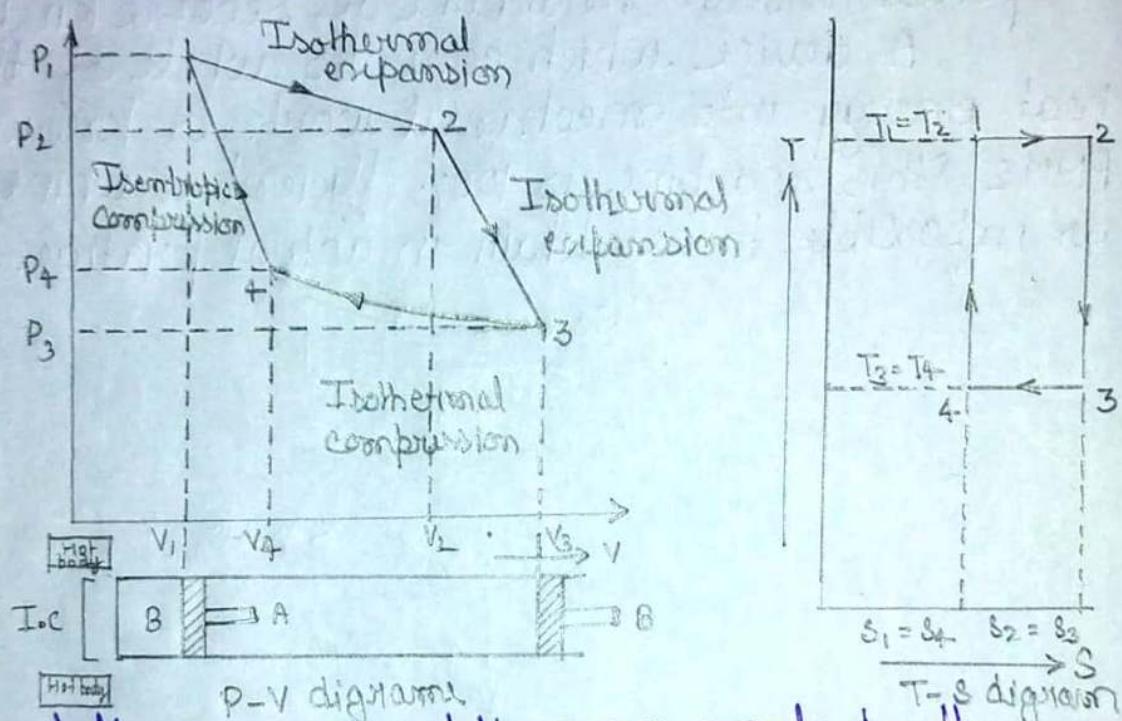
Perpetual motion machine of second kind (PMM2)

$$\eta_{th} = \frac{\text{Maximum work obtained}}{\text{Heat supplied}}$$

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

$$\eta_{th} = \frac{Q_1}{Q_2} = 100\% \quad (\text{As } Q_2 = 0 \text{ in this case})$$

Carnot engine :- This engine was first devised by a french scientist, Sadi Carnot in 1824 which operates on reversible engine. In a Carnot engine, working substance is subjected to two isothermal and two adiabatic or isentropic processes.



The following assumptions are made in the Carnot engine:

1. The wall of the cylinder and Piston are perfect non-conductors of heat.
2. In the cylinder, piston motion should be frictionless.
3. The engine is assumed to work between two source of infinite heat capacity, one at a higher temp. and the other, at a lower temp.
4. Working medium is a perfect gas having constant specific heat.

5 Compression and expansion processes are reversible.

Four stages of Carnot engine :-

1 First stage (Isothermal expansion, 1-2) : The source (hot body) at a high temperature is applied at the bottom of cylinder. The air expands at constant temperature T_1 from V_1 to V_2 . It means that temperature at point 2, T_2 . It may be noted that heat supplied by hot body is fully absorbed by the air for doing work.

2. Second stage (Adiabatic or Isentropic expansion, 2-3) :- As the cylinder is assumed to be a perfect insulator of heat, so no heat flow taking place. The air expands adiabatically and temperature falls from T_2 to T_3 .

3. Third stage (Isothermal Compression, 3-4) :

The cold body is brought in contact with cylinder. The air is compressed at a constant temp. T_3 from V_3 to V_4 . During this process, temp. T_3 is equal to temp T_4 and heat is rejected to the cold body and is equal to the work done on the air.

4. Fourth Stage (Adiabatic or Isentropic Compression, 4-1) :- Again the cylinder head becomes perfect insulator of heat so that no heat flow occurs. The compression process follows reversible adiabatic process during which temp is raised from T_2 to T_1 .

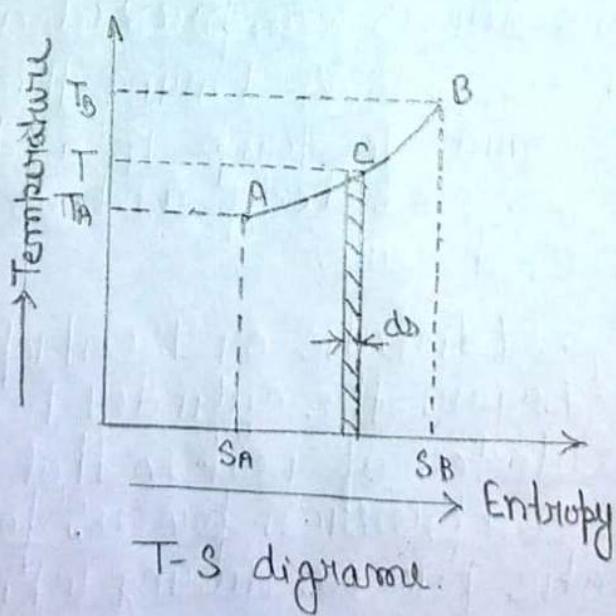
$$\text{Heat supplied} = P_1 V_1 \log_e \left(\frac{V_2}{V_1} \right) = m R T_1 \log_e \left(\frac{V_2}{V_1} \right)$$

$$\text{Heat rejected} = P_2 V_2 \log_e \left(\frac{V_3}{V_4} \right) = m R T_2 \log_e \left(\frac{V_3}{V_4} \right)$$

$$\begin{aligned}\text{Work done} &= m R T_1 \log \left(\frac{V_2}{V_1} \right) - m R T_2 \log \left(\frac{V_3}{V_4} \right) \\ &= m R T_1 \log e^{\eta} - m R T_2 \log e^{\eta}.\end{aligned}$$

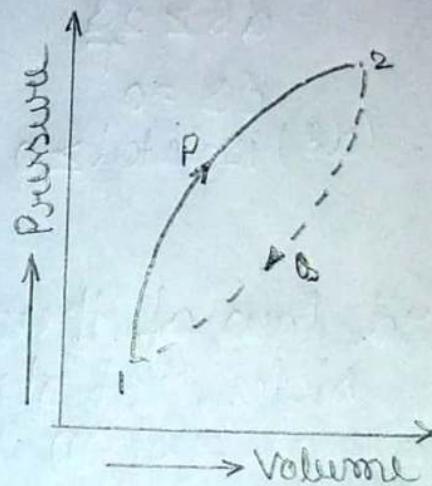
$$\begin{aligned}\text{efficiency of engine, } \eta &= \frac{\text{Work done}}{\text{heat supplied}} \\ &= \frac{m R T_1 \log e^{\eta} - m R T_2 \log e^{\eta}}{m R T_1 \log e^{\eta}} \\ &= \frac{T_1 - T_2}{T_1} \\ &= 1 - \frac{T_2}{T_1}\end{aligned}$$

Entropy :- The term 'entropy' means transformation. It is a function of quantity of heat which shows the possibility of conversion of that heat into work.



Entropy change in an irreversible process

We know that change in entropy in a reversible process is equal to $\frac{\delta Q}{T}$. Let us now find the change in entropy in an irreversible process. Let us take a closed system undergoing a change from state 1 to state 2 by a reversible process 1-P-2 and returns from state 2 to the initial state 1 by an irreversible process 2-Q-1.



Energy change for an irreversible process

As entropy is a thermodynamic property, therefore

$$\oint dS = \int_{1(P)}^{2(P)} (dS)_{\text{rev.}} + \int_{2(Q)}^{1(Q)} (dS)_{\text{irreversible}} = 0 \quad \text{(i)}$$

For reversible process, we know that

$$\int_{1(P)}^{2(P)} (dS)_{\text{rev.}} = \int_{1(P)}^{2(P)} \left(\frac{\delta Q}{T} \right)_{\text{Rev.}}$$

Putting the value of $\int_{1(P)}^{2(P)} (dS)_{\text{rev.}}$ in eqn

$$\oint dS = \int_{1(P)}^{2(P)} (dS)_{\text{Rev.}} + \int_{2(Q)}^{1(Q)} (dS)_{\text{irreversible}} = 0 \quad \text{(ii)}$$

Clausius inequality

$$\oint \frac{dQ}{T} = \int_{1(P)}^{2(P)} \left(\frac{dQ}{T} \right)_{\text{Rev.}} + \int_{2(Q)}^{1(Q)} \left(\frac{dQ}{T} \right)_{\text{irreversible}} < 0$$

Subtracting equation (i) and (ii), we get.

$$\int_{2\Theta}^1 (ds)_{\text{irreversible}} > \int_{2(\Theta)}^1 \left(\frac{d\Theta}{T}\right)_{\text{irreversible}}$$

$$ds_{\text{irreversible}} > \left(\frac{d\Theta}{T}\right)_{\text{irreversible}}$$

$$ds \geq \frac{d\Theta}{T}$$

$$\therefore (ds)_{\text{isolated}} \geq 0$$

Third law of thermodynamics :- This law states, "At absolute zero temp., the entropy of system is zero". Zero entropy means the absence of all molecular, atomic nuclear and electronic disorder. This law helps to calculate the value of absolute entropy at a given state of the system by integrating $\left(\frac{d\Theta}{T}\right)_{\text{rev.}}$ between the state at absolute zero and given state. In actual practice, it is not possible to get data at zero absolute temp. therefore, the change in entropy is calculated either b/w two known states or by selecting some convenient point at which the entropy is given an arbitrary value.

Chapter-05 Ideal and Real gases

Concept of ideal gas, enthalpy and specific heat capacities of an ideal gas, P-V-T surface of an ideal gas, triple point, real gases, Van der waal's equation.

Concept of an ideal gas :- A hypothetical gas which obeys the law $PV = RT$ at all temperature and pressures is known as ideal gas. The real gas does not conform the above equation with complete accuracy, but if $P \rightarrow 0$ or $T \rightarrow \infty$, then real gas approach the behavior of ideal gases. It should be noted that no ideal gas exists.

Enthalpy of an ideal gas

The 'enthalpy' is defined by the relation,

$$H = U + PV$$

$$\text{For unit mass, } h = u + Pv$$

$$\text{for an ideal gas } Pv = RT$$

$$\therefore h = u + (RT) \text{ ideal gas}$$

Since for an ideal gas u is a function of temp., so it follows that the enthalpy is also a function of temp. alone.

Specific heat of an ideal gas

The specific heat at constant volume, C_V and the specific heat at constant pressure, C_P are defined as :

$$C_V = \left(\frac{\partial u}{\partial T} \right)_V$$

$$C_P = \left(\frac{\partial h}{\partial T} \right)_P$$

Since u and h of an ideal gas are functions of temp alone it follows that the specific heats of an ideal gas are also function of temp. alone.

Thus,

$$C_V = \left(\frac{du}{dT} \right)_{\text{ideal gas}}$$

and $C_P = \left(\frac{dh}{dT} \right)_{\text{ideal gas}}$

Since $h = u + (RT)$ ideal gas

$$\therefore \frac{dh}{dT} = \frac{du}{dT} + (R) \text{ ideal gas}$$

$$C_P = C_V + (R) \text{ ideal gas}$$

$$C_P - C_V = (R) \text{ ideal gas}$$

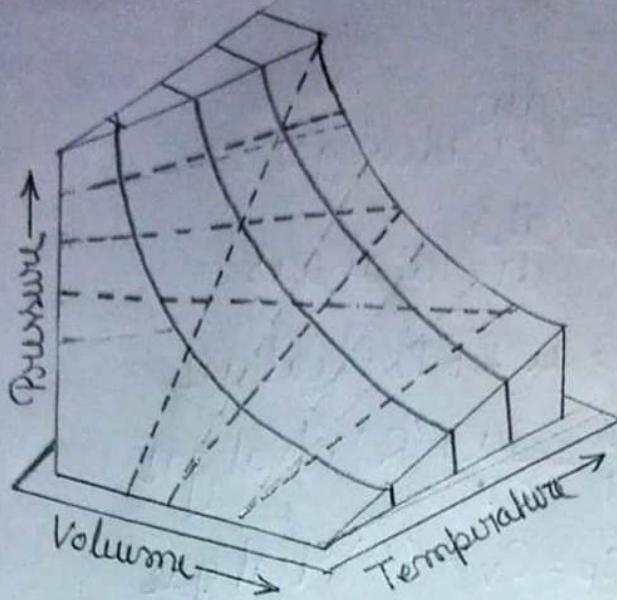
$$\frac{C_P - C_V}{C_P} = (R_u) \text{ ideal gas}$$

where \overline{C}_P and \overline{C}_V denote the molar specific heat at constant pressure and at constant volume respectively.

P-V-T Surface of an ideal gas :- A portion of the P-V-T surface of an ideal gas is shown in fig. Each point on this surface represents a possible equilibrium state and line on the surface represents a quasistatic process.

The lines drawn on the surface may be projected on to P-V and P-T planes.

The lines are graphs of isothermal processes and are thus the graphical representation of Boyle's law, while those are graphs of constant volume processes and are thus the graphical representation of Charles' law.



P-V-T Surface of an ideal gas

Triple point :- Triple point plays a significant role in the study of the general change of phase of a substance.

Its salient features are :-

- (i) The single phase regions are separated from each other by saturation.
- (ii) The fusion line for water has a negative slope ($\partial P / \partial T < 0$) indicating the melting point of ice decreases with increasing pressure. However, for most substance, the slope of fusion curve is positive.
- (iii) The evaporation line ends at the critical point C where there is no distinct change from the liquid phase to the vapour phase i.e the liquid and vapour are indistinguishable.

Real gas :- All gases, commonly used in engg. practice are real gases and not ideal gas. The real gases do not obey the gas laws strictly and their equation of state is not exactly the same as that of perfect gases i.e. $P_V = RT$

It is possible to derive the ideal gas equation $P_V = RT$ analytically using the kinetic theory of gases, provided the following assumption are made :

- (i) The molecules are separated by large distances as compared to their own dimensions.
- (ii) The molecules do not to exert forces on one another except they collide.
- (iii) The collisions of molecules with one another and with the walls of the container are perfectly elastic.
- (iv) A finite volume of gas contains large no. of molecules.

The behavior of a real gas approaches closely to that of ideal gas as long as the above assumption are valid.

The main reasons for this behaviour are :

1. Shape factors and intermolecular forces :-

Molecules are not point masses and have many diverse shapes. Even simple spherical atoms such as argon attract or repel other argon atoms, depending upon the distance of separation. The fact that real molecules have interacting forces and finite molecules

Volume is usually the most important reason why the ideal gas equation is not obeyed.

2. Hydrogen Bonding :- Hydrogen bonding between molecules usually occurs in systems of a polar nature. Such forces are often considered in the same category as electrical forces.

3. Quantum effects :- These are important only in those molecules where the translation energy modes must be quantized.

Vander wall's equation of state

The vander wall's equation of state has been set by incorporating the following two corrections into the equation of state, $v = RT$

(i) Let the equation of state be presented in the form $v = RT/P$. With increasing pressure, the volume diminishes and if $P \rightarrow \infty$, then $v \rightarrow 0$. This aspect is in the full agreement with the definition of an ideal gas, according to which, the molecules occupy an infinitely small vol.

(ii) Due to the presence of forces of molecules interaction in the real gases, there will be a smaller number of impact with the walls of the container. This may be attributed to the fact that the molecules positioned at the walls are attracted to by adjacent molecules inside the container. Consequently, compared to an ideal gas, the pressure exerted by a real gas will be smaller by quantity ΔP .

$$\Delta P = \alpha P^2 = \alpha/v^2$$

$$(P + \alpha/v^2)(v - b) = RT$$

If the volume of one mole of gas is considered, then the Vander Waal's equation can be written as

$$(P + \alpha/v^2)(v - b) = R_u T$$

where P is in N/m^2 , v is in $\text{m}^3/\text{kg mole}$, T is in Kelvin, R_u is 8314 J/kg mole K . The units of coefficient a and b are $\text{Nm}^4(\text{kg mole})^2$ and $\text{m}^3/\text{kg mole}$ respectively.

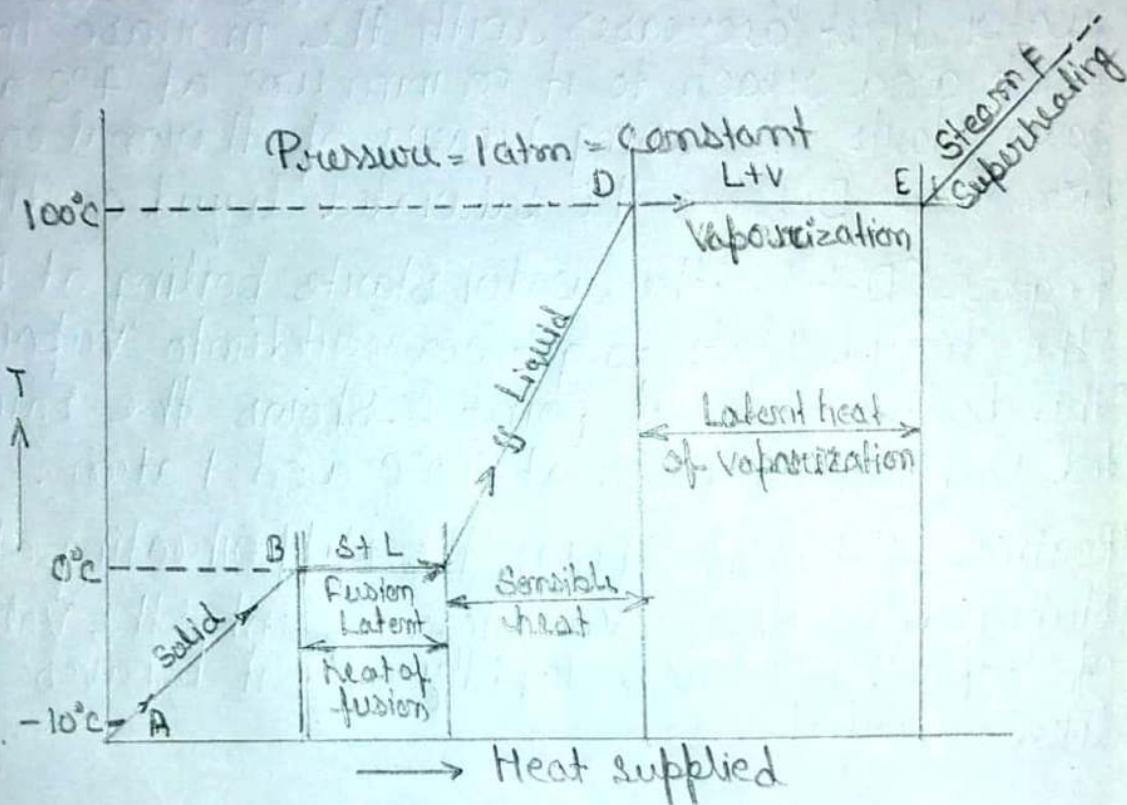
Chapter-06

Properties of steam

Formation of steam and related terms, thermodynamic properties of steam, steam tables, sensible heat, latent heat, internal energy of steam, entropy of water, entropy of steam, T-S diagrams, Mollier diagram (H-s chart), Expansion of steam, Hyperbolic, reversible adiabatic and throttling processes, determination of quality of steam (dryness fraction).

Formation of steam

Let us consider a unit mass of ice at 10°C and atmospheric pressure contained in piston-cylinder arrangement. Let us supply heat to the ice to convert into steam. The distinct regime's of heating are as follow:



Formation of steam

Regime (A-B): The heat given to ice increases its temperature from -10°C to 0°C . The volume of ice increases with increase in temp. Point B shows the saturated solid condition. At B, the ice starts melting.

Regime (B-C): The ice melts into water at const. pressure and temp. At C, the melting process ends.

There is a sudden decrease in volume at 0°C as the ice starts melting. It is a peculiar property of water due to cleavage of hydrogen bonding.

Regime (C-D): The temperature of water increases on heating from 0°C to 100°C . The volume of water first decreases with the increase in temp and reach to its minimum at 4°C and again starts increasing because of thermal expansion. Point D shows the saturated liquid condition.

Regime (D-E):- The water starts boiling at D. The liquid starts to get converted into vapour. The boiling ends at point E shows the saturated vapour condition at 100°C and 1 atm.

Regime (E-F): It shows the superheating of steam above saturated steam point. The volume of vapour increases rapidly and it behaves like a perfect gas.

Important terms for Steam :-

(1) Total heat or Enthalpy of water : The quantity of heat absorbed by one kg of water at constant pressure from its freezing temperature to its saturation temperature is known as total heat or enthalpy of water.

It is denoted by h_f and is approx. equal to sensible heat of water at low pressure.

Total heat of water = Sensible heat + Work required to increase the pressure to that of the boiler.

2. Latent heat of steam :- It is defined as the quantity of heat required to convert one kg of water at its boiling point into dry saturated steam at the same pressure. It is usually represented by h_{fg} .

3. Total heat or enthalpy of steam :- It is the amount of heat absorbed by water from freezing point to saturation temperature plus the heat absorbed during evaporation.

\therefore Enthalpy of steam = Sensible heat + Latent heat.
It is denoted by h_g and its value for the dry saturated steam may be read directly from the steam tables. The expressions for the enthalpy of wet steam, dry steam and superheated steam are as follow :-

(i) Wet steam : The enthalpy of wet steam is given by $h = h_f + xh_g$

where x is the dryness fraction of steam.

(ii) Dry steam : We know that in case of dry steam, $x=1$

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

(iii) Superheated steam :- If the heat is added further to the dry steam, its temperature increases, while pressure remain constant. This increase in temp shows the superheat stage of the steam.

h_{sup} = Total heat for dry steam + heat for superheated steam.

$$h_{\text{sup}} = h_f + h_g + c_p(t_{\text{sup}} - t) \quad \text{if } t < t_{\text{sat}}$$

4. Dryness fraction : Dryness fraction is the ratio of the mass of actual dry steam to the mass of same quantity of wet steam.

It is generally denoted by x . Mathematically,

$$x = \frac{m_d}{m_d + m_w} = \frac{m_d}{m}$$

5. Wetness fraction :- Wetness fraction of steam is the ratio of the mass of water vapour or moisture in suspension to the mass of same quantity of wet steam. It is generally denoted by y . Mathematically,

$$\text{Wetness fraction, } y = 1 - x$$

6. Specific volume of steam :- It is the volume occupied by the steam per unit mass at a given temperature and pressure and is expressed in m^3/kg .

Thermodynamic properties of steam.

The six basic thermodynamic properties: P, V, T, U, H and S at various states are generally required in engg. problems for any fluid which is used as working substance. The values of these properties are determined theoretically and are tabulated in form of tables and charts.

The thermodynamic properties, which are tabulated in form of table are :

P = Absolute pressure (kPa or MPa),

T = Saturated temperature ($^{\circ}\text{C}$ or K),

v_f = Specific volume of saturated liquid (m^3/kg),

v_g = Specific volume of saturated steam (m^3/kg),

h_f = Specific enthalpy of saturated liquid (kJ/kg),

h_g = Specific enthalpy of saturated vapour (kJ/kg),

s_f = Specific entropy of saturated liquid (kJ/kg K),

s_g = Specific entropy of saturated vapour (kJ/kg K),

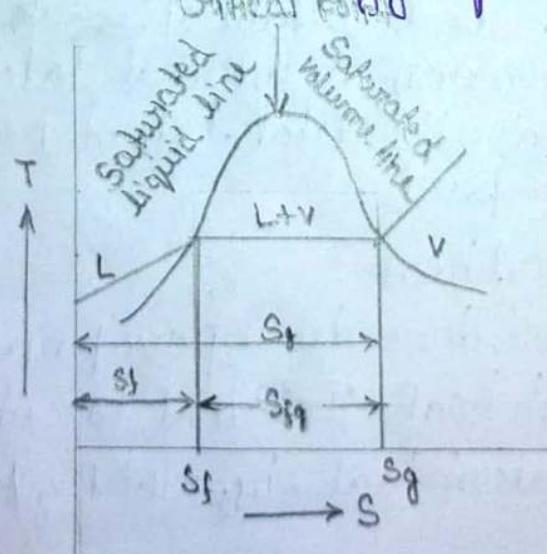
h_{fg} = Specific enthalpy or latent heat of vaporization (kJ/kg),

s_{fg} = Specific entropy of vaporization (kJ/kg K),

u_f = Specific internal energy of saturated liquid (kJ/kg),

u_g = Specific internal energy of saturated vapour (kJ/kg),

u_{fg} = Specific internal energy of vaporization (kJ/kg).



T-s diagram.

Steam tables.

(Pressure)

Absolute Temp. pressure t in °C (P) in bars	Specific Vol. in m³/kg		specific enthalpy in kJ/kg			specific entropy in kJ/kg K		
	Water (Vf)	Steam (Vg)	Water (hg)	Evapora- tion(hfg)	Steam (hg)	Water (Sf)	Evapora- tion(Sfg)	Steam (Sg)
0.010 6.893	0.001000	129.21	29.3	2485.1	2514.4	0.106	8.871	8.977
0.015 13.04	0.001000	87.982	54.7	2470.8	2525.5	0.196	8.634	8.830
0.20 60.09	0.001000	7.649	251.5	2358.4	2608.9	0.832	7.077	7.909

(Temperature)

Temp in (t) in °C	Absolute pressure (P) in bars	Specific Vol. in m³/kg		specific enthalpy in kJ/kg			specific entropy in kJ/kg K		
		Water (Vf)	Steam (Vg)	Water (hg)	Evapora- tion(hfg)	Steam (hg)	Water (Sf)	Evapora- tion(Sfg)	Steam (Sg)
0	0.00611	0.001000	206.16	0.0	2501.6	2501.6	0.000	9.158	9.158
5	0.00872	0.001000	147.16	21.0	2489.7	2510.7	0.076	8.951	9.027
10	0.01272	0.001000	106.43	42.0	2477.9	2519.9	0.151	8.751	8.902

Internal latent heat :- The difference between the latent heat and external work done during evaporation is known as internal latent heat.

This means that the total latent heat absorbed consists of two parts.

(a) Internal latent heat

(b) External work done during evaporation.

i.e Total latent heat = Internal latent + $10^5 P \cdot V_g$

or Internal latent heat = $h_{fg} - 10^5 P \cdot V_g / kg$.

Internal energy of steam :- The actual heat energy stored in the steam above the freezing point of water is known as internal energy of steam. It is generally denoted by u . Let us consider one kg of steam at a pressure of P kPa.

External work during evaporation/Kg of steam

$$= P_{fg} \text{ kJ}$$

$$h = u + P_{fg}$$

$$u = h - P_{fg} \text{ for dry saturated steam.}$$

If the steam is wet having dryness fraction x ,

$$h = h_f + xh_g$$

$$\text{Specific Vol.} = xv_g$$

$$u = h - P_x v_g \text{ for wet steam.}$$

If the steam is superheated to a volume of $v \text{ m}^3/\text{kg}$.

$$h = h_f + h_{sg} + C_p (T_{sup} - T_{sat})$$

$$u = h_g - Pv \text{ for superheated steam.}$$

Where v can be calculated by applying Charles's law.

If one kg of steam with u_1 as internal energy is heated or expanded in a cylinder until its final internal energy is u_2 , then.

$$\text{Change in internal energy/Kg} = u_2 - u_1$$

w = External work done on the piston.

By the law of conservation of energy, the heat supplied, $q = w + (u_2 - u_1)$

Entropy of water :- If water is heated from absolute temp. T_0 K to T K, then the change in entropy per kg of water at constant pressure is given by

$$\text{Change in entropy} = \text{specific heat of water} \times$$

$$+ \log_e \frac{T}{T_0}$$

$$T_0 = 273 \text{ K}$$

$$S_f = C_w \log_e \frac{T}{273}$$

Entropy of steam (S_g)

It is the sum of entropy of water and entropy in evaporation.

(i) Entropy per kg of wet steam above freezing point

$$= S_f + \frac{x_i h_{fg}}{T} = C_w \log_e \frac{T}{273} + \frac{x_i h_{fg}}{T}$$

(ii) Entropy per kg of dry steam above freezing point.

$$= x_g + \frac{h_{fg}}{T} = C_w \log_e \frac{T}{273} + \frac{h_{fg}}{T}$$

(iii) Entropy of superheated steam

$$= C_p \log_e \frac{T_{sub}}{T_{sat}}$$

$$\therefore S_g = S_f + \frac{h_{fg}}{T_{sat}} + C_p \log_e \frac{T_{sub}}{T_{sat}}$$

$$= C_w \log_e \frac{T_{sat}}{273} + \frac{h_{fg}}{T_{sat}} + C_p \log_e \frac{T_{sub}}{T_{sat}}$$

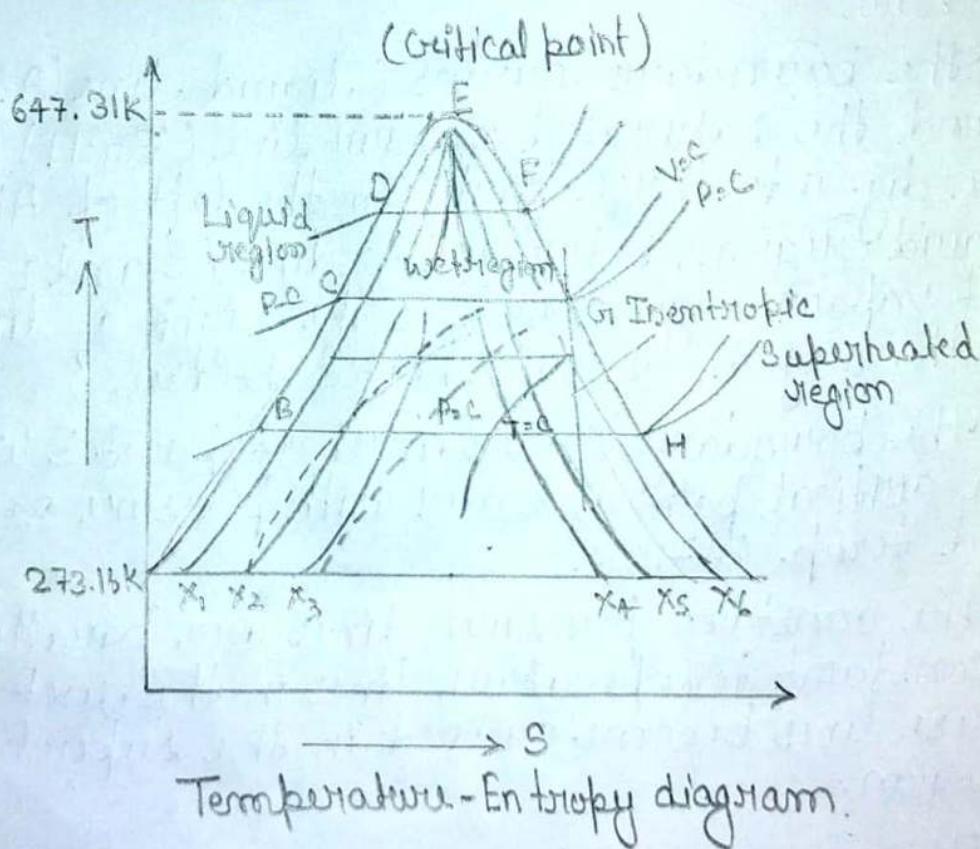
Temperature-entropy (T-S) diagram and enthalpy-entropy (H-S) diagrams.

- (a) Temperature-entropy (T-S) diagram:
 - (i) The absolute temp. is plotted on the ordinate and entropy on the abscissa.
 - (ii) The liquid boundary lines originate at the ordinate at a temp of 273.16 K. This is so because entropy of liquid at the triple point is equal to zero.
 - (iii) The boundary curves (liquid line (ABCDE) and the saturated vapour line (FGHI) divide the dig. into three part: To the left of AE is the liquid region, between the line AE and EI is the wet vapour region and to the right of line EI is the region of superheated steam.
 - (iv) The boundary curves meet at point E which is the critical point of water with pressure 221.27 bar and temp. 647.3 K.
 - (v) The constant pressure lines are parallel to the constant temperature lines in the wet region. These lines become curved in the superheated region.
 - (vi) The wet region has plots of constant dryness fraction and constant volume lines.
 - (vii) The constant volume lines are steeper than constant pressure lines in the superheated zone.
 - (viii) The slopes of constant pressure lines in the liquid, wet and superheated region are governed by

$$\left(\frac{\partial T}{\partial S}\right)_V = \frac{T}{C_V} \text{ and } \left(\frac{\partial T}{\partial S}\right)_P = \frac{T}{C_P}$$

(xi) The area confined between the line of a reversible process and the abscissa represents the quantity of heat added to one kg of working medium and is equal to $q = \int T ds$.

(xii) An isothermal process plots as a horizontal line and a reversible adiabatic process is represented by a vertical line.



(b) Enthalpy-Entropy (h-s) diagram:

It is the most convenient diagram to calculate the change in enthalpy during different processes. The diagram is very useful for solving problems on nozzles and steam power plants.

Enthalpy is represented on Y axis and entropy on X axis for preparing the diagram.

The point where saturated liquid lines and saturated vapour lines meet one another is called critical point. After this point, water directly get changed into superheated steam.

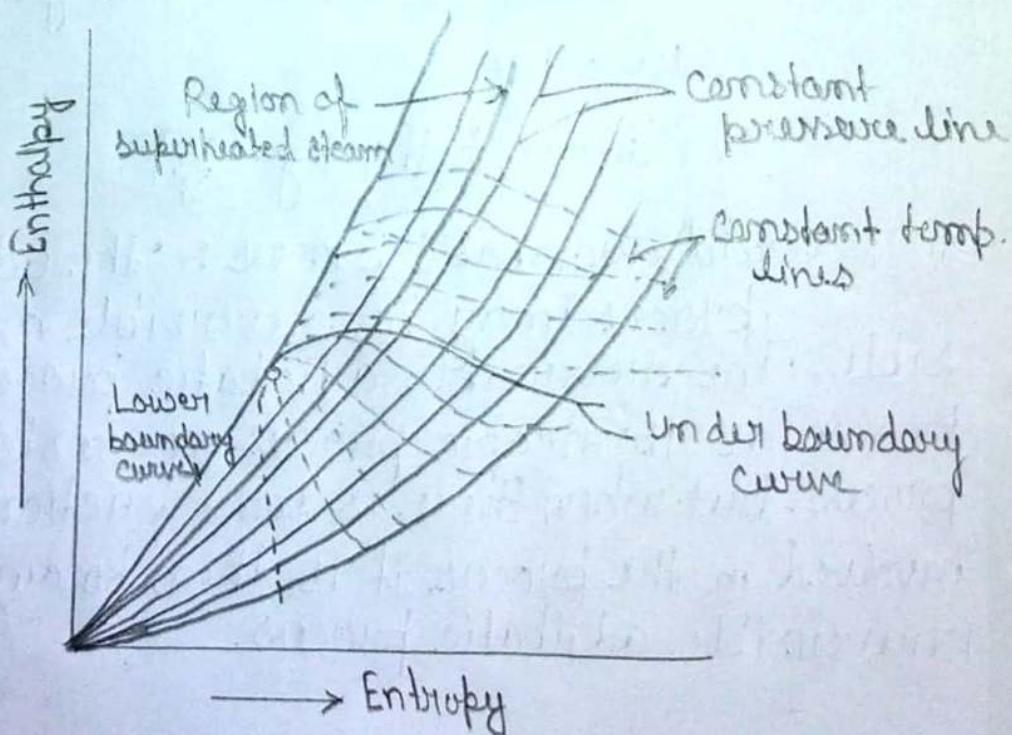
For constant pressure process:

$$d\varphi = T \cdot ds = dh$$

$$\left(\frac{dh}{ds}\right)_P = T$$

The intercepts between saturated liquid lines and saturated vapour lines at different pressure are divided into equal parts and these points are joined to get constant dryness fraction lines.

Since saturated liquid region is not often required for solving engg. problems, therefore only a part of the diagram near the saturated region and superheated region are plotted.



Methods of heating and expanding the steam:- 64

(i) Hyperbolic process :- The process $P_v = \text{constant}$

is known as hyperbolic process. The hyperbolic process is also an isothermal process in the superheated region as the steam behaves like a perfect gas in this region and follow the $P_v = C$. This process was observed to hold good for the expansion in steam engine and so has been thoroughly.

The work done during the hyperbolic expansion in a non-flow system is given by

$$W = \int_{V_1}^{V_2} P dv = \int_{V_1}^{V_2} \frac{P_1 V_1}{V} dv = P_1 V_1 \log_e \left(\frac{V_2}{V_1} \right) \quad (\because P_v = P_1 V_1)$$

Applying the first law of thermodynamics,

$$Q_1 = \Delta u + \int_{V_1}^{V_2} P \cdot dv = (u_2 - u_1) + P_1 V_1 \log_e \left(\frac{V_2}{V_1} \right)$$

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

$$P_2 V_2 = P_1 V_1$$

$$\therefore Q_1 = (h_2 - h_1) + P_1 V_1 \log_e \left(\frac{V_2}{V_1} \right)$$

(ii) Reversible adiabatic process :- The adiabatic process may be reversible or irreversible. The reversible adiabatic process is known as isentropic process or constant entropy process. But when there is some friction involved in the process, it is then known as irreversible adiabatic process.

Initial entropy of steam before expansion,

$$S_1 = S_{s1} + \frac{x_1 h_{fg1}}{T_1} = S_{f1} + x_1 s_{fg1}$$

Final entropy of steam after expansion.

$$S_2 = S_{f2} + \frac{x_2 h_{fg2}}{T_2} = S_{s2} + x_2 s_{fg2}$$

$$S_{s1} + \frac{x_1 h_{fg1}}{T_1} = S_{f2} + \frac{x_2 h_{fg2}}{T_2}$$

$$S_{s1} + x_1 s_{fg1} = S_{f2} + x_2 s_{fg2}$$

In case of superheated steam, the absolute temp. of superheated steam (i.e. T_{sup}) may be obtained by using the Charles's law i.e.

$$\frac{V_{sub}}{T_{sup}} = \frac{V_{g2}}{T_2}$$

(iii) Throttling process:- The process of throttling occurs when steam is expanded through a small aperture such as throat of a nozzle. During this process, no work is done ($w_{1,2} = 0$). There is no heat supplied ($q_{1,2} = 0$) and there is no change in total heat ($h_1 = h_2$) i.e. the total heat remain constant.

$$\text{Total heat before expansion} = h_{s1} + x_1 h_{fg1}$$

$$\text{Total heat after expansion} = h_{f2} + x_2 h_{fg2} \text{ if steam is still wet.}$$

$$= h_{s2} + h_{fg2} + C_p (T_{sup} - T_2), \text{ if the steam is in a super heated state after throttling}$$

Since the total heat during throttling process remains constant,

$$\therefore h_g + x_1 h_{fg1} = h_{f2} + x_2 h_{fg2}, \text{ if steam is finally wet}$$

$$h_g + x_1 h_{fg1} = h_{f2} + x_2 h_{fg2} + C_p (T_{sup} + T), \text{ if the steam is superheated after throttling.}$$

Determination of quality of steam (dryness fraction).

Steam dryness fraction :- The steam dryness fraction is used to quantify the amount of water within steam. If steam contains 10% water by mass, it's said to be 90% dry, or have a dryness fraction of 0.9.

Steam dryness is important because it has a direct effect on the total amount of transferable energy contained within the steam (usually just latent heat), which affects heating efficiency and quality.

For example, saturated steam (100% dry) contains 100% of the latent heat available at that pressure. Saturated water, which has no latent heat and therefore 0% dryness, will only contain sensible heat.

$$\text{Steam dryness} = 100\% - [\% \text{ Entrained water}] \\ (\text{by mass})$$

Chapter-07

Steam Generators

Uses of steam, classification of boilers, function of various boiler mounting and accessories, comparison of fire tube and water tube boilers. Construction and working of Lancashire boiler, Nestler boiler, Babcock & Wilcox Boiler. Introduction to modern boiler.

Uses of Steam.

The steam produced may be used :-

- (i) In an external combustion engine i.e. steam engines and turbines.
- (ii) At low pressures for industrial process work in cotton, mills, sugar factories etc.
- (iii) For producing hot water which can be used for heating installations at much low pressure.
- (iv) For heating the buildings in cold weather and for producing hot water for hot water supply.

Classification of boilers

There are numerous ways in which the boilers may be classified which are as follow:

1. According to the contents in the tubes : The steam boilers, according to the contents in the tubes, may be classified as :

(a) Fire tube boilers:- In fire tube boilers, the flames and hot gases produced by the combustion of fuel pass through the tubes which are surrounded by water. The heat is conducted through the walls of the tubes from the hot gases to the surrounding water. e.g. Cachram boiler, Lancashire boiler, Cornish boiler.

(b) Water tube boilers:- In water tube boilers, the water is contained inside the tubes (called water tubes) which are surrounded by flames and hot gases from outside e.g Babcock & Wilcox boiler.

2. According to the Position of the furnace : The steam boilers, according to the position of the furnace, are classified as :

- (a) Externally fixed boilers :- If the space where the combustion of the fuel takes place is provided outside the boiler shell, the boiler is called externally fixed boiler. e.g. Stirling boiler.
- (b) Internally fixed boilers :- The boiler in which the furnace is provided inside the boiler shell are said to be internally fixed boiler. e.g. Lancashire boiler, Cornish boiler.

3. According to the axis of shell : The steam boilers, according to the axis of the shell, may be classified as :

- (a) Vertical boilers :- If the axis of the boiler is vertical it is called as vertical boiler. e.g. Simple vertical boiler and Cochran boiler.
- (b) Horizontal boilers :- If the axis of the boiler is horizontal, the boiler is called as horizontal boiler e.g. Lancashire boiler, Locomotive boiler.
- (c) Inclined boilers :- If the axis of boiler is inclined, it is known inclined boiler.

4. According to the number of tubes : The steam boilers, according to the number of tubes may be classified as :

- (a) Single tube boilers :- In single tube boiler, there is only one fire tube or water tube.

e.g. Vertical boiler and Cornish boiler.

(b) Multitubular boilers :- In multitubular boiler, there are two or more fire tubes or water tubes e.g. Lancashire boiler, Cochran boiler.

5. According to use : The steam boilers, according to their use, may be classified as :

(a) Stationary boilers ; - Stationary boilers are used for power and industrial process work.

(b) Mobile boilers :- Mobile boiler or portable boilers include locomotive boilers, and other small units for temporary at sites.

6. According to the Method of Circulation of water and steam :- Boilers may be classified depending upon the method of circulation of water which are as follow :

(a) Natural circulation boilers :- When the circulation of water is achieved by the convection currents set up due to the heating of water, then it is known as natural circulation e.g. Lancashire boiler, Babcock and Wilcox boiler.

(b) Forced circulation boilers :- When the circulation of water is achieved by a centrifugal pump, then it is known as forced circulation. Forced circulation is employed in high pressure boiler e.g. Benson boiler, Lamont boiler.

7. According to the heat source :- Under this classification, boilers may be divided into different types depending upon the source of heat supplied for the production of steam.

These sources of heat may be :

- (i) Electrical or nuclear energy,
- (ii) Hot waste gases from chemical processes,
- (iii) Combustion of solid, liquid or gaseous fuels.

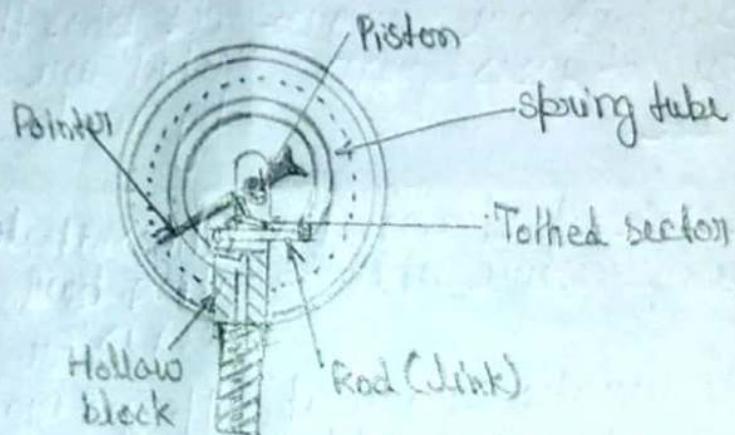
Comparison between Water tube and fire tube boilers.

Water tube boiler	Fire tube boiler
1. Water circulates inside the tubes which are surrounded by hot gases from furnace.	Hot gases from the furnace pass through the tube which are surrounded by water.
2. The rate of steam at a higher pressure upto 165 bar.	The rate of steam generation is low i.e upto 9 tonnes/hr.
3. It generates steam at a higher pressure upto 165 bar.	It generate steam upto 24.5 bar.
4. Its overall efficiency is 90%.	Its overall efficiency is 70%.
5. operating cost is high	Operating cost is low.
6. The bursting chances are more.	The bursting chances are less.
7. It is used for large power plant.	It is not suitable for large plant.
8. These are generally externally fired boilers.	These are generally internally fired boilers.

Function of various boiler mounting and accessories.

Boiler mounting :- Boiler mounting are the comp. parts generally mounted on the surface of the boiler to accomplish safety during operation and to have complete control of steam generation process. The followings are the various important mountings of a boiler :-

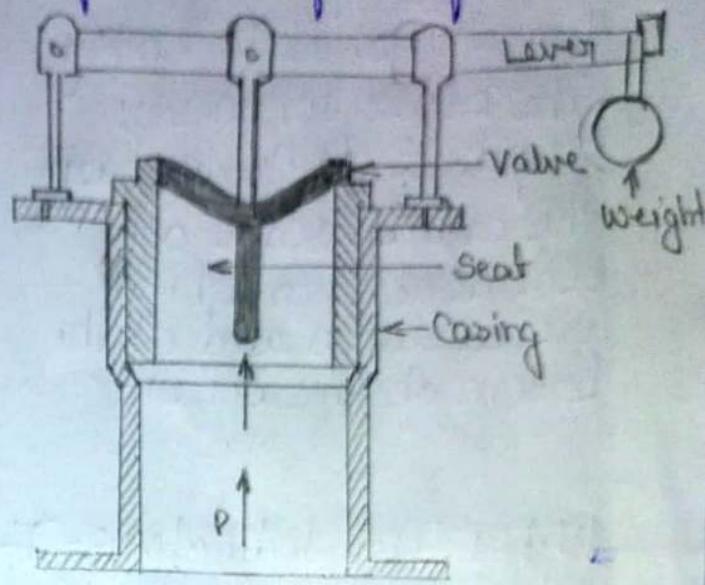
1. Pressure gauge :- It is mounted on the boiler to show the pressure of the steam.



Pressure Gauge

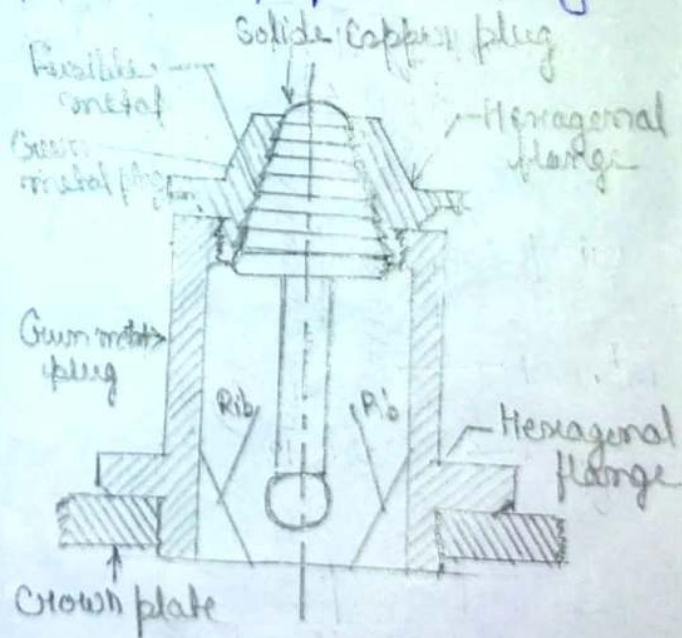
2. Safety Valves :- These are needed to blow-off the steam when pressure of the steam in the boiler exceeds the working pressure. These are placed on the top of the boiler.

3. Feed check valve :- The function of the feed check valve is to allow the supply of water to the boiler at high pressure continuously and to prevent the back flow of the water from the boiler when the pump pressure is less than boiler pressure or when pump fails.



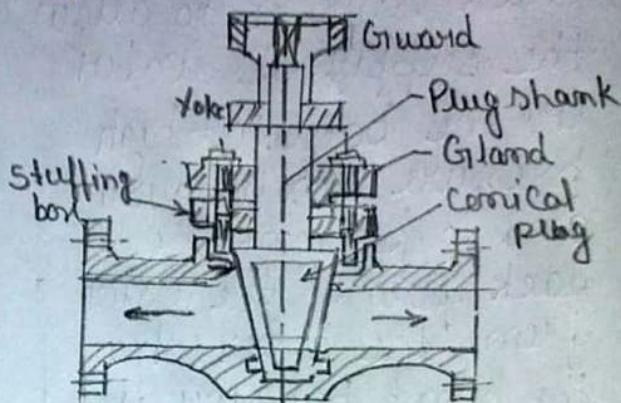
Lever Safety Valve

4. Fusible plug :- The function of fusible plug is to put off the fire in the fire box, when water level in the boiler comes down to an unsafe limit and thus avoids explosion of boiler due to overheating of furnace plates.



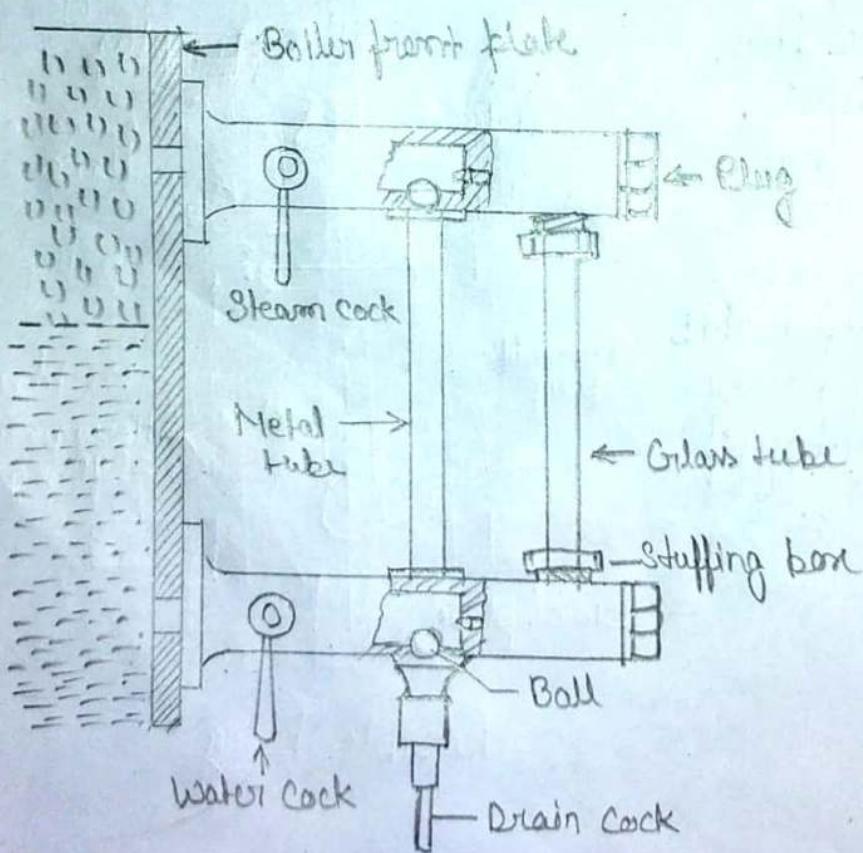
Fusible plug

5. Blow-off Cock :- Blow-off cock has two principle functions: (i) To empty the boiler whenever required. (ii) To discharge the mud, scale or sedimentation which are accumulated at the bottom of the boiler.



Blow off cock.

Water level indicator :- It is an important fitting which indicates the water level inside the boiler to an observer. It is a safety device upon which the correct working of the boiler depends.



Water level Indicator

7. Steam stop valve :-

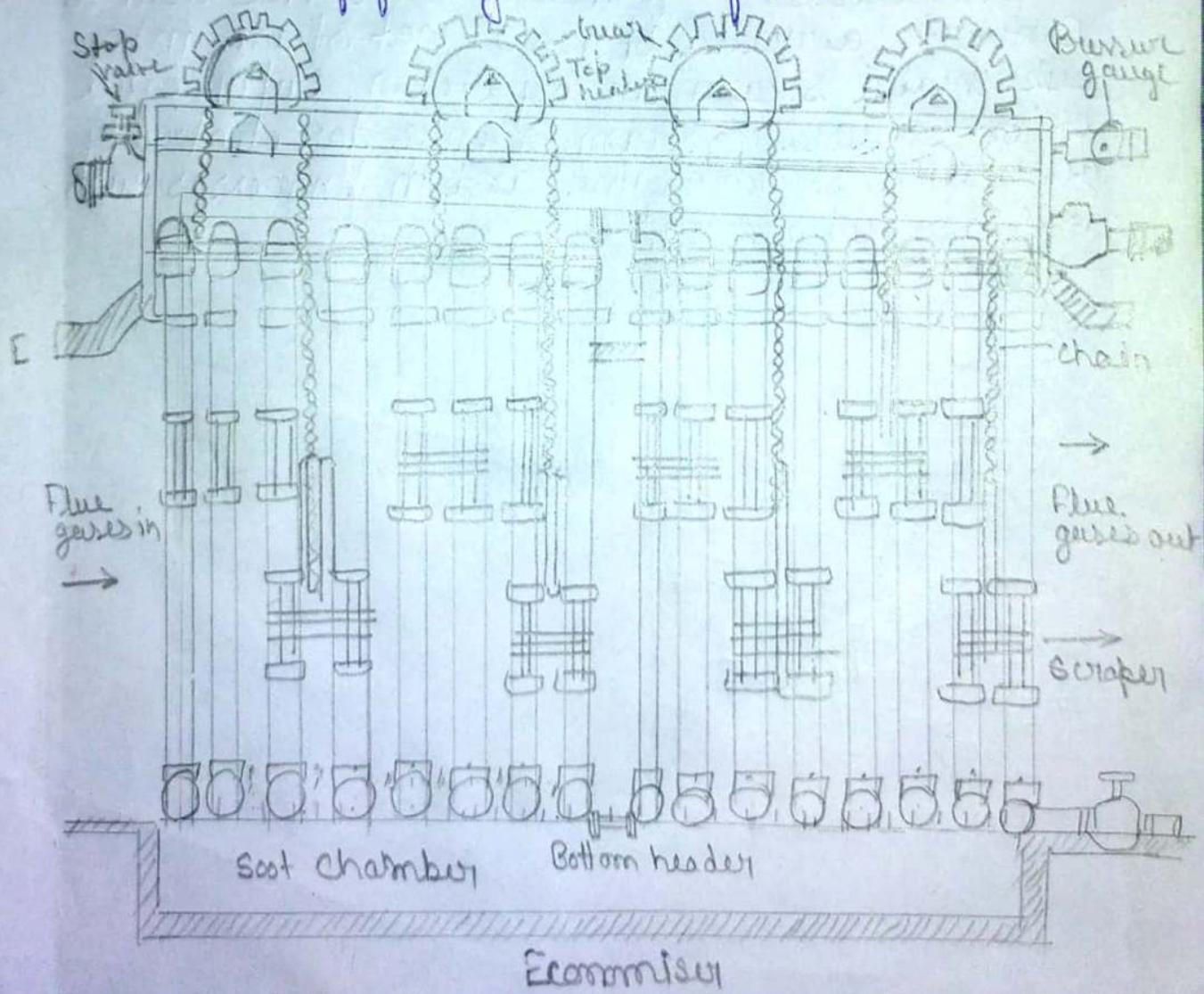
The principle functions of a steam stop valve are:-

- (i) To control the flow of steam from the boiler to the main steam pipe.
- (ii) To shut off the steam completely, when required.

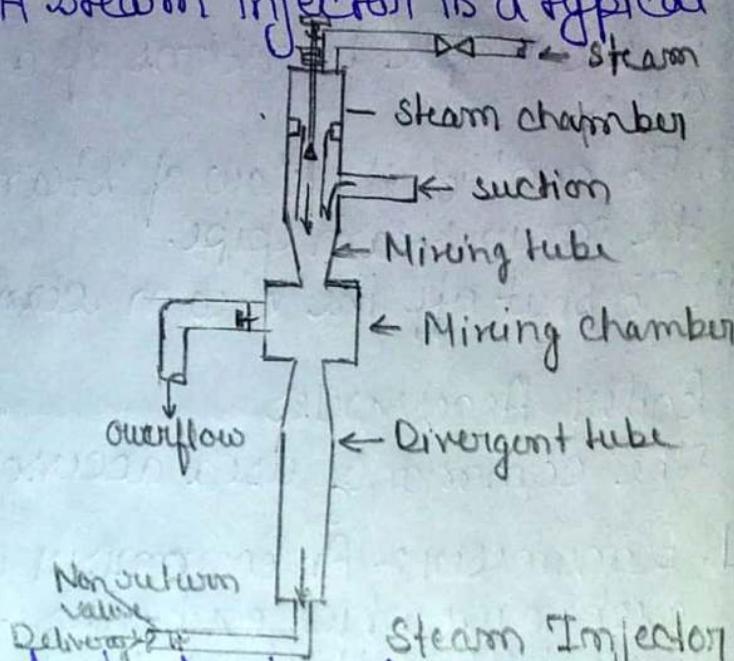
Boiler Accessories

The commonly used accessories are :

1. Economiser :- An economiser is a type of heat exchanger which exchanges some parts of the waste heat of flue gas to the feed water.

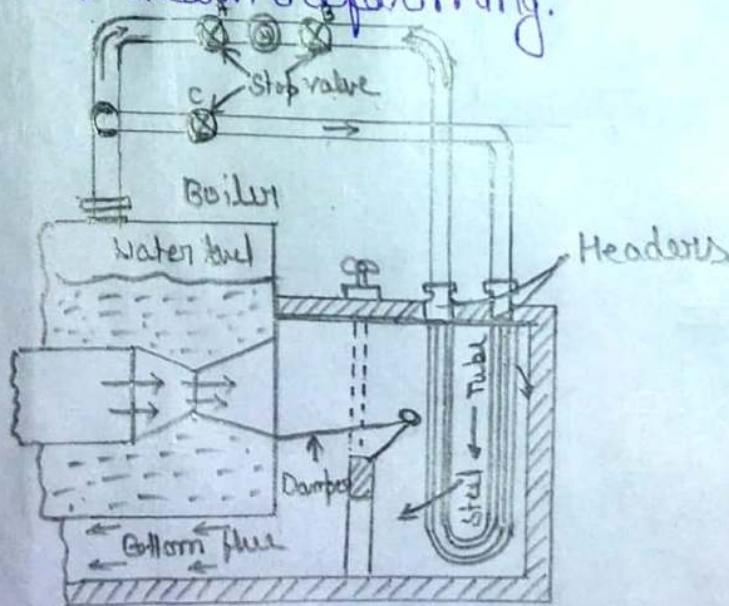


2. Steam Injector :- A steam injector is a typical application of the principle used to deliver cold water to a boiler against its own pressure, using its own live or exhaust steam, replacing any mechanical pump.



Steam Injector

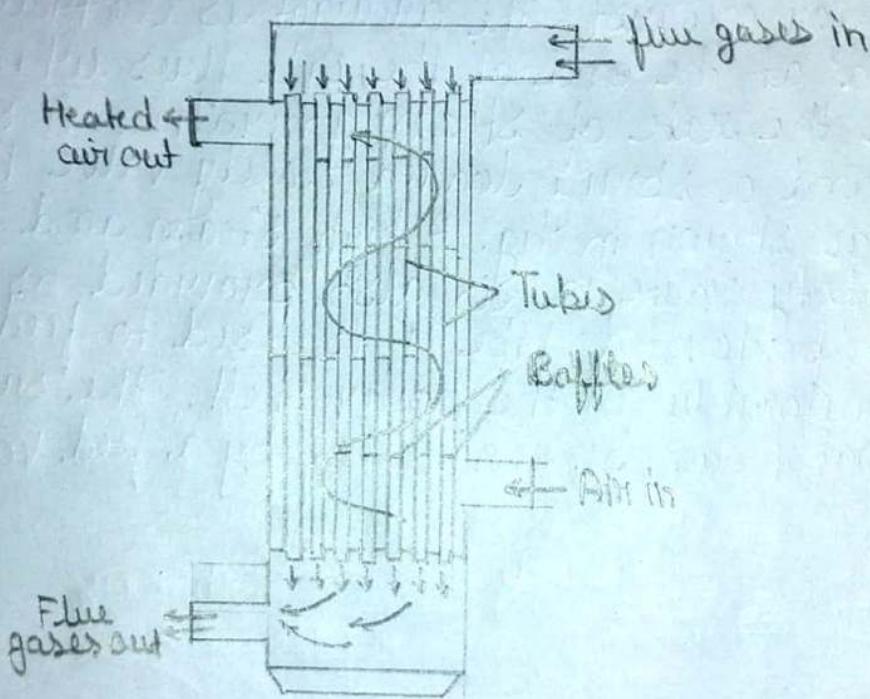
3. Super-heaters :- Superheater is a device used to convert saturated steam or wet steam into superheated steam or dry steam. Superheated steam is used in steam turbines for electricity generation, steam engine, and processes such as steam reforming.



Super Heater

4 Feed pump: Feed pump is used to feed water to steam boiler. Two type of feed pumps are generally used in boilers. In some pump special device is used to keep the water at saturation pressure and release over pressure.

5. Air preheater: - The function of the air preheater is to increase the temperature of air before it enters the furnace.

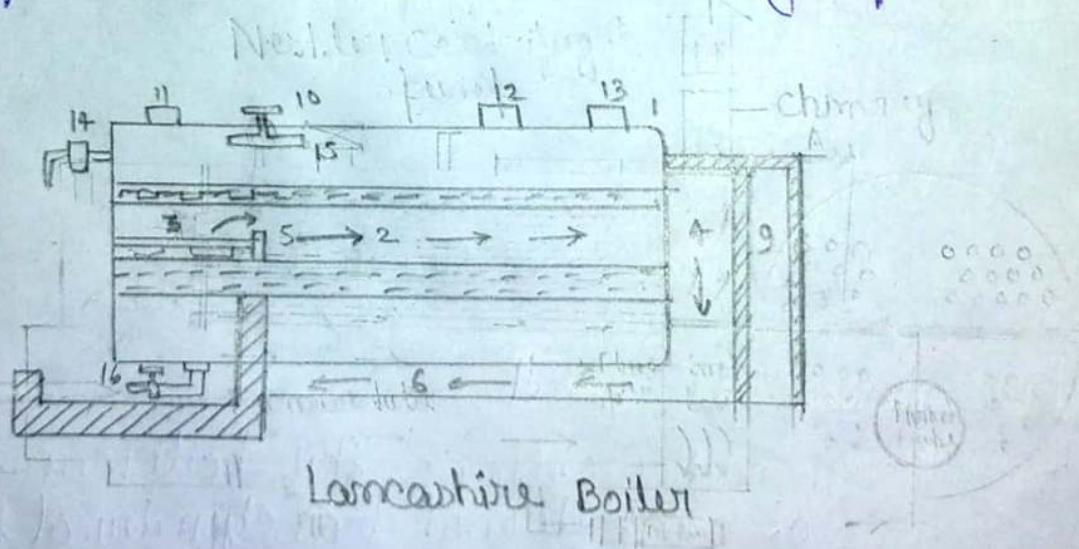


Tubular Tube Air Preheater

Lancashire boiler

Description and working: - This boiler consist of an external long cylindrical shell made up of steel plates riveted together. It has two internal flue tubes whose diameters have been reduced at the back end to provide access to the lower part of the boiler.

A grate 3 is provided at one end of the flue tubes to burn solid fuel here. A brick arch 3 is provided at the end of the grate to deflect the flue gases in the upward direction. The gases after leaving the flue tubes pass down to the bottom tube 6 and then move to the front of the boiler from where these divide and flow into side flue 7. Then the flue gases enter the main flue 9 which takes these to the chimney for exhaust. The draught is controlled by 8 fitted at the end of the side flues which regulates the rate of steam generation. A stop valve 10 and a spring loaded safety valve 11 is provided as shown in fig. A high steam and low water safety valve 12 is also provided as shown in fig. A perforated pipe 14 is used to feed the water uniformly in the boiler shell. The supply of feed water can be controlled by a feed valve.

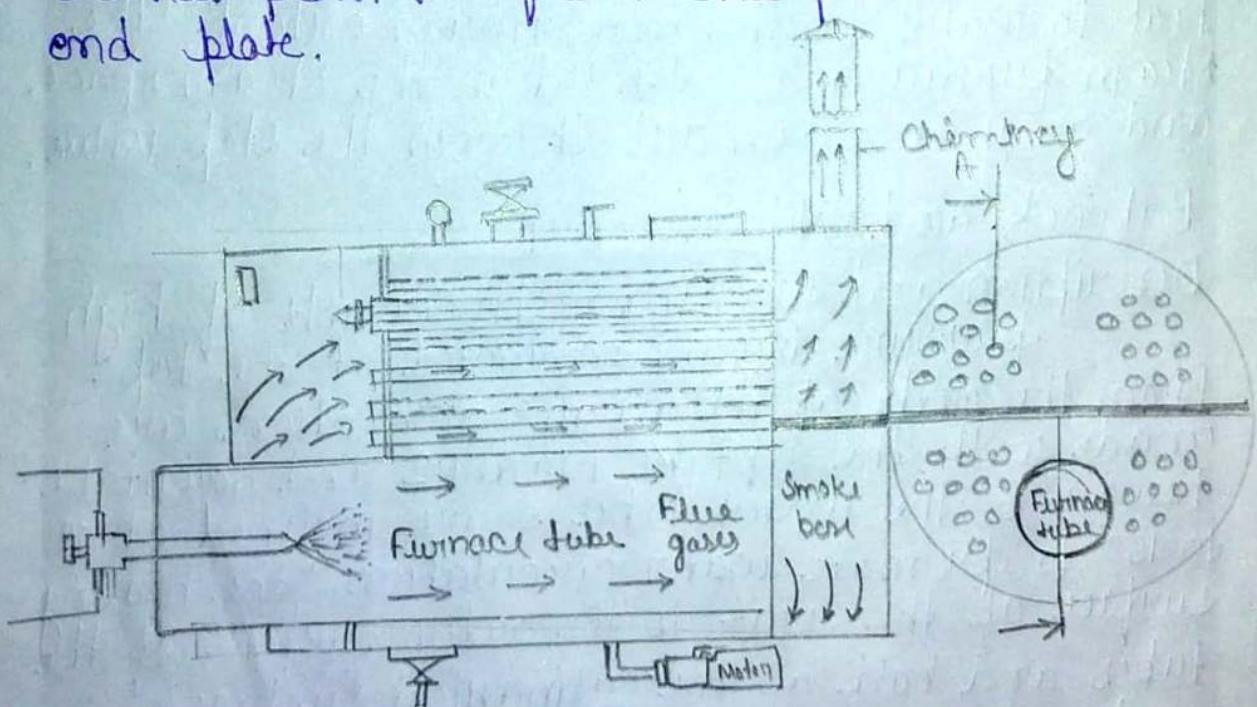


When the boiler is heated strongly, the steam is generated which has a large quantity of water with it in the steam space known as priming. So, to separate the water from steam, an anti-

priming pipe is provided. In this way, the stop valve only receives dry steam. A blow off cock is provided from which mud etc. can be removed. It is also used to empty the boiler required for inspection. For cleaning and repair purpose, the manholes are provided at the top and bottom of the boiler.

Nestler Boiler :-

Construction and Working :- The boiler shell consists of 12 mm thick mild steel plate and is welded with two plates one at each end. A large number of fire tubes of 15 mm diameter each fitted between the two end plates in addition to a 0.5 m diameter furnace tube which extends from the front end plate to the rear end plate.



Nestler Boiler

The burner is provided at the mid of the furnace tube. At each end of the boiler shell, there is a smoke box. In the rear end of smoke box, a deflection arch is provided to divert the flow of flue gases. The flue gases first traverse through the entire length of the furnace tube upto the rear end where they enter the smoke box. There after, they enter lower set of small diameter fire tubes and travel all along through these tubes upto the front end smoke box from where they rise up and get into the upper set of fire tubes. The flue gases are finally discharged into the atmosphere through chimney. The flue gases thus traverse the entire length of the boiler three times so as to provide their heat to water to the maximum extent. The steam produced is collected in the steam space and may be taken out through the stop valve.

Babcock and Wilcox boiler

Description and working :- It consists of high pressure drum 1 mounted at the top.

From the ends of the drum, connections are made with the uptake header 2 and downtake header 3. The water tubes 5 are inclined at 5° to 15° to promote water circulation. The heating surface of the unit is the outer surface of the tubes and half of the cylindrical surface of water drum is exposed to flue gases. A mud box 6 is attached to the bottom of the downtake header.

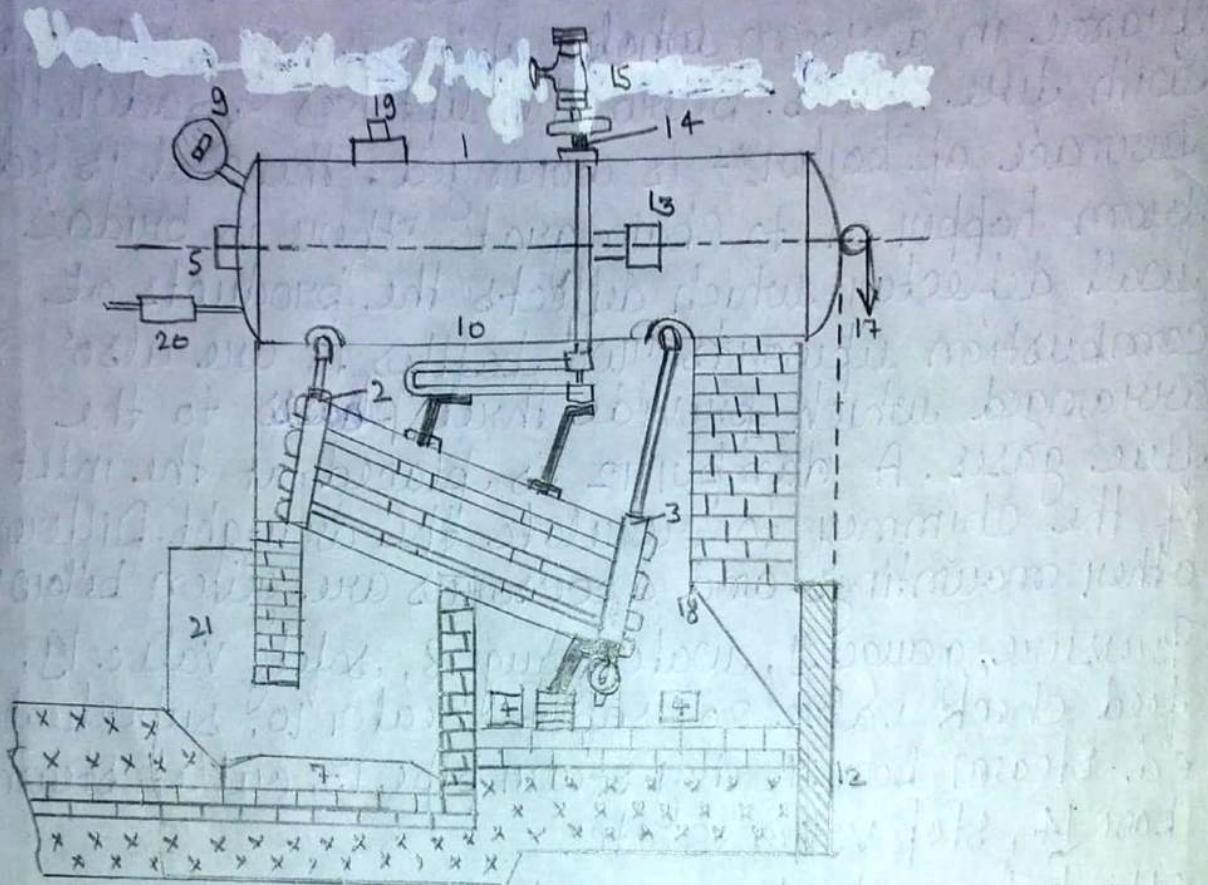
The whole of the assembly of water tubes is hung along with the drum from steel girder frame in a room made of masonry work lined with fire bricks. Below the uptake header, the furnace of boiler 7 is arranged. The coal is fed from hopper 21 to chain grate. There is bridge wall deflector which deflects the products of combustion upwards. Two baffles 16 are also arranged which provide three passes to the flue gases. A damper 12 is placed at the inlet of the chimney to regulate the draught. Different other mountings and accessories are given below:

Pressure gauge 9, water gauge 8, safety valve 19, feed check valve 20, super-heater 10, superheated steam box 11, dry steam pipe 13, outlet steam box 14, stop valve 15 etc.

The hot combustion gases produced by burning of fuel on the grate rise upwards and are deflected by the bridge wall deflector to pass over the front portion of the water tubes and drum. The circulation of water in boiler is due to natural circulation set up by convection currents.

Feed water is supplied by a feed water inlet pipe. The hottest water and steam rises from the tubes to the uptake header and then through the riser, it enters the boiler drum. The steam vapour escape through the water to upper half of the drum. The super heated steam is taken to the steam stop valve through the steam pipe

which is connected to superheated steam box.



Babcock and Wilcox Boiler. How Built.

Modern Boiler / High pressure Boilers :- The modern practice is to generate and use steam at higher pressure and temp. so as to improve the efficiency of the power plant. There are boilers which work in supercritical range i.e. their working pressure is much higher than the critical pressure of steam.

Chapter-08

Air Standard Cycles

83

Meaning of air standard cycle - its use, condition of reversibility of a cycle.

Description of Carnot cycle, Otto cycle, Diesel cycle, simple problems on efficiency for different cycles.

Comparison of Otto, Diesel cycle for same compression ratio, same peak pressure developed and same heat input.

Reasons for higher efficiency of Carnot cycle and all other cycles working between same temperature limits.

Air Standard cycle :- A thermodynamic cycle using air as the working substance is known as air standard cycle.

Condition of reversibility of a cycle.

Following conditions must be satisfied for thermal reversibility of a cycle:

- (i) The temperature of working substance and the hot body should be same when the heat is absorbed.
- (ii) The temperature of working substance and the cold body should be same when the heat is rejected.
- (iii) The heat loss by conduction, convection and radiation should be negligible.
- (iv) The expansion and compression processes should be frictionless. Although the concept of reversibility is an assumption, but it plays a significant role in comparing the efficiency of different cycles.

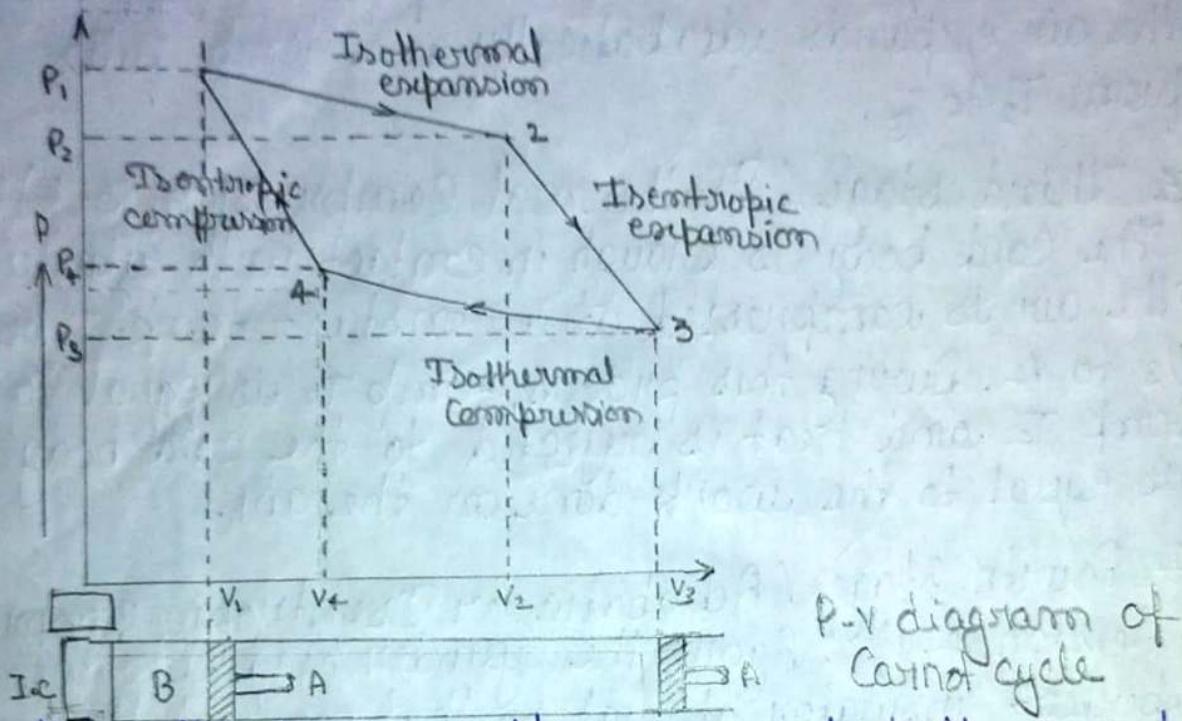
Uses :- These cycles can be used to examine the performance of internal combustion engines, e.g petrol and diesel engines and gas turbine.

dual combustion - this is a combination of constant volume and constant pressure combustion, and results in a slightly more realistic cycle.

Carnot Cycle

The cycle was first devised by a French scientist, Carnot in 1824 which operates on reversible cycle. In a Carnot cycle, working substance is

subjected to two isothermal and two adiabatic processes.



The following assumption are made in the Carnot cycle:-

- (i) The wall of the cylinder and piston are perfect non-conductors of heat.
- (ii) Working medium is a perfect gas having constant specific heat.
- (iii) Compression and expansion processes are reversible.

Four stages of the Carnot cycle:-

1. First stage (Isothermal Expansion, 1-2) :- The source of heat at a high temp. is applied at the bottom of cylinder. The air expands at constant temp. T_1 from V_1 to V_2 . It means that temp. at point 1, T_1 is equal to temp. at point 2, T_2 .

2. Second stage (Adiabatic or Isentropic expansion, 2-3) :- As the cylinder is assumed to be a perfect insulator of heat, so no heat flow taking place. The air expands adiabatically and temp falls from T_2 to T_3 .

3. Third stage (Isothermal Compression, 3-4) :

The cold body is brought in contact with cylinder. The air is compressed at a constant temp. T_1 from V_3 to V_4 . During this process, temp T_3 is equal to temp T_4 and heat is rejected to the cold body is equal to the work done on the air.

4. Fourth stage (Adiabatic or Isentropic compression, 4-1) : Again the cylinder head become perfect insulator of heat so that no heat flow occurs. The compression process follows reversible adiabatic process during which temp. is raised from T_2 to T_1 .

Let the cylinder contains m kg of air

$$\text{Heat supplied} = P_1 V_1 \log_e \left(\frac{V_2}{V_1} \right) = m R T_1 \log_e \left(\frac{V_2}{V_1} \right) \quad (\because PV = mRT)$$

$$\text{Heat rejected} = P_2 V_2 \log_e \left(\frac{V_3}{V_2} \right) = m R T_2 \log_e \left(\frac{V_3}{V_2} \right)$$

$$\begin{aligned} \text{Work done} &= \text{Heat supplied} - \text{Heat rejected} \\ &= m R T_1 \log_e \left(\frac{V_2}{V_1} \right) - m R T_2 \log_e \left(\frac{V_3}{V_2} \right) \end{aligned}$$

$$\begin{aligned} \text{where } H &= \frac{V_2}{V_1} \\ &= \frac{V_3}{V_4} \end{aligned}$$

$$\begin{aligned}
 \text{Efficiency of cycle, } \eta &= \frac{\text{Work done}}{\text{Heat supplied}} \\
 &= \frac{mRT_1 \log_e \frac{T_1}{T_2} - mRT_2 \log_e \frac{T_1}{T_2}}{mRT_1 \log_e \frac{T_1}{T_2}} \\
 &= \frac{T_1 - T_2}{T_1} = 1 - \frac{T_3}{T_1}
 \end{aligned}$$

Otto cycle or Constant Volume cycle

The first successful engine working on Otto cycle was build by A. Otto. These days, many petrol, gas and oil engines work on this cycle.

1. First stage (Reversible Adiabatic or isentropic expansion, 1-2) :- In this process, the pressure, volume and temp. change from P_1, V_1 and P_2, V_2 and due to isentropic expansion, No heat is absorbed or rejected by air during this process.
2. Second stage (Constant volume cooling, 2-3) :- The heat is rejected at constant volume from temp. T_2 to T_3 during this process.
3. Third stage (Reversible Adiabatic Compression, 3-4) :- The compression of air takes place reversibly and adiabatically from temp. T_3 to T_4 . Vol. of air decreases from V_3 to V_4 . No heat is absorbed or rejected by air.
4. Fourth stage (Constant volume Heating, 4-1) : The air is heated at constant volume from temp. T_4 to T_1 .

$$\text{Heat supplied in constant volume process, 4-1} = mC_v(T_1 - T_4)$$

$$\text{Heat rejected in constant volume process, 2-3} = mC_v(T_2 - T_3)$$

Work done = Heat supplied - Heat rejected.

$$= mC_v(T_1 - T_4) - mC_v(T_2 - T_3)$$

$$\therefore \text{Efficiency, } \eta_{\text{Otto}} = \frac{\text{Work done}}{\text{Heat Supplied}}$$

$$= \frac{mC_v(T_1 - T_4) - mC_v(T_2 - T_3)}{mC_v(T_1 - T_4)}$$

$$= 1 - \left(\frac{T_2 - T_3}{T_1 - T_4} \right) = 1 - \frac{T_2 \left(1 - \frac{T_3}{T_2} \right)}{T_1 \left(1 - \frac{T_4}{T_1} \right)} \quad \text{--- (i)}$$

$$\frac{T_1}{T_2} \cdot \left(\frac{V_2}{V_1} \right)^{\gamma-1} = \pi^{\gamma-1} \quad \text{(ii)} \quad \left(\because \pi = \frac{V_2}{V_1} \right)$$

$$\frac{T_4}{T_3} = \left(\frac{V_3}{V_4} \right)^{\gamma-1} = \pi^{\gamma-1} \quad \text{--- (iii)}$$

where π = Compression ratio $= \frac{V_3}{V_4} = \frac{V_2}{V_1}$
from eqn (ii) and (iii),

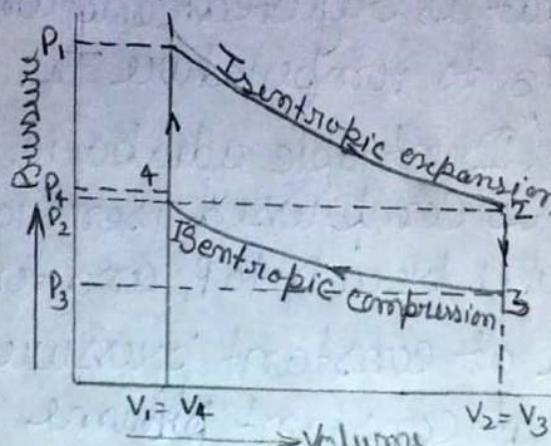
$$\frac{T_1}{T_2} = \frac{T_4}{T_3} = \pi^{\gamma-1}$$

$$\frac{T_3}{T_2} = \frac{T_4}{T_1} = \pi^{\gamma-1}$$

Putting the value of $\frac{T_3}{T_2}$ and $\frac{T_4}{T_1}$ in eqn (i), we get

$$\begin{aligned} \eta_{\text{Otto}} &= 1 - \frac{T_2 (1 - \pi^{\gamma-1})}{T_1 (1 - \pi^{\gamma-1})} \\ &= 1 - \frac{T_2}{T_1} = 1 - \frac{1}{(\pi)^{\gamma-1}} \end{aligned}$$

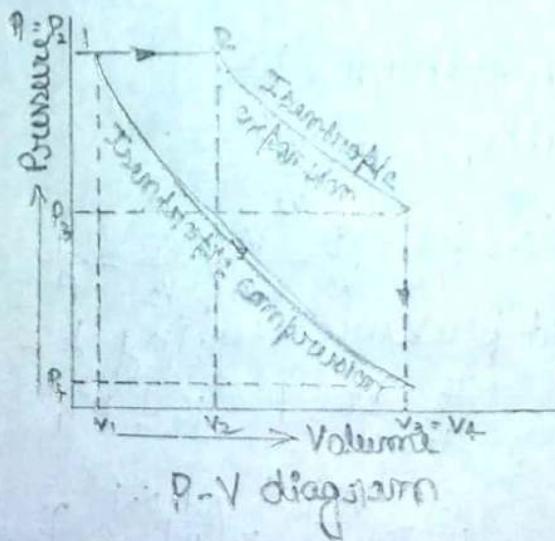
(i) Efficiency of otto cycle is less than than the Carnot cycle as temp. difference during otto cycle is not highest as in case of carnot cycle.



P-V diagram of Otto cycle

Diesel or Constant Pressure cycle

This cycle was given by Dr. Rudolph Diesel in 1893. It differs from Otto cycle in the respect that heat is supplied constant pressure instead of constant volume.



P-V diagram

1. First Stage (Constant Pressure Heating, 1-2) :- In this stage heat is supplied to air at constant pressure. Temp. of air increase from T_1 and T_2 .
2. Second Stage (Isentropic adiabatic expansion, 2-3) :- As the process isentropic no heat is added or rejected by the air. The air is expanded from temp T_2 to T_3 .

3. Third stage (Constant Volume Cooling, 3-4): In this stage, heat is rejected at constant volume from temperature T_3 to temperature T_4 .

4. Fourth stage (Isentropic adiabatic compression, 4-1): The air is compressed isentropically and the pressure rises from P_4 to P_1 , and temp from T_4 to T_1 .

$$\text{Heat supplied at constant pressure} = mC_p(T_2 - T_1)$$

$$\text{Heat rejected at constant volume} = mC_v(T_3 - T_4)$$

$$\begin{aligned}\text{Work done} &= \text{Heat supplied} - \text{Heat rejected} \\ &= mC_p(T_2 - T_1) - mC_v(T_3 - T_4) \\ &= \frac{mC_p(T_2 - T_1)}{mC_p(T_2 - T_1)} \\ &= 1 - \frac{C_v}{C_p} \left(\frac{T_3 - T_4}{T_2 - T_1} \right) \\ &= 1 - \frac{1}{\gamma} \left(\frac{T_3 - T_4}{T_2 - T_1} \right) \quad \text{--- (i)}\end{aligned}$$

$$\text{where } \gamma = \frac{C_p}{C_v}$$

$$\text{Let compression ratio, } \eta = \frac{V_1}{V_2}$$

$$\text{Cut off ratio, } p = \frac{V_2}{V_1}$$

$$\text{Expansion ratio} = \frac{V_3}{V_2} = \frac{V_4}{V_2} = \frac{V_4}{V_1} \times \frac{V_1}{V_2} = \frac{\eta}{p}$$

During constant pressure heating 1-2

$$\frac{T_2}{T_1} = \frac{V_2}{V_1} = p \quad T_2 = pT_1 \quad \text{--- (ii)}$$

$$\text{process 2-3} \quad \frac{T_2}{T_3} = \left(\frac{V_3}{V_2} \right)^{\gamma-1} = \left(\frac{\eta}{p} \right)^{\gamma-1} \quad T_3 = \frac{pT_2}{\left(\frac{\eta}{p} \right)^{\gamma-1}} \quad \text{--- (iii)}$$

$$\text{process 4-1} \quad \frac{T_4}{T_1} = \left(\frac{V_1}{V_2} \right)^{\gamma-1} = \left(\frac{1}{p} \right)^{\gamma-1} \quad T_1 = T_4 \left(\frac{1}{p} \right)^{\gamma-1}$$

Putting the value of T_1 in equation (iii) and (iv), we get - by

$$\begin{aligned}T_2 &= pT_4 \left(\frac{1}{p} \right)^{\gamma-1} \quad \text{--- (v)} \\ T_3 &= \frac{pT_4 \left(\frac{1}{p} \right)^{\gamma-1}}{\left(\frac{\eta}{p} \right)^{\gamma-1}}\end{aligned}$$

$$= \frac{P T_4 (M)^{\gamma-1} \times P^{\gamma-1}}{(M)^{\gamma-1}} = T_4 p^{\gamma} \quad \text{--- (vi)}$$

Now putting the value of T_1, T_2 and T_3 from eqn (iv), (v) and (vi) in eqn (i), we get.

$$\eta_{\text{diesel}} = 1 - \frac{1}{\gamma} \left[\frac{T_4 P^{\gamma} - T_4}{P T_4 (M)^{\gamma-1} - T_4 (M)^{\gamma-1}} \right]$$

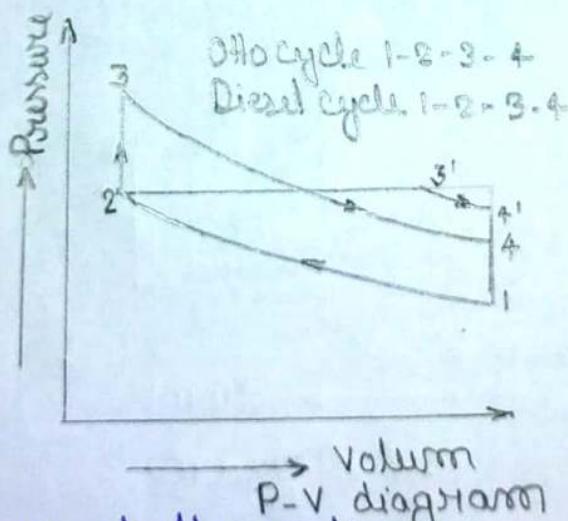
$$\eta_{\text{diesel}} = 1 - \frac{1}{(M)^{\gamma-1}} \left[\frac{P x - 1}{\gamma (P - 1)} \right]$$

Comparison of Otto and Diesel Cycles

Following are the some important variable factors which can be used for comparison b/w Otto and diesel cycles :-

- (a) Compression ratio
- (b) Maximum pressure

(a) For the same compression ratio and same heat input:



Some features of these dig. are

- (i) Heat supplied is same for both cycles. Hence, the area of T-S diagram for both the cycles will be equal. i.e. area e-2-3-4-f = Area e-2-3'-4'-f'.
- (ii) Both cycles start at the same initial conditions corresponding to point 1 with reversible adiabatic

process 1-2 and compression ratio is same for both the cycle.

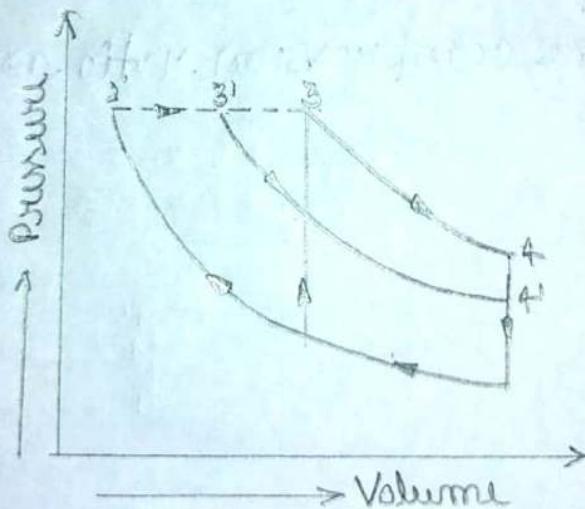
$$(iii) \eta = \frac{\text{Heat supplied} - \text{Heat rejected}}{\text{Heat supplied}} = 1 - \frac{\text{Heat rejected}}{\text{Heat supplied}}$$

For the same quantity of heat input, the cycle which has less heat rejected will have higher efficiency.

Diesel cycle rejects more heat (area e-1-f'-g') than the Otto cycle (area e-1-f-g) according to figure(b)

$$\therefore \eta_{\text{Otto}} > \eta_{\text{diesel}}$$

(b) For same maximum pressure and heat input:



P-V diagram

For the same maximum pressure, point 3 and 3' must lie on the same constant pressure line and for same heat input, the areas (e-2-3-g) and (e-2'-3'-g') on T-S dig. should be equal. As shown from fig(b) heat rejected by diesel cycle (area e-1-f'-g') is less than that of Otto cycle given by (area e-1-f-g)

$$\therefore \eta_{\text{diesel}} > \eta_{\text{Otto}}$$

Air Compressors

Function of air compressor - uses of compressed air, type of air compressors.

Single stage reciprocating air compressor, its construction and working, representation of processes involved on P-V diagram. Calculation of work done.

Multistage compressors - advantages over single stage compressors, use of air cooler, condition of minimum work in two stage compressor (without proof), simple problems.

Rotary compressors - types, working and construction of centrifugal compressor, axial flow compressor, vane type compressor.

Function of air Compressor:- An air compressor is a device which compresses the air and raises its pressure. The air compressor suck air from the atmosphere, compresses it and deliver the compressed air to the storage vessel and it can be distribute through pipelines to the required place.

Uses of Compressed air :-

- (i) It is widely used for powering small engines.
- (ii) It is used for producing blast of air in blast furnace
- (iii) It is used in the operating of lifts, pump etc.
- (iv) It is used in operating tools in factories.

Classification of compressors

Air compressors can be classified by many different ways which are as follow:

1. According to working :-

(a) Reciprocating Compressors, (b) Rotary Compressors.

2. According to number of stages :-

(a) Single stage Compressors, (b) Multi-stage Compressors.

3. According to action :-

(a) Single acting Compressors, (b) Double acting Compressors.

4. According to compressed air capacity :-

(a) Low capacity Compressors, (b) Medium capacity Compressors
(c) High capacity Compressors.

5. According to nature of installation :-

(a) Fixed, (b) Semi-fixed, (c) Portable.

6. According to Cooling :-

(a) Water cooled Compressors, (b) Air cooled compressors.

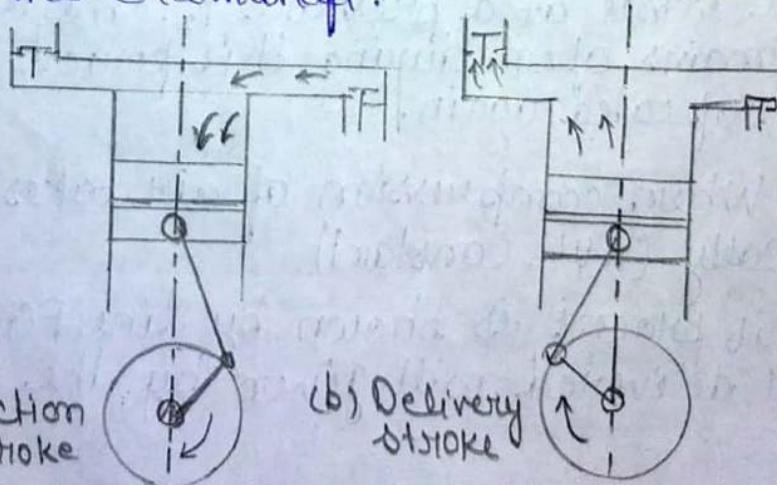
Single Stage Reciprocating air compressor

A single stage reciprocating air compressor consists of a cylinder, piston inlet and discharge valve.

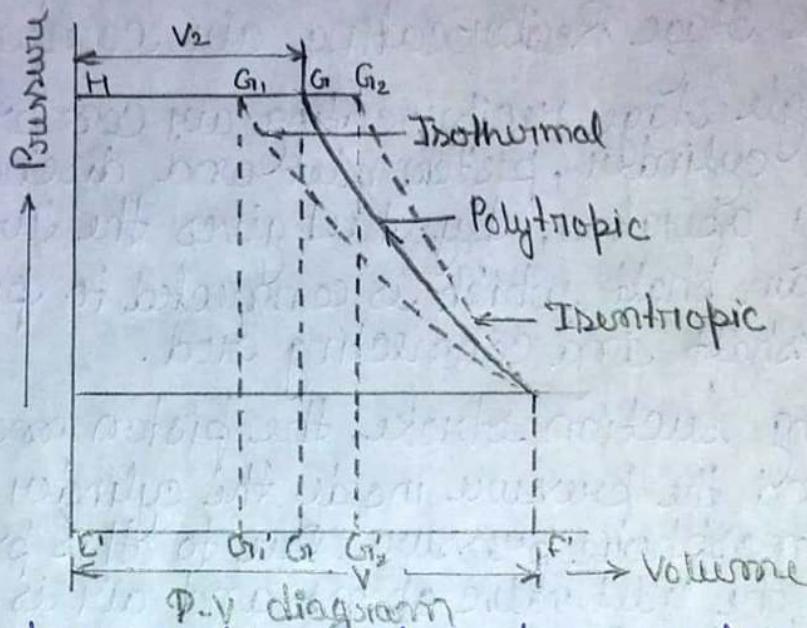
During operation, flywheel gives the turning moment to main shaft which is connected to piston through crankshaft and connecting rod.

During suction stroke, the piston moves downwards and the pressure inside the cylinder falls below the atmospheric pressure. Due to this pressure difference, the inlet valve opens and air is sucked into the cylinder. During compression stroke, the piston moves upwards and the pressure inside the cylinder increases till it reaches the discharge pressure.

When pressure becomes high in cylinder, the discharge valve gets opened and air is delivered to the storage tank. At the completion of delivery stroke, a small quantity of air is left in the clearance space. Whole process of compression, suction and discharge of air takes place in two stroke of piston or one revolution of the crankshaft.



Work done by a single stage reciprocating air compressor without clearance volume.



- During the downward or outward or suction stroke of piston, air is sucked at pressure P_1 . During this operation inlet valve remain open. Shown in process EF.
- Process FG₁ show the compression of air polytropically. during this operation, inlet and delivery valve remain closed. The compression continues till the pressure P_2 in the cylinder is adequate to open the open the delivery valve at point G₁.
- Process GH represents the delivery of air to the storage vessel at a pressure P_2 . The outlet valve remains open during this period and the cycle is repeated again.

A. When compression of air takes place polytropically ($PV^{\gamma} = \text{Constant}$)

This process is shown by line FG₁. The volume of air delivered will given by the line GH

Workdone on the air per cycle,

$$\begin{aligned}
 W &= \text{Area } EFG_1H \\
 &= \text{Area } E'HG_1G_1 + \text{Area } G_1FF'G_1 - \text{Area } E'FF' \\
 &= P_2 V_2 + \frac{P_2 V_2 - P_1 V_1}{(n-1)} - P_1 V_1 \\
 &= \frac{P_2 V_2 (n-1+1) - P_1 V_1 (1+n-1)}{(n-1)} \\
 &= \frac{P_2 V_2 (n-1+1) - P_1 V_1 (1+n-1)}{(n-1)} \\
 &= \frac{n P_2 V_2 - n P_1 V_1}{n-1} = \frac{n (P_2 V_2 - P_1 V_1)}{n-1} \quad \text{(i)} \\
 &= \frac{n}{n-1} \times P_1 V_1 \left(\frac{P_2 V_2}{P_1 V_1} - 1 \right)
 \end{aligned}$$

We also know that for polytropic compression,

$$\begin{aligned}
 P_1 V_1^n &= P_2 V_2^n \\
 \therefore \frac{V_2}{V_1} &= \left(\frac{P_1}{P_2} \right)^{\frac{1}{n}}
 \end{aligned}$$

Putting the value $\frac{V_1}{V_2}$ in equation (i) we get

$$\begin{aligned}
 W &= \frac{n}{n-1} \times P_1 V_1 \left[\frac{P_2}{P_1} \left(\frac{P_1}{P_2} \right)^{\frac{1}{n}} - 1 \right] = \frac{n}{n-1} \times P_1 V_1 \left[\left(\frac{P_2}{P_1} \right)^{\frac{n-1}{n}} - 1 \right] \\
 &= \frac{n}{n-1} \times mRT_1 \left[\left(\frac{P_2}{P_1} \right)^{\frac{n-1}{n}} - 1 \right] \quad (\because PV = mRT)
 \end{aligned}$$

B. Work done when compression of air takes place according to isothermal process :

Work done per cycle = Area EFG_1H

$$\begin{aligned}
 &= \text{Area } E'HG_1G_1 + \text{Area } G_1G_1F'F - \text{Area } E'FF' \\
 &= P_2 V_2 + P_2 V_2 \log_2 \left(\frac{V_1}{V_2} \right) - P_1 V_1
 \end{aligned}$$

$$= P_1 V_1 \log_e \left(\frac{V_1}{V_2} \right) \left(\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2} \text{ or } P_1 V_1 = P_2 V_2 \right)$$

$$W = P_1 V_1 \log_e \left(\frac{P_2}{P_1} \right) \quad W = mRT_1 \log_2 \frac{P_2}{P_1}$$

$\lambda = \frac{P_2}{P_1}$ Pressure ratio

98

C. Work done when compression of air takes place according to isentropic process :-

$$W = \frac{\gamma}{\gamma-1} \times P_1 V_1 \left[\left(\frac{P_2}{P_1} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right] = \frac{\gamma}{\gamma-1} \times m R T \left[\left(\frac{P_2}{P_1} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right]$$

Multi Stage compression

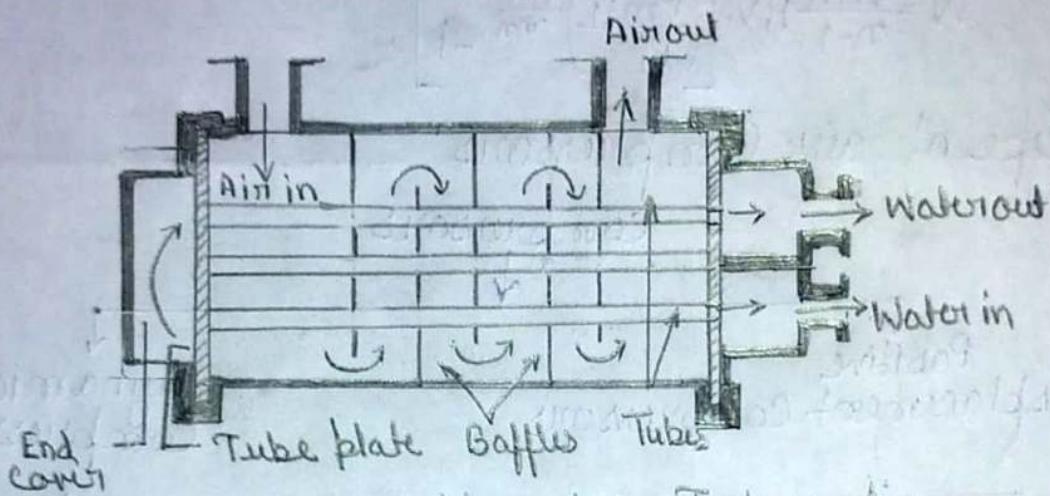
In case of single stage reciprocating air compressor, suction, compression and delivery of air take place in a single stage. But sometimes, the air is required at a pressure. For this, we can either employ a large pressure ratio in a single cylinder or compress the air in two or more cylinder in series.

Advantages of multistage compression :-

1. The power required to drive a multistage compressor with intercooler is less than that would be required by a single stage compressor for the same delivery pressure.
2. Multistage compressor has better mechanical balance and hence, a small sized flywheel is required.
3. It reduces the leakage loss considerably.
4. Effective lubrication is possible because of lower temperature range.
5. It reduces the cost of compressor.
6. The pressure and temp. range may be kept within the desirable limit by using multistage compressor.
7. It improves the volumetric efficiency for the same pressure ratio.

Intercooler

Uses :- The inter-cooler is commonly used b/w two stage with the object of removing heat of compressed air.



Counter flow type Intercooler

The cooling water passes through the tubes which are tightly held b/w two tube plates and the circulation of air over tubes is done with the help of baffles.

Minimum work required for a two stage reciprocating air compression.

The work done will be minimum when the point 3 lies on the isothermal line. As the pressure P_1 and P_3 are constant, therefore, the least value of intermediate pressure P_2 may be obtained by differentiating eqn with respect to P_2 and putting equal to zero.

$$\therefore \frac{dw}{dP_2} = 0$$

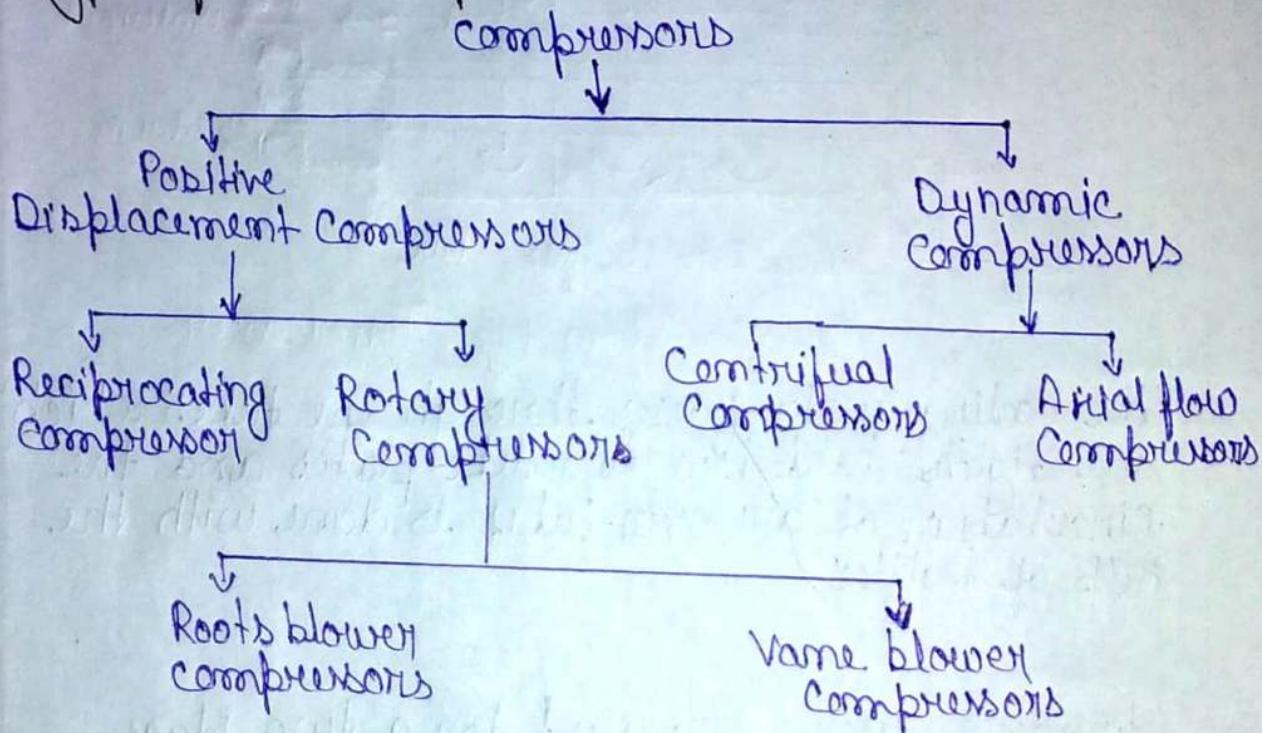
Minimum work required for a two stage reciprocating air compression is

$$W = \frac{2n}{n-1} P_1 V_1 \left[\left(\frac{P_2}{P_1} \right)^{\frac{n-1}{2n}} - 1 \right]$$

Q1 In general, if we have m stages compressor, then minimum work required is

$$W = \frac{mn}{n-1} P_1 V_1 \left[\left(\frac{P_{m+1}}{P_1} \right)^{\frac{n-1}{mn}} - 1 \right]$$

Type of air Compressors

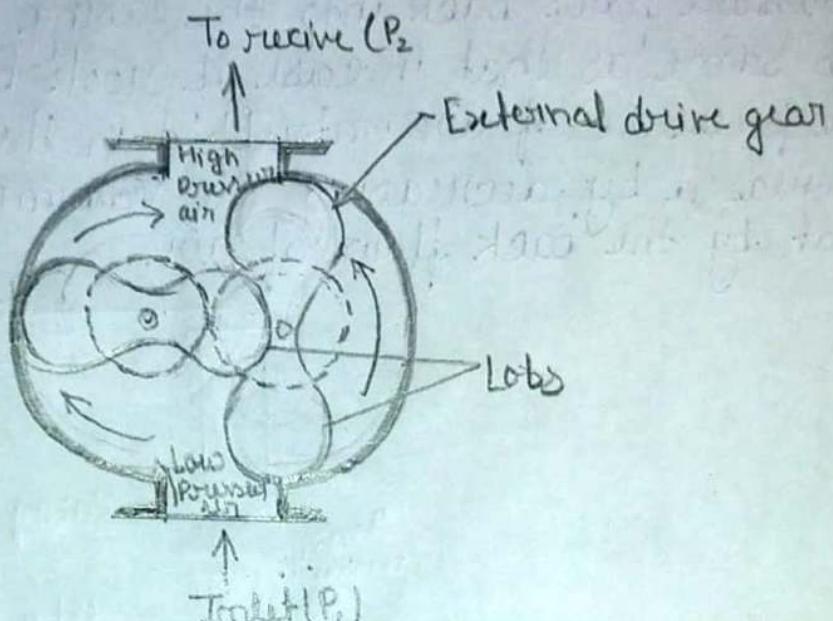


Types of Rotary Compressors :-

There are two main types of rotary compressors:-

1. Roots Blower Compressor :- A root blower compressor consists of two rotors with lobes rotating in opposite direction in an air tight casing with has inlet and outlet ports. The lobes of the rotors are of cycloidal or involute form because this ensure correct mating between lobes. As the rotors rotate, the air at atmospheric pressure is trapped between the lobes and casing.

The rotary motion of lobes delivers the air to the receiver. Therefore, pressure goes on increasing with the addition of more and more air into the receiver. Finally, air is delivered from receiver at a high pressure.

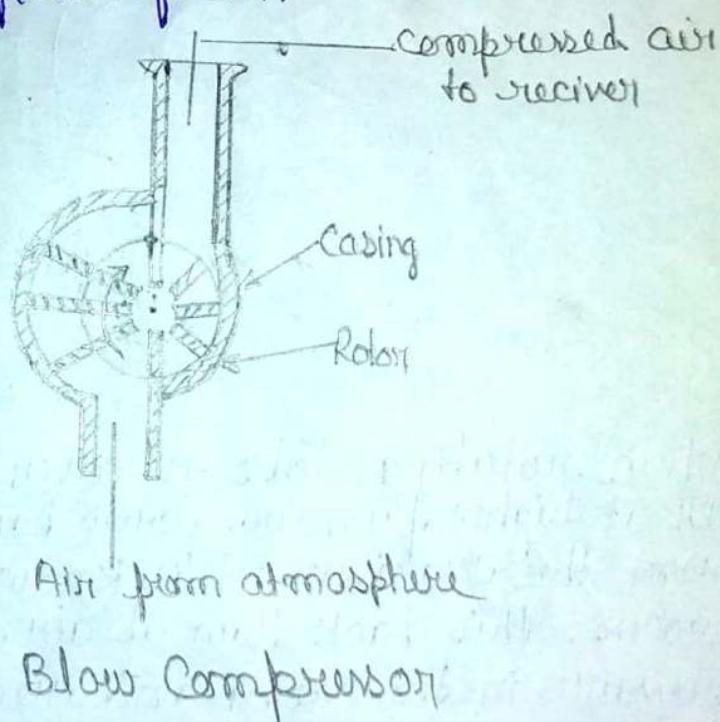


Roots Blower with two lobes

When rotating, lobes uncover the exist port, some air at higher pressure flows back into the casing from the receiver. It is known as backflow process. This back flow of air continues till the pressure in the casing and receiver is equalised.

2. Vane Blower Compressor:- A vane type compressor consists of a motor or disc rotating eccentrically in an tight casing with inlet and outlet ports. The disc has a number of slots containing vane which are made of non-metallic material, usually, fibre or carbon. When the motor rotates the disc, the vanes are pressed against casing, due to centrifugal force and from air tight sockets.

Disc is rotated with the help of some external source which on rotation traps the air between vanes and casing. First of all, the rotary motion of vanes compresses the air. When the rotating vanes uncover the exit port, some air under pressure flows back into the casting. This process is same as that in case of roots blower. Therefore the pressure of air entrapped in the casting is increased by decreasing the volume and after that by the back flow of air.



Vane Blow Compressor

The air under pressure is delivered to the receiver. When the air pressure become high, it is delivered from the receiver to the required place.

Dynamic Compressors

1. Centrifugal Compressor :- A centrifugal compressor consists of the following components:

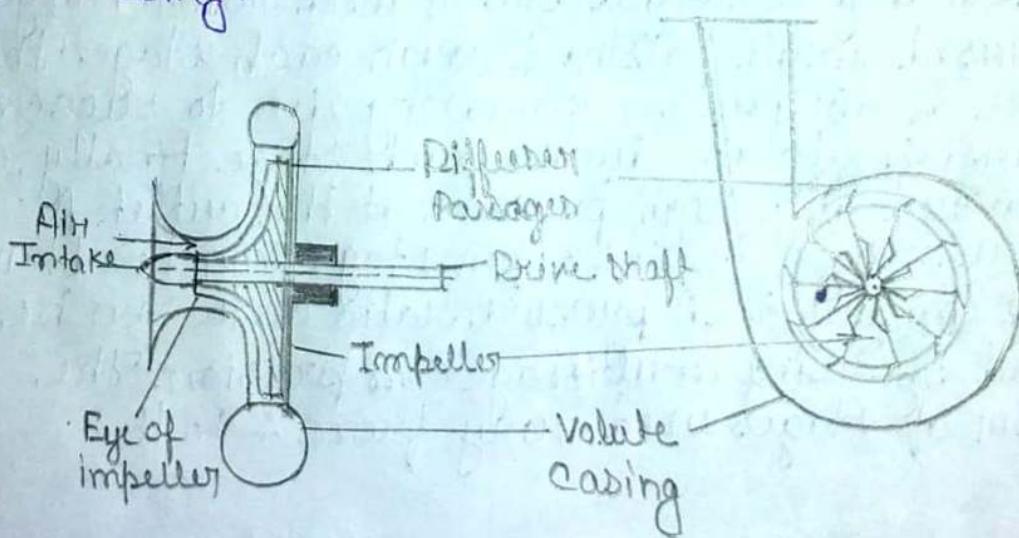
- (i) Series of inlet buckets,
- (ii) Impeller,
- (iii) Casing,
- (iv) Diffuser,

(i) Series of inlet buckets : These buckets are attached to the shaft.

(ii) Impeller :- Impeller is a disc fitted with radial vanes. Air is supplied to these vanes by the inlet buckets.

(iii) Casing :- Casing surrounds the rotating impeller.

(iv) Diffuser :- Diffuser is housed in radial position of the casing.



Centrifugal Compressor

Working :- Air enters the eye of the impeller at mean radius with low velocity and at atmospheric pressure. Depending upon the centrifugal action of the impeller, the air moves radially outwards. The impeller transfers the energy of the

drive to the air causing increases in pressure, temp. and velocity. This air now enters the diverging passage called diffuser where it slows down. The kinetic energy is converted into the pressure energy causing further increase in pressure. It should be noted that half of the total increase in pressure is usually achieved in the impeller and the other half in the diffuser.

2. Axial flow Compressor:- In an axial Compressor, air flows parallel to the axis. An axial compressor consists of a number of rotating blades fixed on a rotating drum and stator blades fixed on casing. Each stage consists of one moving row of blades and one fixed row of blades. The air on entering the compressor flows through the alternately arranged stator and rotor. Air gets compressed while passing through each stage. Thus pressure of air goes on increasing due to successive compression of air during each stage. Finally, air is delivered at a high pressure at the outlet. A pressure ratio of 1.2 to 1.3 per stage can be obtained by this compression. A pressure ratio of 10 can be obtained by using multistage compression. The number of stages used vary from 4 to 16.

