

THERMAL ENGINEERING -I

TH-4

3th SEM

MECHANICAL ENGG.

Under SCTE&VT,Odisha

PREPARED BY



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THERMAL ENGG-I

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MECHANICAL ENGINEERING

DIPLOMA

Ch-1: THERMODYNAMIC CONCEPT & TERMINOLOGY

1.1 Thermodynamics :-

It is defined as the science of heat energy transfer and its effect on physical property of the substance.

OR

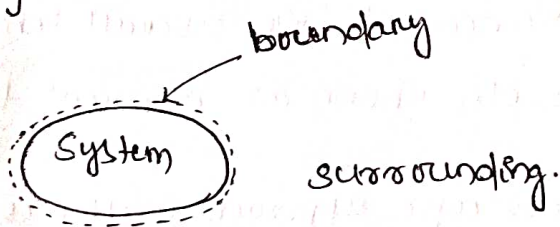
It may be defined as the science which deals with the conversion of heat into mechanical work or energy by using a suitable medium.

1.2 Thermodynamic System :-

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

Surrounding :- Anything external to the system constitute as surrounding.

Boundary :- System is separated from the surrounding by system boundary.



→ Systems are classified into 3 types.

- Open System
- Closed system
- Isolated system.

#) Closed System :- It is also known as non-flow system. In this system the mass within the boundary remains constant, only energy interaction takes place with respect to the surroundings.

Ex: Cylinder piston arrangement, Tea Kettle

#) Open system :- It is also known as flow system. Open system is one in which both mass & energy crosses the boundary. Open system is also called control volume.

Ex: Reciprocating air compressor, turbine, pump etc.

#) Isolated system :- An isolated system is one in which there is no interaction between the system and surrounding. There is no mass & energy transfer across the system.

Ex: Universe, thermoflask etc.

1.3 Macroscopic And Microscopic approach:-

Study of the thermodynamics is done by two different approaches.

#) Macroscopic approach :- The term macroscopic is used in regard to larger units which is visible to the naked eye. In this approach certain quantity of matter is considered without taking into consideration the events occurring at molecular level. In other words macroscopic approach is concerned with overall behaviour of matter. This type of study is also known as classical thermodynamics.

#) Microscopic approach :- In microscopic approach matter is considered to be composed of tiny particles called molecules & study of each particle having a certain position, velocity & energy at a given instant is considered, such a study is also called statistical thermodynamics.

1.4 Thermodynamic Property :-

A thermodynamic property refers to the characteristics by which the physical condition or state of a system can be described such as pressure, volume, temperature etc. & such characteristics are called properties of a system.

1.4.1 Intensive & Extensive Property:

#) Intensive property: The properties which are independent of mass on the size of the system are known as intensive properties. Its value remains the same whether one considers the whole system or only a part of it.

Ex: Pressure, Temperature, density, specific energy, specific volume, specific density etc.

#) Extensive property: The property which depends upon mass of the system or upon the size of the system are known as extensive property.

Ex: Volume, energy, enthalpy, entropy etc.

1.5 Thermodynamic State:

The condition of physical existence of a system at any instant of time is called state. It is defined as a unique set of values of all thermodynamic properties. Even if one thermodynamic property changes, it becomes a new state.

1.6 Thermodynamic Processes: \Rightarrow

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

The commonly used processes are:

1. Isochoric process: The process which takes place at constant volume.
2. Isobaric process: The process which takes place at constant pressure.
3. Isothermal process: The process which takes place at constant temperature.
4. Adiabatic process: The process where there is no heat transfer between the system and the surroundings. The reversible adiabatic process is known as isentropic process.

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

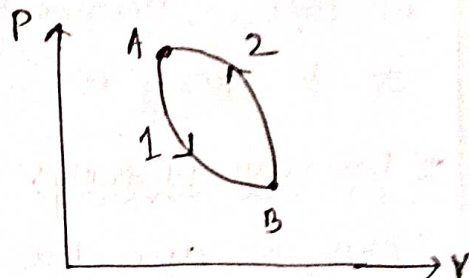
1.7 Thermodynamic Cycle :-

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

In the given fig;

↳ A-1-B & A-2-B represents process

↳ A-1-B-2-A represents thermodynamic cycle.



1.8 Thermodynamic Equilibrium :-

A system is said to be in thermodynamic equilibrium when no change in any macroscopic property is registered, if the system is isolated from its surroundings. A system will be said to be in thermodynamic equilibrium if the following three conditions of equilibrium is satisfied.

a) Mechanical equilibrium \Rightarrow When there is no unbalanced force on any part of the system or in-between the system and surroundings then the system is said to be in mechanical equilibrium.

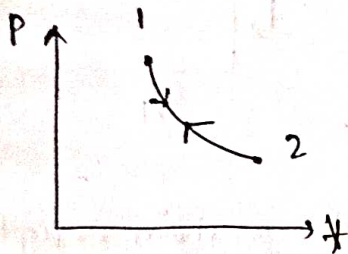
b) Chemical equilibrium \Rightarrow When there is no chemical ~~and~~ reaction or transfer of matter from one part of the system to another such as diffusion or solution, then the system is said to exist in a state of chemical equilibrium.

c) Thermal equilibrium \Rightarrow When there is no temperature difference between the parts of the system or between the system and the surroundings, it is then said to be in thermal equilibrium.

1.9 Reversible Process \Rightarrow

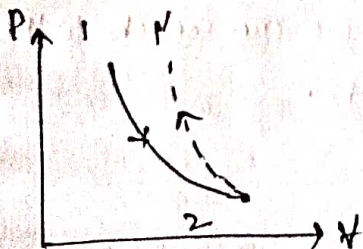
A process which can be reversed in direction and the system retraces the same continuous series of equilibrium states, is said to be reversible process. A reversible process should be carried out with absolute slowness, so that the system will be always in equilibrium. In actual practice a reversible process can not be attained, but it can be approximated as closely as possible.

Ex: A gas confined in a cylinder with a well lubricated piston can be made to undergo a reversible process by pushing or pulling the piston in slow motion.



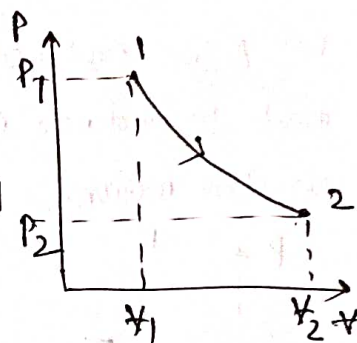
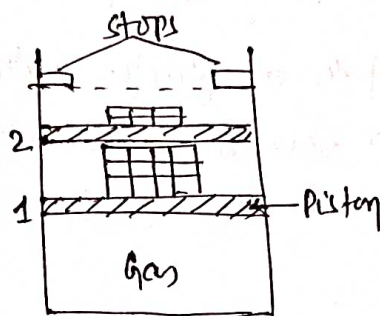
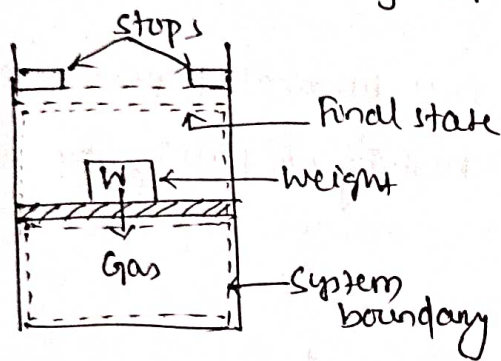
Irreversible Process \Rightarrow

A process in which the system passes through a sequence of non-equilibrium states i.e. the property such as pressure, volume, temperature is not uniform throughout the system, is known as an irreversible process. This process will not retrace the reverse path to restore the original state. The heat transfer by convection, combustion of air & fuel etc are few examples of irreversible process.



1.10 Quasi Static Process \Rightarrow

The word *quasi* means almost. This process is a succession of equilibrium states and infinitesimal slowness is the characteristic feature of quasi-static process. A quasi-static process is also called as reversible process, the basic difference is that in a quasi static process not all the point but almost major points is in equilibrium condition.



(Fig 1)

Let us consider a system of gas contained in a cylinder as shown in fig 1. The system is initially in equilibrium state. The weight W on the piston just balances the upward force exerted by the gas. If the weight is removed there will be an unbalanced force between the system & the surroundings. & the piston will move upward till it hits the stops, the system will be again in a equilibrium state. But it is not a quasi-static process. But if the same process as shown in fig 2 is done by slowly removing very small pieces of weight one by one then the piston will move upward slowly thus the system will be in equilibrium. Through such series of equilibrium processes, we can reach to the state point 2. It is called quasi-static process.

1.7 ENERGY:

It is defined as the capacity of doing work. In other words, a system is said to possess energy when it is capable of doing work. It is of 2 types

(1) Stored energy: The energy possessed by a system within its boundaries.
Ex: Potential energy, Kinetic energy, Internal energy.

(2) Transit energy: It is the energy possessed by a system which is capable of crossing its boundaries.
Ex: heat, work, electrical energy.

- Note** →
- The stored energy is a thermodynamic property.
 - The transit energy is not a thermodynamic property as it depends upon the path.

1.7.1 Types of stored energy

(1) Potential Energy: (PE)

It is the energy possessed by a system or a body for doing work, by virtue of its position above the ground level.

$$PE = m g z$$

$$PE = \left(\text{kg} \times \frac{\text{m}}{\text{s}^2} \right) \times \text{m}$$

$$PE = \text{N} \times \text{m} = \text{J}$$

where $m = \text{mass of body (kg)}$

$g = \text{accel}^n \text{ due to gravity (m/s}^2\text{)}$

$z = \text{distance from the ground level (m)}$

(2) Kinetic Energy: (KE)

It is the energy possessed by a body or a system for doing work, by virtue of its mass & velocity of motion.

$$KE = \frac{1}{2} m v^2$$

$$KE = \text{kg} \times \frac{\text{m}^2}{\text{s}^2} = \left(\text{kg} \times \frac{\text{m}}{\text{s}^2} \right) \times \text{m} = \text{N} \times \text{m} = \text{J}$$

where $m = \text{mass of the body (kg)}$

$v = \text{velocity of the body (m/s)}$

(3) Internal Energy: (IE)

It is the energy posed by a body or a system due to its molecular arrangement and motion of the molecules. It is denoted by U .

NOTE (1) The total energy of the body or system is equal to the sum of the above types of energies.

$$E = PE + KE + U = mgz + \frac{1}{2}mv^2 + U$$

for unit mass $\rightarrow \frac{E}{m} = \frac{mgz}{m} + \frac{\frac{1}{2}mv^2}{m} + \frac{U}{m}$

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

(2) When the system is stationary & the effect of gravity neglected the $PE = 0$ & $KE = 0$. In such a case.

$$\boxed{E = U} \longrightarrow \text{for unit mass } \boxed{e = u}$$

1.8 HEAT

- The heat is defined as the energy transferred, without transfer of mass, across the boundary of a system because of a temperature difference between the system & surroundings.
- It is represented by Q
- Unit: Joule (J) or Kilo-Joule (kJ)

NOTE (1) The heat is transferred across the boundary from a system at a higher temp. to a system at lower temp. by virtue of the temp. difference.

(2) The heat is a form of transit energy which can be identified only when it crosses the boundary of a system.

Specific heat: The amount of heat required to raise the temperature of a unit mass of any substance through one degree.

• It is denoted as c

• Unit: $\frac{kJ}{kg K}$

• If m kg of a substance of specific heat c is required to raise the temperature from an initial temp of T_1 to final temp of T_2

then $\boxed{\text{Heat required } (Q) = m c \Delta T \text{ KJ}}$

$\rightarrow Q = m c (T_2 - T_1)$

• Specific heat of solid or liquid do not change the volume on heating. So they have only one specific heat.

• But gas has two specific heats depending upon the process adopted for heating the gas.

1. Specific heat at constant pressure (C_p)

2. Specific heat at constant volume (C_v)

1.9 WORK

In mechanics, work is defined as the product of force (F) & the distance moved (m) in direction of the force.

$\boxed{W = F \times d}$

$= N \cdot m$

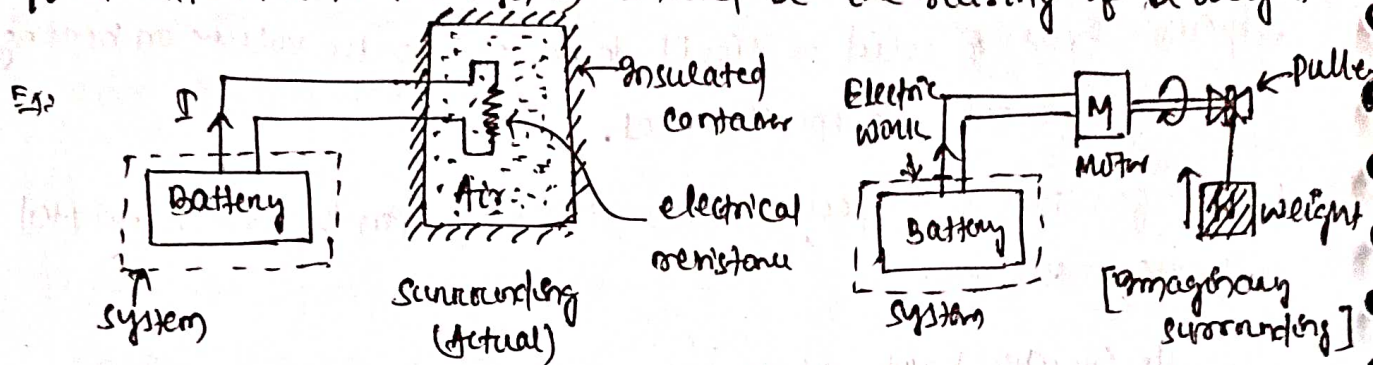
$\boxed{W = J}$ \rightarrow unit of work

In thermodynamics, work may be defined as follows.

(1) According to Iobert, work is defined as the energy transferred (without transfer of mass) across the boundary of a system because of an intensive property difference other than temperature that exist between the system & surroundings.

But in engineering practice, the intensive property difference is the pressure difference. The pressure difference (betn the system & the surrounding) at the surface of the system gives rise to a force and the action of this force over a distance is called mechanical work.

2) According to Keenan, work is said to be done by a system during a given operation if the sole effect of the system on things external to the system (surroundings) can be reduced to the raising of a weight. The weight may not be actually raised but the net effect external to the system should be the raising of a weight.



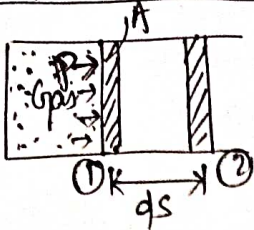
1.10 Equivalence of work & heat

Joule said that heat & work are mutually convertible into each other.

There are many similarities between heat & work. These are

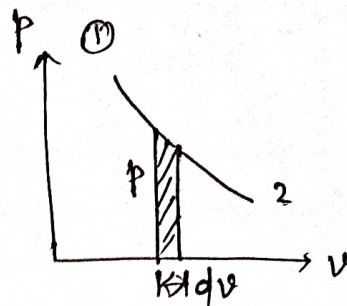
- 1) They both represent the form of energy.
- 2) They both represent the energy in transit. The system doesn't possess heat or work. When a system undergoes a change, heat transfer & work transfer may occur.
- 3) They both are path functions & hence process dependent.
- 4) They are ~~an~~ exact differentials. They are written as δQ & δW .
- 5) They both are boundary phenomenon. They are observed at the boundary of the system.

1.9 Displacement Work:



$\delta W = F \cdot ds$
 $\rightarrow \delta W = (P \cdot A) ds$
 $\rightarrow \delta W = P(A ds)$
 $\rightarrow \delta W = PdV$

$\delta W = PdV$
 $= \text{Area under } pV \text{ diagram}$



$\Rightarrow \delta W = PdV \Rightarrow W = \int PdV$

$\Rightarrow \delta W = PdV = \text{Area under } pV \text{ diag}$

$\rightarrow \frac{\delta W}{m} = \frac{PdV}{m}$

① closed system

$\rightarrow \delta W = PdV$

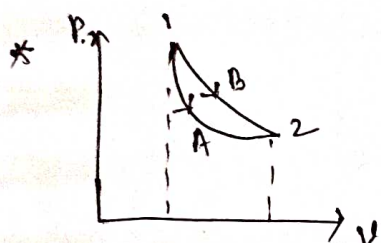
② Quasi-static process

Exact differential

~~System property~~

Ex: $\int du = u_2 - u_1$

$\int_1^2 dV = V_2 - V_1$



Work done = Area under pV diag

so $(W)_{1 \rightarrow A \rightarrow 2} < (W)_{1 \rightarrow B \rightarrow 2}$

\rightarrow Work done depends on path

\rightarrow work is a path function.

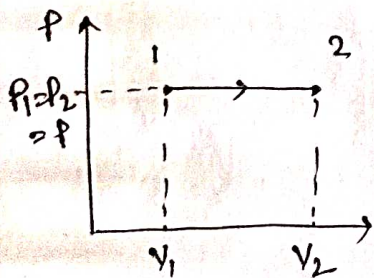
\rightarrow work can't be exact differential.

$W = \int \delta W \neq w_2 - w_1$

Example:

\Rightarrow Displacement work applied to different thermodynamic process.

⊗ Isobaric process / constant pressure process



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

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

$W_{1-2} = P(V_2 - V_1)$

Ch-2: PROPERTIES OF PERFECT GAS

2.1 Laws of Perfect gas:

Normally the physical properties of a gas are controlled by three variables

- 1) Pressure exerted by gas
- 2) Volume occupied by the gas
- 3) Temperature of the gas.

The behaviour of a perfect gas, undergoing any change in the above mentioned variables, is governed by the following laws

- 1) Boyle's Law
- 2) Charles's Law
- 3) Gay-Lussac Law

2.1.1 Boyle's Law: Given by Robert Boyle in 1662.

Defⁿ \Rightarrow "The absolute pressure of a given mass of a perfect gas varies inversely as its volume, when the temperature remains constant."

Mathematically,

$$P \propto \frac{1}{V} \Rightarrow PV = \text{constant}$$

$$\Rightarrow P_1 V_1 = P_2 V_2 = P_3 V_3 = \dots = \text{constant}$$

2.1.2 Charles's Law: Given by a Frenchman Jacques A.C. Charles in 1787.

Defⁿ \Rightarrow "The volume of a given mass of a perfect gas varies directly as its temperature, when the absolute pressure remains constant."

Mathematically,

$$V \propto T \Rightarrow \frac{V}{T} = \text{constant}$$

$$\Rightarrow \frac{V_1}{T_1} = \frac{V_2}{T_2} = \frac{V_3}{T_3} = \dots = \text{constant}$$

2.1.3 Gay-Lussac Law:

Defⁿ \Rightarrow "The absolute pressure of a given mass of a perfect gas varies directly as its absolute temperature, when the volume remains constant."

Mathematically,

$$P \propto T \Rightarrow \frac{P}{T} = \text{constant}$$

$$\Rightarrow \frac{P_1}{T_1} = \frac{P_2}{T_2} = \frac{P_3}{T_3} = \dots = \text{constant}$$

Q.2 a General Gas Equation:

→ In above section we have discussed the gas laws which give us the relation between the two variables when the third variable is constant.

→ But in actual practice, all the three variables i.e. pressure, volume & temperature change simultaneously. In order to deal with all practical cases, the Boyle's law & Charles's law are combined together, which give us a general gas equation.

→ We know that; $P \propto \frac{1}{V}$ } [Boyle's law, $T = \text{constant}$]
 $\Rightarrow V \propto \frac{1}{P}$ — (i)

$V \propto T$ — (ii) [Charles's law, $P = \text{constant}$]

from (i) & (ii); $V \propto \frac{T}{P}$

$$\Rightarrow \boxed{PV \propto T} \Rightarrow \boxed{PV = CT}$$

where C is a constant & its value depend upon the mass & properties of the gas concerned.

$$\Rightarrow PV = CT$$

$$\Rightarrow \frac{PV}{T} = C$$

$$\Rightarrow \frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2} = \frac{P_3 V_3}{T_3} = \dots = \text{constant.}$$

Q.2.11 A gas occupies a volume of 0.1 m^3 at a temperature of 20°C & a pressure of 1.5 bar . Find the temperature of the gas, if it is compressed to a pressure of 7.5 bar and occupies a volume of 0.04 m^3 .

Sol: Given $P_1 = 1.5 \text{ bar}$

$$V_1 = 0.1 \text{ m}^3$$

$$T_1 = 20^\circ\text{C} = 20 + 273 = 293 \text{ K}$$

$$P_2 = 7.5 \text{ bar}$$

$$V_2 = 0.04 \text{ m}^3$$

$$T_2 = ?$$

$$\text{Gas} \Rightarrow \frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2} \Rightarrow \frac{T_2}{T_1} = \frac{P_2 V_2}{P_1 V_1} \Rightarrow \frac{T_2}{293} = \frac{7.5 \times 0.04}{1.5 \times 0.1}$$

$$\Rightarrow T_2 = 586 \text{ K}$$

$$\Rightarrow T_2 = 586 - 273 = 313^\circ\text{C} \quad (\text{Ans})$$

2.3: Joule's Law:

Def: "The change in internal energy of a perfect gas is directly proportional to the change in temperature."

Mathematically; $dU \propto dT \Rightarrow dU = m c dT \Rightarrow \boxed{dU = m c (T_2 - T_1)}$

where $m =$ mass of the gas

$c =$ A proportionality constant
 $=$ specific heat constant.

2.4: Characteristic Equation of Gas \Rightarrow

It is a modified form of general gas equation.

We know that $PV \propto T \Rightarrow PV = CT$

Now divide both side with mass $= m$ kg

$\Rightarrow \frac{PV}{m} = \frac{CT}{m} \Rightarrow P\left(\frac{V}{m}\right) = \left(\frac{C}{m}\right)T \Rightarrow P\frac{V}{m} = RT$ where $R = \frac{C}{m} = \text{const.}$

\square Another gas const.

$\Rightarrow P\frac{V}{m} = RT$

$\Rightarrow \boxed{PV = mRT}$

where $R =$ characteristic gas constant or simply gas constant.

This is called "characteristic gas eqn"

"ideal gas equation"

Unit: $PV = mRT \Rightarrow R = \frac{PV}{mT}$
 $\Rightarrow R = \frac{\frac{N}{m^2} \times m^3}{kg \times K} = \frac{Nm}{kg K} = \frac{J}{kg K}$

Ex: Air \rightarrow ideal gas

$(R)_{Air} = 0.287 \frac{kJ}{kg K} = 287 \frac{J}{kg K}$

2.5: Universal gas constant or Molar Constant \vdash

It is defined as the product of the gas constant of the molecular mass of the gas.

Mathematically

$\boxed{R_u = MR}$

where $M =$ molecular mass

$R =$ characteristic gas const.

Qm general $PV = mRT$ where $m = \text{mass of gas}$

$$m = \frac{nM}{M}$$

where $n = \text{no of kg moles}$
 $M = \text{molecular mass of the gas.}$

$$\Rightarrow PV = nMRT$$

$$\Rightarrow PV = n(MR)T$$

$$\Rightarrow PV = nR_u T$$

[from experiment, we find that the value of R_u is same for all gases. i.e. $R_u = 8.314 \frac{kJ}{kgK}$]

Q-11) A gas occupies a volume of 0.1 m^3 at a temperature of 20°C & a pressure of 1.5 bar . Find the final temperature of the gas, if it is compressed to a pressure of 7.5 bar and occupies a volume of 0.04 m^3 .

Sol: Given $V_1 = 0.1 \text{ m}^3$

$$V_2 = 0.04 \text{ m}^3$$

$$T_1 = 20^\circ\text{C} = 20 + 273 = 293 \text{ K}$$

$$T_2 = ?$$

$$P_1 = 1.5 \text{ bar}$$

$$P_2 = 7.5 \text{ bar}$$

We know $PV = nRT \Rightarrow \frac{PV}{T} = nR \Rightarrow \frac{PV}{T} = \text{const.}$

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

$$\Rightarrow T_2 = \frac{7.5 \text{ bar} \times 0.04 \text{ m}^3}{1.5 \text{ bar} \times 0.1 \text{ m}^3} \times 293 \text{ K}$$

$$\Rightarrow T_2 = 566 \text{ K}$$

$$\Rightarrow T_2 = 566 - 273 = 313^\circ\text{C}$$

Am

Q.21) A vessel of capacity 3 m^3 contains air at a pressure of 1.5 bar and a temperature of 25°C . Additional air is now pumped into the system until the pressure rises to 30 bar & temperature rises to 60°C . Determine the mass of air pumped in and express the quantity as a volume at a pressure of 1.02 bar & a temperature of 20°C .

Given data:

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

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

$P_1 = 1.5 \text{ bar}$

$P_2 = 30 \text{ bar}$

$T_1 = 25^\circ\text{C}$
 $= 25 + 273 = 298 \text{ K}$

$T_2 = 60^\circ\text{C}$
 $= 60 + 273 = 333 \text{ K}$

$m_1 = ?$

$m_2 = ?$

- mass of air pumped in = ?
- express it in terms of
- $P_3 = 1.02 \text{ bar}$
- $T_3 = 20^\circ\text{C}$
 $= 20 + 273 = 293 \text{ K}$

(1) Mass of air pumped in = $m_2 - m_1$

m_1 \Rightarrow We know $P_1 V_1 = m_1 R_1 T_1$

$$\Rightarrow m_1 = \frac{P_1 V_1}{R_1 T_1} = \frac{1.5 \text{ bar} \times 3 \text{ m}^3}{0.287 \frac{\text{kJ}}{\text{kgK}} \times 298 \text{ K}} = \frac{1.5 \times 10^5 \frac{\text{N}}{\text{m}^2} \times 3 \text{ m}^3}{287 \frac{\text{J}}{\text{kgK}} \times 298 \text{ K}}$$

$$\Rightarrow m_1 = \frac{1.5 \times 10^5 \times 3 \text{ J}}{287 \frac{\text{J}}{\text{kg}} \times 298} = \frac{1.5 \times 10^5 \times 3}{287 \times 298} \text{ kg}$$

$\Rightarrow m_1 = 5.26 \text{ kg}$

m_2 \Rightarrow we know $P_2 V_2 = m_2 R_2 T_2$

$$\Rightarrow m_2 = \frac{P_2 V_2}{R_2 T_2} = \frac{30 \times 10^5 \frac{\text{N}}{\text{m}^2} \times 3 \text{ m}^3}{287 \frac{\text{J}}{\text{kgK}} \times 333 \text{ K}} = \frac{30 \times 10^5 \times 3 \text{ J}}{287 \frac{\text{J}}{\text{kg}} \times 333}$$

$\Rightarrow m_2 = 94.17 \text{ kg}$

Now mass of air pumped in = $m_2 - m_1$

$= 94.17 - 5.26 = 88.91 \text{ kg}$

Ans

• Volume of air pumped in at pressure 1.02 bar & temp of 20°C

let $V_3 = \text{Vol. of air pumped}$

$$P_3 V_3 = m_3 R_3 T_3 \Rightarrow V_3 = \frac{m_3 R_3 T_3}{P_3} = \frac{88.91 \text{ kg} \times \frac{287 \text{ J}}{\text{kg K}} \times 293 \text{ K}}{1.02 \times 10^5 \frac{\text{N}}{\text{m}^2}}$$

$$\Rightarrow V_3 = \frac{88.91 \times 287 \times 293}{1.02 \times 10^5} \frac{\text{N} \cdot \text{m}}{\text{m}^2} = 73.3 \text{ m}^3$$

$$\Rightarrow V_3 = 73.3 \text{ m}^3$$

Q2311 A mass of 2.25 kg of nitrogen occupying 1.5 m^3 is heated from 25°C to 200°C at a constant volume. Calculate the initial & final pressure of the gas. Take universal gas constant as $8314 \frac{\text{J}}{\text{kg mol K}}$. The molecular mass of nitrogen is 28 .

Soln: Given: $m_{\text{Nitro}} = 2.25 \text{ kg}$

$$V_1 = 1.5 \text{ m}^3$$

$$T_1 = 25^\circ\text{C} \\ = 25 + 273 = 298 \text{ K}$$

$$P_1 = ?$$

$$V_2 = 1.5 \text{ m}^3$$

$$T_2 = 200^\circ\text{C} \\ = 200 + 273 = 473 \text{ K}$$

$$P_2 = ?$$

$$R_u = 8314 \frac{\text{J}}{\text{kg mol K}}$$

$$M_{\text{Nitro}} = 28$$

$$\text{We know } R_{\text{Nitro}} = \frac{R_u}{M_{\text{Nitro}}} = \frac{8314}{28} = 297 \frac{\text{J}}{\text{kg K}}$$

Initial pressure; $P_1 = ?$

$$\text{We know } P_1 V_1 = m_1 R_1 T_1$$

$$\Rightarrow P_1 = \frac{m_1 R_1 T_1}{V_1}$$

$$P_1 = \frac{2.25 \times 297 \times 298}{1.5 \text{ m}^3}$$

$$\Rightarrow P_1 = \frac{2.25 \times 297 \times 298 \text{ N} \cdot \text{m}}{1.5 \text{ m}^3} = 1.33 \times 10^5 \frac{\text{N}}{\text{m}^2}$$

$$\Rightarrow \boxed{P_1 = 1.33 \text{ bar}}$$

Final Press, $P_2 = ?$

$$\text{We know } P_2 V_2 = m_2 R_2 T_2$$

$$\Rightarrow \frac{P_2 V_2}{m_2 R_2} = T_2$$

$$\therefore P_2 \propto T_2$$

$$\Rightarrow \frac{P_2}{T_2} = \frac{P_1}{T_1}$$

$$\Rightarrow P_2 = P_1 \left(\frac{T_2}{T_1} \right) = 1.33 \times \left(\frac{473}{298} \right)$$

$$\Rightarrow \boxed{P_2 = 2.11 \text{ bar}}$$

(Ans)

Ch-3: THE FIRST LAW OF THERMODYNAMICS :-

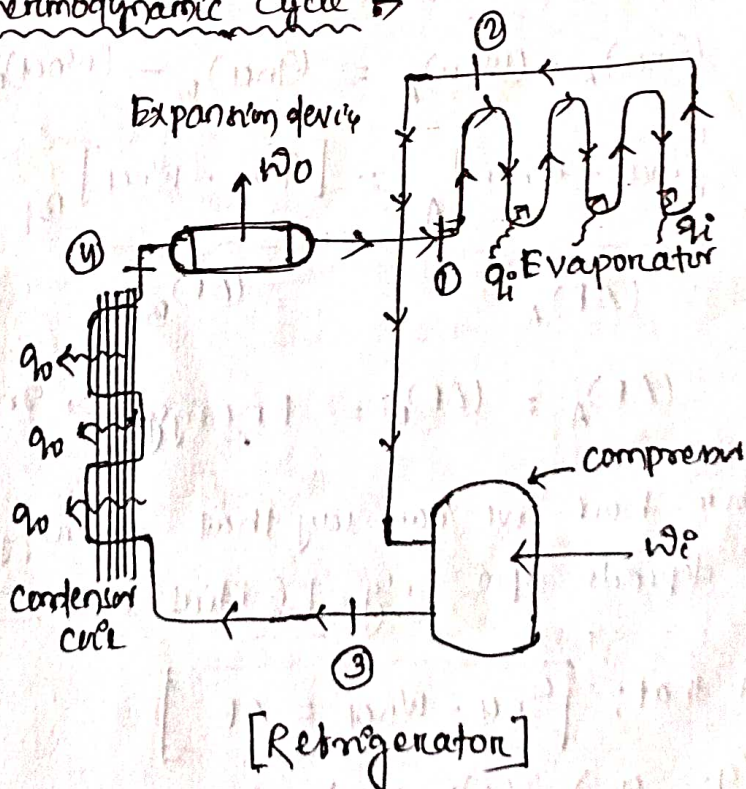
- Heat & work are the different forms of the Energy. Energy is always conserved. Energy may enter a system as heat & leaves as work and vice-versa.
- Energy has two forms: transit energy & stored energy.
- The internal energy is the stored energy. Whenever heat & work enters a system, stored energy increases & when heat & work leaves the system stored energy decreases.
- 1st law of TD can be stated as
 - "The heat & work are mutually convertible."
 - "The energy can neither be created nor destroyed though it can be transformed from one form to another."

Q.1 First law for Thermodynamic Cycle :-

1-2-3-4-1
 Incoming = Outgoing
 → आया = गया

$$\oint (q + w) = 0$$

 1st law of TD



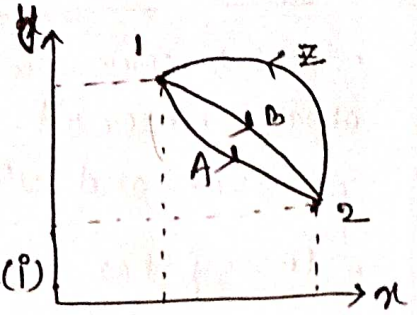
3.2 First Law of thermodynamic for a process :-

x & y are two independent properties.

$1 \rightarrow A \rightarrow 2 \rightarrow Z \rightarrow 1 \Rightarrow$ cycle

$$\Rightarrow \oint (q_i + u_i) = \oint (q_o + u_o)$$

$$\Rightarrow q_{iA} + u_{iA} + q_{iZ} + u_{iZ} = q_{oA} + u_{oA} + q_{oZ} + u_{oZ} \quad \text{--- (i)}$$



$1 \rightarrow B \rightarrow 2 \rightarrow Z \rightarrow 1 \Rightarrow$ cycle

$$\Rightarrow \oint (q_i + u_i) = \oint (q_o + u_o)$$

$$\Rightarrow q_{iB} + u_{iB} + q_{iZ} + u_{iZ} = q_{oB} + u_{oB} + q_{oZ} + u_{oZ} \quad \text{--- (ii)}$$

Now eqn (i) - eqn (ii) $\Rightarrow q_{iA} + u_{iA} - q_{iB} - u_{iB} = q_{oA} + u_{oA} - q_{oB} - u_{oB}$

$$\Rightarrow (q_{iA} - q_{oA}) + (u_{iA} - u_{oA}) = (q_{iB} - q_{oB}) + (u_{iB} - u_{oB})$$

$$\Rightarrow \underbrace{(q_{iA} - q_{oA})}_{\Delta Q_A} - \underbrace{(u_{oA} - u_{iA})}_{\Delta U_A} = \underbrace{(q_{iB} - q_{oB})}_{\Delta Q_B} - \underbrace{(u_{oB} - u_{iB})}_{\Delta U_B}$$

$$\Rightarrow (q_{net})_A - (u_{net})_A = (q_{net})_B - (u_{net})_B$$

$$\Rightarrow \underbrace{[q_{net} - u_{net}]_A}_{(\Delta E)_A} = \underbrace{[q_{net} - u_{net}]_B}_{(\Delta E)_B}$$

$\Rightarrow (\Delta E)_A = (\Delta E)_B = \text{Energy} \Rightarrow$ intrinsic energy of the system.

From here we can say that "energy" is independent of path.

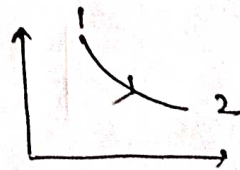
It depends upon only [initial state, final state]. So it's a property.

\hookrightarrow We got that; $\boxed{q_{net} - u_{net} = \Delta E}$

$$\Rightarrow (q_{i1} - q_{o1}) - (u_{o1} - u_{i1}) = E_2 - E_1$$

$$\Rightarrow q_{i1} - q_{o1} - u_{o1} + u_{i1} = E_2 - E_1$$

$$\Rightarrow \boxed{\underbrace{q_i + u_i}_{\text{अवस्था}} = \underbrace{E_2 - E_1}_{\text{अवस्था}} + \underbrace{q_o + u_o}_{\text{अवस्था}}}$$



3.3 Enthalpy Concept:

- Enthalpy is a state property of a system. It is denoted by

$$H = U + PV$$

- It is a point function & an extensive property.
- But specific enthalpy is an intensive property.

$$\text{i.e. } h = \frac{H}{m} = \frac{U + PV}{m} = \frac{U}{m} + P \frac{V}{m} = u + Pv$$

$$\therefore h = u + Pv$$

3.4 Relation between $C_p, C_v, \gamma, \beta R$:

From the 1st law of Thermodynamics

$$q_{\text{net}} - w_{\text{net}} = \Delta E \Rightarrow q_{\text{net}} = \Delta E + w_{\text{net}}$$

for non flow process, $\Delta E = \Delta U$, & $w_{\text{net}} = P\Delta V$

$$q_{\text{net}} = \Delta E + w_{\text{net}}$$

$$\Rightarrow \delta q = \delta u + P\delta v$$

C_v

Constant volume

$$\delta q = \delta u + P\delta v \rightarrow 0$$

$$\Rightarrow (\delta q)_v = (\delta u)_v$$

$$C_v = \left(\frac{\delta q}{\delta T}\right)_v = \left(\frac{\delta u}{\delta T}\right)_v$$

$$C_v = \left(\frac{\partial u}{\partial T}\right)_v$$

C_p

Constant pressure

$$\delta q = \delta u + P\delta v$$

$$\delta q = \delta u + P\delta v + v\delta P - v\delta P \rightarrow 0$$

$$(\delta q)_p = \delta(u + Pv)$$

$$(\delta q)_p = (\delta h)_p$$

$$\text{Now } C_p = \left(\frac{\delta q}{\delta T}\right)_p = \left(\frac{\delta h}{\delta T}\right)_p$$

$$C_p = \left(\frac{\partial h}{\partial T}\right)_p$$

for ideal gas; $u = f(T)$ only & $h = f(T)$ only.

$$\text{So } C_v = \frac{du}{dT} \quad \& \quad C_p = \frac{dh}{dT}$$

(*) Now prove $C_p - C_v = R$

Solⁿ $C_p = \frac{dq}{dT} \Rightarrow C_p = \frac{d(U + PV)}{dT} \Rightarrow C_p = \frac{d(U + RT)}{dT}$

$\Rightarrow C_p = \frac{dU}{dT} + R \frac{dT}{dT} \Rightarrow C_p = C_v + R \Rightarrow \boxed{C_p - C_v = R}$

\therefore We know $R = +ve$ constant for one given gas $\Rightarrow C_p - C_v = +ve$

$\Rightarrow \boxed{C_p > C_v}$

* Adiabatic index (γ) = $\frac{C_p}{C_v}$

$\therefore C_p > C_v \Rightarrow \gamma > 1$

* C_p & C_v in terms of R & γ

$C_p - C_v = R$ & $\frac{C_p}{C_v} = \gamma \Rightarrow C_p = \gamma C_v$

$\hookrightarrow \gamma C_v - C_v = R \Rightarrow C_v(\gamma - 1) = R \Rightarrow \boxed{C_v = \frac{R}{\gamma - 1}}$

Now $C_p = \gamma C_v \Rightarrow \boxed{C_p = \frac{\gamma R}{\gamma - 1}}$

Note \rightarrow for ideal gas ($PV = RT$)

- $\Delta U = C_v \Delta T$
- $\Delta h = C_p \Delta T$

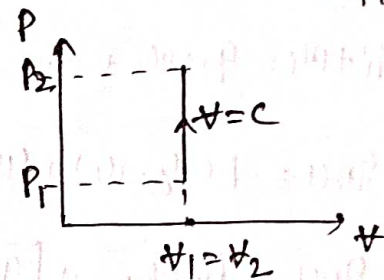
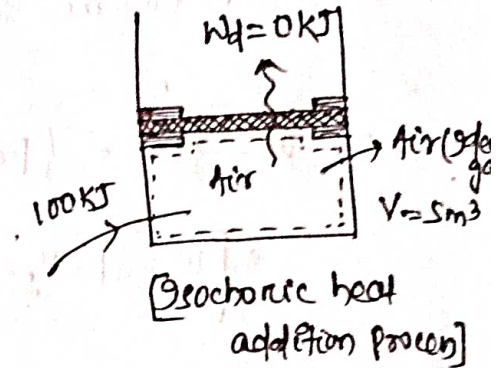
305 Analysis of Non Flow Process \Rightarrow

a) Constant Volume Process [isochoric process] [isometric process]

- Volume remains same ($V = \text{constant}$)
- No work done.

\Rightarrow If we supplied heat;

- \rightarrow Energy increases
- \rightarrow Internal energy increases
- \rightarrow Temperature increases
- \rightarrow Pressure increases
- \rightarrow No displacement of work.



$\Rightarrow w = \int p \, dv = \int p \, dV = 0 \Rightarrow \boxed{w=0} \Rightarrow$ No work done.

$\Rightarrow q_i + w_i = q_o + w_o + \Delta U \Rightarrow q_i - q_o = \Delta U$

$\Rightarrow \boxed{q_{net} = \Delta U}$

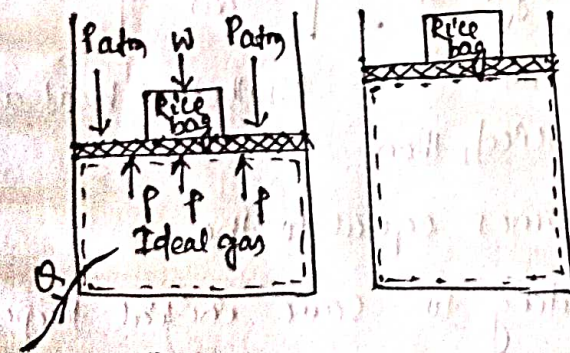
For ideal gas

$q_{net} = \Delta U = C_v \Delta T$

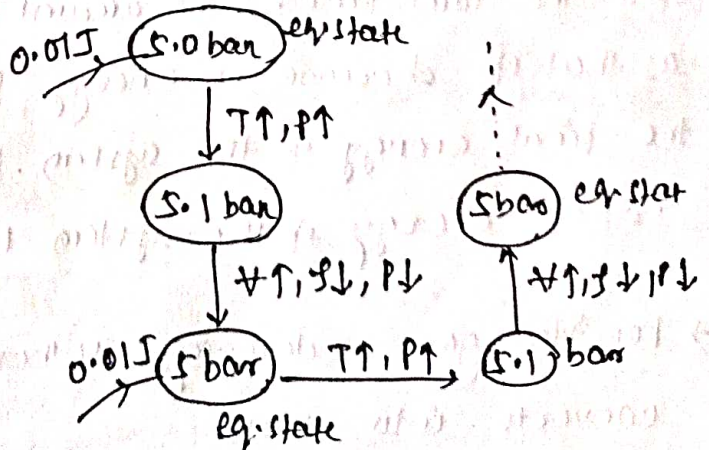
$\Rightarrow \boxed{q_{net} = C_v \Delta T}$

b) Constant Pressure Process \Rightarrow [isobaric process] [isoplestic process]

- Pressure remains constant ($P = \text{const}$)



eg: $P = 5 \text{ bar}$



[Isobaric heat addition process]

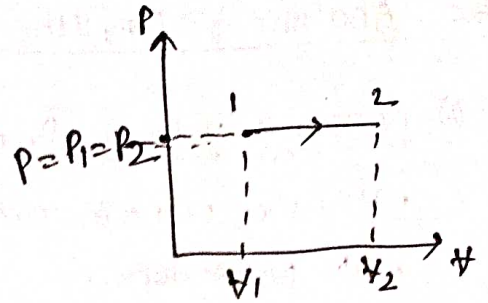
$P_A = P_{atm} \cdot A + W$

$\rightarrow \text{const}$
 $P = P_{atm} + \frac{W}{A} \rightarrow \text{const}$
 $\leftarrow \text{const}$

At every equilibrium state $P = 5 \text{ bar}$.

⇒ Constant pressure heat addition process

- Temperature increases ($T \uparrow$)
- Volume increases ($V \uparrow$)



$$\Rightarrow u = \int \delta u = \int P dv = P \int_1^2 dv = P(V_2 - V_1)$$

$$\Rightarrow \boxed{u = P(V_2 - V_1)}$$

$$\Rightarrow q_2 + u_2 = q_1 + u_1 + \Delta u \Rightarrow q_2 - q_1 = u_2 - u_1 + \Delta u \Rightarrow q_{net} = u_{net} + \Delta u$$

$$\Rightarrow q_{net} = P(V_2 - V_1) + (u_2 - u_1) \Rightarrow q_{net} = (u_2 + PV_2) - (u_1 + PV_1)$$

$$q_{net} = h_2 - h_1 \Rightarrow \boxed{q_{net} = \Delta h}$$

→ Ideal gas, $\Delta h = C_p \Delta T$

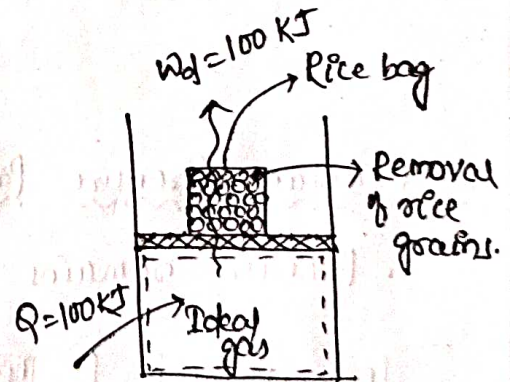
$$\therefore \boxed{q_{net} = C_p \Delta T}$$

Ⓒ Constant Temperature Process ⇒

- Temperature constant ($T = \text{constant}$)

→ On removal of rice grains, work is done by the ideal gas at the expense of energy.

At the same time, same amount of heat as that of decrease in energy supplied, then the total energy of the system becomes equal to the initial energy of the system leading to same critical temperature

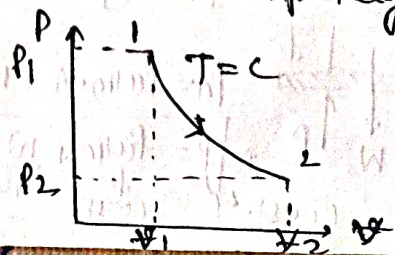


(Isothermal heat addition)

→ For ideal gas undergoing isothermal process heat completely converts into work.

→ Ideal gas undergoing isothermal process

- Volume increases ($V \uparrow$)
- Pressure decreases ($P \downarrow$)



$\Rightarrow w = \int du = \int P du$

for ideal gas; $Pv = RT \Rightarrow P = \frac{RT}{v}$

Now $w = \int P du = \int \frac{RT}{v} du = RT \int \frac{du}{v} = RT [\ln v]_1^2 = RT [\ln v_2 - \ln v_1]$

$w = RT \ln\left(\frac{v_2}{v_1}\right)$

Again $Pv = RT$

for $T = \text{constant} \Rightarrow Pv = c \Rightarrow P_1 v_1 = P_2 v_2 \Rightarrow \frac{v_2}{v_1} = \frac{P_1}{P_2}$

Now $w = RT \ln\left(\frac{v_2}{v_1}\right) = RT \ln\left(\frac{P_1}{P_2}\right)$

$\Rightarrow q = w + \Delta u \rightarrow 0$ [\because for ideal gas, $u = f(T)$ only]

& for isothermal process [$T = \text{const}$]

$q = w$

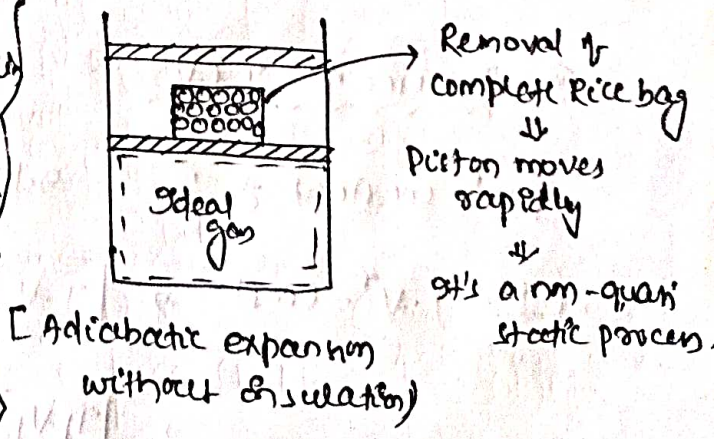
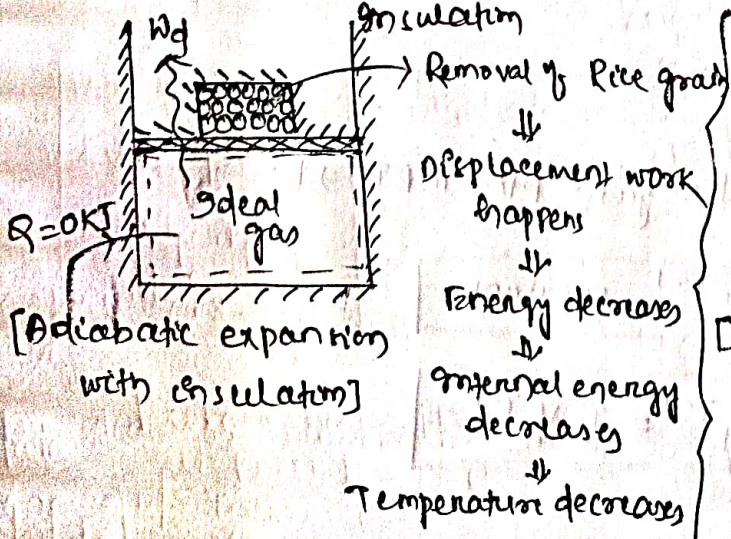
$u = \text{constant}$

$\Delta u = 0$

$q = w = RT \ln\left(\frac{v_2}{v_1}\right) = RT \ln\left(\frac{P_1}{P_2}\right)$

(d) Adiabatic Process:

• No heat interaction ($q = 0$)



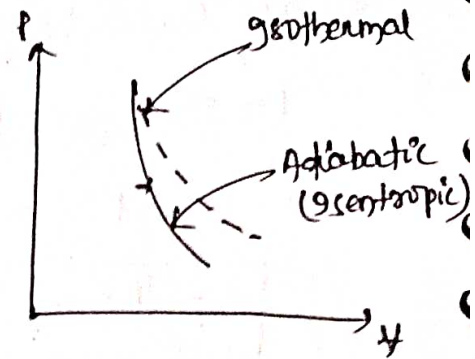
\Rightarrow According to ideal gas eq

$Pv = mRT \Rightarrow P = \frac{mRT}{v}$

$\Rightarrow \uparrow T \Rightarrow P \text{ decreases}$

⇒ Ideal gas undergoing adiabatic process ⇒

- ↳ Volume increases
- ↳ Temperature decreases
- ↳ Pressure decreases.



Various Relation:

For adiabatic process, $PV^\gamma = \text{constant}$

$$\rightarrow P_1 V_1^\gamma = P_2 V_2^\gamma = P_3 V_3^\gamma = \dots$$

⊛ in terms of T & P

$$PV^\gamma = \text{constant}$$

$$\rightarrow P \left(\frac{mRT}{P} \right)^\gamma = \text{const}$$

$$\rightarrow P^{1-\gamma} \cdot T^\gamma = \frac{\text{const}}{m^\gamma R^\gamma} = \text{Constant}$$

ideal gas; $PV = mRT$

$$\rightarrow V = \frac{mRT}{P}$$

$$\rightarrow T^\gamma P^{1-\gamma} = \text{constant}$$

$$\rightarrow T_1^\gamma P_1^{1-\gamma} = T_2^\gamma P_2^{1-\gamma}$$

$$\rightarrow \left(\frac{T_2}{T_1} \right)^\gamma = \left(\frac{P_1}{P_2} \right)^{1-\gamma}$$

$$\rightarrow \left(\frac{T_2}{T_1} \right)^\gamma = \left(\frac{P_2}{P_1} \right)^{\gamma-1}$$

$$\rightarrow \frac{T_2}{T_1} = \left(\frac{P_2}{P_1} \right)^{\frac{\gamma-1}{\gamma}}$$

⊛ in terms of T & V

$$PV^\gamma = \text{constant}$$

ideal gas; $PV = mRT \Rightarrow P = \frac{mRT}{V}$

$$\rightarrow \left(\frac{mRT}{V} \right) \cdot V^\gamma = \text{const}$$

$$\rightarrow TV^{\gamma-1} = \text{constant}$$

$$\rightarrow T_1 V_1^{\gamma-1} = T_2 V_2^{\gamma-1}$$

→ In adiabatic process, $Q=0 \Rightarrow [q_i = q_o = 0]$

$$PV^\gamma = C \Rightarrow P \propto \frac{C}{V^\gamma}$$

$$\Rightarrow W = \int \delta W = \int P dV = \int \frac{C}{V^\gamma} dV = C \int \frac{dV}{V^\gamma}$$

$$W = C \left\{ \int_1^2 V^{-\gamma} dV \right\} = C \left\{ \frac{V_2^{-\gamma+1} - V_1^{-\gamma+1}}{-\gamma+1} \right\}$$

$$W = C \left\{ \frac{V_1^{-\gamma+1} - V_2^{-\gamma+1}}{\gamma-1} \right\} \Rightarrow W = \frac{C V_1^{-\gamma+1} - C V_2^{-\gamma+1}}{\gamma-1}$$

$$W = \frac{P_1 V_1^\gamma \cdot V_1^{-\gamma+1} - P_2 V_2^\gamma \cdot V_2^{-\gamma+1}}{\gamma-1} \Rightarrow \boxed{W = \frac{P_1 V_1 - P_2 V_2}{\gamma-1}}$$

② Polytropic Process

→ $PV^n = \text{constant}$ → where $n = \text{polytropic index}$

$$[-\infty \leq n \leq \infty]$$

$$\Rightarrow W = \int P dV = \int \frac{C}{V^n} dV \Rightarrow \boxed{W = \frac{P_1 V_1 - P_2 V_2}{n-1}}$$

in general $(1 < n < \gamma)$

Q=?

$$\delta Q = dU + P dV$$

for ideal gas; $\delta Q = m C_v dT + P dV$

$$\Rightarrow \int \delta Q = \int m C_v dT + \int P dV \Rightarrow Q_{\text{poly}} = m C_v \int_1^2 dT + \int P dV$$

$$\Rightarrow Q_{\text{poly}} = m C_v (T_2 - T_1) + \frac{P_1 V_1 - P_2 V_2}{n-1} = \frac{m R}{\gamma-1} (T_2 - T_1) + \frac{P_1 V_1 - P_2 V_2}{n-1}$$

$$\Rightarrow Q_{\text{poly}} = \frac{P_2 V_2 - P_1 V_1}{\gamma-1} + \frac{P_1 V_1 - P_2 V_2}{n-1} = \frac{P_1 V_1 - P_2 V_2}{n-1} \left\{ \frac{-(n-1)}{\gamma-1} + 1 \right\}$$

$$\Rightarrow Q_{\text{poly}} = \frac{P_1 V_1 - P_2 V_2}{n-1} \left\{ \frac{-n + \gamma + n - \gamma}{\gamma-1} \right\} = \left(\frac{P_1 V_1 - P_2 V_2}{n-1} \right) \times \left(\frac{\gamma-n}{\gamma-1} \right)$$

$$\Rightarrow Q_{\text{poly}} = W_{\text{poly}} \times \frac{\gamma-n}{\gamma-1} \Rightarrow \boxed{Q_{\text{poly}} = \left(\frac{\gamma-n}{\gamma-1} \right) \times W_{\text{poly}}}$$

3.6: General Laws for expansion & compression

3.6.1: Representation of various process on P-V diagram

Process: $PV^n = \text{const}$

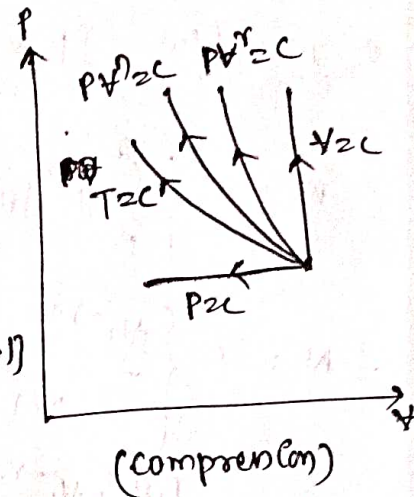
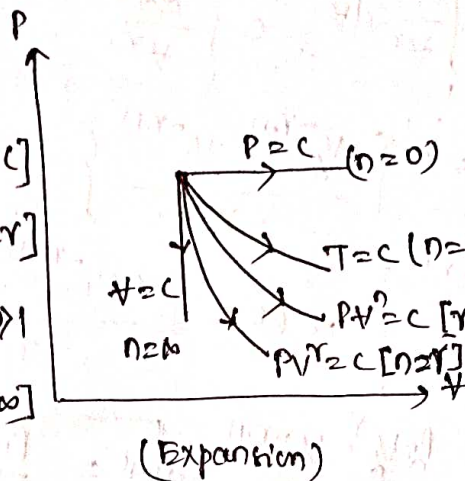
→ Isochoric ($V=c$) [$n=\infty$]

→ Isothermal ($T=c$) [$n=1$]

→ Adiabatic ($PV^\gamma=c$) [$n=\gamma$]

→ Polytropic ($PV^n=c$) [$\gamma > n > 1$]

→ Isobaric ($P=c$) [$n=0$]



Q2-11) A closed vessel contains 2 kg of carbon dioxide at temperature 20°C & pressure 0.7 bar . Heat is supplied to the vessel till the gas acquires a pressure of 1.4 bar . Calculate: (1) Final temperature. (2) Work done on or by the gas (3) Heat added (4) change in internal energy. Take specific heat of the gas at constant volume as 0.657 kJ/kgK .

Soln: Given Closed vessel $\Rightarrow V = \text{constant}$

$$Q = ? , W = ? , \Delta U = ?$$

$$m = 2 \text{ kg}$$

$$T_1 = 20^\circ\text{C} = 20 + 273 = 293 \text{ K}$$

$$P_1 = 0.7 \text{ bar} = 0.7 \times 10^5 \text{ N/m}^2$$

$$T_2 = ?$$

$$P_2 = 1.4 \text{ bar} = 1.4 \times 10^5 \text{ N/m}^2$$

$$C_v = 0.657 \text{ kJ/kgK}$$

1) Final temperature:

We know $PV = mRT$

$$\because V = c \Rightarrow P \propto T \Rightarrow \frac{P_1}{T_1} = \frac{P_2}{T_2} \Rightarrow T_2 = \left(\frac{P_2}{P_1}\right) \times T_1 \Rightarrow T_2 = \left(\frac{1.4}{0.7}\right) \times 293$$

$$\Rightarrow T_2 = 586 \text{ K}$$

$$\therefore T_2 = 586 - 273 = 313^\circ\text{C}$$

2) Work done by or on the gas

Process: Constant volume process, $W = \int P dV = 0$

work done = zero.

3) Heat added

Process: constant volume process, $\delta Q = \Delta U + \delta W \xrightarrow{0} \delta Q = \Delta U$

$$\Rightarrow Q = \Delta U \Rightarrow Q = m C_v (T_2 - T_1) \Rightarrow Q = 2 \times 0.657 \times (586 - 293) \text{ kJ}$$

$$\therefore Q = 385 \text{ kJ}$$

4) Change in internal energy

Process: constant volume process

$$\therefore \delta Q = \Delta U + \delta W \xrightarrow{0} \Delta U = \delta Q \Rightarrow \Delta U = 385 \text{ kJ}$$

(Ans)

Q.21 A gas, having initial pressure, volume & temperature as 275 kN/m^2 , 0.09 m^3 & 185°C respectively, is compressed at constant pressure until its temperature is 15°C . Calculate the amount of heat transferred & workdone during the process. Take $R = 290 \text{ J/kgK}$ & $C_p = 1.005 \text{ kJ/kgK}$.

Solⁿ: Given $P_1 = 275 \text{ kN/m}^2 = 275 \times 10^3 \text{ N/m}^2$ | $P = \text{constant}$
 $V_1 = 0.09 \text{ m}^3$ | $P_2 = P_1 = 275 \times 10^3 \text{ N/m}^2$
 $T_1 = 185^\circ\text{C}$ | $T_2 = 15^\circ\text{C} = 15 + 273 = 288 \text{ K}$
 $= 185 + 273 = 458 \text{ K}$

$R = ?$, $W = ?$, $R = 290 \frac{\text{J}}{\text{kgK}}$, $C_p = 1.005 \frac{\text{kJ}}{\text{kgK}} = 1.005 \times 10^3 \frac{\text{J}}{\text{kgK}}$

* Heat transferred (Q)

Process: Constant Pressure process

$$\delta Q = dH = m C_p \Delta T$$

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

$$\delta Q = dH = 0.186 \times 1.005 \times 10^3 (288 - 458)$$

$$\delta Q = dH = -31.78 \text{ kJ} \quad \frac{\text{kg} \times \frac{\text{kJ}}{\text{kgK}} \times \text{K}}{\text{kgK}}$$

$\therefore \delta Q = -31.78 \text{ kJ}$ [-ve sign indicates that the heat has been extracted from the gas during the process].

ideal gas eqⁿ: $PV = mRT$

$$m = \frac{P_1 V_1}{R_1 T_1} = \frac{(275 \times 10^3 \times 0.09) \frac{\text{N}}{\text{m}^2} \times \text{m}^3}{290 \frac{\text{J}}{\text{kgK}} \times 458 \text{ K}}$$

$$m = 0.186 \text{ kg}$$

* Workdone during the process:

Process: constant Pressure process

$$W = P(V_2 - V_1)$$

$$W = 275 \times 10^3 (0.056 - 0.09)$$

$$\frac{\text{N}}{\text{m}^2} \times \text{m}^3 = \text{J}$$

$$W = -9350 \text{ J} = -9.35 \text{ kJ}$$

[-ve sign indicates work is done on the gas]

ideal gas eqⁿ: $PV = mRT$

$$P_2 V_2 = mRT_2$$

$$V_2 \propto T_2 \quad [\because P = c, m = c, R = c]$$

$$\therefore \frac{V_2}{T_2} = \frac{V_1}{T_1} \Rightarrow V_2 = 0.09 \left(\frac{288}{458} \right)$$

$$\therefore V_2 = 0.056 \text{ m}^3$$

Q.2) A certain gas occupies a space of 0.3 m^3 at a pressure of 2 bar & a temperature of 77°C . It is heated at a constant volume, until the pressure is 7 bar. Determine: (1) Temperature at the end of process

(2) Mass of the gas

(3) Change in internal energy

(4) Change in enthalpy during the process

Assume $C_p = 1.005 \text{ kJ/kgK}$; $C_v = 0.712 \text{ kJ/kgK}$ & $R = 287 \frac{\text{J}}{\text{kgK}} = 0.287 \frac{\text{kJ}}{\text{kgK}}$

Soln: Given $V_1 = 0.3 \text{ m}^3$

$$P_1 = 2 \text{ bar} = 2 \times 10^5 \text{ N/m}^2$$

$$T_1 = 77^\circ\text{C} = 77 + 273 = 350 \text{ K}$$

Constant Volume Process

$$\Rightarrow V_1 = V_2 = 0.3 \text{ m}^3$$

$$P_2 = 7 \text{ bar}$$

(1) Temp. at the end of process: ($T_2 = ?$)

Process: Constant volume process

Ideal gas eqn: $PV = mRT$

$$\text{for } V = C \Rightarrow P \propto T \Rightarrow \frac{P_1}{T_1} = \frac{P_2}{T_2} \Rightarrow T_2 = \left(\frac{P_2}{P_1}\right) T_1$$

$$\Rightarrow T_2 = \left(\frac{7}{2}\right) \times 350 = 1225 \text{ K}$$

$$\Rightarrow T_2 = 1225 - 273 = 952^\circ\text{C}$$

(2) Mass of the gas ($m = ?$)

$$PV = mRT \Rightarrow m = \frac{PV}{RT} = \frac{2 \times 10^5 \frac{\text{N}}{\text{m}^2} \times 0.3 \text{ m}^3}{287 \frac{\text{J}}{\text{kgK}} \times 350 \text{ K}} = \frac{2 \times 10^5 \times 0.3 \frac{\text{Nm}}{\text{m}^2}}{287 \times 350 \frac{\text{J}}{\text{kg}}}$$

$$\Rightarrow m = 0.597 \text{ kg}$$

(3) Change in internal energy ($\Delta U = ?$)

1st Law of TD: $\delta Q = \Delta U_{1-2} + \delta W \rightarrow 0$

$$\Rightarrow \delta Q = \Delta U_{1-2} = m C_v (T_2 - T_1) = 0.597 \text{ kg} \times 0.712 \frac{\text{kJ}}{\text{kgK}} \times (1225 - 350) \text{ K}$$

$$\Rightarrow \Delta U_{1-2} = 0.597 \times 0.712 \times (1225 - 350) = 372 \text{ kJ}$$

(4) Change in enthalpy ($\Delta H = ?$)

$$\Delta H = H_2 - H_1 = m C_p (T_2 - T_1) = 0.597 \times 1.005 \times (1225 - 350) = 525 \text{ kJ}$$

Q24] A quantity of air has a volume of 0.4 m^3 at a pressure of 5 bar & a temperature of 80°C . It is expanded in a cylinder at a constant temperature to a pressure of 1 bar. Determine the amount of work done by the air during expansion.

Soln: Given $V_1 = 0.4 \text{ m}^3$

$$P_1 = 5 \text{ bar} = 5 \times 10^5 \text{ N/m}^2$$

$$T_1 = 80^\circ\text{C} = 80 + 273 = 353 \text{ K}$$

Constant temperature process

$$P_2 = 1 \text{ bar} = 1 \times 10^5 \text{ N/m}^2$$

$$W = ?$$

Work done (W)

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

$$\therefore W = 287 \frac{\text{J}}{\text{kgK}} \times 353 \text{ K} \ln\left(\frac{5}{1}\right)$$

$$W = 163053.764 \frac{\text{J}}{\text{kg}}$$

$$R = 287 \frac{\text{J}}{\text{kgK}}$$

$$P_1 V_1 = mRT_1$$

$$\Rightarrow m = \frac{P_1 V_1}{RT_1} = \frac{5 \times 10^5 \times 0.4}{287 \times 353}$$

$$\Rightarrow m = 1.974 \text{ kg}$$

$$W = m \times w$$

$$W = 1.974 \times 163053.764 \text{ J} = 321887.58 \text{ J}$$

$$\boxed{W = 321.88 \text{ kJ}}$$

Q25] 0.1 m^3 of air at a pressure of 1.5 bar is expanded isothermally to 0.5 m^3 . Calculate the final pressure of the gas & heat supplied during the process. Isothermal temp is 15°C

Soln: Given $V_1 = 0.1 \text{ m}^3$

$$V_2 = 0.5 \text{ m}^3$$

$$T_1 = 15^\circ\text{C} = 15 + 273 = 288 \text{ K}$$

$$P_1 = 1.5 \text{ bar}$$

$$P_2 = ?$$

Isothermal process $\Rightarrow T = \text{constant}$

$$\Rightarrow \text{We know } P_1 V_1 = mRT_1$$

$$\therefore T = C \Rightarrow P_1 V_1 = C \Rightarrow P_1 V_1 = P_2 V_2 \Rightarrow P_2 = \frac{P_1 V_1}{V_2}$$

$$\Rightarrow P_2 = \frac{1.5 \text{ bar} \times 0.1 \text{ m}^3}{0.5 \text{ m}^3} \Rightarrow \boxed{P_2 = 0.3 \text{ bar}}$$

$$P_1 V_1 = mRT_1$$

$$\Rightarrow RT_1 = \frac{P_1 V_1}{m}$$

$$\Rightarrow \text{Heat supplied; } Q = RT \ln\left(\frac{V_2}{V_1}\right) = \frac{P_1 V_1}{m} \times \ln\left(\frac{V_2}{V_1}\right)$$

Q25) Heat supplied; $Q = RT \ln\left(\frac{V_2}{V_1}\right) = \frac{287 \text{ J}}{\text{kgK}} \times 288 \text{ K} \times \ln\left(\frac{0.5}{0.1}\right) = 133029.707 \frac{\text{J}}{\text{kg}}$

Now $Q = m \times 133029.707$

$Q = 0.1814 \times 133029.707$
 $= 24141.56 \text{ J}$

$m = \frac{P_1 V_1}{RT_1} = \frac{1.5 \times 10^5 \times 0.1}{287 \times 288}$

$m = 0.1814 \text{ kg}$

$Q = 241.415 \text{ kJ}$

Q26) 0.336 m³ of gas at 10 bar and 150°C expands adiabatically until its pressure is 4 bar. It is then compressed, isothermally to its original volume. Find the final temperature & pressure of the gas. Also determine the change in internal energy. Take $C_p = 0.996 \text{ kJ/kgK}$; & $C_v = 0.703 \text{ kJ/kgK}$.

Solⁿ: Given $V_1 = 0.336 \text{ m}^3$

$P_1 = 10 \text{ bar} = 10 \times 10^5 \text{ N/m}^2$

$P_2 = 4 \text{ bar} = 4 \times 10^5 \text{ N/m}^2$

$T_1 = 150^\circ\text{C} = 150 + 273 = 423 \text{ K}$

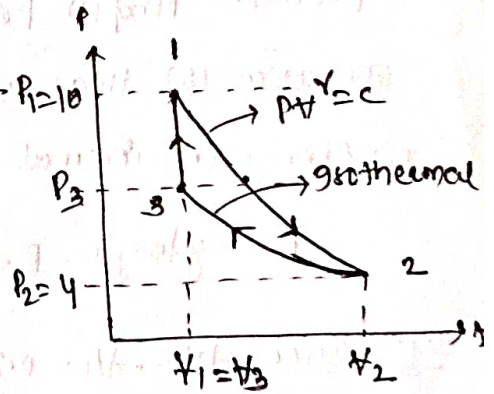
$C_p = 0.996 \frac{\text{kJ}}{\text{kgK}}$

$V_3 = V_1 = 0.336 \text{ m}^3$

$C_v = 0.703 \frac{\text{kJ}}{\text{kgK}}$

$T_3 = ?$

$P_3 = ?$



Adiabatic index, $\gamma = \frac{C_p}{C_v} = \frac{0.996}{0.703} = 1.417$

Process 1-2: $\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} \Rightarrow T_2 = T_1 \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} \Rightarrow T_2 = 423 \times \left(\frac{4}{10}\right)^{\frac{1.417-1}{1.417}}$

$\Rightarrow T_2 = 323 \text{ K}$

$\therefore 2 \rightarrow 3$: Isothermal process; $T_3 = T_2 = 323 \text{ K}$.

Process 3-1: Constant volume process

$PV = mRT \Rightarrow P \propto T \Rightarrow \frac{P_1}{T_1} = \frac{P_3}{T_3}$

$\Rightarrow P_3 = P_1 \left(\frac{T_3}{T_1}\right) \Rightarrow P_3 = 10 \left(\frac{323}{423}\right) \Rightarrow P_3 = 7.6 \text{ bar}$

Change in internal energy: $dU = ?$

$$dU = U_3 - U_1 = m C_v (T_3 - T_1)$$

$$\frac{\text{kg} \times \frac{\text{kJ}}{\text{kgK}} \times \text{K}}{\text{kgK}}$$

$$dU = 2.7 \times 0.703 (323 - 423) \text{ kJ}$$

$$dU = -189.8 \text{ kJ}$$

[-ve sign indicates decrease in internal energy]

$$P_1 V_1 = m R T_1$$

$$\Rightarrow m = \frac{P_1 V_1}{R T_1}$$

$$\Rightarrow m = \frac{10 \times 10^5 \times 0.336}{296 \times 423}$$

$$\Rightarrow m = 2.7 \text{ kg}$$

$$R = C_p - C_v$$

$$= 0.996 - 0.703$$

$$= 0.293 \frac{\text{kJ}}{\text{kgK}}$$

$$= 293 \frac{\text{J}}{\text{kgK}}$$

Q71 0.75 m^3 of hydrogen gas is initially at a pressure of 1 bar & temperature 290 K. It is compressed isentropically to 15 bar. Next it is expanded at constant temperature to original volume. Finally heat rejection takes place at constant volume & the gas pressure is restored to the original condition of pressure. Find (1) Pressure, volume, & temperature at the end of each operation (2) Heat added during isothermal expansion. (3) Change in internal energy during each process.

For hydrogen, $R = 4.126 \frac{\text{J}}{\text{kgK}}$, $C_p = 14.26 \frac{\text{kJ}}{\text{kgK}}$

Soln: Given data, $V_1 = 0.75 \text{ m}^3 = V_3$

$$P_1 = 1 \text{ bar} = 1 \times 10^5 \text{ N/m}^2, P_2 = 15 \text{ bar} = 15 \times 10^5 \text{ N/m}^2$$

$$T_1 = 290 \text{ K}$$

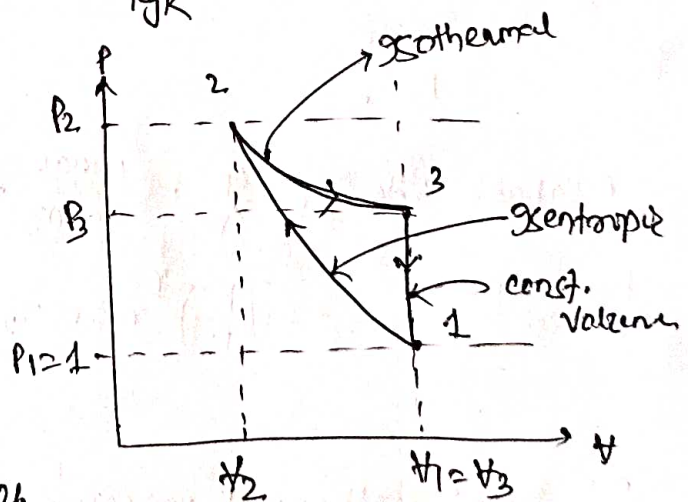
$$R = 4.126 \frac{\text{J}}{\text{kgK}}, C_p = 14.26 \frac{\text{kJ}}{\text{kgK}} = 14260 \frac{\text{J}}{\text{kgK}}$$

$$C_v = C_p - R = 14260 - 4126 = 10134$$

$$C_p - C_v = R \Rightarrow C_v = C_p - R = 14.26 - 4.126 = 10.134 \frac{\text{kJ}}{\text{kgK}}$$

$$\Rightarrow C_v = 10.134 \frac{\text{kJ}}{\text{kgK}}$$

$$\gamma = \frac{C_p}{C_v} = \frac{14.26}{10.134} = 1.407$$



1) Process 1 → 2: isentropic process ($PV^\gamma = c$)

$$\Rightarrow P_1 V_1 = m R T_1$$

$$\Rightarrow m = \frac{P_1 V_1}{R T_1} = \frac{1 \times 10^5 \times 0.75}{4126 \times 290} = 0.063 \text{ kg}$$

$$\Rightarrow P_1 V_1^\gamma = P_2 V_2^\gamma \Rightarrow \left(\frac{V_2}{V_1}\right)^\gamma = \frac{P_1}{P_2} \Rightarrow \frac{V_2}{V_1} = \left(\frac{P_1}{P_2}\right)^{\frac{1}{\gamma}} \Rightarrow V_2 = V_1 \left(\frac{P_1}{P_2}\right)^{\frac{1}{\gamma}}$$

$$\Rightarrow V_2 = 0.75 \left(\frac{1}{15}\right)^{\frac{1}{1.407}} \Rightarrow V_2 = 0.11 \text{ m}^3$$

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} \Rightarrow T_2 = T_1 \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}}$$
$$\Rightarrow T_2 = 290 \left(\frac{15}{1}\right)^{\frac{1.407-1}{1.407}} \Rightarrow T_2 = 638 \text{ K}$$

Process 2 → 3: isothermal process [$T_2 = c$] [$PV = c$]

$$P_2 V_2 = P_3 V_3 \Rightarrow P_3 = P_2 \left(\frac{V_2}{V_3}\right) \Rightarrow P_3 = 15 \left(\frac{0.11}{0.75}\right) \Rightarrow P_3 = 2.2 \text{ bar}$$

$$T_2 = T_3 = 638 \text{ K}$$

2) Heat added in isothermal expansion:

$$Q_{2-3} = P \ln\left(\frac{V_3}{V_2}\right) = P_2 V_2 \ln\left(\frac{V_3}{V_2}\right) = 15 \times 10^5 \times 0.11 \times \ln\left(\frac{0.75}{0.11}\right) = 317 \text{ kJ}$$

$$\therefore Q_{2-3} = 317 \text{ kJ}$$

3) Change in internal energy:

1 → 2: isentropic process:

$$dU = U_2 - U_1 = m C_v (T_2 - T_1) = 0.063 \times 10.134 (638 - 290) = 222.18 \text{ kJ}$$

$\frac{\text{kg}}{\text{kg}} \frac{\text{kJ}}{\text{kg K}} \times \text{K}$

2 → 3: isothermal process

$$T_2 = T_3 \Rightarrow U_2 = U_3 \Rightarrow dU = U_3 - U_2 = 0$$

3 → 1: constant volume process

$$dU = U_1 - U_3 = m C_v (T_1 - T_3) = 0.063 \times 10.134 (290 - 638) = -222.18 \text{ kJ}$$

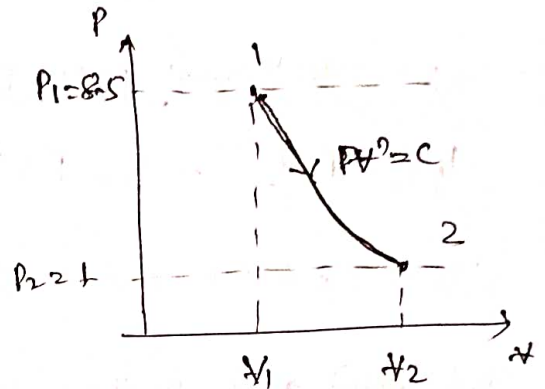
Q-8] A gas initially at 603K expands until its volume is 5.2 times the initial volume, according to $PV^n = \text{constant}$. If the initial & final pressures are observed to be 8.5 bar & 1 bar. Determine

- (1) the index of expansion
- (2) workdone per kg of gas
- (3) heat exchange per kg of gas

Assume $C_v = 0.712 \frac{\text{kJ}}{\text{kgK}}$

$\gamma = 1.4$

Soln: Given $T_1 = 603\text{K}$, $P_1 = 8.5\text{ bar}$
 $V_2 = 5.2 V_1$, $P_2 = 1\text{ bar}$
 $PV^n = C$, $\gamma = 1.4$
 $C_v = 0.712 \frac{\text{kJ}}{\text{kgK}}$



(1) index of expansion ($n = ?$)

$P_1 V_1^n = P_2 V_2^n$

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

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

$\Rightarrow n = \frac{\ln\left(\frac{P_1}{P_2}\right)}{\ln\left(\frac{V_2}{V_1}\right)} \Rightarrow n = \frac{\ln\left(\frac{8.5}{1}\right)}{\ln\left(\frac{5.2 V_1}{V_1}\right)} \Rightarrow n = \frac{\ln(8.5)}{\ln(5.2)} \Rightarrow \boxed{n = 1.3}$

(2) Workdone per kg of gas: ($W = ?$)

$m = 1\text{ kg}$

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

$W = \frac{8.5 \times 10^5 \times 0.202 - 1 \times 10^5 \times 1.05}{1.3-1}$

$\boxed{W = 222\text{ kJ}}$

$P_1 V_1 = mRT_1 \Rightarrow V_1 = \frac{mRT_1}{P_1}$

$\Rightarrow V_1 = \frac{1 \times 0.2848 \times 10^3 \times 603}{8.5 \times 10^5}$

$\Rightarrow V_1 = 0.202\text{ m}^3$

$V_2 = 5.2 V_1 \Rightarrow V_2 = 1.05\text{ m}^3$

$R = C_p - C_v$

$\gamma = \frac{C_p}{C_v} \Rightarrow C_p = \gamma C_v$

$R = (\gamma - 1) C_v$

$R = 0.4 \times 0.712$

$R = 0.2848 \frac{\text{kJ}}{\text{kgK}}$

3) Heat exchange per kg of gas:

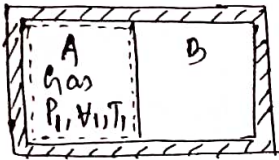
$$m = 1 \text{ kg}$$

$$Q = \left(\frac{\gamma - n}{n - 1} \right) \times W \Rightarrow Q = \left(\frac{1.4 - 1.3}{1.3 - 1} \right) \times 222 \Rightarrow \boxed{Q = 55.5 \text{ KJ}}$$

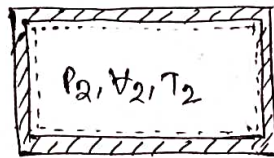
Ans

9.7: Free expansion process is Unresisted expansion process \Rightarrow

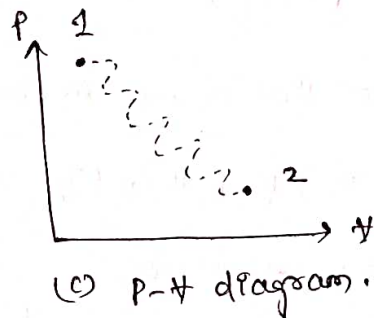
The free expansion (or unresisted expansion) process is an irreversible non-flow process. A free expansion occurs when a fluid is allowed to expand suddenly into a vacuum chamber through an orifice of large dimensions.



(a) before expansion



(b) after expansion



(c) P-V diagram.

Consider two chambers A & B separated by a partition as shown in fig (a). Let the chamber A contains a perfect gas having volume V_1 , pressure P_1 , & temperature T_1 and the chamber B is completely evacuated. These chambers are perfectly insulated so that no heat transfer takes place from or to its surroundings. Now, if the partition is removed, the gas will expand freely & occupy the whole space as shown in fig (b). By this, the volume of the gas increases to V_2 , pressure decreases to P_2 and the temperature may also decrease to T_2 .

The following points may be noted regarding free expansion of a gas.

1) Since the system is perfectly insulated so that no heat transfer takes place (i.e. $Q_{1-2} = 0$), therefore the expansion of gas may be called as an adiabatic expansion.

2) Since the free expansion of the gas from the equilibrium state 1 to the equilibrium state 2 takes place suddenly, therefore the intermediate states will not be in equilibrium states, as shown on the P-V diagram. Thus the process is irreversible & the expansion is, therefore, known as irreversible adiabatic expansion.

3) Since there is no resistance to overcome during free expansion process, therefore, ~~no work~~ no work is done by the system (i.e. $W_{1-2} = 0$). Thus the free expansion process is also known as unresisted expansion process.

4) According to the 1st law of thermodynamics;

$$Q_{1-2} = W_{1-2} + dU \quad [\because Q_{1-2} = 0 \text{ \& } W_{1-2} = 0]$$

$$\Rightarrow dU = 0 \Rightarrow U_2 - U_1 = 0 \Rightarrow \boxed{U_2 = U_1}$$

Thus, the free expansion process is also known as constant internal energy process.

5) We know that change in internal energy.

$$dU = m C_v dT = m C_v (T_2 - T_1)$$

$$\because dU = 0 \Rightarrow dT = 0$$

$$\Rightarrow T_2 - T_1 = 0 \Rightarrow \boxed{T_2 = T_1}$$

i.e. there is no change in temperature of the system. We can say that in a free expansion, temperature of the system remains constant.

Note \rightarrow It can't be called an isothermal process because in actual isothermal process, work is done by the gas during expansion.

6) We know that change in enthalpy,

$$dH = m C_p dT$$

$$\because dT = 0 \Rightarrow H_2 - H_1 = 0 \Rightarrow \boxed{H_2 = H_1}$$

i.e. enthalpy of the system in a free expansion remains constant. Thus the free expansion process may also be called constant enthalpy process.

S No.	Types of reversible non-flow process	Summary of formula for heating and expansion of perfect gas	Workdone (W_{1-2})	Heat change of internal energy (Q_{1-2})	Heat supplied [$Q_{1-2} = W_{1-2} + Q_U$]	change in enthalpy [$dH = H_2 - H_1$]
1.	Constant Volume or Isochoric ($V = \text{const}$)	$P_1 V = P_2 V \Rightarrow \frac{P_1}{T_1} = \frac{P_2}{T_2}$ (Gay-Lussac Law)	0	$dU = m C_V (T_2 - T_1)$	$Q_{1-2} = dU = m C_V (T_2 - T_1)$	$dH = m C_P (T_2 - T_1)$
2.	Constant Pressure or Isobaric ($P = \text{const}$)	$P_1 V_1 = P_2 V_2$ (Charles's Law)	$W_{1-2} = P (V_2 - V_1)$	$dU = m C_V (T_2 - T_1)$	$Q_{1-2} = dH = m C_P (T_2 - T_1)$	$dH = m C_P (T_2 - T_1)$
3.	Constant Temperature or Isothermal ($T = \text{const}$) or Hyperbolic	$P_1 V_1 = P_2 V_2$ (Boyle's Law)	$W_{1-2} = P_1 V_1 \ln \left(\frac{V_2}{V_1} \right)$ $= m R T \ln \left(\frac{V_2}{V_1} \right)$ $= P_1 V_1 \ln \left(\frac{P_1}{P_2} \right)$	$dU = 0$ $\Rightarrow U_2 - U_1 = 0$ $\Rightarrow U_2 = U_1$	$Q_{1-2} = W_{1-2}$ $Q_{1-2} = P_1 V_1 \ln \left(\frac{V_2}{V_1} \right)$ $= P_1 V_1 \ln \left(\frac{P_1}{P_2} \right)$ $= m R T_1 \ln \left(\frac{P_1}{P_2} \right)$	$dH = 0$ $\Rightarrow H_2 - H_1 = 0$ $\Rightarrow H_2 = H_1$
4.	Adiabatic process or Isentropic ($P V^\gamma = \text{const}$)	$P_1 V_1^\gamma = P_2 V_2^\gamma$ $T_1 V_1^{\gamma-1} = T_2 V_2^{\gamma-1}$ $\frac{T_2}{T_1} = \left(\frac{P_2}{P_1} \right)^{\frac{\gamma-1}{\gamma}}$	$W_{1-2} = \frac{P_1 V_1 - P_2 V_2}{\gamma - 1}$ $= \frac{m R (T_1 - T_2)}{\gamma - 1}$	$dU = m C_V (T_2 - T_1)$	$Q_{1-2} = 0$	$dH = m C_P (T_2 - T_1)$
5.	Polytropic process or general expansion ($P V^n = \text{const}$)	$P_1 V_1^n = P_2 V_2^n$ $T_1 V_1^{n-1} = T_2 V_2^{n-1}$ $\frac{T_2}{T_1} = \left(\frac{P_2}{P_1} \right)^{\frac{n-1}{n}}$	$W_{1-2} = \frac{P_1 V_1 - P_2 V_2}{n - 1}$ $= \frac{m R (T_1 - T_2)}{n - 1}$	$dU = m C_V (T_2 - T_1)$	$Q_{1-2} = \left(\frac{\gamma - n}{n - 1} \right) * W_{1-2}$	$dH = m C_P (T_2 - T_1)$

3.8 FLOW PROCESSES:-

We have already discussed that the process occurring in open system which permit the transfer of mass to and from the system, are known as flow processes. The flow process may classified as

- (1) Steady flow process
- (2) Unsteady flow process.

(1) Steady flow processes:-

The following conditions must be satisfied in steady flow processes.

- a) The mass flow rate at inlet & outlet is same.
- b) The rate of heat transfer is constant.
- c) The rate of work transfer is constant.
- d) The state of working substance at any point within the system is same at all times.
- e) There is no change in chemical composition of the system.

(2) Unsteady flow processes:-

If any one of these conditions ^{of steady flow processes} are not satisfied, then the process is said to be non-steady flow processes.

3.9: Application of First law of Thermodynamics to a steady flow process \Rightarrow

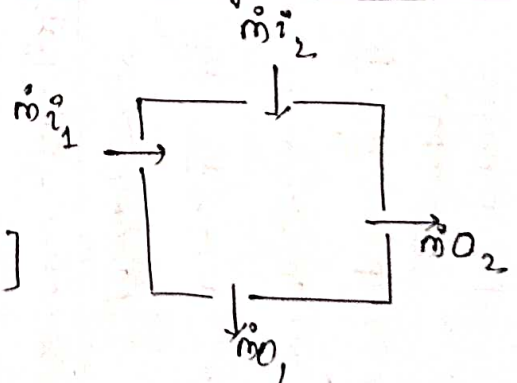
1) Law of mass conservation:-

For steady flow: $\Delta T_{in} = \Delta T_{out}$

$$\rightarrow [\dot{m}_1 + \dot{m}_2 + \dots] = [\dot{m}_0 + \dot{m}_2 + \dots]$$

$$\rightarrow \boxed{[\sum (\dot{m}_i)] = [\sum (\dot{m}_o)]}$$

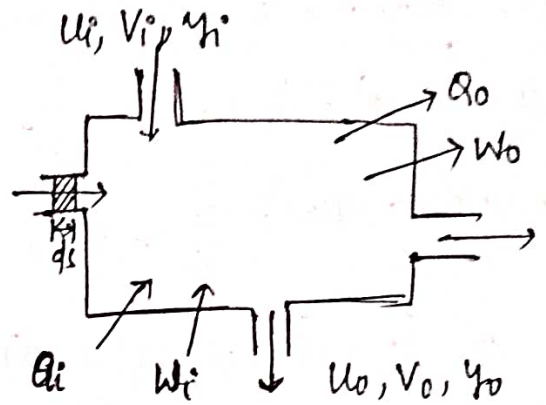
$$\rightarrow \dot{m}_{inlet} = \dot{m}_{outlet}$$



(ii) Energy equation for steady flow process \Rightarrow

flow work / flow energy / displacement work

The flow energy is the energy required to flow & move the working substance against its pressure. It is also known as flow work.



$$W_{flow} = F \cdot ds = P(A ds) = P \Delta V$$

$$W_{flow} = P \Delta V = m P \Delta V$$

$$\dot{W}_{flow} = \frac{W_{flow}}{\Delta t} = \frac{m P \Delta V}{\Delta t} = \dot{m} P \Delta V \Rightarrow \dot{W}_{flow} = \dot{m} P \Delta V$$

A/c to steady flow energy equation

$$\sum \dot{E}_{in} = \sum \dot{E}_{out}$$

$$E_{inlet} = E_{outlet}$$

$$\dot{Q}_i + \dot{W}_i + \dot{W}_{fi} + [U + \frac{1}{2} m v^2 + m g y]_i = \dot{Q}_o + \dot{W}_o + \dot{W}_{fo} + [U + \frac{1}{2} m v^2 + m g y]_o$$

$$\dot{Q}_i + \dot{W}_i + (\dot{m} P \Delta V)_i + \dot{m}_i [u + \frac{v^2}{2} + g y]_i = \dot{Q}_o + \dot{W}_o + (\dot{m} P \Delta V)_o + \dot{m}_o [u + \frac{v^2}{2} + g y]_o$$

$$\frac{\dot{Q}_i}{\Delta t} + \frac{\dot{W}_i}{\Delta t} + \left(\frac{\dot{m}_i P \Delta V}{\Delta t} \right)_i + \frac{\dot{m}_i}{\Delta t} [u + \frac{v^2}{2} + g y]_i = \frac{\dot{Q}_o}{\Delta t} + \frac{\dot{W}_o}{\Delta t} + \left(\frac{\dot{m} P \Delta V}{\Delta t} \right)_o + \frac{\dot{m}_o}{\Delta t} [u + \frac{v^2}{2} + g y]_o$$

$$\dot{Q}_i + \dot{W}_i + (\dot{m}_i P \Delta V)_i + \dot{m}_i [u + \frac{v^2}{2} + g y]_i = \dot{Q}_o + \dot{W}_o + (\dot{m} P \Delta V)_o + \dot{m}_o [u + \frac{v^2}{2} + g y]_o$$

$$\dot{Q}_i + \dot{W}_i + \dot{m}_i [(u + P \Delta V) + \frac{v^2}{2} + g y]_i = \dot{Q}_o + \dot{W}_o + \dot{m}_o [(u + P \Delta V) + \frac{v^2}{2} + g y]_o$$

$$\dot{Q}_i + \dot{W}_i + \dot{m}_i [h + \frac{v^2}{2} + g y]_i = \dot{Q}_o + \dot{W}_o + \dot{m}_o [h + \frac{v^2}{2} + g y]_o$$

$$\dot{Q}_i + \dot{W}_i + \left\{ \dot{m} [h + \frac{v^2}{2} + g y] \right\}_i = \dot{Q}_o + \dot{W}_o + \left\{ \dot{m} [h + \frac{v^2}{2} + g y] \right\}_o$$

$\sum \dot{E}_{in}$

$\sum \dot{E}_{out}$

NOTE Convert all the unit to $\frac{J}{kg}$ for calculation mistake.

3.10: Workdone in a steady flow process \Rightarrow

$$\text{SFEBE: } \dot{Q}_i + \dot{W}_i + \dot{m} \left[h + \frac{V^2}{2} + gY \right]_i = \dot{Q}_o + \dot{W}_o + \dot{m} \left[h + \frac{V^2}{2} + gY \right]_o$$

for unit mass flow: $\frac{\dot{Q}_i}{\dot{m}} + \frac{\dot{W}_i}{\dot{m}} + \left[h + \frac{V^2}{2} + gY \right]_i = \frac{\dot{Q}_o}{\dot{m}} + \frac{\dot{W}_o}{\dot{m}} + \left[h + \frac{V^2}{2} + gY \right]_o$

$$\Rightarrow \dot{Q}_i + \dot{W}_i + \left(h + \frac{V^2}{2} + gY \right)_i = \dot{Q}_o + \dot{W}_o + \left(h + \frac{V^2}{2} + gY \right)_o \quad \text{--- (i)}$$

If the changes in kinetic energy & potential energy are negligible

i.e. $K.E \approx 0$, $P.E \approx 0$, then the eqn (i) may be written as

$$\dot{Q}_i + \dot{W}_i + h_i = \dot{Q}_o + \dot{W}_o + h_o$$

$$\Rightarrow \dot{Q}_i - \dot{Q}_o = \dot{W}_o - \dot{W}_i + h_o - h_i$$

$$\Rightarrow \delta Q = \delta W + dh$$

$$\Rightarrow \boxed{\delta W = \delta Q - dh} \quad \text{--- (ii)}$$

We also know that $h = u + Pv \Rightarrow dh = d(u + Pv)$

$$\Rightarrow dh = du + d(Pv) = du + Pdv + vdp \quad \text{--- (iii)}$$

Acc to first law of TD for a closed system, $\delta Q = du + Pdv$

Now the eqn (iii) becomes, $dh = (du + Pdv) + vdp$

$$\Rightarrow dh = \delta Q + vdp \quad \Rightarrow \delta Q = dh - vdp$$

Substitute the value of δQ in eqn (ii)

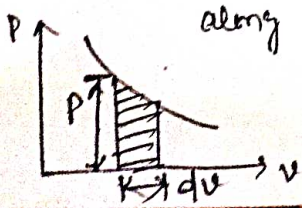
$$\delta W = \delta Q - dh \Rightarrow \delta W = dh - vdp - dh \quad \Rightarrow \delta W = -vdp$$

$$\Rightarrow \boxed{\delta W = -vdp} \rightarrow \text{workdone in flow process}$$

Non flow process (closed system)

$$\boxed{W_{Rev} = \int P dv}$$

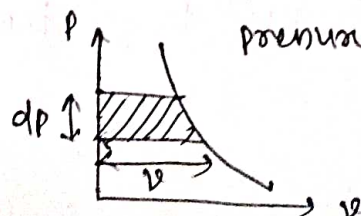
\approx Area under PV diagram along volume axis



Flow process (open system)

$$\boxed{W = -\int v dp}$$

\approx Area under PV diagram along pressure axis.



3.11: Workdone for various steady flow processes:

1) Constant Volume process: ($V=c$)

$$w_{1-2} = - \int_1^2 v dp = -v \int_1^2 dp = -v(p_2 - p_1) = v(p_1 - p_2) \Rightarrow \boxed{w_{1-2} = v(p_1 - p_2)}$$

2) Constant Pressure process: ($p=c$) $\Rightarrow dp=0$

$$w_{1-2} = - \int_1^2 v dp \rightarrow 0 \Rightarrow \boxed{w_{1-2} = 0}$$

3) Constant Temperature process: ($T=c$)

for ideal gas; $PV=c \Rightarrow P_1 V_1 = P_2 V_2$, $PV=c \Rightarrow V = \frac{c}{P}$

$$\text{Workdone, } w_{1-2} = - \int_1^2 v dp = - \int_1^2 \frac{c}{P} dp = -c \int_1^2 \frac{dp}{P} = -c [\ln P]_1^2$$

$$\Rightarrow w_{1-2} = -c [\ln p_2 - \ln p_1] = -c \ln \left(\frac{p_2}{p_1} \right)$$

$$\Rightarrow w_{1-2} = -c \ln \left(\frac{p_2}{p_1} \right) \Rightarrow \boxed{w_{1-2} = c \ln \left(\frac{p_1}{p_2} \right)}$$

$$c = P_1 V_1 = P_2 V_2, \quad \boxed{w_{1-2} = P_1 V_1 \ln \left(\frac{p_1}{p_2} \right) = P_2 V_2 \ln \left(\frac{p_1}{p_2} \right)} \quad \text{or} \quad \boxed{w_{1-2} = P_1 V_1 \ln \left(\frac{V_2}{V_1} \right)}$$

4) Adiabatic process:

$$\text{We know } PV^\gamma = c \Rightarrow P \propto V^{-\gamma} \Rightarrow V = \left(\frac{c}{P} \right)^{\frac{1}{\gamma}}$$

$$\text{Workdone, } w_{1-2} = - \int_1^2 v dp = - \int_1^2 \left(\frac{c}{P} \right)^{\frac{1}{\gamma}} dp = - \left(\frac{c}{P} \right)^{\frac{1}{\gamma}} \int_1^2 P^{-\frac{1}{\gamma}} dp = -c^{\frac{1}{\gamma}} \int_1^2 P^{-\frac{1}{\gamma}} dp$$

$$w_{1-2} = -c^{\frac{1}{\gamma}} \left[\frac{P^{-\frac{1}{\gamma} + 1}}{-\frac{1}{\gamma} + 1} \right]_1^2 = -c^{\frac{1}{\gamma}} \left[\frac{P^{-\frac{1+\gamma}{\gamma}}}{-\frac{1+\gamma}{\gamma}} \right]_1^2 = -c^{\frac{1}{\gamma}} \left[\frac{P^{\frac{\gamma}{\gamma-1}}}{\frac{\gamma-1}{\gamma}} \right]_1^2$$

$$\Rightarrow w_{1-2} = -c^{\frac{1}{\gamma}} \times \frac{\gamma}{\gamma-1} \left[P_2^{\frac{\gamma}{\gamma-1}} - P_1^{\frac{\gamma}{\gamma-1}} \right] = -\frac{\gamma}{\gamma-1} \left[P_2^{\frac{\gamma}{\gamma-1}} \cdot c^{\frac{1}{\gamma}} - P_1^{\frac{\gamma}{\gamma-1}} \cdot c^{\frac{1}{\gamma}} \right]$$

$$\Rightarrow w_{1-2} = -\frac{\gamma}{\gamma-1} \left[P_2^{\frac{\gamma}{\gamma-1}} \cdot (P_2 V_2^\gamma)^{\frac{1}{\gamma}} - P_1^{\frac{\gamma}{\gamma-1}} \cdot (P_1 V_1^\gamma)^{\frac{1}{\gamma}} \right]$$

$$\Rightarrow w_{1-2} = -\frac{\gamma}{\gamma-1} \left[P_2^{\frac{\gamma}{\gamma-1}} \cdot P_2^{\frac{1}{\gamma}} \cdot V_2^{\frac{\gamma}{\gamma-1} \cdot \frac{1}{\gamma}} - P_1^{\frac{\gamma}{\gamma-1}} \cdot P_1^{\frac{1}{\gamma}} \cdot V_1^{\frac{\gamma}{\gamma-1} \cdot \frac{1}{\gamma}} \right]$$

$$\Rightarrow w_{1-2} = -\frac{\gamma}{\gamma-1} \left[P_2^{\frac{\gamma+1}{\gamma}} \cdot V_2 - P_1^{\frac{\gamma+1}{\gamma}} \cdot V_1 \right] \Rightarrow \boxed{w_{1-2} = \frac{\gamma}{\gamma-1} [P_1 V_1 - P_2 V_2]}$$

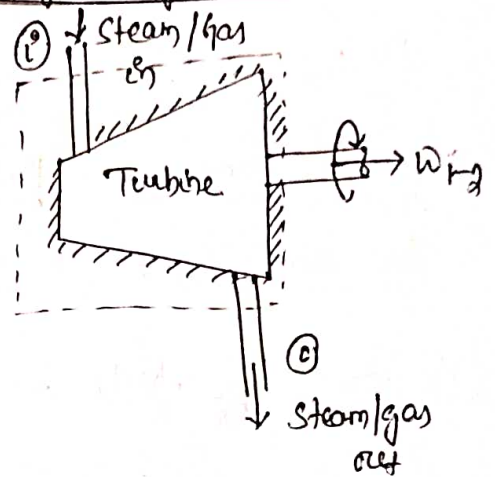
⑤ Polytropic Process: $PV^n = C \rightarrow V = \left(\frac{C}{P}\right)^{\frac{1}{n}}$

Work done; $w_{1-2} = -\frac{n}{n-1} (P_1 V_1 - P_2 V_2)$

Q.12: Application of steady flow energy equation to Engineering System

(1) Turbine: It is a device which converts energy of the working substance into work.

- The turbine is insulated so that there is no transfer of heat i.e. $Q_{in} = 0$ & $Q_{out} = 0$.
- Here the changes in KE & PE is negligible, i.e. $\Delta KE \approx 0$ & $\Delta PE \approx 0$



Now A/E to SFEE;

$$\dot{Q}_1 + \dot{W}_1 + \dot{m}_1 \left(h + \frac{V^2}{2} + gz \right)_1 = \dot{Q}_2 + \dot{W}_2 + \dot{m}_2 \left(h + \frac{V^2}{2} + gz \right)_2$$

$$\dot{W}_1 + \dot{m}_1 h_1 = \dot{W}_2 + \dot{m}_2 h_2 \Rightarrow \dot{W}_2 - \dot{W}_1 = \dot{m}_1 h_1 - \dot{m}_2 h_2$$

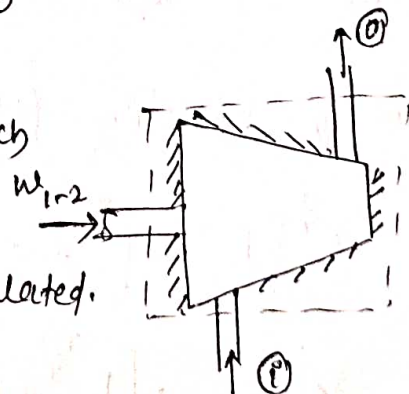
[Steady flow $\dot{m}_1 = \dot{m}_2 = \dot{m}$]

$$\dot{W}_2 = \dot{m} (h_1 - h_2) \Rightarrow \frac{\dot{W}_2}{\dot{m}} = h_1 - h_2$$

$$\dot{W}_2 = \dot{m} (h_1 - h_2) \Rightarrow w_{1-2} = h_1 - h_2$$

work producing device.

(2) Compressor: A compressor is a device which compresses air & supplies the air at higher pressure. • The compressor is insulated.



i.e. $Q_p = 0$ & $Q_o = 0$

• change in KE & PE is negligible.

i.e. $\Delta KE \approx 0$, $\Delta PE \approx 0$.

$$\text{A/c to SFEE, } \dot{Q}_i + \dot{W}_i + \dot{m}_i \left(h + \frac{V^2}{2} + g y \right)_i = \dot{Q}_o + \dot{W}_o + \dot{m}_o \left(h + \frac{V^2}{2} + g y \right)_o$$

$$\dot{W}_i = \dot{m}_o h_o - \dot{m}_i h_i \Rightarrow \dot{W}_i = \dot{m} (h_o - h_i)$$

$$\dot{W}_i = \dot{m} (h_o - h_i) \Rightarrow \boxed{\dot{W}_i = \dot{m} (h_o - h_i)} \Rightarrow \boxed{\dot{W}_{1-2} = \dot{m} (h_2 - h_1)}$$

Work consuming device.

Q-11) In a gas turbine, the gases flow at the rate of 5 kg/s. The gases enter the turbine at a pressure of 7 bar with a velocity of 120 m/s & leaves at a pressure 2 bar with velocity 250 m/s. The turbine is insulated. If the enthalpy of the gas at inlet is 900 kJ/kg and at outlet 600 kJ/kg. Determine the capacity of the turbine.

Solve Given data

$$\dot{m} = 5 \text{ kg/s, } Q = 0$$

$$P_1 = 7 \text{ bar} = 7 \times 10^5 \text{ N/m}^2$$

$$V_1 = 120 \text{ m/s}$$

$$h_1 = 900 \frac{\text{kJ}}{\text{kg}} = 900 \times 10^3 \frac{\text{J}}{\text{kg}}$$

$$W = ?$$

$$P_2 = 2 \text{ bar} = 2 \times 10^5 \text{ N/m}^2$$

$$V_2 = 250 \text{ m/s}$$

$$h_2 = 600 \frac{\text{kJ}}{\text{kg}} = 600 \times 10^3 \frac{\text{J}}{\text{kg}}$$

We know from SFEE,

$$\dot{Q}_i + \dot{W}_i + \dot{m}_i \left(h_i + \frac{V_i^2}{2} + g y_i \right) = \dot{Q}_o + \dot{W}_o + \dot{m}_o \left(h_o + \frac{V_o^2}{2} + g y_o \right)$$

$$\Rightarrow \dot{m} \left(h_1 + \frac{V_1^2}{2} \right) = \dot{W}_o + \dot{m} \left(h_2 + \frac{V_2^2}{2} \right)$$

$$\Rightarrow \dot{W}_o = \dot{m} \left(h_1 + \frac{V_1^2}{2} \right) - \dot{m} \left(h_2 + \frac{V_2^2}{2} \right)$$

$$\Rightarrow \dot{W}_o = 5 \frac{\text{kg}}{\text{s}} \left(900 \times 10^3 \frac{\text{J}}{\text{kg}} + \frac{120^2}{2} \frac{\text{m}^2}{\text{s}^2} \right) - 5 \frac{\text{kg}}{\text{s}} \left(600 \times 10^3 \frac{\text{J}}{\text{kg}} + \frac{250^2}{2} \frac{\text{m}^2}{\text{s}^2} \right)$$

$$\Rightarrow W = 5 \times 907,200 - 5 \times 631,250$$

$$\Rightarrow W = 1379,750 \frac{\text{J}}{\text{s}} \Rightarrow W = 1379,750 \frac{\text{kJ}}{\text{s}} \Rightarrow \boxed{W = 1379,750 \text{ kW}}$$

M

Ch-4: SECOND LAW OF THERMODYNAMICS \Rightarrow

4.1 Limitations of First law of Thermodynamics \Rightarrow

- 1) This law doesn't specify the direction of flow of heat and work (i.e. whether the heat flows from hot body to cold body or from a cold body to a hot body). It also does not give any condition under which these transfers take place.
- 2) The heat energy & mechanical work are mutually convertible. Though the mechanical work can be fully converted into heat energy, but only a part of heat energy can be converted into mechanical work. It means that the heat energy and mechanical work are not fully mutually convertible.

4.1.1: Perpetual Motion Machine - I \Rightarrow (PMM-I)

A machine which violates the first law of thermodynamics (i.e. energy can neither be created nor destroyed, but can be transformed from one form to another) is known as PMM-I (Perpetual Motion Machine of 1st kind).

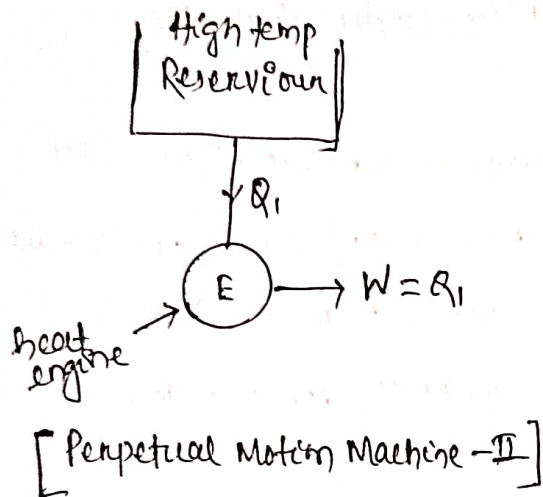
It is defined as a machine which produces work energy without consuming an equivalent of energy from other source. It is impossible in actual practice, because no machine can produce energy of its own without consuming any other form of energy.

4.2: Second law of Thermodynamics \Rightarrow

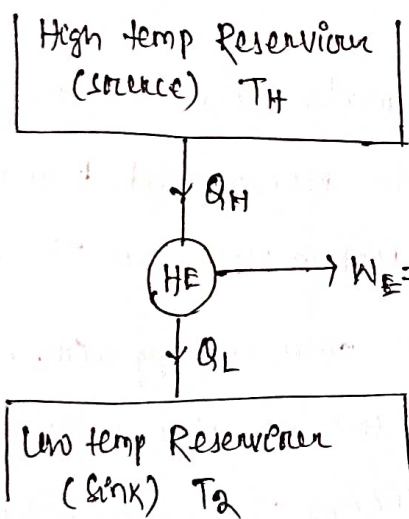
The Second law of thermodynamics may be defined by two common statements as follows.

- 1) Kelvin-Planck Statement: According to Kelvin-Planck "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 of work."

→ In other words, no actual heat engine, working on a cyclic process, can convert whole of the heat supplied to it, into mechanical work. It means that there is a degradation of energy in the process of producing mechanical work from the heat supplied. Thus the Kelvin-Planck statement also known as "law of degradation of energy".



* PMM-II: A heat engine which violates the statement of second law of thermodynamics (i.e. a heat engine which can convert the whole of heat energy into mechanical work) is known as Perpetual Motion Machine of second kind.



Thus for the satisfactory operation of a heat engine which is a device used for converting heat into mechanical work, there should be at least two reservoirs of heat, one at a higher temperature and the other at lower temp as shown in figure. In this case, consider that heat energy (Q_H) from the higher temp reservoir (source) at temperature (T_H)

is supplied to the engine. A part of this heat energy is rejected to the low temperature reservoir (or sink) at temperature T_L . If ' Q_L ' is the heat rejected to the sink, then the remaining heat (i.e. $Q_H - Q_L$) is converted into mechanical work. The ratio of the maximum mechanical work obtained to the total heat supplied to the engine is known as the thermal efficiency (η_{max}) of the engine.

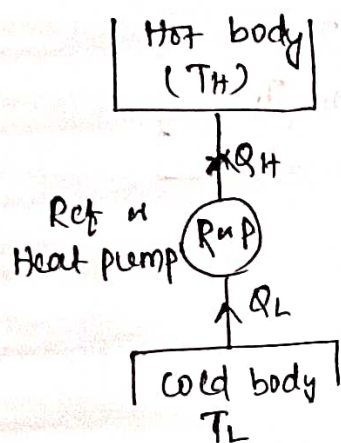
Mathematically,

$$\eta_{th} = \frac{\text{max}^{\text{m}} \text{work obtained}}{\text{Total heat supplied}} = \frac{Q_H - Q_L}{Q_H} = 1 - \frac{Q_L}{Q_H}$$

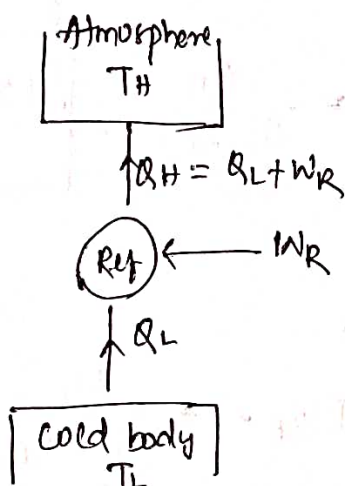
$$(\eta_{th})_{max} = 1 - \frac{T_L}{T_H}$$

3) Clausius Statement: According to Clausius statement "It is impossible for a machine working on a cyclic process to transfer heat from a body at a lower temperature to a body at a higher temperature without the aid of an external agency".

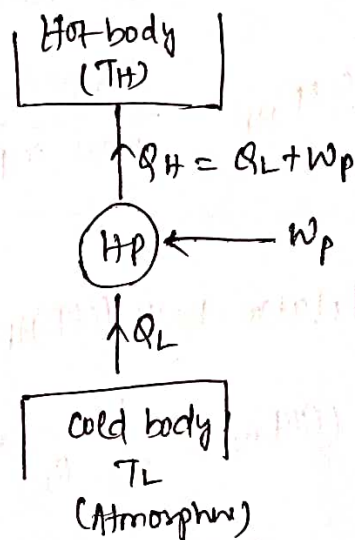
→ In other words, heat cannot flow itself from a cold body to a hot body without the help of an external agency (i.e. without the expenditure of mechanical work)



(a) [PMM-II]



(b) [Refrigerator]



(c) [Heat pump]

In order to achieve the object of transferring heat from a cold body to a hot body, the refrigerator and a heat pump, while operating on a cyclic process, require an input work as shown in fig (b) & fig (c).

* Refrigerator: It is a device which operating on a cyclic process, maintains the temperature of a cold body (refrigerated space) at a temperature lower than the temperature of the surroundings.

→ In case of refrigerator, the atmosphere acts as a hot body while in case of a heat pump, the atmosphere acts as a cold body.

→ The performance of refrigerator and heat pump is measured in terms of coefficient of performance which is defined as the ratio of the max^m heat transferred is desired effect to the amount of work required to produce the desired effect.

Mathematically, $COP = \frac{\text{desired effect}}{\text{work input}}$

$$\boxed{(COP)_{Ref} = \frac{Q_L}{W_R} = \frac{Q_L}{Q_H - Q_L}} \quad , \quad \boxed{[(COP)_{max}]_{Ref} = \frac{T_L}{T_H - T_L}}$$

* Heat pump :- It is a device which operating in a cyclic process maintains the temperature of a hot body (heated space) at a temperature higher than the temperature of surroundings.

$$\rightarrow \boxed{(COP)_{HP} = \frac{\text{desired effect}}{\text{work input}} = \frac{Q_H}{Q_H - Q_L}} \quad \rightarrow \boxed{[(COP)_{HP}]_{max} = \frac{T_H}{T_H - T_L}}$$

* Relation betn $(COP)_{HP}$ & $(COP)_{Ref}$

$$(COP)_{HP} = \frac{Q_H}{Q_H - Q_L} \Rightarrow (COP)_{HP} - 1 = \frac{Q_H}{Q_H - Q_L} - 1$$

$$\Rightarrow (COP)_{HP} - 1 = \frac{Q_H - Q_H + Q_L}{Q_H - Q_L} \Rightarrow (COP)_{HP} - 1 = \frac{Q_L}{Q_H - Q_L}$$

$$\Rightarrow (COP)_{HP} - 1 = (COP)_{Ref} \Rightarrow \boxed{(COP)_{HP} = (COP)_{Ref} + 1}$$

Q-11) An engine works between the temperature limits of 1775 K and 375 K. What can be the maximum thermal efficiency of this engine?

soln: $T_1 = 1775 \text{ K}, T_2 = 375 \text{ K}$

$$\eta_{max} = 1 - \frac{T_2}{T_1} = 1 - \frac{375}{1775} = 0.7887 = 78.87\% \quad \underline{\underline{Ans}}$$

Q-12) A cold storage is to be maintained at -5°C while the surroundings are at 35°C . The heat leakage from the surroundings into the cold storage is estimated to be 29 kW. The actual COP of the refrigeration plant is $\frac{1}{3}$ of an ideal plant working between the same temperatures. Find the power required to drive the plant.

Soln: Given $T_L = -5^\circ\text{C} = 268\text{K}$, $T_H = 35^\circ\text{C} = 308\text{K}$.

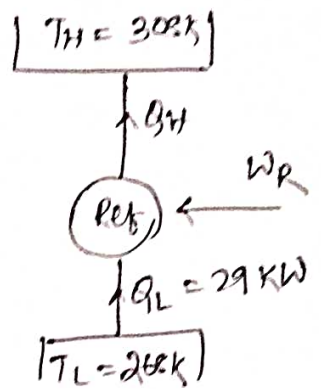
$$Q_L = 29\text{KW}, (\text{COP})_{\text{act}} = \frac{1}{3} (\text{COP})_{\text{ideal}}, W_R = ?$$

$$(\text{COP})_{\text{ideal}} = \frac{T_L}{T_H - T_L} = \frac{268}{308 - 268} = 6.7$$

$$(\text{COP})_{\text{act}} = \frac{1}{3} (\text{COP})_{\text{ideal}} = \frac{1}{3} \times 6.7 = 2.233$$

$$(\text{COP})_{\text{act}} = \frac{Q_L}{W_R - Q_L} \Rightarrow 2.233 = \frac{29}{W_R}$$

$$\Rightarrow W_R = \frac{29}{2.233} = 12.987\text{KW} \underline{\underline{m}}$$



Ch 5: INTERNAL COMBUSTION ENGINE (I.C. Engine)

5.1 Introduction :-

As the name suggests, the internal combustion engines (I.C engine) are those engines in which the combustion of fuel takes place inside the engine cylinder. These are petrol, diesel & gas engines.

⇒ I.C. Engines:

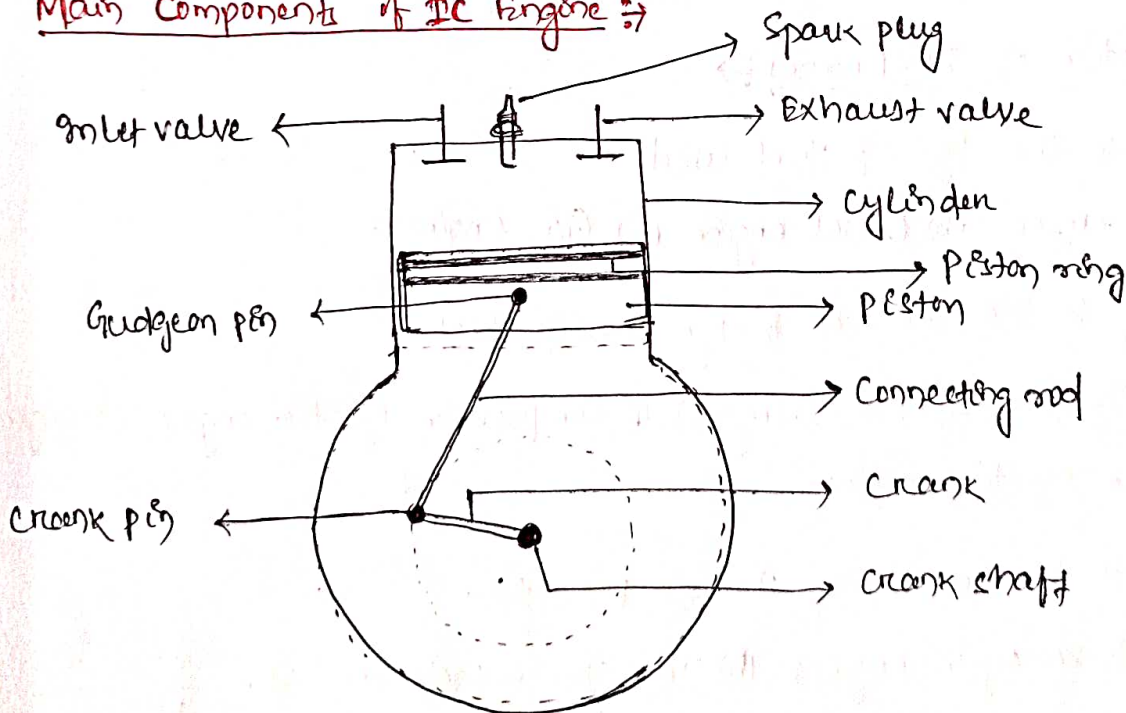
- (i) The combustion of fuel takes place inside the engine cylinder.
- (ii) Since combustion of fuel takes place inside the engine cylinders, these engines are very noisy.
- (iii) The working pressure and temperature inside the cylinder is very high.
- (iv) Because of high pressure & temperature, special alloys are used for the manufacture of engine cylinder & its parts.
- (v) An I.C engine have efficiency about 30-40 percent.
- (vi) It can be started instantaneously.

5.2 Classification of IC Engines ⇒

- 1) According to the type of fuel used:
 - (a) Petrol engine
 - (b) Diesel engine
 - (c) Gas engines.
- 2) According to the method of ignition of fuel:
 - (a) Spark ignition engine (S.I. engine)
 - (b) Compression ignition engine (C.I. engine)
 - (c) Hot spot ignition engine.
- 3) According to the number of strokes per cycle:
 - (a) Four stroke cycle engines
 - (b) Two stroke cycle engines.
- 4) According to the cycle of operation.
 - (a) Otto cycle (K_n as constant volume cycle)
 - (b) Diesel cycle (K_n as constant pressure cycle)
 - (c) Dual cycle (K_n as semi-diesel cycle)

- 5) According to the speed of the engine
- Slow speed engine
 - Medium speed engine
 - High speed engine
- 6) According to the cooling system.
- Air-cooled engines
 - Water-cooled engines.
 - Evaporative cooling engines.
- 7) According to the method of fuel injection.
- Carburettor engines
 - Air injection engines
 - Airless or solid injection engines.
- 8) According to the number of cylinders.
- Single cylinder engines
 - Multi-cylinder engines.
- 9) According to the arrangement of cylinders.
- Vertical engines
 - Horizontal engines
 - Radial engines
 - In-line multi-cylinder engines
 - V-type multi-cylinder engines.
 - Opposite-cylinder engines
 - Opposite-piston engines.

5.3 Main Components of IC Engine :-



① Cylinder :-

- It is one of the most important part of the engine, in which the piston moves to and fro in order to develop power.
- It is made of steel alloys or aluminium alloys.
- The engine cylinder has to withstand more than 50 bar pressure & temperature above 2000°C.

② Cylinder head :-

- It acts as cover to close the cylinder.
- The cylinder head contains inlet valve, exhaust valve & spark plug.

③ Piston :-

- It is the heart of an IC engine.
- The main function is to transmit the force exerted by the burning of charge to the connecting rod.
- It is made of aluminium alloys which are light in weight.

④ Piston rings :-

- These are circular rings & made of special steel alloys which retain elastic properties even at high temperature.
- There are two sets of rings mounted on the piston.
- The function of the upper rings is to provide a tight seal to prevent leakage of the burnt gases into the lower portion.
- The function of the lower rings is to provide effective seal to prevent leakage of the oil into the engine cylinders.

⑤ Connecting Rod :-

- It is the link between the piston and crankshaft.
- Its function is to transmit force from the piston to the crankshaft.
- It converts the reciprocating motion of the piston into circular motion of the crankshaft, in the working stroke.

⑥ Crank case!

→ It is made of cast iron.

→ It serves as a sump for the lubricating oil.

⑦ Flywheel!

→ It is a big wheel, mounted on the crankshaft, whose function is to maintain its speed constant.

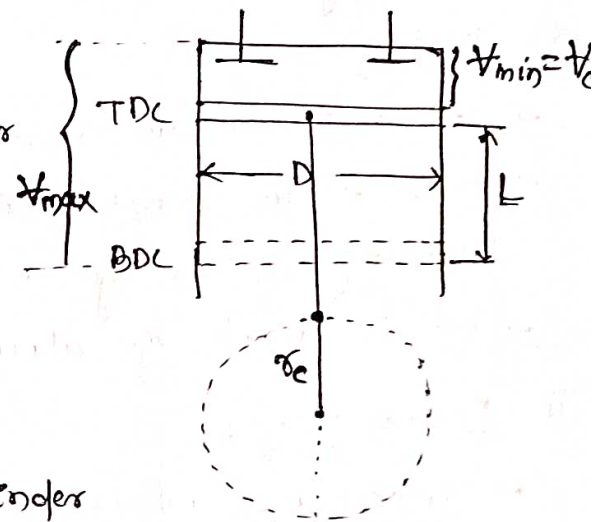
→ It is done by storing excess energy during the power stroke, which is returned during the other strokes.

5.4 Basic Terminologies:

① Top Dead Centre (TDC)

→ A piston is said to be at TDC when cylinder volume is minimum.

→ The minimum cylinder volume is known as clearance volume (V_c).



② Bottom Dead Centre (BDC)

→ A piston is said to be at BDC when cylinder volume is maximum.

③ Stroke Length (L)

→ It is the distance travelled by piston when it moves from TDC to BDC or vice versa.

$$L = 2r_c \quad r_c = \text{Crank radius}$$

④ Bore (D)

→ Internal diameter of the cylinder is known as bore.

⑤ Swept Volume (V_s)

→ The volume swept by piston as it moves from TDC to BDC or vice versa is known as swept volume.

⑥ Displacement Volume (V_d)

→ Displacement volume of an engine is the swept volume multiplied by number of cylinders (n).

$$V_d = n V_s$$

① Clearance Ratio (C) ⇒

→ It is defined as the ratio of clearance volume to the swept volume of the cylinder.

$$C = \frac{V_c}{V_s} \quad [C < 1] \quad [\because V_c < V_s]$$

② Compression Ratio (r) ⇒

→ It is defined as the ratio of maximum volume to the minimum volume in the cylinder.

$$r = \frac{V_{\max}}{V_{\min}} \Rightarrow r = \frac{V_c + V_s}{V_c} = 1 + \frac{V_s}{V_c}$$

NOTE ⇒ Relation between r & C

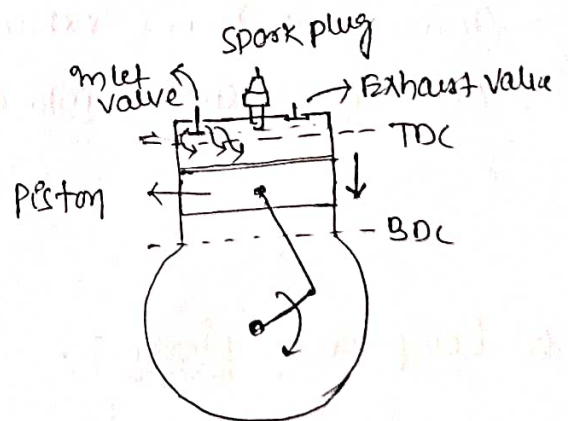
$$r = \frac{V_c + V_s}{V_c} = 1 + \frac{V_s}{V_c} = 1 + \frac{1}{\left(\frac{V_c}{V_s}\right)} = 1 + \frac{1}{C}$$

$$\therefore r = 1 + \frac{1}{C}$$

S.S FOUR STROKE PETROL ENGINE ⇒

① Suction Stroke:-

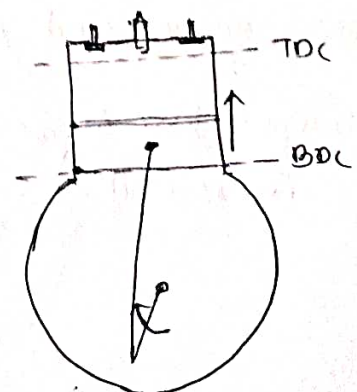
- Piston moves from TDC to BDC
- Inlet valve opens & air-fuel mixture is sucked into the cylinder.
- Exhaust valve closed.



(Suction stroke)

② Compression Stroke:-

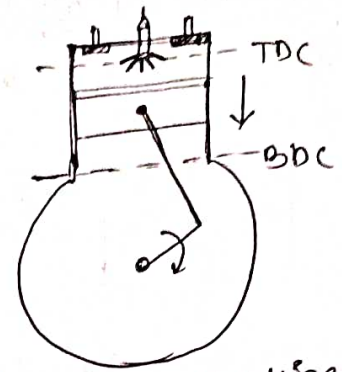
- Piston moves from BDC to TDC
- Inlet valve & exhaust valve closed
- Air-fuel mixture compressed
- The pressure & temperature of air-fuel mixture is increased.



(Compression stroke)

③ Expansion or Working stroke ⇒

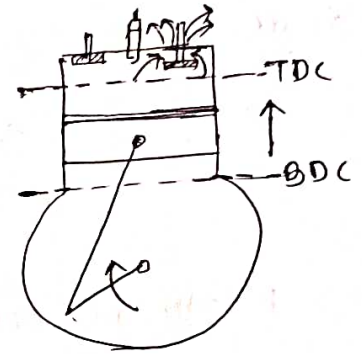
- Piston moves TDC to BDC.
- Inlet valve & exhaust valve closed.
- Air fuel mixture is ignited with the help of sparkplug.
- In this stroke, power is produced.



(Expansion or working stroke)

④ Exhaust Stroke ⇒

- Piston moves BDC to TDC.
- Inlet valve closed & exhaust valve opened.
- The burnt gases passed out through exhaust valve into the atmosphere.

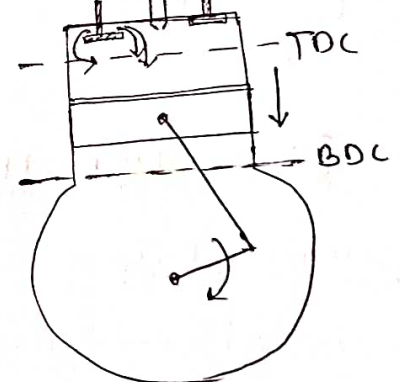


(Exhaust stroke)
fuel injection valve
inlet valve exhaust valve

5.6 FOUR STROKE DIESEL ENGINE ⇒

① Suction Stroke ⇒

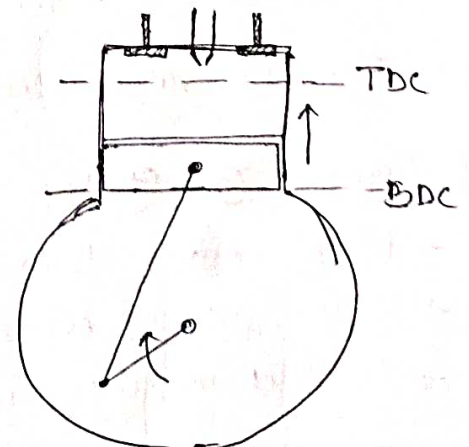
- Piston moves TDC to BDC
- Inlet valve opens & exhaust valve closed
- Only air is sucked into the cylinder.



(Suction stroke)

② Compression Stroke ⇒

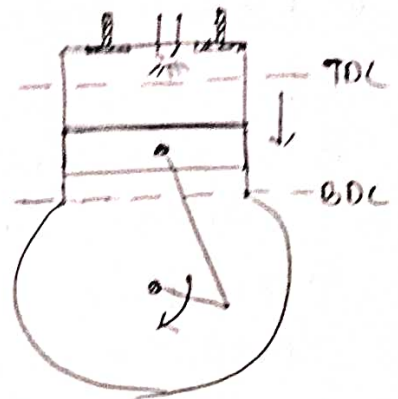
- Piston moves BDC to TDC
- Inlet valve and exhaust valve closed
- Temperature & pressure of the charged (air) is increased.



(Compression stroke)

③ Expansion Stroke :-

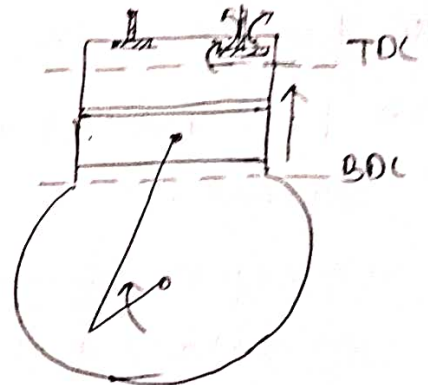
- Piston moves from TDC to BDC
- inlet valve & exhaust valve closed.
- The fuel injector is injected fuel in the form of fine spray into the engine cylinder.



[Expansion stroke]

④ Exhaust Stroke :-

- Piston moves BDC to TDC
- inlet valve closed & exhaust valve open
- The burnt gases pushed out from engine cylinder to atmosphere.

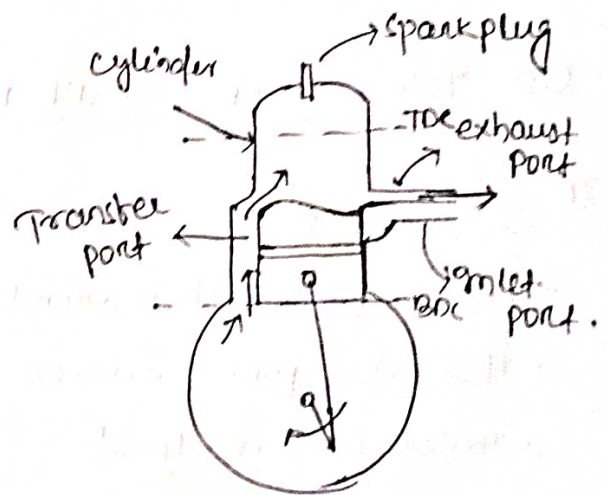


[Exhaust stroke]

S.7 TWO STROKE PETROL ENGINE :-

① Suction Stroke :-

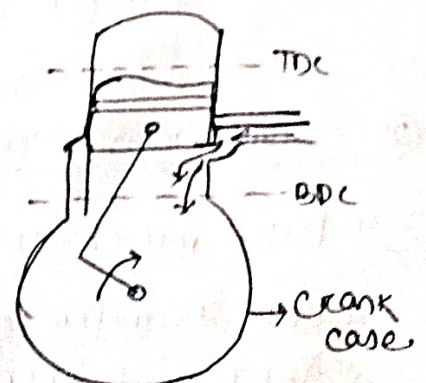
- Piston moves from TDC to BDC
- inlet port closed
- Both transfer port & exhaust port opened.
- The fresh air-fuel mixture entered into the engine cylinder through transfer port.



[Suction stroke]

② Compression Stroke :-

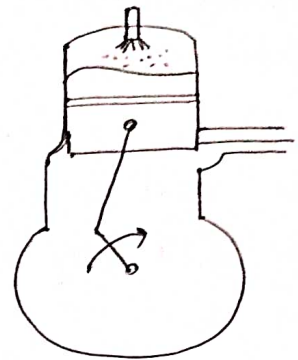
- Piston moves from BDC to TDC
- inlet port open
- Transfer port & exhaust port closed
- The air-fuel is compressed as the piston moves upward & at the same time air-fuel mixture enters into the crank case.



(Compression stroke)

③ Expansion Stroke:-

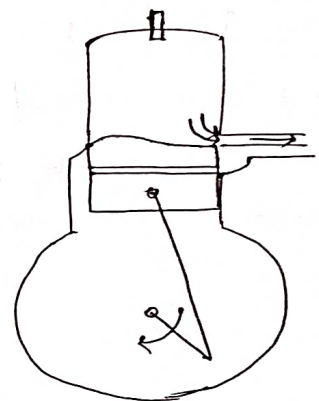
- Piston moves from TDC to BDC
- The air fuel mixture is ignited with the help of a spark plug.
- The pressure & the temperature of the product of combustion increases.
- The hot burnt gas expanded.



[Expansion Stroke]

④ Exhaust Stroke:-

- Piston moves down wards & exhaust port is opened.
- The products of combustion exhausted through the exhaust port into the atmosphere.

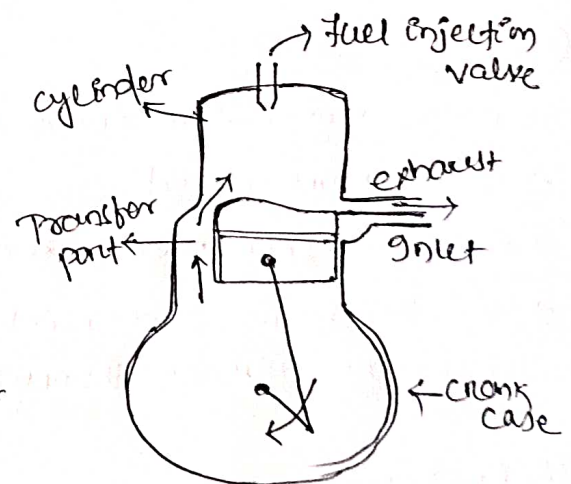


[Exhaust stroke]

5.8 TWO STROKE DIESEL ENGINE ⇒

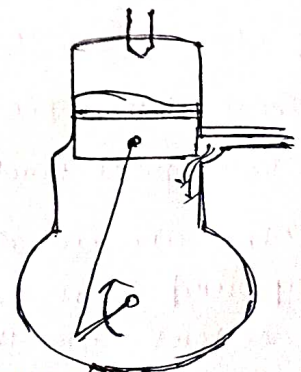
① Suction Stage:-

- Piston moves downwards.
- Transfer port & exhaust port is opened
- inlet port is closed.
- The fresh air flows into the cylinder through transfer port from crank case.



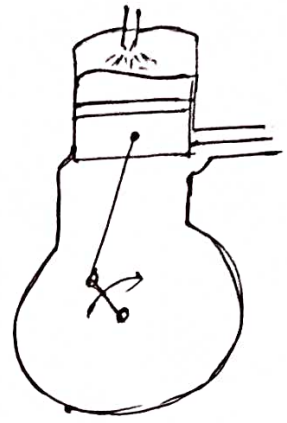
② Compression Stage:-

- Piston moves upward & compressed the air.
- Both transfer port & exhaust port closed.
- inlet port opened & fresh air enters into the crank case.



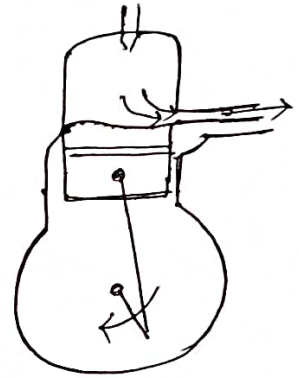
③ Expansion Stage :-

- The fuel oil is injected in the form of fine spray.
- The fuel ignited & the pressure and temperature of the products of combustion increases.
- The hot burnt gases expanded due to high speed of piston i.e. caused by high pressure.



④ Exhaust Stage :-

- The exhaust port is opened.
- Piston moves downwards.
- The products of combustion exhausted through the exhaust port into the atmosphere.



S.9 Differentiation between Four Stroke & Two Stroke engine.

Four Stroke Engine

- One power stroke occurred for every two revolution of crank.
- Valve is used
- It is used mostly in multi-cylinder engine
- Heavier flywheel is used
- Engine is heavy
- Engine design is complicated
- More thermal efficiency
- More loss of mechanical energy
- Less noise & less wear & tear
- It occupies more space
- It is used in car, bus, truck etc

Two Stroke Engine

- One power stroke occurred for one revolution of crank.
- Port is used
- It is used mostly in single cylinder engine
- Lighter flywheel is used
- Engine is lighter
- Engine design is simple.
- Less thermal efficiency.
- Less loss of mechanical energy.
- More noise & more wear & tear.
- It occupies less space.
- It is used in scooter, motorcycle etc.

Ch 6 :- TESTING OF INTERNAL COMBUSTION ENGINES :-

6.1 :- Thermodynamic Tests for I.C. Engine :-

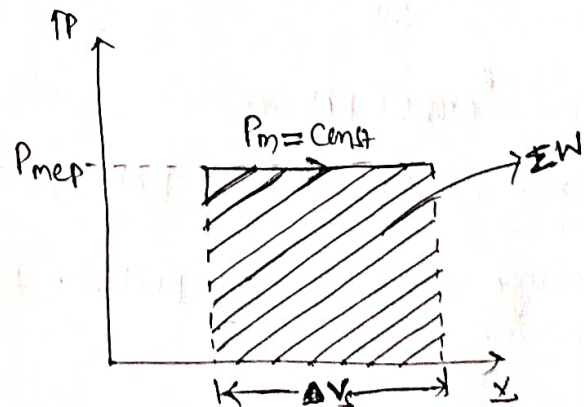
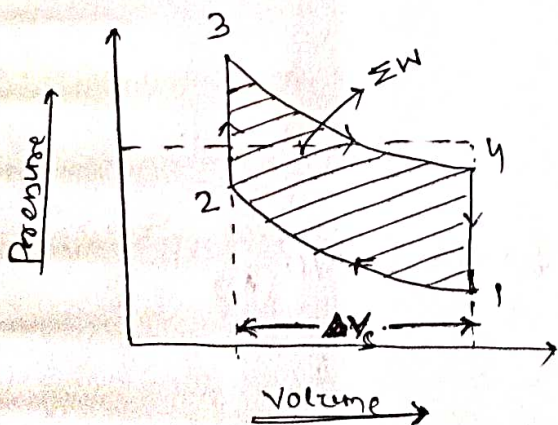
An IC engine is put to thermodynamic tests, so as to determine the following quantities.

- (1) Indicated mean effective pressure.
- (2) Indicated power (I.P)
- (3) Speed of the engine
- (4) Brake torque
- (5) Brake power
- (6) Mechanical losses (Motoring test)
- (7) Mechanical efficiency
- (8) Fuel consumption
- (9) Thermal efficiency
- (10) Air consumption
- (11) Volumetric efficiency
- (12) Various temperatures
- (13) Heat balance sheet.

6.2 Indicated Mean Effective Pressure :-

→ Indicated mean effective pressure is the average pressure, that induced in the combustion chamber during the complete thermodynamic cycle in internal combustion engines.

→ It is determined by the height of a rectangle of an area equal to the area of the indicator diagram. The length of the rectangle is equal to the length of the indicator diagram.



$$P_{mep} = \frac{\text{Work done}}{\text{Stroke volume}} \Rightarrow P_{mep} = \frac{\Sigma W}{V_c}$$

6.3 Indicated Power \Rightarrow (I.P)

\rightarrow I.P is the power actually developed by the engine cylinder.

$$\text{I.P} = \frac{P_m L A n K}{60}$$

where P_m = Actual mean effective pressure from indicator diagram in Pascal

L = Length of stroke (m)

A = Area of piston (m^2)

N = Speed of the engine (r.p.m)

n = Number of working stroke per minute

$\approx N \rightarrow$ for two stroke

$\approx \frac{N}{2} \rightarrow$ for four stroke

K = Number of cylinders

Example: A single cylinder, two stroke petrol engine develops 4 kW indicated power. Find the average speed of the piston, if the mean effective pressure is 6.5 bar & piston diameter is 100 mm.

Solⁿ: Given I.P = 4 kW, $K=1$, $n=N$, $P_m = 6.5 \text{ bar} = 6.5 \times 10^5 \text{ Pa}$,

$$D = 100 \text{ mm} = 0.1 \text{ m}$$

$$\text{Area (A)} = \frac{\pi}{4} D^2 = \frac{\pi}{4} (0.1)^2 = 7.855 \times 10^{-3} \text{ m}^2$$

$$\text{I.P} = \frac{P_m L A n K}{60} = \frac{6.5 \times 10^5 \times L \times 7.855 \times 10^{-3} \times N \times 1}{60}$$

$$\text{I.P} = 0.0851 LN$$

$$4 \times 10^3 = 0.0851 LN \rightarrow LN = 47$$

$$\therefore \text{Average speed of the piston} = 2LN = 2 \times 47 = 94 \text{ m/s. (Ans)}$$

6.4 Brake Power: (B.P)

The Brake Power is the power available at the crank shaft.

$$B.P = \frac{2\pi NT}{60}$$

where $T = \text{Torque (N-m)}$

$N = \text{Speed (r.p.m)}$

Brake torque, $T = W \times L$ where $W = \text{load on brake (N)}$
 $L = \text{length of brake (m)}$

6.5 Efficiencies of D.C. Engine:-

The efficiency of an engine is defined as the ratio of work done to the energy supplied to an engine.

$$\eta = \frac{\text{Work done}}{\text{heat supplied.}}$$

① Mechanical Efficiency :- It is the ratio of brake power (B.P) to the indicated power (I.P)

$$\eta_m = \frac{B.P}{I.P}$$

$$I.P = B.P + F.P$$

F.P = friction power

→ The power lost in overcoming friction.

② Overall efficiency :- It is the ratio of work obtained in the crankshaft in a given time to the energy supplied by the fuel during the same time.

$$\Rightarrow \text{Energy supplied by fuel per minute} = \frac{m_f \times C}{60} \text{ kJ}$$

where $m_f = \text{mass of fuel (kg per hour)}$

$C = \text{calorific value in } \left(\frac{\text{kJ}}{\text{kg}}\right)$

$$\Rightarrow \text{Work obtained in crankshaft per min} = B.P \times 60 \text{ kJ} \left(\frac{\text{kJ}}{\text{s}} \times \text{s}\right)$$

$$\therefore \text{Overall efficiency, } \eta_o = \frac{B.P \times 60}{\frac{m_f \times C}{60}} \Rightarrow \eta_o = \frac{B.P \times 3600}{m_f \times C}$$

$B.P = \text{in kW}$
 $m_f = \text{kg/hr}$
 $C = \frac{\text{kJ}}{\text{kg}}$

③ Indicated thermal efficiency \Rightarrow

It is the ratio of the heat equivalent to one kW hour to the heat in the fuel per I.P hour.

$$\text{Mathematically, } \eta_t = \frac{\text{Heat equivalent to one kW hour}}{\text{Heat in fuel per I.P hour}} = \frac{3600}{\frac{m_f \times C}{\text{I.P}}}$$

$$\eta_t = \frac{\text{I.P} \times 3600}{m_f \times C}$$

Note \Rightarrow Specific fuel consumption per I.P per hour = $\frac{m_f}{\text{I.P}}$

④ Brake thermal efficiency \Rightarrow It is the ratio of the heat equivalent to one kW hour to the heat in fuel per B.P hour.

$$\text{Mathematically, } \eta_b = \frac{\text{Heat equivalent to one kW hour}}{\text{Heat in fuel per B.P hour}} = \frac{3600}{\frac{m_f \times C}{\text{B.P}}}$$

$$\eta_b = \frac{\text{B.P} \times 3600}{m_f \times C}$$

⑤ Air **Note** \Rightarrow Brake specific fuel consumption = $\frac{m_f}{\text{B.P}}$

⑤ Air Standard efficiency \Rightarrow

$$\eta = 1 - \frac{1}{r^{\gamma-1}} \longrightarrow \text{Petrol engine}$$

$$= 1 - \frac{1}{r^{\gamma-1}} \left[\frac{\rho^{\gamma}-1}{\gamma(\rho-1)} \right] \longrightarrow \text{diesel engine}$$

where

r = Compression ratio

γ = Ratio of specific heat

ρ = cut-off ratio

⑥ Relative efficiency \Rightarrow It is also known as efficiency ratio. It is the ratio of indicated thermal efficiency to the air standard efficiency.

$$\text{Mathematically, Relative efficiency} = \frac{\text{Indicated thermal efficiency}}{\text{Air standard efficiency}}$$

⑦ Volumetric efficiency: It is the ratio of actual volume / mass of charge admitted to the swept volume / mass of the piston.

$$\text{Mathematically, } \eta_v = \frac{\text{Actual volume}}{\text{Swept volume}} \Rightarrow \eta_v = \frac{V_a}{V_s}$$

Q-11] A gas engine has piston diameter of 150 mm, length of stroke 400 mm & mean effective pressure 5.5 bar. The engine makes 120 explosions per minute. Determine the mechanical efficiency of the engine, if its B.P is 5 kW.

Sol: Given: $D_p = 150 \text{ mm} = 0.15 \text{ m}$, $L = 400 \text{ mm} = 0.4 \text{ m}$, $P_m = 5.5 \text{ bar} = 5.5 \times 10^5 \text{ Pa}$,

$\eta = 120$, B.P = 5 kW, $K = 1$

Mechanical efficiency;

$$\eta_m = \frac{\text{B.P}}{\text{I.P}} = \frac{5}{7.79}$$

$$\Rightarrow \eta_m = 0.642 = 64.2\% \quad (\text{Ans})$$

I.P. = ?

$$A = \frac{\pi}{4} (D_p)^2 = \frac{\pi}{4} (0.15)^2 = 0.0177 \text{ m}^2$$

$$\text{I.P.} = \frac{P_m L A N K}{60} = \frac{5.5 \times 10^5 \times 0.4 \times 0.0177 \times 120}{60}$$

$$\text{I.P.} = 7.79 \text{ kW}$$

Q-2] A four cylinder two stroke cycle petrol engine develops 23.5 kW brake power at 2500 rpm. The mean effective pressure of each piston is 8.5 bar & the mechanical efficiency is 85%. Calculate the diameter & stroke of each cylinder, assuming length of stroke equal to 1.5 times the diameter of the cylinder.

Sol: $K = 4$, B.P = 23.5 kW, $N = 2500 \text{ rpm}$, $P_m = 8.5 \text{ bar} = 8.5 \times 10^5 \text{ Pa}$, $\eta_m = 0.85$

$$L = 1.5 D_p$$

$$A = \frac{\pi}{4} (D_p)^2 = 0.785 D^2$$

$$n = N = 2500 \text{ (two stroke)}$$

$$\text{I.P.} = \frac{\text{B.P}}{\eta_m} = \frac{23.5}{0.85} = 27.65 \text{ kW}$$

$$N \times \text{I.P.} = \frac{P_m L A N K}{60} \Rightarrow 27.65 \times 10^3 = \frac{8.5 \times 10^5 \times 1.5 D^2 \times 2500 \times 4}{60}$$

$$I.P. = \frac{\rho_m L A N K}{60} \rightarrow 27.65 \times 10^3 = \frac{8.5 \times 10^5 \times 1.5 D \times 0.785 D^2 \times 2500 \times 4}{60}$$

$$\rightarrow D^3 = 0.000165 \rightarrow D = 0.055 \text{ m} = 55 \text{ mm}$$

$$L = 1.5 \times 55 = 82.5 \text{ mm} \quad (\text{Ans})$$

Q-21 An engine uses 6.5 kg of oil per hour of calorific value 30,000 KJ/kg. If the B.P of the engine is 22 kW & mechanical efficiency 85%.

Calculate: 1. Indicated thermal efficiency

2. Brake thermal efficiency.

3. Specific fuel consumption in kg/B.P/h

Sol: Given $m_f = 6.5 \text{ kg/hr}$, $C = 30000 \text{ KJ/kg}$, $B.P = 22 \text{ kW}$, $\eta_m = 85\% = 0.85$

① Indicated thermal efficiency

$$I.P. = \frac{B.P}{\eta_m} = \frac{22}{0.85} = 25.88 \text{ kW}$$

$$\eta_t = \frac{I.P. \times 3600}{m_f \times C} = \frac{25.88 \times 3600}{6.5 \times 30000} = 0.48 \text{ or } 48\%$$

② Brake thermal efficiency

$$\eta_b = \frac{B.P \times 3600}{m_f \times C} = \frac{22 \times 3600}{6.5 \times 30000} = 0.406 \text{ or } 40.6\%$$

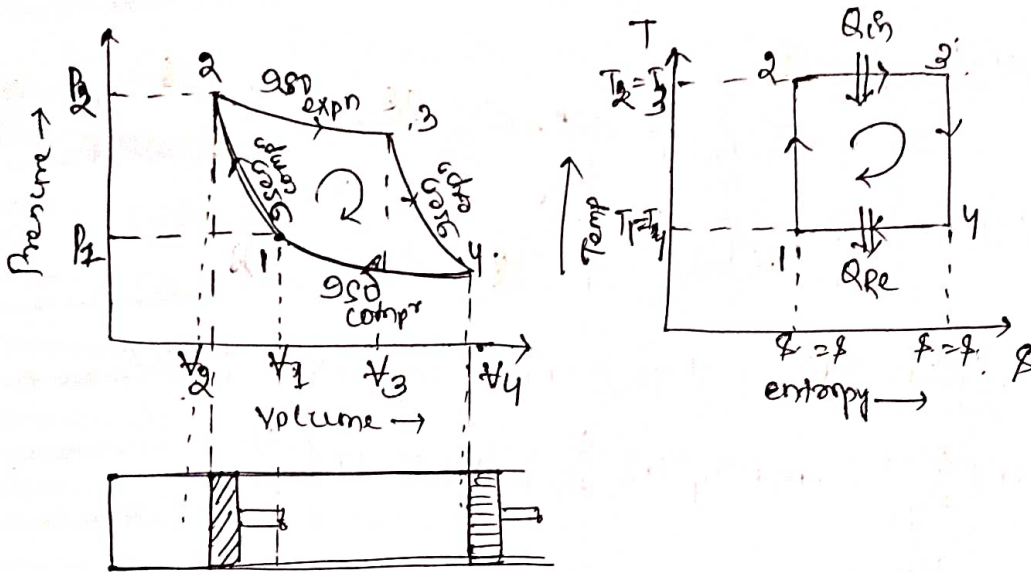
③ Specific fuel consumption.

$$BSFC = \frac{m_f}{B.P} = \frac{6.5}{22} = 0.295 \text{ kg/B.P/h} \quad \underline{\underline{\text{Ans}}}$$

Ch-7: GAS POWER CYCLE ⇒

7.1 CARNOT CYCLE :-

→ Carnot cycle consists of two isothermal & two isentropic processes.



Process: 1-2 ⇒ ~~isentropic~~ isentropic compression is Reversible adiabatic compression

2-3 ⇒ Isothermal expansion

3-4 ⇒ isentropic expansion is Reversible adiabatic expansion.

4-1 ⇒ Isothermal compression

$$\Rightarrow \eta_{th} = \frac{\text{Work done}}{\text{heat supplied}} = \frac{\sum W}{Q_s} = \frac{\sum Q}{Q_s} = \frac{Q_s - Q_R}{Q_s} = 1 - \frac{Q_R}{Q_s}$$

⇒ 1-2 ⇒ isentropic compression process

$$\begin{aligned}
 PV^\gamma &= C \\
 \Rightarrow P_1 V_1^\gamma &= P_2 V_2^\gamma \\
 \Rightarrow \frac{P_2}{P_1} &= \left(\frac{V_1}{V_2}\right)^\gamma
 \end{aligned}
 \quad \left| \quad
 \begin{aligned}
 T_1 V_1^{\gamma-1} &= T_2 V_2^{\gamma-1} \\
 \Rightarrow \frac{T_2}{T_1} &= \left(\frac{V_1}{V_2}\right)^{\gamma-1} \\
 \Rightarrow \frac{T_2}{T_1} &= r^{\gamma-1}
 \end{aligned}
 \quad \left| \quad
 \frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}}$$

where $r = \frac{V_1}{V_2}$ = compression ratio

$$Q_{1-2} = 0$$

$$W_{1-2} = - \left\{ \frac{P_1 V_1 - P_2 V_2}{\gamma - 1} \right\} \text{ (-ve)}$$

$$\hookrightarrow (W_{1-2})_{\text{input}} = \frac{P_2 V_2 - P_1 V_1}{\gamma - 1}$$

⇒ 2-3: isothermal heat addition process / isothermal expansion process

$$Q_{2-3} = W_{2-3} = P_2 V_2 \ln \left(\frac{V_3}{V_2} \right)$$

$$\Rightarrow Q_{in} = Q_{2-3} = m R T_2 \ln \left(\frac{V_3}{V_2} \right) \quad [\because P_2 V_2 = m R T_2]$$

⇒ 3-4: isentropic expansion process:

$$Q_{3-4} = 0$$

$$W_{3-4} = \frac{P_3 V_3 - P_4 V_4}{\gamma - 1}$$

$$\left. \begin{array}{l} P_3 V_3^\gamma = P_4 V_4^\gamma \\ \Rightarrow \frac{P_4}{P_3} = \left(\frac{V_3}{V_4} \right)^\gamma \end{array} \right\} \begin{array}{l} T_3 V_3^{\gamma-1} = T_4 V_4^{\gamma-1} \\ \Rightarrow \frac{T_4}{T_3} = \left(\frac{V_3}{V_4} \right)^{\gamma-1} \end{array} \left| \frac{T_3}{T_4} = \left(\frac{P_3}{P_4} \right)^{\frac{\gamma-1}{\gamma}} \right.$$

⇒ 4-1: isothermal heat rejection process / isothermal compression process.

$$Q_{4-1} = W_{4-1} = -P_4 V_4 \ln \left(\frac{V_1}{V_4} \right) = -m R T_4 \ln \left(\frac{V_1}{V_4} \right) = -m R T_1 \ln \left(\frac{V_1}{V_4} \right)$$

$$Q_{rej} = Q_{4-1} = m R T_1 \ln \left(\frac{V_4}{V_1} \right)$$

Now we can see that for process 1-2; $\frac{T_2}{T_1} = \left(\frac{V_2}{V_1} \right)^{\gamma-1}$ — (I)

for process 3-4; $\frac{T_4}{T_3} = \left(\frac{V_3}{V_4} \right)^{\gamma-1}$ ⇒ $\frac{T_1}{T_2} = \left(\frac{V_2}{V_1} \right)^{\gamma-1}$ ⇒ $\frac{T_2}{T_1} = \left(\frac{V_4}{V_3} \right)^{\gamma-1}$ — (II)

from eq (I) & (II) ⇒ $\left(\frac{V_2}{V_1} \right)^{\gamma-1} = \left(\frac{V_4}{V_3} \right)^{\gamma-1}$

$$\Rightarrow \frac{V_2}{V_1} = \frac{V_4}{V_3} \Rightarrow \frac{V_3}{V_2} = \frac{V_4}{V_1} \Rightarrow \frac{V_2}{V_1} = \frac{V_3}{V_4}$$

$$\therefore \eta_{th} = \frac{\text{work done}}{\text{heat supplied}} = 1 - \frac{Q_R}{Q_S} = 1 - \frac{m R T_1 \ln \left(\frac{V_4}{V_1} \right)}{m R T_2 \ln \left(\frac{V_3}{V_2} \right)} = 1 - \frac{T_1}{T_2}$$

$$\boxed{\eta_{th} = 1 - \frac{T_1}{T_2}}$$

$$\Rightarrow \boxed{\eta_{th} = 1 - \frac{1}{r^{\gamma-1}}}$$

[$\because \frac{T_2}{T_1} = r^{\gamma-1}$] where $r = \text{compression ratio}$
 $r = \frac{V_1}{V_2}$

Q1) A Carnot engine, working between 650 K & 310 K, produces 150 kJ of work. Find the thermal efficiency & heat added during the process.

Soln: Given $T_2 = 650 \text{ K}$, $T_1 = 310 \text{ K}$, $W = 150 \text{ kJ}$

$$\eta = 1 - \frac{T_1}{T_2} = 1 - \frac{310}{650} = 0.523 \text{ or } 52.3\%$$

$$Q_{\text{added}} = \frac{W}{\eta} = \frac{150}{0.523} = 286.8 \text{ kJ} \quad (\text{Ans})$$

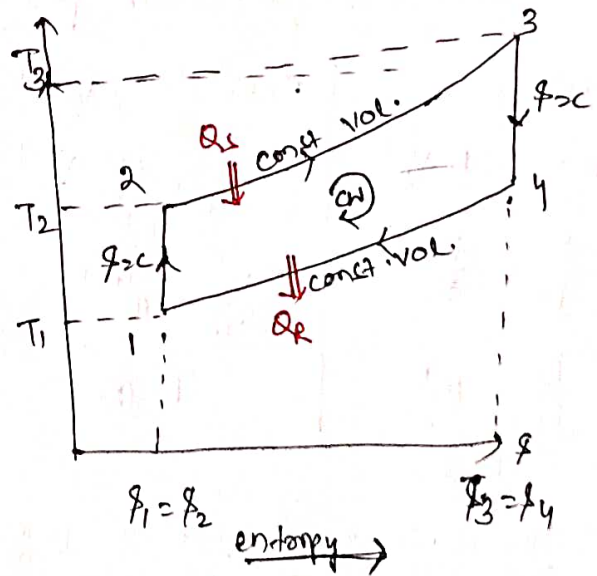
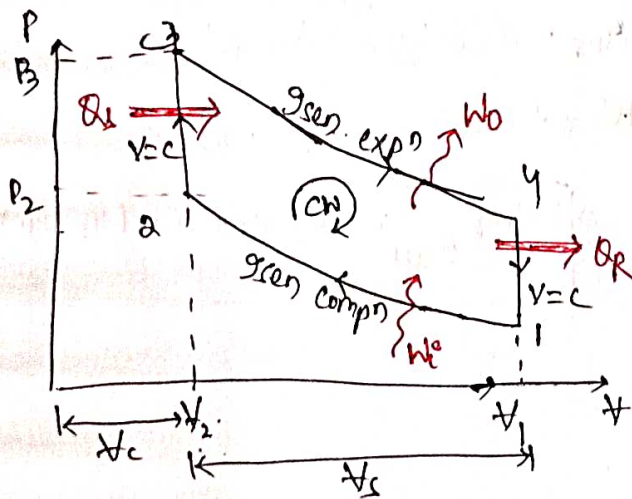
7.2 OTTO CYCLE :-

→ Otto cycle simulates the spark ignition engine (Petrol engine).

→ It is also known as constant volume cycle, as the heat is received & rejected at a constant volume.

→ The working substance is air.

→ The ideal Otto cycle consists of two-constant volume & two reversible adiabatic or isentropic process.



Process:

- 1-2 → isentropic compression / Reversible adiabatic compression
- 2-3 → Constant volume heat addition / Isochoric heat addition
- 3-4 → isentropic expansion / Reversible adiabatic expansion
- 4-1 → Constant volume heat rejection / Isochoric heat rejection.

Q. Otto cycle; $P_{max} = P_3$ | $V_{max} = V_1 = V_4$
 $P_{min} = P_1$ | $V_{min} = V_2 = V_3$

- Clearance volume (V_c) = $V_2 = V_3$
- Swept volume (V_s) = $V_1 - V_2 = V_4 - V_3$
- clearance ratio (C) = $\frac{V_c}{V_s} = \frac{V_2}{V_1 - V_2}$
- Explosion ratio (π_p) = $\frac{P_3}{P_2}$
- Expansion ratio (ϵ) = $\frac{V_4}{V_3}$
- For Otto cycle; $\epsilon = \frac{V_4}{V_3} = \frac{V_1}{V_2} \Rightarrow \boxed{\epsilon = \pi}$

• Compression ratio (π) = $\frac{V_{max}}{V_{min}}$

$\pi = \frac{V_1 + V_c}{V_c} = 1 + \frac{1}{C}$

$\pi = \frac{V_1}{V_2} = \frac{V_4}{V_3}$

• $T_{max} = T_3$

$T_{min} = T_1$

• Relation between swept volume & initial volume.

$V_s = V_1 - V_2 \Rightarrow V_s = V_1 (1 - \frac{V_2}{V_1}) \Rightarrow V_s = V_1 (1 - \frac{1}{\pi}) \Rightarrow V_s = V_1 (\frac{\pi - 1}{\pi})$

$\Rightarrow \boxed{\frac{V_s}{V_1} = \frac{\pi - 1}{\pi}}$

\Rightarrow 1-2: isentropic compression process:

$PV^\gamma = C$

$\Rightarrow P_1 V_1^\gamma = P_2 V_2^\gamma$

$\Rightarrow \frac{P_2}{P_1} = \left(\frac{V_1}{V_2}\right)^\gamma$

$\Rightarrow \boxed{\frac{P_2}{P_1} = \pi^\gamma}$ (L-0)

$T_1 V_1^{\gamma-1} = T_2 V_2^{\gamma-1}$

$\Rightarrow \frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{\gamma-1}$

$\Rightarrow \boxed{\frac{T_2}{T_1} = \pi^{\gamma-1}}$ (L-2)

$Q_{1-2} = 0$, $Q_{1-2} = W_{1-2} + \Delta U_{1-2}$

$\Rightarrow W_{1-2} = -[\Delta U_{1-2}]$

$\Rightarrow \boxed{(W_{1-2})_{out} = U_2 - U_1 = C_V (T_2 - T_1)}$

\Rightarrow 2-3: isochoric heat addition process:

$\frac{P_3}{P_2} = \pi_p$

$\frac{P_3}{T_2} = \frac{P_2}{T_2}$

$\Rightarrow \frac{T_3}{T_2} = \frac{P_3}{P_2}$

$\Rightarrow \frac{T_3}{T_2} = \pi_p$

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

$\Rightarrow Q_{2-3} = \Delta U_{2-3}$

$\Rightarrow \boxed{Q_{2-3} = U_3 - U_2 = C_V (T_3 - T_2)}$

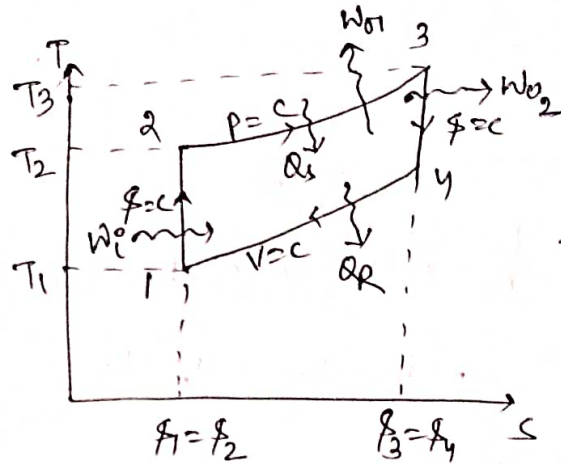
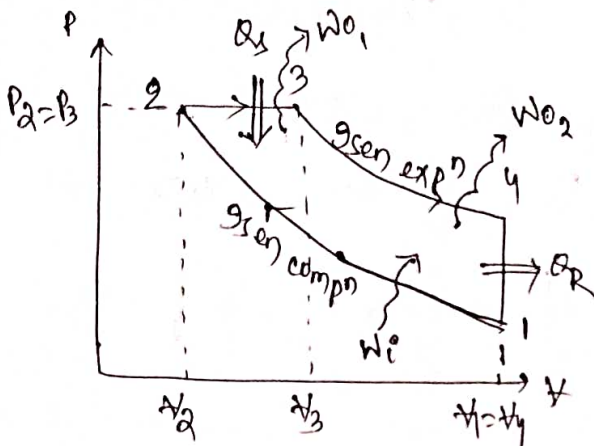
$\rightarrow Q_s$

7.3 DIESEL CYCLE ⇒

→ It simulates compression-ignition engine.

→ It is also known as constant pressure cycle as heat is received at constant pressure.

→ It consists of two isentropic processes, a constant pressure process & a constant volume process.



Processes:

- 1-2 ⇒ Isentropic compression process
- 2-3 ⇒ Constant pressure heat addition
- 3-4 ⇒ Isentropic expansion process
- 4-1 ⇒ Constant volume heat rejection.

- Clearance volume, $v_c = v_2$
- Swept volume, $v_s = v_1 - v_2$
- Clearance ratio, $c = \frac{v_c}{v_s} = \frac{v_2}{v_1 - v_2}$
- Compression ratio, $r_c = \frac{v_{max}}{v_{min}} = \frac{v_1}{v_2} = 1 + \frac{1}{c}$
- Cut-off volume, $v_{co} = v_3 - v_2$
- Cut-off ratio, $\rho = \frac{v_3}{v_2}$
- Expansion ratio, $\epsilon = \frac{v_4}{v_3}$

⇒ Relation betⁿ r_c, ρ, ϵ

$$r_c = \frac{v_1}{v_2} \quad \text{--- (1)}$$

$$\rho = \frac{v_3}{v_2} \quad \text{--- (2)}$$

$$\epsilon = \frac{v_4}{v_3} \quad \text{--- (3)}$$

$$\rho \epsilon = \frac{v_3}{v_2} \times \frac{v_4}{v_3} = \frac{v_4}{v_2} = \frac{v_1}{v_2}$$

$$\Rightarrow \boxed{\rho \epsilon = r_c}$$

$$\Rightarrow P_{max} = P_2 = P_3$$

$$T_{max} = T_3$$

$$P_{min} = P_1$$

$$T_{min} = T_1$$

$$v_{max} = v_1$$

$$v_{min} = v_2$$

⇒ 1-2: isentropic compression process

$$pV^\gamma = c$$

$$\rightarrow p_1 V_1^\gamma = p_2 V_2^\gamma$$

$$\rightarrow \frac{p_2}{p_1} = \left(\frac{V_1}{V_2}\right)^\gamma$$

$$\rightarrow \frac{p_2}{p_1} = \kappa^\gamma$$

$$T_1 V_1^{\gamma-1} = T_2 V_2^{\gamma-1}$$

$$\rightarrow \frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{\gamma-1}$$

$$\rightarrow \frac{T_2}{T_1} = \kappa^{\gamma-1}$$

$$Q_{1-2} = 0$$

$$Q_{1-2}^{\uparrow 0} = W_{1-2} + \Delta U_{1-2}$$

$$\rightarrow W_{1-2} = -[\Delta U_{1-2}]$$

$$\rightarrow W_{\text{input}} = \Delta U_{1-2}$$

$$\rightarrow \boxed{W_p = U_2 - U_1 = C_V(T_2 - T_1)}$$

⇒ 2-3: isobaric/constant pressure heat addition process

$$p_2 = p_3, \quad \frac{V_2}{T_2} = \frac{V_3}{T_3}$$

$$\rightarrow \frac{T_3}{T_2} = \frac{V_3}{V_2} = f$$

$$Q_{2-3} = \Delta h_{2-3}$$

$$\rightarrow Q_{2-3} = h_3 - h_2$$

$$\rightarrow Q_{2-3} = C_p(T_3 - T_2)$$

$$W_{2-3} = p_2(V_3 - V_2)$$

$$\rightarrow \boxed{W_{01} = p_2(V_3 - V_2)}$$

⇒ 3-4: isentropic expansion process

$$pV^\gamma = c$$

$$\rightarrow p_3 V_3^\gamma = p_4 V_4^\gamma$$

$$\rightarrow \frac{p_3}{p_4} = \left(\frac{V_4}{V_3}\right)^\gamma$$

$$\rightarrow \frac{p_3}{p_4} = \varepsilon^\gamma$$

$$T_3 V_3^{\gamma-1} = T_4 V_4^{\gamma-1}$$

$$\rightarrow \frac{T_3}{T_4} = \left(\frac{V_4}{V_3}\right)^{\gamma-1}$$

$$\rightarrow \frac{T_3}{T_4} = \varepsilon^{\gamma-1}$$

$$Q_{3-4}^{\uparrow 0} = W_{3-4} + \Delta U_{3-4}$$

$$\rightarrow W_{3-4} = -[\Delta U_{3-4}]$$

$$\rightarrow W_{3-4} = -(U_4 - U_3) = U_3 - U_4$$

$$\rightarrow \boxed{W_{02} = U_3 - U_4 = C_V(T_3 - T_4)}$$

⇒ 4-1: isochoric heat rejection process

$$\frac{p_4}{p_1} = \frac{p_4}{p_3} \times \frac{p_3}{p_2} \times \frac{p_2}{p_1}$$

$$\rightarrow \frac{p_4}{p_1} = \frac{1}{\varepsilon^\gamma} \times \kappa^\gamma$$

$$\rightarrow \frac{p_4}{p_1} = \left(\frac{\kappa}{\varepsilon}\right)^\gamma = f^\gamma$$

$$\rightarrow \frac{p_4}{p_1} = f^\gamma$$

$$\frac{T_4}{T_1} = \frac{T_4}{T_3} \times \frac{T_3}{T_2} \times \frac{T_2}{T_1}$$

$$\rightarrow \frac{T_4}{T_1} = \frac{1}{\varepsilon^{\gamma-1}} \times f \times \kappa^{\gamma-1}$$

$$\rightarrow \frac{T_4}{T_1} = \left(\frac{\kappa}{\varepsilon}\right)^{\gamma-1} \times f$$

$$\rightarrow \frac{T_4}{T_1} = f$$

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

$$\rightarrow Q_{4-1} = \Delta U_{4-1}$$

$$\rightarrow Q_R = -[\Delta U_{4-1}]$$

$$\rightarrow Q_R = -(U_1 - U_4)$$

$$\rightarrow \boxed{Q_R = U_4 - U_1 = C_V(T_4 - T_1)}$$

$$\eta_{th} = 1 - \frac{Q_R}{Q_S} = 1 - \frac{C_v(T_4 - T_1)}{C_p(T_3 - T_2)} = 1 - \frac{(T_4 - T_1)}{\gamma(T_3 - T_2)}$$

$$\eta_{diesel} = 1 - \frac{(T_4 - T_1)}{\gamma(T_3 - T_2)} = 1 - \frac{1}{\gamma} \frac{T_1 \left(\frac{T_4}{T_1} - 1 \right)}{T_2 \left(\frac{T_3}{T_2} - 1 \right)} = 1 - \frac{1}{\gamma} \frac{T_1 (\gamma^\gamma - 1)}{T_2 (\gamma - 1)}$$

$$\eta_{diesel} = 1 - \frac{1}{\gamma} \left(\frac{T_2}{T_1} \right)^{\gamma-1} \frac{\gamma^\gamma - 1}{\gamma - 1}$$

$$\eta_{diesel} = 1 - \frac{1}{\gamma^{\gamma-1}} \times \frac{\gamma^\gamma - 1}{\gamma(\gamma - 1)}$$

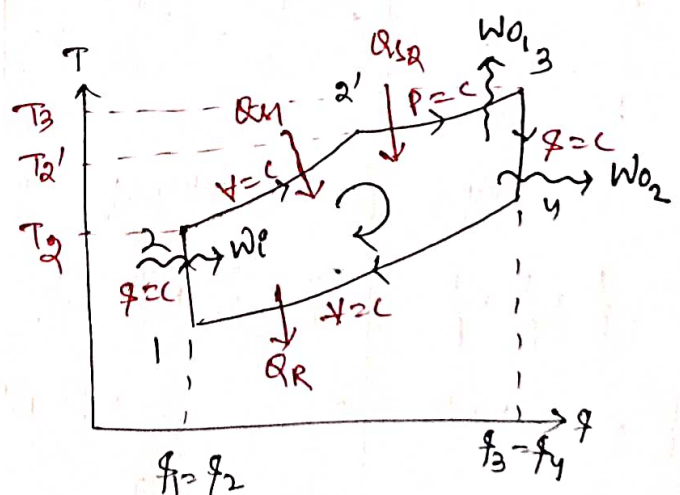
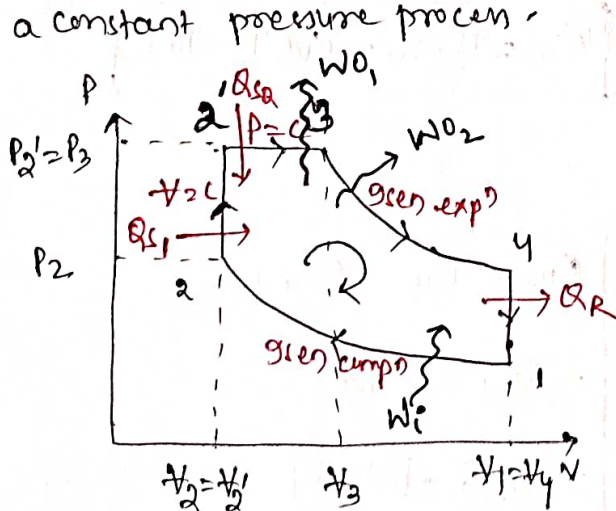
7.4 DUAL COMBUSTION CYCLE \Rightarrow

\rightarrow It is a combination of Otto & Diesel cycle.

\rightarrow It is also called semi-diesel cycle.

\rightarrow In this cycle heat is absorbed partly at constant volume & partly at a constant pressure.

\rightarrow The dual cycle consists of two isentropic, two constant volume & a constant pressure process.



Processes:

1-2 \rightarrow isentropic compression process

2-2' \rightarrow isochoric heat addition process

2'-3 \rightarrow isobaric heat addition process

3-4 \rightarrow isentropic expansion process

4-1 \rightarrow isochoric heat rejection process.

• $v_{max} = v_1 = v_4$, $p_{max} = p_2' = p_3$

$v_{min} = v_2 = v_2'$, $p_{min} = p_1$

• $C = \frac{v_c}{v_s} = \frac{v_2}{v_1 - v_2}$

• $\pi = \frac{v_1}{v_2}$

• $\pi_p = \frac{p_2'}{p_2} = \frac{p_3}{p_2} = \beta$

• $\eta = \frac{v_3}{v_2'} = \frac{v_3}{v_2}$

• $\epsilon = \frac{v_4}{v_3}$

• $\eta \epsilon = \pi$

⇒ 1-2: isentropic compression process:

$p_1 v_1^\gamma = p_2 v_2^\gamma$

⇒ $\frac{p_2}{p_1} = \left(\frac{v_1}{v_2}\right)^\gamma$

⇒ $\frac{p_2}{p_1} = \pi^\gamma$

$T_1 v_1^{\gamma-1} = T_2 v_2^{\gamma-1}$

⇒ $\frac{T_2}{T_1} = \left(\frac{v_1}{v_2}\right)^{\gamma-1}$

⇒ $\frac{T_2}{T_1} = \pi^{\gamma-1}$

$Q_{1-2} = W_{1-2} + \Delta U_{1-2}$

⇒ $W_{1-2} = -[\Delta U_{1-2}]$

⇒ $W_c = \Delta U_{1-2} = U_2 - U_1$

⇒ $W_c = U_2 - U_1 = C_v(T_2 - T_1)$

⇒ 2-2': isochoric heat addition process:

$\frac{p_2}{T_2} = \frac{p_2'}{T_2'}$

⇒ $\frac{p_2}{p_2'} = \frac{T_2}{T_2'}$

⇒ $\frac{p_2'}{p_2} = \frac{T_2'}{T_2} = \pi_p = \beta$

$W_{2-2'} = 0$

$Q_{2-2'} = W_{2-2'} + \Delta U_{2-2'}$

⇒ $Q_{2-2'} = \Delta U_{2-2'}$

⇒ $Q_{s1} = Q_{2-2'} = C_v(T_2' - T_2)$

⇒ 2'-3: isobaric heat addition process:

$p_2' = p_3$

$\frac{v_2'}{T_2'} = \frac{v_3}{T_3}$

⇒ $\frac{T_3}{T_2'} = \frac{v_3}{v_2'}$

⇒ $\frac{T_3}{T_2'} = \eta$

$W_{2'-3} = p_2'(v_3 - v_2') \Rightarrow W_{q1} = p_2'(v_3 - v_2')$

$Q_{2'-3} = \Delta h_{2'-3}$

$Q_{2'-3} = h_3 - h_{2'} = c_p(T_3 - T_2')$

⇒ $Q_{s2} = Q_{2'-3} = c_p(T_3 - T_2')$

3-4: isentropic expansion process:

$$P_3 V_3^\gamma = P_4 V_4^\gamma$$

$$\Rightarrow \frac{P_3}{P_4} = \left(\frac{V_4}{V_3}\right)^\gamma$$

$$\Rightarrow \frac{P_3}{P_4} = \epsilon^\gamma$$

$$T_3 V_3^{\gamma-1} = T_4 V_4^{\gamma-1}$$

$$\Rightarrow \frac{T_3}{T_4} = \left(\frac{V_4}{V_3}\right)^{\gamma-1}$$

$$\Rightarrow \frac{T_3}{T_4} = \epsilon^{\gamma-1}$$

$$Q_{3-4} = 0$$

$$Q_{3-4} = W_{3-4} + \Delta U_{3-4}$$

$$\Rightarrow W_{3-4} = -[\Delta U_{3-4}]$$

$$\Rightarrow W_{3-4} = -[U_4 - U_3] = U_3 - U_4$$

$$\Rightarrow W_{0,2} = W_{3-4} = C_V (T_3 - T_4)$$

4-1: isochoric heat rejection process:

$$\frac{P_4}{T_4} = \frac{n}{T_1}$$

$$\Rightarrow \frac{P_4}{P_1} = \frac{T_4}{T_1}$$

$$\Rightarrow \frac{P_4}{P_1} = \frac{T_4}{T_1} = \beta \beta^\gamma$$

$$\frac{P_4}{P_1} = \frac{P_4}{P_3} \times \frac{P_3}{P_2'} \times \frac{P_2'}{P_2} \times \frac{P_2}{P_1}$$

$$\Rightarrow \frac{P_4}{P_1} = \frac{1}{\epsilon^\gamma} \times 1 \times \pi_p \times \pi_r^\gamma$$

$$\Rightarrow \frac{P_4}{P_1} = \left(\frac{\pi}{\epsilon}\right)^\gamma \times \pi_p = \beta^\gamma \times \pi_p$$

$$\Rightarrow \frac{P_4}{P_1} = \frac{\pi_p \cdot \beta^\gamma}{\beta} = \frac{T_4}{T_1}$$

$$W_{4-1} = 0$$

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

$$Q_{4-1} = \Delta U_{4-1} = U_1 - U_4 \Rightarrow Q_R = -(U_1 - U_4)$$

$$\Rightarrow Q_R = Q_{4-1} = C_V (T_4 - T_1)$$

$$\Rightarrow \eta_{\text{dual}} = 1 - \frac{Q_R}{Q_S} = 1 - \frac{Q_R}{Q_{2-1} + Q_{2-3}} = 1 - \frac{C_V (T_4 - T_1)}{C_V (T_2' - T_2) + C_p (T_3 - T_2')}$$

$$\eta_{\text{dual}} = 1 - \frac{T_4 - T_1}{(T_2' - T_2) + \gamma (T_3 - T_2')}$$

$$\eta_{\text{dual}} = 1 - \frac{T_1 \left(\frac{T_4}{T_1} - 1\right)}{T_2 \left[\left(\frac{T_2'}{T_2} - 1\right) + \gamma \left(\frac{T_3}{T_2} - \frac{T_2'}{T_2}\right) \right]}$$

$$\left[\begin{aligned} \because \frac{T_3}{T_2} &= \frac{T_3}{T_2'} \times \frac{T_2'}{T_2} \\ \Rightarrow \frac{T_3}{T_2} &= \beta \times \pi_p \end{aligned} \right]$$

$$\eta_{\text{dual}} = 1 - \frac{\left(\frac{T_4}{T_1} - 1\right)}{\left(\frac{T_2}{T_1}\right) \left[(\pi_p - 1) + \gamma (\beta \pi_p - \pi_p) \right]}$$

$$\Rightarrow \eta_{\text{dual}} = 1 - \frac{1}{\pi^{\gamma-1}} \cdot \frac{\pi_p \beta^\gamma - 1}{(\pi_p - 1) + \gamma \pi_p (\beta - 1)}$$

$$\eta_{\text{dual}} = 1 - \frac{1}{\pi^{\gamma-1}} \times \frac{\pi_p \beta^\gamma - 1}{\gamma \pi_p (\beta - 1) + (\pi_p - 1)}$$

$$\Rightarrow \eta_{\text{dual}} = 1 - \frac{1}{\pi^{\gamma-1}} \times \frac{\beta \beta^\gamma - 1}{\gamma \beta (\beta - 1) + (\beta - 1)}$$

Q-11 The efficiency of an Otto cycle is 60% & $\gamma = 1.5$. What is the compression ratio?

Soln: Given, $\eta_{\text{otto}} = 60\% = 0.6$

$$\gamma = 1.5$$

$$\eta = 1 - \frac{1}{r^{\gamma-1}} \Rightarrow 0.6 = 1 - \frac{1}{r^{1.5-1}} \Rightarrow \frac{1}{r^{0.5}} = 0.4 \Rightarrow r = 6.25 \quad \underline{\underline{\text{Ans}}}$$

Q-12 In a constant volume "Otto cycle", the pressure at the end of compression is 15 times that at the start, the temperature of air at the beginning of compression is 38°C and maximum temperature attained in the cycle is 1950°C. Determine (i) Compression ratio

(ii) Thermal efficiency of the cycle

(iii) Workdone per kg of air.

Take γ for air = 1.4

Soln: Given data; $P_2 = 15 P_1 \Rightarrow \frac{P_2}{P_1} = 15$.

$$T_1 = 38 + 273 = 311 \text{ K}$$

$$T_3 = 1950 + 273 = 2223 \text{ K}$$

(i) Compression ratio (r)

$$\text{Process 1-2: } P_1 V_1^\gamma = P_2 V_2^\gamma \Rightarrow \frac{P_2}{P_1} = \left(\frac{V_1}{V_2}\right)^\gamma = r^\gamma$$

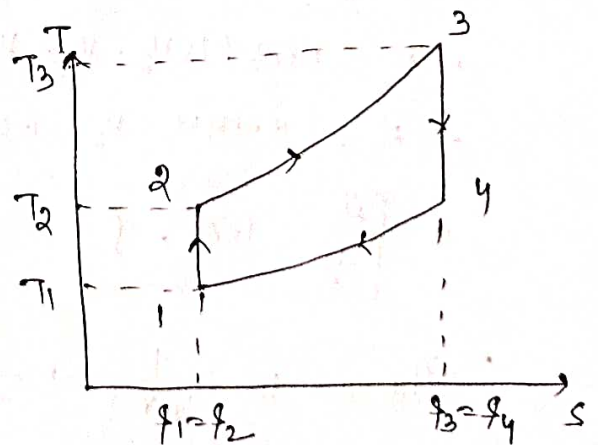
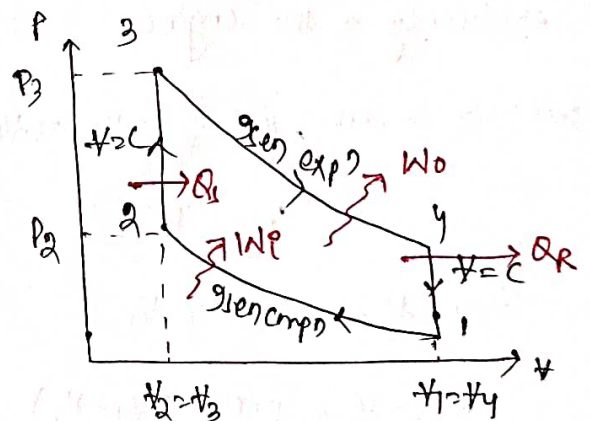
$$\Rightarrow r^\gamma = 15 \Rightarrow r^{1.4} = 15 \Rightarrow r = (15)^{\frac{1}{1.4}}$$

$$\Rightarrow \boxed{r \approx 6.9}$$

(ii) Thermal efficiency (η_0)

$$\eta_0 = 1 - \frac{1}{r^{\gamma-1}} = 1 - \frac{1}{(6.9)^{1.4-1}} = 1 - \frac{1}{(6.9)^{0.4}}$$

$$\boxed{\eta_0 = 0.538 = 53.8\%}$$



(iii) Workdone:

We know $\eta_0 = \frac{\text{Workdone}}{\text{heat supplied}} \Rightarrow \text{Workdone} = \eta_0 \times \text{heat supplied}$

heat supplied: $Q_s \cong Q_{2-3} = C_v(T_3 - T_2)$

$\rightarrow Q_s = 0.717 \frac{\text{kJ}}{\text{kg K}} (2223 - 671.7) \text{ K}$

$\rightarrow Q_s = 1112.3 \frac{\text{kJ}}{\text{kg of air}}$

$T_1 V_1^{\gamma-1} = T_2 V_2^{\gamma-1}$

$\Rightarrow \frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{\gamma-1} = r^{\gamma-1} = (6.9)^{0.4}$

$\therefore T_2 = T_1 \times 2.16 \Rightarrow T_2 = 671.7 \text{ K}$

$\therefore \text{Workdone} \cong \eta_0 \times \text{heat supplied} = 0.538 \times 1112.3 = 598.417 \frac{\text{kJ}}{\text{kg of air}}$ Ans

Q-3 A diesel engine has a compression ratio of 15 & heat addition at constant pressure takes place at 6% of stroke. Find the air standard efficiency of the engine.

Soln: Given data, $r = \frac{V_1}{V_2} = 15 \Rightarrow V_1 = 15 V_2$
 $\gamma = 1.4.$

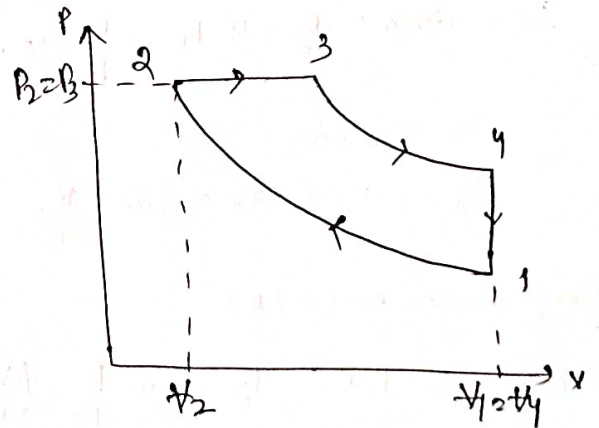
Given: $V_3 - V_2 = 6\% \text{ of } V_3$

$\Rightarrow V_3 - V_2 = 0.06 \times (V_1 - V_2)$

$\rightarrow V_3 = 0.06 (15 V_2 - V_2) + V_2$

$\Rightarrow V_3 = 0.84 V_2 + V_2 = 1.84 V_2$

$\Rightarrow \boxed{\frac{V_3}{V_2} = 1.84 = f}$



$\therefore \eta_{\text{diesel}} = 1 - \frac{1}{r^{\gamma-1}} \times \frac{f^{\gamma} - 1}{\gamma(f-1)} = 1 - \frac{1}{15^{0.4}} \times \frac{(1.84)^{1.4} - 1}{1.4(1.84 - 1)}$

$\eta_d = 0.612 = 61.2\%$ Ans

Q) The stroke & cylinder diameter of a compression ignition engine are 250 mm & 150 mm respectively. If the clearance volume is 0.0004 m^3 & fuel injection takes place at constant pressure for 5% of the stroke. Determine the efficiency of the engine. Assume the engine working on the diesel cycle.

Ans: Given $L = 250 \text{ mm} = 0.25 \text{ m}$

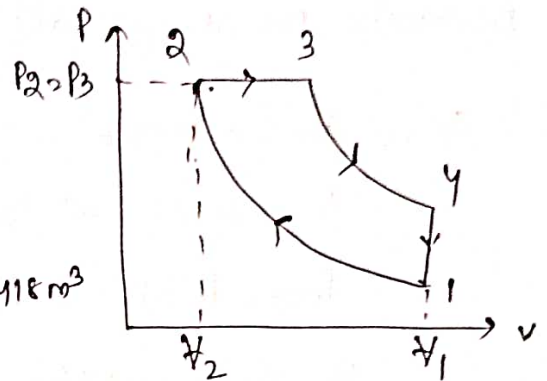
$D = 150 \text{ mm} = 0.15 \text{ m}$

$V_c = V_2 = 0.0004 \text{ m}^3$

$V_s = \frac{\pi}{4} D^2 L = \frac{\pi}{4} \times (0.15)^2 \times 0.25 = 0.004418 \text{ m}^3$

$V_1 = V_c + V_s = 0.0004 + 0.004418$

$\rightarrow V_1 = 0.004818 \text{ m}^3$



Volume at point of cut off; $V_3 - V_2 = 0.05 \times V_s$

$\rightarrow V_3 - V_2 = 0.05 \times 0.004418 \Rightarrow V_3 = 0.0004 + 0.05 \times 0.004418$

$\rightarrow V_3 = 0.000621 \text{ m}^3$

\therefore cut off ratio, $\rho = \frac{V_3}{V_2} = \frac{0.000621}{0.0004} = 1.55$

Compression ratio, $r = \frac{V_1}{V_2} = \frac{0.004818}{0.0004} = 12.04$

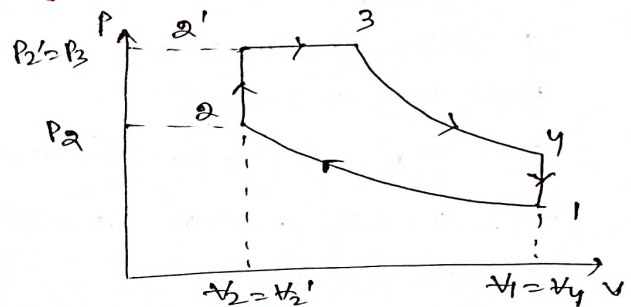
$\eta_{dies} = 1 - \frac{1}{r^{\gamma-1}} \times \frac{\rho^{\gamma} - 1}{\gamma(\rho-1)} = 1 - \frac{1}{(12.04)^{0.4}} \times \frac{1.55^{1.4} - 1}{1.4(1.55-1)}$

$\therefore \eta_d = 0.593 = 59.3\%$

Ans

Q) The swept volume of a diesel engine working on dual cycle is 0.0053 m^3 & clearance volume is 0.00035 m^3 . The maximum pressure is 65 bar. Fuel injection ends at 5% of the stroke. The temperature & pressure at the start of the compression are 80°C & 0.9 bar. Determine the air standard efficiency of the cycle. Take γ for air = 1.4

Soln: Given $V_s = 0.0053 \text{ m}^3$
 $V_c = 0.00035 \text{ m}^3 = V_2 = V_2'$
 $P_{\text{max}} = P_2' = P_3 = 65 \text{ bar}$
 $T_1 = 80^\circ\text{C} = 80 + 273 = 353 \text{ K}$
 $P_1 = 0.9 \text{ bar}$



• ~~compression~~ $\eta_{\text{dual}} = 1 - \frac{1}{r^{\gamma-1}} \cdot \frac{\beta \cdot f^{\gamma} - 1}{\gamma \beta (\gamma - 1) + (\beta - 1)}$

• Compression ratio, $r = \frac{V_1}{V_2} = \frac{V_c + V_s}{V_c} = \frac{0.00035 + 0.0053}{0.00035} = 16.14$

• Cut off volume $\Rightarrow V_3 - V_2' = 0.05 \cdot V_s$

$\Rightarrow V_3 = V_2' + 0.05 \cdot V_s \Rightarrow V_3 = 0.00035 + 0.05 \cdot 0.0053 = 0.000615$

• Cut off ratio $\Rightarrow f = \frac{V_3}{V_2'} = \frac{0.000615}{0.00035} = 1.76$

• 1-2: $P_1 V_1^{\gamma} = P_2 V_2^{\gamma} \Rightarrow P_2 = P_1 \left(\frac{V_1}{V_2}\right)^{\gamma} \Rightarrow P_2 = 0.9 (r)^{\gamma} = 0.9 \times (16.14)^{1.4}$
 $\Rightarrow P_2 = 44.22 \text{ bar}$

• Pressure ratio, π_p or $\beta = \frac{P_2'}{P_2} = \frac{65}{44.22} = 1.469 \approx 1.47$

$\therefore \eta_d = 1 - \frac{1}{r^{\gamma-1}} \cdot \frac{\beta f^{\gamma} - 1}{\gamma \beta (\gamma - 1) + (\beta - 1)} = 1 - \frac{1}{(16.14)^{1.4-1}} \cdot \frac{1.47 \cdot (1.76)^{1.4} - 1}{1.47 \cdot 1.4 (1.76-1) + (1.47-1)}$

$\Rightarrow \eta_d = 1 - 0.322 \left[\frac{3.243 - 1}{1.564 + 0.47} \right] = 0.6383 \approx 63.83\%$ Ans