

**ORISSA SCHOOL OF MINING ENGINEERING,  
KEONJHAR**

**DEPARTMENT OF MECHANICAL ENGINEERING**

**THERMAL ENGINEERING-I  
LECTURE NOTES**

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# CHAPTER-1

## Thermodynamic concept & Terminology

### CONCEPTS AND TERMINOLOGY

- **Thermodynamics**

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

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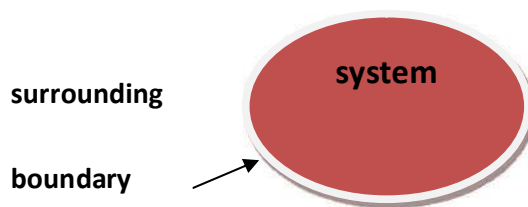
It may be defined as the science which deals with the conversion of heat into mechanical work or energy by using a suitable medium.

- **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. This boundary may be fixed or movable.



system are classified into three types :-

- Open system
- Closed system
- Isolated system

**Open System**

It is also known as *flow system*. Open system is one in which both mass and energy crosses the boundary. Open system is also called control volume. Ex- reciprocating air compressor, turbine, pump etc.

**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 surrounding. Ex – Cylinder piston arrangement, Tea kettle.

**Isolated System**

An isolated system is one in which there is no interaction between the system and surrounding. There is no mass and energy transfer across the system. Ex- Universe, thremoflask etc.

## MACROSCOPIC AND MICROSCOPIC APPROACH

Study of 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 macroscopic 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 and study of each particle having a certain position, velocity and energy at a given instant is considered such a study is also called as *Statistical thermodynamics*.

## CONCEPT OF CONTINUUM

The system is regarded as a continuum i.e. the system is assumed to contain continuous distribution of matter. Thus, from the continuum point of view, the matter is seen as being distributed through space and treats the substance as being continuous disregarding the action of individual molecules. There are no voids and values of action of many molecules and atoms.

## THERMODYNAMIC PROPERTY

- **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.
- **PRESSURE**-Pressure is defined as force per unit area.

Units of pressure are as follows In S.I Pascal (Pa) and  $1 \text{ Pa} = 1 \text{ N/m}^2$

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

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

- **TEMPERATURE**-The temperature is a thermal state of a body which determines the hotness or coldness of a body. The temperature of a body is proportional to the stored molecular energy i.e. the average molecular kinetic energy of the molecules in a system.  
Units of temperature are degree Celsius or Kelvin.

## Intensive and Extensive Property:

- **Intensive property:** The properties which are independent of mass 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. The intensive property includes pressure, temperature, specific volume, specific energy, specific density etc.

- Extensive property: the property which depends upon mass of the system are known as extensive property. The extensive properties include volume, energy, enthalpy, entropy etc.

**State:** The condition of physical existence of a system at any instant of time is called state.

### **Thermodynamic Processes:**

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

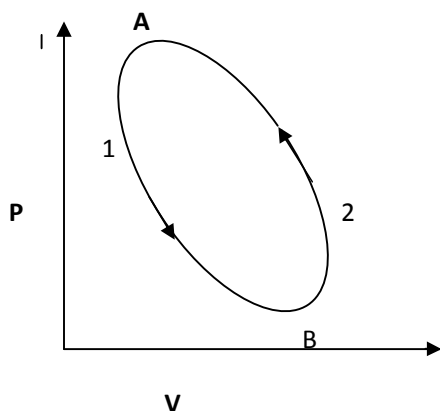
The commonly used processes are:

1. Isochoric Process – The process which takes place at constant volume is said to be isochoric process.
2. Isobaric Process – The process which takes place at constant pressure is said to undergo an isobaric process.
3. Isothermal Process- The process which takes place at constant temperature is said to undergo an isothermal process.
4. Adiabatic Process- The process where there is no heat transfer between the system and the surrounding. The reversible adiabatic process is known as isentropic process.

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

### **Thermodynamic Cycle:**

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



In the fig above:

**A-1-B** and **A-2-B** represents *process*

Whereas **A-1-B-2-A** represent a *thermodynamic cycle*.

### **THERMODYNAMIC EQUILIBRIUM:**

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

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

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

- a) Mechanical Equilibrium
- b) Chemical Equilibrium
- c) Thermal Equilibrium

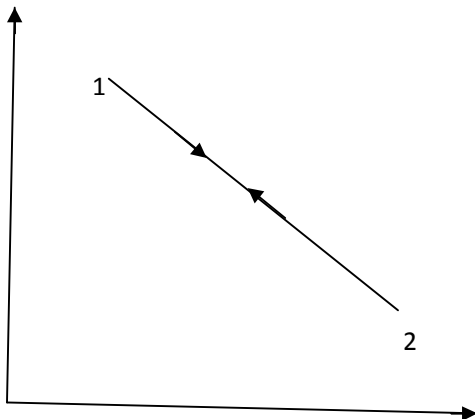
*Mechanical Equilibrium*- when there is no unbalanced force on any part of the system or in-between the system and surrounding then the system is said to be in mechanical equilibrium. For example if the pressure is not uniform throughout the system, then internal changes in the state of the system will take place until the mechanical equilibrium is reached.

*Chemical Equilibrium*- when there is no chemical reaction or transfer of matter from one part of the system to another such as diffusion or solution, then the system is said to exists in a state of chemical equilibrium.

*Thermal Equilibrium*- when there is no temperature difference between the parts of the system or between the system and the surrounding, it is then said to be in thermal equilibrium.

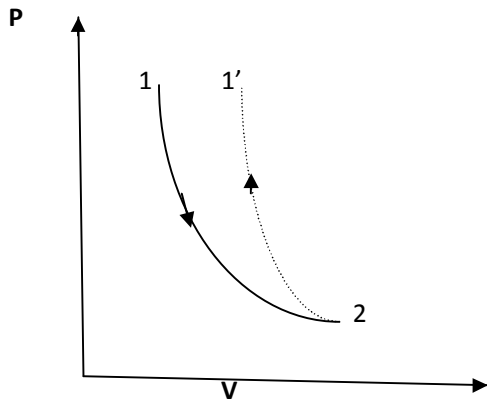
### **REVERSIBLE PROCESS:**

A process which can be reversed in direction and the system retraces the same continuous series of equilibrium states it 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 practise a reversible process cannot be attained, but it can be approximated as a closely as a possible. For example 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

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 it 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 and fuel etc are few examples of irreversible process.



## QUASI-STATIC PROCESS

The word quasi means *almost*. This process is a succession of equilibrium states and infinite slowness is the characteristic feature of quasi-static process. 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.

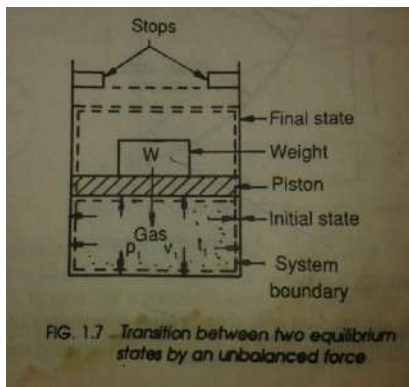


Fig 1

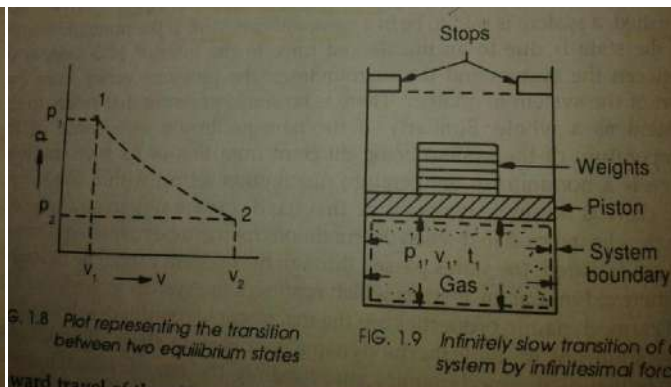


Fig 2

Let us consider a system of gas contained in a cylinder as shown in fig 1 . The system is initially an 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 and the surrounding, and the piston will move upward till it hits the stops .the system will be again in a equilibrium state but if the same process as shown if fig 2 is done by slowing removing very small pieces of weight one by one then the piston will move upward slowly thus the system will be in equilibrium.

## ENERGY AND WORK TRANSFER

A closed system interacts with the surrounding by energy transfer and this energy transfer takes place in two ways i.e. *Work transfer* and *Heat transfer*.

Heat and work are the main mode of energy transfer and there are certain similarities and differences between heat and work.

- The heat and work are boundary phenomena. They are observed at the boundary of the system.
- When a system undergoes a change in state, heat transfer or work done may occur.
- Heat and work are path function and depends upon the process. Hence they are not thermodynamic property and are inexact differential.
- Work is said to be *high grade energy* and heat *low grade energy*. The complete conversion of low grade energy into high grade energy is impossible.

### Work Transfer

The action of a force on a moving body is identified as work. For the work transfer the system has to be such selected that its boundary just move. There cannot be work transfer in a closed system, without moving the system boundaries. In a cylinder piston arrangement the top of the system is moving system boundary and the work is transferred by the movement of the piston.

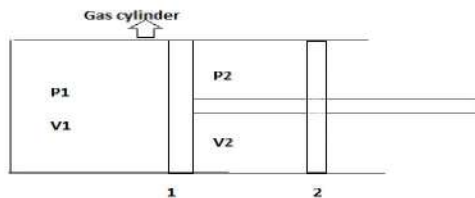
Work done by the system is considered to be *positive* and work done on the system is taken as *negative*.

Work done= force X displacement

Unit of work: Newton-meter (N-m) or Joule(J)

The rate at which work is done upon or by the system is known as *power*. The unit of power is J/s or watt.

### **PdV work or Displacement Work**



Let us consider a gas in the cylinder as shown in the fig above. Let the system initially be at pressure  $P_1$  and volume  $V_1$ . The system is in thermodynamic equilibrium, the piston is the system boundary which moves due to gas pressure. Let the piston move out to a new final position 2 which is also in thermodynamic equilibrium specified by pressure  $P_2$  and volume  $V_2$ . When the piston moves an infinitesimal distance  $dl$  if  $a$  be the area of the piston.

The force  $F$  acting on the piston will be

$$F = p \times a$$

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

$$dW = F \cdot dl = p \times a \times dl = p dV$$

where  $dV = a \times dl$

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

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

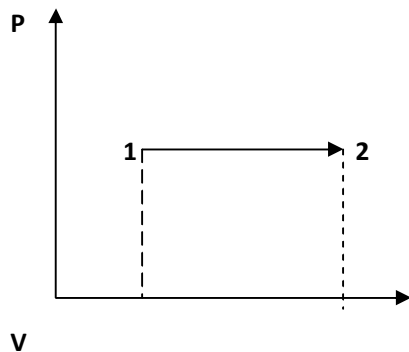
The above equation represents the displacement work.

Displacement work applied to different thermodynamic process

### 1. Isobaric process

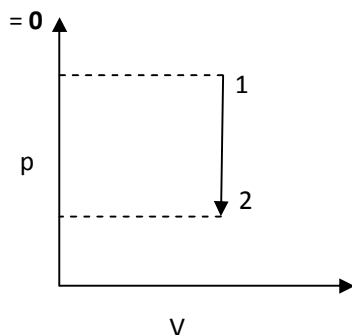
$$W_{1-2} = \int_{V_1}^{V_2} p dV$$

$$= p(V_2 - V_1)$$



### 2. Isochoric process

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





### 3. Isothermal process

In this process  $pV = \text{constant}$

$$pV = P_1 V_1 = C$$

$$P = P_1 V_1 / V$$

$$W_{1-2} = \int_{v_1}^{v_2} p dv$$

$$W_{1-2} = p_1 V_1 \int_{v_1}^{v_2} dV/V$$

$$= p_1 V_1 \ln p_1/p_2$$

### 4. Polytrophic process

The process in which expansion and contraction takes place according to the law  $pV^n = C$

$$pV^n = p_1 v_1^n = p_2 V_2^n = C$$

$$W_{1-2} = \int_{v_1}^{v_2} p dv$$

$$= \int_{v_1}^{v_2} (p_1 V_1^n / V^n) \cdot dV$$

$$= p_1 V_1^n [V^{-n+1} / -n+1]_{v_1}^{v_2}$$

$$= [p_2 V_2^n * V_2^{1-n} - p_1 V_1^n * V_1^{1-n}] / (1-n)$$

$$= (p_1 V_1 - p_2 V_2) / (n-1)$$

### HEAT TRANSFER

Heat is defined as the form of energy that is transferred across a boundary by virtue of temperature difference between the system and the surroundings.

If the heat flows into the system or the system receives heat then heat transfer  $Q$  is taken as *positive* and if heat is rejected from the system then  $Q$  is taken as *negative*.

The heat transfer takes place by three different modes

1. Conduction: the transfer of heat between two bodies in direct contact is called conduction. It is a process of heat transfer from one particle of a body to another in the direction of fall of temperature. For example heat transfer through solids is by conduction.
2. Convection : The process of heat transfer from one particle to another by convection currents i.e. transfer of heat between the wall and fluid system in motion. In this case, the particles of the body move relative to each other.
3. Radiation : Heat transfer between two bodies separated by empty space or gases through electromagnetic waves is radiation.

**Sensible heat:** The heat required for change from liquid state to vapourisation/boiling point is called sensible heat. It is the amount of heat absorbed by one kg of water, when heated at a constant pressure, from the freezing point ( $0^{\circ}\text{C}$ ) to the temperature of formation of steam.

**Latent heat:** It is the amount of heat absorbed to evaporate one kg of water at its boiling point without change of temperature.

**Specific Heat :** The amount of heat required to raise the temperature of unit mass of a substance through one degree is known as specific heat.

The unit of specific heat is  $\text{KJ/kg K}$

Mathematically heat required to raise the temperature of a body is

$$Q = m C(T_2 - T_1) \text{ in kJ}$$

Where,  $m$  = mass of the substance in kg

$C$  = specific heat in  $\text{KJ/Kg K}$

$T_1$  = initial temperature in degree Celsius or Kelvin

$T_2$  = final temperature in degree Celsius or Kelvin

Specific heat at constant volume ( $C_v$ ) : It is defined as amount of heat required to raise the temperature of a unit mass of a gas by one degree at constant volume.

Specific heat at constant pressure ( $C_p$ ) : It is defined as amount of heat required to raise the temperature of a unit mass of a gas by one degree at constant pressure

### **ENERGY:**

The energy is defined as the capacity to do work. In broad sense energy is classified as *stored energy* and *transient energy*.

The energy that remains within the system boundary is called **stored energy** e.g. potential energy, kinetic energy and internal energy.

The energy which crosses the system boundary is known as energy in transition e.g. heat, work, electricity etc.

### **DIFFERENT FORM OF STORED ENERGY**

1. **POTENTIAL ENERGY**-The energy posed by a body by a virtue of its position or state of rest is known as potential energy  
 $P.E = W \times h = mgh$   
 $W$  = weight of the body in N  
 $M$  = mass of the body in kg  
 $g$  = acceleration due to gravity  
 $h$  = height in meter

2. KINETIC ENERGY-The energy posed by a body by virtue of its motion.

Mathematically kinetic energy,

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

V=velocity of the body

3. INTERNAL ENERGY –The energy posed by a body or a system by virtue of its intermolecular arrangement and motions of molecules. The change in temperature causes the change in internal energy. It is usually denoted by U.

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

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

But when the system is stationary and the effect of gravity is neglected then P.E=0 and K.E=0. Thus

$$E = U$$

I.E the total energy is equal to the total energy of system.

# CHAPTER-2

## Laws of Thermodynamics

### Introduction

Heat and work are different forms of the same entity called energy. Energy is always conserved. Energy may enter a system as heat and leave as work and vice-versa.

Energy has two forms-transit energy and stored energy.

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

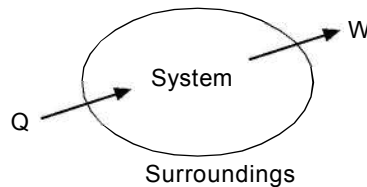
### First law of thermodynamics

Whenever heat is absorbed by a system it goes to increase its internal energy plus to do some external work (Pdv work) i.e.

$$Q = \Delta E + W$$

Where Q is the energy entering a system,  $\Delta E$  increase in internal energy, W – producing some external work.

$$\delta Q = dE + PdV$$

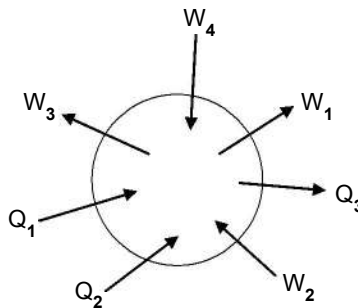


Sometimes more than two energy transfers, so it becomes.

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

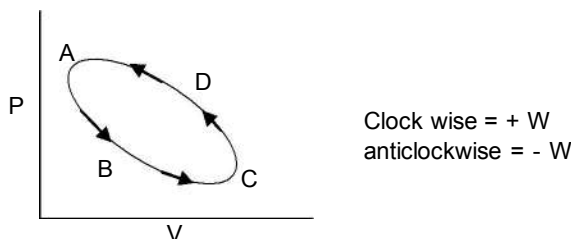
### Sign convention

It will be '+Q' if heat goes into the system and '-Q' if heat goes out of the system +W when it is done by the system and -w is done on the system.



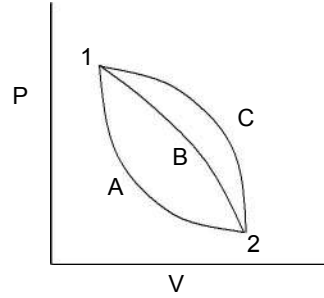
### Cyclic process

For a cyclic process, the work done is the area enclosed by the PV curve.



## Energy as a system property

Let a system changes from state 1 to state 2 via path A path B and Path C, which as follows



Applying first law of thermodynamics to path A.

$$Q_A = \Delta E_A + W_A$$

$$\text{For path B } Q_B = \Delta E_B + W_B$$

If process A & B form a complete cycle

$$\Sigma Q = \Sigma W$$

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

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

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

$$\text{Similarly } \Delta E_A = -\Delta E_B$$

$$\Rightarrow \Delta E_B = \Delta E_C$$

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

### Different forms of stored energy

Energy can be stored in a system by two modes.

- (i) Macroscopic mode
- (ii) Microscopic mode

#### (i) Macroscopic mode

In this mode, the mode of stored energy is stored in two forms,

$$E_{KE} = \left(\frac{1}{2}\right)MV^2$$

$$E_{PE} = mgz$$

#### (ii) Microscopic mode

This mode of stored energy refers to energy stored in molecular and atomic structure. Hence it is called molecular internal energy or simply internal energy. Then including

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

$$L = L_{\text{translation}} + L_{\text{rotational}} + L_{\text{vibration}} + L_{\text{electronic}} + L_{\text{chemical}} + L_{\text{nuclear}}$$

Total energy

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

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

So  $E = U$

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

**First law for a closed system undergoing a cyclic process.**

**Enthalpy concept**

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

$$H = U + Pv$$

It is a point function and an intensive property.

Specific enthalpy is given by

$$h = u + \frac{1}{m} PV = u + Pv$$

**First law for a steady flow process**

**Steady flow process**

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

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

**Important terms**

Flow work – whenever a certain amount of mass enters a system, an amount of work is required to push the mass into the system and out of it to maintain the continuity of flow.

i.e. Flow work =  $PV$

**Control Volume**

For computation of mass and energy notes during a flow process, it is convenient to focus attention upon a certain fixed region in space called control volume.

**Control surface**

The boundary line defining the control volume is called control surface.

**Stored energy of a system in a flow process**

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

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

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

Now, the total energy of a fluid at any section of the control volume.

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

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

## STEADY FLOW ENERGY EQUATION

As all energy is conserved

$$\Sigma \text{Energy}_{\text{in}} + \text{Heat flux} = \Sigma \text{Energy}_{\text{in}} + \text{Work}_{\text{output}}$$

i.e.

$$U_1 + \frac{1}{2} m V_1^2 + m g z_1 + P_1 V_1 + Q$$

$$= U_2 + \frac{1}{2} m V_2^2 + m g z_2 + P_2 V_2 + W$$

$$\left[ h_1 + \frac{1}{2} m V_1^2 + m g z_1 + Q \right] + \left[ h_2 + \frac{1}{2} m V_2^2 + m g z_2 + W \right]$$

On the basis of per unit mass flow rate

$$h_1 + \frac{V_1^2}{2} + g z_1 + \frac{Q}{m}$$

$$h_2 + \frac{V_2^2}{2} + g z_2 + \frac{W}{m}$$

$$\text{or } h_1 + \frac{V_1^2}{2} + g z_1 + \frac{Q}{m} = h_2 + \frac{V_2^2}{2} + g z_2 + \frac{W}{m}$$

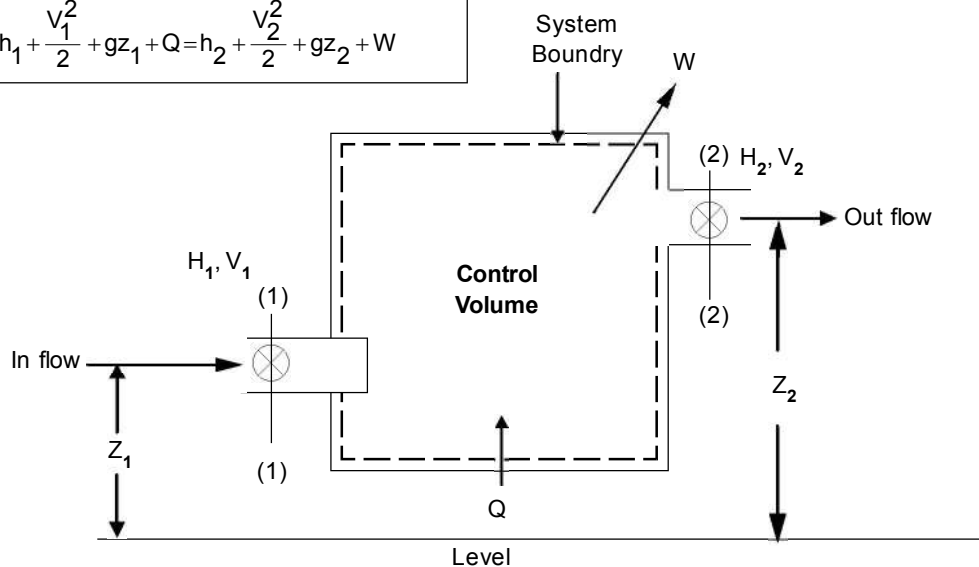


Fig- Steady flow

## NOZZLE

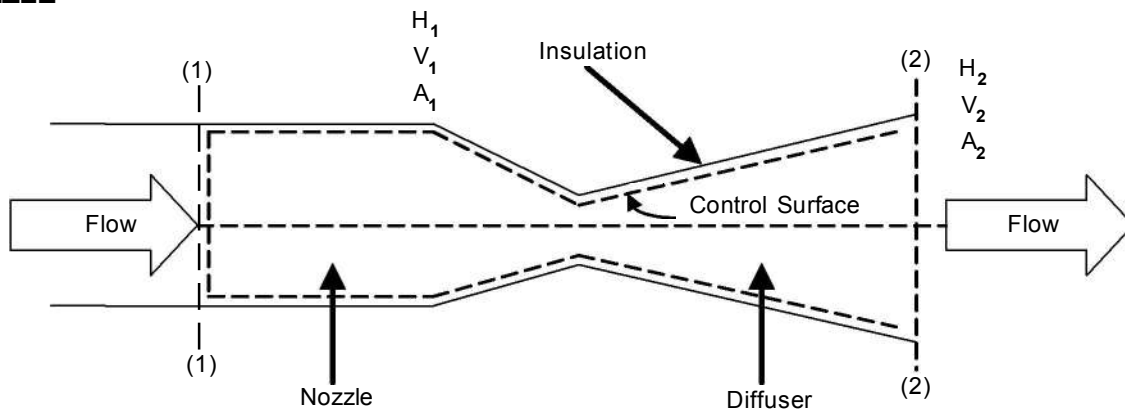


Fig- A Steady flow process through a nozzle.

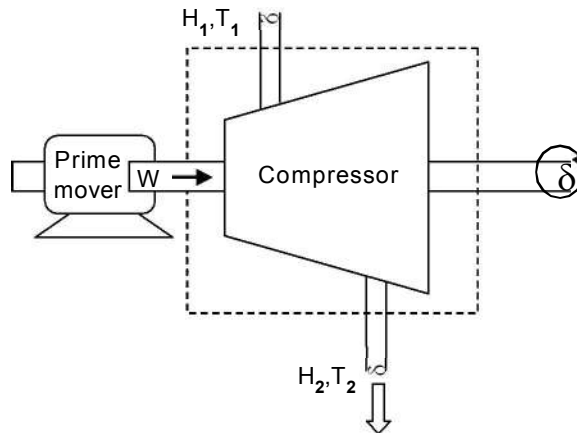
A nozzle is a device used to throttle a fluid whereupon its pressure energy is converted into kinetic energy. The enthalpy of fluid decreases as the velocity of the fluid increases because of a higher fluid velocity at the nozzle outlet, a nozzle is harnessed to gain a high thrust in rockets and jet engines and drive impulse type steam and gas turbines.

## Compressor

A compressor compresses air or a gas by harnessing external work fed from a prime mover. The increase in the gas pressure is accompanied by the temperature rise. If the compressor is perfectly insulated and the compression is adiabatic then it requires the minor work input to increase the gas pressure. All the generated heat of compression is expanded to compresses the gas as no heat is allowed to escape.

So  $Q = 0$

Mass flow rate of the gas =  $M$  and  $V_1 = V_2$



$Z_1 = Z_2$ ,

By applying SFEE

$$h_1 = h_2 + (-W_C)$$

(-) sign before  $W_C$  refers to the work done on the gas (system)

$$W_C = M(h_2 - h_1)$$

$$= MC_p (T_2 - T_1)$$

### Example

An air compressor compresses air from  $0.1 \text{ MP}_a$  /  $300 \text{ K}$  to  $1 \text{ MP}_a$ . The compressor casing is well insulated, yet there is a heat loss to the surrounding to the extent of 5% of the compressor work.

Determine air temp at outlet and power input given

$$V_1 = 40 \text{ m/s}, V_2 = 100 \text{ m/s}, A_1 = 100 \text{ cm}^2, A_2 = 20 \text{ cm}^2, C_p = 10^3 \text{ J Kg}^{-1} \text{ K}^{-1}$$

### Solution

$$P_2 V_2 = RT_2 \text{ or } T_2 = P_2 \frac{v_2}{R}, v_2 - \text{Specific volume.}$$

We have  $m_1 = m_2$

$$\frac{a_1 V_1}{v_1} = \frac{a_2 V_2}{v_2}$$

$$P_1 v_1 = RT_1$$

$$v_1 = \frac{RT_1}{P_1} = \frac{287 \times 300}{0.1 \times 10^6}$$

$$= 0.861 \text{ m}^3 \text{ kg}^{-1}$$

$$\text{and } v_2 = \frac{a_2 V_2}{a_1 V_1} \times V_1 = \left( \frac{20}{100} \right) \left( \frac{100}{40} \right) \times 0.861$$

$$= 0.4305 \text{ m}^3 \text{ kg}^{-1}$$

$$T_2 = P_2 v_2 / R$$

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



$$Z_1 = Z_2$$

$$Q = 5\% W_C$$

– Q as rejected

–  $W \cap W.D$  on the system

$$H_1 + \frac{1}{2} M V_1^2 + (-Q)$$

$$= H_2 + \frac{1}{2} M V_2^2 + (W_C)$$

$$-0.5 W_C + W_C$$

$$= M(h_2 - h_1) + m(V_2^2 - V_1^2)$$

$$0.95 W_C = 0.4646 \times C_P \left[ (T_2 - T_1) + \frac{1}{2} (V_2^2 - V_1^2) \right]$$

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

$$= (100 \times 10^4 \text{ m}^2) \times \frac{40 \text{ m}^5 - 1}{0.861} = 0.46457 \text{ kg s}^{-1}$$

$$W_C$$

$$= 0.4646 \times \left[ 10^3 (1500 - 300) + \frac{1}{2} (100^2 - 40^2) \right]$$

$$= 59889 \text{ J/s}$$

$$= 588.9 \text{ kW (Ans)}$$

### Nozzle

There is no work output :  $W = 0$

No heat influx or escape  $Q = 0$

For a horizontal disposition

$$Z_1 = Z_2$$

And so the SFEE applied to the nozzle boils down to

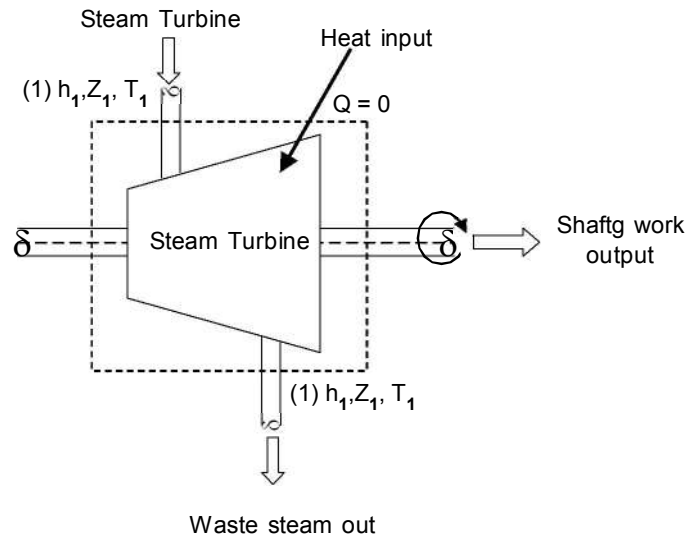
$$h_1 + \frac{1}{2} (V_1)^2 = h_2 + \frac{1}{2} (V_2)^2$$

If  $V_2 \gg V_1$ , then

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

$$= \sqrt{2C_P(T_1 - T_2)}$$

## Turbine



A steam turbine receives a superheated, high pressure steam that experiences its. Enthalpy drop as the steam passes over the turbine blades. This enthalpy drop is converted into the kinetic energy of rotation of the blades mounted on the turbine drum. The turbine is well insulated which gives rise to the maximum work output. The turbine is well insulated.

$$Q = 0$$

Steam velocity at the turbine input = the steam velocity at the output

$$\text{i.e. } V_1 = V_2$$

The turbine is positioned horizontally

$$Z_1 = Z_2$$

Applying SFEE to the control volume

$$H_1 = h_2 + W$$

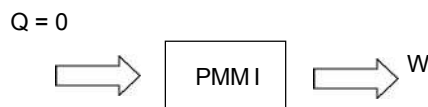
$$W = h_1 - h_2$$

$$= C_p (T_1 - T_2)$$

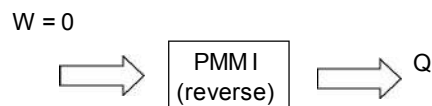
$$W = MC_p (T_1 - T_2)$$

### **perpetual motion machine**

PMMI refers to the perpetual motion machine of the first kind. It is a hypothetical machine that will continuously churn out work but without absorbing heat from its surroundings.



But such a machine is not feasible from a practical point of view, for it violates law of conservation of energy (first law of thermodynamics).



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

### Limitation of first law

There are two basic limitations of the first law of thermodynamics

(1) First law does not differentiate between heat and work.

It assumes complete inter-convertibility of the two. Though work being a high grade energy can be fully converted into heat but heat cannot be completely converted to work.

(2) It does not permit us to know the direction of energy transfer. We cannot ascertain whether heat will flow from a higher temperature body to a lower temperature body vice versa.

### Thermal Reservoir

A thermal reservoir is a heat source or heat sink that remains at a constant temperature, regardless of energy interaction.

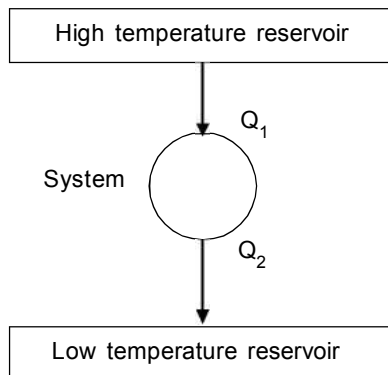
Otherwise a thermal energy reservoir (TER) is a large system body of infinite heat capacity which is capable of absorbing or rejecting a finite amount of heat without any changes in its thermodynamic co-ordinates.

The high temperature reservoir ( $T_H$ ) that supplies heat is a source.

Sink – Low temperature reservoir to which heat is rejected.

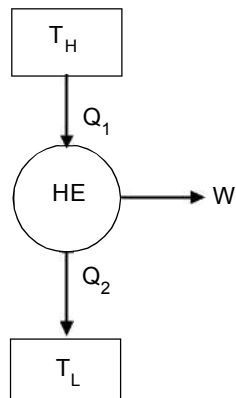
### Example

Ocean water and atmospheric air are two good examples.



### Concept of heat engine

A heat engine is a device that can operate continuously to produce work receiving heat from a high temperature  $T_H$  and rejecting non-converted heat to a low temperature sink.



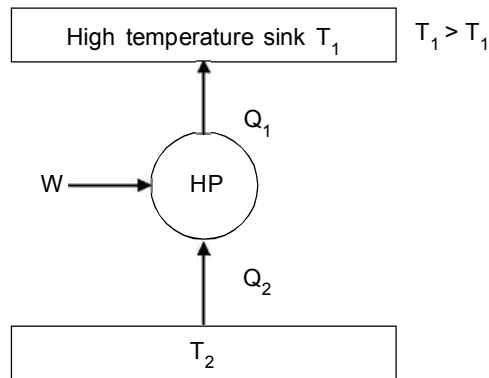
$$\text{Effect} = \frac{\text{output}}{\text{input}} = \frac{W}{Q_1}$$

But,  $W = Q_1 - Q_2$  in a cycle

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

## Heat Pump

A heat pump is a reversed heat engine. It receives heat from a low temperature reservoir (source) and rejects it to high temperature reservoir (sink) for which an external work which is supplied to the pump.



The efficiency of a heat pump cycle is usually called the coefficient of performance. It is the desired effect upon the external work supplied for obtaining that desired effect.

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

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

$$\text{Again } \sum Q_{\text{cycle}} = \sum W_{\text{cycle}}$$

$$\therefore Q_1 - Q_2 = W$$

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

## Refrigerator

A refrigerator is similar to a heat pump. It operates as a reversed heat engine. Its duty is to extract heat as much as possible from the cold body and deliver the same to high temperature body.

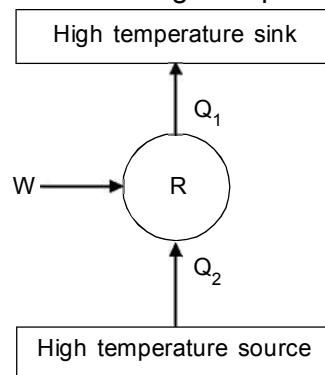
The desired effect of a refrigerator is to remove  $Q_2$  heat infiltrating into the cold space. By using the external work it rejects  $Q_1$  heat to the high temperature reservoir. Therefore,

$$\text{COP}_{\text{ref}} = \frac{Q_2}{W}$$

$$\text{Again } \sum Q_{\text{cycle}} = \sum W_{\text{cycle}}$$

$$\therefore Q_1 - Q_2 = W$$

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



## Statement of second law of the thermodynamics

### Clausius statement

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

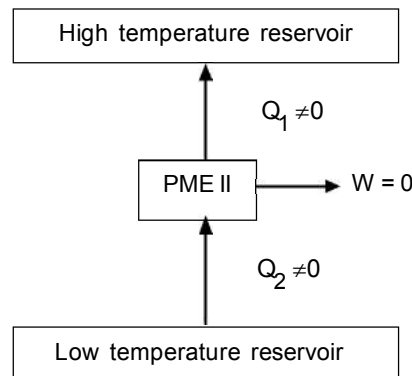
## Kelvin Planck statement

No heat engine, operating in cycle, can convert entire heat into work. It is impossible to build a heat engine that can register 100% efficiency.

**Note** –  $T_C$  K-P statement is of relevance to a heat engine. The C-statement relates more directly to a reversed heat engine.

## Perpetual motion machine II

It is a hypothetical machine that will continuously pump out heat from a low temperature reservoir ( $T_2$ ) and delivers the same to a high temperature reservoir at ( $T_1$ ) without taking up any input work from surroundings.



## Carnot cycle

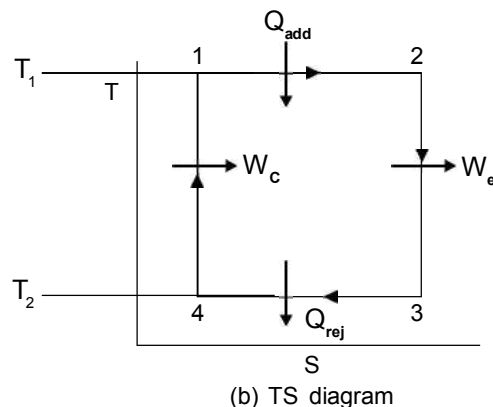
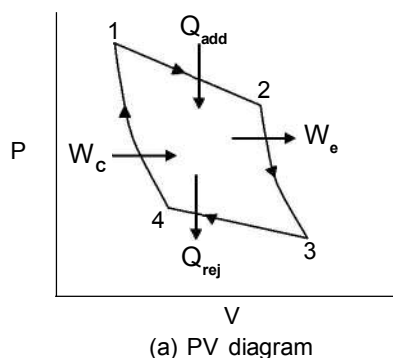
The Carnot cycle is a hypothetical cycle developed by Nicholas Sadi Carnot (1796-1832), a French military engineer. It is meant for a heat engine or a reversed heat engine. All the processes involved in this cycle are reversible, thereby ensuring the best possible device that one could construct. This cycle comprises 4 reversible processes.

### Process 1-2 reversible isothermal heat addition

Heat ( $Q_{add}$ ) flows from a high temperature reservoir to the working fluid which is at a constant temperature but only infinitesimally below that of the source.

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

$$Q_{add} = W_{1-2} \text{ (as isothermal process)}$$



### Process 2-3 (adiabatic expansion)

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

$$\text{here } Q = 0$$

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

### Process 3-4 (Isothermal heat rejected)

Heat ( $Q_{rej}$ ) is rejected by the fluid to the sink-both one at a constant temperature, but differ only by an infinitesimal amount.

$\Delta U=0$ , isothermal proces

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

–  $Q$  implies heat has been rejected by the system.

–  $W$  implies work has been done on the system.

### Process 4-1 (Reversible adiabatic compression)

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

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

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

As the two isothermal and two adiabatic complete the cycle.

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

$$\text{Or, } Q_{\text{add}} + (-Q_{\text{rej}}) = W_{1-2} + W_{2-3} - (W_{3-4} + W_{4-1})$$

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

So, the efficiency

$$\begin{aligned} \eta &= \frac{\text{Net work output}}{\text{Net heat input}} = \frac{W_e - W_c}{Q_{\text{add}}} \\ &= \frac{Q_{\text{add}} - Q_{\text{rej}}}{Q_{\text{add}}} = 1 - \frac{Q_{\text{rej}}}{Q_{\text{add}}} \end{aligned}$$

### Aliter

Refer to the TS diagram

Net work done,  $W_{\text{net}} = \text{area } 1-2-3-4$

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

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

$$Q_{\text{add}} = T_1(S_2 - S_1)$$

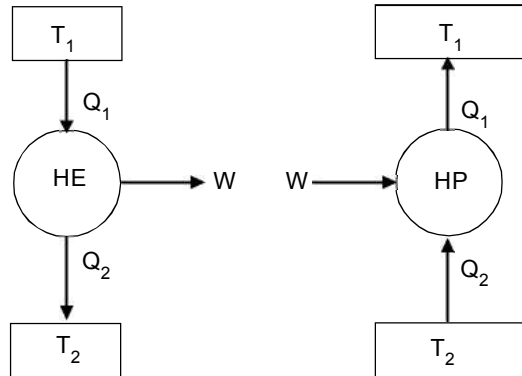
$$\text{So efficiency, } \eta = \frac{W_{\text{net}}}{Q_{\text{add}}} = \frac{(T_1 - T_2)\Delta S}{T_1 \Delta S} = 1 - \frac{T_2}{T_1}$$

**Application of second law is heat engine, heat pump, refrigerator and determination of cop and efficiencies.**

### **Clausius statement**

According to second law without work input heat cannot flow from low temperature to high temperature.

### **Case of heat engine**



### **Kelvin plank statement**

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

in the above engine.

$$Q_1 = Q_2 + W$$

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

$$\Rightarrow Q_1 \neq W$$

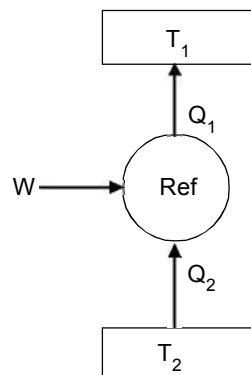
### **In a heat pump**

$$W + Q_2 = Q_1$$

$$W = 0, Q_2 = Q_1$$

which is impossible,  $\Rightarrow W \neq 0$

### **In a refrigerator**



as like heat pump.

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

$$\text{as } \frac{Q_1}{T_1} = \frac{Q_2}{T_2} \text{ (according to Carnot's theory)}$$

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

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

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

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



# CHAPTER-3

## Properties Processes of perfect gas

### Thermodynamics

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 and the surroundings. It is usually represented by  $Q$  and is expressed in Joule (J) or Kilo-Joule (KJ).

### Work

Work is defined as the product of the force ( $F$ ) and the distance moved ( $X$ ) in the direction the force. Mathematically, work done,  $W = F \times X$ ,

The unit of work depends upon the unit of force and the distance moved. In S.I. system of units, the practical unit of work is Newton-metre (N-m). The work of 1N-m is known as Joule such that  $1\text{N-m} = 1\text{J}$ .

**1st law of thermodynamics** : This law may be stated as follow :

(a) The heat and mechanical work are mutually convertible. According to this law, when a closed system undergoes a thermodynamic cycle, the net heat transfer is equal to the net work transfer. In other words, the cyclic integral of heat transfers is equal to the cyclic integral of work transfers, mathematically,  $\oint \delta Q = \oint \delta W$

Where symbol  $\oint$  stands for cyclic integral, and  $\delta Q$  ,  $\delta W$  represent infinitesimal elements of heat and work transfers respectively.

(b) The energy can neither be created nor destroyed though it can be transferred from one form to another. According to this law, when a system undergoes a change of state, then both heat transfer and work transfer takes place. The net energy transfer is stored within the system and is known as stored energy or total energy of the system. Mathematically  $\delta Q - \delta W = dE$

The symbol  $\delta$  is used for a quantity which is inexact differential and symbol  $d$  is used for a quantity which is an exact differential. The quantity  $E$  is an extensive property and represents the total energy of the system at a particular state.

### Laws of perfect gas.

The physical properties of a gas are controlled by the following three variables :

1. Pressure exerted by the 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 which have been established from experimental results.

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

### 1. Boyle's Law

This law was formulated by Robert Boyle in 1662. It states, "The absolute pressure of a given mass of a perfect gas varies inversely as its volume, when the temperature remains constant".

Mathematically,  $p \propto \frac{1}{V}$  or  $pV = \text{constant}$

### 2. Charles's Law

This law was formulated by a Frenchman A.c. Charles in about 1787. It may be stated in the following two different forms :

(i) The volume of a given mass of a perfect varies directly as its absolute temperature, when the absolute pressure remains constant". Mathematically,  $V \propto T$  or  $\frac{V}{T} = \text{constant}$

### 3. Gay-Lussac Law

This law states, "The absolute pressure of a given mass of a perfect gas varies directly as its absolute temperature when the volume remains constant". Mathematically  $p \propto T$  or  $\frac{P}{T} = \text{constant}$

### Specific heats of a gas

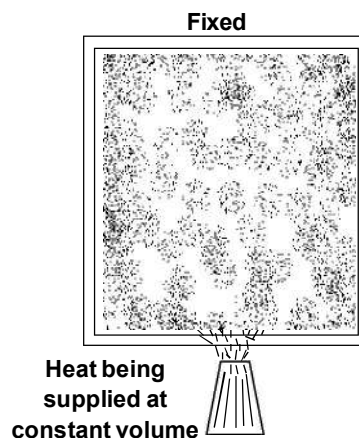
The specific heat of a substance may be broadly defined as the amount of heat required to raise the temperature of its unit mass through one degree. All the liquids and solids have one specific heat only. But a gas can have any number of specific heats (lying between zero and infinity) depending upon the conditions, under which it is heated. The following two types of specific heats of a gas are important from the subject point of view.

1. Specific heat at constant volume
2. Specific heat at constant pressure

#### Specific heat at constant volume

It is the amount of heat required one to raise the temperature of a unit mass of gas through one degree when it is heated at a constant volume. It is generally denoted by  $C_v$ .

Consider a gas contained in a container with a fixed lid as shown in the figure. Now, if this gas is heated, it will increase



the temperature and pressure of the gas in the container. Since the lid of the container is fixed, therefore the volume of gas remains unchanged.

Let  $m$  = Mass of the gas

$T_1$  = Initial temperature of the gas

$T_2$  = Final temperature of the gas

Total heat supplied to the gas at constant volume  $Q_{1-2}$  = mass  $\times$  supplied heat at constant volume  $\times$  rise in temperature =  $mC_v (T_2 - T_1)$ .

It may be noted that whenever a gas is heated at constant volume, no work is done by the gas. The whole heat energy is utilised in increasing the temperature and pressure of the gas.

### Specific heat at constant pressure

It is the amount of heat required to raise the temperature of a unit mass of a gas through one degree, when it is heated at constant pressure. It is generally denoted by  $C_p$ .

Consider a gas contained in a container with a movable lid as shown in figure. Now if this gas is heated, it will increase the temperature and pressure of the gas in container. Since the lid of the container is movable, therefore it will move upwards in order to counter balance the tendency for pressure to rise.

Let

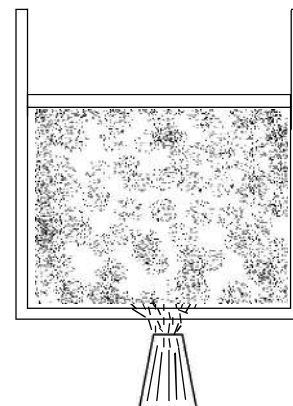
$m$  = Mass of the gas

$T_1$  = Initial temperature of the gas

$V_1$  = Initial volume of the gas

$T_2, V_2$  = Corresponding values for the final condition of the gas

$\therefore$  Total heat supplied to the gas, at constant pressure.



Heat being supplied at constant pressure

$Q_{1-2}$  = Mass  $\times$  Sp. heat at constant pressure  $\times$  rise in temperature =  $mC_p (T_2 - T_1)$ .

Whenever a gas is heated at a constant pressure, the heat supplied to the gas is utilised for the following two purposes.

1. To raise the temperature of the gas. The heat remains within the body of the gas and represents the increase in internal energy.  $dU = mC_v (T_2 - T_1)$ .

2. To do some external work during expansion. Mathematically, work done by the gas  $W_{1-2} = P(V_2 - V_1) = mR (T_2 - T_1)$ .

## Relationship between specific heats

Consider a gas enclosed in a container and being heated, at a constant pressure, from the initial state 1 to the final state 2.

$m$  = Mass of the gas

$T_1$  = Initial temperature of the gas

$T_2$  = Final temperature of the gas

$V_1$  = Initial volume of the gas

$V_2$  = Final volume of the gas

$C_p$  = Specific heat at constant pressure

$C_v$  = Specific heat at constant volume

$P$  = Constant pressure

We know that heat supplied to the gas at constant pressure

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

A part of this heat is utilised in doing the external work, and the rest remains within the gas and is used in increasing the internal energy of the gas.

$$\therefore \text{Heat utilised for external work } W_{1-2} = P(V_2 - V_1) \dots\dots\dots (i)$$

$$\text{And increase in internal energy } dU = mC_v(T_2 - T_1) \dots\dots\dots (ii)$$

$$\text{We know that } Q_{1-2} = W_{1-2} + dU \dots\dots\dots (iii)$$

$$\therefore mC_p(T_2 - T_1) = P(V_2 - V_1) + mC_v(T_2 - T_1) \dots\dots\dots (iv)$$

Using characteristic gas equation (i.e.  $Pv = mRT$ ), we have

$$PV_1 = mRT_1 \dots\dots\dots (\text{for initial condition})$$

$$PV_2 = mRT_2 \dots\dots\dots (\text{for final condition})$$

$$\therefore P(V_2 - V_1) = mR(T_2 - T_1)$$

$$\text{Now substituting the value of } P(V_2 - V_1) \text{ in equation } \dots\dots\dots (v)$$

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

$$\therefore C_p = R + C_v \text{ or } C_p - C_v = R \dots\dots\dots (vi)$$

The above equation may be rewritten as

$$C_p - C_v = R \text{ or } C_v (\gamma - 1) = R \left[ \gamma = \frac{C_p}{C_v} \right]$$

$$C_v = \frac{R}{\gamma - 1} \dots\dots\dots (vii)$$

The equation (v) gives an important result as it proves that characteristic constant of a gas ( $R$ ) is equal to the difference of its two specific heats i.e. ( $C_p - C_v$ ).

### **i. Wet steam**

When the steam contains moisture or particles of water in suspension, it is said to be wet steam. It means that evaporation of water is not complete and the whole of the latent heat has not been absorbed. The enthalpy of wet steam is given by:  $h = h_f + Xh_{fg}$  where  $x$  is the dryness fraction of steam.

### **ii. Dry saturated steam**

When the wet steam is further heated and it does not contain any suspended particles of water, it is known as dry saturated steam. The dry saturated steam has absorbed its full latent heat. The enthalpy of dry saturated steam is given by:  $h = h_g = h_f + h_{fg}$  where dryness fraction  $X = 1$ .

### **iii. Superheated steam**

When the dry steam is further heated at a constant pressure this rising its temperature, it is said to be superheated steam since the pressure is constant, therefore the volume of superheated steam increases.

The total heat required for the steam to be superheated is

$h_{sup}$  = total heat for dry steam + heat for superheated steam

$$= h_f + h_{fg} + C_p(t_{sup} - t) = h_g + C_p(t_{sup} - t)$$

Where  $C_p$  = mean specific heat at constant pressure for superheated steam.

$t_{sup}$  = temperature of the superheated steam.

$t$  = saturation temperature at the given constant pressure.

The difference ( $t_{sup} - t$ ) is known as degree of superheat.

### **Steam table and their uses**

The properties of dry superheat steam like its temperature of formation (saturation temperature), sensible heat, latent heat of vaporisation, enthalpy or total heat, specific volume, entropy etc., vary with pressure and can be found by experiments only. These properties have been carefully determined and made available in a tabular form known as steam tables.

# CHAPTER-4

## Internal Combustion Engine

### Introduction

As the name implies or suggests, the internal combustion engines (briefly written as I.C engine) are those engines in which the combustion of fuel takes place inside the engine cylinder. These are petrol, diesel, and gas engines. We have seen in steam engines or steam turbines that the fuel, fed into the cylinder, is in the form of steam which is already heated (or superheated), and is ready for working in the combustion cycle of the engine. But, in case of internal combustion engines the combustion of fuel takes place inside the engine cylinder by a spark and produces very high temperature.

### Four stroke Cycle Petrol Engine

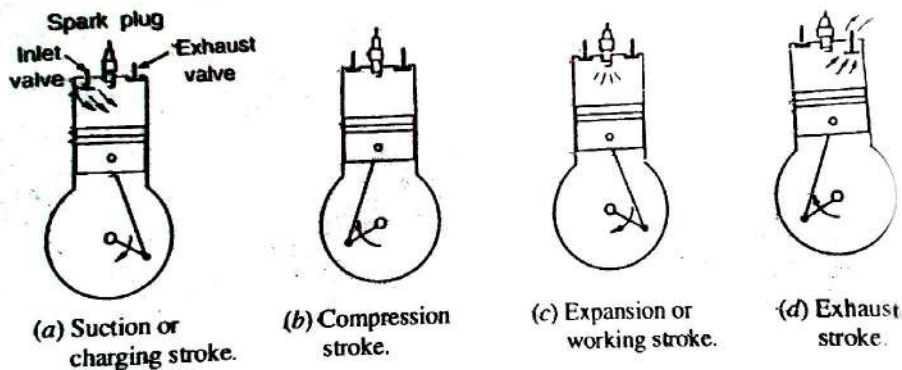
It is also known as Otto cycle. It requires four strokes of the piston to complete one cycle of operation in the engine cylinder. The four stroke of a petrol engine sucking fuel air mixture (petrol and Air operation with proportionate quantity of air in the carburetor known as charge) are described below :

#### 1. Suction or charging stroke

In this stroke, the inlet valve opens and charge is sucked into the Cylinder as the piston moves downward from top dead centre (T.D.C). It continues till the piston reaches Its bottom dead centre (B.D.C) as show in Fig. (a).

#### 2. Compression stroke

In this stroke, both the inlet and exhaust valves are closed and charge is compressed as the piston moves upwards from B.D.C. to T.D.C. As a result of compression the pressure and temperature of the charge increases considerably (the actual values depend upon compression ratio). This completes one revolution of the crankshaft. The compression stroke is showing in Fig. (b).



Four stroke Cycle Petrol Engine

#### 3. Expansion or working stroke

Shortly before the piston reaches T.D.C. (during compression stroke), the charge is ignited with the help of a spark plug. It suddenly increases the pressure temperature of the products of combustion but the volume, practically, remains constant. Due to rise in pressure, the piston is pushed down with a great force. The hot burnt gases expand due high speed of the piston. During this expansion, some of the heat energy produced is transformed mechanical work. It may be noted that during this working stroke, as shown in Fig. (c), both valves are closed and piston moves from T.D.C. to B.D.C.

#### 4. Exhaust stroke

In this stroke, the exhaust valve is open as piston moves from B.D.C to T.D.C. This movement of the piston pushes out the products of combustion, from the engine cylinder and are exhausted through the exhaust valve into the atmosphere, as shown in Fig. (d). This completes the cycle, and the engine cylinder is ready to suck the charge again.

**Note :** The four stroke cycle petrol engine are usually employed in light vehicles such as cars, jeeps, aero planes

#### Four stroke Cycle Diesel Engine

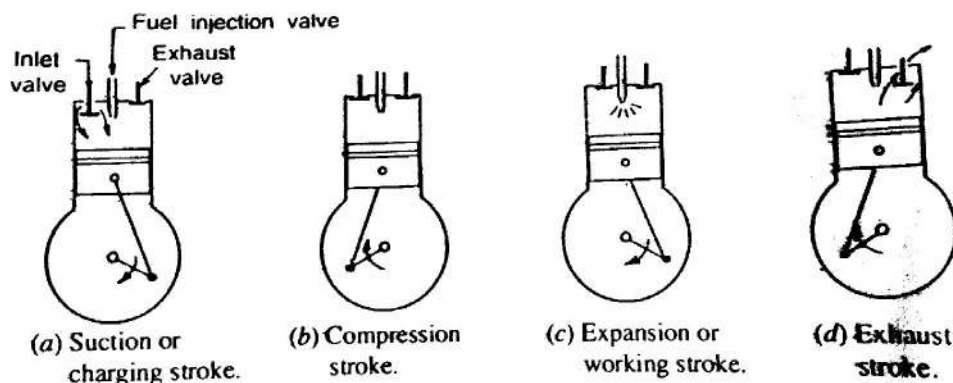
It is also known as compression ignition engine because the ignition takes place due to the compression produced in the engine cylinder at the end of compression stroke. The four strokes of a diesel engine sucking pure air are described below :

##### 1. Suction or charging stroke

In this stroke, the inlet valve opens and pure air is sucked into the cylinder as the piston moves downwards from the top dead centre (TDC). It continues till the piston reaches its bottom dead centre (BDC) as shown in Fig. (a).

##### 2. Compression stroke

In this stroke, both the valves are closed and the air is compressed as the piston moves upwards from BDC to TDC. As a result of compression, pressure and temperature of the air increases considerably (the actual value depends upon the compression ratio). This completes one revolution of the crank shaft. The compression stroke is shown in Fig. (b).



Four stroke Cycle Diesel Engine

##### 3. Expansion or working stroke

Shortly before the piston reaches the TDC (during the compression stroke), fuel oil is injected in the form of very fine spray into the engine cylinder, through the nozzle, known as fuel injection valve. At this moment, temperature of the compressed air is sufficiently high to ignite the fuel. It suddenly increases the pressure and temperature of the products of combustion. The fuel oil is continuously injected for a fraction of the revolution. The fuel oil is assumed to be burnt at constant pressure. Due to increased pressure, the piston is pushed down with a great force. The hot burnt gases expand due to high speed of the piston. During this expansion, some of the heat energy is transformed into mechanical work. It may be noted that during this working stroke, both the valves are closed and the piston moves from TDC to BDC.

#### 4. Exhaust stroke

In this stroke, the exhaust valve is open as the piston moves from BDC to TDC. This movement of the piston pushes out the products of combustion from the engine cylinder through the exhaust valve into the atmosphere. This completes the cycle and the engine cylinder ready to suck the fresh air again.

**Note :** The four stroke cycle diesel engines are generally employed in heavy vehicles such as buses, trucks, tractors, pumping sets, diesel locomotives and in earth moving machinery.

#### Two-stroke Cycle Petrol Engine

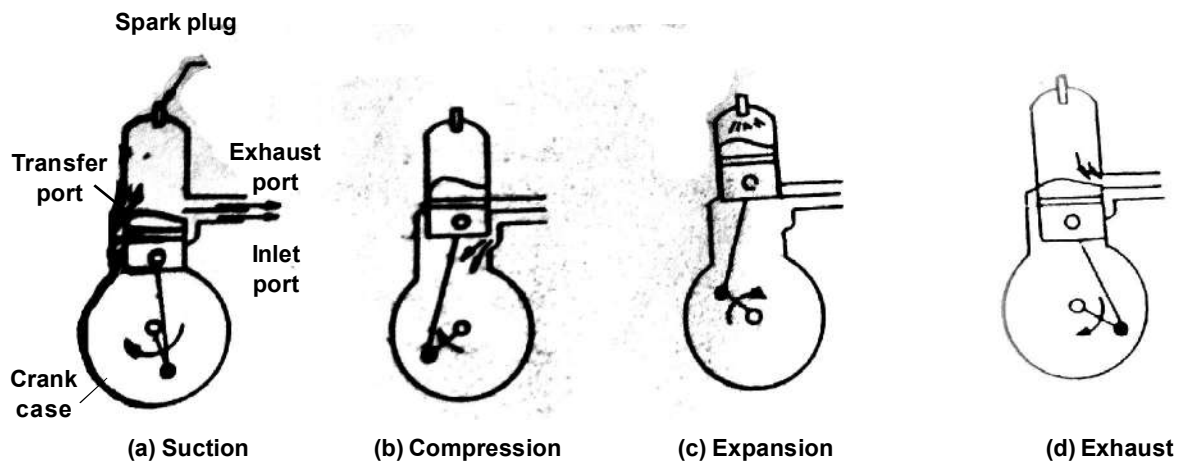
A two-stroke cycle petrol engine was devised by Duglad Clerk in 1880. In this cycle, the suction, compression, expansion and exhaust takes place during two strokes of the piston. It means that there is one working stroke after every revolution of the crank shaft. A two stroke engine has ports instead of valves. All the four stages of a two stroke petrol engine are described below :

##### 1. Suction stage

In this stage, the piston, while going down towards BDC, uncovers both the transfer port and the exhaust port. The fresh fuel-air mixture flows into the engine cylinder from the crank case, as shown in Fig. (a).

##### 2. Compression stage

In this stage, the piston, while moving up, first covers the transfer port and then exhaust port. After that the fuel is compressed as the piston moves upwards as shown in Fig.(b) in this stage, the inlet port opens and fresh fuel-air mixture enters into the crank case.



#### Two-stroke Cycle Petrol Engine

##### 3. Expansion stage

Shortly before this piston reaches the TDC (during compression stroke, the charge is ignited with the help of a spark plug. It suddenly increases the pressure and temperature of the products of combustion. But the volume, practically, remains constant. Due to rise of the pressure the piston is pushed downwards with a great force as shown in Fig. (c). The burnt gases expand due to high speed of the piston. During this expansion, some of the heat energy produced is transformed into mechanical work.



#### 4. Exhaust stage

In this stage, the exhaust port is opened as the piston moves downwards, products of combustion, from the engine cylinder are exhausted through the exhaust port into atmosphere as shown in Fig. (d). This completes the cycle and the engine cylinder is ready for the charge again.

**Note :** Two stroke petrol engines are generally employed in very light vehicles such as scooters, motor cycles, and sprayers.

#### Two-stroke Cycle Diesel Engine

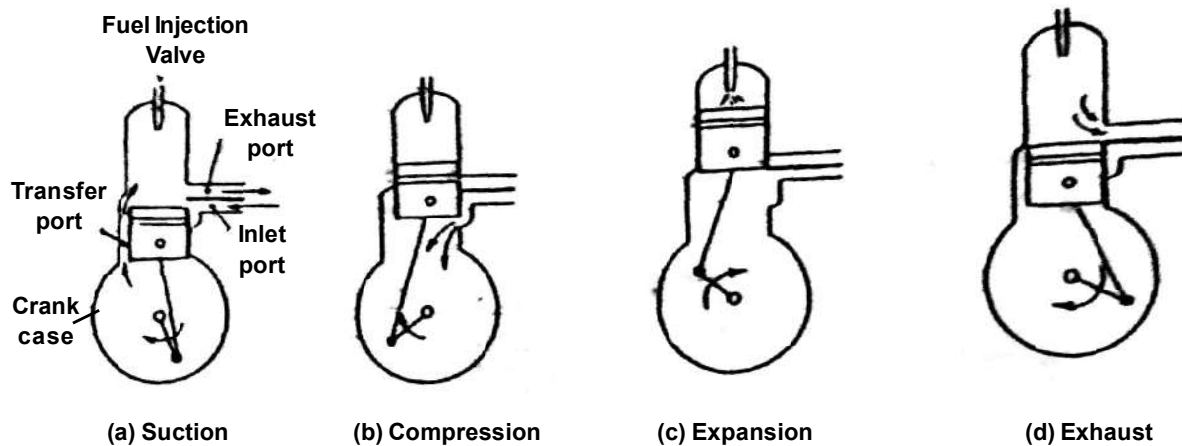
A two-stroke cycle diesel engine also has one working stroke after every revolution of the crank shaft. All the four stages of a two stroke cycle diesel engine are described below :

##### 1. Suction stage

In this stage, the piston while going down towards BDC uncovers the transfer port and the exhaust port. The fresh air flows into the engine cylinder from the crank case as shown in Fig.(a).

##### 2. Compression stage

In this stage, the piston while moving up, first covers the transfer port and then exhaust port. After that the air is compressed as the piston moves upwards as shown Fig. (b). In this stage, the inlet port opens and the fresh air enters into crank case.



Two-stroke Cycle Diesel Engine

##### 3. Expansion stage

Shortly before the piston reaches the TDC (during compression stroke) the fuel oil is injected in the form of very fine spray into the engine cylinder through the nozzle shown as fuel injection valve, as shown in fig. (c). At this moment, temperature of the compressed air is sufficiently high to ignite the fuel. It suddenly increases the pressure and temperature of the products of combustion. The fuel oil is continuously injected for a fraction of the crank rotation. The fuel oil is assumed to be burnt at constant pressure. Due to increased pressure, the piston is pushed with a great force. The hot burnt gases expand due to high speed of the piston. During expansion some of the heat energy produced is transformed into mechanical work.

#### 4. Exhaust stage

In this stage, the exhaust port is opened and the piston moves downwards. The products of combustion from the engine cylinder are exhausted through the exhaust port into the atmosphere as shown in Fig. (d). This completes the cycle, and the engine cylinder is ready to suck the air again.

**Notes :** Two stroke diesel engines are mainly used in marine propulsion where space and lightness are the main considerations.

#### **Difference between two stroke and four stroke cycle engine.**

In a two-stroke engine, the working cycle is completed in two strokes of the piston or one revolution of the crankshaft. This is achieved by carrying out the suction and compression process in one stroke (or more precisely in inward stroke), expansion and exhaust processes in the second stroke (or more precisely in outward stroke). In a four-stroke engine, the working cycle is completed in four-strokes of the piston or two-revolutions of the crankshaft. This is achieved by carrying suction, compression, expansion and exhaust processes in each stroke.

It will be interesting to know that from the thermodynamic point of view, there is no difference between two-stroke and four-stroke cycle engines. The difference is purely mechanical which are as follows :

1. A two stroke cycle engine gives twice the number of power strokes than the four stroke cycle engine at the same engine speed. Theoretically, a two-stroke cycle engine should develop twice power as that of a four-stroke cycle engine. But in actual practice, a two-stroke cycle engine develops 1.7 to 1.8 times (greater value for slow speed engines) the power developed by four-stroke cycle engine of the same dimensions and speed. This is due to lower compression ratio and effect stroke being less than the theoretical stroke.

2. For the same power developed, a two-stroke cycle engine is lighter, less bulky and occupies less floor area. Thus it makes, a two-stroke cycle engine suitable for marine engine other light vehicles.

3. As the number of working strokes in a two-stroke cycle engine are twice than four-stroke cycle engine, so the turning moment of a two-stroke cycle engine is more uniform. So it makes a two-stroke cycle engine to have a lighter flywheel and foundations. This also leads to higher mechanical efficiency of a two-stroke cycle engine.

4. The initial cost of a two-stroke cycle engine is considerably less than a four-stroke cycle engine.

5. The mechanism of a two-stroke cycle engine is much simpler than a four-stroke cycle engine

6. The two-stroke cycle engines are much easier to start.

7. Thermal efficiency of a two-stroke cycle engine is less than that a four-stroke cycle engine because a two-stroke cycle engine has less compression ratio than that of a four-stroke cycle engine

8. Overall efficiency of a two-stroke cycle engine is also less than that of a four-stroke cycle engine because in a two-stroke cycle, inlet and exhaust ports remain open simultaneously for sometime. In spite of careful design, a small quantity of charge is lost from the engine cylinder.

9. In case of a two-stroke cycle engine, the number of power strokes are twice as those of fourstroke cycle engine. Thus the capacity of the cooling system must be higher. Beyond a certain limit, the cooling capacity offers a considerable difficulty. Moreover, there is a greater wear and in a two-stroke cycle engine.

10. The consumption of lubricating oil is large in a twp-stroke cycle engine because of the high operating temperature.

11. The exhaust gases in a two-stroke cycle engine creates noise, because of short time available for their exhaust.

### **Difference between petrol and diesel engine.**

Following points are important for the comparison of petrol engines and diesel engine

<b>Petrol Engines</b>	<b>Diesel Engines</b>
1. A petrol engine draws a mixture of petrol and air during suction stroke.	A diesel engine draws only air during suction stroke.
2. The carburetor is employed to mix air and petrol in the required proportion and to supply it to the engine during suction stroke.	The injector or atomiser is employed to inject fuel at the end of compression stroke.
3. Pressure at the end of compression is about 10 bar.	Pressure at the end of compression is about 35 bar.
4. The charge (i.e. petrol and air mixture) is ignited with the help of spark plug.	The fuel is injected in the form of fine spray. The temperature of the compressed air (about 600°C at a pressure of about 35 bar) is sufficiently able to ignite the fuel.
5. The combustion of fuel takes place approximately at constant volume. In other words, it works on Otto cycle.	The combustion of fuel takes place approximately at constant pressure. In other words, it works on Diesel cycle.
6. A petrol engine has compression ratio approximately from 6 to 10.	A diesel engine has compression ratio approximately from 15 to 25.
7. The starting is easy due to low compression ratio.	The starting is little difficult due to high compression ratio.
8. As the compression ratio is low, the petrol engines are lighter and cheaper.	As the compression ratio is high, the diesel engines are heavier and costlier.
9. The running cost of a petrol engine is high because of the higher cost of petrol.	The running cost of diesel engine is low because of the lower cost of diesel.

<b>Petrol Engines</b>	<b>Diesel Engines</b>
10. The maintenance cost is less.	The maintenance cost is more.
11. The thermal efficiency is upto about 26%.	The thermal efficiency is upto about 40%.
12. Overheating trouble is more due to low thermal efficiency.	Oveheating trouble is less due to high thermal efficiency.
13. These are high speed engines.	These are relatively low speed engines.
14. The petrol engines are generally employed in light duty vehicles such as scooters, motorcycles, cars. These are also used in aeroplanes.	The diesel engines are generally employed in heavy duty vehicles like buses, bucks, and cars moving machines etc.

# CHAPTER-5

## Gas Power Cycle

### CONCEPT OF IC ENGINE:

Gas engines are designed most frequently as internal combustion engines. These IC engines harness air as the working fluid. The air also serves as the oxidant for the hydrocarbon fluid fired. The combustion of fuel that takes place inside the combustion chamber transforms the chemical energy of the fuel to thermal energy; which is then converted by the engine to the mechanical work output.

The ideal cycle for a gas turbine is the brayton cycle, whereas the ideal cycle for the IC engines is the Carnot cycle. The IC engine operates on Otto or diesel cycle, which is the modified version of the Carnot cycle in order to render the cycles realistic.

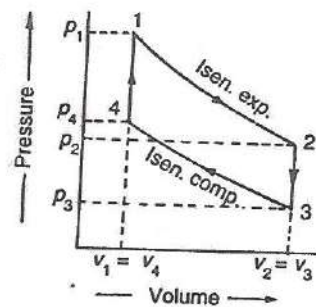
### OTTO CYCLE:

The first successful engine working on this cycle was built by A. Otto. These days, many gas, petrol and many of the oil engines run on this cycle. It is also known as constant volume cycle, as the heat is received and rejected at a constant volume.

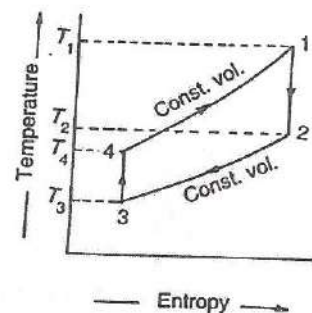
The cycle is taken as a standard of comparison for IC engines. For the purpose of comparison with other cycle, the air is assumed to be the working substance.

The engine conceived by Otto has air enclosed in a cylinder, whose walls are perfectly non-conductor of heat. There is also a hot body and cold body and an insulating cap, which are alternately brought in contact with the bottom of the cylinder.

The ideal Otto cycle consists of two constant volume and two reversible adiabatic or isentropic processes as shown in the figure.



(a) p-v diagram.



(b) T-s diagram.

Let the engine cylinder contain  $m$  kg of air at point 1. At this point, let  $p_1$ ,  $T_1$  and  $v_1$  be the pressure, temperature, and volume of the air. Following are the four stages of the ideal cycle:-

**1. FIRST STAGE** (reversible adiabatic or isentropic expansion):

The air is expanded reversibly and adiabatically from initial temperature  $T_1$  to a temperature  $T_2$  as shown by the curve 1-2. In this process, no heat is absorbed or rejected by the air.

**2. SECOND STAGE** (constant volume cooling):

The air is cooled at constant volume from temp.  $T_2$  to temp.  $T_3$  as shown by the curve 2-3. We know that heat rejected by the air during this process.

$$Q_{2-3} = m.C_v (T_2 - T_3)$$

**3. THIRD STAGE** (reversible adiabatic or isentropic compression):-

The air is compressed reversibly and adiabatically from temperature  $T_3$  to a temperature  $T_4$  as shown by the curve 3-4 in fig. In this process, no heat is absorbed or rejected by the air.

**4. FOURTH STAGE** (constant volume heating):-

The air is now heated at constant volume from temp.  $T_4$  to a temp.  $T_1$  as shown by the curve 4-1. We know heat absorbed by the air during this process.

$$Q_{4-1} = m.C_v (T_1 - T_4)$$

We see that the air has been brought back to its original conditions of pressure, volume and temperature, thus completing the cycle.

We know that Work done = heat absorbed – heat rejected

$$= m C_v (T_1 - T_4) - m C_v (T_2 - T_3)$$

$$\begin{aligned} \text{Ideal efficiency} &= \frac{\text{work done}}{\text{Heat absorbed}} \\ &= \frac{m C_v (T_1 - T_4) - m C_v (T_2 - T_3)}{m C_v (T_1 - T_4)} \end{aligned}$$

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

We know that for reversible adiabatic or isentropic expansion process 1-2,

$$\frac{T_2}{T_1} = \left( \frac{v_1}{v_2} \right)^{\gamma-1} = \left( \frac{1}{r} \right)^{\gamma-1} \quad \dots (ii)$$

$$r = \text{Expansion ratio} = v_2 / v_1$$

Similarly, for reversible adiabatic or isentropic compression process 3-4,

$$\frac{T_3}{T_4} = \left( \frac{v_4}{v_3} \right)^{\gamma-1} = \left( \frac{1}{r} \right)^{\gamma-1} \quad \dots (iii)$$

$$r = \text{Compression ratio} = v_3 / v_4 = v_2 / v_1$$

From equations (ii) and (iii), we find that

$$\frac{T_2}{T_1} = \frac{T_3}{T_4} = \left( \frac{1}{r} \right)^{\gamma-1} = \frac{1}{(r)^{\gamma-1}} \quad \text{or} \quad \frac{T_1}{T_4} = \frac{T_2}{T_3}$$

Substituting the value of  $T_1 / T_4$  in equation (i),

$$\eta = 1 - \frac{T_3}{T_4} = 1 - \frac{T_2}{T_1} = 1 - \frac{1}{(r)^{\gamma-1}} \quad \dots \left( \because \frac{T_3}{T_4} = \frac{T_2}{T_1} \right) \dots (iv)$$

**Example 1.** An engine, working on the Otto cycle, has a cylinder diameter of 150 mm and a stroke of 225 mm. The clearance volume is  $1.25 \times 10^{-3} \text{ m}^3$ . Find the air standard efficiency of this engine. Take  $\gamma = 1.4$ .

**Solution.** Given :  $d = 150 \text{ mm} = 0.15 \text{ m}$  ;  $l = 225 \text{ mm} = 0.225 \text{ m}$  ;  $v_c = 1.25 \times 10^{-3} \text{ m}^3$  ;  $\gamma = 1.4$

We know that swept volume

$$v_s = \frac{\pi}{4} \times d^2 \times l = \frac{\pi}{4} (0.15)^2 (0.225) = 3.976 \times 10^{-3} \text{ m}^3$$

$$\therefore \text{Compression ratio, } r = \frac{v_c + v_s}{v_c} = \frac{1.25 \times 10^{-3} + 3.976 \times 10^{-3}}{1.25 \times 10^{-3}} = 4.18$$

We know that air standard efficiency

$$\begin{aligned} \eta &= 1 - \frac{1}{(r)^{\gamma-1}} = 1 - \frac{1}{(4.18)^{1.4-1}} = 1 - \frac{1}{1.772} \\ &= 1 - 0.564 = 0.436 \text{ or } 43.6\% \text{ Ans.} \end{aligned}$$

**Example 2.** A certain quantity of air at a pressure of 1 bar and temperature  $70^\circ \text{C}$  is compressed reversibly and adiabatically until the pressure is 7 bar in an Otto cycle engine. 460 kJ of heat per kg of air is now added at constant volume. Determine : 1. compression ratio of the engine, 2. temperature at the end of compression, and 3. temperature at the end of heat addition.

Take for air,  $c_p = 1 \text{ kJ/kg K}$  and  $c_v = 0.707 \text{ kJ/kg K}$ .

**Solution.** Given :  $p_3 = 1 \text{ bar}$  ;  $T_3 = 70^\circ \text{C} = 70 + 273 = 343 \text{ K}$  ;  $p_4 = 7 \text{ bar}$  ;  $Q_{4-1} = 460 \text{ kJ}$  ;  $m = 1 \text{ kg}$  ;  $c_p = 1 \text{ kJ/kg K}$  ;  $c_v = 0.707 \text{ kJ/kg K}$

We know that ratio of specific heats,

$$\gamma = c_p / c_v = 1 / 0.707 = 1.41$$

1. Compression ratio of the engine

Let  $r = \text{Compression ratio of the engine} = v_3 / v_4$ .

We know that  $p_3 v_3^\gamma = p_4 v_4^\gamma$

$$\therefore \frac{v_3}{v_4} = \left( \frac{p_4}{p_3} \right)^{\frac{1}{\gamma}} \text{ or } r = \left( \frac{7}{1} \right)^{\frac{1}{1.41}} = (7)^{0.709} = 3.97 \text{ Ans.}$$

2. Temperature at the end of compression

Let  $T_4 = \text{Temperature at the end of compression.}$

$$\text{We know that } \frac{T_3}{T_4} = \left( \frac{v_4}{v_3} \right)^{\gamma-1} = \left( \frac{1}{r} \right)^{\gamma-1} = \left( \frac{1}{3.97} \right)^{1.41-1} = (0.252)^{0.41} = 0.568$$

$$\therefore T_4 = T_3 / 0.568 = 343 / 0.568 = 604 \text{ K} = 331^\circ \text{C Ans.}$$

3. Temperature at the end of heat addition

Let  $T_1 = \text{Temperature at the end of heat addition.}$

We know that heat added at constant volume ( $Q_{4-1}$ ),

$$460 = m c_v (T_1 - T_4) = 1 \times 0.707 (T_1 - 604) \text{ kJ}$$

$$\therefore T_1 - 604 = 460 / 0.707 = 651 \text{ or } T_1 = 1255 \text{ K} = 982^\circ \text{C Ans.}$$

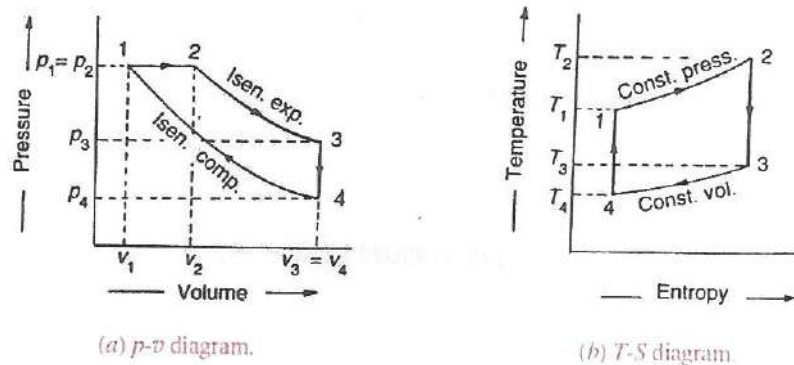


## DIESEL CYCLE:

This cycle was devised by dr. Rudolph diesel in 1893,. With an idea to attain a higher thermal efficiency, with a high compression ratio. This is an important cycle on which all the diesel engine work. It is also called constant pressure cycle as heat is received at a constant pressure.

The engine imagined by diesel has air enclosed in the cylinder , whose walls are perfectly non-conductor of heat, but bottom is a perfect conductor of heat. Again, there is a hot body, cold body and an insulating cap, which are alternately brought in contact with the cylinder.

The ideal diesel cycle consists of two reversible adiabatic or isentropic, a constant pressure and a constant volume processes. These processes are represented on p-v and T-S diagrams as shown in fig.



At this point let,  $P_1, T_1$  and  $v_1$  be the pressure, temperature and volume of the air. Following are four stages of an ideal diesel cycle.

1. FIRST STAGE(constant pressure heating):  
The air is heated at constant pressure from initial temp.  $T_1$  to a temp.  $T_2$  represented by the curve 1-2 in figure.
2. SECOND STAGE(reversible adiabatic or isentropic expansion):  
The air is expanded reversibly and adiabatically from temperature  $T_2$  to a temperature  $T_3$  as shown by the curve 2-3 in fig.  
In this process, no heat absorbed or rejected by the air.
3. THIRD STAGE(constant volume cooling):  
The air is now cooled at constant volume from temperature  $T_3$  to  $T_4$  as shown by the curve 3-4 in fig.  
Heat rejected by the air,  $Q_{3-4} = m.C_v(T_3 - T_4)$

4. FOURTH STAGE(Reversible adiabatic or isentropic compression):-

The air is compressed reversibly and adiabatically from temperature  $T_4$  to a temperature  $T_1$  represented by the curve 4-1 in fig.

In this process, no heat is absorbed or rejected by the air. We see that the air has been brought back to its original conditions of pressure, volume and temperature, thus completing the cycle.

$$\begin{aligned}\text{Work done} &= \text{Heat absorbed} - \text{Heat rejected} \\ &= m c_p (T_2 - T_1) - m c_v (T_3 - T_4)\end{aligned}$$

∴ Air standard efficiency,

$$\begin{aligned}\eta &= \frac{\text{Work done}}{\text{Heat absorbed}} = \frac{m c_p (T_2 - T_1) - m c_v (T_3 - T_4)}{m c_p (T_2 - T_1)} \\ &= 1 - \frac{c_v}{c_p} \left( \frac{T_3 - T_4}{T_2 - T_1} \right) = 1 - \frac{1}{\gamma} \left( \frac{T_3 - T_4}{T_2 - T_1} \right) \quad \dots (i)\end{aligned}$$

Now let compression ratio,

$$r = \frac{v_4}{v_1}$$

Cut-off ratio,  $\rho = \frac{v_2}{v_1}$

Expansion ratio,  $r_1 = \frac{v_3}{v_2} = \frac{v_4}{v_2} \quad \dots (\because v_3 = v_4)$

$$= \frac{v_4}{v_1} \times \frac{v_1}{v_2} = r \times \frac{1}{\rho} = \frac{r}{\rho}$$

We know for constant pressure heating process 1-2,

$$\frac{v_1}{T_1} = \frac{v_2}{T_2} \quad \dots (\text{Charles's law})$$

$$\therefore T_2 = T_1 \times \frac{v_2}{v_1} = T_1 \times \rho \quad \dots (ii)$$

Similarly, for reversible adiabatic or isentropic expansion process 2-3,

$$\frac{T_3}{T_2} = \left( \frac{v_2}{v_3} \right)^{\gamma-1} = \left( \frac{1}{r_1} \right)^{\gamma-1} = \left( \frac{\rho}{r} \right)^{\gamma-1}$$

$$\therefore T_3 = T_2 \left( \frac{\rho}{r} \right)^{\gamma-1} = T_1 \times \rho \left( \frac{\rho}{r} \right)^{\gamma-1} \quad \dots (iii)$$

for reversible adiabatic or isentropic compression process 4-1,

$$\frac{T_1}{T_4} = \left( \frac{v_4}{v_1} \right)^{\gamma-1} = (r)^{\gamma-1} \quad \text{or} \quad T_1 = T_4 (r)^{\gamma-1} \quad \dots (iv)$$

Substituting the value of  $T_1$  in equations (ii) and (iii),

$$T_2 = T_4 (r)^{\gamma-1} \times \rho \quad \dots (v)$$

$$T_3 = T_4 (r)^{\gamma-1} \times \rho \left( \frac{\rho}{r} \right)^{\gamma-1} = T_4 \rho^{\gamma} \quad \dots (vi)$$

Now substituting the values of  $T_1$ ,  $T_2$  and  $T_3$  in equation (i),

$$\eta = 1 - \frac{1}{\gamma} \left[ \frac{(T_4 \rho^\gamma) - T_4}{T_4 (r)^{\gamma-1} \rho - T_4 (r)^{\gamma-1}} \right]$$

$$= 1 - \frac{1}{(r)^{\gamma-1}} \left[ \frac{\rho^\gamma - 1}{\gamma (\rho - 1)} \right] \quad \dots (vii)$$

**Notes : 1.** The efficiency of the ideal Diesel cycle is lower than that of Otto cycle, for the same compression ratio. This is due to the fact that the cut-off ratio ( $\rho$ ) is always greater than unity and hence the term within the bracket of equation (vii) increases with the increase of cut-off ratio. Thus the negative term increases and the efficiency is reduced.

**2.** The Diesel cycle efficiency increases with decrease in cut-off ratio and approaches maximum (equal to Otto cycle efficiency) when the term within the bracket is unity.

**Example 6.15.** In a diesel engine, the compression ratio is 13 : 1 and the fuel is cut-off at 8% of the stroke. Find the air standard efficiency of the engine. Take  $\gamma$  for air as 1.4.

**Solution.** Given :  $r = v_4 / v_1 = 13$  ;  $\gamma = 1.4$

Since the cut-off takes place at 8% of the stroke, therefore volume at cut-off,

$$v_2 = v_1 + 8\% \text{ of stroke volume} = v_1 + 0.08 (v_4 - v_1)$$

Let us assume that the clearance volume ( $v_1$ ) = 1 m<sup>3</sup>.

$$\therefore v_4 = 13 \text{ m}^3 \quad \dots (\because v_4 / v_1 = 13)$$

and stroke volume,  $v_4 - v_1 = 13 - 1 = 12 \text{ m}^3$

$\therefore$  Volume at cut-off

$$v_2 = v_1 + 0.08 (v_4 - v_1) = 1 + 0.08 \times 12 = 1.96 \text{ m}^3$$

We know that cut-off ratio,

$$\rho = v_2 / v_1 = 1.96 / 1 = 1.96$$

$\therefore$  Air standard efficiency,

$$\eta = 1 - \frac{1}{(r)^{\gamma-1}} \left[ \frac{\rho^\gamma - 1}{\gamma (\rho - 1)} \right] = 1 - \frac{1}{(13)^{1.4-1}} \left[ \frac{(1.96)^{1.4} - 1}{1.4 (1.96 - 1)} \right]$$

$$= 1 - 0.417 = 0.583 \text{ or } 58.3\% \text{ Ans.}$$

**Example 6.16.** In an ideal Diesel cycle, the temperatures at the beginning and end of compression are 57° C and 603° C respectively. The temperatures at the beginning and end of expansion are 1950° C and 870° C respectively. Determine the ideal efficiency of the cycle.  $\gamma = 1.4$ .

If the compression ratio is 14 and the pressure at the beginning of the compression is 1 bar, calculate the maximum pressure in the cycle.

**Solution.** Given :  $T_4 = 57^\circ \text{C} = 57 + 273 = 330 \text{ K}$  ;  $T_1 = 603^\circ \text{C} = 603 + 273 = 876 \text{ K}$  ;  $T_2 = 1950^\circ \text{C} = 1950 + 273 = 2223 \text{ K}$  ;  $T_3 = 870^\circ \text{C} = 870 + 273 = 1143 \text{ K}$  ;  $\gamma = 1.4$  ;  $r = v_4 / v_1 = 14$  ;  $p_4 = 1 \text{ bar}$

*Ideal efficiency of the cycle*

We know that ideal efficiency of the cycle,

$$\eta = 1 - \frac{1}{\gamma} \left( \frac{T_3 - T_4}{T_2 - T_1} \right) = 1 - \frac{1}{1.4} \left( \frac{1143 - 330}{2223 - 876} \right)$$

$$= 1 - 0.431 = 0.569 \text{ or } 56.9\% \text{ Ans.}$$

*Maximum pressure in the cycle*

Let  $p_1$  = Maximum pressure in the cycle.

We know that for reversible adiabatic compression,

$$p_1 v_1^\gamma = p_4 v_4^\gamma \text{ or } p_1 = p_4 \left( \frac{v_4}{v_1} \right)^\gamma = 1 (14)^{1.4} = 40.23 \text{ bar Ans.}$$

**Example 6.17.** An ideal Diesel engine has a diameter 150 mm and stroke 200 mm. The clearance volume is 10 per cent of the swept volume. Determine the compression ratio and the air standard efficiency of the engine if the cut-off takes place at 6 per cent of the stroke.

**Solution.** Given :  $d = 150 \text{ mm} = 0.15 \text{ m}$  ;  $l = 200 \text{ mm} = 0.2 \text{ m}$  ;  $v_c = 10\%$  of  $v_s = 0.1 v_s$

*Compression ratio*

We know that stroke volume,

$$v_s = \frac{\pi}{4} \times d^2 \times l = \frac{\pi}{4} (0.15)^2 \times 0.2 = 3.53 \times 10^{-3} \text{ m}^3$$

$$\therefore v_c = 0.1 v_s = 0.1 \times 3.53 \times 10^{-3} = 0.353 \times 10^{-3} \text{ m}^3$$

We know that compression ratio,

$$\begin{aligned} r &= \frac{\text{Total volume}}{\text{Clearance volume}} = \frac{v_c + v_s}{v_c} = \frac{0.353 \times 10^{-3} + 3.53 \times 10^{-3}}{0.353 \times 10^{-3}} \\ &= 11 \text{ Ans.} \end{aligned}$$

*Air standard efficiency*

Since the cut-off takes place at 6% of the stroke, therefore volume at cut-off,

$$\begin{aligned} v_2 &= v_1 + 0.06 v_s = v_c + 0.06 v_s \quad \dots (\because v_1 = v_c) \\ &= 0.353 \times 10^{-3} + 0.06 \times 3.53 \times 10^{-3} = 0.565 \times 10^{-3} \text{ m}^3 \end{aligned}$$

$$\therefore \text{Cut-off ratio, } \rho = \frac{v_2}{v_1} = \frac{v_2}{v_c} = \frac{0.565 \times 10^{-3}}{0.353 \times 10^{-3}} = 1.6$$

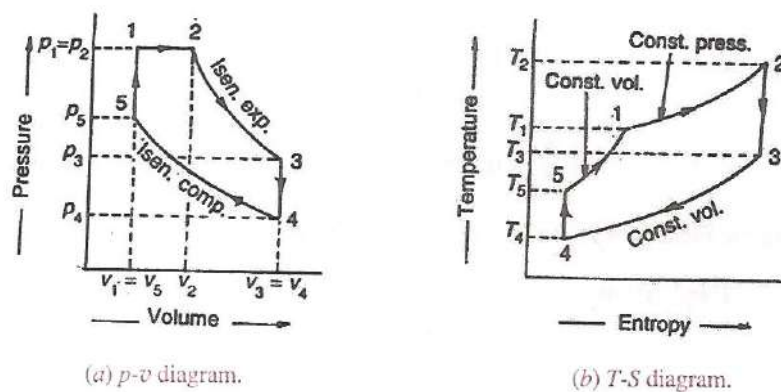
We know that air standard efficiency,

$$\begin{aligned} \eta &= 1 - \frac{1}{(r)^{\gamma-1}} \left[ \frac{\rho^\gamma - 1}{\gamma(\rho - 1)} \right] = 1 - \frac{1}{(11)^{1.4-1}} \left[ \frac{(1.6)^{1.4} - 1}{1.4(1.6 - 1)} \right] \\ &= 1 - \frac{1}{2.61} \times 1.11 = 1 - 0.4246 = 0.5753 \text{ or } 57.53\% \text{ Ans.} \end{aligned}$$

## DUAL COMBUSTION CYCLE:-

This cycle is a combustion of otto and diesel cycles. It is sometimes called semi-diesel cycle, because semi-diesel engines work on this cycle. In this cycle, heat is absorbed partly at a constant volume and partly at a constant pressure.

The ideal dual combustion cycle consists of two reversible adiabatic or isentropic, two constant volume and a constant pressure processes. These processes are represented on p-v and T-S diagram as shown in fig.



Let the engine cylinder contain  $m$  kg of air at point 1. At this point let,  $P_1, T_1$  and  $v_1$  be the pressure, temperature and volume of the air. Following are the five stages of an ideal dual combustion cycle.

1. **FIRST STAGE(constant pressure heating):-**  
The air is heated at constant pressure from initial temperature  $T_1$  to a temperature  $T_2$  represented by the curve 1-2 in fig.  
Heat absorbed by the air,  $Q_{1-2} = m.C_p (T_2 - T_1)$
2. **SECOND STAGE(reversible adiabatic or isentropic expansion):-**  
The air is expanded reversibly and adiabatically from temp.  $T_2$  to temp.  $T_3$  as shown by the curve 2-3 in fig .  
In this process, no heat is absorbed or rejected by the air.
3. **THIRD STAGE(Constant volume cooling):-**  
The air is now cooled at constant volume from temperature  $T_3$  to the temperature  $T_4$  as shown by the curve 3-4 in fig.  
Heat rejected by the air,  $Q_{3-4} = m.C_v (T_3 - T_4)$
4. **FOURTH STAGE(Reversible adiabatic or isentropic compression):-**  
The air is compressed reversibly and adiabatically from temperature  $T_4$  to a temperature  $T_5$  as shown by the curve 4-5 in fig.  
In this process, no heat is absorbed or rejected by the air.
5. **FIFTH STAGE(constant volume heating):-**

The air is finally heated at constant volume from temperature  $T_5$  to the temperature  $T_1$  as shown by the curve 5-1 in fig.

Heat absorbed by the air,  $Q_{5-1} = m.C_v (T_1 - T_5)$ . We see that the air has been brought back to its original conditions of pressure, volume, and temperature, thus completing the cycle. We know = heat absorbed – heat rejected =  $m.C_p (T_2 - T_1) + m.C_v (T_1 - T_5) - m.C_v (T_3 - T_4)$

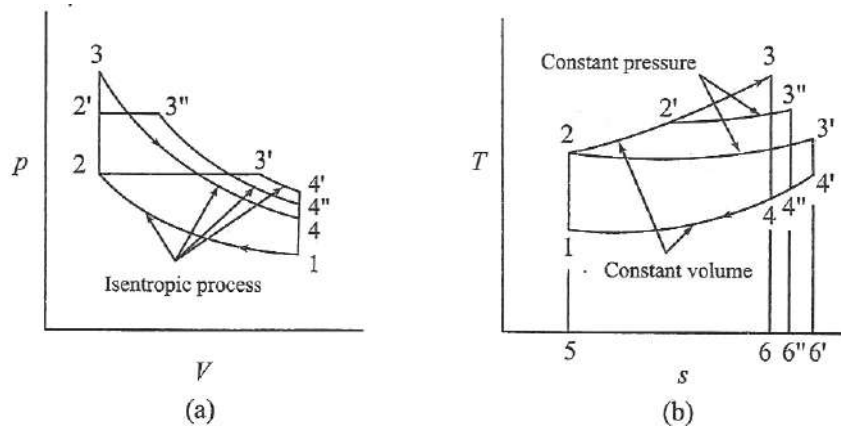
### COMPARISON OF OTTO, DIESEL AND DUAL CYCLES:

The important variable factors which are used as the basis for comparison of the cycles are compression ratio, peak pressure, heat addition, heat rejection and the net work. In order to compare the performance of the Otto, Diesel and Dual combustion cycles some of the variable factors must be fixed.

### SAME COMPRESSION RATIO AND HEAT ADDITION:

The Otto cycle 1-2-3-4-1, the Diesel cycle 1-2-3'-4'-1 and the Dual cycle 1-2''-3''-4''-1 are shown in figure for the same compression ratio and heat input

For the T-s diagram, it can be seen that Area 5236 = Area 5236 = area 52236 as this area represents the heat input which is the same for all cycles.



All the cycles start from the same initial state point 1 and the air is compressed from state 1 to 2 as the compression ratio is same. It is seen from the T-s diagram for the same heat input, the heat rejection in Otto cycle (area 5146) is minimum and heat rejection in Diesel Cycle (5146) is maximum. Consequently Otto cycle has the highest work output and efficiency. Diesel cycle has the least efficiency and Dual cycle having the efficiency between the two. For same compression ratio and heat addition,

One more observation can be made that is Otto cycle allows the working medium to expand more where as Diesel cycle is least in this respect the reason is heat is added before expansion in the case of Otto cycle and the last portion of heat supplied to the fluid has relatively short expansion in case of the diesel cycle.

#### SAME COMPRESSION RATIO AND HEAT REJECTION

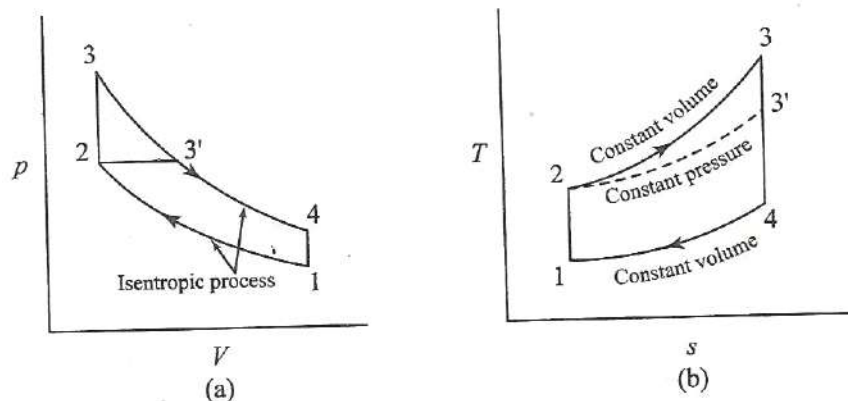
The p-V and T-s diagrams are in figure

$$\text{Now } \eta_{\text{Otto}} = 1 - \frac{Q_R}{Q_s}$$

Where  $Q_s$  is the heat supplied in the Otto cycle and is equal to the area under the curve 23 on the T-s diagram. The efficiency of the diesel cycle is given by

$$\eta_{\text{Diesel}} = 1 - \frac{Q_R}{Q'_s}$$

where  $Q'_s$  is heat supplied in the diesel cycle and is equal to area under the curve 23' on the Ts diagram



From the T-s diagram as in figure it is clear that  $Q_s > Q'_s$  i.e., heat supplied in the Otto cycle is more than that of the diesel cycle. Hence, it is evident that, the efficiency of the Otto cycle is greater than the efficiency of the Diesel cycle for a given compression ratio and heat rejection. Also, for the same compression ratio and heat rejection

$$\eta_{\text{Otto}} < \eta_{\text{Dual}} < \eta_{\text{Diesel}}$$

### SAME PEAK PRESSURE, PEAK TEMPERATURE, AND HEAT REJECTION:

The above figure show the Otto cycle 1234 and diesel cycle 12'34 on p-V and T-s co-ordinates, where the peak pressure and temperature and the amount of heat rejected are the same.

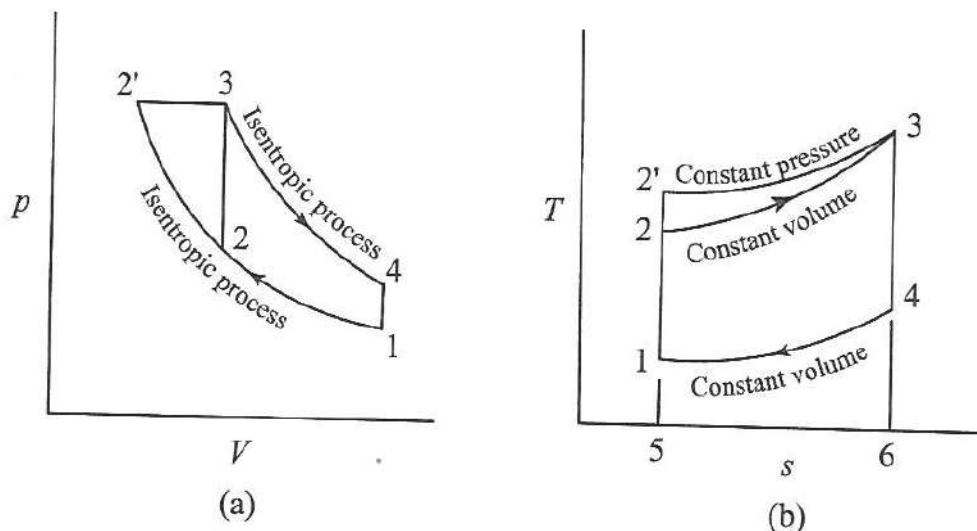
The efficiency of the Otto cycle 1234 is given by

$$\eta_{\text{Otto}} = 1 - \frac{Q_R}{Q_S}$$

where  $Q_S$  is the area under the curve 2w3 in figure

The efficiency of the diesel cycle, 12'34 is

Where  $Q_R$  is the area under the curve 23

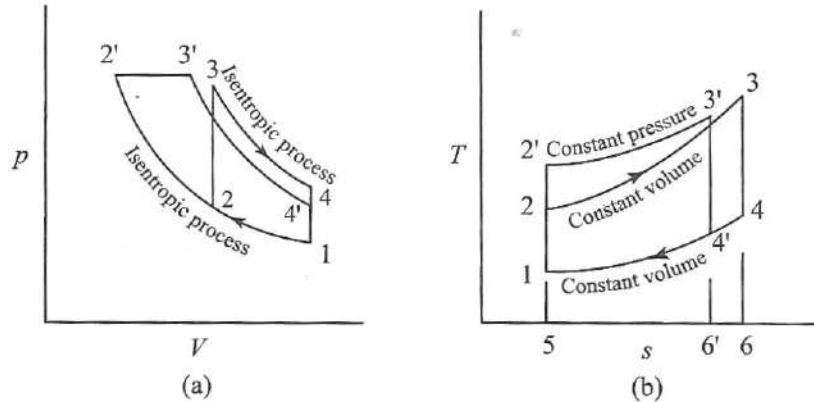


It is evident from figure that Therefore, the diesel cycle efficiency is greater than the Otto cycle efficiency when both engines are built to withstand the same thermal and mechanical stresses. Also, for the same peak pressure, peak temperature and heat rejection,



### SAME MAXIMUM PRESSURE AND HEAT INPUT

For same maximum pressure and same heat input the Otto cycle and diesel cycle are shown on p-V and T-s diagrams in the figure



It is evident from the figure that the heat rejection for Otto cycle is more than the heat rejected in diesel cycle. Hence Diesel cycle is more efficient than Otto cycle for the condition of same maximum pressure and heat input. One can make a note that with these conditions the Diesel cycle has higher compression ratio than that of Otto cycle. One should also note that the cycle which is having higher efficiency allows maximum expansion. The dual cycle efficiency will be between these two. Hence, for the same maximum pressure and heat input,

### SAME MAXIMUM PRESSURE AND WORK OUTPUT

The efficiency, can be written as

$$\eta = \frac{\text{Work done}}{\text{Heat Supplied}}$$

$$= \frac{\text{Work done}}{\text{Work done} + \text{Heat rejected}}$$

Refer to T-s diagram in the figure. For same work output the area 1234 (work output) and area 123'4' (work output of Diesel Cycle) are same. To achieve this, the entropy at 3 should be greater than entropy at 3'. It is clear that the heat rejection for Otto cycle is more than that of Diesel cycle. Hence, for these conditions the diesel cycle is more efficient than the Otto cycle. The efficiency of

Dual cycle lies between the two cycles. Hence, for the same maximum pressure and work out put ,

#### ADVANTAGES AND DISADVANTAGES OF TWO STROKE OVER FOUR STROKE CYCLE ENGINES:

1. A two stroke cycle engine gives twice the number of power strokes than the four stroke cycle engines at the same engine speed. Theoretically, a two stroke cycle engine should develop twice the power as that of a four stroke cycle engine. Two stroke cycle engine develops 1.7 to 1.8 times the power developed by four stroke cycle engines of the same dimension and speed. This is due to the lower compression ratio and effective stroke being less than the theoretical stroke.
2. For the same power developed , a two stroke cycle engine is lighter , less bulky, and occupies less floor area. Thus it makes , a two stroke cycle engine suitable for marine engines and other lighting vehicles.
3. As the no. of working strokes in a two stroke cycle engines are twice than the four stroke cycle engines., so the turning moment of a two stroke cycle engine is more uniform. Thus, it makes a two stroke cycle engine to have a lighter fly wheel and foundations. This also leads to a higher mechanical efficiency of a two stroke cycle engine.
4. The initial cost of a two stroke cycle engine is considerably less than a four stroke cycle engine
5. The mechanism of two stroke engine is much simpler than four stroke engine.
6. The two stroke cycle engines are much easier to start.

#### DISADVANTAGES:

1. Thermal efficiency of a two stroke engine is less than that a four stroke engine because a two stroke engine has less compression ratio than that of a four stroke engine.
2. Overall efficiency of a two stroke engine is also less than that of a four stroke engine because in a two stroke cycle, inlet and exhaust ports remain

open simultaneously for some time. In spite of careful design, a small quantity of charge is lost from the engine cylinder.

3. In case of two stroke engine, the number of power strokes are twice as those of a four stroke cycle engine. Thus the capacity of cooling system must be higher. Beyond a certain limit, the cooling capacity offers a considerable difficulty. Moreover, there is a greater wear and tear in a two stroke engine.
4. The consumption of lubricating oil is large in a two stroke cycle engine because of high operating temperature.

The exhaust gases in a two stroke cycle engine create noise, because of short time available for their exhaust

# **CHAPTER – 6**

## **Fuels and Combustion**

### **Hydrocarbon fuels**

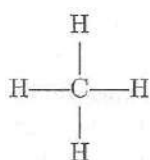
The carbon and hydrogen combine in different proportions and molecular structures to form a variety of hydrocarbon. The carbon to hydrogen ratio which is one of the important parameters and their nature of bonding determine the energy characteristics of the hydrocarbon fuels. Depending upon the number of carbon and hydrogen atoms the petroleum products are classified into different groups. The differences in physical and chemical properties between the different types of hydrocarbon depend on their chemical composition and affect mainly the combustion processes and hence, the properties of fuel and air required in the engine. The basic families of hydrocarbons, their general formulae and their molecular arrangement are shown in Table

Table Basic Families of Hydrocarbons

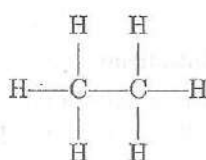
Family of hydrocarbons	General formula	Molecular structure	Saturated/Unsaturated	Stability
Paraffin	$C_nH_{2n+2}$	Chain	Saturated	Stable
Olefin	$C_nH_{2n}$	Chain	Unsaturated	Unstable
Naphthene	$C_nH_{2n}$	Ring	Saturated	Stable
Aromatic	$C_nH_{2n-6}$	Ring	Highly unsaturated	Most unstable

### Paraffin Series

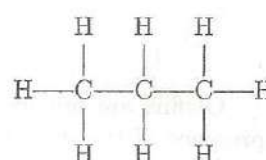
The normal paraffin hydrocarbons are of straight chain molecular structure. They are represented by a general chemical formula,  $C_nH_{2n+2}$ . The molecular structures of the first few members of the paraffin family of hydrocarbons are shown below.



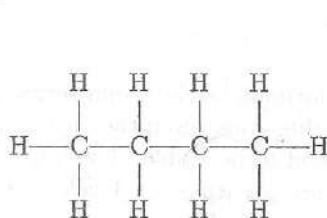
Methane



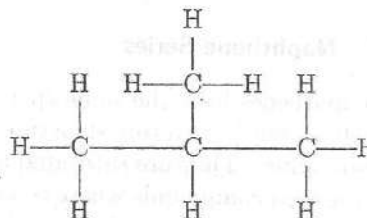
Ethane



Propane



Butane



Isobutane

In these hydrocarbons the valency of all the carbon atoms is fully utilized by single bonds with hydrogen atoms. Therefore, the paraffin hydrocarbons are saturated compounds and are characteristically very stable.

A variation of the paraffin family consists of an open chain structure with an attached branch and is usually termed a branched chain paraffin. The hydrocarbons which have the same chemical formulae but different structural formulae are known as isomers.

Isobutane shown above has the same general chemical formula and molecular weight as butane but a different molecular structure and physical characteristics. It is called an isomer of butane and is known as isobutane. Isoparaffins are also stable compounds.

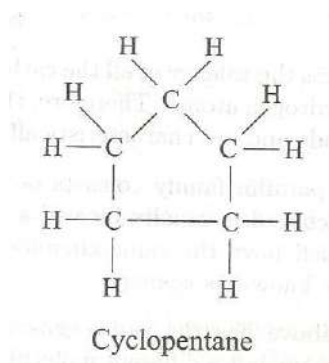
### olefin series

Olefin are also straight chain compounds similar to paraffins but are unsaturated because they contain one or more double bonds between carbon atoms. Their chemical formula is  $C_nH_{2n}$ . Mono-olefins have one double bond whereas diolefin have two in their structure.

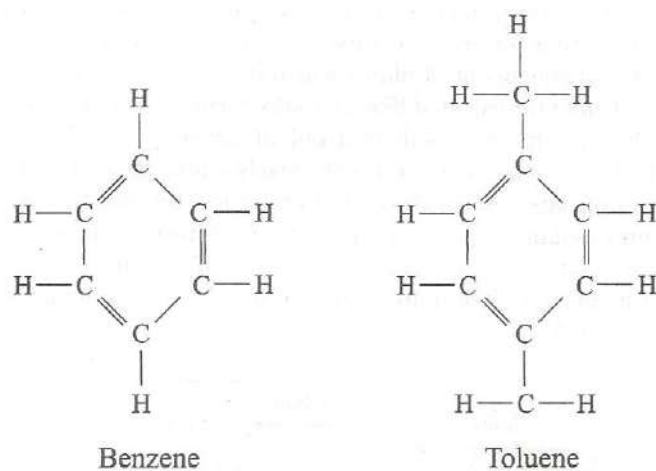
Olefins are not as stable as the single bond paraffins because of the presence of the double bonds in their structure. Consequently, these are readily oxidized in storage to form gummy deposits. Hence, olefin content in certain petroleum products is kept low by specification.

### Naphthene series

The naphthenes have the same chemical formula as the olefin series of hydrocarbons but have a ring structure and therefore, often they are called as cyclo-paraffins. They are saturated and tend to be stable. The naphthenes are saturated compounds whereas olefins are unsaturated. Cyclopentane is one of the naphthene series( $C_nH_{2n}$ ).



Aromatic compounds are ring structured having a benzene molecule as their central structure and have a general chemical formula  $C_nH_{2n-6}$ . Though the presence of double bonds indicate that they are unsaturated, peculiar nature of these double bonds causes them to be more stable than the other unsaturated compounds. Various aromatic compounds are formed by replacing one or more of the hydrogen atoms of the benzene molecules with an organic radical such as paraffins, naphthenes and olefins. By adding a methyl group ( $CH_3$ ), benzene is converted to toluene( $C_6H_5CH_3$ ), the base for the preparation of Trinitrotoluene (TNT) which is a highly explosive compound.



The above families of hydrocarbons some general characteristics due to their molecular structure which are summarized below

- I. Normal paraffins exhibit the poorest antiknock quality when used in an SI engine. But the antiknock quality improves with the increasing number of carbon atoms and the compactness of the molecular structure. The aromatics offer the best resistance to knocking in SI Engines.
- II. For CI engines, the order is reversed i.e., the normal paraffins are the best fuels and aromatics are the least desirable.
- III. As the number of atoms in the molecular structure increases, the boiling temperature increases. Thus fuels with fewer atoms in the molecule tend to be more volatile.
- IV. The heating value generally increases as the proportion of hydrogen atoms to carbon atoms in the molecule increases due to the higher heating value of hydrogen than carbon. Thus, paraffins have the highest value and the aromatics the least.

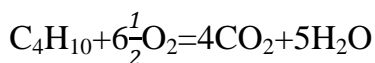
## Combustion reactions

The important combustion reactions are

1.  $\text{H}_2 + \frac{1}{2}\text{O}_2 \rightarrow$   
 $\text{H}_2\text{O (vap)} + 242,050 \text{ kJ kmol}^{-1} \text{ of H}_2$
2.  $\text{H}_2 + \frac{1}{2}\text{O}_2 \rightarrow$   
 $\text{H}_2\text{O (liq)} + 286,223 \text{ kJ kmol}^{-1} \text{ of H}_2$
3.  $\text{C} + \frac{1}{2}\text{O}_2 \rightarrow$   
 $\text{CO}_2 + 123,223 \text{ kJ kmol}^{-1} \text{ of C}$
4.  $\text{CO} + \frac{1}{2}\text{O}_2 \rightarrow$   
 $\text{CO}_2 + 285,637 \text{ kJ kmol}^{-1} \text{ of CO}$
5.  $\text{C} + \text{O}_2 \rightarrow$   
 $\text{CO}_2 + 408,860 \text{ kJ kmol}^{-1} \text{ of C}$
6.  $\text{CO}_2 + \text{C} \rightarrow$   
 $2\text{CO} - 162,413 \text{ kJ kmol}^{-1} \text{ of C}$
7.  $\text{C} + \text{H}_2\text{O} \rightarrow$   
 $\text{CO} + \text{H}_2 - 118,827 \text{ kJ kmol}^{-1} \text{ of C}$
8.  $\text{CH}_4 + 2\text{O}_2 \rightarrow$   
 $\text{CO}_2 + 2\text{H}_2\text{O} + 805,579 \text{ kJ kmol}^{-1} \text{ of CH}_4$
9.  $\text{C}_2\text{H}_2 + 2\frac{1}{2}\text{O}_2 \rightarrow$   
 $2\text{CO}_2 + \text{H}_2\text{O} + 1,308,019 \text{ kJ kmol}^{-1} \text{ of C}_2\text{H}_2$
10.  $\text{C}_2\text{H}_4 + 3\text{O}_2 \rightarrow$   
 $2\text{CO}_2 + 2\text{H}_2\text{O} + 1,447,864 \text{ kJ kmol}^{-1} \text{ of C}_2\text{H}_4$
11.  $\text{H}_2\text{S} + 1\frac{1}{2}\text{O}_2 \rightarrow$   
 $\text{H}_2\text{O} + \text{SO}_2 + 522.747 \text{ kJ kmol}^{-1} \text{ of H}_2\text{S}$
12.  $\text{S} + \text{O}_2 \rightarrow$   
 $\text{SO}_2 + 292,252 \text{ kJ kmol}^{-1} \text{ of S}$

## Stoichiometric of combustion:

Stoichiometric of combustion takes place in a Stoichiometric mixture of a fuel and oxygen. A Stoichiometric mixture of a fuel and oxygen contains the precise amount of oxygen to completely burn out all the combustible elements present in the fuel. This implies conversion of all C content to  $\text{CO}_2$  and all H content to  $\text{H}_2\text{O}$ . There is neither an excess nor deficiency of oxygen present in the reaction of mixture. And, as a result, there is no free oxygen in the reaction products, while all the combustibles in the fuel are completely oxidized. For instance, the Stoichiometric of combustion of n-butane is





The equation is balanced w.r.t all elements and presents the precise amount of oxygen in the reactants just sufficient to ensure a complete burn out of the fuel.

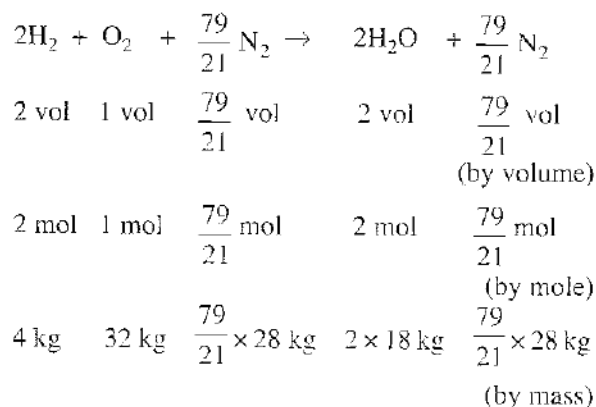
### Complete combustion:

Complete combustion means complete conversion of all combustible elements of a fuel into its stable oxides and as such the entire carbon of the fuel now exists as  $\text{CO}_2$  and hydrogen as  $\text{H}_2\text{O}$  in the products of combustion.

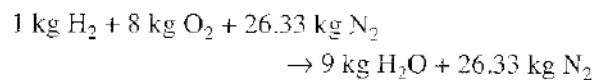
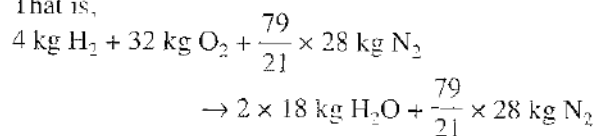
All practical combustion processes use air as a source of oxygen, the oxidizer of fuel. With 1 kmol of oxygen, there are 79/21 kmol of nitrogen. Hence,

#### 1. The combustion equation of hydrogen

$2\text{H}_2 + \text{O}_2 \rightarrow 2\text{H}_2\text{O}$  becomes

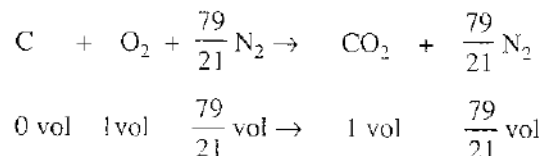


That is,



#### 2. The complete combustion equation of carbon

$(\text{C} + \text{O}_2 \rightarrow \text{CO}_2)$  becomes



$$\begin{array}{rclcl}
 1 \text{ mol} & 1 \text{ mol} & \frac{79}{21} \text{ mol} & \rightarrow & 1 \text{ mol} & \frac{79}{21} \text{ mol} \\
 & & & & & \text{(by mole)} \\
 12 \text{ kg} & 32 \text{ kg} & \frac{79}{21} \times 28 \text{ kg} & & 44 \text{ kg} & \frac{79}{21} \times 28 \text{ kg} \\
 & & & & & \text{(by mass)}
 \end{array}$$

That is,

$$\begin{array}{l}
 12 \text{ kg C} + 32 \text{ kg O}_2 + \frac{79}{21} \times 28 \text{ kg N}_2 \\
 \rightarrow 44 \text{ kg CO}_2 + \frac{79}{21} \times 28 \text{ kg N}_2 \\
 1 \text{ kg C} + 2.666 \text{ kg O}_2 + 8.777 \text{ kg N}_2 \\
 \rightarrow 3.666 \text{ kg CO}_2 + 8.777 \text{ kg N}_2
 \end{array}$$

### Incomplete combustion:

An Incomplete combustion refers to the condition when some unburnt fuel remains in the products. This may occur either due to an insufficient supply of oxygen to combust the fuel elements completely or due to inadequate fuel air mixing, leading to an inadequate exposure of fuel particles to oxygen during the period of combustion.

The Incomplete combustion leads to C, CO, H<sub>2</sub>, or OH in the product stream. If oxygen deficiency leads to an incomplete combustion of a fuel, then the hydrogen in the fuel will preferentially get oxidized to H<sub>2</sub>O than carbon to CO.

### Enthalpy of formation:

Combustion of hydrocarbon fuels lead to the formation of two major components: H<sub>2</sub>O and CO<sub>2</sub>

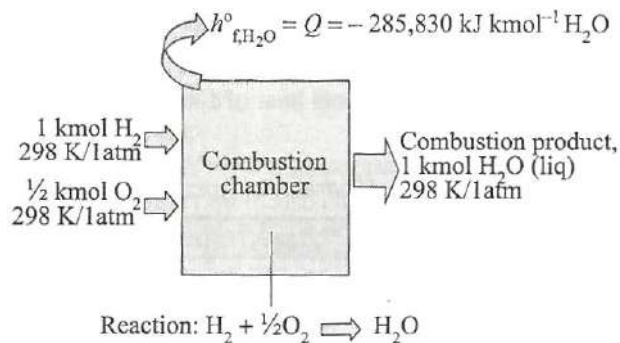
#### 1. Formation of water vapour

Consider a combustion chamber to which are introduced two separate streams-1 kmol of H<sub>2</sub>O and 1/2 kmol of O<sub>2</sub> - both at 298 K/1 atm. They are mixed and burned. The product, H<sub>2</sub>O(liq), also leaves the combustion at 298 K/1 atm

Before combustion

Enthalpy of elemental H<sub>2</sub> and O<sub>2</sub> at 298 K/1 atm is zero

i.e. the enthalpy of the mixture of hydrogen and oxygen prior to the combustion process is zero



### After combustion:

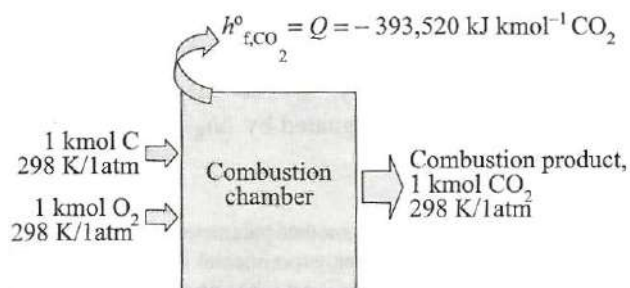
Since the combustion process is exothermic, heat must be removed from the combustion chamber to allow the product  $\text{H}_2\text{O}$  leave at standard condition.

### 2. Formation of Carbon dioxide:

Consider a combustion chamber into which are introduced 1 kmol of C and 1 kmol of  $\text{O}_2$  - both at 298K/1atm temperature.

Before combustion:

Enthalpy of elemental C and  $\text{O}_2$  at 298K.1atm is zero. i.e. the enthalpy of the mixture of carbon and oxygen prior to the combustion process is zero.



### After combustion:

Since the combustion process is exothermic, heat must be extracted from the combustion chamber to allow the product  $\text{CO}_2$  leave at standard conditions(298K/1atm)

### Determination of Enthalpy of Formation:

Applying the first law to the formation of a chemical substance:

$$Q = H_p - H_r$$

Where  $H_p$  = total enthalpy of product

$H_r$  = totals enthalpy of the reactants

Subscripts R and P refer to reactants and product.

A more general expression of this reaction will be

$$Q = \sum_P N_i h_i - \sum_R N_i h_i$$

Where  $N_i$  stands for the molar flow rate of component  $i$ ,  $h_i$  represents the molar specific enthalpy of constituent  $i$ , i.e., the difference between the enthalpy fluxes for the products and the reactants is the heat transfer rate during a chemical process.

Now, if this chemical process leads to the formation of a specified chemical compound, the enthalpy of the reactant elements can be set equal to zero at the Standard reference state. And as such the heat transfer for the process equals the specific enthalpy of the compound multiplied by its flow rate. This very quantity is the same as the enthalpy of formation of the said compound for the reaction occurring at the standard reference condition of 298 K/1 atm,

The enthalpy of formation of water(see above)

$$\begin{aligned} &= \text{heat transfer to the surroundings} \\ &\quad (\text{as determined by using a constant pressure calorimeter}) \\ &= 285,830 \text{ KJ Kmol of H}_2\text{O(liq) formed} \end{aligned}$$

Since the reaction is exothermic,

$$H = -285,830 \text{ KJ Kmol H}_2\text{O(l)}$$

The enthalpy of formation of carbon dioxide(see above)

$$\begin{aligned} &= \text{heat transfer to the surroundings} \\ &= 393,522 \text{ KJ Kmol of CO}_2 \text{ formed} \end{aligned}$$

Since the reaction is exothermic,

$$h_0 = -393,522 \text{ KJ Kmol CO}_2$$

### ENTHALPY OF REACTION:

The chemical energy which is stored as the potential Energy in the bond between the constituent atoms is Either released or absorbed during a chemical reaction .

The total enthalpy change associated with a chemical reaction When the temperature of the products equals the temperature of the reactants Is called the enthalpy of the reaction at that temperature. It is designated by  $H_g$ .

Such a change is depicted in fig. 13.3. it portrays the enthalpy versus temperature profile Of an exothermic reaction in which the heat generated

is transferred to the surrounding to set the reaction proceed at a fixed temperature.

Since  $Q = H$  for a constant pressure process, the enthalpy of reaction is also called heat of reaction at constant pressure or simply the heat of reaction . for a reaction at the standard reference state (298K/1atm):

This implies that the enthalpy of reaction at the standard reference state depends only on the Enthalpies of formation of the reactants/products and their number of moles.

### **HEAT OF COMBUSTION:**

The heat of combustion of a fuel is the enthalpy of stoichiometric combustion of the fuel when

1 kmol of fuel is burned with 100% theoretical air at a constant pressure at given reference state.

The enthalpy of combustion at a specified reference state is the same as the enthalpy of combustion reaction of the fuel with air at the same specified reference state. It is designated as

### **HEATING VALUES FOR FUELS:**

Fuels are of various kind. They are compared on the basis of their heating values.

The heating value of a fuel is the quantity of heat that is evolved when 1 kmol or Kg of the fuel

Is completely burned in air (in a steady-flow process) at the standard reference state(298 K\1atm).

$HV_f = -h_c$

Where  $HV_f$  stands for heating value of the fuel.

Now, as and when a hydrocarbon fuel is burned. Water is produced along with  $CO_2$ . When the  $H_2O$

In the produced is liquid ,i.e.,  $H_2O (l)$ ,the heating value is called higher heating value(HHV).the heating

Value when the  $H_2O$  products is vapour, i.e.,  $H_2O (g)$  is referred to as lower heating value (HLV).

Steady flow systems

Consider a steady flow system with a chemical reaction taking place within the control volume.

While there is practically a negligible change in the Kinetic and potential energies between

The inlet and exit stream (fig.13.4).state I represents the state of the state of the reactants just

Before the reaction, while state of the products just after the reaction. With the KE and PE factor

Gone. The overall energy balance leads to.