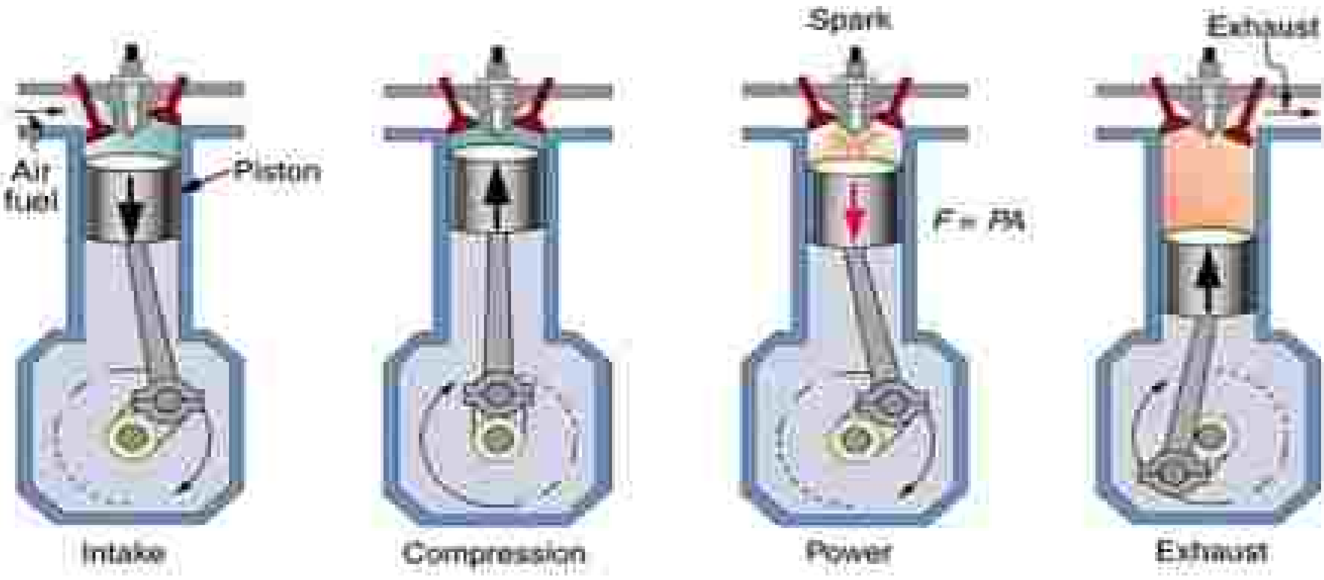
BHADRAK ENGINEERING SCHOOL & TECHNOLOGY (BEST), ASURALI, BHADRAK

Thermal Engineering- I

(Th- 04)

(As per the 2020-21 syllabus prepared by the SCTE&VT, Bhubaneswar, Odisha)



Third Semester

Mechanical Engg.

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THERMAL ENGINEERING-I

TOPIC WISE DISTRIBUTION PERIODS

Sl. No.	Name of the chapter as per the Syllabus	No. of Periods as per the Syllabus	No. of periods actually needed	Expected marks
01	Thermodynamic concept & Terminology	12	11	10
02	Laws of Thermodynamics	12	11	20
03	Properties Processes of perfect gas	10	12	15
04	Internal combustion engine	08	08	20
05	Air Standard Cycle	10	10	20
06	Fuels and Combustion	08	06	15
	Total	60	58	100

CHAPTER NO. – 01

THERMODYNAMIC CONCEPT AND TERMINOLOGY

Learning Objectives:

1.1 Thermodynamic Systems (closed, open, Isolated)
1.2 Thermodynamic properties of a system (pressure, volume, temperature, entropy, enthalpy, Internal energy and units of measurement).
1.3 Intensive and extensive properties
1.4 Define thermodynamic processes, path, cycle, state, path function, point function.
1.5 Thermodynamic Equilibrium.
1.6 Quasi-static Process.
1.7 Conceptual explanation of energy and its sources
1.8 Work, heat and comparison between the two.
1.9 Mechanical Equivalent of Heat.
1.10Work transfer, Displacement work

Introduction:

Thermodynamics is the science of energy transfer and its effect on the physical properties of substance. Thermal engineering is the field of applied science which deals with energy by heated gases and the laws which give the conversion of this energy into mechanical energy and vice versa.

1.1 Thermodynamic System:

A thermodynamic system is defined as a quantity of matter or a region in space upon which attention is concentrated in the analysis of a problem.

Surrounding: Everything external to the system is called surrounding.

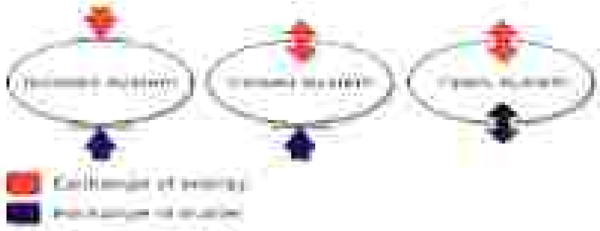
Boundary: The separation between the system and surrounding is called system boundary.

Closed system: It is a system of fixed mass. There is no mass transfer across the system boundary. Energy may transfer into or out of the system.
Example: A certain quantity of fluid bounded by a piston and cylinder.

Open system: A system in which matter crosses the system boundary but energy may or may not transfer.
Example: Air compressor.

Isolated system: It is the system in which there is no interaction between the system and surrounding. It is of fixed mass and energy. So, there is no mass and energy transfer take place across the system boundary.
Example: Universe, 100% or perfectly insulated thermo flask.

Sl.No	System	Mass	Energy
01	Closed	x	√
02	Open	√	√
03	Isolated	x	x



<u>Macroscopic and microscopic approach</u>:

Study of thermodynamics is done by two different approaches.

- **<u>Macroscopic approach</u>**: 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 behavior of matter. This type of study is also known as classical thermodynamics.
- **<u>Microscopic approach</u>**: 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.

1.2 <u>Thermodynamic Properties</u>:

Every system has certain characteristics by which its physical condition may be described.

<u>Example</u>: Pressure (P), Volume (V), Temperature (T), Entropy (S), Enthalpy (H), Internal energy(U).

<u>Pressure</u> (P): The normal applied force per unit area of the body is called pressure.

Unit: N/m^2 (Pa), MPa, GPa.

***1bar =10^5 N/m^2 or 10^5 Pa.**

<u>Volume</u> (V): The space occupied by a body is called volume.

Unit: m^3, cm^3, mm^3.

<u>Temperature</u> (T): Temperature is the thermal state of a body which determines the hotness or coldness of a body.

Unit: ^0C, K.

1.3 <u>Types of thermodynamic properties</u>:

1. Intensive properties.
2. Extensive properties.

<u>Intensive properties</u>: The properties of the system which are independent of mass is called intensive properties.

Example: pressure, temperature, specific volume, specific enthalpy, specific density.

<u>Extensive properties</u>: The properties of the system which are depending upon mass are called extensive properties.

Example: volume, enthalpy, density, energy.

<u>1.4 Define thermodynamic processes, path, cycle, state, path function, point function</u>

<u>Thermodynamic state</u>: The thermodynamic state is the condition of the system as characterized by certain thermodynamic properties like pressure, temperature, specific volume etc.

<u>Thermodynamic process</u>: The transformation of a thermodynamic system from one thermodynamic state to another is called a thermodynamic process.

<u>Path</u>: If all the change of states of a system is plotted and all the points are joined then the line joining the change of states of the system is called the path.

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

OR

Thermodynamic processes with identical end states are known as thermodynamic cycle.

Here 1-2, 2-3, 3-4, 4-1 represents 4 processes but 1-2-3-4-1 represents a thermodynamic cycle.

Path function: A path function is a function whose value depends on the path followed by the thermodynamic process irrespective of the initial and final states of the process.

*Work and Heat both are path function.

Point function: A point function is a function whose value depends on the final and initial length of the thermodynamic process irrespective of the path followed by the process.

Example: all the properties of the system are point function, i.e. pressure, volume, temperature, density, entropy, enthalpy etc..

1.5 Thermodynamic equilibrium:

A system is said to be exist in a state of thermodynamic equilibrium when there is no change in any macroscopic property, if the system is isolated from its surrounding.

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

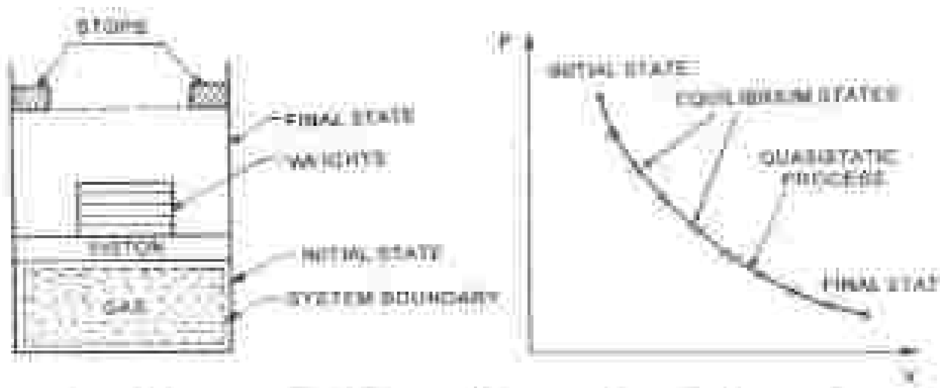
Mechanical equilibrium: A system is said to be in mechanical equilibrium if there is no unbalanced force acting on the system.

Chemical equilibrium: A system is said to be in chemical equilibrium if there is no chemical reaction or no transfer of matter from one part of the system to another.

Thermal equilibrium: A system is said to be in thermal equilibrium when there is no temperature difference between any points of the system or between the system and surrounding.

1.6 Quasi-static process

The word quasi means almost. If a process takes place infinitesimally and its each and every state passes through an equilibrium condition, then this process is known as quasistatic process. It is a reversible process.



Let us consider a system of gas contained in a cylinder as shown in figure. 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 an equilibrium state but if the same process 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.

1.7 ENERGY:

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

- *Unit: Joule (J), Kilo Joule (KJ).*

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 or **transient energy** e.g. heat, work, electricity etc.

<u>Different form of stored energy</u>:

1. **<u>Potential energy</u>**: The energy possessed by a body or a system for doing work by virtue of its position above the ground level is known as potential energy.

Mathematically: $P.E. = mgh$

Where, m = mass of the body in kg
g = acceleration due to gravity in m/s^2
h = height in meter

2. **<u>Kinetic energy</u>**: The energy possessed by a body or a system for doing work by virtue of its mass and velocity of motion is known as kinetic energy.

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

Where, m = mass of the body in kg
v = velocity of the body in m/s

3. **<u>Internal energy</u>**: The energy possessed by a body or a system by virtue of its intermolecular arrangement and motions of the molecules is known as internal energy. 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 internal energy of system).

1.8 <u>Heat</u>:

Heat is defined as the energy transferred without transfer of mass, across the boundary of a system because of temperature difference between the system and surrounding.

- It is represented by 'Q' and is expressed in ***'Joule'***.
- Heat can be transferred from a higher temperature region to a lower temperature region.
- Heat can be transferred in 3 modes: ***Conduction, Convection and Radiation***.
- Heat flowing into a system is taken as positive (+ve) and heat flowing out of the system is taken as negative (-ve).

<u>Work</u>:

- In **Mechanics** work is done by a force as it acts upon a body moving in the direction of force.
- In **Thermodynamics** work is said to be done by a system if the sole effect on things external to the system can be reduced to the raising of a weight.
- Work done by the system is considered to be positive and work done on the system is taken as negative.
- ***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***

<u>Comparison of Work and Heat</u>:

Similarities:

- Both are path functions and inexact differentials.
- Both are boundary phenomena i.e. both are recognised at the boundaries of the system as they cross them.
- Both are associated with a process, not a state. Unlike properties, work or heat has no meaning at a state.
- Systems possess energy, but not work or heat.

Dissimilarities:

- In heat transfer temperature difference is required.
- In a stable system there cannot be work transfer, however, there is no restriction for the transfer of heat.
- The sole effect external to the system could be reduced to rise of a weight but in the case of a heat transfer other effects are also observed.
- Work is said to be high grade energy and heat is said to be low grade energy.
- The complete conversion of low-grade energy into high grade energy is impossible.

1.9 Mechanical Equivalent of Heat:

According to '*James Prescott Joule*', whenever heat is converted into work or work into heat, the quantity of energy disappearing in one form is equivalent to the quantity of energy appearing in the other.

- If an amount of Work (W) results in the production of an amount of Heat (H), then

$$W \propto H$$
$$\Rightarrow W = JH$$

- Where, J is a constant and is called ***Joule's mechanical equivalent of heat.***
- If $H = 1$, $W = J$.
- **Definition of *J***: Joule's mechanical equivalent of heat is defined as the amount of work required to produce a unit quantity of heat.
- Mathematically: $J = W/H$
- Where, Value of $J = 4.2 \times 10^7$ *erg cal*$^{-1}$

$$= 4.2\ J\ cal^{-1}$$

1.10 Work Transfer:

For the work transfer the system has to be such selected that its boundary just moves. 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.

Displacement Work: Consider a piston cylinder arrangement as given in the Figure 2.4. If the pressure of the fluid is greater than that of the surroundings, there will be an unbalanced force on the face of the piston. Hence, the piston will move towards right.

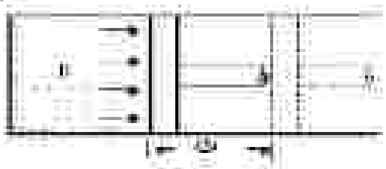


Figure 2.4 Displacement work

$$Force\ acting\ on\ the\ piston = pressure \times area$$
$$= p \times A$$
$$\therefore Work\ done = Force \times distance$$
$$= p\,A\,dx$$
$$= p\,dv$$
$$Where\ dv = change\ in\ volume$$

This work is known as displacement work or $p\,dv$ work corresponding to the elemental displacement dv. To obtain the total work done in a process, this elemental work must be added from the initial state to the final state.

$$W_{1-2} = \int_1^2 p\,dv$$

$\Rightarrow \quad W_{1-2} = p(v_2 - v_1)$

The above equation represents the total displacement work in a process 1-2.

POSSIBLE SHORT TYPE QUESTIONS WITH ANSWERS

1. Define thermodynamic system. [w-2022]

Ans: A thermodynamic system is defined as a quantity of matter or a region in space upon which attention is concentrated in the analysis of a problem.

2. Define closed system.

Ans: It is a system of fixed mass. There is no mass transfer across the system boundary. Energy may transfer into or out of the system.

Example: A certain quantity of fluid bounded by a piston and cylinder.

3. Define open system.

Ans: A system in which matter crosses the system boundary but energy may or may not transfer.

Example: Air compressor.

4. Define isolated system.

Ans: It is the system in which there is no interaction between the system and surrounding. It is of fixed mass and energy. So, there is no mass and energy transfer take place across the system boundary.

Example: Universe, 100% or perfectly insulated thermo flask.

5. Define thermodynamic properties of a system.

Ans: Every system has certain characteristics by which its physical condition may be described. These characteristics are known as thermodynamic properties of a system.

Example: Pressure (P), Volume (V), Temperature (T), Entropy (S), Enthalpy (H), Internal energy(U).

6. Define intensive properties. [w-2020,w-2022]

Ans: The properties of the system which are independent of mass is called intensive properties.

Example: pressure, temperature, specific volume, specific enthalpy, specific density.

7. Define extensive properties. [w-2020,w-2022]

Ans: The properties of the system which are depending upon mass are called extensive properties.

Example: volume, enthalpy, density, energy.

8. Define thermodynamic state.

Ans: The thermodynamic state is the condition of the system as characterized by certain thermodynamic properties like pressure, temperature, specific volume etc.

9. Define thermodynamic process.

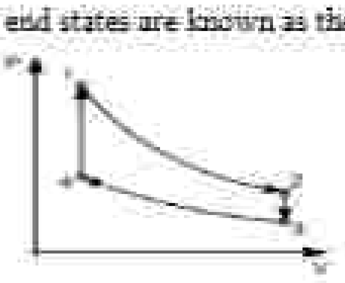
Ans: The transformation of a thermodynamic system from one thermodynamic state to another is called a thermodynamic process.

10. Define thermodynamic cycle.

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

OR

Thermodynamic processes with identical end states are known as thermodynamic cycle.



Here 1-2, 2-3, 3-4, 4-1 represents 4 processes but 1-2-3-4-1 represents a thermodynamic cycle.

11. Define path function. [W-2019]

Ans: A path function is a function whose value depends on the path followed by the thermodynamic process irrespective of the initial and final states of the process.

*Work and Heat both are path function.

12. Define point function.

Ans: A point function is a function whose value depends on the final and initial length of the thermodynamic process irrespective of the path followed by the process.

Example: all the properties of the system are point function, i.e. pressure, volume, temperature, density, entropy, enthalpy etc.

13. Define thermodynamic equilibrium.

Ans: A system is said to be exist in a state of thermodynamic equilibrium when there is no change in any macroscopic property, if the system is isolated from its surrounding.

14. Define quasistatic process. [W-2020]

Ans: The word quasi means almost. If a process takes place infinitesmally and its each and every state passes through an equilibrium condition, then this process is known as quasistatic process. It is a reversible process.

15. Define heat.

Ans: Heat is defined as the energy transfered without transfer of mass, across the boundary of a system because of temperature difference between the system and surrounding.

*It is represented by 'Q' and is expressed in ***'Joule'***.

16. Define work.

Ans: In **Mechanics** work is done by a force as it acts upon a body moving in the direction of force.

- In **Thermodynamics** work is said to be done by a system if the sole effect on things external to the system can be reduced to the raising of a weight.
- *Unit of work: Newton-meter (N-m) or Joule (J).*

17. Define mechanical equivalent of heat. [W-2020]

Ans: Joule's mechanical equivalent of heat is defined as the amount of work required to produce a unit quantity of heat.

Mathematically: $J = W/H$

Where, Value of $J = 4.2\times10^7\ erg\ cal^{-1}$

$= 4.2\ J\ cal^{-1}$

POSSIBLE LONG TYPE QUESTIONS

1. Compare heat and work.
2. A vacuum recorded in the condenser of a steam power plant is 740mm of Hg. Find the absolute pressure in the condenser in Pascal. The barometric reading is 760mm of Hg. [W-2019]
3. Explain the thermodynamic system.[w-2021]
4. Explain the quasi-static process.[w-2022]
5. Discuss in the details about point function and path function and differentiate between them. [w-2022]

CHAPTER NO. - 02

LAWS OF THERMODYNAMICS

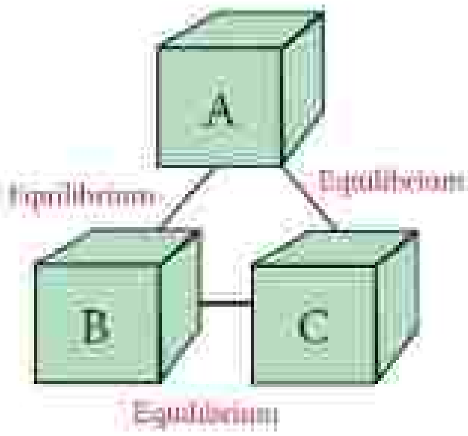
Learning objectives:

- *2.1 State & explain Zeroth law of thermodynamics.*
- *2.2 State & explain First law of thermodynamics.*
- *2.3 Limitations of First law of thermodynamics*
- *2.4Application of First law of Thermodynamics (steady flow energy equation and its*
- *application to turbine and compressor)*
- *2.4 Second law of thermodynamics (Clausius & Kelvin Plank statements)*
- *2.5 Application of second law in heat engine, heat pump, refrigerator & determination of efficiencies & C.O.P (solve simple numerical)*

2.1 State & explain Zeroth law of thermodynamics:

This law states that, "when two systems are each in thermal equilibrium with a third system, then the two systems are also in thermal equilibrium with one another".

Explanation: Let A, B, C are three thermodynamic systems.
T_A = Temperature of system A
T_B . Temperature of system B
T_C . Temperature of system C



According to this law
$T_A = T_C$ .... (i)
$T_B = T_C$ .... (ii)
So from equation (i) & (ii)
$T_A = T_B$ .... (iii)
From equation (i), (ii) & (iii) we get,
$\mathbf{T_A = T_B = T_C}$

2.2 First law of thermodynamics:

This law may be stated as follows:
(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 network transfer. In other words, the cyclic integral of heat transfer is equal to the cyclic integral of work transfer.

- **Mathematically,**

$$\oint \delta Q = \oint \delta W$$

Where the symbol $\oint$ stands for cyclic integral, and **δQ, δW** represent infinitesimal element of heat and work transfer respectively.

(b) The energy can neither be created nor be destroyed, though it can be transformed 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,**

$$\delta Q - \delta W = dE$$

Where the symbol δ 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.

2.3 limitations of first law of thermodynamics:

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 is being high grade energy, it can be fully converted into heat but heat cannot be completely converted into 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 or vice versa.

Enthalpy(H): Enthalpy, a property of a thermodynamic system, is the sum of the system's internal energy (U) and the product its pressure (P) and volume (V).

Mathematically,

$$H = U + PV$$

- **Unit: J, Kj**
- The enthalpy of unit mass system is known as specific enthalpy and is denoted by '**h**'
- **Unit: Kj/kg**
- **Mathematically,**

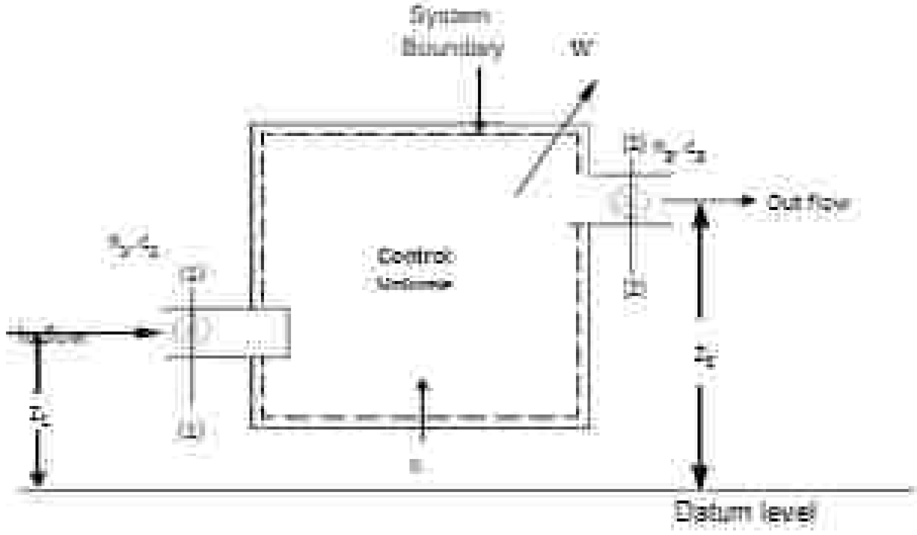
$$h = u + pv,$$

Steady flow process:

- Steady flow means that the rate of flow of mass and energy across the control surface are constant.
- At the steady state of a system, any thermodynamic property will have a fixed value at a particular location, and will not alter with time.
- Steady state means that the state is steady or invariant with time.
- In a steady flow process the following process must be satisfied.
  - The rate of mass flow at inlet and outlet must be same.
  - The rate of heat transfer is constant.
  - The rate of work transfer is constant.
  - The state of working substance at any point within the system is same at all times.
  - There is no change in the chemical composition of the system.

2.4 Application of first law of thermodynamics:

Steady flow energy equation (S.F.E.E):



Consider an open system through which the working substance flows at a steady rate. The working substance enters the system at section-1 and leaves the system at section-2.

Let p_1 = Pressure of the working substance entering the system in, N/m².
v_1 = Specific volume of the working substance entering the system in, m³/kg.
c_1 = Velocity of the working substance entering the system in, m/s.
u_1 = Specific internal energy of the working substance entering the system in, J/kg.
z_1 = Height of the inlet from datum level in, m.
p_2, v_2, c_2, u_2, z_2 = Corresponding values of the working substance at outlet.
q_{1-2} = Heat supplied to the system in, J/kg.
w_{1-2} = Work delivered by the system in, J/kg.

Consider 1kg of mass of the working substance flowing through the system. We know that, total energy entering the system per kg of the working substance,

$e_{in} = u_1 + p_1v_1 + \frac{c_1^2}{2} + gz_1 + q_{1-2}$

Similarly total energy of the working substance leaving the system,

$e_{out} = u_2 + p_2v_2 + \frac{c_2^2}{2} + gz_2 + w_{1-2}$

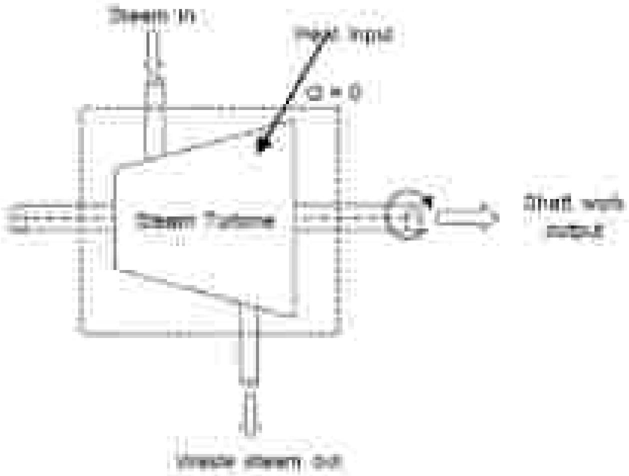
According to law of conservation of energy or first law of thermodynamics,

- **Energy at inlet = Energy at outlet**
- $u_1 + p_1v_1 + \frac{c_1^2}{2} + gz_1 + q_{1-2} = u_2 + p_2v_2 + \frac{c_2^2}{2} + gz_2 + w_{1-2}$
- $h_1 + \frac{c_1^2}{2} + gz_1 + q_{1-2} = h_2 + \frac{c_2^2}{2} + gz_2 + w_{1-2}$

Application of steady flow energy equation:

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

So, $q = 0$

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

i.e. $c_1 = c_2$

The turbine is positioned horizontally

So, $z_1 = z_2$

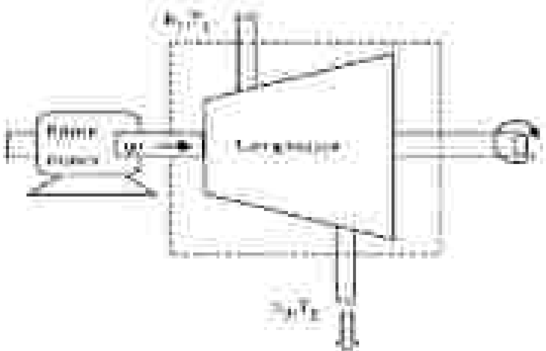
Applying SFEE to the control volume

$\Rightarrow \quad h_1 = h_2 + w_{1-2}$

$\Rightarrow \quad w_{1-2} = h_1 - h_2$

It is seen that work is done by the fluid at the expenses of its enthalpy.

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, $q = 0$

Velocity of air at inlet = Velocity of air at outlet

i.e. $c_1 = c_2$

The compressor is positioned horizontally

So, $z_1 = z_2$

Applying SFEE to the control volume

$\Rightarrow \quad h_1 = h_2 - w_{1-2}$

$\Rightarrow \quad w_{1-2} = h_2 - h_1$

Here enthalpy of the fluid increases by the amount of work input.

Perpetual motion machine of first kind (PMM-1):

- First law states the general principle of the conservation of energy i.e. energy can neither be created nor be destroyed, but it can be transformed from one form to another.
- There can be no machine which would continuously supply mechanical work without some other form of energy disappearing simultaneously. Such a fictitious machine is called a perpetual motion machine of first kind (PMM-1). So, a PMM-1 is thus impossible.

- The converse of the above statement is also true i.e. there can be no machine which would continuously consume work without some other form of energy appearing simultaneously.

2.5 Second Law of Thermodynamics:

Kelvin Planck statement: The Kelvin Planck statement of second law states, it is impossible for a heat engine to produce network in a complete cycle if it exchanges heat only with bodies at a single fixed temperature.

Perpetual motion machine of second kind (PMM-2):

The efficiency of heat engine is given by: -

$$\eta_e = \frac{W_{net}}{Q_{input}}$$

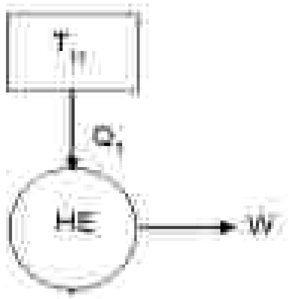
$$= \frac{Q_1 - Q_2}{Q_1}$$

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

If $Q_2 = 0$, then $W_{net} = Q_1$

So, $\eta_e = 1$ or 100%

The heat engine will produce network in a complete cycle by exchanging heat with only one reservoir, thus violating the Kelvin Planck statement. Such a heat engine is called perpetual motion machine of second kind (PMM-2).



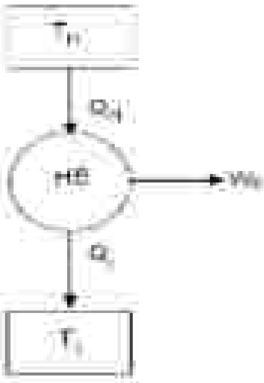
Clausius statement: Clausius statement of second law states, it is impossible to construct a device that will produce no affect other than the transfer of heat from a low temperature body to a high temperature body without doing any external work, while operating in a cycle.

- Heat can't flow of itself from a lower temperature body to a higher temperature body, some external work must be done to achieve this.

2.6 Application of Second Law of Thermodynamics:

Heat engine:

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



Here, $Q_H = W_E + Q_L$

$\Rightarrow \quad W_E = Q_H - Q_L$

Thermal efficiency: It is defined as the ratio of work out put to the energy input.

$$\eta_E = \frac{net\ work\ output}{energy\ input}$$

$$= \frac{W_E}{Q_H} = \frac{Q_H - Q_L}{Q_H}$$

Where, Q_H = Heat received from the source

Q_L = Heat rejected to the sink

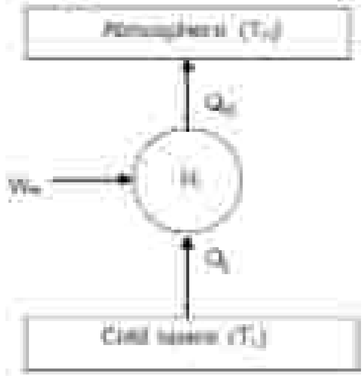
Or $\eta_E = \frac{T_H - T_L}{T_H}$

Where, T_H = Temperature of the source

T_L = Temperature of the sink

Refrigerator:

- A refrigerator is a device, which operating in a cycle, maintains a body temperature lower than the temperature of its surrounding.
- A refrigerator extracts heat continuously from a controlled space and thus maintained at a lower temperature than its surrounding.
- The working fluid working in the refrigerator is called refrigerant.



Here, $Q_H = W_E + Q_L$

$\Rightarrow \quad W_E = Q_H - Q_L$

Coefficient of performance (COP_R):

- The performance of a refrigerator is measured in terms of COP_R.

- It is defined as the ratio of desired output (refrigerating effect) to the energy input (work input).

- $COP_R = \frac{Refrigerating\ effect\ or\ Heat\ absorbed\ by\ the\ Refrigerant}{Work\ input}$

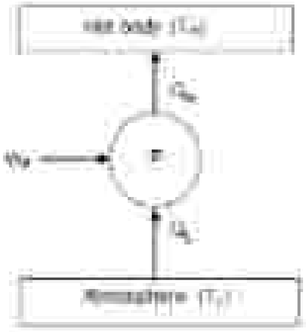
  $= \frac{R_E}{W_R} = \frac{Q_L}{W_R}$

  $= \frac{Q_L}{Q_H - Q_L}$

- Or $COP_R = \frac{T_L}{T_H - T_L}$

Heat pump:

- A heat pump is a device, which operating in a cycle, maintains a space at a higher temperature than its surrounding.
- The heat pump supplies heat continuously to the controlled space and thus maintained at a higher temperature than its surrounding.



Here, $Q_H = W_P + Q_L$

$\Rightarrow W_P = Q_H - Q_L$

Coefficient of performance (COP_P)

- $COP_P = \frac{Heat\ supplied\ to\ the\ hot\ body}{Work\ input}$

  $= \frac{Q_H}{W_P}$

  $= \frac{Q_H}{Q_H - Q_L}$

- Or $COP_P = \frac{T_H}{T_H - T_L}$

Note: we know that

- $COP_P = \frac{Q_H}{W_P\ or\ Work\ input}$

  $= \frac{W_P + Q_L}{W_P}$

  $= 1 + \frac{Q_L}{W_P\ or\ Work\ input}$

  $= 1 + COP_R$

Problem-1: *A heat engine operates on a cycle between source and sink temperatures of 337°C & 57°C respectively. If the heat engine receives 400Kj of heat from the source, find the efficiency, net work done and heat rejected to the sink.*

Solution. Data given: T_H = 337°C = 337 + 273 = 610 K; T_L = 57 + 273 = 330 K; Q_H = 400Kj

1. *Efficiency of the engine:*

   We know that, $\eta_E = \frac{T_H - T_L}{T_H} = \frac{610-330}{610} = 0.459$ or 45.9% Ans.

2. *Net work done:*

   We know that, $\eta_E = \frac{W_E}{Q_H}$

   $\Rightarrow \quad W_E = \eta_E \times Q_H$

   $\Rightarrow \quad W_E = 0.459 \times 400 = 183.6\ Kj$ Ans.

3. *Heat rejected to the sink:*

   We know that, $Q_H = W_E + Q_L$

   $\Rightarrow \quad Q_L = Q_H - W_E$

   $\Rightarrow \quad Q_L = 400 - 183.6 = 216.4\ Kj$ Ans.

Problem-2: *A cyclic heat engine operates between a source temperature of 800°C and a sink temperature of 30°C. What is the least rate of heat rejection per kw net output of the engine?*

Solution. Data given: T_H = 800 + 273 = 1073 K; T_L = 30 + 273 = 303 K; W_E = 1kw;

We know that, $\eta_E = \frac{T_H - T_L}{T_H} = \frac{1073-303}{1073} = 0.718$

We also know that, $\eta_E = \frac{W_E}{Q_H}$

$\Rightarrow \quad Q_H = \frac{W_E}{\eta_E} = \frac{1}{0.718} = 1.392$ kw

Least rate of heat rejection:

We know that, $Q_L = Q_H - W_E$

$= 1.392 - 1$

$= 0.392$ kw Ans.

Problem-3: *A domestic food freezer maintains a temperature of -15°C. The ambient temperature is 30°C. The heat leaks into the freezer at 1.75kj/s, what is the minimum power necessary to pump this heat out?*

Solution. Data given: T_H = 30 + 273 = 303 K; T_L = -15 + 273 = 258 K; Q_L = 1.75 kj/s;

We know that, $COP_R = \frac{T_L}{T_H - T_L} = \frac{258}{303-258} = 5.73$

Minimum power necessary to pump the heat out:

We know that, $COP_R = \frac{Q_L}{W_R}$

$\Rightarrow \quad W_R = \frac{Q_L}{COP_R} = \frac{1.75}{5.73} = 0.305\ kw$ Ans.

Problem-4: A heat pump delivers 2kw of heat to a room maintained at 25°C and receives heat from a reservoir at -10°C. If the actual COP is 50% of that of an ideal heat pump operating between the same temperature limits, what is the actual power required in kw to run the heat pump?

Solution.

Data given:

Q_H = 2 kw

T_H = 25 + 273 = 298 K

T_L = -10 + 273 = 263 K

$(COP)_{P,\ Actual} = 0.5\ (COP)_{P,\ Ideal}$

We know that, $(COP)_{P,\ Ideal} = \frac{T_H}{T_H - T_L} = \frac{298}{298-263} = 8.514$

So, $(COP)_{P.\ Actual} = 0.5 \times 8.514 = 4.257$

Actual power required to run the heat pump:

We know that, $(COP)_{P.\ Actual} = \frac{Q_H}{W_P}$

$$\Rightarrow \quad W_P = \frac{Q_H}{(COP)_{P.\ Actual}}$$

$$\Rightarrow \quad W_P = \frac{2}{4.257} = 0.47\ kw \quad \text{Ans.}$$

POSSIBLE SHORT TYPE QUESTIONS WITH ANSWER

1. State zeroth law of thermodynamics. [W-2020,w-2022]

Ans: This law states that, "when two systems are each in thermal equilibrium with a third system, then the two systems are also in thermal equilibrium with one another".

2. State first law of thermodynamics.

Ans: This law may be stated as follows:

(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 network transfer. In other words, the cyclic integral of heat transfer is equal to the cyclic integral of work transfer.
- **Mathematically,**

$$\oint \delta Q = \oint \delta W$$

Where the symbol $\oint$ stands for cyclic integral, and **δQ, δW** represent infinitesimal element of heat and work transfer respectively.

(b) The energy can neither be created nor be destroyed, though it can be transformed 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,**

$$\delta Q - \delta W = dE$$

Where the symbol δ 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.

3. State second law of thermodynamics. [W-2019]

Ans: **Kelvin Planck statement**: The Kelvin Planck statement of second law states, it is impossible for a heat engine to produce network in a complete cycle if it exchanges heat only with bodies at a single fixed temperature.

Clausius statement: Clausius statement of second law states, 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 without doing any external work, while operating in a cycle.

- Heat can't flow of itself from a lower temperature body to a higher temperature body, some external work must be done to achieve this.

4. Define enthalpy

Ans: Enthalpy, a property of a thermodynamic system, is the sum of the system's internal energy (U) and the product its pressure (P) and volume (V).

Mathematically,

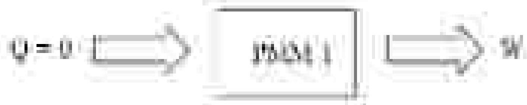
$$H = U + pv$$

- **Unit: J, Kj**
- The enthalpy of unit mass system is known as specific enthalpy and is denoted by '**h**'
- **Unit: Kj/Kg**
- **Mathematically,**

$$h = u + pv_s$$

5. Define PMM-1.

Ans: There can be no machine which would continuously supply mechanical work without some other form of energy disappearing simultaneously. Such a fictitious machine is called a perpetual motion machine of first kind (PMM-1). So a PMM-1 is thus impossible.



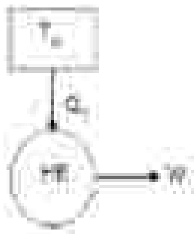
6. What are the limitations of first law of thermodynamics? [W-2019]

Ans: There are two basic limitations of the first law of thermodynamics:

- First law does not differentiate between heat and work. It assumes complete inter-convertibility of the two. Though work is being high grade energy, it can be fully converted into heat but heat cannot be completely converted into work.
- 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 or vice versa.

7. Define PMM-2. [W-2019]

Ans: The heat engine will produce net work in a complete cycle by exchanging heat with only one reservoir, thus violating the Kelvin Planck statement. Such a heat engine is called perpetual motion machine of second kind (PMM-2).



8. Define $(COP)_R$. [W-2020]

- Ans: It is defined as the ratio of desired output (refrigerating effect) to the energy input (work input).

- $COP_R = \frac{\text{Refrigerating effect or Heat absorbed by the Refrigerant}}{\text{Work input}}$

$$= \frac{R_E}{W_R} = \frac{Q_L}{W_R} = \frac{Q_L}{Q_H - Q_L}$$

- Or $COP_R = \frac{T_L}{T_H - T_L}$

POSSIBLE LONG TYPE QUESTIONS

1. What is steady flow? Derive the steady flow energy equation. [W-2020]

2.State and explain the first law of thermodynamic.[w-2020]

3.State the general energy equation of a gas for a steady flow process.[w-2020],[w-2021]

4.Derive the relation between COP of a refrigerator and COP of heat pump.[w-2021]

6.Air flow steady at the rate of 1kg/s through an air compressor at 7m/s velocity, 100kpa pressure and specific volume of $0.95m^3/kg$ and leaving at 5m/s, 700kpa and $0.19m^3/kg$. The difference in internal energy between outlet and inlet is 90kj/kg.Cooling water absorb heat from the air at the rate of 60kw-

1. Rate of work output
2. Ratio of inlet and outlet pipe diameter

Problem-1: *A cyclic heat engine operates between a source temperature of 1000^0C and a sink temperature of 40^0C. What is the least rate of heat rejection per kw net output of the engine?* **[W-2019]**

Problem-2: *A heat pump delivers 2kw of heat to a room maintained at 25^0C and receives heat from a reservoir at -10^0C. If the actual COP is 50% of that of an ideal heat pump operating between the same temperature limits, what is the actual power required in kw to run the heat pump?*

Problem-3: *A domestic food freezer maintains a temperature of -15^0C. The ambient temperature is 30^0C. The heat leaks into the freezer at 1.75kj/s, what is the minimum power necessary to pump this heat out?*

Problem-3:*In a heat engine, the temperature of the source and sink are 650^0C and 60^0C respectively. The heat supplied is 4.5MJ/min.Find the power developed by the engine.[w-2022]*

2. Discuss about the limitation of first law of thermodynamic.[w-2022]

3. Prove C_P-C_V=R.[w-2022]

4.State the equivalence of two statement of 2[nd] law of thermodynamic.[w-2022]

CHAPTER NO.- 03

PROPERTIES PROCESSES OF PERFECT GAS

Learning Objectives:

- *3.1 Laws of perfect gas:*
- *Boyle's law, Charle's law, Avogadro's law, Dalton's law of partial pressure, Guy lussac*
- *law, General gas equation, characteristic gas constant, Universal gas constant.*
- *3.2 Explain specific heat of gas (Cp and Cv)*
- *3.3 Relation between Cp & Cv.*
- *3.4 Enthalpy of a gas.*
- *3.5 Work done during a non- flow process.*
- *3.6 Application of first law of thermodynamics to various non flow process (Isothermal,*
- *Isobaric, Isentropic and polytrophic process)*
- *3.6 Solve simple problems on above.*
- *3.7 Free expansion & throttling process.*

INTRODUCTION:

A perfect gas or an ideal gas may be defined as a state of a substance, whose evaporation from its liquid state is complete and strictly obeys all the gas laws under all conditions of pressure and temperature.

3.1 Laws of Perfect Gas:

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 $pv = constant$

$$or\ p_1v_1 = p_2v_2 = p_3v_3 = \cdots = constant$$

Charles's Law:

This law was formulated by a Frenchman Jacques A.C. Charles in about 1787. It states, ***"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 $\frac{v}{T} = constant$

$$or\ \frac{v_1}{T_1} = \frac{v_2}{T_2} = \frac{v_3}{T_3} = \cdots = constant$$

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 $\frac{p}{T} = constant$

$$or\ \frac{p_1}{T_1} = \frac{p_2}{T_2} = \frac{p_3}{T_3} = \cdots = constant$$

Avogadro's Law:

This law states, ***"Equal volumes of all gases, at the same temperature and pressure, contain equal no of molecules".***

- Avogadro's experiments shows that the average volume for 1 Kg-mole of any perfect gas is 22.413 m^3 at standard atmospheric pressure (1.01325 bar) and 0^oC NTP condition.

General Gas Equation:

The Boyle's law and Charles's law are combined together, which give us a general gas equation.
According to Boyle's law

$$\Rightarrow \quad p \propto \frac{1}{v} \; or \; v \propto \frac{1}{p}$$

According to Charles's law

$$\Rightarrow \quad v \propto T$$

It is thus obvious that

$$\Rightarrow \quad v \propto \frac{T}{p}$$

$$\Rightarrow \quad pv \propto T$$

$$\Rightarrow \quad pv = CT$$

$$\Rightarrow \quad \frac{pv}{T} = C$$

Where C is a constant, whose value depends upon the mass and properties of the gas.

$$\Rightarrow \quad \frac{p_1v_1}{T_1} = \frac{p_2v_2}{T_2} = \frac{p_3v_3}{T_3} = \cdots = constant$$

Characteristic Equation of Gas:

It is a modified form of general gas equation. If the volume (v) in the general gas equation is taken as that of 1kg of gas (known as its specific volume, and denoted by v_s), then the constant C (in the general gas equation) is represented by another constant R (in the characteristic equation of gas).
Thus, the general gas equation may be rewritten as:

$$pv_s = RT$$

Where, R is known as ***characteristic gas constant*** or simply ***gas constant***.
For any mass m kg of a gas, the characteristic gas equation becomes:

$$mpv_s = mRT$$

$$or \quad pv = mRT \qquad \ldots(mv_s = v)$$

- In S.I. units, the value of R for atmospheric air is taken as ***0.287 kJ/kg K or 287 J/kg K.***

Universal Gas Constant:

The universal gas constant or molar constant of a gas is the product of the gas constant and the molecular mass of the gas. It is generally denoted by R_u.

Mathematically,

$$R_u = MR$$

Where, M = Molecular mass of the gas expressed in kg-mole
R = Gas constant

- The value of R_u is same for all gases.
- In S.I. units, the value of R_u is taken as 8314 ***J/kg-mol K or 8.314 kJ/kg-mol K***

Dalton's Law of Partial Pressure:

When two or more gases which don't react chemically with one another are enclosed in a vessel, then the total pressure exerted by the mixture of gases will be equal to the sum of the partial pressures which each gas would exert if present alone in that space.

Mathematically,

$$p = p_a + p_b + p_c + \cdots\cdots\cdots$$

Where, p = Total pressure of the mixture of gases
p_a, p_b, p_c = Partial pressures of each gas

Problem.1: *A gas occupies a volume of 0.1 m³ of a temperature of 20⁰ C and a pressure of 1.5 bar. Find the final temperature of the gas, if it is compressed to a pressure of 7.5 bar and occupies a volume of 0.04 m³.*

Solution: Data given: $v_1 = 0.1\ m^3$, $T_1 = 20^0\ C = 20 + 273 = 293\ K$, $p_1 = 1.5\ bar = 1.5 \times 10^5\ N/m^2$, $p_2 = 7.5\ bar = 7.5 \times 10^5\ N/m^2$, $v_2 = 0.04\ m^3$, $T_2 = ?$

According to general gas equation.

We know that, $\frac{p_1 v_1}{T_1} = \frac{p_2 v_2}{T_2}$

$$\Rightarrow\ T_2 = \frac{p_2 v_2 T_1}{p_1 v_1}$$

$$\Rightarrow\ T_2 = \frac{7.5 \times 10^5 \times 0.04 \times 293}{1.5 \times 10^5 \times 0.1}$$

$$\Rightarrow\ T_2 = 586\ K\ or\ 313^0 C$$ Ans.

Problem.2: *A vessel of capacity 3 m³ contains air at a pressure of 1.5 bar and a temperature of 25⁰ C. Additional air is now pumped into the system until the pressure rises to 30 bar and temperature rises to 60⁰ C. Determine the mass of air pumped in and express the quantity as a volume at a pressure of 1.02 bar and a temperature of 20⁰ C. If the vessel is allowed to cool until the temperature is again 25⁰ C, calculate the pressure in the vessel.*

Solution: Data given: $v_1 = 3\ m^3$, $p_1 = 1.5\ bar = 1.5 \times 10^5\ N/m^2$, $T_1 = 25^0\ C = 25 + 273 = 298\ K$, $p_2 = 30\ bar = 30 \times 10^5\ N/m^2$, $T_2 = 60^0\ C = 60 + 273 = 333\ K$, $p_3 = 1.02\ bar = 1.02 \times 10^5\ N/m^2$, $T_3 = 20^0\ C = 20 + 273 = 293\ K$

Mass of air pumped in

We know that, $p_1 v_1 = m_1 R T_1$

$$\Rightarrow\ m_1 = \frac{p_1 v_1}{R T_1} = \frac{1.5 \times 10^5 \times 3}{287 \times 298} = 5.26\ kg$$ ....(Taking R for air = $287\ J/kg\ K$)

Similarly, $p_2 v_2 = m_2 R T_2$

$$\Rightarrow\ m_2 = \frac{p_2 v_2}{R T_2} = \frac{30 \times 10^5 \times 3}{287 \times 333} = 94.17\ kg$$ ....($\because v_2 = v_1$)

∴ Mass of air pumped in, $m = m_2 - m_1 = 94.17 - 5.26 = 88.91\ kg$ Ans.

Volume of air pumped in at a pressure of 1.02 bar and temperature of 20⁰ C

Let v_3 = volume of air pumped in.

We know that, $p_3 v_3 = m R T_3$

$$\Rightarrow\ v_3 = \frac{m R T_3}{p_3} = \frac{88.91 \times 287 \times 293}{1.02 \times 10^5} = 73.29\ m^3$$ Ans.

Pressure in the vessel after cooling

Let p_4 = pressure in the vessel after cooling

We know that the temperature after cooling, $T_4 = T_1 = 25^0\ C = 298\ K$

Since the cooling is at constant volume, therefore

$$\frac{p_2}{T_2} = \frac{p_4}{T_4}$$

$$\Rightarrow\ p_4 = \frac{T_4 p_2}{T_2} = \frac{298 \times 30 \times 10^5}{333} = 26.8 \times 10^5\ N/m^2$$

$$\Rightarrow\ p_4 = 26.8\ bar$$ Ans.

3.2 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.

Mathematically,

$$C = \frac{Q}{m \times \Delta t}$$

Where, C = Specific heat of a substance
Q = Amount of heat transfer
m = Mass of the substance
Δt = Rise in temperature

- S.I. unit, ***J/kg K or kJ/kg K***
- 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.

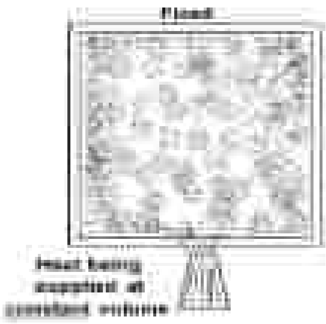
- Specific heat at constant volume
- Specific heat at constant pressure

Specific Heat at Constant Volume:

It is the amount of heat required 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,

$$Q_{1-2} = Mass \times Specific\ heat\ at\ constant\ volume \times Rise\ in\ temperature$$

$$\Rightarrow \quad Q_{1-2} = mc_v(T_2 - T_1)$$

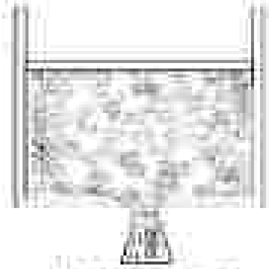
It may be noted that whenever a gas is heated at constant volume, no work is done by the gas. The whole heat energy is utilised in increasing the temperature and pressure of the gas. In other words, all the amount of heat supplied remains within the gas, and represents the increase in internal energy 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
T_2 = Final temperature of the gas
v_1 = Initial volume of the gas
v_2 = Final volume of the gas

∴ Total heat supplied to the gas at constant pressure,

$$Q_{1-2} = Mass \times Specific\ heat\ at\ constant\ pressure \times Rise\ in\ temperature$$
$$\Rightarrow \quad Q_{1-2} = mc_p(T_2 - T_1)$$

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. This heat remains within the gas and represents the increase in internal energy.
   Mathematically, 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,
   $$W_{1-2} = p(v_2 - v_1) = mR(T_2 - T_1)$$

3.3 Relation Between (*Cp* & *Cv*):

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

Let 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 of the gas

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

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

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

So, Heat utilized for external work, $W_{1-2} = p(v_2 - v_1) = mR(T_2 - T_1)$
And increase in internal energy, $dU = mc_v(T_2 - T_1)$

We know that, $Q_{1-2} = dU + W_{1-2}$

$\Rightarrow mc_p(T_2 - T_1) = mc_v(T_2 - T_1) + mR(T_2 - T_1)$

$\Rightarrow c_p = c_v + R$

$\Rightarrow c_p - c_v = R$

$\Rightarrow c_v\left(\frac{c_p}{c_v} - 1\right) = R$

$\Rightarrow c_v(\gamma - 1) = R$ (where $\frac{c_p}{c_v} = \gamma$)

$\Rightarrow c_v = \frac{R}{\gamma - 1}$

3.4 Enthalpy Of a Gas:

Enthalpy, a property of a thermodynamic system, is the sum of the system's internal energy (U) and the product its pressure (P) and volume (V).

Mathematically,

$$H = U + pv$$

- **Unit:** *J, kj*
- The enthalpy of unit mass system is known as specific enthalpy and is denoted by '*h*'
- **Unit:** *kj/kg*
- **Mathematically**,

$$h = u + pv_s$$

Problem.3: *A closed vessel contains 2 kg of carbon dioxide at temperature 20⁰ C and pressure 0.7 bar. Heat is supplied to the vessel till the gas acquires a pressure of 1.4 bar. Calculate: 1. Final temperature, 2. Work done on or by the gas, 3. Heat added, and 4. Change in internal energy. Take specific heat of the gas at constant volume as 0.657 kj/kg K.*

Solution: Data given: $m = 2$ kg, $T_1 = 20^0$ C $= 20 + 273 = 293$ K, $p_1 = 0.7$ bar $= 0.7 \times 10^5$ N/m², $p_2 = 1.4$ bar $= 1.4 \times 10^5$ N/m², $C_v = 0.657$ kj/kg K

1. *Final temperature*:

According to Gay-Lussac Law

$$\frac{p_1}{T_1} = \frac{p_2}{T_2}$$

$$\Rightarrow T_2 = \frac{p_2 T_1}{p_1} = \frac{1.4 \times 293}{0.7} = 586\ K \text{ or } 313^0\ C$$

2. *Work done on or by the gas*

Since there is no change in volume, therefore work done ($W_{1,2}$) on or by the gas is zero.

3. *Heat added*

We know that, $Q_{1-2} = mc_v(T_2 - T_1) = 2 \times 0.657\,(586 - 293) = 385\ kj$ Ans.

4. *Change in internal energy*

We know that, $Q_{1-2} = W_{1-2} + dU$

$\Rightarrow dU = Q_{1-2} = 385\ kj$ Ans.

Problem.4: *One kg of a perfect gas occupies a volume of 0.85 m³ at 15⁰ C and at a constant pressure of 1 bar. The gas is first heated at constant volume, and then at a constant pressure. Find the specific heat at constant volume and constant pressure of the gas. Take $\gamma = 1.4$.*

Solution: Data given: $m = 1$kg, $v = 0.85$ m³, $T = 15^0$ C $= 15 + 273 = 288$ K, $p = 1$ bar $= 1 \times 10^5$ N/m², $\gamma = c_p/c_v = 1.4$

Specific heat of gas at constant volume

We know that, $pv = mRT$

$$\Rightarrow R = \frac{pv}{mT} = \frac{1 \times 10^5 \times 0.85}{1 \times 288} = 295\ J/kgK = 0.295\ kj/kgK$$

We also know that, $c_v = \frac{R}{\gamma-1} = \frac{0.295}{1.4-1} = 0.7375\ kJ/kgK$ Ans.

Specific heat of gas at constant pressure

We know that, $c_p = 1.4c_v = 1.4 \times 0.7375 = 1.0325\ kJ/kgK$ Ans.

Problem5: *The volume of air at a pressure of 5 bar and 47° C is 0.5 m³. Calculate the mass of air, if the specific heats at constant pressure and volume are 1 kJ/kg K and 0.72 kJ/kg K respectively.*

Solution: Data given: $p = 5\ bar = 5 \times 10^2\ KN/m^2$, $T = 47^0\ C = 47 + 273 = 320\ K$, $v = 0.5\ m^3$, $c_p = 1\ kJ/kg\ K$, $c_v = 0.72\ kJ/kg\ K$

Mass of air

We know that, $c_p - c_v = R$

$\Rightarrow R = 1 - 0.72 = 0.28\ kJ/kgK$

We know that, $pv = mRT$

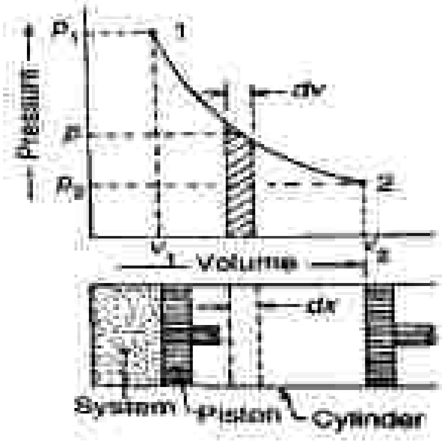
$\Rightarrow m = \frac{pv}{RT} = \frac{5\times10^2\times0.5}{0.28\times320} = 2.79\ kg$ Ans.

Non-flow Processes: The processes occurring in closed systems which do not permit the transfer of mass across their boundaries are known as non-flow processes.

- It may be noted that in a non-flow process, the energy crosses the system boundary in the form heat and work but, there is no mass flow into or out of the system.

3.5 Work Done During a Non-Flow Process:

Consider a system contained in a frictionless piston and cylinder arrangement as shown in the figure below. As the system expands from its initial state 1 to final state 2, some work must be done.



Let at any small section (shown shaded), the pressure (p) of the system is constant. If A is the cross-sectional area of the piston, then force on the piston ($F = p\,A$) causes the piston to move through a distance dx,

Thus work done by the system,

$$\delta W = F\,dx = p\,A\,dx = p\,dv \quad \text{.........}(\because dv = A\,dx)$$

$\therefore$ Work done for non-flow process from state 1 to state 2,

$$W_{1-2} = \int_1^2 \delta W = \int_1^2 p\,dv$$

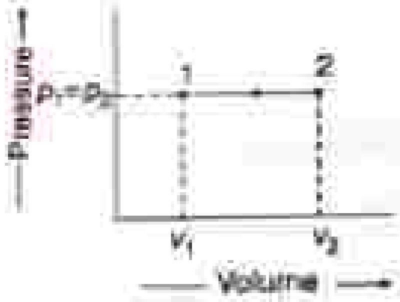
From above, we see that the work done is given by the area under the p-v diagram.

3.6 Application of First Law of Thermodynamics to Various Non-flow Processes:

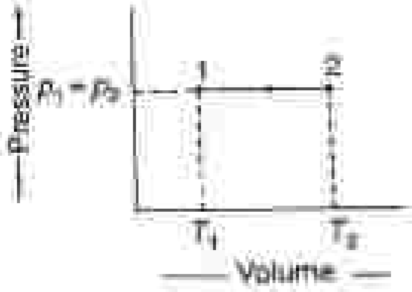
Isobaric Process (Constant Pressure Process):

This process is governed by Charles's Law. Consider *m* kg of a certain gas, contained in a closed container, is being heated at constant pressure from an initial state 1 to a final state 2.

Let p_1, v_1 and T_1 = Pressure, volume and temperature of the gas at the initial state 1.
p_2, v_2 and T_2 = Pressure, volume and temperature of the gas at the final state 2.



(a) p-v diagram



(b) p-T diagram

Now let us derive the following relations for the reversible isobaric process.

1. ***Pressure-volume-temperature (p-v-T) relationship***

We know that the general gas equation is

$$\frac{p_1 v_1}{T_1} = \frac{p_2 v_2}{T_2}$$

Since the gas is heated at constant pressure, therefore $p_1 = p_2$

$$\frac{v_1}{T_1} = \frac{v_2}{T_2} = \frac{v}{T} = Constant$$

Thus, the isobaric process is governed by Charles's Law.

2. ***Work done by the gas***

We know that, $\delta W = p\, dv$

On integrating from state 1 to state 2,

$$\int_1^2 \delta W = \int_1^2 p\, dv = p \int_1^2 dv$$

Or $W_{1-2} = p\,(v_2 - v_1) = mR\,(T_2 - T_1)$

3. ***Change in internal energy***

We know that change in internal energy, $dU = m\, c_v\, dT$

On integrating from state 1 to state 2,

$$\int_1^2 dU = m\,c_v \int_1^2 dT$$

Or $\quad U_2 - U_1 = m\,c_v\,(T_2 - T_1)$

4. ***Heat supplied or heat transfer***

We know that, $\quad \delta Q = dU + \delta W$

On integrating from state 1 to state 2,

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

$$\begin{aligned} \text{Or} \quad Q_{1-2} &= (U_2 - U_1) + W_{1-2} \\ &= m\,c_v\,(T_2 - T_1) + m\,R\,(T_2 - T_1) \\ &= m\,(T_2 - T_1)\,(c_v + R) \\ &= m\,c_p(T_2 - T_1) \qquad \ldots\ldots\ldots(\because c_p - c_v = R) \end{aligned}$$

5. ***Change in enthalpy***

We know that change in enthalpy, $\quad dH = dU + d\,(pv)$

On integrating from state 1 to state 2,

$$\int_1^2 dH = \int_1^2 dU + \int_1^2 d\,(pv)$$

$$\begin{aligned} \text{Or} \quad H_2 - H_1 &= (U_2 - U_1) + (p_2 v_2 - p_1 v_1) \\ &= m\,c_v\,(T_2 - T_1) + m\,R\,(T_2 - T_1) \\ &= m\,(T_2 - T_1)\,(c_v + R) \\ &= m\,c_p(T_2 - T_1) \qquad \ldots\ldots\ldots(\because c_p - c_v = R) \end{aligned}$$

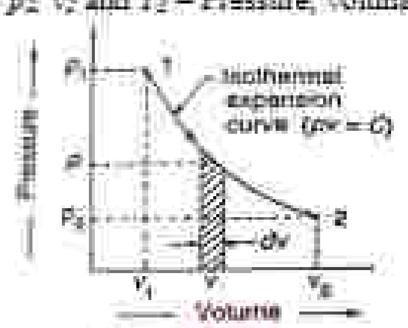
We see that change in enthalpy is equal to the heat supplied or heat transferred.

Isothermal Process (Constant Temperature Process): This process is governed by Boyle's Law.

- A process in which the temperature of the working substance remains constant during its expansion or compression is called constant temperature process or isothermal process.
- It is thus obvious that in a isothermal process:
  a) There is no change in temperature.
  b) There is no change in internal energy.
  c) There is no change in enthalpy.

Now consider m kg of a certain gas, being heated at constant temperature from an initial state 1 to a final state 2.

Let $\quad p_1$, v_1 and T_1 = Pressure, volume and temperature of the gas at the initial state 1.
p_2, v_2 and T_2 = Pressure, volume and temperature of the gas at the final state 2.



(a) p-v diagram

(b) p-T diagram

Now let us derive the following relations for the reversible isothermal process.

1. ***Pressure-volume-temperature (p-v-T) relationship***

We know that the general gas equation is

$$\frac{p_1 v_1}{T_1} = \frac{p_2 v_2}{T_2}$$

Since the gas is heated at constant temperature, therefore $T_1 = T_2$

$$p_1 v_1 = p_2 v_2 \quad or \quad pv = Constant$$

Thus, the isothermal process is governed by Boyle's Law.

2. ***Work done by the gas***

We know that, $\delta W = p\,dv$

On integrating from state 1 to state 2,

$$\int_1^2 \delta W = \int_1^2 p\,dv \quad or \quad W_{1-2} = \int_1^2 p\,dv \qquad \ldots\ldots (i)$$

Since the expansion of the gas is isothermal *i.e.* $p\,v = C$, therefore

$$pv = p_1 v_1 \quad or \quad p = \frac{p_1 v_1}{v}$$

Substituting this value of p in equation (*i*), we have

$$W_{1-2} = \int_{v_1}^{v_2} \frac{p_1 v_1}{v} dv = p_1 v_1 \int_{v_1}^{v_2} dv$$

$$= p_1 v_1 [\log_e v]_{v_1}^{v_2} = p_1 v_1 \log_e \left(\frac{v_2}{v_1}\right)$$

$$= 2.3\, p_1 v_1 \log\left(\frac{v_2}{v_1}\right) = 2.3\, p_1 v_1 \log(r) \qquad \ldots\ldots (ii)$$

$$\text{Where, } r = \frac{v_2}{v_1}, \textit{and is known as expansion ratio.}$$

We know that $p_1 v_1 = p_2 v_2 = mRT$

So the equation (*ii*) may also be written as follows:

$$W_{1-2} = 2.3\, mRT \log\left(\frac{v_2}{v_1}\right) = 2.3\, mRT \log(r)$$

Since $p_1 v_1 = p_2 v_2$, $therefore\ \frac{v_2}{v_1} = \frac{p_1}{p_2}$

$$\therefore W_{1-2} = 2.3\, mRT \log\left(\frac{p_1}{p_2}\right)$$

3. ***Change in internal energy***

We know that change in internal energy, $dU = U_2 - U_1 = m\,c_v\,(T_2 - T_1)$

Since it is a isothermal process, *i.e.* $T_2 = T_1$, therefore

$$dU = U_2 - U_1 = 0 \quad or \quad U_1 = U_2$$

4. ***Heat supplied or heat transfer***

We know that, $Q_{1-2} = dU + W_{1-2} = W_{1-2}$ ...... $(\because dU = 0)$

This shows that total heat supplied to the gas is equal to the work done by the gas.

5. ***Change in enthalpy***

We know that change in enthalpy, $dH = H_2 - H_1 = m\,c_p(T_2 - T_1)$

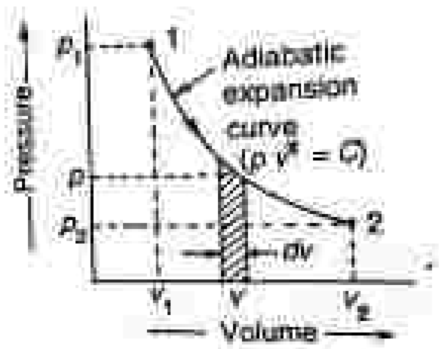
Since it is a isothermal process, *i.e.* $T_2 = T_1$, therefore

$$dH = H_2 - H_1 = 0 \quad or \quad H_1 = H_2$$

<u>**Adiabatic Process (Isentropic Process):**</u> A process, in which the working substance neither receives nor gives out heat to its surroundings, during its expansion or compression, is called an adiabatic process. This will happen when the working substance remains thermally insulated, so that no heat enters or leaves it during the process.

- It is thus obvious that, in an adiabatic or isentropic process:
  a) No heat leaves or enters the gas.
  b) The temperature of the gas changes, as the work is done at the cost of internal energy.
  c) The change in internal energy is equal to the work done.

Now consider *m* kg of a certain gas, being heated adiabatically from an initial state 1 to a final state 2.
Let p_1, v_1 and T_1 = Pressure, volume and temperature of the gas at the initial state 1.
p_2, v_2 and T_2 = Pressure, volume and temperature of the gas at the final state 2.



Now let us derive the following relations for a reversible adiabatic process.

1. ***Pressure-volume-temperature (p-v-T) relationship***
Adiabatic expansion of the gas follows the law, $pv^\gamma = C \quad or \quad p_1v_1^\gamma = p_2v_2^\gamma = \dots = C$

- $\frac{p_2}{p_1} = \left(\frac{v_1}{v_2}\right)^\gamma$
- $\frac{T_2}{T_1} = \left(\frac{v_1}{v_2}\right)^{\gamma-1}$
- $\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}}$

2. ***Work done during adiabatic expansion***

We know that, $\delta W = p\,dv$

On integrating from state 1 to state 2,

$$\int_1^2 \delta W = \int_1^2 p\,dv \quad or \quad W_{1-2} = \int_1^2 p\,dv \qquad \text{.........(i)}$$

Since adiabatic expansion of the gas follows the law,

$$pv^{\gamma} = p_1 v_1^{\gamma} \quad or \quad p = \frac{p_1 v_1^{\gamma}}{v^{\gamma}}$$

Substituting this value of p in equation (i), we have

$$W_{1-2} = \int_1^2 \frac{p_1 v_1^{\gamma}}{v^{\gamma}}\, dv = p_1 v_1^{\gamma} \int_1^2 v^{-\gamma}\, dv$$

$$= p_1 v_1^{\gamma} \left(\frac{v^{-\gamma+1}}{-\gamma+1}\right)_1^2 = \frac{p_1 v_1^{\gamma}}{1-\gamma}\left[v_2^{1-\gamma} - v_1^{1-\gamma}\right]$$

$$= \frac{p_1 v_1^{\gamma}\, v_2^{1-\gamma} - p_1 v_1^{\gamma}\, v_1^{1-\gamma}}{1-\gamma}$$

$$= \frac{p_2\left(v_2^{\gamma} v_2^{1-\gamma}\right) - p_1\left(v_1^{\gamma} v_1^{1-\gamma}\right)}{1-\gamma} \quad \ldots\ldots\left(p_1 v_1^{\gamma} = p_2 v_2^{\gamma}\right)$$

$$= \frac{p_2 v_2 - p_1 v_1}{1-\gamma}$$

$$= \frac{p_1 v_1 - p_2 v_2}{\gamma - 1} \quad \ldots\ldots \textit{For expansion}$$

$$= \frac{p_2 v_2 - p_1 v_1}{\gamma - 1} \quad \ldots\ldots \textit{For compression}$$

The above equation for work done may also be expressed as:

$$W_{1-2} = \frac{mR(T_1 - T_2)}{\gamma - 1} \quad \ldots\ldots \textit{For expansion}$$

$$= \frac{mR(T_2 - T_1)}{\gamma - 1} \quad \ldots\ldots \textit{For compression}$$

3. ***Change in internal energy***

We know that change in internal energy, $dU = U_2 - U_1 = m\, c_v\, (T_2 - T_1)$

4. ***Heat supplied or heat transfer***

We know that heat supplied or heat transferred in case of adiabatic process is zero, therefore

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

5. ***Change in enthalpy***

We know that change in enthalpy, $dH = H_2 - H_1 = m\, c_p (T_2 - T_1)$

Polytropic Process: The polytropic process follows the general law for the expansion and compression of gases, and is given by the relation:

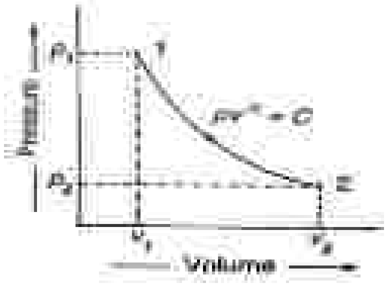
$$pv^n = C \quad or \quad p_1 v_1^n = p_2 v_2^n = \cdots = C$$

Where n is a polytropic index, which may have any value from zero to infinity.

Now consider m kg of a certain gas, being heated polytropically from an initial state 1 to a final state 2.

Let p_1, v_1 and T_1 = Pressure, volume and temperature of the gas at the initial state 1.

p_2, v_2 and T_2 = Pressure, volume and temperature of the gas at the final state 2.



Now let us derive the following relations for the polytropic process.

1. ***Pressure-volume-temperature (p-v-T) relationship***

- $\frac{p_2}{p_1} = \left(\frac{v_1}{v_2}\right)^n$
- $\frac{T_1}{T_2} = \left(\frac{v_2}{v_1}\right)^{n-1}$
- $\frac{T_1}{T_2} = \left(\frac{p_1}{p_2}\right)^{\frac{n-1}{n}}$

2. ***Work done during polytropic expansion***

The equation for the work done during a polytropic process may also be expressed by changing the index n for γ in the adiabatic process.

∴ Work done during a polytropic process from state 1 to state 2,

$$W_{1-2} = \frac{p_1v_1 - p_2v_2}{n-1} = \frac{mR(T_1 - T_2)}{n-1} \quad \text{......For expansion}$$

$$= \frac{p_2v_2 - p_1v_1}{n-1} = \frac{mR(T_2 - T_1)}{n-1} \quad \text{......For compression}$$

3. ***Change in internal energy***

We know that change in internal energy, $dU = U_2 - U_1 = m\,c_v\,(T_2 - T_1)$

4. ***Heat supplied or heat transfer***

We know that the heat supplied or heat transferred,

$$Q_{1-2} = W_{1-2} + dU$$

$$= \frac{p_1v_1 - p_2v_2}{n-1} + m\,c_v\,(T_2 - T_1)$$

$$= \frac{mR(T_1 - T_2)}{n-1} + m \times \frac{R}{\gamma - 1}(T_2 - T_1)$$

$$= mR(T_1 - T_2)\left[\frac{1}{n-1} - \frac{1}{\gamma - 1}\right]$$

$$= mR(T_1 - T_2)\left[\frac{(\gamma - 1) - (n-1)}{(n-1)(\gamma - 1)}\right]$$

$$= mR(T_1 - T_2)\left[\frac{\gamma - n}{(n-1)(\gamma - 1)}\right]$$

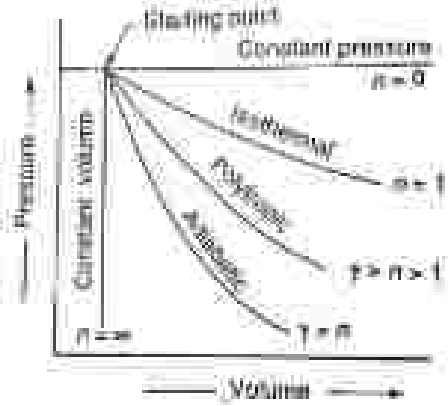
$$= \frac{\gamma - n}{\gamma - 1} \times \frac{mR(T_1 - T_2)}{n-1}$$

5. ***Change in enthalpy***

We know that change in enthalpy, $dH = H_2 - H_1 = m\,c_p(T_2 - T_1)$

General Laws for Expansion and Compression:

The general law of expansion or compression of a perfect gas is pv^n = Constant. It gives the relationship between pressure and volume of a given quantity of gas. The value of 'n' may be varies between zero and infinity.

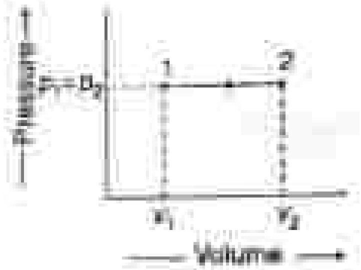


3.6 SOLVE SIMPLE PROBLEMS ON ABOVE:

Example 3.6: *The values of specific heats at constant pressure and at constant volume for an ideal gas are 0.984 kj/kg K and 0.728 kj/kg K. Find the values of characteristic gas constant (R) and ratio of specific heats (γ) for the gas. If one kg of this gas is heated at constant pressure from 25^0 C to 200^0 C, estimate the heat added, ideal work done and change in internal energy. Also calculate the pressure and final volume, if the initial volume was 2 m^3.*

Solution: Data given: $c_p = 0.984$ kj/kg K, $c_v = 0.728$ kj/kg K, $m = 1$ kg, $T_1 = 25^0\ C = 25 + 273 = 298$ K, $T_2 = 200^0\ C = 200 + 273 = 473$ K, $v_1 = 2\ m^3$

The heating of gas at constant pressure is shown in figure below



(a) p-v diagram

Characteristic gas constant
We know that characteristic gas constant,

$$R = c_p - c_v$$
$$= 0.984 - 0.728$$
$$= 0.256\ kj/kg\ K$$

Ratio of specific heats
We know that ratio of specific heats,

$$\gamma = \frac{c_p}{c_v}$$
$$= \frac{0.984}{0.728} = 1.35$$

Heat added
We know that heat added during constant pressure operation,

$$Q_{1-2} = mc_p(T_2 - T_1)$$
$$= 1 \times 0.984(473 - 298)$$
$$= 172.2\ kj$$

Work done
We know that work done during constant pressure operation,

$$W_{1-2} = p(v_2 - v_1)$$
$$= m\,R(T_2 - T_1)$$
$$= 1 \times 0.256(473 - 298) = 44.8\ kJ$$

Change in internal energy

We know that change in internal energy,

$$dU = mc_v(T_2 - T_1)$$
$$= 1 \times 0.728(473 - 298) = 127.4\ kJ$$

Pressure and final volume of the gas if the initial volume, $v_1 = 2\ m^3$

Let $p_1 = p_2$ = Pressure of the gas, and

v_2 = Final volume of the gas.

We know that,

$$\frac{p_1 v_1}{T_1} = \frac{p_2 v_2}{T_2} \quad \text{or} \quad \frac{v_1}{T_1} = \frac{v_2}{T_2}$$

$$\Rightarrow v_2 = \frac{v_1 T_2}{T_1} = \frac{2 \times 473}{298} = 3.17\ m^3$$

We also know that,

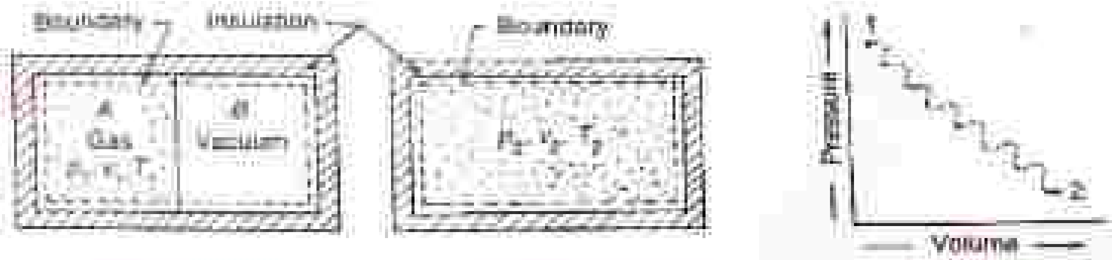
$$p_1 v_1 = m\,R\,T_1$$

$$\Rightarrow p_1 = \frac{m\,R\,T_1}{v_1}$$

$$= \frac{1 \times 256 \times 298}{2} = 38140\ N/m^2$$
$$= 0.3814\ bar$$

3.7 Free Expansion & Throttling Process:

Free Expansion Process: The free expansion process is an irreversible non-flow process. A free expansion occurs when a fluid is allowed to expand suddenly into a vacuum chamber through an orifice of large dimensions.



(a) Before expansion. (b) After expansion. (c) p-v diagram.

Consider two chambers *A* and *B* separated by a partition as shown in the figure (*a*). Let the chamber *A* contains a perfect gas having volume v_1, pressure p_1, and temperature T_1, and the chamber *B* is completely evacuated. These chambers are perfectly insulated so that no heat transfer takes place from or to its surroundings. Now, if the partition is removed, the gas will expand freely and occupy the whole space as shown in the figure (*b*).

- Since the system is perfectly insulated, therefore no heat transfer takes place between the system and surroundings i.e. $Q_{1-2} = 0$.
- Since there is no expansion of the boundary of the system, because it is rigid, therefore no work is done i.e. $W_{1-2} = 0$.
- We know that, $Q_{1-2} = dU + W_{1-2}$

$\Rightarrow \quad dU = 0$

$\Rightarrow \quad U_2 = U_1$

- We know that, $dU = mc_v(T_2 - T_1)$

$\Rightarrow \quad 0 = mc_v(T_2 - T_1)$

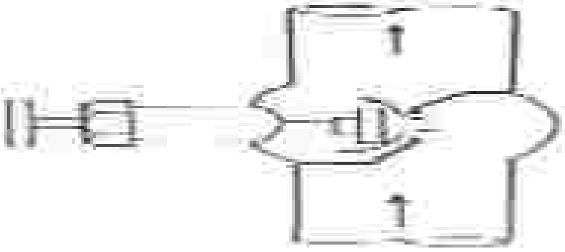
$\Rightarrow \quad T_2 = T_1$

- We know that, $dH = mc_p(T_2 - T_1)$

$\Rightarrow \quad dH = 0$

$\Rightarrow \quad H_2 = H_1$

Throttling Process:



The throttling process is an irreversible steady flow expansion process in which a perfect gas is expanded through a slightly opened valve as shown in the figure above. Due to the fall in pressure during expansion, the gas should come out with a large velocity, but due to high frictional resistance between the gas and the wall of the aperture, there is no considerable change in velocity. The kinetic energy of the gas is converted into heat which is utilised in warming the gas to its initial temperature. Since no heat is supplied or rejected during the throttling process, and also no work is done, therefore

$$q_{1-2} = 0 \quad and \quad w_{1-2} = 0$$

We know that steady flow energy equation for unit mass flow is

$$h_1 + \frac{V_1^2}{2} + gz_1 + q_{1-2} = h_2 + \frac{V_2^2}{2} + gz_2 + w_{1-2}$$

Since there is no considerable change in velocity and the inlet and outlet are at the same level, therefore $V_1 = V_2$ and $z_1 = z_2$. Now the steady flow energy equation becomes,

$$h_1 = h_2$$

POSSIBLE SHORT TYPE QUESTIONS WITH ANSWER

1. State Boyle's Law. [W-2020]

Ans: 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, $p \propto \frac{1}{v} \quad or \quad pv = constant$

$or\ p_1v_1 = p_2v_2 = p_3v_3 = \cdots = constant$

2. State Charles's Law. [W-2020]

Ans: This law was formulated by a Frenchman Jacques A.C. Charles in about 1787. It states, ***"The volume of a given mass of a perfect varies directly as its absolute temperature, when the absolute pressure remains constant"***.

Mathematically, $v \propto T \quad or \quad \frac{v}{T} = constant$

$or\ \frac{v_1}{T_1} = \frac{v_2}{T_2} = \frac{v_3}{T_3} = \cdots = constant$

3. State Gay-Lussac Law.

Ans: 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, $p \propto T \quad or \quad \frac{p}{T} = constant$

$or \frac{p_1}{T_1} = \frac{p_2}{T_2} = \frac{p_3}{T_3} = \dots = constant$

4. State Avogadro's Law.

Ans: This law states, ***"Equal volumes of all gases, at the same temperature and pressure, contain equal no of molecules"***.

Avogadro's experiments shows that the average volume for 1 Kg-mole of any perfect gas is 22.413 m^3 at standard atmospheric pressure (1.01325 bar) and 0°C NTP condition.

5. State Dalton's Law of Partial Pressure.

Ans: When two or more gases which don't react chemically with one another are enclosed in a vessel, then the total pressure exerted by the mixture of gases will be equal to the sum of the partial pressures which each gas would exert if present alone in that space.

Mathematically,

$$p = p_a + p_b + p_c \dots\dots\dots$$

Where, p = Total pressure of the mixture of gases

p_a, p_b, p_c = Partial pressures of each gas

6. Define specific heat of the gas.

Ans: 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.

Mathematically,

$$C = \frac{Q}{m \Delta t}$$

Where, C = Specific heat of a substance

Q = Amount of heat transfer

m = Mass of the substance

Δt = Rise in temperature

- S.I. unit, ***J/kg K or kJ/kg K***

6.What do you understand by an ideal gas?[W-2022]

Ans: An ideal gas is defined as one for which both the volume of molecules and forces between the molecules are so small that they have no effect on the behavior of the gas.

7.What is meant by free expansion?

Ans-It is a thermodynamic process.Here there is no heat transfer, no work transfer as well as no change in internal energy.

δQ=0,du=0, δW=0

POSSIBLE LONG TYPE QUESTIONS

1. Derive the relationship between C_p and C_v. [W-2019] [W-2020]

2. Derive the general gas equation from Boyle's Law and Charles's Law.

3. The values of specific heats at constant pressure and at constant volume for an ideal gas are 0.984 kj/kg K and 0.728 kj/kg K. Find the values of characteristic gas constant (R) and ratio of specific heats (γ) for the gas. If one kg of this gas is heated at constant pressure from 25° C to 200° C, estimate the heat added, ideal work done and change in internal energy. Also calculate the pressure and final volume, if the initial volume was 2 m^3.

4. A system contains 0.20 m^3 of a gas at a pressure of 4.8 bar and 180° C. it is expanded adiabatically till the pressure falls to 1 bar. The gas is then heated at a constant pressure till its enthalpy increases by *70 kj*. Determine the total work done. Take C_p = *1 kj/kg K* and C_v = *0.714 kj/kg K.*

Hints: Refer example 3.10. [W-2019]

5.What is an isothermal process?Derive an expression for the work done during isothermal process.[W-2020] [W-2021]

CHAPTER NO. – 04

INTERNAL COMBUSTION ENGINE

Learning Objectives:

- *4. Internal combustion engine*
- *4.1 Explain & classify I.C engine.*
- *4.2 Terminology of I.C Engine such as bore, dead centers, stroke volume, piston speed &RPM.*
- *4.3 Explain the working principle of 2-stroke & 4- stroke engine C.I & S.I engine.*
- *4.4 Differentiate between 2-stroke & 4- stroke engine C.I & S.I engine.*

INTRODUCTION:

Heat Engine:

A heat engine is a device which transforms the chemical energy of a fuel into thermal energy and uses this energy to produce mechanical work. It is classified into two types:

- External combustion engine
- Internal combustion engine

External combustion engine: The engine in which the combustion of fuel takes place outside the engine cylinder, then the engine is known as external combustion engine.
Example: Steam engine, Steam turbine plant etc.

4.1 Internal Combustion Engine:

The engine in which the combustion of fuel takes place inside the engine cylinder, then the engine is known as internal combustion engine.
Example: Petrol engine, Diesel engine, Gas engine etc.

Classification of I.C. Engine:

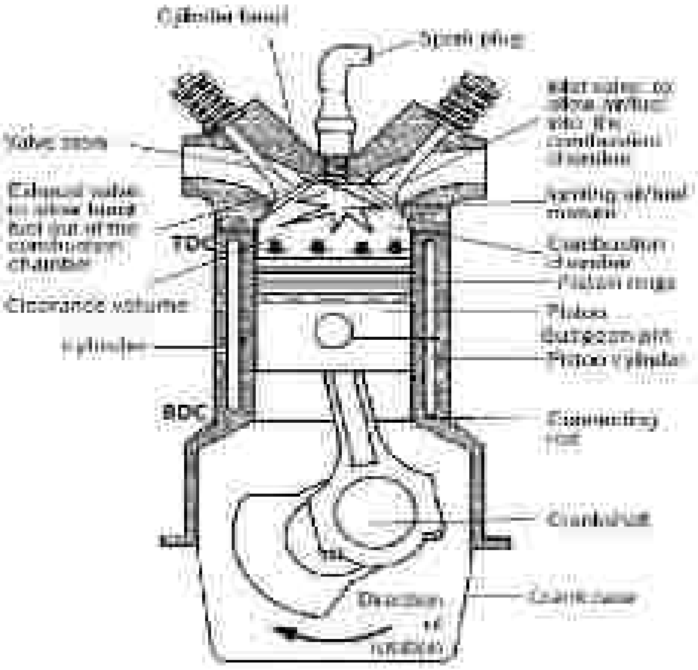
1. According to the type of fuel used - (a) Petrol engine, (b) Diesel engine, (c) Gas engine.
2. According to the method of igniting the fuel - (a) Spark ignition engine, (b) Compression ignition engine and (c) Hot spot ignition engine.
3. According to the working cycle - (a) Otto cycle (constant volume cycle) engine, (b) Diesel cycle (constant pressure cycle) engine, (c) Dual combustion cycle (semi diesel cycle) engine.
4. According to the number of strokes per cycle - (a) Four stroke cycle engine (b) Two stroke cycle engine.
5. According to the method of cooling - (a) Water cooled engine (b) Air cooled engine (c) Evaporative cooling Engine.
6. According to the number of cylinder - (a) Single cylinder engine (b) Multi cylinder engine.
7. According to the speed of the engine - (a) Slow speed engine (b) Medium speed engine (c) High speed engine.
8. According to the fuel supply and mixture preparation - (a) Carburetted type (fuel supplied through the carburettor), (b) Injection type (fuel injected into inlet ports or inlet manifold, fuel injected into the cylinder just before ignition).
9. According to the cylinder arrangement - (a) Vertical engine, (b) Horizontal engine, (c) In-line multi cylinder engine, (d) V-type multi cylinder engine, (e) Radial engine, (f) Opposite cylinder engine and (g) Opposite piston engines.
10. According to the valve mechanism - (a) Overhead valve engine, (b) Side valve engine.
11. According to the method of governing - (a) Hit and miss governed engine, (b) Quantitatively governed engine and (c) Qualitatively governed engine.

<u>Main Components of IC Engine</u>:

Cylinder: It is the main part of the engine inside which piston reciprocates to and fro. It should have high strength to withstand high pressure above 50 bar and temperature above 2000 °C. The ordinary engine is made of cast iron and heavy-duty engines are made of steel alloys or aluminium alloys. In the multi-cylinder engine, the cylinders are cast in one block known as cylinder block.

Cylinder head: The top end of the cylinder is covered by cylinder head over which inlet and exhaust valve; spark plug or injectors are mounted. A copper or asbestos gasket is provided between the engine cylinder and cylinder head to make an air tight joint.

Piston: Transmit the force exerted by the burning of charge to the connecting rod. Usually made of aluminium alloy which has good heat conducting property and greater strength at higher temperature.



Piston rings: These are housed in the circumferential grooves provided on the outer surface of the piston and made of steel alloys which retain elastic properties even at high temperature. 2 types of rings- compression and oil rings. Compression ring is upper ring of the piston which provides air tight seal to prevent leakage of the burnt gases into the lower portion. Oil ring is lower ring which provides effective seal to prevent leakage of the oil into the engine cylinder.

Connecting rod: It converts reciprocating motion of the piston into circular motion of the crank shaft, in the working stroke. The smaller end of the connecting rod is connected with the piston by gudgeon pin and bigger end of the connecting rod is connected with the crank with crank pin. The special steel alloys or aluminium alloys are used for the manufacture of connecting rod.

Crankshaft: It converts the reciprocating motion of the piston into the rotary motion with the help of connecting rod. The special steel alloys are used for the manufacturing of the crankshaft. It consists of eccentric portion called crank.

Crank case: It houses cylinder and crankshaft of the IC engine and also serves as sump for the lubricating oil.

Flywheel: It is big wheel mounted on the crankshaft, whose function is to maintain its speed constant. It is done by storing excess energy during the power stroke, which is returned during other stroke.

4.2 Terminology of I.C Engine:

1. **Bore** (*D*): The inner diameter of the working cylinder is called Bore.
2. **Piston area** (*A*): The area of circle of diameter equal to the cylinder bore.
3. **Stroke** (*L*): The distance through which a working piston moves between two successive reversals of its direction of motion is called stroke.
4. **Dead centre**: The position of the working piston and the moving parts which are mechanically connected to it at the moment when the direction of the piston motion is reversed (at either end point of the stroke) is called Dead centre.
(a) **Bottom dead centre** (*BDC*): Dead centre when the piston is nearest to the crankshaft or farthest from the cylinder head.
(b) **Top dead centre** (*TDC*): Dead centre when the position is farthest from the crankshaft or nearest to the cylinder head.
5. **Displacement volume or swept volume** (*Vs*): The volume occupied by the working piston when travelling from the one dead centre to the other is called swept volume and given as,

$$V_s = A \times L = \frac{\pi}{4} d^2 L$$

6. **Clearance volume** (*Vc*): The volume of the space between the cylinder head and top dead centre is called clearance volume.
7. **Cylinder volume** (*V*): Total volume of the cylinder, $V = V_C + V_S$
8. **Compression ratio** (*r*): The ratio of swept volume to the clearance volume is called compression ratio.

$$r = \frac{V_S}{V_C}$$

9. **RPM:** It is the speed of rotation of crank shaft of an I.C. Engine, and is expressed as revolution per minute or rotation per minute.

4.3 Four Stroke Cycle Petrol Engine:

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

- **Suction or charging stroke:** In this stroke, the inlet valve opens and charge is sucked into the engine 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 shown in Fig. (a).
- **Compression stroke:** In this stroke, both the inlet and exhaust valves are closed and the 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 shown in Fig. (b).

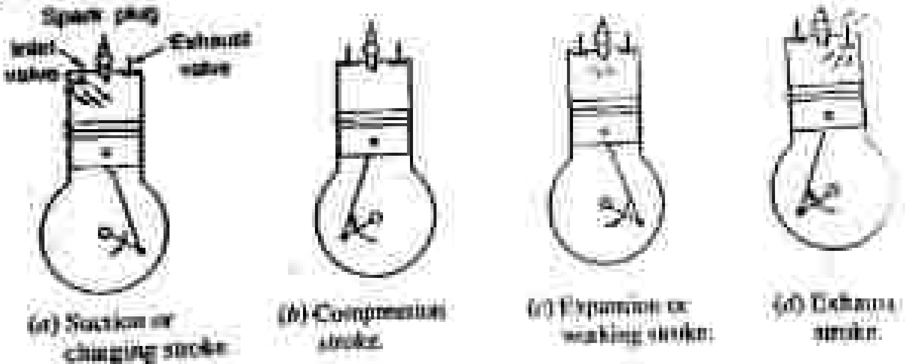


Fig: Four stroke Cycle Petrol Engine

- **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 and temperature of the products of combustion but the volume, practically, remains constant. Due to the rise in 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 produced is transformed into mechanical work. It may be noted that during this working stroke, as shown in Fig. (c), both the valves are closed and piston moves from T.D.C. to B.D.C.

- **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.

Four stroke Cycle Diesel Engine:

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

- **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).
- **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).

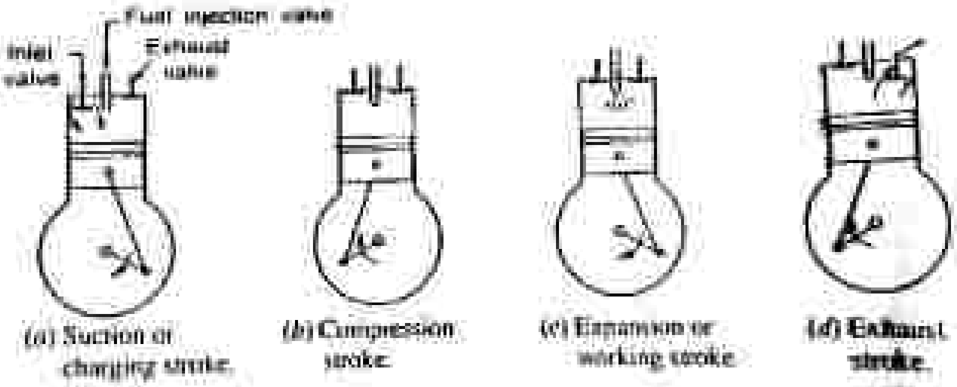


Fig. Four stroke Cycle Diesel Engine

- **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 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.
- **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.

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 take 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:

- **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).

- **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.

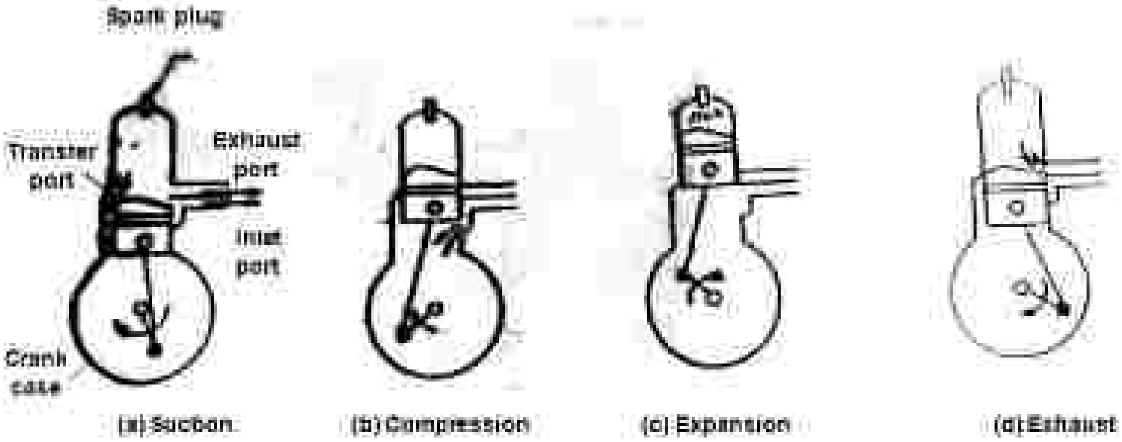


Fig. Two-stroke Cycle Petrol Engine

- **Expansion stage:** Shortly before the 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 in the pressure, the piston is pushed downwards with a great force as shown in Fig. (c). The hot burnt gases expand due to high speed of the piston. During this expansion, some of the heat energy produced is transformed into mechanical work.
- **Exhaust Stage:** In this stage, the exhaust port is opened as 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 charge again.

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:

- **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).
- **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 the crank case.

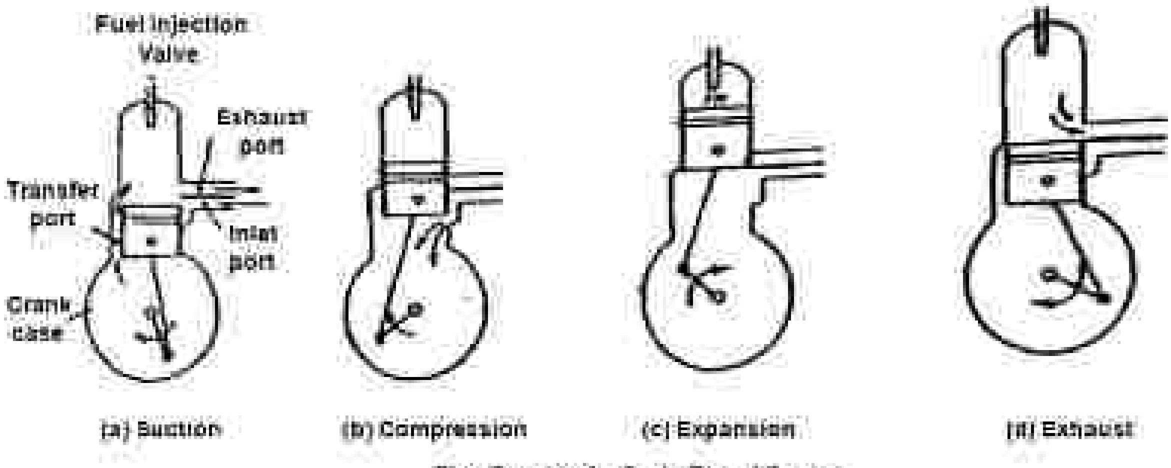


Fig. Two-stroke Cycle Diesel Engine

- **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 known 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 this expansion, some of the heat energy produced is transformed into mechanical work.
- **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.

4.4 Comparison of Four-stroke and two-stroke engine:

	Four-stroke engine	Two-stroke engine
1.	Four stroke of the piston and two revolutions of crankshaft	Two stroke of the piston and one revolution of crankshaft
2.	One power stroke in every two revolutions of crankshaft	One power stroke in each revolution of crankshaft
3.	Heavier flywheel due to non-uniform turning movement	Lighter flywheel due to more uniform turning movement
4.	Power produce is less	Theoretically power produce is twice than the four-stroke engine for same size
5.	Heavy and bulky	Light and compact
6.	Lesser cooling and lubrication requirements	Greater cooling and lubrication requirements
7.	Lesser rate of wear and tear	Higher rate of wear and tear
8.	Contains valve and valve mechanism	Contains ports arrangement
9.	Higher initial cost	Cheaper initial cost
10.	Volumetric efficiency is more due to greater time of induction	Volumetric efficiency less due to lesser time of induction
11.	Thermal efficiency is high and also part load Efficiency is better	Thermal efficiency is low and part load Efficiency is lesser
12.	It is used where efficiency is important.	It is used where low cost, compactness and light weight are important.
	Ex-cars, buses, trucks, tractors, industrial engines, aero planes, power generation etc.	Ex-lawn mowers, scooters, motor cycles, mopeds, propulsion ship etc.

Comparison of SI and CI engine:

SI engine	CI engine
1. Working cycle is Otto cycle.	Working cycle is diesel cycle.
2. Petrol or gasoline or high octane fuel is used.	Diesel or high cetane fuel is used.
3. High self-ignition temperature.	Low self-ignition temperature.
4. Fuel and air introduced as a gaseous mixture in the suction stroke.	Fuel is injected directly into the combustion chamber at high pressure at the end of compression stroke.
5. Carburettor used to provide the mixture. Throttle controls the quantity of mixture introduced.	Injector and high pressure pump used to supply of fuel. Quantity of fuel regulated in pump.
6. Use of spark plug for ignition system.	Self-ignition by the compression of air which increased the temperature required for Combustion.

7. Compression ratio is 6 to 10.5	Compression ratio is 14 to 22
8. Higher maximum RPM due to lower weight.	Lower maximum RPM.
9. Maximum efficiency lower due to lower compression ratio.	Higher maximum efficiency due to higher compression ratio.
10. Lighter due to lower pressure	Heavier due to higher pressure.

POSSIBLE SHORT TYPE QUESTIONS WITH ANSWER

1. Define I.C. Engine. [W-2019]
Ans: The engine in which the combustion of fuel takes place inside the engine cylinder, then the engine is known as internal combustion engine.
Example: Petrol engine, Diesel engine, Gas engine etc.

2. Define Swept volume.
Ans: The volume occupied by the working piston when travelling from the one dead centre to the other is called swept volume and given as,

$$V_s = A \times L = \frac{\pi}{4} d^2 L$$

3. Define Dead Centre.
Ans: The position of the working piston and the moving parts which are mechanically connected to it at the moment when the direction of the piston motion is reversed (at either and point of the stroke) is called Dead centre.

4. Define Stroke Length. [W-2020]
Ans: The distance through which a working piston moves between two successive reversals of its direction of motion is called stroke.

5. Classify IC engine according to the types of fuel used?[w-2022]
Ans: IC engine classified according to the types of fuel used are gasoline,diesel,LPG and CNG

6. What is the significance of octane number in IC engine fuel?[w-2022]
Ans: The higher the number ,the better the fuel burns within the engine of a vehicle.

7. What is meant by compression ratio in an IC Engine? [w-2022]
Ans- It is the ratio between the volume of the cylinder with the piston in the bottom position V_{bottom} (largest volume) and in the top position V_{top}(smallest volume).

8. Define a heat Engine? [w-2022]
Ans- It is a device that convert thermal energy into work. The thermal energy results from a temp. difference that is provided by a hot and cold reservoir.

9. Define Thermal Efficiency? [w-2022]
Ans-The efficiency of heat engine measured by the ratio of the work done by it to the heat supplied to it.

POSSIBLE LONG TYPE QUESTIONS

1. Describe the working principle of:-

- Four stroke petrol engine.
- Four stroke diesel engine. [W-2019]
- Two stroke petrol engine.
- Two stroke diesel engine.

2. Differentiate Between:-

- Four stroke and two stroke engine. [W-2020]
- C.I. and S.I. engine. [W-2019]

3. Explain the working of a four stroke Engine. [w-2022]

4.An engine uses 6kg of fuel per hour of calorific value 41000 kj/kg. If IP of the engine is 21 kw and mechanical efficiency is 82%. Calculate

I. Indicated thermal efficiency.

II. Brake specific fuel consumption.

III. Brake thermal efficiency.

5. Explain the working principle of two strokes and four stroke S.I. Engine with neat sketch.

CHAPTER NO. - 05

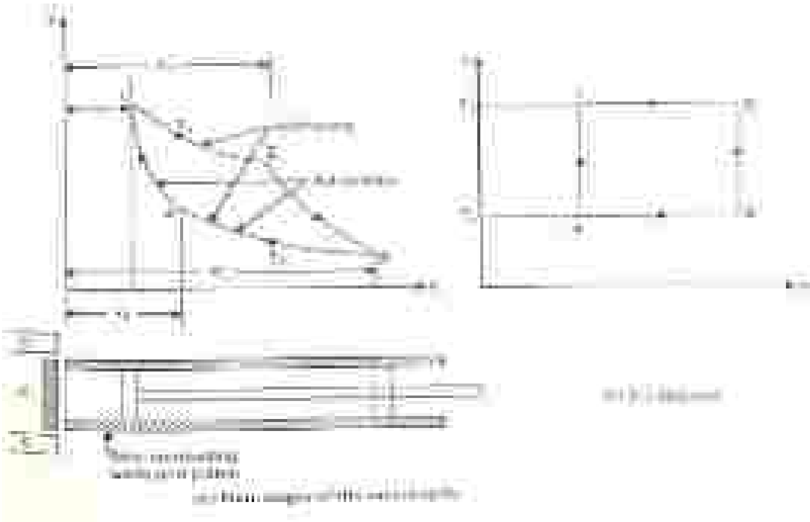
AIR STANDARD CYCLE OR GAS POWER CYCLE

Learning Objectives:

- *51. Carnot Cycle*
- *5.2 Otto Cycle*
- *5.3 Diesel Cycle*
- *5.4 Dual Cycle or Limited Pressure Cycle*

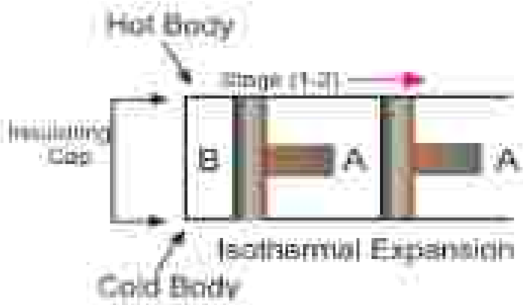
5.1 Carnot Cycle:

- Carnot cycle is an ideal cycle as adopted for an ideal heat engine. It consists of two isothermal processes (expansion and compression) and two adiabatic processes (expansion and compression). The cylinder and piston of the engine are considered as perfect non-conductor of heat but the cylinder cover head is a good conductor of heat. The hot body at a higher temperature is brought in contact with the bottom 'B' of the cylinder. The cylinder is fitted with a weightless and a frictionless piston.
- The French engineer Nicolas Leonard Sadi Carnot was the first scientist who realizes the problem of the efficiency of heat engine and invented the *Carnot cycle*. The pressure-volume (p-v) and temperature-entropy (T-S) graph are shown in the fig.



From the above two p-v and T-S graph, the horizontal axis represents volume 'V' and entropy 'S' and the vertical axis represents pressure 'p' and temperature 'T'. Let, engine cylinder contains m kg of air at its original condition represented by point 1 on the p-v and T-S diagrams. At this point, let p_1, v_1 and T_1 be the pressure, temperature and volume.

First Stage (Isothermal Expansion)



Let, unit mass of perfect gas is admitted into the cylinder at the beginning of the outward moment of the piston and the pressure, temperature, volume of the gas at a point 1 is p_1, v_1 and T_1 respectively. The bottom 'B' of the cylinder can be covered by an insulating cap. During the movement of the piston, the heat Q_1 is supplied to the perfect gas and the gas expands isothermally keeping temperature T_1 constant until the volume v_2 and pressure p_2. The heat supplied by the hot body is fully absorbed by the air and is utilised by doing external work. So, heat is supplied during this process is equal to the work done during this process. This isothermal expansion is represented by the curve 1-2 on p-v and T-S diagram.

∴ Heat supplied = Work done by the air during Isothermal Expansion

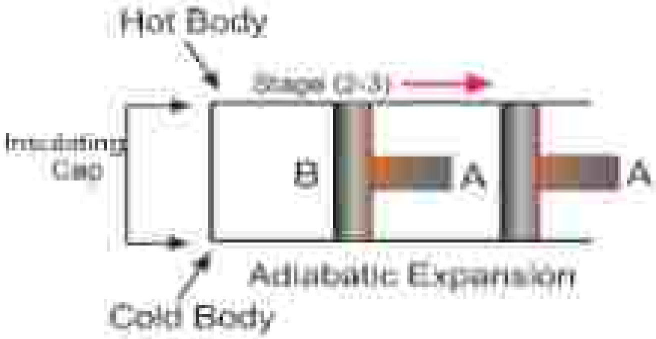
$$Q_{1-2} = p_1 v_1 \log_e\left(\frac{v_2}{v_1}\right)$$

$$= mRT_1 \log_e\left(\frac{v_2}{v_1}\right) \qquad (\because p_1 v_1 = mRT_1)$$

$$= 2.3mRT_1 \log r \qquad (r = expansion\ ratio = v_2/v_1)$$

Since, there is no change of temperature from point 1to2, so, (T_1=T_2) and as per first law of thermodynamics internal energy is also zero (E=0).

Second Stage (Isentropic Expansion)



As the piston moves outward, the gas expands adiabatically till the pressure p_3, volume v_3 and temperature T_3 and the hot body is removed from the bottom of the cylinder 'B' and the insulating cap is brought in contact. In this process, there is no interchange of heat of the surrounding gases (Q = 0). So the mechanical work has been done by the system only at the expense of its internal energy. The reversible adiabatic expansion is represented by the curve 2-3 on pv diagram.

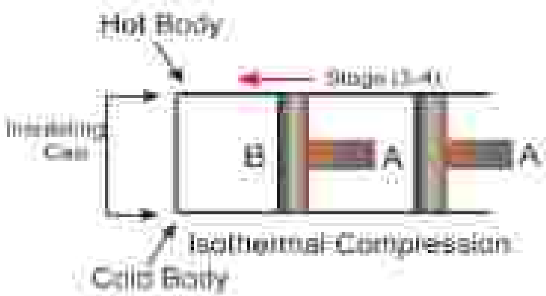
So, decrease in internal energy = work done by the air during adiabatic expansion

$$W_{2-3} = \frac{p_2 v_2 - p_3 v_3}{\gamma - 1} = \frac{mRT_2 - mRT_3}{\gamma - 1}$$

$$= \frac{mR(T_2 - T_3)}{\gamma - 1} = \frac{mR(T_1 - T_3)}{\gamma - 1} \qquad (\because T_1 = T_2)$$

The change of internal energy E = - W (from 1st Law)

Third Stage (Isothermal Compression)



Now the piston moves inward and insulating cap I.C. is also removed from the bottom of the cylinder and bring the cold body in its contact. The air is compressed isothermally keeping temperature constant T_3 from v_3 to v_4. It means at point 4 temperature T_4 is equal T_3. That's why heat is rejected to the cold body is equal to the work done on the air. The isothermal compression curve is represented by 3-4 on p-v curve.

∴ Heat Rejected = Work done by the air during Isothermal Compression

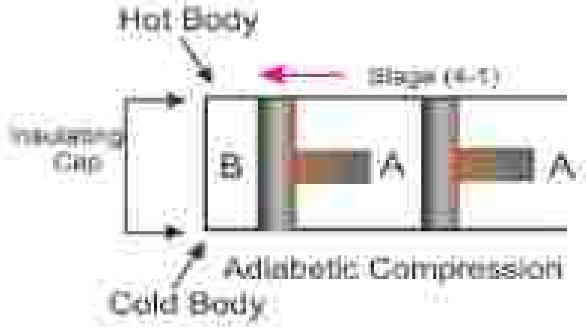
$$Q_{3-4} = p_3 v_3 \log_e\left(\frac{v_3}{v_4}\right)$$

$$= mRT_3 \log_e\left(\frac{v_3}{v_4}\right) \qquad (\because p_3 v_3 = mRT_3)$$

$$= 2.3mRT_3 \log r \quad (r = compression\ ratio = v_3/v_4)$$

Here change of internal energy E = 0

Fourth Stage (Isentropic Compression)



As the piston moves inwards, the gas insides the cylinder is compressed adiabatically till the pressure p_1, volume v_1, and temperature T_1 such that the gas returns to its original condition to complete the Carnot cycle and insulated cap I.C. is brought in contact with the bottom of the cylinder B. The temperature of air increases from T_4 to T_1 and no heat is absorbed or rejected by the air (Q=0). The reversible adiabatic compression is represented by the curve 4-1 on p-v and T-S diagram.

So, Increase in internal energy = work done on the air during adiabatic compression

$$W_{4-1} = \frac{p_1 v_1 - p_4 v_4}{\gamma - 1} = \frac{mRT_1 - mRT_4}{\gamma - 1}$$

$$= \frac{mR(T_1 - T_4)}{\gamma - 1} = \frac{mR(T_1 - T_3)}{\gamma - 1} \qquad (\because T_3 = T_4)$$

Work done and Thermal Efficiency

From the above discussion, it is seen that the total internal energy decrease in reversible adiabatic expansion shown in curve 2-3 is equal to the increase in internal energy during reversible adiabatic compression 4-1. So, the net effect of the whole Carnot cycle is zero.

Work done,

$$W = Heat\ supplied - Heat\ rejected$$

$$= 2.3mRT_1 \log r - 2.3mRT_3 \log r$$

$$= 2.3mR \log r\,(T_1 - T_3)$$

And Carnot efficiency,

$$\eta = \frac{Work\ done}{Heat\ supplied}$$

$$= \frac{2.3mR \log r (T_1 - T_3)}{2.3mRT_1 \log r}$$

$$= \frac{T_1 - T_3}{T_1}$$

$$= 1 - \frac{T_3}{T_1}$$

From the Carnot cycle efficiency equation, T_1 is greater than T_3. For the smaller value of T_3, the thermal efficiency will be maximum. That's why Carnot cycle has highest thermal efficiency of all heat engines.

Notes:

- *From the above equation, we see that the efficiency of Carnot's cycle increases as T_1 is increases or T_3 is decreased. In other words, the heat should be taken in at as high a temperature as possible, and rejected at as low a temperature as possible. It may be noted that 100% efficiency can be achieved, only, if T_3 reaches absolute zero, though it is impossible to achieve in practice.*
- *In the above theory, we have taken the temperature at points 1, 2, 3 and 4 as T_1, T_2, T_3 and T_4 respectively in order to keep similarity between Carnot cycle and other cycles. But some authors take it T_1 (For points 1 and 2) and T2 (for points 3 and 4). In that case, they obtain the relation for efficiency as,*

$$\eta = \frac{T_1 - T_2}{T_1} = 1 - \frac{T_2}{T_1}$$

Why Carnot cycle can't be used in actual practice?

- *It can be noted that it is difficult to make the engine working on Carnot's cycle. The reasons for the same is that the isothermal expansion 1-2 will have to be carried out very slow to ensure that the air is always at temperature T_1. Similarly, the isothermal compression 3-4 will have to be carried out very slow. But reversible adiabatic expansion 2-3 and reversible adiabatic compression 4-1 should be carried out as quickly as possible, in order to approach ideal adiabatic conditions. We know that sudden changes in the speed of an engine are not possible in actual practice.*
- *It is impossible to completely eliminate friction between the multiple moving parts of the engine, and also heat losses due to conduction, radiation, etc.*
- *Thus, it is difficult to realize Carnot's engine in actual practice.*
- *However, such an imaginary engine is used as the ultimate standard of comparison of all heat engines.*

Problem – 01: ***A Carnot engine working between 650 K and 310 K, produces 150 kJ of work. Find thermal efficiency and heat added during the process.***

Solution: $T_1 = 650$ K, $T_3 = 310$ K, W = 150 kJ

Thermal efficiency:

We know that thermal efficiency,

$$\eta = \frac{T_1 - T_3}{T_1} = \frac{650 - 310}{650} = 0.523 = 52.3\%$$

Heat added during the process:

We also know that efficiency,

$$\eta = \frac{Work\ done}{Heat\ supplied} = \frac{W}{Q_{1-2}}$$

$$\Rightarrow \quad Q_{1-2} = \frac{W}{\eta} = \frac{150}{0.523} = 286.8kJ$$

Problem – 02: ***An ideal engine is imagined to be working on Carnot cycle. The working fluid receives heat at a temperature of 590 K and rejects at a temperature of 295 K. Find the theoretical efficiency of the cycle, if the engine working on this cycle absorbs 35 kJ of heat per second from the hot body. Calculate the net work done/second.***

Solution: $T_1 = 590$ K, $T_3 = 295$ K, $Q_{1-2} = 35$ kJ/s

Theoretical efficiency:

We know that efficiency,

$$\eta = \frac{T_1 - T_3}{T_1} = \frac{590 - 295}{590} = 0.5 = 50\%$$

Net work done per second:

We know that,

$$\eta = \frac{Work\ done}{Heat\ supplied} = \frac{W}{Q_{1-2}}$$

$$\Rightarrow \quad W = \eta \times Q_{1-2} = 0.5 \times 35 = 17.5kJ/s$$

Problem – 03: ***In a Carnot engine, the temperature of the source and sink are 700⁰ C and 50⁰ C. The heat supply is 84 kJ/s. Find the power developed by the engine. If the temperature of source is 500⁰ C and the heat supply and work done are 420 kJ and 200 kJ respectively, find the sink temperature.***

Solution: T_1 = 700⁰ C = 700 + 273 = 973 K, T_2 = 50⁰ C = 50 + 273 = 323 K, Q = 84 kJ/s

Power developed by the engine:

We know that efficiency,

$$\eta = \frac{T_1 - T_2}{T_1} = \frac{973 - 323}{973} = 0.668 = 66.8\%$$

We also know that efficiency,

$$\eta = \frac{Work\ done}{Heat\ supplied} = \frac{W}{Q}$$

$$\Rightarrow \quad W = \eta \times Q = 0.668 \times 84 = 56.112 kJ/s$$

$$\Rightarrow \quad W = 56.112\ kW$$

Sink temperature:

Here T_1 = 500⁰ C = 500 + 273 = 773 K, Q = 420 kJ, W = 200 kJ

We know that efficiency,

$$\eta = \frac{W}{Q} = \frac{200}{420} = 0.476 = 47.6\%$$

We also know that efficiency,

$$\eta = \frac{T_1 - T_2}{T_1} = 1 - \frac{T_2}{T_1}$$

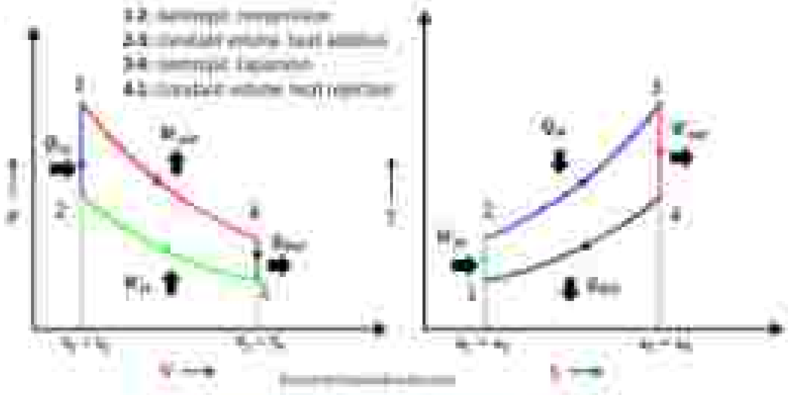
$$\Rightarrow \quad 0.476 = 1 - \frac{T_2}{773}$$

$$\Rightarrow \quad \frac{T_2}{773} = 1 - 0.476$$

$$\Rightarrow \quad T_2 = 0.524 \times 773 = 405.052\ K \cong 405\ K\ or\ 132^0C$$

5.2 Otto Cycle:

- Otto Cycle is the ideal cycle for the spark-ignition engines which is named as honour of the German engineer named Nikolaus Otto who made a very big contribution to the evolution of the internal combustion engines (ICE).
- This is the ideal cycle for Spark ignition engine. It is also known as constant volume cycle as heat is received at a constant volume.
- Otto Cycle is a 4-process cycle wherein it is composed of 2 isometric processes (constant volume process) and 2 isentropic processes (constant entropy process). These 4 processes are as follows.



P-V and T-S Diagram of Otto Cycle

Process 1 – 2: Isentropic Compression

- Air is compressed in this process reversibly and adiabatically.

Process 2 – 3: Isometric Addition of Heat

- Heat is added to air reversibly at constant volume in this process.

Process 3 – 4: Isentropic Expansion

- Work is done by air in expanding reversibly and adiabatically in this process.

Process 4 – 1: Isometric Rejection of Heat

- Heat is then rejected by air reversibly at constant volume in this process and the system comes back to its initial state.

Efficiency of Otto cycle:

Let 'm' be the fixed mass of air undergoing the cycle of operation as described above.

- Heat supplied, $Q_1 = Q_{2-3} = mc_v(T_3 - T_2)$
- Heat rejected, $Q_2 = Q_{4-1} = mc_v(T_4 - T_1)$

- Efficiency, $\eta = \frac{Q_1 - Q_2}{Q_1} = 1 - \frac{Q_2}{Q_1}$

$$= 1 - \frac{mc_v(T_4 - T_1)}{mc_v(T_3 - T_2)}$$

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

- Process (1-2):

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

- Process (3-4):

$$\frac{T_3}{T_4} = \left(\frac{v_4}{v_3}\right)^{\gamma - 1} = \left(\frac{v_1}{v_2}\right)^{\gamma - 1}$$

- From the above we see that,

$$\frac{T_2}{T_1} = \frac{T_3}{T_4}$$

$$\Rightarrow \frac{T_4}{T_1} = \frac{T_3}{T_2}$$

$$\Rightarrow \frac{T_4}{T_1} - 1 = \frac{T_3}{T_2} - 1$$

$$\Rightarrow \frac{T_4 - T_1}{T_1} = \frac{T_3 - T_2}{T_2}$$

$$\Rightarrow \frac{T_4 - T_1}{T_3 - T_2} = \frac{T_1}{T_2} = \left(\frac{v_2}{v_1}\right)^{\gamma - 1}$$

- Substituting the value of $\frac{T_4 - T_1}{T_3 - T_2} = \left(\frac{v_2}{v_1}\right)^{\gamma - 1}$ in equation (i) we have,

$$\eta = 1 - \left(\frac{v_2}{v_1}\right)^{\gamma - 1}$$

$$\Rightarrow \eta_{otto} = 1 - \frac{1}{(r_k)^{\gamma - 1}}$$

Where, $r_k = compression\ ratio = \frac{v_1}{v_2}$

Problem – 01: ***In an Otto cycle the temperature at the beginning and end of isentropic compression is 316 K and 596 K respectively. Determine the air standard efficiency and compression ratio. Take $\gamma = 1.4$.***

Solution: $T_1 = 316$ K, $T_2 = 596$ K, $\gamma = 1.4$

Compression ratio:

We know that for isentropic compression ratio,

$$\frac{T_2}{T_1} = \left(\frac{v_1}{v_2}\right)^{\gamma - 1} = (r_k)^{\gamma - 1}$$

$$\Rightarrow (r_k)^{\gamma - 1} = \frac{T_2}{T_1}$$

$$\Rightarrow (r_k)^{1.4 - 1} = \frac{596}{316}$$

$$\Rightarrow (r_k)^{0.4} = \frac{596}{316}$$

$$\Rightarrow \quad r_k = \left(\frac{386}{316}\right)^{1/0.4}$$
$$\Rightarrow \quad r_k = 4.885$$

Air standard efficiency:

We know that air standard efficiency,

$$\eta = 1 - \frac{1}{(r_k)^{\gamma-1}}$$
$$= 1 - \frac{1}{(4.885)^{1.4-1}}$$
$$= 0.47 \text{ or } 47\%$$

Problem – 02: *The efficiency of an Otto cycle is 50% and $\gamma = 1.5$. Find the compression ratio.*

Solution: $\eta = 50\% = 0.5$, $\gamma = 1.5$

Compression ratio:

We know that efficiency of Otto cycle,

$$\eta = 1 - \frac{1}{(r_k)^{\gamma-1}}$$
$$\Rightarrow 0.5 = 1 - \frac{1}{(r_k)^{1.5-1}}$$
$$\Rightarrow \frac{1}{(r_k)^{0.5}} = 1 - 0.5$$
$$\Rightarrow (r_k)^{0.5} = \frac{1}{0.5}$$
$$\Rightarrow r_k = \left(\frac{1}{0.5}\right)^{1/0.5}$$
$$\Rightarrow r_k = 2^2$$
$$\Rightarrow r_k = 4$$

Problem – 03: *A certain quantity of air at a pressure of 1 bar and temperature 70°C is compressed isentropically 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, (i) compression ratio of the engine (ii) temperature at the end of compression (iii) temperature at the end of heat addition. Take for air, $C_p = 1$ kj/kg k and $C_v = 0.707$ kj/kg k.*

Solution: $P_1 = 1$ bar, $T_1 = 70°$ C = 70 + 273 = 343 K, $P_2 = 7$ bar, $Q_1 = Q_{2-3} = 460$ kJ, $C_p = 1$ kj/kg k and $C_v = 0.707$ kj/kg k.

Compression ratio of the engine:

We know that, $\gamma = \frac{C_p}{C_v} = \frac{1}{0.707} = 1.41$

For isentropic compression process (1-2),

$$\frac{v_1}{v_2} = \left(\frac{p_2}{p_1}\right)^{1/\gamma}$$
$$\Rightarrow r_k = (7)^{1/1.41}$$
$$\Rightarrow r_k = 3.97$$

Temperature at the end of compression:

For isentropic compression process,

$$\frac{T_2}{T_1} = \left(\frac{v_1}{v_2}\right)^{\gamma-1} = (r_k)^{\gamma-1}$$
$$\Rightarrow \frac{T_2}{T_1} = (3.97)^{1.41-1}$$
$$\Rightarrow T_2 = 343 \times (3.97)^{0.41}$$
$$\Rightarrow T_2 = 604\,K \text{ or } 331°C$$

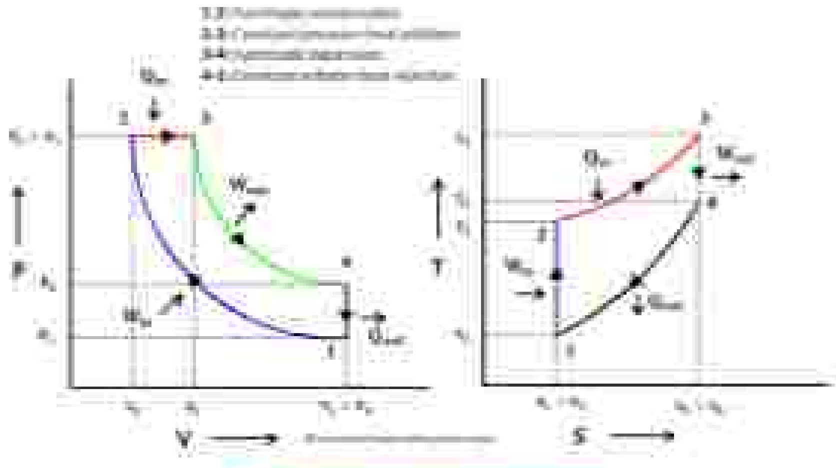
Temperature at the end of heat addition:

We know that heat addition,

$$Q_1 = Q_{2-3} = mC_v(T_3 - T_2)$$
$$\Rightarrow 460 = 1 \times 0.707(T_3 - 604)$$
$$\Rightarrow T_3 - 604 = \frac{460}{0.707}$$
$$\Rightarrow T_3 = \frac{460}{0.707} + 604$$
$$\Rightarrow T_3 = 1255\ K\ or\ 982^{\circ}C$$

5.3 <u>Diesel Cycle:</u>

- This cycle is named as it was devised by Rudolph Diesel in 1893, with an idea to attain a higher thermal efficiency, with a high compression ratio.
- This is the ideal cycle for compression ignition engine. It is also known as constant pressure cycle as heat is received at a constant pressure.
- Diesel Cycle is a 4-process cycle wherein it is composed of 2 isentropic processes (constant entropy process), 1 isobaric process (constant pressure process), and 1 isometric process (constant volume process). These 4 processes are as follows:



P-V and T-S Diagram of Diesel Cycle

Process 1 – 2: Isentropic Compression

- Air is compressed isentropically in this process.

Process 2 – 3: Isobaric Addition of Heat

- Heat is added to air from an external source reversibly at constant pressure in this process.

Process 3 – 4: Isentropic Expansion

- Air is then expands isentropically in this process.

Process 4 – 1: Isometric Rejection of Heat

- Heat is rejected by air reversibly at constant volume in this process and the cycle repeats itself.

<u>Efficiency of Diesel cycle:</u>

Let 'm' be the fixed mass of air undergoing the cycle of operation as described above.

- Heat supplied, $Q_1 = Q_{2-3} = mc_p(T_3 - T_2)$
- Heat rejected, $Q_2 = Q_{4-1} = mc_v(T_4 - T_1)$
- Efficiency, $\eta = \frac{Q_1 - Q_2}{Q_1} = 1 - \frac{Q_2}{Q_1}$

$$= 1 - \frac{mc_v(T_4 - T_1)}{mc_p(T_3 - T_2)}$$

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

- Compression ratio, $r_k = \frac{v_1}{v_2}$
- Expansion ratio, $r_e = \frac{v_4}{v_3}$
- Cut off ratio, $r_c = \frac{v_3}{v_2}$
- It is seen that, $r_k = r_e \cdot r_c$

- Process (3-4):

$$\frac{T_4}{T_3} = \left(\frac{v_3}{v_4}\right)^{\gamma-1} = \frac{1}{(r_e)^{\gamma-1}}$$

$$\Rightarrow \frac{T_4}{T_3} = \frac{1}{\left(\frac{r_k}{r_c}\right)^{\gamma-1}} = \frac{(r_c)^{\gamma-1}}{(r_k)^{\gamma-1}}$$

$$\Rightarrow T_4 = T_3 \times \frac{(r_c)^{\gamma-1}}{(r_k)^{\gamma-1}}$$

- Process (2-3):

$$\frac{p_2 v_2}{T_2} = \frac{p_3 v_3}{T_3}$$

$$\Rightarrow \frac{v_2}{T_2} = \frac{v_3}{T_3} \qquad \because p_2 = p_3$$

$$\Rightarrow T_2 = T_3 \times \frac{v_2}{v_3}$$

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

- Process (1-2):

$$\frac{T_1}{T_2} = \left(\frac{v_2}{v_1}\right)^{\gamma-1} = \frac{1}{(r_k)^{\gamma-1}}$$

$$\Rightarrow T_1 = T_2 \times \frac{1}{(r_k)^{\gamma-1}}$$

$$\Rightarrow T_1 = \frac{T_3}{r_c} \times \frac{1}{(r_k)^{\gamma-1}}$$

Putting the value of T_1, T_2 and T_4 in equation (i) we get

$$\eta = 1 - \frac{T_3 \cdot \frac{r_c^{\gamma-1}}{r_k^{\gamma-1}} - \frac{T_3}{r_c} \cdot \frac{1}{r_k^{\gamma-1}}}{\gamma\left(T_3 - \frac{T_3}{r_c}\right)}$$

By simplifying the above equation we get

$$\eta_{diesel} = 1 - \frac{1}{\gamma} \cdot \frac{1}{r_k^{\gamma-1}} \cdot \frac{r_c^{\gamma} - 1}{r_c - 1}$$

<u>**Problem – 01**</u>: <u>***A diesel engine has a compression ratio of 14 and cut off takes place at 6% of the stroke. Find the air standard efficiency. Take γ for air as 1.4.***</u>

Solution: $r_k = \frac{v_1}{v_2} = 14$, $\gamma = 1.4$

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

$$v_3 - v_2 = 0.06(v_1 - v_2)$$

$$\Rightarrow v_3 - v_2 = 0.06(14v_2 - v_2)$$

$$\Rightarrow v_3 - v_2 = 0.06 \times 13v_2$$

$$\Rightarrow v_3 - v_2 = 0.78v_2$$

$$\Rightarrow v_3 = 0.78v_2 + v_2$$

$$\Rightarrow v_3 = 1.78v_2$$

$$\Rightarrow \frac{v_3}{v_2} = 1.78 = r_c \quad \text{(cut off ratio)}$$

We know that air standard efficiency of diesel cycle,

$$\eta_{diesel} = 1 - \frac{1}{\gamma} \cdot \frac{1}{r_k^{\gamma-1}} \cdot \frac{r_c^{\gamma} - 1}{r_c - 1}$$
$$= 1 - \frac{1}{1.4} \cdot \frac{1}{14^{0.4}} \cdot \frac{1.78^{1.4} - 1}{1.78 - 1}$$
$$= 0.605 \ or \ 60.5\%$$

<u>Problem – 02</u>: ***In an air standard diesel cycle, the compression ratio is 16, and at the beginning of the isentropic compression, the temperature is 15°C and the pressure is 0.1 MPa. The heat is added until the temperature at the end of the constant pressure process is 1480°C. Calculate – (a) the cut off ratio (b) Heat supplied per kg of air (c) The cycle efficiency (d) The mean effective pressure (m.e.p.).***

Solution: $r_k = \frac{v_1}{v_2} = 16$, $T_1 = 15 + 273 = 288$ K, $p_1 = 0.1$ MPa = 100 KN/m², $T_3 = 1480 + 273 = 1753$ K

We know that in process 1-2,

$$\frac{T_2}{T_1} = \left(\frac{v_1}{v_2}\right)^{\gamma-1} = 16^{0.4} = 3.03$$
$$\Rightarrow T_2 = 288 \times 3.03 = 873\ K$$

(a) The cut off ratio:

$$\frac{p_2 v_2}{T_2} = \frac{p_3 v_3}{T_3}$$

$$\Rightarrow \frac{v_3}{v_2} = \frac{T_3}{T_2} = \frac{1753}{873} = 2.01$$
$$\Rightarrow r_c = 2.01$$

(b) Heat supplied per kg of air:

$$Q_1 = c_p(T_3 - T_2)$$
$$= 1.005(1753 - 873)$$
$$= 884.4\ kj/kg$$

(c) The cycle efficiency:

$$\eta_{diesel} = 1 - \frac{1}{\gamma} \cdot \frac{1}{r_k^{\gamma-1}} \cdot \frac{r_c^{\gamma} - 1}{r_c - 1}$$
$$= 1 - \frac{1}{1.4} \cdot \frac{1}{16^{0.4}} \cdot \frac{2.01^{1.4} - 1}{2.01 - 1}$$
$$= 0.612 \ or \ 61.2\%$$

(d) The mean effective pressure (m.e.p.):

We know that net work done,

$$W_{net} = Q_1 \times \eta_{diesel}$$
$$= 884.4 \times 0.612$$
$$= 541.3\ kj/kg$$

We know that,

$$p_1 v_1 = mRT_1$$
$$\Rightarrow v_1 = \frac{mRT_1}{p_1}$$
$$\Rightarrow v_1 = \frac{1 \times 0.287 \times 288}{100} = 0.827\ m^3/kg$$

So, $v_2 = \frac{v_1}{16} = \frac{0.827}{16} = 0.052\ m^3/kg$

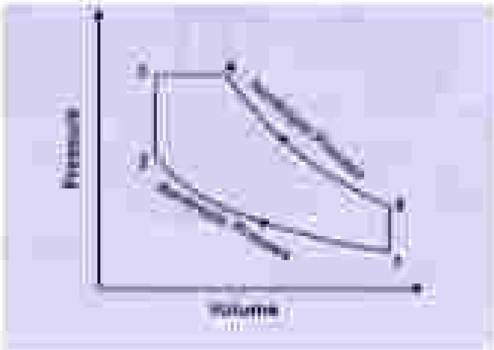
∴ Stroke volume, $v_1 - v_2 = 0.827 - 0.052 = 0.775\ m^3/kg$

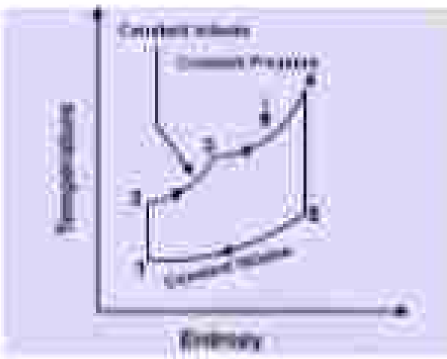
We know that,

$$m.e.p. = \frac{Net\ work\ done}{stroke\ volume} = \frac{W_{net}}{v_1 - v_2}$$
$$= \frac{541.3}{0.775} = 698.45\ KPa$$

5.4 <u>Dual Cycle or Limited Pressure Cycle:</u>

- It is difficult to achieve constant volume heat addition in S.I. engines (Otto cycle) and similarly it is far from reality to achieve constant pressure heat addition in C.I. engines (Diesel cycle). This is due to a certain amount of time required to complete the combustion step.
- To overcome this limitation, the dual cycle has been adopted. It is a compromise between the Otto cycle and Diesel cycle.
- In this cycle, a part of heat addition takes place in a constant volume mode and the rest part of heat addition takes place in a constant pressure mode.





Process 1 → 2:

- The process 1 → 2 is the isentropic compression of the air in the cylinder while piston moves from the bottom dead centre (BDC) to the top dead centre (TDC).

Process 2 → 3 & 3 → 4:

- During the process, 2 → 3 First the heat is supplied at a constant volume and then the remaining part of heat will be added at the constant pressure process 3 → 4.

Process 4 → 5 & 5 → 1:

- These two processes 4 → 5 & 5 → 1 will represent the isentropic expansion (Piston moves from the Top dead centre to the bottom dead centre) and the constant volume heat rejection respectively.

<u>Thermal Efficiency</u>:

- Thermodynamically, the efficiency of the Dual cycle is given by

$$\eta_{Dual} = \frac{Work\ done\ by\ the\ system}{Heat\ supplied\ to\ the\ system}$$

- Work done by the system (W) = Heat supplied (Q_S) - Heat rejected (Q_R)

$$Q_R = mC_v(T_5 - T_1)$$

$$Q_S = mC_v(T_3 - T_2) + mC_p(T_4 - T_3)$$

$$\eta_{Dual} = \frac{mC_v(T_3 - T_2) + mC_p(T_4 - T_3) - mC_v(T_5 - T_1)}{mC_v(T_3 - T_2) + mC_p(T_4 - T_3)}$$

$$\eta_{Dual} = 1 - \frac{T_5 - T_1}{(T_3 - T_2) + \gamma(T_4 - T_3)}$$

- From the processes 1 → 2

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

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

Where r is the Compression Ratio

- Now from the process 2 → 3 constant Volume process

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

$$T_3 = T_2\left(\frac{P_3}{P_2}\right) = T_1 r_p r^{(\gamma-1)}$$

(Substituted the T_2 in the above equation)
Where r_p is the pressure ratio in the constant volume process which is equal to the P_3/P_2

- From the 3 → 4 Constant pressure process

$$\frac{T_4}{T_3} = \frac{V_4}{V_3}$$

$$T_4 = T_3\left(\frac{V_4}{V_3}\right) = T_3 r_c = T_1 r_c r_p r^{(\gamma-1)}$$

(Substituted the T_3 & T_2 in the above equation)
Where r_c is the Cut-Off ratio in the constant pressure process which is equal to the V_4/V_3

- From the Isentropic process 4 → 5

$$\frac{T_5}{T_4} = \left(\frac{V_4}{V_5}\right)^{(\gamma-1)}$$

$$T_5 = T_4\left(\frac{V_4}{V_5}\right)^{(\gamma-1)}$$

$$\frac{V_4}{V_5} = \frac{V_4}{V_5} = \frac{V_4}{V_3}\times\frac{V_3}{V_5} = \frac{V_4}{V_3}\times\frac{V_2}{V_1} \quad \text{Since } V_2 = V_3$$

$$T_5 = T_4\left(\frac{V_4}{V_3}\times\frac{V_2}{V_1}\right)^{(\gamma-1)}$$

$$T_5 = T_4\left(\frac{r_c}{r}\right)^{(\gamma-1)}$$

$$T_5 = \left(T_1 r_c r_p r^{(\gamma-1)}\right)\left(\frac{r_c}{r}\right)^{(\gamma-1)}$$

$$T_5 = T_1 r_p r_c^{\gamma}$$

(Substituted the T_4 & T_3 & T_2 in the above equation)

- Let's substitute all these above equations in the main efficiency equation

$$\eta_{dual} = 1 - \frac{T_5 - T_1}{(T_3 - T_2) + \gamma(T_4 - T_3)}$$

$$\eta_{dual} = 1 - \left[\frac{T_1 r_p r_c^{\gamma} - T_1}{\left(T_1 r_p r^{(\gamma-1)} - T_1 r^{(\gamma-1)}\right) + \gamma\left(T_1 r_c r_p r^{(\gamma-1)} - T_1 r_p r^{(\gamma-1)}\right)}\right]$$

$$\eta_{dual} = 1 - \frac{1}{r^{(\gamma-1)}}\left[\frac{r_p r_c^{\gamma} - 1}{(r_p - 1) + \gamma r_p (r_c - 1)}\right]$$

From the above equation, we can observe that the value of $r_p > 1$ results in increased efficiency for the given value of r_c and γ.
Where $r_c = 1$ then it will give the Otto cycle efficiency and with the $r_p = 1$ it will give the diesel cycle efficiency.

Problem – 01: *An air standard dual cycle has a compression ratio of 16 and compression begins at 1 bar and 50⁰ C. The maximum pressure is 70 bar. The heat transferred to air at constant pressure is equal to that at constant volume. Estimate – (a) the pressure and temperature at cardinal points of the cycle (b) the cycle efficiency (c) the mean effective pressure of the cycle, take for air C_V = 0.718 kj/kg K, C_P = 1.005 kj/kg K.*

Solution: $r_k = \frac{v_1}{v_2} = 16$, $T_1 = 50 + 273 = 323$ K, $p_1 = 1$ bar, $p_3 = 70$ bar, C_v=0.718 kj/kg K, C_p=1.005 kj/kg K

(a) The pressure and temperature at cardinal points of the cycle:

We know that, $\frac{T_2}{T_1} = \left(\frac{v_1}{v_2}\right)^{\gamma-1} = 16^{0.4}$

$\Rightarrow \quad T_2 = 323 \times 16^{0.4} = 979\ K$

We also know that, $p_2 = p_1\left(\frac{v_1}{v_2}\right)^{\gamma} = 1 \times 16^{1.4} = 48.5\ bar$

And, $T_3 = T_2\left(\frac{p_3}{p_2}\right) = 979 \times \frac{70}{48.5} = 1413\ K$

Heat added at constant volume, $Q_{2-3} = C_v(T_3 - T_2) = 0.718(1413 - 979) = 312\ kj/kg$

Now, $\quad Q_{2-3} = Q_{3-4} = C_p(T_4 - T_3)$

$\Rightarrow \ T_4 = \frac{312}{1.005} + 1413 = 1723\ K$

Here, $\frac{v_4}{v_3} = \frac{T_4}{T_3} = \frac{1723}{1413} = 1.22$

So, $\frac{v_5}{v_4} = \frac{v_1}{v_2} \times \frac{v_3}{v_4} = \frac{16}{1.22} = 13.1$

Now, $T_5 = T_4\left(\frac{v_4}{v_5}\right)^{\gamma-1} = 1723 \times \frac{1}{13.1^{0.4}} = 615\ K$

And, $p_5 = p_1\left(\frac{T_5}{T_1}\right) = 1 \times \frac{615}{323} = 1.9\ bar$

(b) The cycle efficiency:

$$\eta_{cycle} = 1 - \frac{C_v(T_5 - T_1)}{C_v(T_3 - T_2) + C_p(T_4 - T_3)}$$
$$= 1 - \frac{0.718(615 - 323)}{312 + 312}$$
$$= 1 - \frac{0.718 \times 292}{624}$$
$$= 0.665\ or\ 66.5\%$$

(c) The mean effective pressure of the cycle:

We know that net work done,

$$W_{net} = Q_1 \times \eta_{cycle}$$
$$= 624 \times 0.665$$
$$= 414.96\ kj/kg$$

We know that,

$$p_1 v_1 = mRT_1$$
$$\Rightarrow \ v_1 = \frac{mRT_1}{p_1}$$
$$\Rightarrow \ v_1 = \frac{1 \times 0.287 \times 323}{100} = 0.927\ m^3/kg$$

So, $v_2 = \frac{v_1}{16} = \frac{0.927}{16} = 0.058\ m^3/kg$

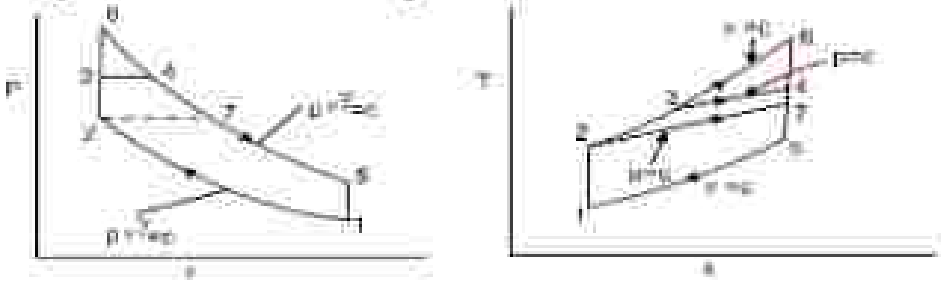
∴ Stroke volume, $v_1 - v_2 = 0.927 - 0.058 = 0.869\ m^3/kg$

We know that,

$$m.e.p. = \frac{Net\ work\ done}{stroke\ volume} = \frac{W_{net}}{v_1 - v_2}$$
$$= \frac{414.96}{0.869} = 477.5\ KPa$$

Comparison of Otto, Diesel & Dual Cycles:

- **For same compression ratio and heat rejection**



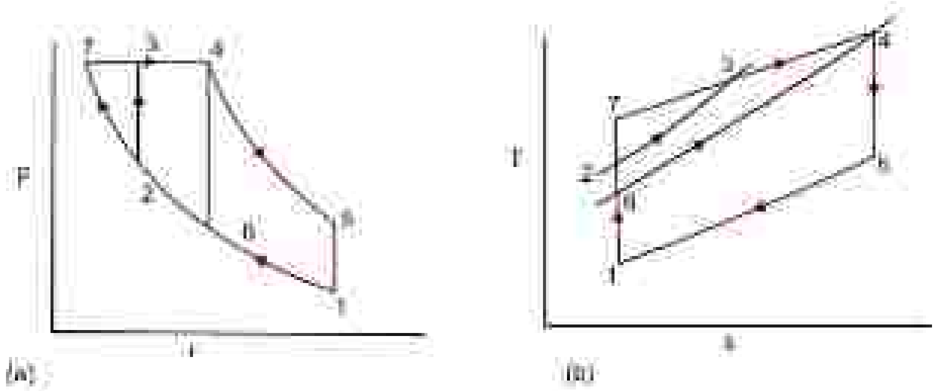
From the figure:
1-2-6-5: Otto cycle
1-2-7-5: Diesel cycle
1-2-3-4-5: Dual cycle

Q_1 is represented by:
Area under 2 - 6 → for Otto cycle
Area under 2 - 7 → for Diesel cycle and
Area under 2 - 3 - 4 → for Dual cycle and Q_2 is same for all the cycles

For the same compression ratio and heat rejection,

$$\eta_{Otto} > \eta_{Dual} > \eta_{Diesel}$$

- **For the same maximum pressure and temperature**



From the figure:
1-6-4-5: Otto cycle
1-7-4-5: Diesel cycle
1-2-3-4-5: Dual cycle

Q_1 is represented by:
Area under 6 - 4 → for Otto cycle
Area under 7 - 4 → for Diesel cycle and
Area under 2 - 3 - 4 → for Dual cycle and Q_2 is same for all the cycles

For the same maximum pressure and temperature,

$$\eta_{Diesel} > \eta_{Dual} > \eta_{Otto}$$

POSSIBLE SHORT TYPE QUESTIONS WITH ANSWER

1. What is the air standard efficiency of Otto cycle?

Ans: $\eta_{otto} = 1 - \frac{1}{(r_k)^{\gamma-1}}$

Where, $r_k = compression\ ratio = \frac{v_1}{v_2}$

2. What is the air standard efficiency of Diesel cycle?

Ans: $\eta_{diesel} = 1 - \frac{1}{\gamma} \cdot \frac{1}{r_k^{\gamma-1}} \cdot \frac{r_c^{\gamma}-1}{r_c-1}$

Where, $r_k = compression\ ratio = \frac{v_1}{v_2}$

$r_c = cut\ off\ ratio = \frac{v_3}{v_2}$

3. What is the air standard efficiency of Dual cycle?

Ans: $\eta_{dual} = 1 - \frac{1}{(r_k)^{\gamma-1}} \times \left[\frac{r_p r_c^{\gamma} - 1}{(r_p - 1) + \gamma r_p (r_c - 1)}\right]$

Where, $r_k = compression\ ratio = \frac{v_1}{v_2}$

$r_c = cut\ off\ ratio = \frac{v_3}{v_2}$

$r_p = constant\ volume\ pressure\ ratio = \frac{p_3}{p_2}$

POSSIBLE LONG TYPE QUESTIONS

1. Explain briefly about Carnot cycle with the help of p-v and T-S diagram and derive an expression for the thermal efficiency of Carnot cycle. [W-2019], **[w-2022]**

2. Explain briefly about Otto cycle with the help of p-v and T-S diagram and derive an expression for the air standard efficiency of Otto cycle. [W-2020], [W-2019]

3. Explain briefly about Diesel cycle with the help of p-v and T-S diagram and derive an expression for the air standard efficiency of Diesel cycle. **[w-2022]**

4. Explain briefly about Dual cycle with the help of p-v and T-S diagram and derive an expression for the air standard efficiency of Dual cycle.

<u>Problem – 01</u>: In a Carnot engine, the temperature of the source and sink are 700° C and 30° C. The heat supply is 84 kJ/s. Find the power developed by the engine. If the temperature of source is 500° C and the heat supply and work done are 420 kJ and 200 kJ respectively, find the sink temperature.

<u>Problem – 02</u>: A certain quantity of air at a pressure of 1 bar and temperature 70°C is compressed isentropically 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, (i) compression ratio of the engine (ii) temperature at the end of compression (iii) temperature at the end of heat addition. Take for air, C_P = 1 kj/kg k and C_V = 0.707 kj/kg k.

<u>Problem – 03</u>: In an air standard diesel cycle, the compression ratio is 16, and at the beginning of the isentropic compression, the temperature is 15°C and the pressure is 0.1 MPa. The heat is added until the temperature at the end of the constant pressure process is 1480°C. Calculate – (a) the cut off ratio (b) Heat supplied per kg of air (c) The cycle efficiency (d) The mean effective pressure (m.e.p.).

<u>Problem – 04</u>: An air standard dual cycle has a compression ratio of 16 and compression begins at 1 bar and 50° C. The maximum pressure is 70 bar. The heat transferred to air at constant pressure is equal to that at constant volume. Estimate – (a) the pressure and temperature at cardinal points of the cycle (b) the cycle efficiency (c) the mean effective pressure of the cycle, take for air C_V = 0.718 kj/kg K, C_P = 1.005 kj/kg K.

CHAPTER NO. – 06
FUELS AND COMBUSTION

Learning Objectives:

- *6.1 Define Fuel*
- *6.2 Types of fuel.*
- *6.3 Application of different types of fuel.*
- *6.4 Heating values of fuel.*
- *6.5 Quality of I.C engine fuels: Octane number, Cetane number.*

6.1 INTRODUCTION:

- **Definition of fuel:**
  The fuel may be defined as a substance which, on burning with oxygen in the atmospheric air, produces a large amount of heat. The amount of heat generated is known as calorific value of fuel.
- As the principal constituents of a fuel are carbon and hydrogen, therefore, it is also known as hydrocarbon fuel.

6.2 Types of Fuel:

The fuels may be classified into the following three general forms:

1. Solid fuels
2. Liquid fuels
3. Gaseous fuels

Each of these fuels may be further subdivided into the following two types:

a. Natural fuels
b. Prepared fuels

6.3 Application of Different Types of Fuel:

Solid fuels:

- Solid fuel refers to various forms of solid material that can be burnt to release energy, providing heat and light through the process of combustion.
- The natural solid fuels are wood, peat, lignite or brown coal, bituminous coal and anthracite coal.
- The prepared solid fuels are wood charcoal, coke, briquetted coal and pulverised coal.

Wood:

- It consists of mainly carbon and hydrogen.
- The wood is converted into coal when burnt in the absence of air.
- The average calorific value of the wood is 19700 kj/kg.
- **Uses:** It can be used for cooking and heating, and occasionally for fuelling steam engines and steam turbines that generate electricity. It may be used indoors in a furnace, stove, or fireplace, or outdoors in furnace, campfire, or bonfire.

Peat:

- It is a spongy humid substance found in boggy land.
- It may be regarded as the first stage in the formation of coal.
- It has a large amount of water contents and therefore has to be dried before use.
- It has a characteristics odour at the time of burning, and has a smoky flame.
- Its average calorific value is 23000 kj/kg.
- **Uses:** Peat is used for domestic heating purposes as an alternative to firewood and forms a fuel suitable for boiler firing in either briquetted or pulverized form. Peat is also used for household cooking in some places and has been used to produce small amounts of electricity. In horticulture, peat is used to increase the moisture-holding capacity of sandy soils.

Lignite:

- It represents the next stage of peat in the coal formation.
- It contains nearly 40% of moisture and 60% of carbon.
- Its average calorific value is 25000 kj/kg.

- **Uses:** It is used in power plants mainly for electricity/steam production. Because of its high moisture content and low heat characteristics, lignite is not feasible for shipping, and so lignite is burned close to the place it is mined. It is also used to generate synthetic natural gas and to produce various fertilizer products.

Bituminous coal:

- It represents the next stage of lignite in the coal formation and contains very little moisture (4 to 6%) and 75 to 90% of carbon.
- It is weather resistant and burns with a yellow flame.
- Its average calorific value is 33500 kj/kg.
- It is of two types: (a) Caking bituminous coal and (b) Non-caking bituminous coal.
- **Uses:** The high carbon and low moisture content of this particular type of coal makes it ideal in the production of steel and cement, as well as in electricity generation and coke production.

Anthracite coal:

- It represents the final stage in the coal formation, and contains 90% or more carbon with a very little volatile matter.
- It is thus obvious, that the anthracite coal is comparatively smokeless, and has very little flame.
- It possesses a high calorific value of about 36000 kj/kg.
- **Uses:** Hundreds of thousands of homeowners currently use anthracite and many others are converting to it for home heating. Many universities, schools, nursing homes, hospitals and even museums save money on heating costs by using anthracite. Anthracite is used as a heat source, and carbon additive for steel making plants and factories in a number of industries. Municipalities use anthracite for water filtration.

Wood charcoal:

- It is made by heating wood with a limited supply of air to a temperature not less than 280°C.
- It is a good prepared solid fuel.
- **Uses:** It is used for various metallurgical processes.

Coke:

- It is produced when coal is strongly heated continuously for 42 to 48 hours in the absence of air in a closed vessel. This process is known as carbonisation of coal.
- Coke is dull black in colour, porous and smokeless.
- It has high carbon content (85 to 90%) and has a higher calorific value than coal.
- If the carbonisation of coal is carried out at 500 to 700° C, the resulting coke is called soft coke.
- If the carbonisation of coal is carried out at 900 to 1100° C, the resulting coke is called hard coke.
- **Uses:** Soft coke is used as a domestic fuel. Hard coke is mostly used as a blast furnace fuel for extracting pig iron from iron ores, and to some extent as a fuel in cupola furnace for producing cast iron.

Briquetted coal:

- It is produced from the finely ground coal by moulding under pressure with or without a binding material.
- The binding materials usually used are pitch, coal tar, crude oil and clay etc.
- **Uses:** It can be used to heat boilers in manufacturing plants.

Pulverised coal:

- The low grade coal with high ash content, is powdered to produce pulverised coal.
- The coal is first dried and then crushed into a fine powder by pulverising machines.
- **Uses:** It is widely used in the cement industry and also in metallurgical processes.

Liquid Fuels:

- Almost all the commercial liquid fuels are derived from natural petroleum or crude oil. The crude oil is obtained from bore-holes in the earth's crust in certain parts of the world.
- The liquid fuels consist of hydrocarbons.
- The natural petroleum may be separated into petrol or gasoline, paraffin oil or kerosene, fuel oils and lubricating oils by boiling the crude oil at different temperatures and subsequent fractional distillation or by a process such as cracking.
- The solid products like Vaseline and paraffin wax are recovered from the residue in the still.

Petrol or gasoline:

- It is the lightest and most volatile liquid fuel, mainly used for petrol engines.
- It is distilled at a temperature from 65° to 220° C.

Kerosene or paraffin oil:

- It is heavier and less volatile fuel than the petrol, and is used as heating and lighting fuel.
- It is distilled at a temperature from 220° to 345° C.

Heavy fuel oils:

- The liquid fuels distilled after petrol and kerosene are known as heavy fuel oils. These oils are used in diesel engines and in oil fired boilers.
- These are distilled at a temperature from 345° to 470° C.

Gaseous Fuels:

- The natural gas is, usually, found in or near the petroleum fields, under the earth's surface.
- It, essentially, consists of marsh gas or methane (CH_4) together with small amounts of other gases such as ethane (C_2H_6), carbon dioxide (CO_2) and carbon monoxide (CO).

Coal gas:

- It is also known as a town gas.
- It is obtained by the carbonisation of coal and consists mainly of hydrogen, carbon monoxide and various hydrocarbons.
- Its calorific value is about 21000 to 25000 kJ/m³.
- It is largely used in towns for street and domestic lighting and heating. It is also used in furnaces and for running gas engines.

Producer gas:

- It is obtained by the partial combustion of coal, coke, anthracite coal or charcoal in a mixed air stream blast.
- Its manufacturing cost is low.
- Its calorific value is about 5000 to 6700 kJ/m³.
- It is, mostly, used for furnaces particularly for glass melting and also power generation.

Water gas:

- It is a mixture of hydrogen and carbon monoxide and is made by passing steam over incandescent coke.
- As it burns with a blue flame, it is also known as *blue water gas*.
- It is usually mixed with coal gas to form town gas.
- The water gas is used in furnaces and for welding.

Mond gas:

- It is produced by passing air and a large amount of steam over waste coal at about 650° C.
- Its calorific value is about 5850 kJ/m³.
- It is used for power generation and heating. It is also suitable for use in gas engines.

Blast furnace gas:

- It is a by-product in the production of pig iron in the blast furnace.
- Its calorific value is about 3750 kJ/m³.
- This gas serves as a fuel in steel work, for power generation in gas engines, for steam raising in boilers and for preheating the blast furnace. It is extensively used as a fuel for metallurgical furnaces.

Coke oven gas:

- It is a by-product from coke oven, and is obtained by the carbonisation of bituminous coal.
- Its calorific value varies from 14500 to 18500 kJ/m³.
- It is used for industrial heating and power generation.

6.4 Heating values of fuel:

- The heating value or calorific value of a fuel may be defined as the amount of heat liberated by the complete combustion of unit mass of fuel.

- S.I. unit: kj/kg (for solid and liquid fuel), kj/m³ (for gaseous fuel).
- Following are the two types of the calorific value of fuels:
  a. Gross or higher calorific value (HCV)
  b. Net or lower calorific value (LCV)

Gross or higher calorific value (HCV):

- It is the total amount of heat produced, when unit mass/volume of the fuel has been burnt completely and the products of combustion have been cooled to room temperature (15°C or 60°F).

Net or lower calorific value (LCV):

- It is the net heat produced, when unit mass/volume of the fuel is burnt completely and the products are permitted to escape.

6.5 Quality of I.C engine fuels Octane number, Cetane number

Octane Number:

- Octane number is defined as the percentage of isooctane present in a standard mixture of isooctane and n-heptane, which knocks at the same compression ratio as the petrol being tested.
- Isooctane is the branched chain hydrocarbon has least knocking rate, hence its octane number is arbitrarily fixed as 100. N-heptane a straight chain hydrocarbon has highest tendency to knock hence its octane number is fixed as zero. Octane number of petrol is 80 means it contains 80% by volume isooctane and 20% by volume n- heptane.

Cetane Number:

- It is defined as the percentage of cetane present in standard mixture of a cetane and Alfa-methylnaphthalene, which knocks at the same compression ratio as the diesel fuel being tested.
- The cetane which is a straight chain paraffin with good ignition quality is assigned a cetane number of 100 and alpha-methyl-naphthalene which is a hydrocarbon with poor ignition quality, is assigned a zero (0) cetane number.

POSSIBLE SHORT TYPE QUESTIONS WITH ANSWER

1. Define calorific value of fuel. [w-2022]

Ans: The heating value or calorific value of a fuel may be defined as the amount of heat liberated by the complete combustion of unit mass of fuel.

2. Define Gross or higher calorific value of fuel.

Ans: It is the total amount of heat produced, when unit mass/volume of the fuel has been burnt completely and the products of combustion have been cooled to room temperature (15°C or 60°F).

3. **Define Cetane number. [w-2020]**

Ans- It is defined as the percentage of cetane present in standard mixture of a cetane and alpha-methyl napthanalane, which knocks at the same compression ratio as the diesel fuel being tested.

POSSIBLE LONG TYPE QUESTIONS

1. Explain types of fuel with example.
2. Differentiate between octane number and cetane number. [w-2022]
3. Define fuel and explain the various classification of the fuel. [w-2020]