Module 1

1.1. Introduction to thermodynamics

An excellent definition of thermodynamics is that it is the science of energy, entropy and equilibrium. Since we have not defined the terms energy, entropy and equilibrium, we can define thermodynamics as the science that deals with heat and work. The study of thermodynamics is of special importance to the engineers since it finds applications in almost all power producing as well as power absorbing devices. For an efficient utilization of energy a deep knowledge of the subject is essential.

Macroscopic and microscopic approach

A thermodynamic analysis can be carried out either by considering the gross behavior of matter or by considering the behavior of individual molecules of the matter. The former is called macroscopic approach and the later is called microscopic approach. Macroscopic approach is concerned with the effect of many molecules together. These effects can be perceived by human senses and can be measured directly. In microscopic approach the matter is considered to be composed of molecules and the analysis is carried out by considering the position, velocity and energy of each molecule at a given instant. ie, in microscopic approach we are concerned with the events happening at the molecular level. The microscopic approach is not essential for solving many of the engineering problems and we can obtain excellent solutions using the simple macroscopic approach.

System

A system is any prescribed and identifiable collection of matter. It can be any object, any quantity of matter, any region of space etc, selected for study. The matter or region outside the system is termed as surroundings.The real or imaginary envelope which encloses a system and separate it from its surroundings is called boundary of the system. A boundary which does not permit matter to pass through it is called impermeable boundary.A boundary which resists any normal or shear forces without changing shape or size is called rigid boundary. A boundary which does not permit matter and energy to pass through it is called isolating boundary. Fig. 1.1 shows the usual representation of system, boundary and surroundings.

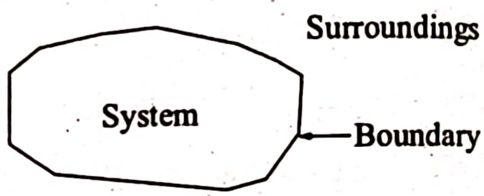


Fig. 1.1. Representation of system, boundary and surroundings

Thermodynamic systems are classified into three groups.

i) Closed system (ii) Open system and (iii) Isolated system

Closed system

If there is no transfer of mass across the boundary of a system and if the boundary permits transfer of energy across it, then such a system is known as closed system. A gas heated in a cylinder fitted with a piston, as shown in Fig. 1.2 is an example of a closed system.

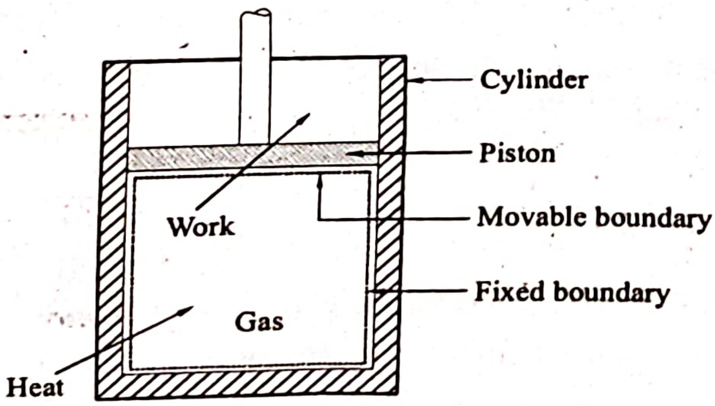


Fig. 1.2 Closed system

In this case energy (heat and work) crosses the boundary of the system but the mass does not cross the boundary. It should be noted that the boundary of a closed system may or may not move and change the position.

Open system

An open system is one with transfer of mass and energy across its boundary. Steam turbines, pumps etc, are examples of open system. In the case of a steam turbine, mass (steam) as well as energy crosses the boundary of the system as shown in Fig 1.3.

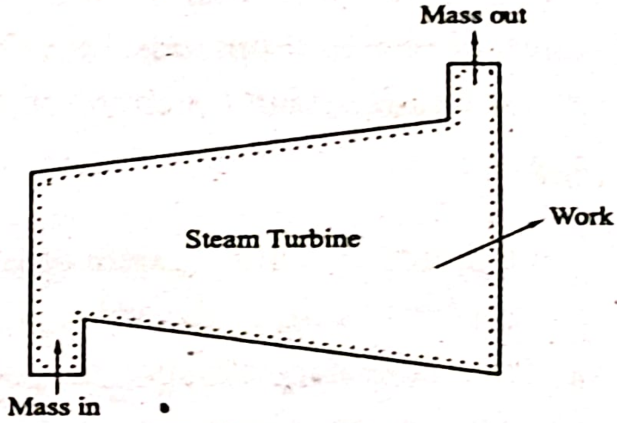


Fig 1.3 Open System

Isolated system

It is a system enclosed by an isolating boundary. It is not influenced by the surroundings. Since the system is bounded by an isolating boundary, there is no flow of mass or energy across the boundary of the system. Though such a system has no practical interest, it is a useful concept in the study of thermodynamics. If the universe itself is taken as a system then it will be an isolated system.

State of a system

The condition of physical existence of a system at any instant is called its state. The state of a system is its condition or configuration described in sufficient details such that one state may be distinguished from all other states. The state of a thermodynamic system is described by specifying its thermodynamic co-ordinates. Pressure, temperature, volume, density etc are typical examples of thermodynamic co-ordinates. Thus the state of a thermodynamic system is its condition or configuration which can be well defined by the above said thermodynamic co-ordinates.

Property of a system

Property can be defined as any quantity that depends on the state of the system and is independent of how the system is arrived at that state. The thermodynamic co - ordinates such as temperature, pressure, volume, density etc, which are used to identify or describe the state of a system are called properties. Since properties are functions of states only, these are called point functions or state functions.

Path

If a thermodynamic system passes through a series of states, it is said to describe a path. If the value of thermodynamic variable depends upon the path followed in going from one state to another, then the variable is a path function.

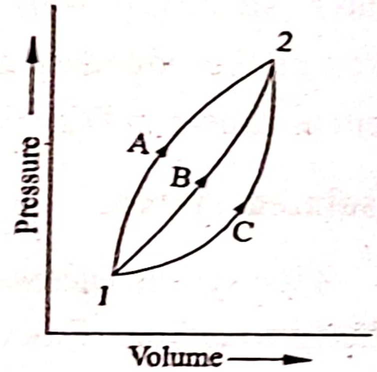


Fig. 1.4.

Consider the change of state of a system from state 1 defined by pressure p_1, volume V_1 and temperature T_1 to state 2 defined by pressure p_2 volume V_2 and temperature T_2. It is possible to go from state 1 to state 2 along different paths such as 1-A-2, 1 - B - 2 or 1 - C - 2 as shown in Fig. 1.4. At state 2 the value of pressure volume and temperature will be the same whether the state 2 is arrived along the path 1 - A - 2, 1 - B - 2 or 1 - C - 2. ie., the value of pressure , volume and temperature at state 2 is independent of the path followed and depends only on the state 2. Hence these quantities are state functions or point functions. A state function or point function is a property of the system. The change in the value of a property during a process depends only on the end states and is independent of the path followed

A variable whose value depends on the path folllowed during a change of state, is a path function. A path function is not a property of the system. Work and heat interactions during a process are examples of path functions.

Process

When a thermodynamic system changes from one state to another it is said to have undergone a process. The state of a system can be represented by a point located on a diagram using two properties as co-ordinates. When a system changes its state in such a way that at any instant during the process the state point can be located on the diagram, the

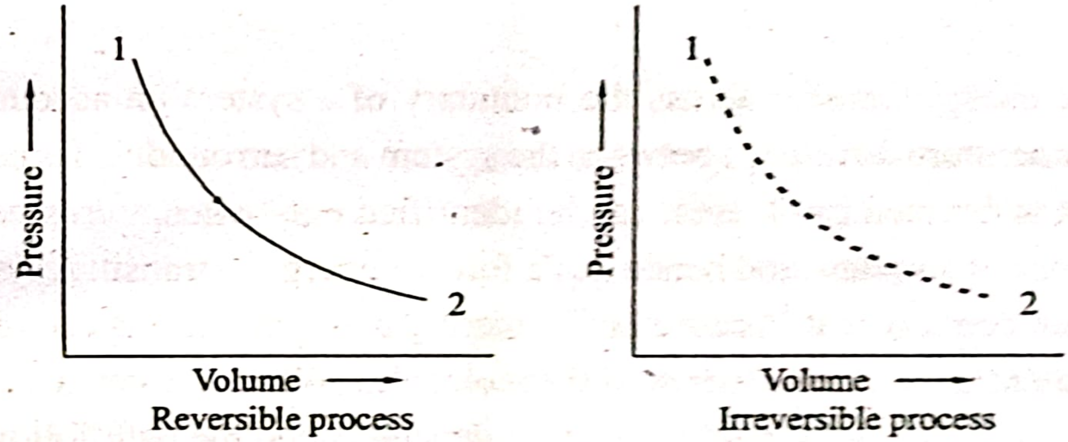


Fig. 1.5. Representation of reversible and irreversible processes.

process is said to be reversible. Thus a reversible process between two states can be shown by a continuous line on any diagram of properties. In a real process the intermediate state points cannot be located on the property diagrams. Such a real process is called irreversible process. An irreversible process is usually represented by a dotted line joining the end states to indicate that the intermediate states are indeterminate. Fig. 1.5 shows the usual representation of reversible and irreversible processes.

When a system undergoes a reversible process both the system and its surroundings can always be restored to their original state by reversing the process.

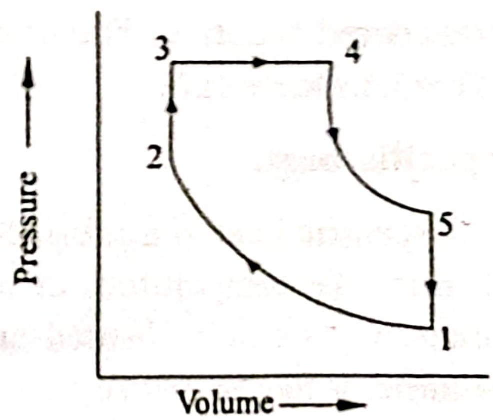


Fig. 1.6

Cycle

When a thermodynamic system changes from one state to another, it is said to have undergone a process. At the end of the last process if the system returns to its original state, it is said to have completed one thermodynamic cycle. When these processes are plotted on a property diagram, they form a closed contour as shown in Fig. 1.6. The net change in any property of the system is zero for a cycle. $\oint dx = 0$ where x is any property and the symbol $\oint$ represents integration around a cycle.

Heat

The energy transfer across the boundary of a system on account of the temperature difference between the system and surroundings is called heat. It is denoted by Q. Heat can be identified only when it crosses the boundary of a system and hence it is a form of energy in transit. A system does not contain heat because upon entering a system, heat is converted into potential or kinetic energy of the molecules. When a system changes its state the amount of heat transferred depends upon the path followed. Hence heat is a path function and therefore it is not a property of the system. The integral of a differential change in heat, dQ can be written as

$\int_1^2 dQ = {}_1Q_2$ or Q_{1-2} It should be noted that $\int_1^2 dQ \neq Q_2 - Q_1$

Q_{1-2} is the amount of heat transferred during a process 1-2.

Heat transferred to a system is considered positive and heat transferred from a system is considered negative. The unit of heat is Joule (J) or kilo Joule (kJ).

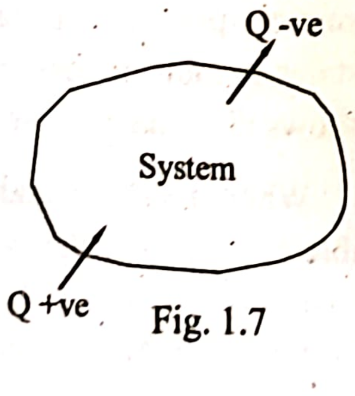


Fig. 1.7

Specific heat.

Specific heat of a substance is defined as the amount of heat required to raise the temperature of unit mass of the substance by unit degree. Since a gas can be heated under constant pressure and under constant volume, it has two specific heats, specific heat at constant pressure and specific heat at constant volume.

Specific heat at constant pressure

Whenever a gas is heated at constant pressure, the temperature and volume of the gas increases. The amount of heat required to raise the temperature of unit mass of a gas through unit degree, when it is heated at constant pressure is the specific heat of that gas at constant pressure and is denoted by C_P.

Let Q be the amount of heat supplied to a gas at constant pressure in J, m, mass of the gas in kg, T_1 and T_2 the initial and final temperature of the gas in K, then,

$$\text{Specific heat, } C_P = \frac{Q}{m(T_2 - T_1)} \text{ J/kg.K}$$

Specific heat at constant volume

Whenever a gas is heated at constant volume, the temperature and pressure of the gas increases. The amount of heat required to raise the temperature of unit mass of a gas through unit degree, when it is heated at constant volume is the specific heat of that gas at constant volume and is denoted by C_V.

Let Q be the amount of heat supplied to the gas at constant volume in J, m, mass of a gas in kg, T_1 and T_2, the initial and final temperature of the gas in K, then,

$$\text{Specific heat, } C_V = \frac{Q}{m(T_2 - T_1)} \text{ J/kg.K}$$

For air, $C_P = 1.005$ kJ/ kg. K and

$C_V = 0.718$ kJ/kg. K

Work

In mechanics work is defined as the product of force and distance moved in the direction of force. It is denoted by W and the unit of work is N - m. 1 Nm = 1 J. In thermodynamics, the energy transfer across the boundary of a system on account of reasons other than temperature difference is called work. Work is said to be done by a system if the sole effect external to the system can be reduced to the lifting of a weight.

Consider a storage electric battery as a system, which is connected to a resistor by means of a switch as shown in Fig. 1.8. When the switch is closed, current flows through the resistor and the resistor becoms warmer.

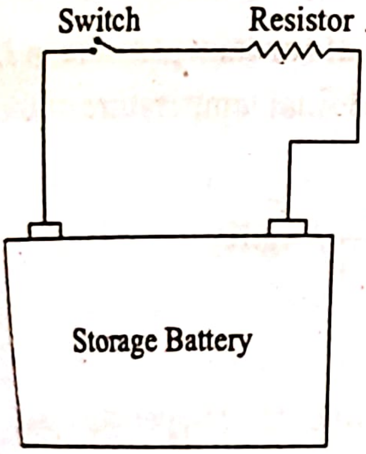


Fig. 1.8

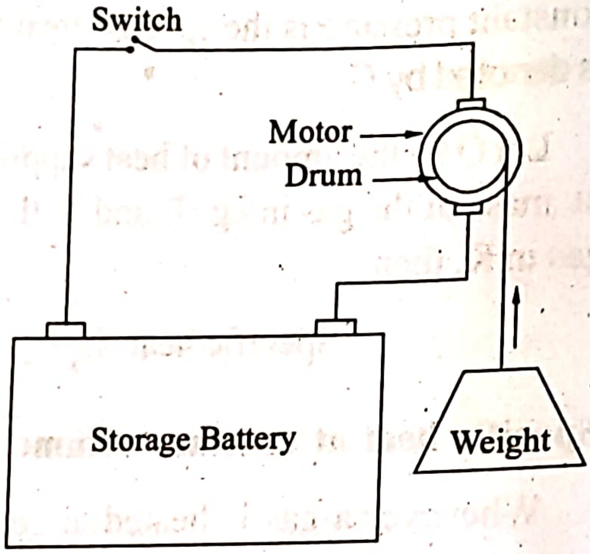


Fig. 1.9

According to the definition of work in mechanics, no work is done. The sole effect external to the system, ie., warming of resistor can be reduced to the lifting of weight, if the resistor is replaced by a motor and a load as shown in Fig. 1.9. When the switch is closed, motor shaft rotates and the load is lifted. Hence when the switch is closed, the system interacts with its surroundings and the sole effect could be reduced to the lifting of a weight. Therefore the system (battery) does work when the switch is closed.

Like heat, work is also energy in transit. A system does not contain work, upon entering the system it is converted into stored energy. Work is a path function and hence it is not a property of the system $\int_1^2 dW \neq W_2 - W_1$. $\int_1^2 dW = {}_1W_2$. ${}_1W_2$ is the amount of work transferred during a process 1 - 2.

Consider the expansion of a gas inside a cylinder fitted with a piston. Refer Fig. 1.10. Let the pressure and volume of the gas at state 1 be p_1 and V_1 respectively. This gas is expanded to state 2. This expansion process is represented in the p - V diagram by the curve 1 -2. Now consider a point A on the curve. Let the pressure of gas at state point A be p. This gas pressure acts on the piston and causes movement of the piston. At this instant the force on the piston is given by $p \times a$, where 'a' is the area of cross section of the piston. Let the piston moves through a small distance dx, the work done is $p \times a \times dx$. But $a \times dx$ is the change in volume of gas when the piston moves through the small distance dx. Hence work done is equal to $p \times dV$, the shaded area in the p - V diagram. Therefore the area under the curve 1 - 2, $\int_1^2 p\, dV$ will give the work done when the gas changes its volume from V_1 to V_2 or when the gas expands from state 1 to state 2. Work done during the process 1 - 2, ${}_1W_2 = \int_1^2 p\, dV$. Work is taken as positive when it is done by the system and negative when it is done on the system. The unit of work is Joule (Nm).

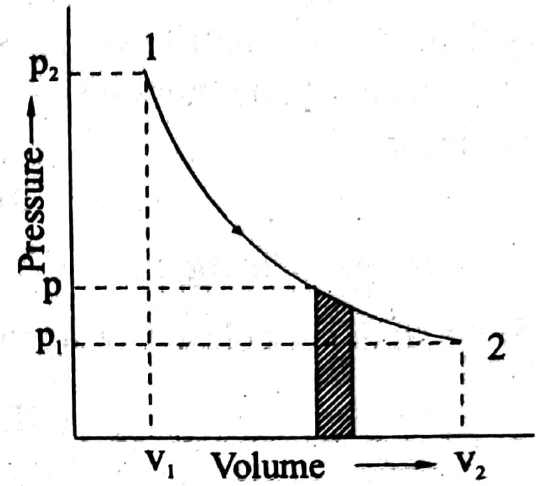


Fig. 1.10

Internal energy

Internal energy of a substance may be defined as the algebric sum of internal kinetic energy and internal potential energy of its molecules and is denoted by U. It is very difficult to determine the absolute value of internal energy possessed by a substance. In most of the thermodynamic applications we are mainly interested only in the changes in the internal energy of a system. The total energy of a system is the sum of potential energy, kinetic energy, internal energy and other energies due to electricity, magnetism etc. In engineering thermodynamics the concern is with the first three types of energies and electrical energy, magnetic energy etc, can be neglected.

$$\therefore E = PE + KE + U$$

Change in energy, $\Delta E = \Delta PE + \Delta KE + \Delta U$

For a stationary closed system undergoing a process 1 - 2,

$$\Delta PE = 0, \ \Delta KE = 0$$

$$\Delta E = \Delta U = {}_1Q_2 - {}_1W_2$$

$${}_1Q_2 = {}_1W_2 + \Delta U$$

When heat is supplied to a closed system, a portion of it is converted into work and the remaining portion is used to increase the internal energy of the system.

Problem 1.1.

5 kg of gas is contained in a cylinder fitted with a piston. 160 kJ of heat is transferred to the gas and simultaneously the piston is forced to compress the gas with an expenditure of work equivalent to 120 kJ. Determine the change in specific internal energy of the gas.

Solution:

Given: $m = 5$ kg, $W = -120$ kJ, $Q = 160$ kJ

To find: $\dfrac{\Delta U}{m}$

Using the relation,

$$\Delta U = {}_1Q_2 - {}_1W_2$$

$$\Delta U = 160 - (-120) = 280 \text{ kJ}$$

$$\therefore \frac{\Delta U}{m} = \frac{280}{5} = 56 \text{ kJ/kg}$$

Problem 1.2

A tank containing a fluid is stirred by a stirrer. The power input to the stirrer is 3 kW. Heat is transferred from the tank at the rate of 6000 kJ/hour. Considering the tank and the fluid as a system, determine the change in internal energy of the system in one hour.

Given: $W = -3 \text{ kW} = -3 \text{ kJ/s}$

$= -3 \times 3600 \text{ kJ/hr}$

$W = -10800 \text{ kJ/hr.} \quad Q = -6000 \text{ kJ/hr}$

To find: ΔU

We have,

$$\Delta U = Q - W$$

$$\Delta U = -6000 - (-10800) = 4800$$

$$\Delta U = 4800 \text{ kJ}$$

1.2. Thermodynamic processes

When a system changes its state from one equilibrium condition to another it is said to have undergone a process. When a gas undergoes a thermodynamic process, the various properties of the gas such as pressure, volume, temperature, energy, entropy , etc. may change. The thermodynamic process may be performed in different ways. Some of them are:

a. Constant volume (isochoric) process

b. Constant pressure (isobaric) process

c. Constant temperature (isothermal) process

d. Adiabatic process

Using the laws of thermodynamics some useful relations applicable to the above said processes can be developed.

a) Constant volume (isochoric) process

Consider 'm' kg of a gas being heated in a cylinder at constant volume from an initial temperature T_1 to final temperature T_2. This process is represented on a p-V diagram, shown in Fig. 1.11. The path of the process is represented by the vertical line 1-2 in the p-V diagram. Since there is no change in volume, no external work is done by the gas. The entire heat supplied will be stored in the form of internal energy.

(i) p - V - T relationship

For a perfect gas,

$$\frac{p_1 V_1}{T_1} = \frac{p_2 V_2}{T_2}$$

Since $V_1 = V_2$

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

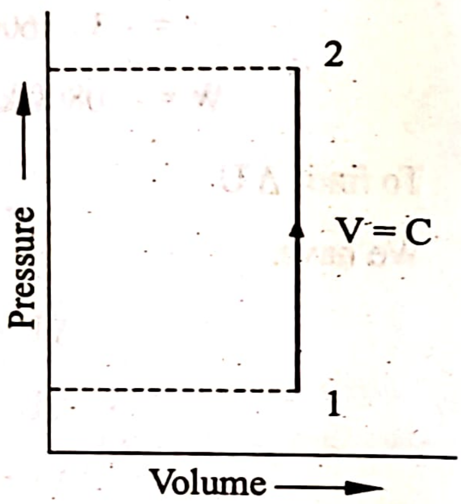


Fig. 1.11

(ii) Work done

$${}_1W_2 = \int p\,dV$$

Since V is constant, $dV = 0$

$$\therefore \; {}_1W_2 = 0$$

(iii) Change in internal energy

Since there is a temperature rise from T_1 to T_2

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

(iv) Heat supplied

From first law of thermodynamics,

$${}_1Q_2 = \Delta U + {}_1W_2$$

But ${}_1W_2 = 0$

$$\therefore \; {}_1Q_2 = \Delta U$$

ie., ${}_1Q_2 = m\,C_v (T_2 - T_1)$

(b) Constant pressure (isobaric) process

Consider 'm' kg of gas being heated at constant pressure from state 1 to 2 . The heating of the gas under constant pressure causes an increase in the volume and temperature. There will be some external work done due to the increase in the volume. This process, represented on a p-V diagram is as shown in Fig. 1.12. The horizontal line 1-2 in Fig. 1.12 represents the process in pV diagram. A part of heat supplied during the process is utilised to increase the internal energy and the remaining part is utilised to do external work.

(i) p - V - T relationship

For a perfect gas,

$$\frac{p_1V_1}{T_1} = \frac{p_2V_2}{T_2}$$

Since $p_1 = p_2$, $\frac{V_1}{T_1} = \frac{V_2}{T_2}$

(ii) Work done

$${}_1W_2 = \int_1^2 p\,dV$$

$$= p\{V\}_{V_1}^{V_2}$$

$${}_1W_2 = p\,(V_2 - V_1)$$

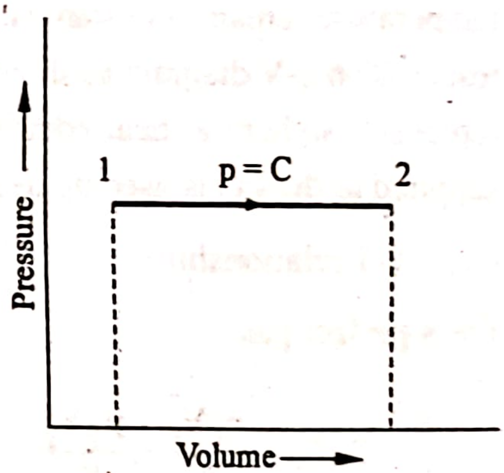


Fig. 1.12

(iii) Change in internal energy

Since there is a temperature rise from T_1 to T_2

$$\Delta U = mC_V\,(T_2 - T_1)$$

(iv) Heat supplied

From first law of thermodynamics,

$${}_1Q_2 = \Delta U + {}_1W_2$$

$$= m\,C_V\,(T_2 - T_1) + p\,(V_2 - V_1)$$

For a constant pressure process, $p_1 = p_2$

$$_1Q_2 = m\,C_V\,(T_2 - T_1) + (p_2\,V_2 - p_1\,V_1)$$

For a perfect gas $\qquad pV = mRT$

$$\therefore {}_1Q_2 = m\,C_V\,(T_2 - T_1) + (mRT_2 - mRT_1)$$

$$= m\,C_V\,(T_2 - T_1) + mR\,(T_2 - T_1)$$

$$= m\,(T_2 - T_1)\,(C_V + R)$$

But , $C_V + R = C_P$

$$\therefore {}_1Q_2 = mC_p\,(T_2 - T_1)$$

(c) Constant temperature (isothermal) process

A process in which a gas receives or rejects heat in such a way that its temperature remains constant is called isothermal process. It can be represented on p-V diagram as shown in Fig 1.13. The line 1-2 in the figures represent isothermal heat addition process. In this case, the entire heat supplied to the gas is used up in doing external external work.

(i) p - V-T relationship

For a perfect gas,

$$\frac{p_1 V_1}{T_1} = \frac{p_2 V_2}{T_2}$$

Since $T_1 = T_2$

$$p_1 V_1 = p_2 V_2$$

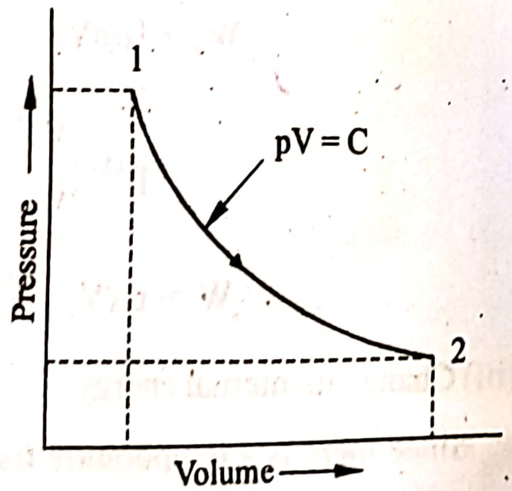


Fig. 1.13

(ii) Work done

$$_1W_2 = \int_{V_1}^{V_2} p\,dV \text{..............(i)}$$

For an isothermal process, $pV = p_1V_1 = p_2V_2 = \text{Constant}$

$$\text{or} \quad p = \frac{p_1V_1}{V}$$

Substituting this value of 'p' in eq. (i)

$$_1W_2 = \int_{V_1}^{V_2} \frac{p_1V_1}{V}\, dV$$

$$= p_1V_1 \int_{V_1}^{V_2} \frac{dV}{V}$$

$$= p_1V_1 \left[\ln V\right]_{V_1}^{V_2}$$

$$= p_1V_1 (\ln V_2 - \ln V_1)$$

$$_1W_2 = p_1V_1 \ln\left\{\frac{V_2}{V_1}\right\}$$

Also for an isothermal process

$$p_1V_1 = p_2V_2$$

$$\therefore \frac{V_2}{V_1} = \frac{p_1}{p_2}$$

Substituting this,

$$_1W_2 = p_1V_1 \ln\left\{\frac{p_1}{p_2}\right\}$$

(iii) Change in internal energy

Since $T_1 = T_2$

$$\Delta U = 0$$

(iv) Heat supplied

From the first law,

$$ {}_1Q_2 = \Delta U + {}_1W_2 $$

Since $\Delta U = 0$

$$ {}_1Q_2 = {}_1W_2 $$

$$ = p_1 V_1 \ln\left\{\frac{V_2}{V_1}\right\} $$

$$ {}_1Q_2 = p_1 V_1 \ln\left\{\frac{V_2}{V_1}\right\} $$

(d) Adiabatic process

In an adiabatic process, the gas neither receives nor rejects heat. In this process, the heat exchange, Q = 0. Work is done by the gas at the expense of internal energy.

From the first law,

$$ {}_1Q_2 = \Delta U + {}_1W_2 $$

But for an adiabatic process, ${}_1Q_2 = 0$

$$ 0 = \Delta U + {}_1W_2 $$

$$ \text{or} \quad {}_1W_2 = -\Delta U \text{.............(i)} $$

Work done, $$ {}_1W_2 = \int_{V_1}^{V_2} p\, dV $$

Change in internal energy, $\Delta U = m\, C_V (T_2 - T_1)$

Substituting in eqn (i)

$$\int_{V_1}^{V_2} p\,dV = -mC_V(T_2 - T_1)$$

Writing in differential form

$$p\,dV = -\,m\,C_V\,dT \quad \text{..................(ii)}$$

Consider the general gas equation,

$$pV = mRT$$

Differentiating,

$$p\,dV + V\,dp = m\,RdT$$

$$\text{ie., } m\,dT = \frac{pdV + Vdp}{R}$$

Substituting this in eqn (ii)

$$p\,dV = -C_V\left\{\frac{pdV + Vdp}{R}\right\}$$

$$\text{ie., } R\,p\,dV = -\,C_V(pdV + Vdp)$$

$$\text{But } R = C_P - C_V$$

$$\therefore\ (C_P - C_V)\,p\,dV = -\,C_V\,pdV - C_V\,Vdp$$

$$C_P\,pdV = -\,C_V\,Vdp$$

Rearranging,

$$\frac{C_P}{C_V}\frac{dV}{V} = -\frac{dp}{p}$$

$$\text{or } \gamma\frac{dV}{V} + \frac{dp}{p} = 0$$

Integrating

$$\gamma \ \ln V + \ln p = C_1$$

$$\ln (PV^{\gamma}) = C_1$$

where C_1 is the constant of integration.

$$\text{or } pV^{\gamma} = C \text{ where } C \text{ is another constant}$$

Therefore, for an adiabatic process 1 - 2,

$$p_1 V_1^{\gamma} = p_2 V_2^{\gamma} = \text{constant}$$

An adiabatic process can be represented an a p-V diagram as shown in Fig. 1.14. The path of the process is represented by curve 1-2 in the p-V diagram.

(i) p-V - T relationship

Relation between p and V

For an adiabatic process,

$$p_1 V_1^{\gamma} = p_2 V_2^{\gamma}$$

$$\therefore \frac{p_1}{p_2} = \left\{\frac{V_2}{V_1}\right\}^{\gamma}$$

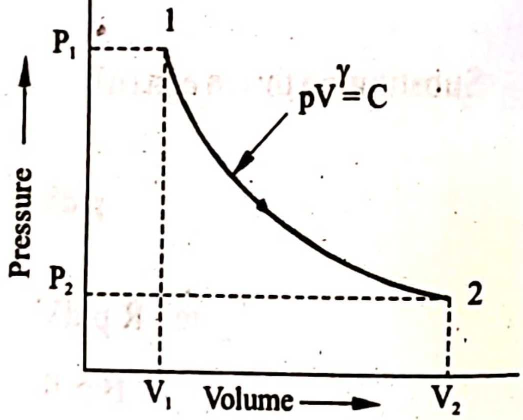


Fig. 1.14

Relation between p and T

$$p_1 V_1^{\gamma} = p_2 V_2^{\gamma}$$

$$\frac{V_2}{V_1} = \left\{\frac{p_1}{p_2}\right\}^{\frac{1}{\gamma}} \quad \text{........(i)}$$

From the general gas equation

$$\frac{p_1 V_1}{T_1} = \frac{p_2 V_2}{T_2}$$

$$\text{or } \frac{V_2}{V_1} = \frac{T_2}{T_1} \times \frac{p_1}{p_2} \text{.........(ii)}$$

From (i) and (ii)

$$\left\{\frac{p_1}{p_2}\right\}^{\frac{1}{\gamma}} = \left\{\frac{T_2}{T_1}\right\}\left\{\frac{p_1}{p_2}\right\}$$

$$\text{or } \frac{T_2}{T_1} = \left\{\frac{p_1}{p_2}\right\}^{\frac{1}{\gamma}-1}$$

$$= \left\{\frac{p_1}{p_2}\right\}^{\frac{1-\gamma}{\gamma}}$$

$$\text{or } \frac{p_1}{p_2} = \left\{\frac{T_2}{T_1}\right\}^{\frac{\gamma}{1-\gamma}} = \left\{\frac{T_1}{T_2}\right\}^{\frac{\gamma}{\gamma-1}}$$

$$= \left\{\frac{T_1}{T_2}\right\}^{\frac{\gamma}{\gamma-1}}$$

Relation between V and T

We have,

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

$$\text{Also } \frac{p_1}{p_2} = \left\{\frac{T_1}{T_2}\right\}^{\frac{\gamma}{\gamma-1}}$$

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

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

Thus, the p - V - T relations for an adiabatic process are:

1. $$\frac{p_1}{p_2} = \left\{\frac{V_2}{V_1}\right\}^{\gamma}$$

2. $$\frac{p_1}{p_2} = \left\{\frac{T_1}{T_2}\right\}^{\frac{\gamma}{\gamma-1}}$$

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

(ii) Work done, $${}_1W_2 = \int_{V_1}^{V_2} p\,dV$$

For an adiabatic process,

$$p_1 V_1^{\gamma} = p_2 V_2^{\gamma} = pV^{\gamma} = C$$

$$p = \frac{C}{V^{\gamma}}$$

$$\therefore {}_1W_2 = \int_{V_1}^{V_2} C \frac{dV}{V^{\gamma}}$$

$$= C \int_{V_1}^{V_2} V^{-\gamma}\, dV$$

$$= C \left\{ \frac{V^{(-\gamma+1)}}{(-\gamma+1)} \right\}_{V_1}^{V_2}$$

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

$$= \frac{1}{1-\gamma} \left\{ p_2 V_2^{\gamma} V_2^{(-\gamma+1)} - p_1 V_1^{\gamma} V_1^{(-\gamma+1)} \right\}$$

$$= \frac{1}{1-\gamma} \left\{ p_2 V_2^{(-\gamma+1+\gamma)} - p_1 V_1^{(-\gamma+1+\gamma)} \right\}$$

$$= \frac{1}{1-\gamma} (p_2 V_2 - p_1 V_1)$$

$$= \frac{p_2 V_2 - p_1 V_1}{1-\gamma}$$

$${}_1W_2 = \frac{p_1 V_1 - p_2 V_2}{\gamma - 1}$$

Also, for perfect gas

$$pV = mRT$$

$$\text{or } p_1V_1 = mRT_1$$
$$\text{and } p_2V_2 = mRT_2$$

Substituting in the equation for $_1W_2$,

$$_1W_2 = mR\frac{(T_1 - T_2)}{(\gamma - 1)}$$

(iii) Change in internal energy

$$\Delta U = m\,C_V\,(T_2 - T_1)$$

Also for adiabatic process, the heat exchanged $_1Q_2 = 0$ ie., work is done at the expense of internal energy.

$$\therefore \Delta U = -\,_1W_2 = -\frac{mR\,(T_1 - T_2)}{(\gamma - 1)}$$

$$\Delta U = \frac{mR(T_2 - T_1)}{(\gamma - 1)}$$

(iv) Heat exchanged

For an adiabatic process, heat exchanged is zero

$$\text{ie., } _1Q_2 = 0$$

Process	p,V,T relationship	$_1W_2$	$_1Q_2$
Const. Volume $V = C$	$\frac{p_1}{T_1} = \frac{p_2}{T_2}$	0	$mC_v(T_2 - T_1)$
Const. Pressure	$\frac{V_1}{T_1} = \frac{V_2}{T_2}$	$p\,(V_2 - V_1)$	$mC_p(T_2 - T_1)$
Const. Temp $T = C$	$p_1V_1 = p_2V_2$	$p_1V_1 \ln\frac{V_2}{V_1}$	$p_1V_1 \ln\frac{V_2}{V_1}$
Adiabatic $pV^\gamma = C$	$p_1V_1^\gamma = p_2V_2^\gamma$	$\frac{p_1V_1 - p_2V_2}{\gamma - 1}$	0

1.3 Air cycles.

When any property of a system changes, there is a change of state and the system is said to have undergone a process. At the end of the last process if the system returns to its original state, it is said to have completed one cycle. When these processes are plotted on a p-V diagram they form a closed contour as shown in Fig. 1.15.

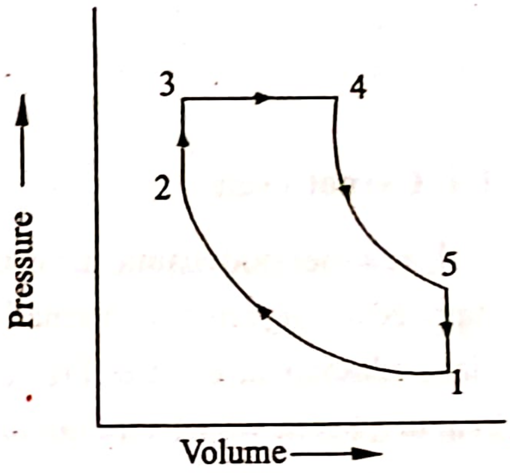


Fig. 1.15

Many of the power producing device use gas as the working fluid. The working fluid in an internal combustion engine does not operate on a cycle. For the sake of simplification, the analysis of internal combustion engine is carried out in terms of an air standard cycle. An air standard cycle is an idealized cycle in which air is taken as the working fluid. The actual combustion process is replaced by a heat transfer process. The exhaust process is replaced by a heat rejection process. All the processes are assumed to be reversible.

A part of heat transferred to the air is converted into useful work and the remainder is rejected. Therefore the work done by the air is equal to the difference between the heat supplied and heat rejected, if there is no mechanical loss, then,

Work done during a cycle = Heat supplied - Heat rejected.

Thermal efficiency of a cycle may be defined as the ratio of the work done to the heat supplied during the cycle. The thermal efficiency obtained with air as the working fluid is known as air standard efficiency.

$$\text{Air standard efficiency} = \frac{\text{Work done}}{\text{Heat supplied}}$$

$$= \frac{\text{Heat supplied} - \text{Heat rejected}}{\text{Heat supplied}}$$

$$= 1 - \frac{\text{Heat rejected}}{\text{Heat supplied}}$$

1.4. Carnot cycle

It is a thermodynamic air cycle consisting of four processes. Heat is supplied and rejected isothermally, expansion and compression of air takes place adiabatically. Refer Fig. 1.16. Consider a given mass of air in the cylinder, inside which a frictionless piston slides. Let the pressure, volume and temperature of air at state 1 be p_1, V_1 and T_1 respectively. Heat is supplied to this air isothermally from an external hot body. The air expands at constant temperature T_1 till the state 2 is reached. This process is represented by curve 1-2 in the p-V diagram. During this process heat is absorbed from the hot body and an equal amount of work is done by the

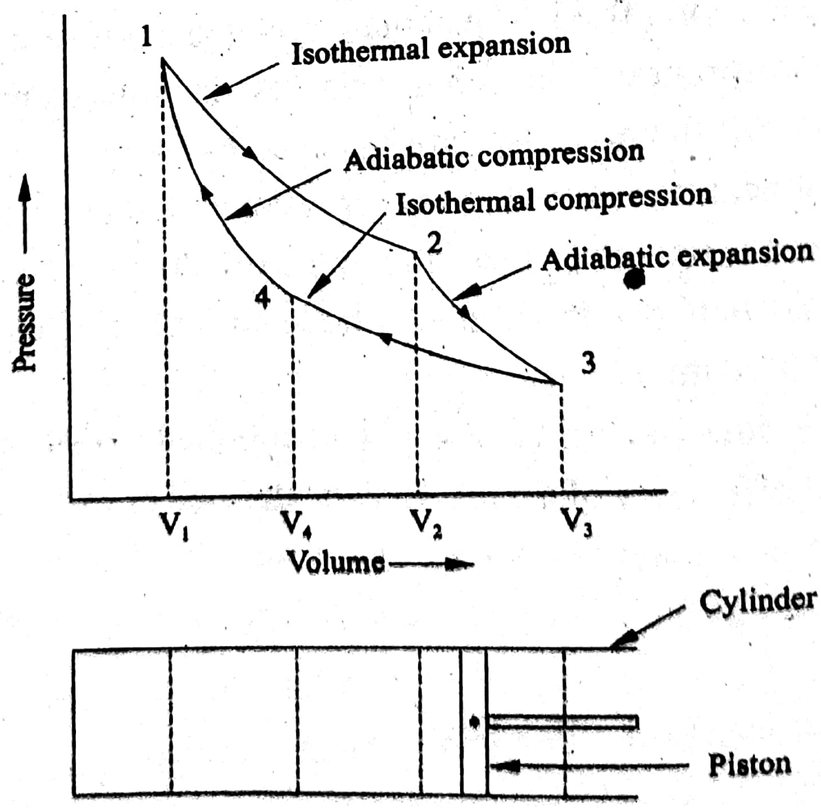


Fig. 1.16. Carnot cycle

air. At state 2, the source of heat is removed and the air is allowed to expand adiabatically till state 3. This is represented by curve 2-3 in the p-V diagram . Let the pressure, volume and temperature of the air at state 3 be p_3, V_3 and T_3 respectively. During the process 2-3 work is done by the air utilising its internal energy. At state 3, an external cold body is brought in contact with the cylinder and heat is rejected isothermally to the cold body at constant temperature T_3. This isothermal compression is represented by the curve 3-4 in the p-V diagram. During this process work is done on the air and an equal amount of heat is rejected to the cold body. At state 4, the cold body is removed and the air is compressed adiabatically to the initial state. In the p-V diagram this adiabatic compression process is representedd by curve 4-1. During this process work is done on the air to bring it to the original state.

For the adiabatic expansion process 2-3,

$$\frac{V_3}{V_2} = \left\{\frac{T_2}{T_3}\right\}^{\frac{1}{\gamma-1}} \quad \text{.....................(i)}$$

For the adiabatic compression process 4-1,

$$\frac{V_4}{V_1} = \left\{\frac{T_1}{T_4}\right\}^{\frac{1}{\gamma-1}}$$

Since $T_1 = T_2$ and $T_4 = T_3$

$$\frac{V_4}{V_1} = \left\{\frac{T_2}{T_3}\right\}^{\frac{1}{\gamma-1}} \quad \text{.....................(ii)}$$

From (i) and (ii) $\qquad \dfrac{V_3}{V_2} = \dfrac{V_4}{V_1}$

ie., adiabatic expansion ratio = adiabatic compression ratio and

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

i.e., isothermal expansion ratio = isothermal compression ratio.

During the entire cycle heat is supplied during 1-2 and rejected during 3-4

$$\text{Heat supplied} = p_1 V_1 \ln\left\{\frac{V_2}{V_1}\right\}$$

$$= mRT_1 \ln\left\{\frac{V_2}{V_1}\right\}$$

$$\text{Heat rejected} = p_3 V_3 \ln\left\{\frac{V_3}{V_4}\right\}$$

$$= mRT_3 \ln\left\{\frac{V_3}{V_4}\right\}$$

$$\text{Air standard efficiency,} \quad \eta = \frac{\text{Heat supplied} - \text{Heat rejected}}{\text{Heat supplied}}$$

$$= \frac{mRT_1 \ln\left\{\frac{V_2}{V_1}\right\} - mRT_3 \ln\left\{\frac{V_3}{V_4}\right\}}{mRT_1 \ln\left\{\frac{V_2}{V_1}\right\}}$$

$$\eta = \frac{mRT_1 \ln\left\{\frac{V_2}{V_1}\right\} - mRT_3 \ln\left\{\frac{V_2}{V_1}\right\}}{mRT_1 \ln\left\{\frac{V_2}{V_1}\right\}}$$

$$= \frac{mR \ln\left\{\frac{V_2}{V_1}\right\}(T_1 - T_3)}{mR \ln\left\{\frac{V_2}{V_1}\right\} \times T_1}$$

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

$$\text{or } \eta = 1 - \frac{T_3}{T_1} = 1 - \frac{\text{Temperature of cold body}}{\text{Temperature of hot body}}$$

Generally the temperature of hot body is taken as T_1 and that of cold body is taken as T_2.

$$\text{Then, } \eta = 1 - \frac{T_2}{T_1}$$

Although Carnot cycle gives maximum possible efficiency, yet no engine can be made to work on this cycle due to the following reasons.

The expansion and compression processes are adiabatic and hence the two operations should be carried out as quickly as possible sothat there is hardly any time for the heat exchange to take place. On the otherhand, heat supply and heat rejection takes place isothermally which means the operations must be slow to maintain the constant temperature. It is obvious that such sudden changes in the speed of an engine in one cycle is not possible in actual practice.

Problem : 1.3

During a Carnot cycle the working fluid receives heat at a temperature of 317°C and rejects heat at a temperature of 22°C. Find the theoritical efficiency of the cycle.

Solution:

Given: $T_1 = 317^0C = 590\text{ K}, T_2 = 22^0C = 295\text{ K}$

To find: η

$$\eta = 1 - \frac{T_2}{T_1} = 1 - \frac{295}{590}$$

$$= 0.5$$

$$\eta = 50\%$$

Problem : 1.4.

A Carnot cycle works with adiabatic compression ratio of 5 and isothermal expansion ratio of 2. The volume of air at the begining of the isothermal expansion is 0.3 m^3. If the maximum temperature and pressure is limited to 550 K and 21 bar, determine (i) minimum temperature in the cycle (ii) thermal efficiency of the cycle (iii) pressure at all salient points and (iv) work done per cycle. Take $\gamma = 1.4$

Solution:

Given: $\frac{V_4}{V_1} = 5 \quad \frac{V_2}{V_1} = 2$

$V_1 = 0.3 m^2 \quad T_1 = T_2 = 550$ K

$\gamma = 1.4 \quad p_1 = 21 \text{ bar} = 21 \times 10^5 \text{ N/m}^2$

To find:

$T_4, \eta, p_2, p_3, p_4, W$

For the adiabatic process 4-1,

$$\frac{T_4}{T_1} = \left\{\frac{V_1}{V_4}\right\}^{\gamma-1}$$

$$T_4 = T_1 \left\{\frac{V_1}{V_4}\right\}^{\gamma-1}$$

$$= 550 \left\{\frac{1}{5}\right\}^{1.4-1}$$

$$= 288.92 \text{ K}$$

$$T_3 = T_4 = 288.92 \text{ K}$$

For Carnot cycle,

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

$$= 1 - \frac{288.92}{550} = 0.4747$$

$$= 47.47\%$$

For the isothermal process 1-2,

$$p_1 V_1 = p_2 V_2$$

$$p_2 = \frac{p_1 V_1}{V_2}$$

Since, $\dfrac{V_2}{V_1} = 2$

$$V_2 = 2\,V_1 = 2 \times 0.3 = 0.6\ m^3$$

$$p_2 = \frac{21 \times 10^5 \times 0.3}{0.6}$$

$$= 10.5 \times 10^5\ N/m^2$$

$$p_2 = 10.5\ bar$$

For the adiabatic process 2-3,

$$\frac{p_3}{p_2} = \left\{\frac{T_3}{T_2}\right\}^{\frac{\gamma}{\gamma-1}}$$

$$p_3 = 10.5 \times 10^5 \times \left\{\frac{288.92}{550}\right\}^{\frac{1.4}{1.4-1}}$$

$$p_3 = 1.10\ bar$$

For the adiabatic process 4 – 1,

$$\frac{p_4}{p_1} = \left\{\frac{T_4}{T_1}\right\}^{\frac{\gamma}{\gamma-1}}$$

$$p_4 = 21\times10^5 \times \left\{\frac{288.92}{550}\right\}^{\frac{1.4}{1.4-1}}$$

$$p_4 = 2.2 \text{ bar}$$

Heat supplied during the isothermal process 1-2,

$${}_1Q_2 = p_1V_1 \ln \frac{V_2}{V_1}$$

$$= 21 \times 10^5 \times 0.3 \times \ln 2 = 4.37 \times 10^5 \text{ J}$$

$$\text{Heat supplied} = 437 \text{ kJ}$$

Heat rejected during the isothermal process 3-4,

$${}_3Q_4 = p_3V_3 \ln \frac{V_4}{V_3}$$

$$= p_4V_4 \ln \frac{V_4}{V_3}$$

Since isothermal expansion ratio = isothermal compression ratio,

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

$$\frac{V_4}{V_3} = \frac{V_1}{V_2} = \frac{1}{2}$$

$$\therefore\ {}_3Q_4 = 2.2\times10^5 \times (5\times0.3) \ln\left\{\frac{1}{2}\right\}$$

$$= -228.74 \text{ kJ}$$

$$\text{Heat rejected} = 228.74 \text{ kJ}$$

$$\text{Work done} = \text{Heat supplied} - \text{Heat rejected}$$

$$= 437 - 228.74$$

$$\text{Work done} = 208.26 \text{ kJ}$$

1.5. Otto cycle

Otto cycle is the theoretical cycle of spark ignition engine. Air standard Otto cycle consists of four reversible process. Heat is supplied and rejected at constant volume. Expansion and compression of air takes place adiabatically. Fig. 1.17 shows these processes on p-V diagram

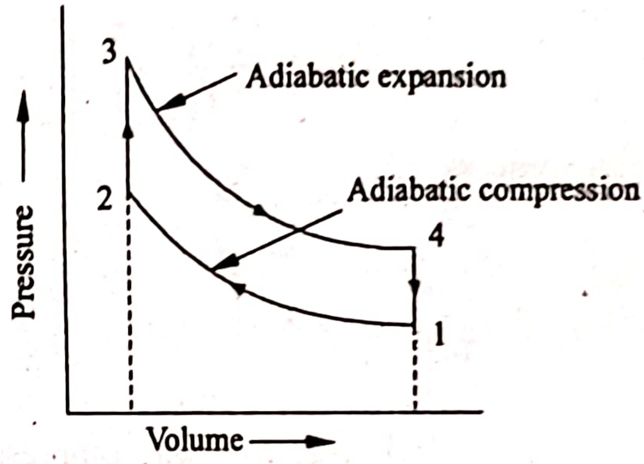


Fig. 1.17. Otto cycle

Consider a cylinder containing 'm' kg of air. Let p_1, V_1 and T_1 be the pressure, volume and temperature of air inside the cylinder, at state 1. This air is compressed adiabatically to state 2, doing work on the air. Curve 1-2 in the p-V diagram represents this process. Now heat is supplied to this compressed air at constant volume from an external hot body till state 3 is reached.

This process is represented by a vertical line 2-3 in the p-V diagram. At state 3 the hot body is removed and the air is allowed to expand adiabatically to state 4, doing external work. This process is represented by curve 3-4 in the p-V diagram. Heat is rejected at constant volume to an external cold body till state 1 is reached. This process is represented by vertical line 4-1 in the p-V diagram. Thus the air finally returns to its original state after completing a cycle.

Heat supplied during constant volume process, 2 - 3 = $m\,C_V(T_3 - T_2)$

Heat rejected during constant volume process, 4 - 1 = $m\,C_V(T_4 - T_1)$

Air standard efficiency,

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

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

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

For the adiabatic process 1-2,

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

$$= r^{\gamma-1}\text{, where r is the compression ratio, } \frac{V_1}{V_2}$$

$$\therefore T_2 = T_1 \times r^{\gamma-1} \text{...............(ii)}$$

For the adiabatic process 3- 4,

$$\frac{T_3}{T_4} = \left\{\frac{V_4}{V_3}\right\}^{\gamma-1} = \left\{\frac{V_1}{V_2}\right\}^{\gamma-1} = r^{\gamma-1}$$

$$\therefore T_3 = T_4 \times r^{\gamma-1} \text{.............(iii)}$$

Substituting equations (ii) and (iii) in the expression for efficiency, equation (i),

$$\eta = 1 - \frac{(T_4 - T_1)}{T_4 r^{\gamma-1} - T_1 r^{\gamma-1}} = 1 - \frac{(T_4 - T_1)}{(T_4 - T_1) r^{\gamma-1}}$$

$$\eta = 1 - \frac{1}{r^{\gamma-1}}$$

The above expression shows that the efficiency of Otto cycle increases with increases of the compression ratio.

Problem : 1.5.

The efficiency of an Otto cycle is 45% and $\gamma = 1.5$. Find its compression ratio.

Solution:

Given: $\eta = 45\%$ $\gamma = 1.5$

To find: r

For an Otto cycle,

$$\eta = 1 - \frac{1}{(r)^{\gamma-1}}$$

$$0.45 = 1 - \frac{1}{(r)^{1.5-1}}$$

$$r = 3.31$$

Problem : 1.6.

In an Otto cycle, condition of air is 27°C and 1 bar at the start of compression. If the clearance colume is 20% of the swept volume, estimate: (i) Temperature at the end of compression and (ii) Air standard efficiency of the cycle.

Solution:

Given: $T_1 = 27^0C = 300\ K$

$p_1 = 1\ bar = 1 \times 10^5\ N/m^2$

$V_2 = 0.20\ (V_1 - V_2)$

To find:

T_2, η

$$V_2 = 0.20\ (V_1 - V_2) = 0.2\ V_1 - 0.2\ V_2$$

$$\text{ie., } 1.2\ V_2 = 0.2\ V_1$$

$$\frac{V_1}{V_2} = \frac{1.2}{0.2} = 6$$

For the adiabatic compression process 1-2,

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

$$\therefore\ T_2 = T_1 \times \left\{\frac{V_1}{V_2}\right\}^{\gamma-1} = 300 \times 6^{1.4-1}$$

$$T_2 = 614.30\ K = 341.30^oC$$

For an Otto cycle,

$$\eta = 1 - \frac{1}{r^{\gamma-1}}$$

$$= 1 - \frac{1}{6^{1.4-1}} = 0.5116$$

$$\eta = 51.16\%$$

Problem : 1.7.

Calculate the ideal air standard thermal efficiency based on the Otto cycle for a petrol engine with a cylinder bore of 50 mm and stroke of 75 mm and a clearance volume of 21.3 cm^3.

Given: D = 50 mm = 5 cm $V_2 = 21.3\ cm^3$ L = 75 mm = 7.5 cm

To find:

η

$$V_1 = V_2 + \frac{\pi D^2}{4} \times L$$

$$= 21.3 + \frac{\pi \times 5^2}{4} \times 7.5 = 168.56\, cm^3$$

$$r = \frac{V_1}{V_2} = \frac{168.56}{21.3} = 7.91$$

$$\eta = 1 - \frac{1}{r^{\gamma-1}}$$

$$= 1 - \frac{1}{(7.91)^{1.4-1}} = 0.5628$$

$$\eta = 56.28\%$$

Problem : 1.8.

In an ideal Otto cycle engine the expansion and compression are adiabatic. The pressure and temperature at the beginning of compression are 1 bar and 35°C respectively. The pressure at the end of compression is 8 bar and at the end of combustion is 20 bar. If the volume at the beginning of compression is 0.03 m³, find the efficiency of Otto cycle.

Solution:

Given: $V_1 = 0.03\ m^3$ $\quad p_2 = 8\ bar = 8 \times 10^5\ N/m^2$

$T_1 = 35^oC = 308\ K$ $\quad p_3 = 20\ bar = 20 \times 10^5\ N/m^2$

$p_1 = 1\ bar = 1 \times 10^5\ N/m^2$

To find: η

For the adiabatic compression process 1-2,

$$\frac{V_1}{V_2} = \left\{\frac{p_2}{p_1}\right\}^{\frac{1}{\gamma}}$$

$$= \left\{\frac{8}{1}\right\}^{\frac{1}{1.4}} = 4.42$$

$$r = 4.42$$

$$\eta = 1 - \frac{1}{r^{\gamma-1}} = 1 - \frac{1}{(4.42)^{1.4-1}}$$

$$\eta = 44.81\%$$

Problem : 1.9.

Find the efficiency of an Otto cycle engine relative to the Carnot cycle using the same maximum pressure 21 bar and temperature 1650°C and the same minimum pressure 1.05 bar and temperature 38°C . Assume working fluid to be air.

Solution:

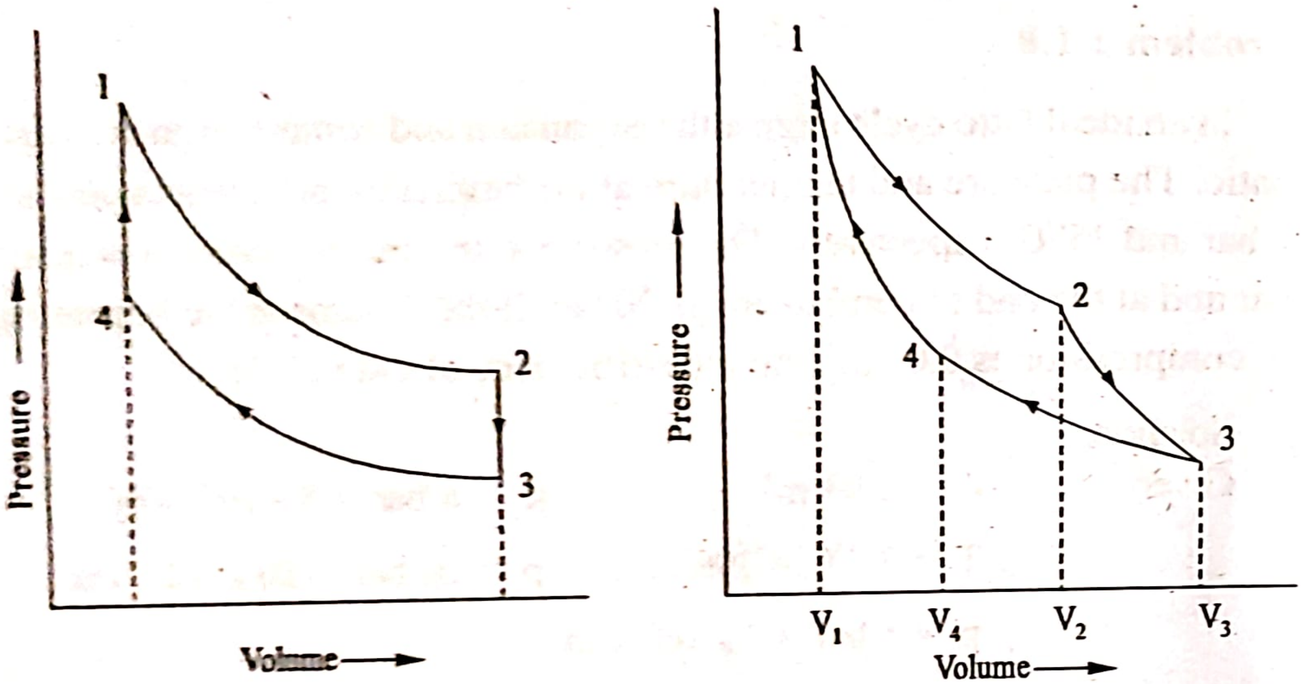


Fig. 1.18.

Given:

$T_1 = 1650°C = 1923$ K $\quad p_1 = 21$ bar $= 21 \times 10^5$ N/m^2

$T_3 = 38°C = 311$ K $\quad p_3 = 1.05$ bar $= 1.05 \times 105$ N/m^2

To find: $\dfrac{\eta(\text{Otto})}{\eta(\text{Carnot})}$

For Otto cycle,

$$\eta = 1 - \frac{1}{(r)^{\gamma-1}}$$

$$r = \frac{V_3}{V_4} = \frac{V_3}{V_1}$$

We have,

$$\frac{p_1 V_1}{T_1} = \frac{p_3 V_3}{T_3}$$

$$\therefore \frac{V_3}{V_1} = \frac{p_1 T_3}{p_3 T_1} = \frac{21\times10^5\times311}{1.05\times10^5\times1923} = 3.23$$

ie., $r = 3.23$

$$\eta = 1 - \frac{1}{(3.23)^{1.4-1}} = 0.3744$$

$$\eta = 37.44\%$$

$$\eta\ (\text{Carnot}) = 1 - \frac{T_3}{T_1}$$

$$= 1 - \frac{311}{1923} = 0.8383$$

$$\eta = 83.83\%$$

$$\frac{\eta(\text{Otto})\times100}{\eta(\text{Carnot})} = \frac{0.3744\times100}{0.8383}$$

$$= 44.66\%$$

Problem : 1.10.

An engine working on the Otto cycle has an air standard efficiency of 56 %. It rejects heat at the rate of 544 kJ per kg of air. The pressure and temperature of air at the beginning of compression are 0.1 MPa and 60°C respectively. Compute,

(i) The compression ratio of the engine

(ii) The work done per kg of air

(iii) The pressure and temperature at the end of compression and

(iv) The maximum pressure in the cycle.

Assume suitable values for C_p and C_v.

Solution:

Given: $\eta = 56\ \%$ $\quad Qr = 544$ kJ/kg,

$p_1 = 0.1$ MPa $= 0.1 \times 10^6$ N/m^2

$T_1 = 60^oC = 60 + 273 = 333$ K

To find : $r, W, p_2\ T_2\ p_3$

$$\eta = 1 \frac{1}{r^{\gamma-1}} = 1 - \frac{1}{r^{1.4-1}}$$

$$0.56 = 1 - \frac{1}{r^{0.4}}$$

$$r^{0.4} = 2.27$$

$$r = 7.76$$

$$\eta = 1 - \frac{Qr}{Qs}$$

$$0.56 = 1 - \frac{544}{Q_s}$$

$$Qs = 1236.36 \text{ kJ/kg}$$

$$\text{Work done} = Qs - Qr$$

$$= 1236.36 - 544$$

$$= 692.36 \text{ kJ/kg}$$

For the adiabatic process 1-2,

$$\frac{p_2}{p_1} = \left\{\frac{V_1}{V_2}\right\}^{\gamma} = r^{\gamma} = 7.76^{1.4} = 17.61$$

$$p_2 = 17.61 \times p_1 = 17.61 \times 0.1 \times 10^6 = 17.61 \times 10^5 \text{ N/m}^2$$

$$\frac{T_2}{T_1} = \left\{\frac{V_1}{V_2}\right\}^{\gamma-1} = r^{\gamma-1} = 7.76^{1.4-1} = 2.27$$

$$T_2 = 2.27\,T_1 = 2.27 \times 333 = 755.91 \text{ K}$$
$$= 482.91^{\circ}\text{C}$$

$$Qs = C_v\,(T_3 - T_2)$$
$$1236.36 = 0.718\,(T_3 - 755.91)$$
$$T_3 = 2477.86 \text{ K}$$

For the constant volume process 2-3,

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

$$p_3 = p_2 \times \frac{T_3}{T_2} = 17.61 \times 10^5 \times \frac{2477.86}{755.91}$$
$$= 57.73 \times 10^5 \text{ N/m}^2$$

Problem : 1.11.

In an air standard Otto cycle the compression ratio is 7 and compression begins at 35°C, 0.1 MPa. The maximum temperature of the cycle is 1100°C. Find,

(i) Heat supplied per kg of air

(ii) Work done per kg of air

(iii) The cycle efficiency and

Take $C_p = 1.005$ kJ/kg K. and $C_v = 0.718$ kJ/kg K

Solution:

Given:

$$r = 7,\ T_1 = 35^{\circ}\text{C} = 35 + 273 = 308 \text{ K}$$
$$p_1 = 0.1 \text{ MPa} = 0.1 \times 10^6 \text{ N/m}^2,$$
$$T_3 = 1100^{\circ}\text{C} = 1100 + 273 = 1373 \text{ K}$$

To find: Qs, W, η

$$Qs = mC_v\,(T_3 - T_2)$$

For adiabatic process 1-2,

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

$$T_2 = T_1 \times 7^{1.4-1}$$

$$= 308 \times 7^{1.4-1} = 670.8 \text{ K}$$

$$Qs = 0.718\,(1373 - 670.8)$$

$$= 504.18 \text{ kJ/kg}$$

$$\frac{T_3}{T_4} = \left(\frac{V_4}{V_3}\right)^{\gamma-1} = (7)^{1.4-1} = 2.18$$

$$T_4 = \frac{T_3}{2.18} = \frac{1373}{2.18} = 629.82 \text{ K}$$

$$W = Qs - Qr$$

$$Qr = mC_v\,(T_4 - T_1) = 1 \times 0.718\,(629.82 - 308)$$

$$= 231.07 \text{ kJ/kg}$$

$$W = Qs - Qr$$

$$= 504.18 - 231.07$$

$$= 273.11 \text{ kJ/kg}$$

$$\eta = \frac{W}{Qs} = \frac{273.11}{504.18} = 0.5417$$

$$= 54.17\ \%$$

Problem : 1.12.

The peak pressure in an Otto cycle is 210 N/cm^2, with a compression ratio of 5 and minimum pressure of 10 N/cm^2, determine the thermal efficiency. Assume the working substance as air with $\gamma = 1.4$.

Solution:

Given:

$p_3 = 210 \text{ N/cm}^2 = 210 \times 10^4 \text{ N/m}^2$

$r = 5,$

$p_1 = 10 \text{ N/cm}^2 = 10 \times 10^4 \text{ N/m}^2$

$\gamma = 1.4$

To find: η

$$\eta = 1 - \frac{1}{r^{\gamma-1}} = 1 - \frac{1}{5^{1.4-1}}$$

$$= 1 - 0.525 = 0.475$$

$$\eta = 47.5\%$$

1.6. Diesel cycle

Diesel cycle is the cycle on which the diesel engine works. Diesel cycle consists of four reversible processes. Heat is supplied at constant pressure and rejected at constant volume. Expansion and compression of air takes place adiabatically. Fig. 1.19 shows these processes on p-V diagram.

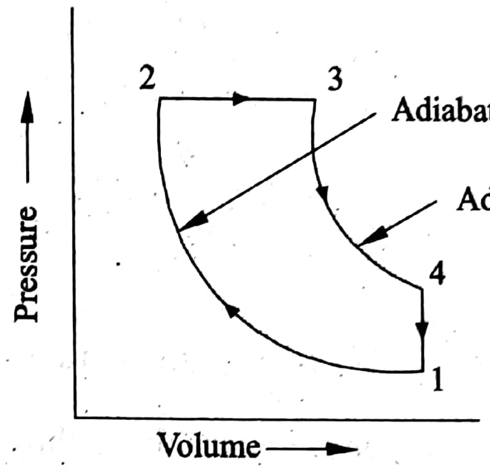


Fig. 1.19. Diesel cycle.

Consider a cylinder containing 'm' kg of air. Let p_1, V_1 and T_1 be the pressure, volume and temperature of air inside the cylinder at state 1. This air is compressed adiabatically to state 2, doing work on the air. Curve 1-2 in the p-V diagram represents this process. Now heat is supplied to the air at constant pressure from an external hot body till state 3 is reached. This process is represented by a horizontal line 2-3 in the p-V diagram. At state 3, the hot body is removed and the air is allowed to expand adiabatically to state 4, doing external work. This process is represented by curve 3-4 in the p-V diagram. Heat is rejected at constant volume to an external cold body till state 1 is reached. This process is represented by a vertical line 4-1 in the p-V diagram. Thus the air finally returns to its original state after completing a cycle.

Heat supplied during constant volume process 2-3 = $m C_p (T_3 - T_2)$.

Heat rejected during constant volume process 4-1 = $m C_v (T_4 - T_1)$.

Air Standard efficiency,

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

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

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

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

Let $\frac{V_3}{V_2}$ be the cutoff ratio ρ, $\frac{V_4}{V_3}$ be the expansion ratio r_1 and $\frac{V_1}{V_2}$ be the compression ratio r. The relation between these three ratios is obtained as follows.

$$\frac{V_4}{V_3} = \frac{V_4}{V_2} \times \frac{V_2}{V_3}$$

$$= \frac{V_1}{V_2} \times \frac{V_2}{V_3}$$

$$r_1 = r \times \frac{1}{\rho} = \frac{r}{\rho}$$

$$r_1 = \frac{r}{\rho}$$

For the adiabatic process 1-2,

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

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

$$T_2 = T_1\, r^{\gamma-1} \quad \text{..............(ii)}$$

For the constant pressure process 2-3,

$$\frac{T_3}{T_2} = \frac{V_3}{V_2} = \rho$$

$$T_3 = T_2 \times \rho$$

$$T_3 = T_1\, r^{\gamma-1} \times \rho \quad \text{............(iii)}$$

For the adiabatic process 3-4,

$$\frac{T_3}{T_4} = \left[\frac{V_4}{V_3}\right]^{\gamma-1} = r_1^{\gamma-1}$$

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

$$T_4 = T_3 \times \frac{\rho^{\gamma-1}}{r^{\gamma-1}}$$

Substituting for T_3 from equation (iii)

$$T_4 = T_1 r^{\gamma-1} \rho \times \frac{\rho^{\gamma-1}}{r^{\gamma-1}}$$

$$T_4 = T_1 \rho^{\gamma} \quad \text{..................(iv)}$$

Substituting the expressions for T_2, T_3 and T_4 in equation (i),

$$\eta = 1 - \frac{1}{\gamma}\frac{T_1\rho^{\gamma} - T_1}{\left(T_1 r^{\gamma-1}\rho - T_1 r^{\gamma-1}\right)}$$

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

The above expression shows that the air standard efficiency of Diesel cycle is a function of compression ratio, cutoff ratio and the ratio of specific heats.

Problem : 1.13.

1 kg of air at temperature of 15°C and pressure of 100 kPa is taken through a Diesel cycle. The compression ratio is 15 and the heat added is 1850 kJ. Calculate the ideal cycle efficiency.

Solution:

Given: $m = 1$ kg $\quad T_1 = 15^{\circ}C = 288$ K

$p_1 = 100$ kPa $\quad$ Q added = 1850 kJ, $\quad r = 15$

To find: η

We have:

$$p_1V_1 = mRT_1$$

$$\therefore V_1 = \frac{mRT_1}{p_1} = \frac{1\times287\times288}{100\times10^3} = 0.827\,m^3$$

Given,

$$\frac{V_1}{V_2} = 15$$

$$\therefore V_2 = \frac{V_1}{15} = \frac{0.827}{15} = 0.055\,m^3$$

For the adiabatic process 1-2,

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

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

$$= 288 \times (15)^{1.4-1} = 850.8\ \text{K}$$

For the constant pressure process 2-3,

$${}_2Q_3 = mC_P\ (T_3 - T_2)$$

$$1850 = 1 \times 1.005 \times (T_3 - 850.8)$$

$$T_3 = 2691.6\ \text{K}$$

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

$$V_3 = V_2 \times \frac{T_3}{T_2}$$

$$= 0.055 \times \frac{2691.6}{850.8} = 0.174\ \text{m}^3$$

$$\text{Cut off ratio } \rho = \frac{V_3}{V_2} = \frac{0.174}{0.055} = 3.16$$

Air standard efficiency,

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

$$= 1 - \frac{1}{1.4(15)^{0.4}}\left\{\frac{(3.16^{1.4} - 1)}{(3.16 - 1)}\right\}$$

$$= 55.15\ \%$$

Problem : 1.14.

Find the percentage loss in the ideal efficiency of a diesel engine with compression ratio 15, by delaying the fuel cut off from 5 to 10 % of the stroke.

Solution:

Given: $r = 15$

Cut off is at $0.05\,(V_1 - V_2)$ and $0.10\,(V_1 - V_2)$

To find : % loss in η when the cut off is delayed from 5 to 10% of stroke volume.

When cut off is at 5 % of stroke volume,

$$V_3 = V_2 + 0.05\,(V_1 - V_2)$$

$$V_1 = 15\,V_2 \text{ (given)}$$

$$\therefore\ V_3 = V_2 + 0.05\,(15\,V_2 - V_2)$$

$$= 1.7\,V_2$$

$$\frac{V_3}{V_2} = 1.7 \text{ ie., } \rho = 1.7$$

$$\eta = 1 - \frac{1}{\gamma r^{\gamma-1}}\,\frac{(\rho^{\gamma} - 1)}{(\rho - 1)}$$

$$= 1 - \frac{1}{1.4\,(15)^{1.4-1}}\,\frac{(1.7^{1.4} - 1)}{(1.7 - 1)}$$

$$\eta = 61.94\%$$

When cut off is at 10% of stroke volume,

$$V_3 = V_2 + 0.1\,(V_1 - V_2)$$

$$= V_2 + 0.1\,(15\,V_2 - V_2) = 2.4\,V_2$$

$$\frac{V_3}{V_2} = 2.4 \quad \text{i.e., } \rho = 2.4$$

$$\eta = 1 - \frac{1}{1.4(15)^{1.4-1}}\left\{\frac{2.4^{1.4}-1}{(2.4)-1}\right\}$$

$$\eta = 58.44\%$$

$$\% \text{ of loss in } \eta = \left\{\frac{61.94 - 58.44}{61.94}\right\} \times 100 = 5.65$$

$$\% \text{ of loss in } \eta = 5.65$$

Problem : 1.15.

An ideal diesel cycle operates on 1 kg of air with an initial pressure of 1 bar and a temperature of 35°C. The pressure at the end of compression is 33 bar and cut off is 6 % of the stroke. Determine (i) the compression ratio (ii) the heat supplied (iii) the heat rejected and (iv) the thermal efficiency.

Solution:

Given:

$m = 1$ kg

$p_1 = 1 \text{ bar} = 1 \times 10^5 \text{ N/m}^2$

$T_1 = 35^\circ C = 308 \text{ K}$

$p_2 = 33 \text{ bar} = 33 \times 10^5 \text{ N/m}^2$

Cut off = 6 % stroke volume

To find :

r, Qs, η, Qr

For the adiabatic process 1-2,

$$\frac{V_1}{V_2} = \left\{\frac{p_2}{p_1}\right\}^{\frac{1}{\gamma}} = \left\{\frac{33}{1}\right\}^{\frac{1}{1.4}} = 12.15$$

$$r = 12.15$$

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

$$T_2 = T_1\left\{\frac{p_2}{p_1}\right\}^{\frac{\gamma-1}{\gamma}} = 308\times\left\{\frac{33}{1}\right\}^{\frac{1.4-1}{1.4}}$$

$$T_2 = 836.4 \text{ K}$$

$$V_3 = V_2 + 0.06\,(V_1 - V_2)$$

$$V_3 = V_2 + 0.06\,(12.15\,V_2 - V_2) = 1.669\,V_2$$

$$\therefore \rho = \frac{V_3}{V_2} = 1.669$$

For the constant pressure process 2-3

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

$$\frac{T_3}{T_2} = \frac{V_3}{V_2} = 1.669$$

$$T_3 = 1.669\times T_2 = 1.669\times 836.4 = 1395.95\text{K}$$

$$\text{Heat supplied} = mC_p\,(T_3 - T_2)$$

$$= 1\times 1.005\,(1395.95 - 836.4)$$

$$\text{Heat supplied} = 562.35 \text{ kJ}$$

$$\eta = 1 - \frac{1}{r^{\gamma-1}}\frac{(\rho^{\gamma}-1)}{\gamma(\rho-1)}$$

$$= 1 - \frac{1}{(12.15)^{1.4-1}}\frac{(1.669^{1.4}-1)}{1.4(1.669-1)}$$

$$\eta = 58.77\ \%$$

$$\eta = 1 - \frac{Q\text{rejected}}{Q\text{supplied}}$$

$$0.5877 = 1 - \frac{Q\text{rejected}}{562.35}$$

$$Q \text{ rejected} = (1 - 0.5877) \times 562.35$$

$$= 231.86 \text{ kJ}$$

Problem : 1.16.

The following data pertains to a Diesel cycle:

Pressure at the suction stroke = 1 bar

Temperature at suction stroke = 300 K

Heat added = 2500 kJ/kg

Compression ratio = 16

Calculate:

(i) Pressure and temperature at each point of the cycle.

(ii) Thermal efficiency

(iii) Power output for air flow rate of 0.6 kg/s

Assume $C_P = 1$ kJ/kg K $\quad C_V = 0.714$ kJ/kg K

Solution:

Given:

$$p_1 = 1 \text{ bar} = 1 \times 10^5 \text{ N/m}^2$$

$$T_1 = 300 \text{ K}, \qquad r = 16$$

$$Qs = 2500 \text{ kJ/kg} \qquad m = 0.6 \text{ kg/s.}$$

$$C_P = 1 \text{ kJ/kg K} \qquad C_V = 0.714 \text{ kJ/kgK}$$

To find: $p_2, T_2, p_3, T_3, p_4, T_4, \eta$, Power.

$$\frac{p_2}{p_1} = \left\{\frac{V_1}{V_2}\right\}^\gamma = r^\gamma$$

$$p_2 = p_1 r^\gamma = 1 \times 10^5 \times 16^{1.4} = 48.5 \times 10^5 \text{ N/m}^2$$

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

$$T_2 = T_1 . r^{\gamma-1} = 300 \times 16^{1.4-1} = 909.43 \text{ K}$$

$$Qs = mC_p (T_3 - T_2)$$

$$2500 = 1 (T_3 - 909.43)$$

$$T_3 = 3409.43 \text{ K}$$

$$p_3 = p_2 = .48.5 \times 10^5 \text{ N/m}^2$$

$$V_4 = V_1 = \frac{RT_1}{p_1} = \frac{287 \times 300}{1 \times 10^5} = 0.861 \text{m}^3\text{/kg}$$

$$V_3 = \frac{RT_3}{p_3} = \frac{287 \times 3409.43}{48.5 \times 10^5} = 0.20 \text{ m}^3\text{/kg}$$

$$\frac{p_4}{p_3} = \left\{\frac{V_3}{V_4}\right\}^{\gamma} = \left(\frac{0.20}{0.861}\right)^{1.4} = 0.129$$

$$p_4 = p_3 \times 0.129 = 48.5 \times 10^5 \times 0.129$$

$$= 6.26 \times 10^5 \text{ N/m}^2$$

$$\frac{T_4}{T_3} = \left\{\frac{V_3}{V_4}\right\}^{\gamma-1} = \left(\frac{0.2}{0.861}\right)^{1.4-1} = 0.558$$

$$T_4 = T_3 \times 0.558 = 3409.43 \times 0.558$$

$$= 1902.46 \text{ K}$$

$$\eta = 1 - \frac{1}{(r)^{\gamma-1}}$$

$$= 1 - \frac{1}{(16)^{1.4-1}} = 0.670$$

$$= 67\ \%$$

$$\text{Workdone} = \eta \times Q_s$$

$$= 0.67 \times 2500 = 1675 \text{ kJ/kg}$$

$$\text{Power} = \text{work done} \times \text{mass flow rate}$$

$$= 1675 \times 0.6$$

$$= 1005 \text{ kW}$$

Problem : 1.17.

In an air standard diesel cycle, the compression ratio is 16 and at the beginning of compression the temperature is 15°C and the pressure is 0.1 MPa. Heat is added until the temperature at the end of the constant pressure process is 1480°C . Calculate

(i) The cut off ratio .

(ii) The heat supplied per kg of air

(iii) The cycle efficiency

Assume $C_P = 1.005$ kJ/kg K and $C_V = 0.718$ kJ/kg K

Solution:

Given:

$$r = 16, \quad T_1 = 15^\circ C = 15 + 273 = 288 \text{ K}$$

$$p_1 = 0.1 \text{ MPa} = 0.1 \times 10^6 \text{ N/m}^2$$

$$T_3 = 1480^\circ \text{ C} = 1480 + 273 = 1753 \text{ K}$$

$$C_P = 1.005 \text{ kJ/kg K}$$

$$C_V = 0.718 \text{ kJ/kg K}$$

To find: ρ, Qs , η

$$\frac{T_2}{T_1} = \left\{\frac{V_1}{V_2}\right\}^{\gamma-1} = (16)^{1.4-1} = 3.03$$

$$T_2 = 3.03 \times T_1 = 3.03 \times 288 = 872.64 \text{ K}$$

$$\text{Cut off ratio } \rho = \frac{V_3}{V_2} = \frac{T_3}{T_2} = \frac{1753}{872.64} = 2$$

$$\rho = 2$$

$$Q_S = C_P (T_3 - T_2)$$

$$= 1.005\,(1753 - 872.64)$$

$$= 884.76 \text{ kJ/kg}$$

$$\eta = 1 - \frac{1}{r^{\gamma-1}} \frac{(\rho^{\gamma} - 1)}{(\rho - 1)\gamma}$$

$$= 1 - \frac{1}{16^{1.4-1}} \frac{(2^{1.4} - 1)}{(2-1)1.4} = 0.6138$$

$$\eta = 61.38\,\%$$

1.7. Comparison of Otto and Diesel cycles for the same compression ratio and heat rejection.

Fig.1.20 shows the Otto and Diesel cycles for the same compression ratio and heat rejection. Here, 1-2-3-4-1 is Otto cycle and 1-2-3'-4-1 is Diesel cycle.

$$\text{Air standard cycle efficiency} = 1 - \frac{\text{Heat rejected}}{\text{Heat supplied}}$$

For the same heat rejection, efficiency will be more when heat supplied is more. Since work done is equal to the difference between heat supplied and heat rejected, for the same heat rejection work done will be more when heat supplied is more. From Fig. 1.20 it is clear that, for the same compression ratio and heat rejection, work done and hence heat supplied is more

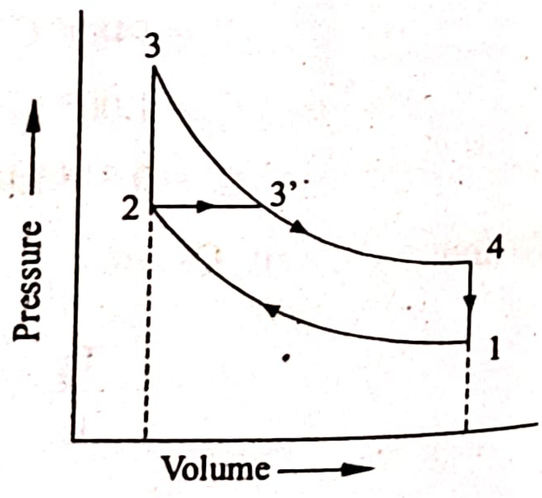


Fig. 1.20

for Otto cycle.

Therefore, η Otto $> \eta$ Diesel

In practice, the compression ratio of diesel engine ranges from 16 to 20 whereas that of Otto engine ranges from 6 to 10. Because of the higher compression ratio the diesel engines generally have higher efficiency than Otto engines.

Problems for practice

Problem 1.

An engine working on ideal Otto cycle has temperature and pressure at beginning of adiabatic compression as 25°C and 15 bar respectively. If $\gamma = 1.4$ and thermal efficiency of the engine is 50%, find its compression ratio. Also find the temperature and pressure at the end of compression. (5.66, 323.55°C, 17.03 bar).

Problem 2.

A certain quantity of air at a pressure of 1 bar and temperature of 70°C is compressed adiabatically until the pressure is 7 bar in an Otto cycle. 320 kJ of heat per kg of air is now added at constant volume. Determine (i) the compression ratio of the engine (ii) the temperature at the end of compression and (iii) the temperature at the end of heat addition. For air $C_P = 1.005$ kJ/kg. K. and $C_V = 0.718$ kJ/kg.K (4.01, 324.79°C, 770.47°C).

Problem 3.

An IC engine working on Otto cycle takes the air in at 0.97 bar a 35°C. The compression ratio is 7. The heat supplied during the cycle is 1.5 MJ/kg. of the working fluid. Determine:

(i) the air standard efficiency

(ii) the maximum temperature attained and

(iii) the work done per kg of working fluid.

Problem 4.

The initial conditions of air in an Otto cycle are 30°C and 1.1 bar. The air is compressed to a pressure of 12.5 bar. Then heat is added till the pressure becomes 35 bar. Determine:

(i) Compression ratio.

(ii) Air standard efficiency.

Problem 5.

An ideal Diesel cycle operates on 1 kg. of standard air with an initial pressure of 0.01 N/mm^2 and a temperature of 35°C. The pressure at the end of compression is 3.5 N/mm^2 and cut-off is 6% of the stroke. Determine

(i) the compression ratio

(ii) the percentage clearance

(iii) the heat supplied

(iv) the heat rejected

1.8. IC Engines

A device which transforms one form of energy into another form is called an engine. An engine which converts thermal energy into mechanical energy is called heat engine. Heat engine transforms the chemical energy of a fuel into thermal energy and this thermal energy is converted into mechanical energy to perform useful work. Heat engines can be broadly classified into two categories.

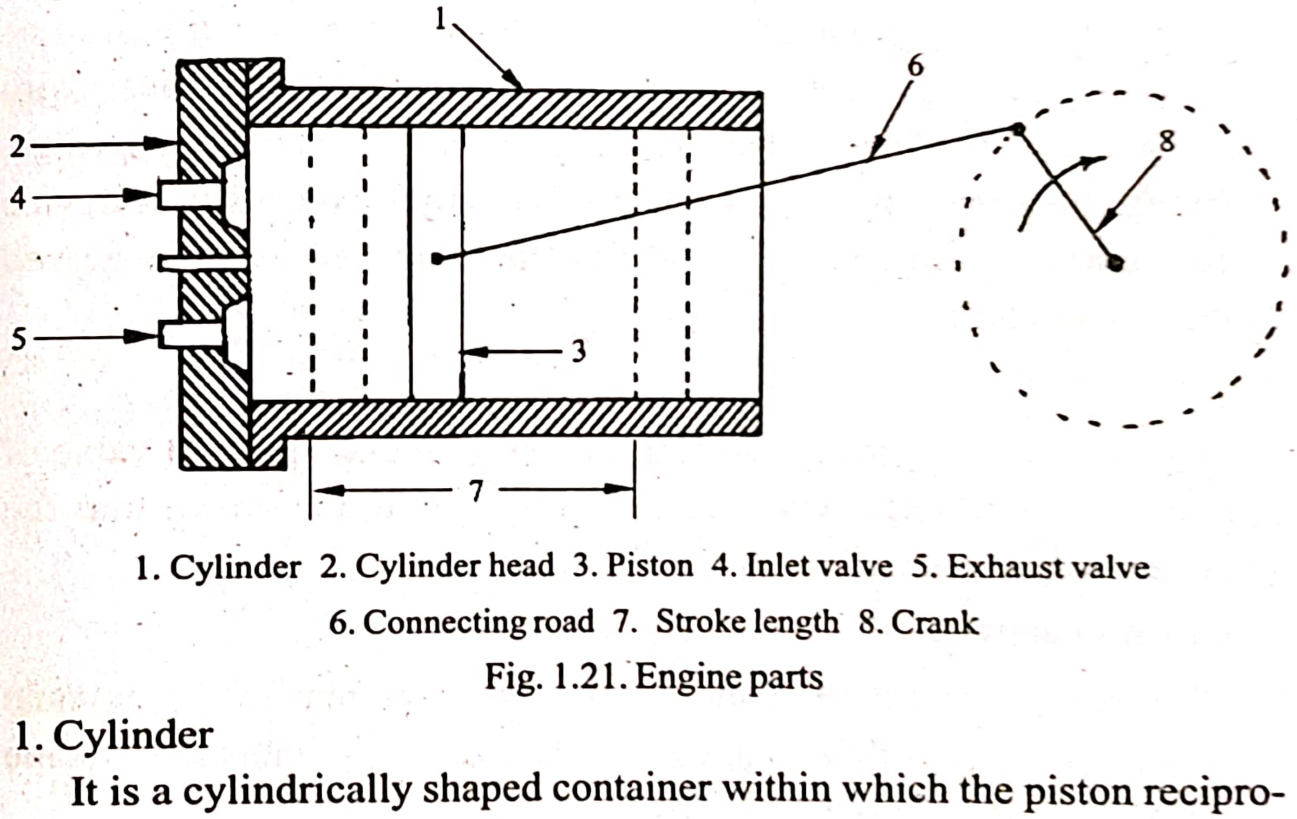
(i) External combustion engines (EC engines)

(ii) Internal combustion engines (IC engines)

In an external combustion engine, a working fluid is used for transferring the heat of combustion to the engine where the heat of combustion is converted into mechanical energy. Steam engines and steam turbines are common examples of this category. As these engines require big boilers and bulky heat exchangers, this type of engines are not generally desirable for mobile power plants. In an internal combustion engine air is taken from the atmosphere and the combustion of fuel and air occurs in the engine which converts thermal energy into mechanical energy. This eliminates the need for heavy and bulky devices such as boilers and heat exchangers. Also high thermal efficiencies can be achieved in internal combustion engines. These factors give rise to the wide use of internal combustion engines for mobile power plants such as those used in automobiles, ships and slow speed aircrafts.

1.9. Parts of IC engines

The following are the major parts of internal combustion engine. Refer Fig. 1.21.



1. Cylinder 2. Cylinder head 3. Piston 4. Inlet valve 5. Exhaust valve 6. Connecting road 7. Stroke length 8. Crank

Fig. 1.21. Engine parts

1. Cylinder

It is a cylindrically shaped container within which the piston reciprocates. The cylinder is closed by the cylinder head at one end and the other end is covered by the moving piston. Combustion of fuel takes place inside the cylinder and power is developed.

2. Cylinder head

It is a cast iron piece bolted to one end of the cylinder. It acts as a cover to close the cylinder. It contains provisions for placing inlet and exhaust valves. In petrol engines, it houses a spark plug for igniting fuel air mixture. In diesel engines, it houses a fuel injector for injecting the fuel into the cylinder.

3. Piston

It is a close fitting member which reciprocates inside the engine cylinder. The gas tight compartment which serves as the combustion chamber is formed between the cylinder head and the piston. The main function of the piston is to transmit the force exerted by the high pressure gas to the connecting rod. It is shaped like an inverted cup and is generally made of aluminium alloy.

4. Inlet and exhaust valves

These are valves provided in the cylinder head for the admission of fresh air into the engine cylinder and for the rejection of burnt gases from the engine cylinder. These valves are usually kept closed by valve springs. Openings of these valves are made mechanically by means of a device called cam. The cam is keyed to a shaft called camshaft which is geared to the engine shaft.

5. Inlet manifold

The metal tube which connects the intake system to the inlet valve of the engine and through which air or air fuel mixture is drawn into the cylinder is called inlet manifold.

6. Exhaust manifold

The metal tube which connects the exhaust system to the exhaust valve of the engine and through which the product of combustion escape is called exhaust manifold.

7. Connecting rod

It is the element which interconnects the piston and the crank. Connecting rod transmits the gas force from the piston to the crank shaft and transforms the reciprocating motion of piston inside the cylinder into rotary motion of the crank.

8. Crank

It is a rotating member which receives power from the connecting rod and transmits to the crank shaft.

9. Flywheel

It is a heavy wheel mounted on the crank shaft. Its main function is to maintain the angular velocity of crank shaft fairly constant.

Additional parts for petrol engines

1. Carburetor

Carburetor is used to discharge into the air stream the desired quantity of liquid fuel to produce a homogeneous air - fuel mixture. A good carburetor must produce automatically the desired air-fuel ratio at all speeds and loads of the engine. The basic principle used in carburetor is that when a volatile fuel is placed in the passage of high velocity air, the fuel gets vapourised at a faster rate.

2. Low pressure fuel pump

As high pressure is not required to pump the fuel in petrol engines, a low pressure fuel pump is used to pump fuel from the fuel storage tank to the carburetor.

3. Spark Plug

The spark plug provides the required air gap between two electrodes to generate a spark to ignite the fuel-air mixture in the cylinder.

Additional parts for diesel engines

1. Fuel injector

It is used to inject fuel into the cylinder in the form of fine spray.

2. High pressure fuel pump

It is used to supply measured quantity of fuel at high pressure to the injector.

Nomenclature

The following are the various nomenclatures used in internal combustion engines

1. Cylindrical Bore

The inside diameter of cylinder is called cylinder bore.

2. Top Dead Centre (TDC) or Inner Dead Centre (IDC)

The extreme position of the piston at the top of the cylinder is the top dead centre (TDC). In the case of horizontal engines it is known as inner dead centre (IDC)

3. Bottom Dead Centre (BDC) or Outer Dead Centre (ODC)

The position of the piston when it is farthest from the top of the cylinder is the bottom dead centre (BDC). In horizontal engines, it is known as outer dead centre (ODC)

4. Stroke

The travel of the piston from one dead centre to the other is called stroke. The distance between the two dead centres is called the stroke length.

5. Swept volume

The volume of the cylinder in between the two dead centres is the swept volume. It is denoted by Vs.

6. Clearance volume

The volume of the cylinder in between the top dead centre and the cylinder head is the clearance volume. It is denoted by Vc.

7. Compression ratio

The ratio of the volume of the cylinder between the bottom dead centre and the cylinder head to the clearance volume is the compression ratio of the engine. It is denoted by 'r'

1.10. Classification of IC engines

IC engines may be classified in many ways based on the criterion selected for classification.

A. Based on the ignition system

According to the ignition system employed for igniting the charge in the engine cylinder, IC engines are classified as,

i) Spark Ignition (SI) engines : in which an electric spark is used for igniting the fuel air mixture. Most of the engines using petrol or gaseous fuel belong to this category.

ii) Compression Ignition (CI) engines : in which air is compressed to a very high temperature and pressure and fuel is injected to it in the form of a spray. The fuel gets ignited due to the high temperature of the compressed air. Most of the engines using diesel as fuel belong to this category.

B. Based on the type of fuel used

i) Gas engines : in which gaseous fuel such as methane is used as the main fuel.

ii) Petrol engines : in which highly volatile liquid fuel such as petrol is used .

iii) Diesel engines: in which less volatile liquid fuel such as diesel oil is used.

iv) Dual - fuel engines: in which a gaseous fuel or a highly volatile liquid fuel is supplied along with air during the suction stroke and a viscous liquid fuel is injected into the combustion space near the end of the compression stroke.

C. Based on the working cycle.

i) Otto engine : in which the engine works based on the Otto cycle (constant volume cycle). Most of the petrol and gas engines work on this cycle.

ii) Diesel engine: in which the engine works based on the diesel cycle. Most of the low speed oil engines work on this cycle.

iii) Dual combustion engine: in which the engine works on the dual combustion cycle. Most of the high speed oil engines work on this cycle.

D. Based on the number of strokes per cycle

i) Four stroke engines : in which one cycle of operation is completed in four strokes of the piston. ie., one power stroke is obtained in four strokes of the piston ie., in two revolutions of the crank shaft.

ii) Two stroke engines : in which one cycle of operation is completed in two strokes of the piston, giving one power stroke per two strokes of the piston ie., in each revolution of the crank shaft.

E. Based on the application of the engine

i) Stationary engines: which are used in power plants.

ii) Mobile engines: which are used in automobiles, aircrafts, etc.

F. Based on the cooling system

i) Air cooled engines : in which heat is directly dissipated into the air around the cylinder.

(ii) Water cooled engines : in which excess heat is removed from the engine cylinder and cylinder head by circulating water through the jackets provided in the engine cylinder and cylinder head

G. Based on the speed of the engine

i) Low speed engines (up to 350 rpm)

ii) Medium speed engines (350 - 1000 rpm)

iii) High speed engines (above 1000 rpm)

H. Based on the number of cylinders

i) Single cylinder engines: in which there is only one cylinder in an engine.

ii) Multi cylinder engines: in which there are more than one cylinder in an engine.

I. Based on the cylinder arrangement

i) Vertical engine: in which the axis of the cylinder is vertical

ii) Horizontal engine : in which the axis of the cylinder is horizontal

iii) In - line engine : in which all the cylinders are arranged linearly transmitting power to a single crankshaft.

iv) V- engine : in which two cylinders are kept at an angle forming the shape of the letter 'V' and utilise the same crankshaft.

v) Radial engine: in which the cylinders are placed radially and equally spaced around a common crankshaft.

vi) Opposed cylinder engine: in which two cylinders are placed on opposite sides of a common crank

1.11. Working principle of diesel engines (Compression Ignition engines)

Diesel engine is based on the work of Rudolph Diesel. It operates based on the theoretical air cycle known as Diesel cycle. These engines operate on four stroke or two stroke cycle.

Diesel cycle (Constant pressure cycle)

Atmospheric air is drawn into the engine cylinder during the suction stroke and is compressed by the piston during the compression stroke to high pressure and temperature. The temperature of compressed air will be above the ignition temperature of fuel. Just before the end of the compression stroke a metered quan-

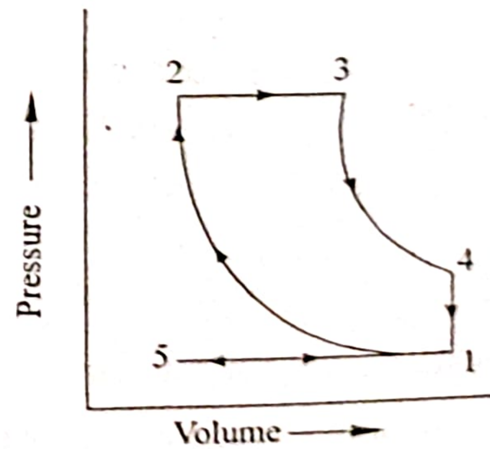
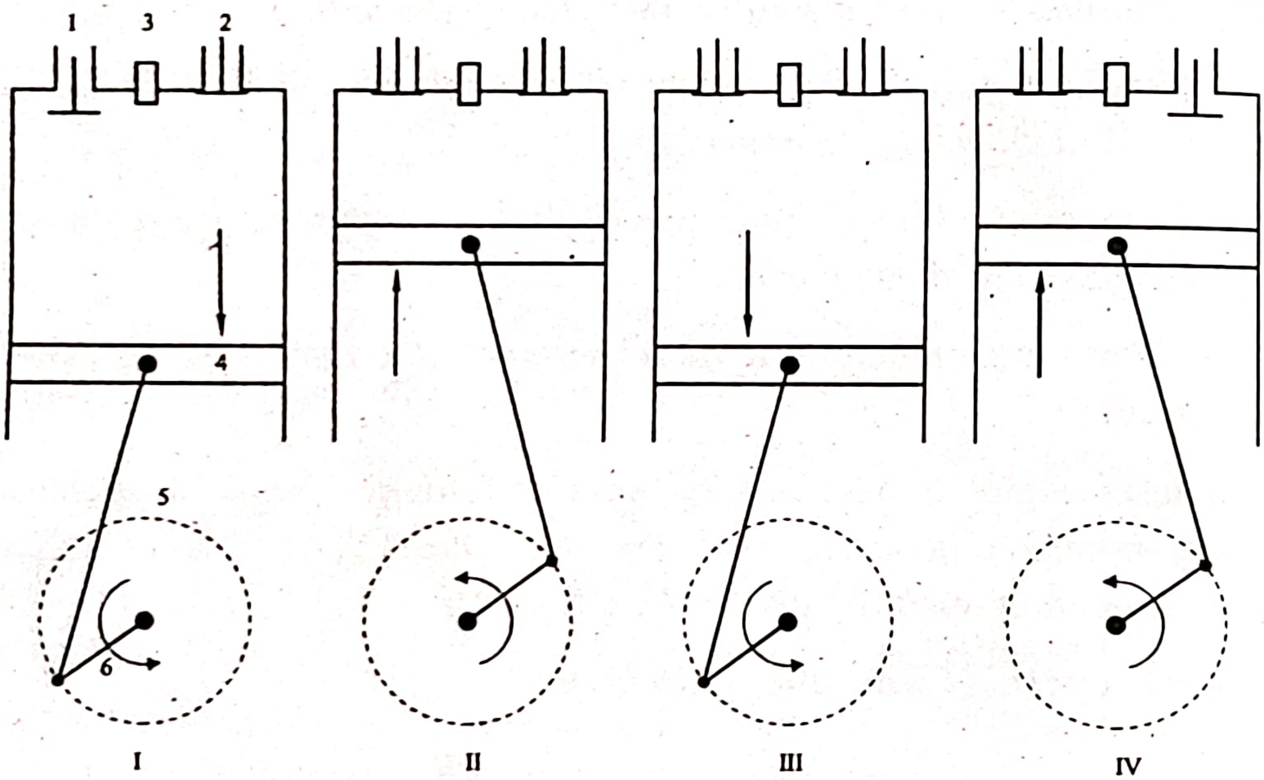


Fig. 1.22. Diesel cycle

tity of fuel under pressure is injected in the form of fine spray by means of a fuel injector. Due to very high pressure and temperature of the air the fuel ignites and the gases expand displacing the piston. After doing work on the piston the burnt gases escape from the engine cylinder through the exhaust valve. As the ignition takes place due to heat of compressed air, it is called compression ignition engine (CI engine).

1.12. Working of four stroke diesel engine

In four stroke cycle engine one cycle of operation is completed in four strokes of the piston (ie., two revolutions of crank shaft) . The various strokes of a four stroke diesel engine are detailed below. Refer Fig. 1.23.



I. Suction stroke II. Compression stroke III. Working stroke IV. Exhaust stroke

1. Inlet valve 2. Exhaust valve 3. Fuel Injector 4. Piston 5. Connecting rod 6. Crank

Fig. 1.23. Working of four stroke diesel engine

1. Suction stroke

During this stroke the piston moves from top dead centre (TDC) to bottom dead centre (BDC). The inlet valve opens and air at atmospheric pressure is drawn into the engine cylinder. The exhaust valve remains closed. This operation is represented by the line 5-1 in Fig. 1.22.

2. Compression stroke

In this stroke the piston moves towards TDC and compresses the enclosed air to high temperature and pressure. This operation is represented by line 1-2 in Fig. 1.22. Both the inlet and exhaust valves remains closed during this stroke.

3. Expansion or working stroke.

Towards the end of compression stroke a metered quantity of fuel is injected into the hot compressed air in the form of fine spray by means of a fuel injector. The fuel starts burning, theoretically, at constant pressure and pushes the piston from TDC. This is shown by line 2-3 in Fig. 1.22. At point 3, fuel supply is cut off. The high pressure gas in the cylinder expand upto point 4, doing work on the piston. The inlet and exhaust valves remain closed during this stroke. At the end of this stroke the exhaust valve opens.

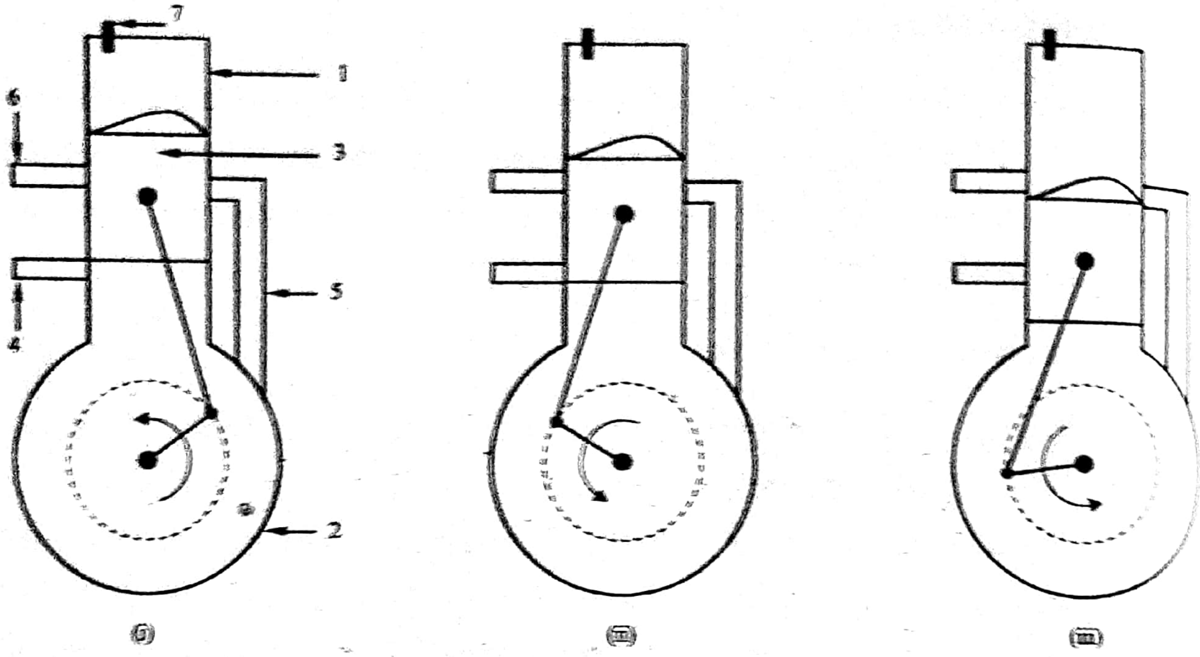
4. Exhaust stroke

The piston moves from BDC to TDC and the burnt gases escape through the exhaust valve. During this stroke the inlet valve remains closed. This stroke is represented by the line 1-5 in Fig. 1.22. During this stroke the exhaust valve remains opened and the inlet valve remains closed. By this one cycle is completed.

1.13. Working of two stroke diesel engine.

In two stroke diesel engine, one cycle of operation is completed in two strokes of the piston, (in one revolution of the crankshaft) by eliminating separate suction and exhaust strokes. Here ports are provided in place of valves.

Fig. 1.24. shows the working of a two stroke diesel engine. The cylinder is connected to a closed crankcase. During the upward stroke of the piston, the air in the cylinder is compressed. At the same time fresh air enters the crank case through the air inlet port. Fig. 1.24 (i). Towards the end of this stroke fuel is introduced in the form of fine spray by the fuel



1. Cylinder 2. Crank case 3. Piston 4. Air inlet port 5. Transfer port 6. Exhaust port 7. Fuel Injector

Fig. 1.24. Working of two stroke diesel engine

injector and due to the high pressure and temperature of the air, the fuel starts burning. The piston, then travels downwards due to the expansion of the gases (Fig. 1.24 (ii)) and near the end of this stroke the piston uncovers the exhaust port and the burnt gases escape through this port. The transfer port is then uncovered (Fig. 1.24 (iii)) and the compressed air from the crankcase flows into the cylinder. The incoming fresh air helps to remove the burnt gases from the engine cylinder.

1.14. Working principle of petrol engines. (Spark Ignition engines)

Petrol engines operate on the so called Otto cycle. These engines work based on either four stroke or two stroke cycle.

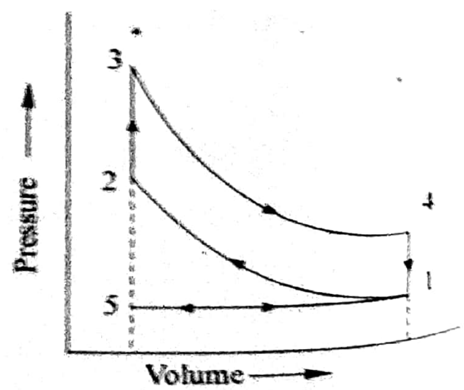


Fig. 1.25. Otto cycle

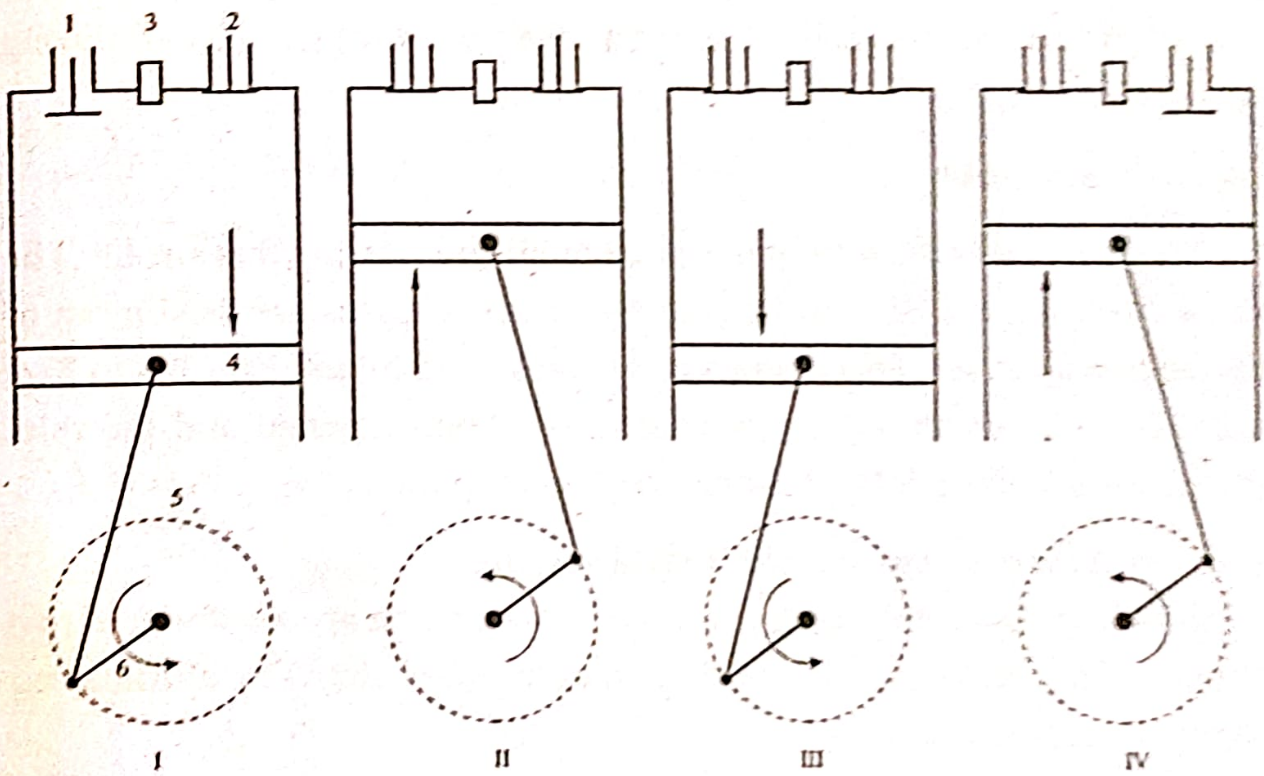
Otto cycle (Constant volume cycle)

In this cycle, heat is supplied and rejected at constant volume. A homogeneous mixture of air and petrol is supplied to the engine cylinder during the suction stroke.

A carburetor provides a mixture of petrol and air in the required proportion. The fuel air mixture (charge) gets compressed during the compression stroke. At the end of this stroke, fuel is ignited and combustion occurs at constant volume. thus heat is supplied at constant volume. The gas expands and moves the piston downwards, doing work. The product of combustion is exhausted at constant volume.

1.15. Working of four stroke petrol engine

The various strokes of a four stroke petrol engine are detailed below. Refer Fig. 1.26



I. Suction stroke II. Compression stroke III. Working stroke IV. Exhaust stroke

1. Inlet valve 2. Exhaust valve 3. Spark plug 4. Piston 5. Connecting rod 6. Crank

Fig. 1.26. Working of four stroke petrol engine

(i) Suction stroke

During this stroke the piston moves from top dead centre (TDC) to bottom dead centre (BDC). The inlet valve opens and the fuel air mixture is sucked into the engine cylinder. The exhaust valve remains closed throughout this stroke . This is represented by the line 5-1 in Fig. 1.25.

(ii) Compression stroke

The air fuel mixture is compressed as the piston moves from BDC to TDC. Just before the end of this stroke, the spark plug initiates a spark which ignites the mixture and combustion takes place at constant volume (line 2-3 in Fig. 1.25). Both the inlet and exhaust valves remains closed throughout this stroke.

(iii) Expansion or working stroke.

As the fuel air mixture burns, hot gases are produced which drive the piston towards BDC and thus work is done . This expansion process is shown by the line 3-4 in Fig. 1.25. Both the valves remain closed during this stroke.

(iv) Exhaust stroke

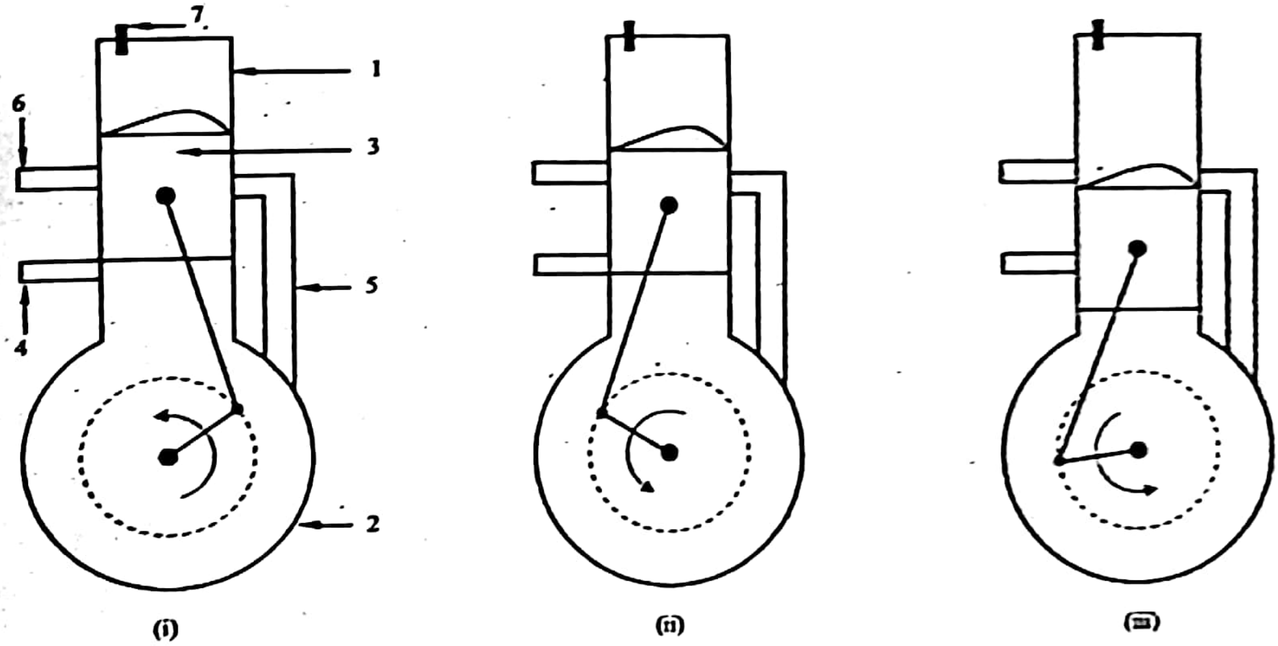
The removal of the burnt gases is accomplished during this stroke. The piston moves from BDC to TDC and the exhaust gases are driven out of the engine cylinder. This operation is represented by the line 1-5 in Fig. 1.25. During this stroke the exhaust valve remain opened and the inlet valve remains closed. By this one cycle is completed.

1.16. Working of two stroke petrol engine

In two stroke petrol engine, one cycle of operation is completed in two strokes of the piston, (in one revolution of the crankshaft) by eliminating separate suction and exhaust strokes.

Fig. 1.27 shows the working of a two stroke petrol engine. The cylinder is connected to a closed crankcase. During the upward stroke of the piston, the air fuel mixture in the cylinder is compressed. At the same time fresh air - fuel mixture enters the crank case through the inlet port. Fig. 1.27 (i) . Towards the end of this stroke, the fuel air mixture is ignited using an electric spark from the spark plug.

The piston, then travels downwards due to the expansion of the gases (Fig. 1.27 (ii)) and near the end of this stroke the piston uncovers the exhaust port and the burnt gases escape through this port. The transfer port is then uncovered (Fig. 1.27 (iii)) and the compressed air fuel mixture from the crankcase flows into the cylinder. The incoming fresh air fuel mixture helps to remove the burnt gases from the engine cylinder. Refer Fig. 1.27. In a two stroke petrol engine the operations are the same as that of a two stroke diesel engine with some difference. In this engine, fuel- air mixture is admitted into the crank case and compressed. A carburetor is used for mixing the fuel and air in the correct proportion. For the ignition of the fuel air mixture at the end of compression in the engine cylinder, a spark plug is provided. In this case, combustion process is assumed to take place at constant volume.



1. Cylinder 2. Crank case 3. Piston 4. Air inlet port 5. Transfer port 6. Exhaust port 7. Spark plug

Fig. 1.27. Working of two stroke petrol engine

1.17. Comparison of SI and CI engines

1. Working cycle

The SI engine, in general, works based on Otto cycle while the CI engine, in general, works based on Diesel cycle.

2. Fuel

A highly volatile fuel such as petrol is used in SI engines while non- volatile fuel such as diesel is used in CI engines.

3. Method of fuel introduction

In most of the SI engines, the fuel and air are introduced into the engine cylinder as a gaseous mixture while in CI engines, the fuel is directly introduced into the cylinder in the form of fine spray. Mixing of fuel and air takes place inside the cylinder.

4. Method of fuel ignition

The SI engine requires a spark to initiate combustion while CI engine utilizes the condition of high temperature and pressure, produced by the compression of air in the cylinder, to initiate combustion when fuel is injected.

5. Fuel economy

CI engines have better fuel economy at all operating conditions.

6. Compression ratio

Compression ratio of SI engines range from 6 to 10, whereas that of CI engines range from 16 to 20. The higher compression ratio of CI engines result in higher thermal efficiency and hence a greater power output for the same amount of fuel consumed.

7. Weight

Because of the higher compression ratio and higher pressure , CI engines require stronger engine parts and hence are heavier.

8. Initial cost

Initial cost of a SI engine is less than a comparable CI engine.

9. Maintenance costs

The maintenance costs of the two types of engines are generally about the same, with CI engine costs slightly higher.

1.18. Comparison of two stroke and four stroke engines

1. In a two stroke engine, there is one working stroke for every revolution of the crank shaft whereas in a four stroke engine there is only one power stroke for two revolutions of the crank shaft. Hence, theoretically, the power developed in two stroke engine will be double that of a four stroke engine of the same dimensions. However in practice, only about 30 percent extra power is developed. That is, in order to produce the same amount of power, a two stroke cycle engine will be of less weight and occupies less space.

2. As there is one working stroke in every revolution of the crank shaft, the turning moment of a two stroke engine will be more uniform.

3. As there is no valves in a two stroke engine the construction will be simple and hence low initial cost. The maintenance of the engine will also be easy. The mechanical efficiency will be higher.

4. As there is no separate exhaust stroke in a two stroke engine the scavenging will be poor. Due to this, the fresh charge gets diluted with exhaust gases and the thermal efficiency decreases. Also there is possibility of the fresh charge escaping with the exhaust. This will increase the fuel consumption.

5. The separate exhaust and intake strokes of the four stroke cycle provide greater opportunity for the dissipation of heat from critical parts like piston, and essentially permit the four stroke cycle engine to run at higher speed than two stroke cycle engine.

6. In two stroke engine the power needed to operate suction and exhaust valves is saved.

7. The construction of combustion chamber is simple in a two stroke engine compared to four stroke engine.

1.19. Mean effective pressure (mep)

The variations of pressure versus volume inside the cylinder of a reciprocating engine is drawn using an engine indicator. The resulting closed contour is called indicator diagram. The area enclosed by the contour is a measure of the work done per cycle.

Mean effective pressure (mep) is defined as the constant pressure acting on the piston which will produce the same amount of work as done by the actual varying pressure acting on the piston during a cycle.

The height of rectangle 1-2 -3-4 as shown in Fig. 1.28 will be the mep provided the area of the rectangle 1-2-3-4 is equal to the area of the indicator diagram. Since the area of indicator diagram gives the work done during a cycle,

$$\text{mep} \times (V_1 - V_2) = \text{Work done/ cycle}$$

$$\therefore \text{ mep} = \frac{\text{Work done / cycle}}{V_1 - V_2} = \frac{\text{Work done / cycle}}{\text{swept volume}}$$

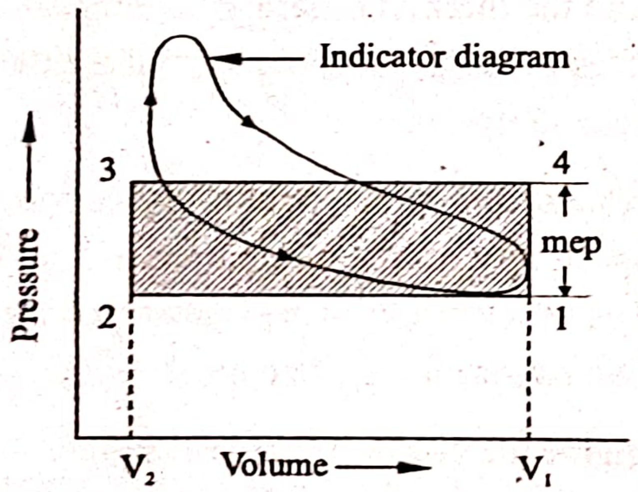


Fig. 1.28

Unit of mep is N/m^2. Mean effective pressure is used as a parameter to compare the performance of reciprocating engines of the same size

1.20. Efficiencies of IC engines.

Power developed inside the cylinder, calculated using the indicator diagram (actual p-V diagram) is known as indicated power (IP) of the engine. The power available at the crank shaft is less than that developed in the cylinder due to various frictional losses. This power available at the crank shaft is called brake power (BP) of the engine. The difference of IP and BP is called friction power (FP).

$$FP = IP - BP$$

$$IP = BP + FP$$

Brake power of an engine can be measured by dynamometer in the laboratory. Indicated power can be calculated as follows:

When,

p_m = mean effective pressure in kN/m^2

A = area of piston in m^2

L = stroke length in m

N = speed of crank shaft in rpm

n = number of working stroke per minute

$= N$, for two stroke engine and

$= \frac{N}{2}$, for four stroke engine.

$$\text{then, } IP = p_m\, A\, L \times \frac{n}{60}\ kW$$

Thermal energy supplied per second can be calculated as follows,

When, m is the mass of fuel burnt per hour and CV is the calorific value of fuel in kJ/kg.

Then, Thermal energy $= m \times CV \times$ kJ/hr

$$= m \times CV \times \frac{1}{3600} \text{ kJ/s}$$

$$= \frac{m \times CV}{3600} \text{ kW}$$

The various efficiencies of IC engines are:

1. Mechanical efficiency
2. Indicated thermal efficiency
3. Brake thermal efficiency
4. Relative efficiency
5. Volumetric efficiency
6. Combustion efficiency

1. Mechanical efficiency

It is the ratio of brake power to indicated power

$$\eta_{mech} = \frac{BP}{IP}$$

2. Indicated thermal efficiency

It is the ratio of indicated power to the energy supplied by the fuel.

$$\text{Indicated thermal efficiency, } \eta = \frac{IP}{m \times CV \times \frac{1}{3600}}$$

$$= \frac{IP \times 3600}{m \times CV}$$

3. Brake thermal efficiency

It is the ratio of brake power to the energy supplied by the fuel

$$\text{Brake thermal efficiency, } \eta = \frac{BP}{m \times CV \times \frac{1}{3600}}$$

$$= \frac{BP \times 3600}{m \times CV}$$

4. Relative efficiency

It is the ratio of indicated thermal thermal efficiency to the theoritical thermal efficiency. Theoritical thermal efficiency is the thermal efficiency when the power developed inside the cylinder is calculated based on theoritical pV diagram.

$$\eta_{\text{relative}} = \frac{\text{Indicated thermal } \eta}{\text{Theoritical thermal } \eta} = \frac{\text{Indicated thermal } \eta}{\text{Air standard efficiency}}$$

5. Volumetric efficiency

it is the ratio of actual volume of air or air fuel mixture admitted into the cylinder to the swept volume of cylinder.

$$\eta_{\text{volumetric}} = \frac{\text{Actual volume of air or charge admitted into the cylinder}}{\text{swept volume of cylinder}}$$

Swept volume of cylinder $= \frac{\pi D^2}{4} \times L$, where D is the diameter of cylinder and L is the stroke length.

6. Combustion efficiency

Hundred percent of chemical energy of fuel admitted into the cylinder cannot be converted to thermal energy. This is mainly due to the incomplete combustion of fuel inside the cylinder. Combustion efficiency is the ratio of actual heat energy liberated to the heat energy in the fuel admitted into the cylinder.

$$\eta_{combustion} = \frac{\text{Actual amount of heat energy liberated}}{\text{Heat energy of fuel admitted into the cylinder}}$$

1.21. Air system for petrol engine

Air system for petrol engine essentially consists of air filter and carburetor. For burning of fuel, oxygen is required. In internal combustion engine oxygen is obtained from the atmospheric air. Air after cleaning in the air filter is mixed with fuel in correct ratio using a carburetor. For complete combustion, the air - fuel ratio must be about 15:1 by weight. There is a range of air - fuel ratio within which combustion of fuel can occur. This range of air - fuel ratio is approximately 8:1 to 20:1 by weight. Outside this range the mixture is either

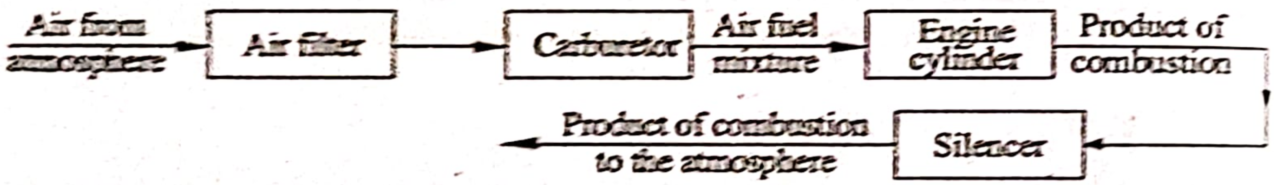


Fig. 1.29. Air system for petrol engine.

too rich or too lean. The carburetor provides air fuel mixture in the required ratio in accordance with the requirements of the engine. At the time of starting of the engine a rich mixture, about 10:1 is required. During normal running a comparatively lean mixture, 15:1, serves the purpose. During acceleration period a rich mixture is needed. This air fuel mixture is supplied to the engine cylinder through the inlet valve. Inside the cylinder, the mixture is burned and there by the chemical energy of fuel is converted into thermal energy. The product of combustion, after expanding, is discharged to the atmosphere. Generally a silencer or muffler is used to reduce the noise.

1.22. Fuel system for petrol engine

Fuel supply system for a petrol engine consists of a fuel storage tank, fuel pump, filter, carburetor, and inlet manifold from where the fuel enters the engine cylinder through inlet valve.

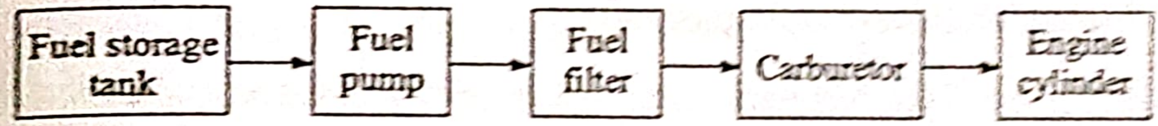


Fig. 1.30. Fuel supply system for petrol engine.

The fuel can be supplied to the engine either under gravity or using a pump. In the gravity system, the fuel storage tank is placed at a higher level than the carburetor so that the fuel flows to the carburetor under gravity. When storage tank is kept below the level of carburetor fuel pump is required to force the fuel to the carburetor.

1.23. Fuel system for diesel engines

Fuel supply system for diesel engine consists of a fuel storage tank, filter, low pressure or transfer pump, high pressure fuel pump and fuel injector.

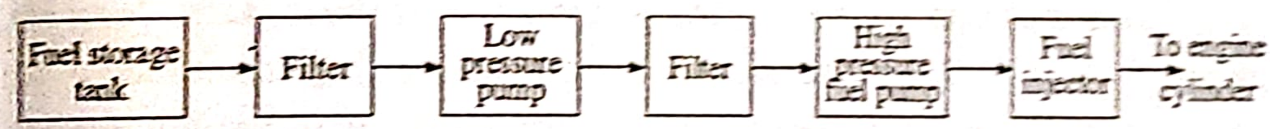


Fig. 1.31. Fuel supply system for diesel engine

The main parts of this system are fuel pump and fuel injector. The fuel is supplied at very high pressure from the fuel pump to the fuel injector and is injected to the engine cylinder towards the end of compression stroke. There are two types of injection systems . (i) Air injection (ii) Solid injection

Air injection

In this method, fuel is forced into the cylinder by means of compressed air. This method is obsolute these days as it requires multistage air compressor which increases the engine weight and cost. Moreover the compressor consumes about 10% of the power developed by the engine and hence the output of the engine is reduced .

Solid injection (Mechanical injection)

In this method a fuel pump is used to supply measured quantity of fuel at high pressure to the injector. The injector injects the fuel at a very high velocity into the engine cylinder in the form of fine spray.

1.24. Cooling system

The entire heat generated by the combustion of the fuel inside the cylinder cannot be converted into work. An IC engine at the best can convert only about 30% of heat into work. About 30% of heat generated is absorbed by the piston, cylinderhead and the cylinder wall. If the heat absorbed by the engine parts is not removed it will cause excessive rise in temperature of these parts.The temperature of the cylinder wall should not exceed 250°C. At high temperature the piston will expand and it will seize with the cylinder wall. Hence the engine parts must be provided with some means of cooling so that the temperature of these parts does not exceed about 250°C. Therefore a cooling system is required to keep the engine parts from getting too hot yet permit the engine to run hot enough to ensure maximum overall efficiency. Thus the purpose of cooling system is to keep the engine parts from getting too hot and not to keep the engine parts cool.

The two types of cooling systems normally used in IC engines are,

(1) Air cooling and

(2) Liquid cooling (water cooling)

Air cooling

The cooling method in which heat is directly dissipated into the air around the cylinder is called air cooling. The basic principle involved in this type of cooling system is to have a current of air flowing continuously over the heated surface from where the heat is to be removed. It is used in motor cycles, airplane engines and small stationary engines. In this type, heat is dissipated directly to the air after being conducted through the cylinder walls. Usually, fins are provided on the outer surface of the cylinder and cylinder head to increase the area exposed to the cooling air. In some cases, a blower is fitted which throws air on these fins to increase the heat transfer rate. This is shown in Fig. 1.32. In mobile engines, the forward velocity of the engine helps in increasing the air velocity.

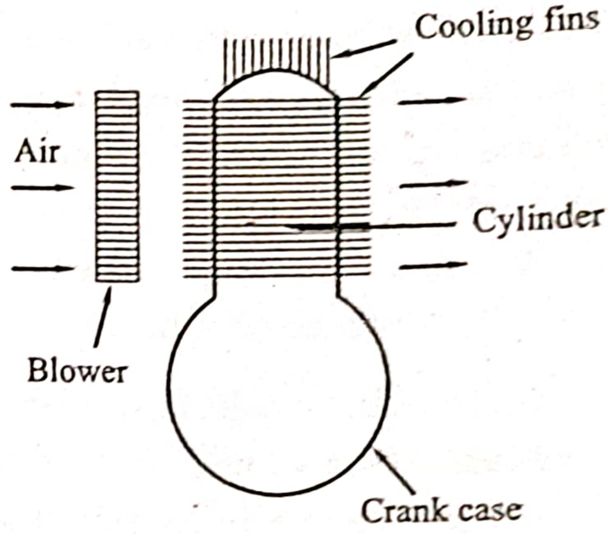


Fig. 1.32. Air cooled engine

The advantages of air cooling includes simplicity, lightness, cheapness and absence of water and its circulation system. The main disadvantage of this system is the non uniformity in cooling. Also, it is difficult to control the cooling rate.

Liquid cooling (water cooling)

In liquid cooling water is generally used as the cooling medium. It is circulated through passages around the main components which are getting heated. These passages are called water jackets. The circulation of water is obtained either by using a pump or by gravity force.

Fig. 1.33 shows water cooling system used in an automobile engine. In this, the water after passing through the engine jackets flows to a radiator. In the radiator the heated water gets cooled by an air flow caused by the forward motion of the automobile. To increase the heat transfer area the radiator tubes are provided with

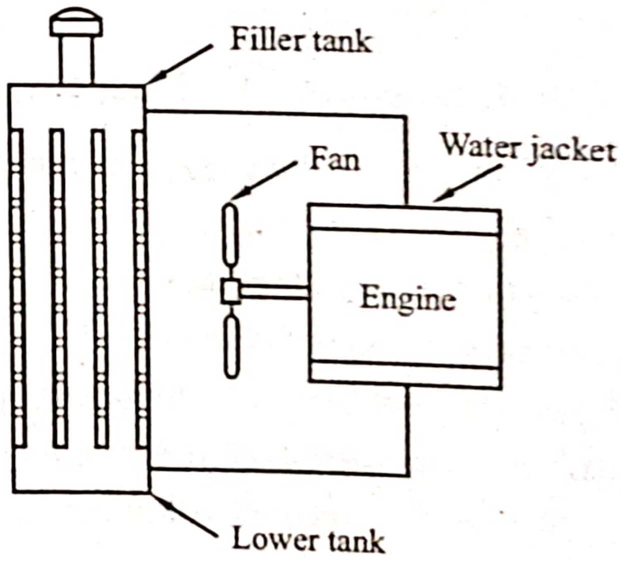


Fig. 1.33. Water cooled engine

fins. In most cases, a fan is provided to establish forced circulation of air over the radiator tubes which increases the heat transfer rate. The radiator consists essentially of an upper filler tank and a lower tank. Radiating elements are provided in between these tanks. The upper tank is connected to the water outlet from the engine jacket by a rubber hose and the lower tank is connected by a hose to the jacket inlet.

Under extreme cold, to avoid freezing of water in radiator tubes, sometimes anti-freeze solution containing ethylene glycol is added with the cooling water. Water cooling system is classified as natural or gravity circulation system, forced circulation system and open circulation system. In natural circulation system the change in density of water due to change in temperature causes it to circulate in the system. This system is also known as thermo-syphon cooling system. In forced circulation system water is circulated through the water jackets using pump. The power required to run the pump is taken from the engine itself. In this a pump is used to draw water from a cooling pond and to circulate it thorough the engine jackets. The water after circulation returns to the cooling pond as shown in Fig. 1.34.

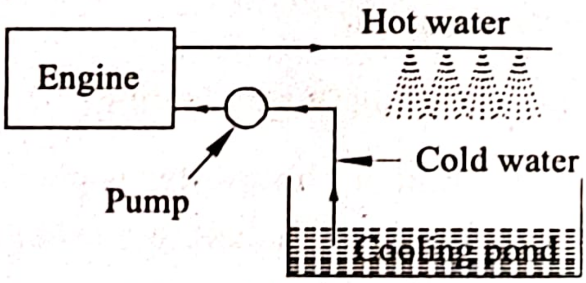


Fig. 1.34. Open circulating system

1.25. Lubrication of IC engines

Lubrication of engine parts are necessary in order to reduce friction between moving parts of the engine. If the moving parts are allowed to rub against each other, they will develop considerable friction and heat, resulting in excessive wear. This can be reduced by placing a film of lubricating oil between the moving part so that they ride on the oil film instead of against each other. This will decrease the power required to overcome friction and will reduce the wear between rubbing parts.

The oil in the engine has several functions to perform. It must remove the heat from the parts it comes in contact with, keep the metal surfaces apart and prevent friction and wear by maintaining an unbroken film of oil between the moving and stationary surface. The oil must also seal the space between piston rings and cylinder walls to prevent leakage of working gases. In addition, the oil must clean the metal parts it comes in contact with and hold in suspension any dirt, metal and carbon particles in the oil.

Main parts to be lubricated in an IC engine are crankshaft, bearings, crank pin, piston, cylinder walls, cams, valve stems, gears etc.

Types of lubricating systems

Several types of lubricating systems are employed to provide efficient lubrication for the internal moving parts of an engine. The various systems supply oil to the moving parts by splash, by gravity, by pressure feed or by some combination of these methods.

The splash system is the simplest method of lubrication. Such systems are usually designed with an oil reservoir in the base of the engine. When the connecting rod moves up it splashes the oil in the form of a spray. The internal parts of the engine are lubricated by this oil spray. This type of lubrication is employed in some types of small single cylinder stationary engines and on engines employed in scooters.

The splash and circulating system is similar in operation to the splash system, except that an oil pump is employed to keep the reservoir with oil.

In a splash and pressure system, an oil pump supplies oil under pressure to the main and crankshaft bearings. The oil pump also supplies oil to the reservoir. Other main parts to be lubricated get oil by the splash system.

In a forced feed (pressure) system, oil is forced by an oil pump to all main bearings connecting rod bearings, camshaft bearings and the gears. The valve mechanism also gets oil under pressure. The cylinder walls, piston and the piston pins are lubricated by the oil spray thrown off from the connecting rod and crank shaft. Most of the present day engines are lubricated by this type of lubricating system.

Desirable properties of lubricants

1. The oil should maintain sufficient viscosity under all ranges of temperatures. Oil with high viscosity index is preferred. This will avoid very high viscosity at cold temperatures and very low viscosity at high temperatures.

2. The oil must not vaporise in its operating temperature range.

3. The oil should have high specific heat to remove the heat generated in the parts.

4. The oil must be free from corrosive acids, moisture etc.

5. The oil should have considerable adhesive quality to permit the oil particles to cling to metal surface.

6. The oil should have good cohesive quality so that a continuous film is formed betwen rubbing surfaces.

1.26. CRDI vehicles

Common Rail Direct Injection [CRDI] is a modern variant of direct injection system for diesel engines. It features a high pressure solenoid or piezoelectric valves make possible fine electronic control over the injection time and amount. In the conventional diesel engines a distributor type injection pump regulated by the engine itself supplies bursts of fuel to injectors through which the diesel is sprayed into the engines combustion chamber. As the fuel is at relatively low pressure and precise control of fuel delivery is not possible the spray is relatively coarse and the combustion process is relatively crude and inefficient. In common rail system the distributor injection pump is eliminated. Instead an extremely high pressure pump stores a reservoir of fuel at high pressure upto 200 MPa, in a common rail. The common rail is basically a tube which in turn branches off to computer controlled injector valves. Each of these injection valves contains a precision machined nozzle and a plunger driven by a solenoid. Driven by a computer the valves control the precise moment when the fuel injection into the cylinder occurs and also allow the pressure at which the fuel is injected into the cylinders to be increased. The computer also controls the amount of fuel to the pump. As a result the fuel that is injected atomises easily and burns cleanly reducing exhaust emissions and increasing efficiency. Common rail engines require no heating up time and produce lower engine noise and lower emissions than traditional systems. In order to lower engine noise the engines electronic control unit can inject a small amount of diesel just before the main injection event. This reduces the explosiveness and vibration. Some advanced common rail fuel systems perform as many as five injections per stroke which gives a more uniform and controlled combustion and helps extract maximum energy from the combustion cycle. In the 90's all major european passenger vehicle manufacturers used this technology to get more refined, powerful and fuel efficient diesel engines into the demanding market. Some Indian companies have also successfully implemented this technology. Different car makers refer to thier common rail engines by different names as given below.

BMW - D-engines, Honda - i - CTDi, Hyundai-CRDi, Mitsubishi - DI-D, Toyota - D-4D, Mahindra - CRDe, Maruti - DDiS

In CRDI engine high pressure fuel is supplied by one pump unit to a manifold [Common Rail] and individual cylinders have solenoid valves timely injection. The advantages of this system are:

1. Higher efficiency due to variable injection timing.

2. Better combustion and low speeds.

3. Better power balance.

4. Less moving parts.

5. More compact engine.

1.27. MPFI vehicles

Gasoline injection system can be classified as

1. Gasoline direct injection into the cylinder

2. Port injection

3. Manifold injection

In single point injection system one or two injectors are mounted inside the throttle body assembly of the engine. Multi Point Fuel Injection [MPFI] system has one injector for each engine cylinder. Fuel is injected in more than one location. This system injects fuel into individual cylinders based on commands from the on board engine management system computer popularly known as Engine Control Unit [ECU]. The ECU primarily controls the ignition timing and quantity of fuel to be injected.

The ECU is controlled by the data input from a set of sensors located all over the engine and its auxillaries. These sensors detect the various operating conditions of the engine and the performance required out of it. Such sensors constantly monitor, ambient temperature, engine coolant temperature, exhaust gas temperature, oxygen content of exhaust, engine speed, vehicle road speed etc. Based on a programme interpretation of all these input data the ECU gives the various commands to the engines fuel and a spark ignition timing system.

Fig 1.35 shows the block diagram of an MPFI system. Air enters into the intake manifold. The manifold pressure sensor detects the intake manifold vaccum and sends the information to the ECU. The speed sensors also sends information about the rpm of the engine to the ECU. The ECU in turn sends commands to the injector to control the amount of gasoline supply for injection. When the injectors spray fuel into the intake manifold the gasoline mixes with the air and the mixture enters the cylinder of the engine.

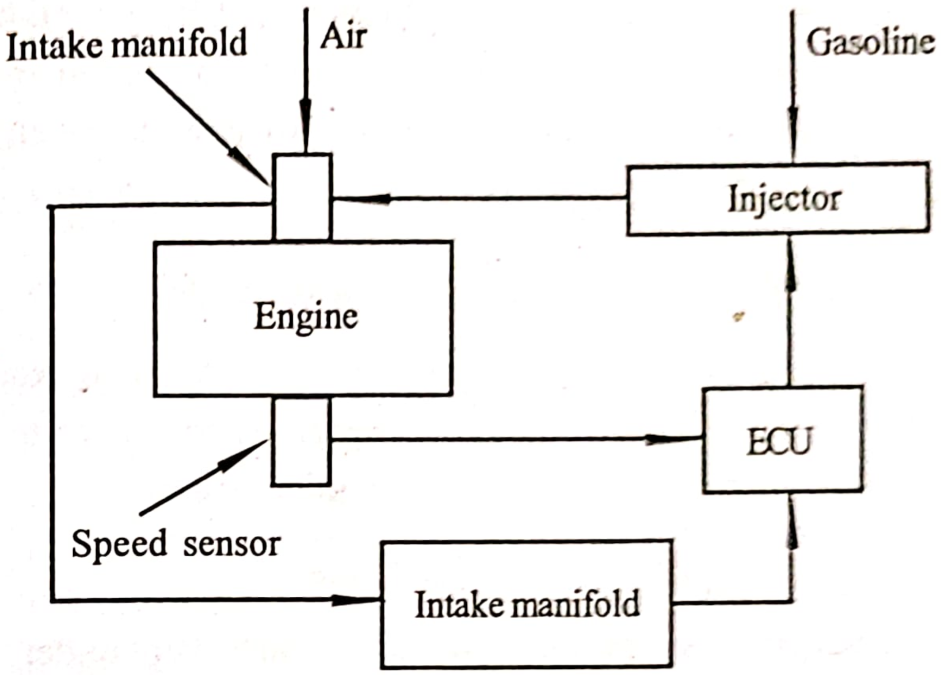


Fig. 1.35. MPFI system

Advantages of MPFI

1. The difference in power developed in each cylinder is minimum.
2. Vibration of engine equipped with the system is less.
3. Immediate response to sudden acceleration and deceleration
4. Since the engine is controlled by ECM [Engine Control Module] more accurate amount of air fuel mixture will be supplied and as a result complete combustion takes place. This leads to effective uti lization of fuel supplied and hence low emission level.
5. The mileage of the vehicle is more.

1.28. Concept of hybrid engines

The sharply rising crude oil price has put a technical challenge to the automotive sector to reduce the fuel consumption of the engine. Automotive business is looking towards electric vehicles to reduce the dependance on oil. Vehicles that make use of two or more distinct power sources are known as hybrid vehicles. they usually come with a fuelled power source and an onboard rechargable energy storage system for powering the vehicle. Petroleum Electric Hybrid Vehicles [PEHV] or Hybrid Electric Vehicles [HEV] generally make use of an internal combustion engine and electric batteries to provide the required power to the electric motor.

Advantages of Hybrid vehicles

1. Reduced petroleum consumption due to less weight.

2. Since braking is controlled by the electric motor to some extent, a part of the kinetic energy of the vehicle is recaptured and is used to recharge the batteries. This process is called regenerative braking.

3. Higher efficiency due to regenerative braking.

4. Due to less fuel consumption, air pollution can be kept under control to a great extent.

5. Less noise due to substantial use of the electric motor.