UNIT 6 INTERNAL COMBUSTION ENGINES

Structure

6.1 INTRODUCTION

The machines that produce power or energy are called engines. The engines work as prime movers meaning "producers of motion". There are other machines which are run by prime movers. Engines have become well known these days because of widespread popularity of automobile – the cars, trucks, buses and motor cycles are machines that are used for transport almost by everybody and everywhere. Doubtless no other engineering wonder can claim such wider use and engines provide the power for automobile. There are of course other uses of these engines also.

Engines in general are reciprocating and rotary. The latter are commonly recognized as turbines, though there are some which are not turbine.

An engine which was first introduced perhaps used a hot air which expanded on top of a piston. It was steam at high pressure which was then used against the piston which was pushed and moved in a cylinder linearly. The engine piston was connected to a crank through connecting rod caused the crank to rotate about its axis. Thus, rotary motion is generated. An engine would definitely need an expanding medium which will push the piston when expanding. The expanding medium will have to be at higher temperature and pressure. The heat required for increasing the temperature and pressure of expanding medium can be given to the medium outside the cylinder in which the piston moves. In such a case the engine is called external combustion engine. The steam engine and hot air engine are examples. Fuel is burnt out of engine and heat is supplied to working fluid which enters the cylinder of the engine with high energy due to temperature and pressure.

In internal combustion engine the fuel is burnt in the cylinder in confined space between walls and top of the cylinder. The heat causes the gases, which become mixture of air and product of combustion, to expand and, thus, creates thrust on piston to cause its linear motion in the cylinder.

Objectives

After studying this unit, you should be able to know

- how internal combustion engines are classified,
- on which cycles these engines work,
- how and how many times the piston has to move to and fro to complete a cycle,
- what fuels are used in these engines, and
- if there are any bad effects.

Figure 6.1 shows a so called reciprocating engine which is a machine consisting of following parts.

(a) Cylinder,

(b) Piston,

(c) Connecting rod, and

(d) Crank.

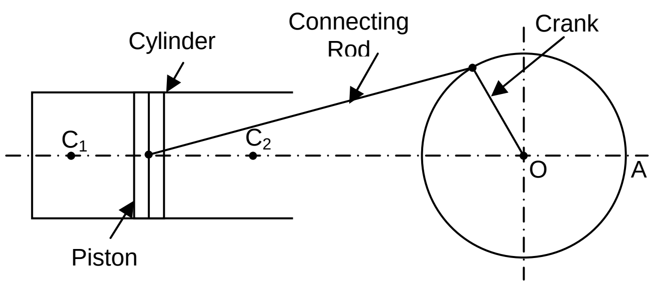


Figure 6.1

The piston is pushed to right in the cylinder. The connecting rod is then pushed and in turn it causes the crank to rotate about its centre *O*. The engine shaft (perpendicular to plane of paper) rotates and gives power to any machine. The piston reciprocates between two extreme positions C_1 and C_2, called *dead centres*. When piston is at C_1, there is clearance between the piston and head of the cylinder. The volume of this space is called clearance volume. The volume between C_1 and C_2 is called *swept volume* or stroke volume. The linear distance between C_1 and C_2 is known as *stroke* and apparently stroke is two times the radius of the crank.

Apparent requirements of the engine arise in our mind. Firstly there should be an arrangement for drawing in the fuel and fresh air so that fuel may burn on top of the piston. This will provide motive force. This will also allow maximum expansion of gases in the cylinder in which case piston will be at C_2 and crank will be along *OA*. The other requirement is that the expanded gases should leave the cylinder to make new charge to enter. That means proper openings are to be provided both for entry of fresh charge and exit of spent gases. Whether both openings are to be provided at the head or top of the cylinder or exit opening may be provided at end near C_2 is a question of engine design. The other question is which form of the fuel is to be pushed into the cylinder and how it is to be ignited. We shall proceed to learn the IC Engines in still greater detail.

6.2 CLASSIFICATION

The IC Engines are classified in several ways. The criteria of classifications are fuel, cycle of operation, method of ignition, number of strokes of piston to complete cycle.

The necessary operations have already been spelt out in last section. Here we enumerate again starting from the piston position at C_1, which is called *top dead centre*.

Step 1

The suction, the charge is inducted and cylinder is completely filled, the piston reaching C_2 which is called *bottom dead centre*.

Step 2

The **compression**, the charge is compressed to clearance volume, resulting in high pressure and temperature. Ignition occurs here.

Step 3

The **expansion**, due to temperature and pressure gas expands, piston is pushed to bottom dead centre under great pressure and torque is generated on crank. It is also called power stroke.

Step 4

The **exhaust**, the residual gases are pushed out of the cylinder by motion of the piston.

For these four steps to complete the piston may move between TDC and BDC two times or four times. During one to and fro motion the crank rotates once (i.e. one rotation) but if piston has two to and fro motions the crank rotates two times (i.e. two rotations). We will take up this type of classification at a later stage. Table 6.1 describes the engine classification based on fuels while other variables are also mentioned.

Table 6.1 : IC Engine Classification Based on Fuels

Sl. No.	Fuel Type	Specific Fuel	Ideal Cycle	Piston Strokes	Ignition	Governing
1.	Gas	Coal gas, Producer gas	Otto cycle	Four	Spark or Heated tube	Hit and miss, Throttle
2.	Petrol	Petrol, Benzol, Alcohol	Otto cycle	Four or Two	Spark	Throttle
3.	Light Oil	Paraffin	Otto cycle	Four or Two	Spark or Hot Tube	Throttle
4.	Heavy Oil	Diesel or Paraffin	Diesel or Dual cycle	Four or Two	Self	Change of point of cut

						off

The fuel, and ideal cycles have already been discussed in the last unit.

Which fuel is to be used in which cycle will depend upon the highest temperature achieved after compression, which will in turn depend upon the compression ratio. The compression ratio of course is to be fixed during design stage. If compression ratio is around 8 or 8.5 then the highest temperature may not be such that can cause the ignition and a separate device to initiate ignition may be required. A spark plug which strikes a spark at desired moment is very commonly used in IC Engine where highest temperature may not cause self ignition. The other igniting devices are porcelain or ceramic tube which may be heated from outside or may retain heat from previous combustion.

A petrol engine works on Otto cycle in which highest temperature is not high enough to cause self ignition. Hence, a spark plug ignition is used. In this case, the charge sucked in the cylinder of the engine contains a mixture of vapourized petrol and air. In earlier engine, a carburetor was used for vapourizing the petrol and allow the vapours to mix with air in its passage. In new design, the liquid petrol is injected in air stream through inlet manifolds which are the air passages attached to the body of the engine. The injection occurs at several points hence the system is known as *multipoint fuel injection* (MPFI). The control of quantity of fuel becomes much more convenient and accurate in MPFI than in carburettor system.

In a diesel engine which works on Diesel standard air cycle and burns diesel fuel the compression ratio is higher than 14. The resulting temperature and pressure are much higher than in petrol engine. The fuel is allowed to enter in the clearance space at high pressure and temperature (675^{o}C) is greater than the self ignition temperature (400^{o}C) of fuel. The fuel burns and expansion occurs causing a great force on the piston. Since compression produces required temperature for ignition the engine is also called **compression ignition** (CI) engine. For pushing the fuel inside the cylinder at high pressure a device, called *injector*, is used and process is called injection. The amount of fuel to be injected is controlled by the injector itself.

In gas engines, the gas and air through separate passages are entered through a single valve controlled passage into the cylinder.

The heat generated due to combustion results in very high temperature. Such temperature may cause damage to all metallic parts such as cylinder and valves. The lubricants used in engine, between several moving parts (such as piston and cylinder), may lose their viscosity at high temperature. It is, therefore, necessary that some of the heat generated in the cylinder must be removed. The heat is removed by air surrounding the cylinder. The air is particularly made to move faster over entire cylinder and in many air cooled engine the external surface of cylinder is enlarged by making extended surfaces called fins. Smaller IC Engines are normally air cooled. Engines of motor cycles are the example. In many cases the heat is removed by circulating water around cylinder and on top of cylinder head. For this purpose special water jackets are made around cylinder and in the head of the cylinder. It may be mentioned here that the valves which control the inlet and exit of the gases are situated in the cylinder head. Special arrangements are made for oil to splash on the inside of the piston to carry away the extra heat.

Governing is yet another characteristic associated with types of engine, as mentioned in Table 6.1. Governing is varying of the power of the engine according to load, while the speed of engine may be required to be maintained within certain limits. The actual governor (i.e. the mechanism) may be practically the same but the way the fuel supply to the cylinder is regulated may differ. Following methods of governing are used :

Hit and Miss method consists of completely cutting off the supply of fuel to the cylinder. During such cut off period no power is generated. The mechanism of governor operates either on exhaust valve or on gas valve in gas engines. In former, the residual gases do not exit hence no suction effect is created and new charge does not enter. In latter, the fuel gas does not enter hence no combustion takes place. Only the air is exited. The second method which is used in small gas engine offers the advantage of fixed air to gas ratio for all power strokes. Idle cycles, however, generate uneven torque on crank. This method is now not preferred.

Quantitative Method controls the quantity of fuel by throttling the air fuel mixture. The throttle is placed in the passage of air fuel mixture in which A/F ratio does not change due to throttling. However, since the weight of the charge varies the final pressure will vary ($pV = mRT$). This will result in lower thermal efficiency but the combustion will be complete even at light loads on the engine. In gas engine the gas and air may be separately throttled. In Table 6.1, it has been mentioned as throttle governing and is commonly used in petrol engines.

Quality Governing may perhaps be the best method in diesel engines in which quantity of air is kept unaltered but the quantity of oil to be injected is varied. The change A/F ratio occurs thus, changing the quality. The fuel quantity is controlled by one of the following methods :

(a) Varying the stroke of the oil pump,

(b) By passing the part of the fuel to the oil tank, or

(c) Delaying the closing of the suction valve of the fuel pump.

The variation of the quantity of fuel will change the cut-off ratio in the ideal diesel air cycle. However, since the air intake remains unchanged, the maximum pressure is always the same. Yet the pressure after the explosion will reduce if fuel supply has been reduced. The combustion is less efficient but theoretical efficiency is likely to increase with diminishing cut-off.

6.3 CYCLES

A cycle has already been defined as sequence of processes which end in the same final state of the substance as the initial. The heat engines are devices which produce work by using heat from a reservoir and rejecting heat to another constant temperature reservoir called heat sink. Perhaps in earlier days some heat engines were developed which directly used the heat from sun, hitherto all engines have been using heat produced from combustion of fuel. Apart from heat source the engine has to have some working fluid that will absorb and reject heat and undergo such processes as expansion are compression. For theoretical study of cycles for engines it is assumed that some working fluid remains in the machine and undergoes different processes over and over again. A number of standard cycles, consisting of well known processes have been developed. We will study a few of them.

6.3.1 Carnot Cycle

Carnot was the first to study the performance of heat engine. Most of his work has been discussed in the last section. Here, we describe the cycle as shown in

Figure 6.2. The engine is made of a piston in a cylinder again shown in the same Figure. The cycle consists of four processes.

1-2-isothermal expansion

2-3-adiabatic expansion

3-4-isothermal compression

4-1-adiabatic compression

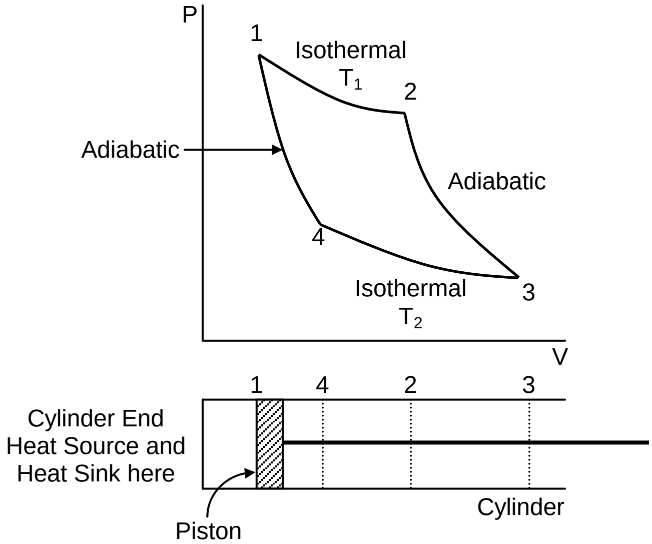


Figure 6.2

During 1-2 and 2-3, work is performed by gas (air) on the piston, whereas during 3-4 and 4-1, work is performed on the gas by the piston.

At 1, a volume of air equal to v_1 is contained in confined space between the piston and cylinder walls. Also assume the mass of the air is m = 1kg.

During isothermal expansion 1-2, a heat source (reservoir) is brought in contact with the cylinder end and since expansion is at constant temperature, entire heat transferred from hot body to the air is converted into work without any change in the internal energy.

Thus
$$W_{12} = Q_{12} = p_1 V_1 \ln \frac{V_2}{V_1} = RT_1 \ln \frac{V_2}{V_1} \quad \ldots \text{(i)}$$

Similarly, at point 3, a heat sink at T_3 is brought in contact with the cylinder end and heat is transferred at T_3 to the sink from air. Work is performed on the air by the piston and is entirely equal to heat transferred to the sink without any change in the internal energy.

Thus
$$W_{34} = Q_{34} = p_3 V_3 \ln \frac{V_3}{V_4} = RT_2 \ln \frac{V_3}{V_4} \quad \ldots \text{(ii)}$$

During adiabatic expansion 2-3 no heat is transferred, so $Q_{23} = 0$.

The internal energy changes to perform work on piston.

$$W_{23} = \frac{p_2V_2 - p_3V_3}{\gamma - 1} = \frac{R}{\gamma - 1}(T_2 - T_3) \quad \ldots \text{(iii)}$$

During adiabatic compression 4-1, work is done upon air, no heat is transferred so $Q_{41} = 0$ and

$$W_{41} = \frac{p_1 V_1 - p_4 V_4}{\gamma - 1} = \frac{R}{\gamma - 1}(T_1 - T_4) \quad \ldots$$

(iv)

Work obtained from the engine = W = Work done upon the piston – Work done by the piston.

$$RT_1 \ln \frac{V_2}{V_1} + \frac{R}{\gamma - 1}(T_2 - T_3) - RT_2 \ln \frac{V_3}{V_4} - \frac{R}{\gamma - 1}(T_1 - T_4)$$

For adiabatic expansion

$$\frac{T_1}{T_2} = \left(\frac{V_3}{V_2}\right)^{\gamma - 1}$$

For adiabatic compression

$$\frac{T_1}{T_2} = \left(\frac{V_4}{V_1}\right)^{\gamma - 1}$$

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

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

Also note that $T_1 = T_2$ and $T_3 = T_4$

$$W = RT_1 \ln \frac{V_2}{V_1} - RT_3 \ln \frac{V_2}{V_1} + \frac{R}{\gamma - 1}(T_2 - T_3) - \frac{R}{\gamma - 1}(T_2 - T_3)$$

$$= R \ln \frac{V_2}{V_1}(T_1 - T_3) \quad \ldots \text{(v)}$$

The heat received by the engine

$$= Q_{12} = RT_1 \ln \frac{V_2}{V_1} \quad \ldots \text{(vi)}$$

The efficiency of the engine is defined as the ratio of work obtained to heat supplied

$\therefore$ $$\eta = \frac{R \ln \left(\frac{V_2}{V_1}\right)(T_1 - T_3)}{R \ln \left(\frac{V_2}{V_1}\right) T_1}$$

or $$\eta = \frac{T_1 - T_3}{T_1} \quad \ldots (6.1)$$

which is same as was derived earlier as Eq. (5.29). Note that here T_1 is the temperature of hot reservoir and T_3 is the temperature of cold reservoir of heat. Heat is abstracted by the engine from hot reservoir and rejected to cold reservoir. The efficiency of the Carnot cycle is highest.

6.3.2 Otto Cycle

The most practical air cycle on which petrol engines work is the Otto cycle comprising four processes, viz.,

1-2 Adiabatic expansion

2-3 Constant volume heat rejection

3-4 Adiabatic compression

4-1 Constant volume heat addition (Figure 6.3).

Apparently no work is done on the piston or by the piston during constant volume processes. Assume mass of air in the engine is 1 kg.

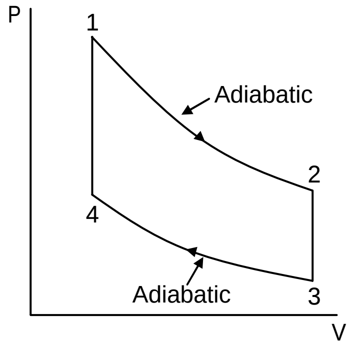


Figure 6.3 : Otto Cycle

Heat rejected by the air in the engine during the process 2-3

$$Q_{23} = C_v (T_2 - T_3)$$

Heat received during the process 4-1

$$Q_{41} = C_v (T_1 - T_4)$$

$\therefore$ $$W = Q_{41} - Q_{23}$$

$\therefore$ $$\eta = \frac{Q_{41} - Q_{23}}{Q_{41}} = \frac{T_1 - T_4 - T_2 + T_3}{T_1 - T_4} = 1 - \frac{T_2 - T_3}{T_1 - T_4}$$

Note $\frac{V_2}{V_1} = \frac{V_3}{V_4} = r$, where r is called compression ratio. It may also be pointed out here that $V_1 = V_4$ is called the clearance volume

$$\frac{p_1 V_1}{p_2 V_2} = \frac{T_1}{T_2} \text{ from gas equation}$$

Also for adiabatic expansion

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

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

Similarly $$\frac{T_4}{T_3} = (r)^{\gamma-1}$$

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

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

Also $$\eta = 1 - \frac{T_3}{T_4}\left(\frac{\frac{T_2}{T_3} - 1}{\frac{T_1}{T_4} - 1}\right)$$

or $$\eta = 1 - \frac{1}{(r)^{\gamma - 1}} \qquad \ldots (6.2)$$

From above expression it can be concluded that efficiency of Otto cycle increases with compression ratio *r*. A compression ratio in the vicinity of 7-8 is commonly used in petrol engines.

Example 6.1

Calculate efficiencies of a Carnot cycle for compression ratios of 7, 8, 9 and 10 for air as working fluid.

Solution

Use γ = 1.4 for air,

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

r	$r^{\gamma-1}$	$1 / (r)^{\gamma-1}$	$\eta = 1 - 1/(r)^{\gamma-1}$
7	2.18	0.46	0.54
8	2.30	0.435	0.565
9	2.41	0.415	0.584
10	2.51	0.400	0.600

6.3.3 Diesel Cycle

This cycle is shown in Figure 6.4. Diesel engines using diesel fuel work on this cycle. The main difference lies in the fact that at the end of compression process sufficiently high temperature is obtained and fuel which is injected at this point ignites without any aid. In case of Otto cycle, a spark is needed to cause ignition of the fuel which is present during process of compression.

In this cycle, the heat is transferred to fuel during constant pressure process when fuel is injected. The fuel burns during constant pressure process only. The gas (air) then expands adiabatically followed by heat rejection which occurs at constant volume. The air is then compressed adiabatically.

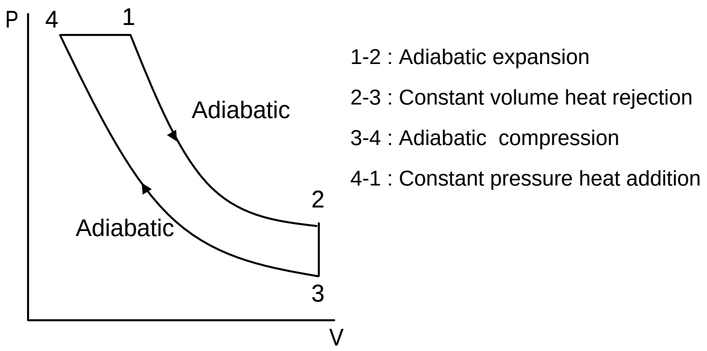


Figure 6.4 : Diesel Cycle

Efficiency of the cycle, $\eta = \dfrac{\text{Work obtained}}{\text{Heat added}} = \dfrac{\text{Heat added} - \text{Heat rejected}}{\text{Heat added}}$

$$\eta = \frac{Q_{41} - Q_{23}}{Q_{41}}$$

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

$$= 1 - \frac{C_v\ (T_2 - T_3)}{C_p\ (T_1 - T_4)} = 1 - \frac{T_3 \left(\dfrac{T_2}{T_3} - 1\right)}{\gamma\, T_4 \left(\dfrac{T_1}{T_4} - 1\right)}$$

It may be noted that in case of diesel cycle the compression ratio is greater than expansion ratio.

For adiabatic compression, $\dfrac{T_4}{T_3} = \left(\dfrac{V_3}{V_4}\right)^{\gamma - 1}$

For adiabatic expansion, $\dfrac{T_1}{T_2} = \left(\dfrac{V_2}{V_1}\right)^{\gamma - 1}$

Calling $V_4 = 1$, $V_1 = \rho$, the cut off ratio and $V_2 = V_3 = r$ = compression ratio

$$\frac{V_3}{V_4} = r, \quad \frac{V_2}{V_1} = \left(\frac{r}{\rho}\right)$$

For constant pressure process 4-1, $p_4 = p_1$

$\therefore \qquad \dfrac{p_1 V_1}{T_1} = \dfrac{p_4 V_4}{T_4}$

or $\qquad \dfrac{\rho}{T_1} = \dfrac{1}{T_4}$

or $\qquad \dfrac{T_1}{T_4} = \rho$

For constant volume process, 2-3

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

or $\qquad \dfrac{p_2}{p_3} = \dfrac{T_2}{T_3}$

For adiabatic process 1-2,

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

For adiabatic process 3-4,

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

Also, $p_2 V_2^\gamma = p_1 V_1^\gamma = p_1 \rho^\gamma$ or $p_2 (r)^\gamma = p_1 (\rho)^\gamma$

and $p_3 V_3^\gamma = p_4 V_4^\gamma$ or $p_3 (r)^\gamma = p_4$

$$\therefore \quad \frac{p_2}{p_3} = \frac{p_1}{p_4} (\rho)^\gamma = (\rho)^\gamma = \frac{T_2}{T_3}$$

Substituting for $\frac{T_2}{T_3}$, $\frac{T_1}{T_4}$ and $\frac{T_3}{T_4}$ in expression for η

$$\eta = 1 - \frac{1}{\gamma (r)^{\gamma - 1}} \times \frac{\rho^\gamma - 1}{\rho - 1} \qquad \ldots (6.3)$$

Diesel cycle normally has much higher compression ratio. For same compression ratio the efficiency decreases for increasing cut off ratio.

Example 6.2

Calculate the efficiency of a diesel cycle for which compression ratio is 14 and cut off ratio is 2. What will be the efficiency if cut off ratio is increased to 3. Given $\gamma = 1.4$.

Solution

Use $r = 14$ and $\rho = 2$ with $\gamma = 1.4$ in Eq. (6.3).

$$\eta = 1 - \frac{1}{1.4\,(14)^{0.4}} \times \frac{2^{1.4} - 1}{2 - 1}$$

$$= 1 - \frac{1}{4.02} \times \frac{1.64}{1} = 0.59$$

or $\eta = 59\%$. . . . (i)

Use $r = 14$ and $\rho = 3$ with $\gamma = 1.4$ in Eq. (6.3)

$$\eta = 1 - \frac{1}{1.4\,(14)^{0.4}} \frac{3^{1.4} - 1}{3 - 1}$$

$$= 1 - \frac{1}{4.02} \times \frac{3.655}{2} = 0.545$$

or $\eta = 54.5\ \%$ . . .(ii)

6.3.4 Dual Combustion Cycle

It is more practical that heat is supplied partly during constant volume and partly during constant pressure processes. Such a cycle, shown in Figure 6.5, is called dual combustion cycle.

Heat addition during 4-5 (constant volume) and 5-1 (constant pressure) processes.

Heat rejection during 2-3 (constant volume process).

$$V_5 = 1, \frac{P_5}{P_4} = \alpha, \frac{V_3}{V_4} = r, \frac{V_1}{V_5} = \rho$$

It can be shown that efficiency of dual combustion cycle is

$$\eta = 1 - \frac{1}{r^{\gamma - 1}} \left[\frac{\alpha \, \rho^{\gamma - 1}}{(\alpha - 1) + \alpha^{\gamma} \, (\rho - 1)} \right] \quad \ldots (6.4)$$

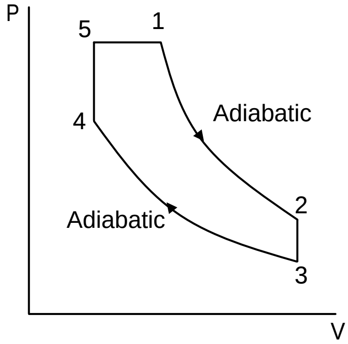


Figure 6.5

There are many other cycles that are used in practice but we do not deal with them since scope of the text is limited. Stirling cycle, Ericsson cycle and Brayton cycle are just mentioned here. Another important cycle used with steam as working medium will be discussed.

6.3.5 Steam Cycle

The cycles which use air as medium are known as *air standard cycles*. They are used in internal combustion engines like petrol and diesel engines and in gas turbine. They are also referred to as *power cycles*.

Apart from internal combustion engines and gas turbines in which heat is provided by burning of fuel inside the body of engine or very close to turbine in combuster, a very common and popular source of power is steam which was earlier used in steam engines and turbine but former has been almost phased out because of its lower efficiency. Steam turbine still remains the major source of power in large capacity in the range of few hundred MW. The present day is seeing the advent of combined cycle power plants in which both gas and steam turbines are used together.

The use of steam is based upon large latent heat which water absorbs when changes into steam. Steam is produced at high pressure where its boiling point is high but when it expands in the turbine its pressure reduces continuously and its boiling point simultaneously reduces so it remains vapour until the end of expansion to very low pressure. Thus, enough expansion work is obtained from steam.

The total cycle consists of water converting into steam, expansion of steam and steam condensing into water.

The raising of steam requires a separate system called boiler which is a strong vessel with a series of tubes. The water may evaporate in tube or outside the tube. In first case hot gases pass outside the tubes and second case they pass inside the tube. The steam is stored in the vessel from where it passes into turbine. The hot gases are produced by burning fuel in the furnace which in earlier days used to be mainly coal but now-a-days liquid fuel, gaseous fuel and pulverized coal are being preferred. The steam after passing through turbine passes into condenser where it condenses into water at very low pressure. This water through a pump is injected into the vessel (drum of the boiler) and thus the cycle repeats.

The cycle on which the above system works is named *Rankine cycle* but before we go for its description let us get familiar with some of the properties of water (steam) which is known as pure substance because no impurities in it are permitted.

Since the fuel burns outside the engine, in the boiler, the steam engines and turbines have also been sometimes called external combustion engines. This term, however, is not popular.

Definition Related to Steam

Steam is a state of water, partially or fully vapourized. If steam contains water particles it is *wet*. A *saturated* steam does not contain water particles. Water vapourises at *saturation temperature*. There is a unique saturation temperature at each pressure. The amount of heat absorbed by water anywhere between 0^{o}C to its saturation temperature is called *Sensible heat* (h_f). This is also known as *enthalpy of saturation.* The heat absorbed by water at saturation temperature is called *latent heat* (L). The process of evaporation will continue at constant temperature for a given pressure until whole of water is converted into steam. The steam at the saturation temperature is known as saturated steam. If water particles to the extent of w kg are present along with M_s kg of saturated steam then the quality of steam (or dryness fraction), x, is defined as

$$x = \frac{M_s}{M_s + w} \qquad \text{. . . (6.5)}$$

The enthalpy of wet steam is given by

$$h = h_f + xL \qquad \text{. . . (6.6)}$$

The enthalpy of saturated steam (x = 1)

$$h_{sat} = h_f + L \qquad \text{. . . (6.7)}$$

If steam continues to be heated from its saturation state then it absorbs heat and gets superheated. The superheating is done at constant pressure. The enthalpy of superheated steam is

$$h_{\text{sup}} = h_f + L + C_p\,(T_{\text{sup}} - T) \qquad \text{. . . (6.8)}$$

C_p is the specific heat at constant pressure.

Volume of steam is much larger than the volume of water from which the steam is obtained. The latter is negligible. Specific volume of wet steam and saturated steam are correlated as

$$v_{\text{sw}} = x\, v_{\text{sat}}$$

v_{sw} is volume of 1 kg of wet steam and v_{sat} is volume of 1 kg of saturated steam. The specific volumes of superheated and saturated steam are related as

$$v_{\text{sup}} = v_{\text{sat}} \frac{T_{\text{sup}}}{T_{\text{sat}}} \qquad \text{. . . (6.9)}$$

since superheating is a constant pressure process.

A pressure volume diagram of Figure 6.6 illustrates water-vapour phases.

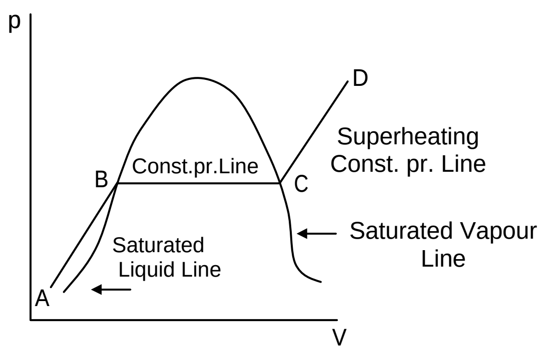


Figure 6.6

Steam can be expanded in all those manners as described in case of gas. One process which was not described earlier is very common in steam practice and that is *throttling*. It can be understood as expansion through a minute aperture like opening of a valve. In this process, neither the work is done ($W = 0$) nor the heat is exchanged ($Q = 0$). Due to drop in pressure the gas or steam comes out with a great velocity. But due to friction at the exit heat is added and thus kinetic energy is converted into heat. This type of expansion is very common with steam as it is produced at a much higher pressure and it may be necessary to use it at a lower pressure. The steam is often throttled to much larger volume and lower pressure in which process steam gets superheated even if it is wet.

6.3.6 Rankine Cycle

As was stated earlier a Rankine cycle consists of following processes :

1-2 : Pumping water from condenser to boiler, it requires work but the work is very small in comparison of work and heat in other processes, hence negligible.

2-3 : Constant pressure heat addition in the boiler, it can heat water into wet, saturated or superheated steam.

3-4 : Expansion of steam in an engine or turbine, converting heat into work, normally an adiabatic process.

4-1 : Condensing steam into water at low pressure which is the exit pressure of engine or turbine.

The work is obtained from expansion process 3-4 and heat is supplied during heating process 2-3. The pumping work during 1-2 is negligible. The heat is rejected during condensation process 4-1.

The cycle is represented in Figure 6.7.

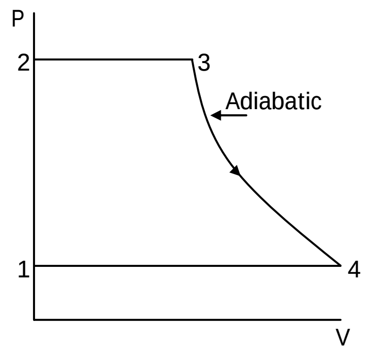


Figure 6.7

$$W = (h_3 - h_4)$$

$$Q = h_3 - h_2$$

$$\eta = \frac{W}{Q} = \frac{(h_3 - h_4)}{h_3 - h_2}$$

$(h_2 - h_1)$ may be very small.

A schematic layout of plant working on Rankine cycle is shown in Figure 6.8.

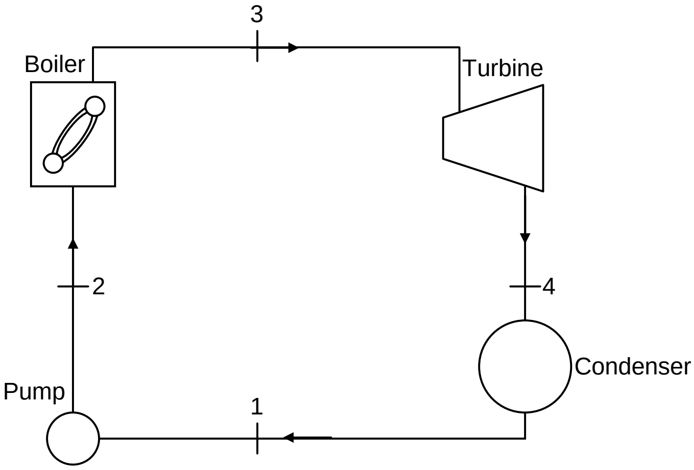


Figure 6.8

6.3.7 Modified Rankine Cycle

In a modified Rankine cycle, steam is not allowed to expand fully to point *d* as shown in Figure 6.6 as it takes a long piston stroke, or several stages in the turbine. Steam is cut off at some point '*D*'. Before *D*, the steam passes into condenser at constant volume. It reduces the work but saves condenser space considerably.

Example 6.3

In a Rankine cycle, steam leaves the boiler and enters the turbine at 4 MPa and 400^{o}C. It is expanded in two stages to 10 kPa.

At p_3 = 4 MPa and 400^{o}C, h_3 = 3214.3 kJ/kg
(Enthalpy of superheated steam)

At p_4 = 10 kPa and exhaust temp., h_4 = 2135.7 kJ/kg

At $p_2 = p_3$, h_{2f} = 1087.3 kJ / kg

At $p_1 = p_4$, h_{1f} = 194 kJ / kg

Calculate work done in the cycle and its efficiency.

Solution

Refer Figure 6.7

Work done, $W = (h_3 - h_4)$

$= (3214.3 - 2135)$

Heat supplied $= h_3 - h_2$

$= 3214.3 - 194$

$$\therefore \quad \eta = \frac{3214.3 - 2135}{3214.3 - 194}$$

$$= \frac{1079.3}{3020.3}$$

or $\eta = 0.357$ or 35.7 %.

6.3.8 Cycles in Engines

Standard air cycles were discussed in last unit. Out of these the Carnot cycle is practically not used. It involves an isothermal process followed by an adiabatic process in one stroke of the piston. Isothermal process is very slow whereas adiabatic is very fast and practically it is impossible to vary the speed of the piston in a single stroke.

The Otto and Diesel cycles are practically followed in petrol and diesel engines respectively. There are gas engines and paraffin engines which work on Otto cycle. Diesel engine also works on dual combustion cycle. The paraffin engine can also work on Diesel cycle.

It may be understood that for same compression ratio Otto cycle is more efficient than Diesel cycle. Even otherwise, when diesel cycle works with a higher compression ratio this cycle is not as efficient as Otto cycle. It is because burning of fuel at constant pressure is less efficient than burning of fuel at constant volume. For this reason modern diesel engines operate on dual combustion cycle in which, part of combustion occurs at constant volume also.

In actual engine cylinders, the entry and exit of gases takes place through valves which are opened and closed at right moments. Separate mechanisms for valves are provided in the engine. The pressure losses occur at the valves and the ideal cycles lose their sharpness at points where process changes. For example, sharp change at point 2 in Figure 6.5 will not be practically as sharp as shown in this Figure. If we obtain actual *pV* diagram from an engine, this diagram must be the operation cycle of the engine. For example if *pV* diagram is obtained from a spark ignition (petrol) engine then this diagram should be an Otto cycle. Further the ideal cycle assumes some air or medium being heated and cooled cycle after cycle but in actual engine fresh charge is taken in and spent gases are exhausted. Therefore, this effect will also appear on the diagram obtained from the engine. The *pV* diagram sensed from the engine is called its indicator diagram. Figure 6.9 shows an indicator diagram of a petrol engine and an Otto cycle is superimposed upon it (shown in broken lines).

The suction and exhaust lines can be clearly seen in indicator diagram. The area enclosed between these lines represent the loss of work.

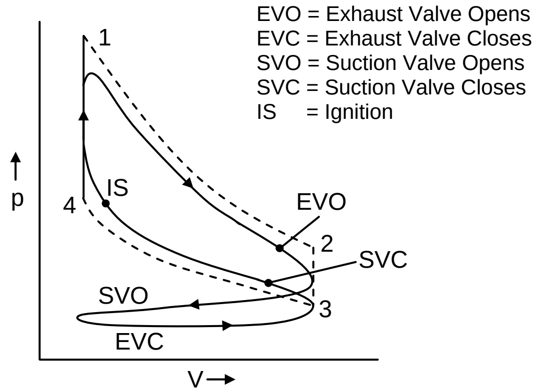


Figure 6.9 : An Indicator Diagram of a Petrol Engine

6.3.9 Mean Effective Pressure

Mean effective pressure is the mean height of the *pV* diagram. It can be calculated theoretically from

$$\text{m.e.p} = \frac{\text{Work done per cycle}}{\text{Stroke volume}} \quad \ldots (6.10)$$

Mean effective pressure is that imaginary pressure which when will act continuously on the piston will perform the same work as the varying pressure will perform. The m.e.p is supposed to perform work only in one stroke which is power stroke. When from an experimental measurement actual indicator diagram of the engine is obtained, the mean effective pressure is calculated from

$$\text{m.e.p} = \frac{\text{Area of indicator diagram}}{\text{Length of the diagram}} \quad \ldots (6.11)$$

Example 6.4

In a petrol engine the swept volume (stroke volume) is 0.13 m^3. The temperature T_1 = 2000 K, T_2 = 977 K, T_3 = 333 K and T_4 = 681 K. The engine produces power stroke once in 2 revolution. The engine runs at 1000 r.p.m. Calculate

(a) Heat supplied

(b) Heat rejected

(c) Work done (all per cycle and per minute).

If the CV of the fuel is 45000 J/kg, what amount of fuel is required per minute? Use C_v = 713 J/kg K, m = 0.1615 kg.

Solution

Refer Figure 6.9.

Heat is supplied from 4 to 1 which is constant volume process.

$$Q_{41} = m\,C_v\,(T_1 - T_4)$$
$$= 0.1615 \times (2000 - 681) \times 713$$
$$= 152 \times 10^3 \text{ J/cycle}$$

Heat is rejected from 2 to 3 (a constant volume process)

$$Q_{23} = m\,C_v\,(T_2 - T_3)$$
$$= 0.1615 \times 713\,(977 - 333)$$
$$= 74.2 \times 10^3 \text{ J/cycle}$$

∴ Work done by the engine

$$W = Q_{41} - Q_{23} = (152 - 74.2)\,10^3$$
$$= 77.8 \times 10^3 \text{ J/cycle} \quad \ldots \text{(i)}$$

Since engine requires two revolution to complete a cycle and engine makes 1000 revolution in a minute.

Work done in a minute

$$= \frac{W \times N}{2} = \frac{77.8 \times 10^3 \times 1000}{2}$$

$$= 38.9 \times 10^6 \text{ J/min} \quad \ldots \text{(ii)}$$

$$\text{Power} = \frac{\text{Work}}{s} = \frac{38.9 \times 10^6}{60} \text{ J/s or W}$$

$$= 648 \text{ kW} \quad \ldots \text{(iii)}$$

$$\eta = \frac{\text{Work done}}{\text{Heat supplied}} = \frac{W}{Q_{41}}$$

or $$\eta = \frac{77.8 \times 10^3}{152} = 0.51 \text{ or } 51\% \qquad \ldots \text{(iv)}$$

Heat is supplied by fuel

$$Q_{41} = m_f \times CV$$

$$\text{Mass of fuel} = m_f = \frac{Q_{41}}{CV} = \frac{152 \times 10^3}{45 \times 10^3} \text{ kg per cycle}$$

$$= 3.37 \text{ kg/cycle}$$

$$\text{Mass of fuel per min} = \frac{3.37 \times 1000}{2} = 1685 \text{ kg/min} \qquad \ldots \text{(v)}$$

$$\text{m.e.p} = \frac{\text{Work done}}{\text{Stroke volume}}$$

$$= \frac{77.8 \times 10^3}{0.13}$$

$$= 0.6 \text{ MPa}$$

Example 6.5

If stroke of the engine is two times its diameter of the cylinder in the Example 6.4, can you calculate the work done upon the piston in one cycle?

Solution

Let diameter of the cylinder = d

Then area on which m.e.p acts $= \frac{\pi}{4} d^2$

Swept volume (stroke volume) $= \frac{\pi}{4} d^2 \times 2d$

Since stroke, $l = 2d$

$$\therefore \qquad \frac{\pi}{2} d^3 = 0.13 \text{ m}^3$$

$$\therefore \qquad d = \frac{(2 \times 0.13)^{1/3}}{\pi}$$

$$d = 0.436 \text{ m}$$

$$l = 0.872 \text{ m}$$

The force on the piston, F = m. e. p × area of piston

$$\text{m.e.p} = 0.6 \times 10^6 \text{ N/m}^2 \text{ (from Ex. 6.1)}$$

$$\therefore \qquad F = 0.6 \times 10^6 \times \frac{\pi}{4} (0.436)^2$$

$$= 0.09 \times 10^6 \text{ N}$$

This force displaces the piston over a distance equal to stroke.

$$W = F \times l$$

$= 0.09 \times 10^6 \times 0.872$

$= 78 \times 10^3$ J/stroke or per cycle.

In Example 6.4, this work was calculated as 77.8×10^3 J/cycle.

There is negligible difference.

SAQ 1

(a) On how many criteria you can classify an IC Engine?

(b) In Example 6.4 all the heat of fuel has been assumed to have been converted in work. Is it possible? Is there any other way of using the heat of fuel?

(c) A gas engine working on Otto cycle has a cylinder dia 178 mm and stroke of 254 mm. The clearance volume is 1.5×10^6 mm^3. Calculate air standard efficiency.

(d) In an air standard Carnot cycle heat is transferred to the working fluid at 410 K and heat is rejected at 276 K. The heat transfer to working fluid is 110 kJ/kg. The minimum pressure in the cycle is one atm. Assuming constant specific heat of air, determine the cycle efficiency.

Use $R = 287$ J/kg K.

6.4 FOUR-STROKE AND TWO-STROKE ENGINES

We have very clearly understood that following operation have to be performed in the engine cylinder.

(a) Suction of charge which could be a mixture of vapourized fuel and air or only air. When whole cylinder (swept volume of cylinder) has been filled the suction operation is complete.

(b) Compression of charge in an adiabatic process, when the whole volume of the charge has been compressed into clearance volume compression is complete.

(c) Combustion of fuel either at constant volume or at constant pressure. Even at constant pressure piston moves a very small distance. In constant volume combustion piston does not move.

(d) Expansion of gases all through the stroke volume. During this expansion the gases perform work on the piston which is transmitted to crank.

(e) Heat rejection at constant volume, the piston does not move.

(f) Exhaust of spent gases from the cylinder so that fresh charge may be sucked in.

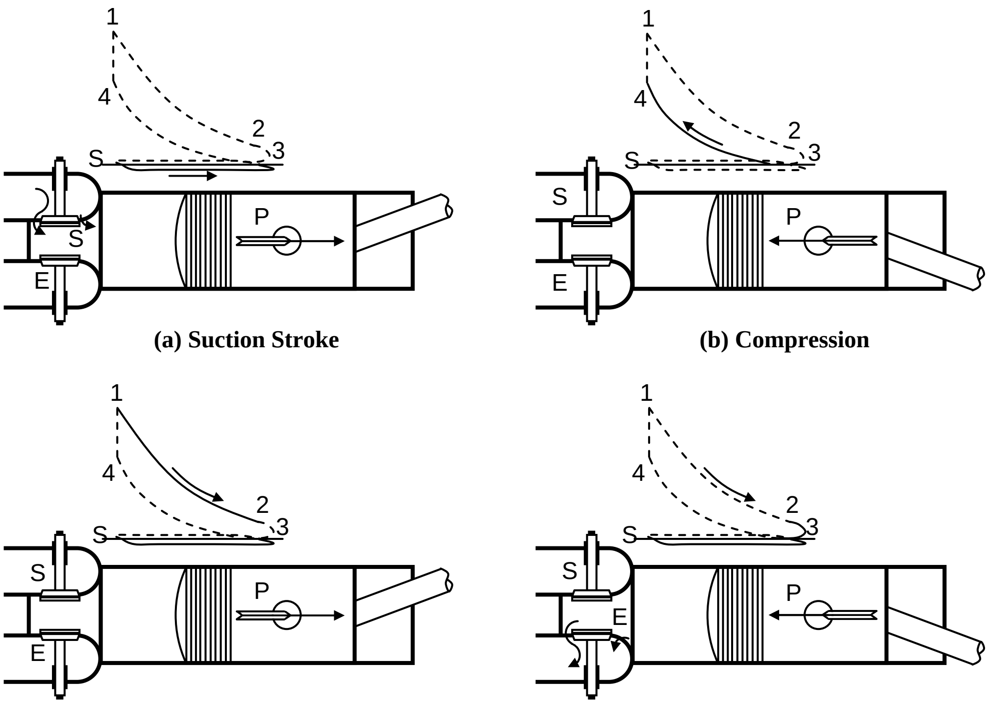
Out of these six, two, i.e. (c) and (e) do not require piston displacement (or very little in one case). The other four require piston to move all the way from top to bottom and from bottom to top. The question faced by the designer of the engine will be in how many piston strokes he should complete the four operations – the suction, compression, expansion and exhaust.

Two answers have evolved. You can complete these operations either in two strokes (1 crank revolution) or in four strokes (2 crank revolution) resulting in 2-stroke and 4-stroke engines.

6.4.1 Four-stroke Otto Cycle Engine

These are petrol engines. Four operations i.e. suction, compression, expansion and exhaust are performed separately in four strokes of the piston. The operations, each of which is a process, are shown in Figure 6.3 (a), (b), (c) and (d) and they

occur in this order. The cylinder, with head having inlet (*S*) and exit (*E*) valves is shown in Figure 6.10.



(a) Suction Stroke **(b) Compression**

(c) Working Stroke **(d) Exhaust Stroke**

Figure 6.10 : 4-Stroke Operation

Suction Stroke

In Figure 6.10(a) exhaust valve (*E*) is closed and suction valve *S* is opened. The mixture of air and fuel is sucked in the cylinder as piston *P* moves away from top or inner dead centre (TDC or IDC). The suction stroke is complete when the piston reaches end of the stroke, bottom or outer dead centre (BDC or ODC). On the top of the cylinder the process is shown by the line S3 in the indicator diagram (also see Figure 6.9).

Compression Stroke

In Figure 6.10(b), both the suction and exhaust valves (S and E) are closed. The piston starts moving from BDC to TDC and charge is compressed. The compression ends at 4 and the compression process is shown by 3-4. Just near the end of the stroke (i.e. point 4) the charge is ignited by the spark. S-3-4-1 is indicator diagram of Figure 6.10(b). (Also see Figure 6.9.)

Expansion Stroke

Both the suction and exhaust valves are kept closed and due to addition of heat the gas expands from 1 to 2 (indicator diagram) and piston move from TDC to BDC, as shown in Figure 6.10(c).

Exhaust Stroke

The suction valve remains closed and exhaust valve is open. As the piston moves from BDC to TDC it pushes the gases out through exhaust valves. The process is shown as 2-3-S in the indicator diagram.

6.4.2 Four-stroke Diesel Cycle Engine

The spark plug in the petrol engine is screwed into head of the cylinder. In a diesel engine an injector is placed instead of spark plug. Injector pushes fuel into cylinder at right time.

The suction and exhaust valves like petrol engine are present in diesel engine also.

Suction Stroke

The exhaust valve is closed. Suction valve opens and air is sucked in along S-3 when the piston moves from TDC to BDC.

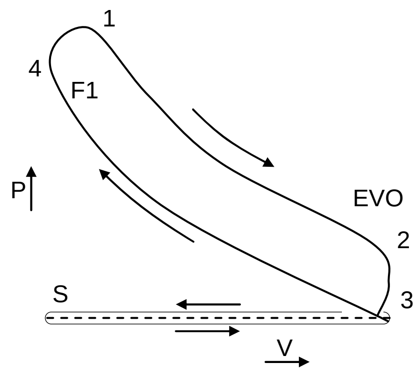


Figure 6.11 : Indicator Diagram of 4-stroke Diesel Engine

Compression Stroke

Both the valves are closed and air is compressed along 3-4. The piston moves from BDC to TDC. The fuel injection begins slightly before end of compression as shown by F1 and continues until sometimes after the piston has started return.

Expansion Stroke

The temperature just before point 4 is sufficiently high to cause fuel to ignite and combustion continues until injection stops at cut off (point 1). Both the valves remain closed. The gases expand from 1 to 2. Piston moves from TDC to BDC. During the process before piston reaches BDC the exhaust valve opens.

Exhaust Stroke

Exhaust valve open just before the end of expansion, i.e. slightly before piston reaches BDC. The piston begins its motion from BDC toward TDC pushing gases through exhaust valves. The inlet or suction valve opens at the end of exhaust stroke, i.e. when the piston is at TDC. The exhaust valve closes slightly after that.

Valve setting diagram of Figure 6.12 also shows the four operations of 4-stroke cycle. The diagram is applicable to both diesel and petrol engines. 1S is applicable to petrol engine to which INJ and INJC are not applicable. INJ and INJC are applicable to diesel engine to which 1S is not applicable.

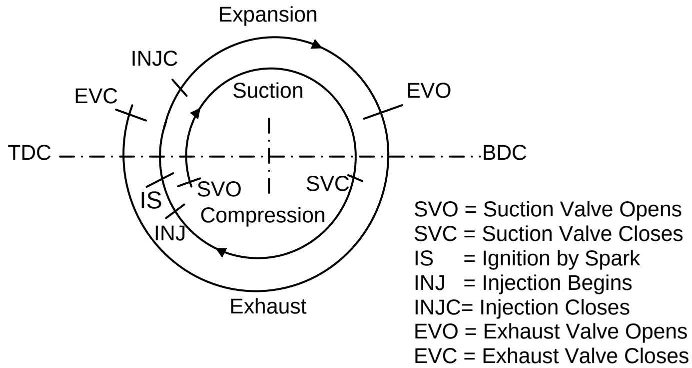


Figure 6.12 : Valve Setting Diagram

6.4.3 Two-stroke Cycle Engine

The four operations of suction, compression, expansion and exhaust are completed in only two strokes of the piston or one revolution of crank. The expansion, exhaust and intake occur in the same stroke. The exhaust begins close to the end of expansion stroke and suction begins immediately after. In both petrol and diesel engines, suction and exhaust take place through ports in the cylinder which are almost at the same level. When piston is moving to BDC it first begins to uncover the top of exhaust port and piston top is so shaped that it facilitates the flow of gases through exhaust port. Before the piston has completely uncovered the exhaust port, the initial port is uncovered and fresh charge (either mixture of petrol vapour and air or only air) enters the cylinder through inlet port which is diametrically opposite to the exhaust port. The piston top is so shaped that it helps the charge to rise up in the cylinder.

In moving from BDC to TDC the piston compresses the charge and just before it reaches the TDC the spark ignites the charge or fuel is injected depending upon whether engine is operating on Otto cycle or Diesel cycle.

The charge or air is compressed slightly in crankcase which facilitates the suction. There is a separate suction port into crankcase which is closed during charge intake into cylinder.

Figure 6.13 shows the scheme of a two-stroke engine. See the shape of the top of piston in particular which allows incoming charge to move up while helping the outgoing gases to push out. Yet there is always a risk that some fresh charge may also leave through exhaust or some spent gas may not leave the cylinder. The removal of exhaust gases from the cylinder is known as scavanging. The engine, shown in Figure 6.13, is crank case scavanged. In a uniflow scavanged engine, the exhaust ports are provided all around the cylinder at BDC but the charge enters at the top. The inlet valve may be spring loaded and cam operated.

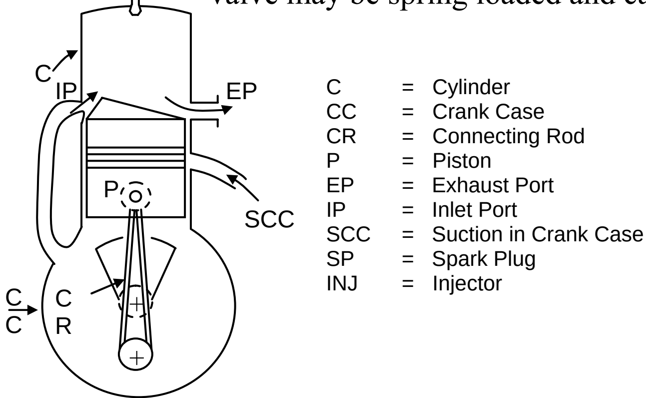


Figure 6.13 : A Two-stroke Engine

6.4.4 Advantages of Spark Ignition Engine

These engines operate on Otto cycle with compression ratio varying between 6 : 1 to 12 : 1 with final pressure between 1030 to 2060 kPa. They employ carburettor, gas mixing system or fuel injection system. Commonly used fuels are petrol, compressed gas, coal gas, coke oven gas and producer gas. They are commonly used in automobiles, small aircraft and tractors. Throttle governing is employed.

The initial cost of these engines is low. Their specific weight is low and they require less cranking torque. Wide variation in speed and load is obtainable, with fairly low specific fuel consumption they result in high mechanical efficiency.

6.4.5 Advantages of Compression Ignition Engine

These engines operate on diesel or dual combustion cycle, use less volatile fuel (diesel being very common) and have compression ratio vary between 11 : 1 to 22 : 1. The compression pressure is between 2760 to 4830 kPa. Generally, no ignition device is required. Governing is qualitative by controlling quantity of fuel.

These engines produce high thermal efficiency at low specific fuel consumption even at partial loads. Preignition does not occur, less CO is produced and hydrocarbon emission is also low at low and moderate loads. The engine is suited to both 2 and 4-stroke operation. The low compression 2-stroke engines offer advantage of low initial cost and higher mechanical efficiency because of absence of valves.

6.4.6 Advantages of 2-stroke Engine

The major advantage is 50 to 80% greater output per unit piston displacement and same speed as 4-stroke engine. The cost of these engines is low because the construction is valveless. The NO_x emission is low in SI engines. The overall weight is less.

6.5 ENGINE PERFORMANCE

Power in engine is produced by burning fuel which gives heat. The heat supplied by fuel is divided as follows :

Heat supplied by fuel = Heat converted into useful work +

Heat rejected to cooling water +

Heat rejected to surrounding +

Heat carried away by exhaust gases

The power produced in the cylinder of the engine is called *indicated power*. The indicated power is also calculated from *indicator diagram. Brake power* is that which is obtained from shaft of the engine. The difference between indicated power and brake power is the power lost in friction of various moving parts. This friction power is required to move the engine when it is not producing any power.

Indicated power can be calculated from mean effective pressure obtainable from indicator diagram.

$$\text{IP} = (\text{mep})\ l\ An \qquad \ldots (6.12)$$

where, m. e. p = Mean effective pressure,

l = Length of stroke,

n = Number of power stroke per second which is equal to revoluation per second in 2-stroke engine and half this number in 4-stroke engine, and

A = Area of piston or cross section of cylinder.

Brake power of the engine is measured in several ways but the easiest is applying a belt round a pulley on the engine shaft (Figure 6.14). The tension in the belt can be increased or decreased. If higher tension is T_1 (Newton), lower tension is T_2 (Newton) and D is the diameter of the pulley which rotates at N rpm, then

$$\text{BP} = (T_1 - T_2)\,\frac{D}{2}\,\frac{2\pi N}{60} \qquad \ldots (6.13)$$

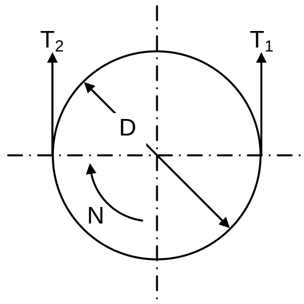


Figure 6.14 : Pulley on Engine Shaft

Mechanical Efficiency of the engine is the ratio of BP to IP.

$$\eta_m = \frac{\text{BP}}{\text{IP}} \qquad \ldots (6.14)$$

Specific Output is defined as ratio of BP to swept (stroke) volume

$$\text{Specific Output} = \frac{\text{BP}}{Al} \qquad \ldots (6.15)$$

It can be easily understood that at the beginning of each suction stroke there is some volume of remaining gases in clearance space. As the piston moves toward BDC these gases will also expand. Of course simultaneously new charge will enter. Due to expansion of residual gases the volume of new charge will not be exactly equal to the stroke volume. This deficiency is taken care of by defining volumetric efficiency.

$$\text{Volumetric efficiency, } \eta_v = \frac{\text{Actual volume of charge inhaled at suction condition}}{\text{Stroke volume}}$$

Other efficiencies are defined as under.

m = Mass of fuel supplied per sec.

$$\text{Indicated thermal eff.} = \eta_i = \frac{IP}{m \times (CV)} \qquad \ldots (6.16)$$

$$\text{Brake thermal eff.} = \eta_b = \frac{BP}{m \times (CV)} \qquad \ldots (6.17)$$

Relative eff. $= \eta_r = \dfrac{\eta_b}{\text{Eff. of cycle}}$ . . . (6.18)

Specific fuel consumption $= \dfrac{m}{BP} \times 3600$ kg/BP/Hr . . . (6.19)

Example 6.6

An IC Engine rotates at 2400 rpm. The 4-stroke engine has a cylinder bore diameter of 100 mm and crank radius of 100 rpm. From indicator diagram m.e.p is found as 100 kPa. If mechanical efficiency is 80%, find BP.

Solution

Stroke, $l = 2 \times$ Crank radius

$l = 2 \times 100 = 200$ m $= 0.2$ m

$$A = \frac{\pi}{4} d^2 = \frac{\pi}{4} (0.1)^2 = 7.854 \times 10^{-3} \text{ m}^2$$

n = Number of power stroke per sec.

$$= \frac{\text{rpm}}{2 \times 60} = \frac{2400}{2 \times 60} = 20$$

IP = mep Al n

$= 100 \times 10^3 \times 7.854 \times 10^{-3} \times 0.2 \times 20$

$= 3141.6$ W or 3.14 kW . . . (i)

$$\eta_m = \frac{BP}{IP}$$

$\therefore$ $BP = \eta_m \times IP$

$= 0.8 \times 3.14$

or $BP = 2.51$ kW . . . (ii)

Example 6.7

If the engine of Example 6.6 has a specific fuel consumption of 315 kg/BP/hr and calorific value of the fuel is 46×10^3 J/kg, find brake thermal efficiency. If compression ratio is 6, find relative efficiency. Use $\gamma = 1.4$.

Solution

With compression ratio of 6, it can be assumed that the 4-stroke engine works on Otto cycle.

$\therefore$ Cycle efficiency, $\eta_a = 1 - \dfrac{1}{(r)^{\gamma - 1}}$

$$= 1 - \frac{1}{(6)^{1.4-1}} = 1 - \frac{1}{(6)^4}$$

or $$\eta_a = 51.2\% \quad \ldots \text{(i)}$$

$$m = \text{Mass of fuel per sec} = \text{Specific Fuel consumption} \times \frac{BP}{3600}$$

$$= 315 \times \frac{2.51}{3600} = 0.22 \text{ kg}$$

$$\text{Brake thermal eff.,}\ \eta_b = \frac{BP}{m\,(CV)} = \frac{2.51\ \text{(kW)}}{0.22 \times 46} = 0.248 \quad \ldots \text{(ii)}$$

or $$\eta_b = 24.8\%$$

$$\text{Relative efficiency,}\ \eta_r = \frac{\eta_b}{\eta_a} = \frac{24.8}{51.2} = 0.48 \quad \ldots \text{(iii)}$$

$$\eta_r = 48\%\ .$$

SAQ 2

(a) Define different efficiencies and explain volumetric efficiency.

(b) Compare 2-stroke and 4-stroke engines.

(c) A single cylinder four-stroke diesel engine, having swept volume of 850×10^{-6} m^3 is tested at 300 rpm. When a braking torque of 50 Nm is applied, analysis of the indicator diagram results in mean effective pressure of 0.8 MPa. Calculate BP and mechanical efficiency.

(d) Compare petrol and diesel engines.

(e) What is the difference between indicated and brake power of an engine? Define mechanical efficiency. By monitoring an engine it is found that the engine requires 10 kW with all cylinders simply inhaling and exiting air. The engine produces 98 kW on full load. Find the mechanical efficiency at

  (i) full load,

  (ii) half load, and

  (iii) quarter load.

6.6 OCTANE AND CETANE NUMBERS

Self ignition temperature (SIT) of a fuel is the temperature at which the fuel ignites on its own without spark. If large amount of mixture in an engine cylinder auto ignites rapid rise in pressure occurs causing direct blow on engine structure accompanied by thudding sound. This causes vibrations in the engine. The phenomenon is called *knocking*.

If, however, a small pocket of fuel-air mixture auto ignites, pressure waves are generated which travel with speed of sound across the cylinder. These pressure waves are of such small duration that indicator diagram mechanism fails to record them. These waves interact within themselves and with the cylinder walls, creating characteristic *ping* sound. The phenomenon is called *pinking*. The engine runs rough, overheats and loses efficiency due to knocking and pinking.

The processes of knocking and pinking are related to the nature of the fuel and relative merits of the fuel are decided on the basis of their antipinking and antiknock property. The merit is measured by *octane number* such that a fuel of high octane number will be liable to less pink or knock as compared to a fuel of low octane number in the same engine. It is important to note that the same fuel will not show same tendency to pink or knock in all engines.

Commonly used fuel in SI engines is a mixture of iso-octane and *n*-heptane. Iso-octane has minimum tendency to knock and this fuel is arbitrarily assigned an octane number of 100 ($ON = 100$). *n*-heptane has maximum knocking tendency with $ON = 0$. The octane number of a given fuel is percentage of iso-octane in the mixture of iso-octane and *n*-heptane. Thus, a fuel other than mixture of iso-octane and *n*-heptane if assigned an *ON* of 80 will knock under standard operating condition similar to the mixture of 80% iso-octane and 20% *n*-heptane.

The tendency to knock increases with increase in compression ratio. The highest compression upto which no knocking occurs in a given engine is called *highest useful compression ratio* (HUCR).

Certain chemical compounds when added to the fuel successfully suppress the knocking tendency. Tetraethyl lead [$Pb (C_2 H_5)_4$], also commonly called TEL and tetramethyl lead [$Pb (CH_3)_4$], also referred to as TML, are effective dopes in the automobile fuel to check knocking. However, because of lead poisoning effects TEL and TML are not being used. Some organic anti-knocking agents have been developed.

In CI engine, air alone is compressed to a compression ratio of 15 to 20 (commonly). The fuel is injected under a pressure of 120 to 210 bars about 20^o to 35^o before TDC. As the fuel evaporates the pressure in the cylinder drops. The ignition begins a little while latter. The time between beginning of injection and the beginning of combustion is known as *delay period* which consists of time for atomization, vapourization and mixing alongwith time for chemical reaction prior to auto-ignition. The combustion of fuel continues in the expansion and is called *after burning.* Increased delay period causes accumulation of atomized fuel in the combustion chamber and as the pressure and temperature continue to rise at one instant the bulk of fuel auto-ignites. This would result in high forces on the structure of the engine causing vibration and rough running.

The CI engine fuel rating is based on ignition delay and is measured in terms of cetane number. *Cetane* fuel [$C_{16}H_{10}$] has very low delay period and is arbitrarily assigned a cetane number of 100. Another fuel *α-methyl-napthalene* [$C_{11}H_{10}$] has poor ignition quality and is assigned zero cetane number. The volume percentage of cetane in a mixture of cetane and α-methyl-napthalene is the cetane number of the fuel that produces same delay period as the mixture under specified test conditions.

Additives such as methyl nitrate, ethyl thionitrate and amyl nitrate increase cetane number respectively by 13.5%, 10% and 9% if added to the extent of 0.5%.

6.7 POLLUTION

Pollution has become a catchword these days. Pollution deteriorates air quality whereby human health is badly affected. The plants, crops, concrete and steel structure are also damaged. Even the climatic changes are effected due to pollution which is understood as addition of such compounds and substances to environment components which will affect their functioning. Out of three components of environment – the air, water and the soil – the one which is most influenced by the IC Engines is air. Although all the engines and industrial furnaces throwing polluting gases in the atmosphere have considerably increased the amount of pollutant yet they taken together have not exceeded 1%.

The most important product of combustion is CO_2. This gas is a greenhouse gas in that it causes atmospheric temperature to rise. More than 150 years ago CO_2 in air was only 250 ppm (parts per million). Now it is more than 350 ppm and has certainly caused average temperature of atmosphere to increase by half a degree. Today, the effect is felt in the warmth and change in climatic and rain patterns but if it continues like this it may cause melting of ice cap. Water will flow to oceans and raise sea level thus drowning big chunks of land. Not much scope is available in this text to go into further details but there is fair amount of warning for future since the use of IC engine in automobile has no indication of subsiding.

CO, oxides of nitrogen (NO_x) , hydroxyl radicals, atomic oxygen and hydrogen, SO_2 and unburnt hydrocarbons are invariably there in the exhaust of engines. CO is a poison which can kill. Nitrogen oxide and unburnt hydrocarbons produce an effect which is combination of smoke and fog and has been nick named as smog. Smog reduces visibility to almost zero. Many hydrocarbons (polynuclear aromatic) are known carcenogenic. Soot is also formed if fuels do not mix with air before combustion. Soot are particulate matter which remain suspended in the air and may cause respiratory problems and damage the vegetation.

CO_2 and CO in the exhaust vary opposite to each other. At stoichiometric A/F ratio CO_2 is maximum at 13% and CO very low at about 2%. When A/F is high (like idling) CO is as high as 16% and CO_2 is lowest at 4 %. NO_x is low even at A/ F of 12 but becomes much at 0.4% if A/F is 16. In an automobile NO_x is high during acceleration and during cruising. CO is high during deceleration.

Although all products of combustion can be calculated, yet, it is preferable that they are measured. Methods of measurement include chemical absorption in liquid or solid reagents or physical method based on thermal conductivity, infrared absorption, chromatography, paramagnetism and sonic velocity.

It has been recognized that all those pollutants mentioned above are also naturally added to environment. But economic activities of man have increased the atmospheric burden to a level where harmful effects have become most obvious. Out of several sources which the man has created, automobile seems to be greatest culprit of last century. There appears to be no respite from automobiles. Any country where the use of automobile is high (or very high) very large amount of CO_2 will be produced. USA produces 15% of all the CO_2 produced artificially. A survey conducted by environmental protection agency of USA in 1980 found that automobiles were responsible for 42% of all the artificial pollution. It was also found in the survey that CO, about half of hydrocarbon and one third of NO_x due to transportation come from petrol engines. Diesel automobiles contributed only toward suspended particulate matter.

Besides several design changes brought in the automobile, devices are also being used to reduce pollution. Changes have been brought in induction of charge, combustion process, ignition system etc. Perhaps the most successful is exhaust treatment. The device called catalytic converter is capable of reducing CO, NO_x and hydrocarbons. Three-way single-stage catalytic converters are successful but require precise fuel control. Catalyst consists of two metals reducing and oxidizing. NO_x is to be reduced (removal of oxygen) whereas CO and HC are to be oxidized (addition of oxygen). Rhodium, monel and ruthenium are used as reducing catalyst. Platinum and palladium are used as oxidizing catalyst.

6.8 SUMMARY

Internal combustion engine is a power producing device having fuel combustion inside its cylinder. It consists of a closed cylinder in which piston slides. Piston through a connecting rod is connected to a crank on the main shaft of the engine. The fuel is burnt in the confined space between piston and walls and head of the cylinder. The gases then expand, exert force on the piston and make it move to the other end (BDC). The motion and force through connecting rod are transmitted to the crank and power obtained at the engine shaft.

The natural process requirement is that charge should be inhaled, be compressed to the smallest possible volume (clearance volume), fuel should burn and expansion should take place. The charge may consist of a mixture of fuel and air in case of engine operating on Otto cycle and fuel will be such that can evaporate easily and mixed intimately with air. The gaseous fuel and petrol (gasoline) are such fuels. The charge is compressed to the extent, the fuel does not ignite on its own. The compression ratio is limited to 7 or 8. To cause ignition a spark is generated.

The other kind of IC engine is the one which operates on Diesel cycle and uses diesel fuel, another petroleum derivative. The air is the charge which is compressed to a high pressure and temperature (compression ratio of 14 to 22). The temperature of compressed air is greater than auto ignition temperature of diesel fuel which is injected into clearance volume through an injector. The combustion occurs without any external aid.

The processes of inletting the charge, its compression, expansion exiting out of the cylinder, each may be accomplished through one full travel of piston from one end of the cylinder to the other. This motion is one stroke and for two such strokes the cranks will move one full rotation. The admission and exhaust of charge and remaining gases will be through valves which will open and close, actuated by mechanism at the proper instants of the time. Such engines are four-stroke engines and produce power in one of four strokes or two shaft rotation.

On the other hand in two stroke engines the admission of the charge and exhaust of burnt gases take place at the end of expansion stroke through openings (ports) provided in the lower region of the cylinder. Naturally it is possible that some charge may also exit or some burnt gases may remain in the cylinder. Yet the two-stroke engine provides the advantage of producing same energy in two strokes or one revolution as the comparable four-stroke engine will do in four strokes or two revolution and no power loss in valve mechanism. But exhaust of fresh charge without combustion is loss and polluting.

The engine performance is checked through the power produced at the shaft and is called brake power (BP). BP is compared with the power produced in the cylinder, called indicated power (IP). The ratio, BP/IP, is mechanical efficiency and difference (IP – BP) is power lost in friction. Another quantity to compare with BP is the heat produced by combustion of fuel (Heat of fuel). The ratio of BP/Heat of fuel is brake thermal efficiency. Since engine operates upon an ideal cycle it will have an air standard efficiency which can have no relationship with mechanical efficiency. It is compared with brake thermal efficiency and ratio is called relative efficiency.

The exhaust from IC engines contain CO_2, CO, NO_x, SO_2 and unburnt hydrocarbons alongwith some soot. All these have bad effects. There is no way to avoid CO_2 but others can be reduced by design or devices. Hence attempts are made to reduce the polluting gases and smoke.

6.9 ANSWERS TO SAQs

SAQ 1

(a) Fuel type, Ideal cycle of operation, Number of strokes of piston per cycle of operation, Type of ignition, Governing, Number of cylinders.

(b) All the heat produced by the fuel is not converted into work. Part of the heat is carried away by exhaust gases and this has been taken into account by way of "heat rejected". Some heat is also rejected to cooling medium which is mostly water flowing through jacket of cylinder and head. This heat is about 25% of heat of fuel, which means

$$\text{Work done per cycle} = Q_{41} - 0.25\, Q_{41} - Q_{23}$$

$$= (0.75 \times 152 - 74.2)\, 10^3$$

$$= 39.8 \times 10^3 \text{ J}$$

$$\text{Work done per sec.} = \frac{39.8 \times 10^3 \times 1000}{2 \times 60}$$

$$= 331.7 \text{ kJ/s}$$

$$\text{Power} = 331.7 \text{ kW}$$

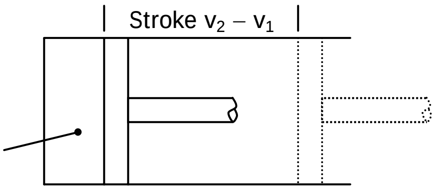
(c) $$\text{Stroke Volume} = \frac{\pi}{4} d^2 L = \frac{\pi}{4} (177.56)^2 \times 254 = 6.286 \times 10^6 \text{ mm}^3$$

$$= v_2 - v_1$$

Total cylinder volume

$$= v_2 - v_1 + v_1 = (6.286 + 1.5) \times 10^6 = v_2 = 7.786 \times 10^6 \text{ mm}^3$$

$$\text{Compression ratio} = r = \frac{v_2}{v_1} = \frac{7.786}{1.5} = 5.2$$



Use $\gamma = 1.4$

$\therefore$

$$\eta = 1 - \frac{1}{r^{\gamma - 1}} = 1 - \frac{1}{(5.2)^{0.4}} = 0.475 \text{ or}$$

47.5%.

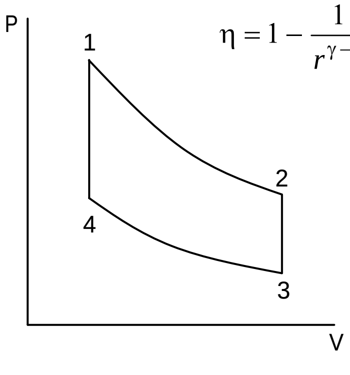


Figure 6.15

(d) $T_1 = 410$ K, $T_3 = 276$ K

$$\eta = \frac{T_1 - T_3}{T_1} = \frac{410 - 276}{410} = 0.327 \quad \text{or} \quad 32.7\%.$$

SAQ 2

(c) BP = Torque × Angular velocity

(W) = (Nm) × (rad/s)

$$\text{BP} = 50 \times \frac{2\pi \times 300}{60}$$

$$= 1570.8 \text{ W} \qquad \ldots \text{(i)}$$

$$\text{IP} = \text{m.e.p} \times A \times l \times \frac{N}{2}$$

mep = 0.8×10^6 N/m^2 , (Al) = swept vol = 850×10^{-6} m^3

$$N = \frac{300}{60} \text{ rps}$$

$$\therefore \qquad \text{IP} = 0.8 \times 10^6 \times 850 \times 10^{-6} \times \frac{300}{120}$$

$$\text{IP} = 1700 \text{ W}$$

$\therefore$ Mechanical Efficiency, $\eta_m = \frac{\text{BP}}{\text{IP}} = \frac{1.57}{1.70}$

$$\eta_m = 0.92 \quad \text{or} \quad 92\%.$$

(d) Petrol engines have low initial cost, low weight, and smaller size for same power as diesel engine. They require less cranking effort for starting and their exhausts have less objectionable odour. For these reasons they are preferred for cars, aeroplanes and where less noise is required. They are preferably used for intermittent service.

Diesel engines have low specific fuel consumption at both full and part loads, less fire hazard, perhaps longer life. Though more suited to 2-stroke, yet not used in small size. Large marine engines are made

2-stroke. Diesel engines are good for continuous running like generator and long distance transport on road and in sea.

(e) Further note that IP = BP + FP

FP is power to overcome friction.

FP remains same under all load conditions.

Under full load condition the BP = 98 kW

$$\therefore \quad \text{IP} = 98 + \text{FP} = 98 + 10 = 108 \text{ kW}$$

$$\therefore \quad \eta_m = \frac{\text{BP}}{\text{IP}} = \frac{98}{108}$$

or $\eta_m = 0.907$ or 90.7% . . . (i)

At half load, $\text{BP} = \frac{98}{2} = 49 \text{ kW}$

$$\therefore \quad \eta_m = \frac{49}{49 + 10} = \frac{49}{59}$$

$\therefore \quad \eta_m = 0.83$ or 83%

At quarter load, $\text{BP} = \frac{98}{4} = 24.5 \text{ kW}$

$$\therefore \quad \eta_m = \frac{24.5}{24.5 + 10} = \frac{24.5}{34.5}$$

or $\eta_m = 0.71\%$ or 71%.