Mechanical Engineering

Internal Combustion Engines

Comprehensive Theory

with **Solved Examples** and **Practice Questions**

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Contents

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CHAPTER 04

Ignition, Engine Friction, Lubrication and Cooling

4.1 Introduction

In a SI engine, the combustion process is initiated by an electrical discharge between the spark plug electrodes when the piston is close to the end of compression process. The ignition system carries the electric current to the spark plug where the spark necessary to ignite the fuel-air mixture is produced. The high temperature plasma kernel created by the spark develops into a self-sustaining and propagating flame front, a thin reaction sheet, where the exothermic chemical reactions occur. The ignition Initiates this flame propagation process in a repeatable manner cycle-by-cycle, under all operating conditions of load and speed, and at the appropriate point in the engine cycle.

Times the sole objective of the ignition system is to initiate the combustion process and it is not associated with the gross behaviour of combustion phenomena. Therefore, the ignition system should be considered from the standpoint of the beginning of the combustion process that it initiates.

4.2 Energy Requirement

The development of a high compression ratio engine led to the development of a system which can product a light-tension spark across a short fixed gap in the combustion chamber for the ignition of the charge. A spark can be produced from one plug electrode to other only if a sufficiently high voltage is applied. In a typical spark discharge, the electrical potential across the electrode gap is increased until the breakdown of the intervening mixture occurs. This breakdown voltage (preceded by arc and (low discharge) is the critical voltage below which there can be no spark. About 0.2 mJ of energy is required to ignite a quiescent stoichiometric fuel-air mixture at normal engine conditions by means of a spark. If the mixture is rich or lean, the energy required Is about 3 mJ. It has been found that the critical spark energy required to ignite a given mixture decreases rapidly as the sparking voltage is increased. Thus, in a typical instance, for a mixture strength of 12.5 : 1, the spark energy required to ignite this charge was 5 mJ at 5 kV, 2 mJ at 6 kV and 0.7 mJ at 7 kV. Figure shows the minimum spark energy required for different air-fuel (gasoline) ratios.

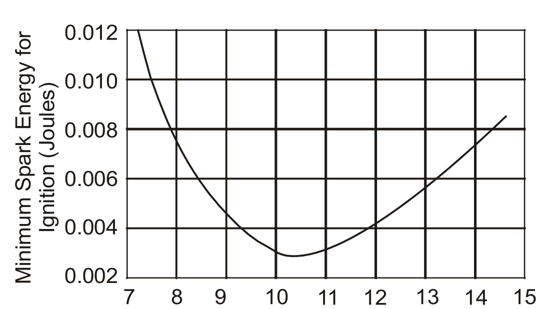

Figure 4.1 Ratio of air to Gasoline

The conventional ignition system delivers about 30 mJ of electrical energy to the spark. Thus a small fraction of the energy supplied to the spark gap is transmitted to the gas mixture and the rest of the energy is lost as heat energy.

It may be mentioned that the mixture in the spark gap is never entirely homogenous-it may be very rich or may be a lean mixture and sometimes it may contain a few droplets of fuel or oil. Therefore, the practical picture of ignition to suit all conditions not only demands that energy be furnished quickly, but also requires a definite duration of spark. The conventional ignition systems deliver 30 to 50 mJ of electrical energy to the spark and the duration is longer than 0.5 ms to ignite the charge and initiate the combustion process.

4.3 Requirements of An Ignition System

The requirements of a smooth and reliable ignition system can be listed as following :

1. The system must provide sufficient voltage across the spark plug electrodes to produce a spark discharge.
2. The system should supply sufficient energy during spark discharge to ignite the combustible mixture adjacent to the plug electrodes under all operating conditions.
3. The spark should be produced at the appropriate point during the compression process and in a repeatable manner cycle-by-cycle. The duration of the voltage pulse should be sufficient to ensure ignition.
4. The system should have the means for automatically changing the spark timing with changes in load and engine speed.
5. The peak voltage produced by the system must be safe so that there is no damage to the spark plug electrodes.

Since the ignition system should have a source of electrical energy and that can be obtained either by a battery or by a generator or magnets, three methods have been generally employed to produce the necessary high voltage, and they are based on the principles of mutual electromagnetic induction. These are :

(a) Battery Ignition System, (b) Magnet Ignition System, and
(c) Electronic Ignition System.

4.4 Battery Ignition System

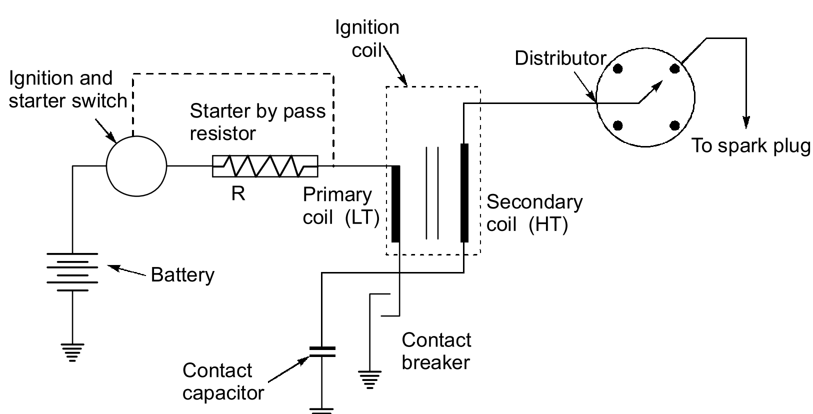

Figure 4.2 Mechanically Operated Battery Ignition System

The components of a conventional battery system shown in figure are a 12 V battery, an ignition switch, an ignition coil, a resistor, a distributor (which houses the breaker points, cam condenser, rotor and advance mechanism), spark plugs, and low and high-tension wiring.

Battery : The storage battery is an electrochemical device which converts chemical energy into electrical energy. The main functions of a battery are : (i) to supply a high current (upto 200 amperes) to the starter motor and a low current to the ignition system, (iii) to supply current to the electrical units when the total demand exceeds the power output of the generator fitted to the engine. The battery is charged by a dynamo driven by the engine. Automobiles generally use two types of batteries-lead-acid, and nickel-alkaline type. The fully charged battery has an electrolyte of 1.26 - 1.28 specific gravity and contains 23% sulphuric acid.

Ignition Switch : The 12 V storage battery is connected to the primary winding of the ignition coil through an ignition switch and a resistor. The ignition system becomes operative when the switch is on.

Ignition Coil : In the conventional ignition system, the ignition coil is the source of energy needed for ignition. The coil stores the energy in its magnetic field and delivers it at the appropriate time in the form of a ignition pulse through the high-tension ignition cables to the respective spark plug. The high-tension ignition coil consists of an iron wire and primary and secondary wirings.

A typical ignition coil has a primary winding of 100 to 180 turns of No. 20 copper wire (N_p) and a secondary winding of about 18000 turns of No. 38 wire (N_s) wound around a cylindrical soft iron core. Each layer of winding is insulated from the next by a sheet of lead paper and entire assembly is sealed within an oil filled case, for better cooling and insulation from air with its humidity. The primary and secondary windings are connected to a common ground leaving three electrical terminals on the casing. The primary winding has its end connected to two primary terminals. The low tension terminal is connected to the battery and the contact breaker points. High tension current from the secondary winding flows to the distributor and the spark plug, as shown in figure.

Resistor : A resistance is usually added in the series with the primary winding to regulate the primary current. Sometimes, the resistance is bypassed or shorted by the starter switch so that the full battery voltage is available across the primary winding to provide higher current while starting the engine. The resistance may be temperature compensated so that extreme low temperatures will not lower its resistance to draw excessive primary current, and high temperatures do not increase its resistance to draw a reduced primary current. The resistance also decreases the time constant of the primary circuit.

Ignition Points : The ignition points are always arranged in such a way that the grounded one is stationary and the insulated one is attached to a movable breaker arm. The breaker arm is connected to the primary circuit and separated form the breaker cam by a non-conducting rubbing block. This way, when the cam lobe passes by the rubbing block of the insulated breaker arm, it separates the point and the primary circuit is disconnected.

The cam rotates with the camshaft, the speed is equal to the speed of the crankshaft in four-stroke engines. The contact points close when the ignition switch is on, the current flows from the battery through the primary winding, building a magnetic field. In the growing process, the magnetic field cuts the primary winding and a back emf is induced. This opposes the battery current and therefore delays the building process of the field. This time is required to attain maximum current and field strength. During this time, the distributor is rotating and approaching a terminal leading to a spark plug.

When the breaker points open, the magnetic field collapses, the current flows in both primary and secondary windings and the capacitances of the two circuits are charged. The voltage increases at the spark plug until it reaches a value that breaks down the spark gap. This process takes about 0.1 millisecond. Once the spark discharge takes place, the voltage falls and most of the electrical energy stored in the magnetic field is dissipated as heat to initiate combustion. The condenser in the circuit interrupts the primary current as quickly as possible and causes the flux field to collapse rapidly. When the contact points open, the current instead of passing across the points in the form of an arc, flows into the condenser charging the condenser. The charge in condenser immediately discharges back into the primary circuit in a direction reverse to the flow of battery current, thus assisting in a quicker collapse of the magnetic field when the breaker points open. If condenser is not there, the induced current would establish an arc across the contact points on separation and the collapse of the magnetic field would be prolonged.

Distributor : The distributor has three main functions to performs :

(a) allow the primary circuit to make and break (b) to interrupt the flow of current through the primary winding so that a high voltage is produced in the secondary winding and (c) to distribute the produced high voltage surge to different spark plugs of a multicylinder engine at the right time.

The major limitation of the breaker-operated ignition coil system are :

(a) the available voltage increase with increasing engine speed due to the limitating in the current switching capability of the breaker system, leading to poor efficiency.

(b) the time available to build up the primary coil stored energy decreases with increasing speed.

(c) the system is sensitive to side-tracking across the spark plug insulator.

(d) the breaker points are subjected to electrical and mechanical wear due to their high current load and this leads to reduce maintenance intervals.

(e) the life of the breaker points depends on the current they are required to switch. The life decreases with increasing current and so the reliability.

4.4.1 Spark Plug

The spark plug is probably the most important component of any ignition system. It provides the two electrodes at which the high voltage produces the spark for igniting the mixture. It is designed in operate under 20 to 30 kV and withstand pressure as high as 40 bar. For satisfactory performance the central electrode of the sparking plug should operate in the temperature range 350 to 700°C. If the electrode is too hot, pre-ignition is likely to occur. If the temperature is too low carbon deposits will build upon the central insulator leading to electrical breakdown. The heat flows from the central electrode through the ceramic insulator and a cool running engine requires a hot or soft sparking plug with a long heat flow path in the central electrode figure. A cool or hard sparking plug, figure is suitable for a high performance or high compression ratio engine and has a much shorter flow path for heat flow.

The electrical resistance of a spark plug depends on the nature and compression of the air-fuel mixture and upon the distance between the electrodes, called gap. This eaplth the engine design (0.5 mm to 1.25 mm). Too large or too small a spark plug gap reduces the efficiency of the entire ignition system, which in turn reduces the engine power and the operating efficiency. Thus, the requirements to be fulfilled by the plugs are as follows:

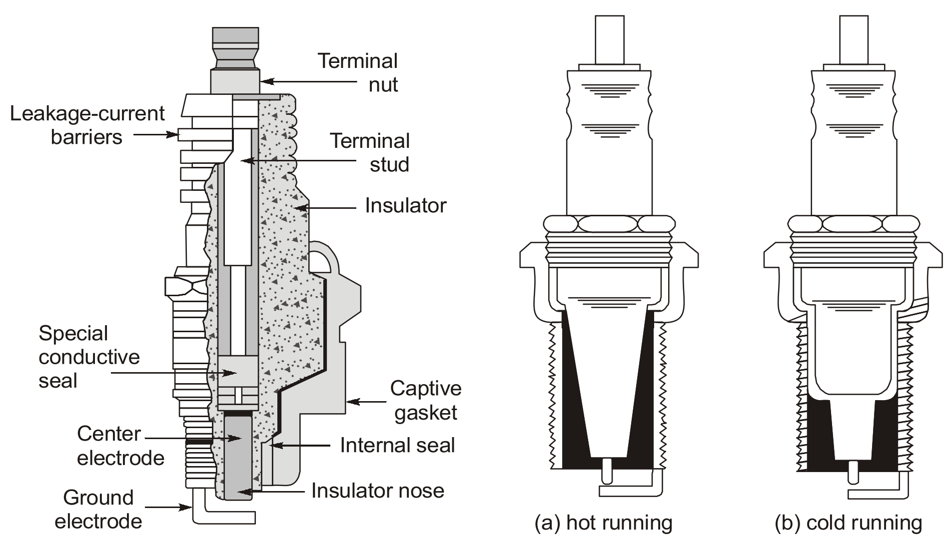

Figure 4.3 A typical spark plug

(i) They must operate satisfactorily under all conditions of load, engine speed, mixture strength and compression ratio of modern high output SI engines.

(ii) They must possess a high heat resistance so that the electrodes do not becomes sufficiently hot to cause pre-ignition effects.

(iii) They must offer the maximum resistance to erosion, or burning away of the spark plug points whatever type of fuel is employed.

(iv) The insulating material should have excellent insulating properties, good thermal conductivity and the insulation must be hermetically sealed in a water-height casing.

(v) There should be complete electrical screening to prevent electrical interference with the radio apparatus

(vi) There should be ease of dismantling for cleaning and inspection purposes.

4.5 Magneto-Ignition System

This system is being extensively used in mopeds, scooters, three wheelers, motor cycles, stationary engines and aircraft reciprocating engines. The system has got its own current generating unit without the assistance of a battery and ignition coil. The main components of the system are magnets, breaker-points, condenser, distributor and spark plug. The schematic block diagram is shown in figure. The magnets substituting the battery and ignition coil, has a four-pole magnet, two-pole shoes, the primary and secondary coils. When the magnet rotates, the direction of the magnetic flux through the soft iron core of the coil reverses direction. As a result of which, a voltage is induced in the primary and secondary coils. The breaker points and the condenser produce an increase in the rate of change of magnetic flux. When the breaker points are opened by the cam mounted on the rotor shaft, the condenser gets charged by currents from the primary coil. The highly charged condenser discharges itself into the primary circuit and this produces a rapid change In the magnetic flux. Due to this rapid change in the magnetic flux, a very high voltage is induced in the secondary coil and that will be sufficient to produce a spark discharge and ignite the fuel-air combustible mixture.

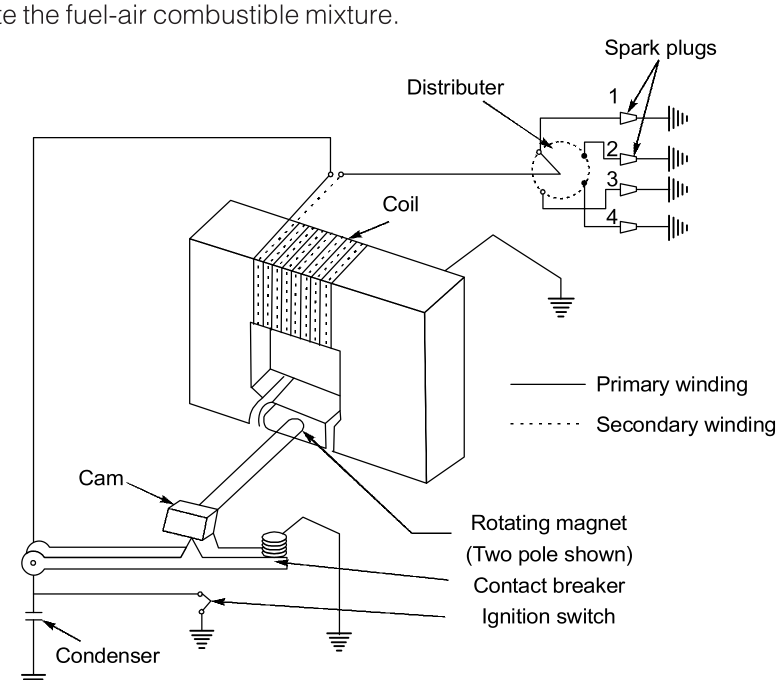

Figure 4.4 Schematic of a magneto ignition system

The magneto-ignition system occupies less space, is cheap and require little maintenance. The starting of engine is difficult because the spark is poor at low speeds and the efficiency of the system improves with the increasing speed.

In comparing the merits of the two methods of ignition, the advantages may be summarized, briefly, as follows ;

A. Magneto-Ignition :

1. More reliable as there is no battery of connecting cable. Moreover, with the coil ignition unit, if the battery has run down, the engine cannot be started unless a spare battery is available.
2. Is more suitable for ignition at medium to very high engine speeds although there is a tendency to give excessive voltages in the latter case, unless the magneto is designed specifically for these high speeds.
3. In modern designs of magneto, using the more recent cobalt steel and nickel-aluminium magnet metals, very light and compact units can be made which occupies a very limited space.
4. The more recent magnetos with modern magnet alloys are capable of giving very low starting speed ignition characteristics.
5. Automatic timing of the ignition can now be effected as readily as with coil ignition.
6. The powerful spark at high engine speeds which previously caused the plug electrodes to burn away can now be prevented by the use of suitable shunts on the magneto.

B. Coil Ignition System :

1. Gives a better spark for low speed starting.
2. Is cheaper to manufacture and to replace its component parts.
3. The half speed engine driver is usually simpler than the magneto drive.
4. It has no effect over the complete ignition timing range, whereas with the ordinary magneto, the spark timing adjustment (advance or retard) affects the voltage or energy.
5. Except the battery, the entire system is reliable.
6. Can be easily maintained.

4.6 Friction Power

Friction power (fp) can be defined as the difference between the indicated power (ip) and the brake power (bp),

i.e. Friction power (fp) = indicated power (ip) – brake power (bp) . . . (4.1)

The indicated power is the power delivered to the piston by the cylinder gases, and the brake power is the power measured as output at the crankshaft . All the indicated power transferred to the piston from the gases contained inside the cylinder is not available as brake power at the drive shaft. That portion of the power which is not available is usually termed friction power. The friction power is a sufficiently large fraction of the indicated power. It is about 10% at full-load and 100% at idle or no-load. Friction is an important factor taken into account while determining engine performance and efficiency. It directly affects the maximum brake torque and the minimum brake specific fuel consumption. A large part of the friction losses appears as heat in the coolant and lubricating oil which must be removed in the radiator and in the oil cooler system. Thus, die friction losses influence the size of the coolant system.

4.7 Components of engine Friction

Engine friction losses in a standard engine can be divided into three main types : (a) rubbings losses, (b) pumping losses, and (c) auxiliary component losses.

4.7.1 Rubbing Losses

Rubbing losses are defined as those which result from relative motion between solid surfaces in the engine. They include friction between the piston rings, piston skirt, and the cylinder wall; friction in the wrist pin, big end, crankshaft, and camshaft bearing; friction in the valve mechanism; friction in the gears, pulley or belts, which drive the camshaft and engine accessories.

4.7.2 Pumping Losses

Pumping losses are defined as those which are associated with transporting fluids through the cylinder and they are made up of intake and exhaust pumping. Intake pumping means that fresh mixture is drawn through the intake system and into the cylinder, and the exhaust pumping means that the burned gases are expelled from the cylinder and out of the exhaust system. The pumping work is divided into two parts one part is the throttling work, it includes the effect of restrictions outside the cylinder in the inlet and exhaust systems, i.e. air filters, carburettor, throttle valve, intake manifold, exhaust manifold and tail pipe, catalytic converter and muffler. The other parts is the valve flow work. It corresponds mainly to pressure losses in the inlet and exhaust valves. As the load is reduced in an SI engine, the throttle restriction is increased, which increases the throttling work and decreases the valve flow work. The increase in throttling work is much more rapid than the decrease in valve flow work. Both throttling work and valve flow work increase as speed increases at constant load.

4.7.3 Auxiliary Components Losses

Auxiliary components losses include both rubbing and pumping losses due to driving of the engine accessories. These may include the fan, the water pump, the oil pump, the fuel pump, the generator, a power steering pump, and air-conditioner, etc.

As all the above losses are eventually dissipated as heat, the term friction work or friction power is therefore appropriate.

4.8 Total Friction Work

The total friction work, W_{tf} is the sum of the rubbing friction work, W_{rf} the pumping work, W_p and the accessory work W_a.

$$W_{tf} = W_{rf} + W_p + W_a \quad \text{. . . (4.2)}$$

Rubbing friction work is the work per cycle dissipated in overcoming the friction due to relative motion of adjacent components within the engine.

Pumping work is defined as the net work per cycle done by the piston on the gases during the inlet and exhaust strokes. It is represented by the area *B* in figure. The area *A* in the diagram represents the gross indicated work. The pumping work is the negative work, i.e. die work done by the piston on the gas and the gross indicated work is a positive work. i.e. the work done by the gases on the piston. Therefore, the net work per cycle is the difference between gross work and pumping work. i.e. area A - area B.

Accessory work is the work per cycle required to drive the engine accessories. e.g. pumps, fans, generator, etc.

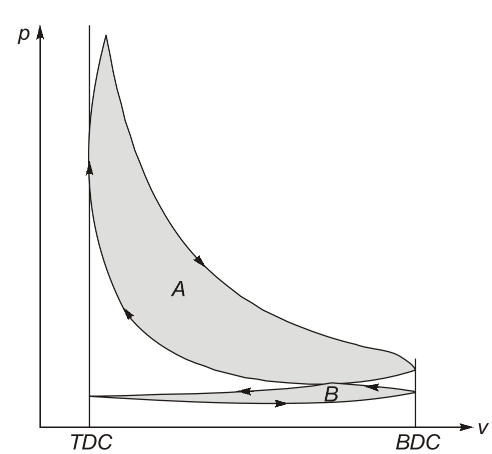

Figure 4.5 Pressure volume (p-V) diagram of a four-stroke engine indicating pumping work (area B) and gross work (area A)

4.9 Some More Components of Engine Friction

In two-stroke engines, a scavenging pump is used for the scavenging process. In such cases the power taken from the crankshaft to drive a scavenging pump is included in the friction power. In supercharged engines the power taken from the crankshaft to drive a supercharger is also included in the friction power. In some engines, an exhaust turbine is geared to the crankshaft. In such cases the power developed by the turbine will add to the brake power of the engine and could be classed as negative friction loss.

4.10 Friction Mean Effective Pressure

Engines are made up of different size and they run at different speeds, therefore, the most meaningful method of classifying and comparing frictional losses is in terms of mean effective pressure. The mean effective pressure (mep) can be related to work per cycle or power term as follows :

$$\text{Work per cycle, } W = (mep)\, V_s \qquad \ldots (4.3)$$

$$\text{Power, } \dot{W} = (mep) V_s \left(\frac{N}{n}\right) \qquad \ldots (4.4)$$

where V_s = Swept volume

N = Engine speed

n = Number of revolutions per cycle.

The friction mean effective pressure can be related to other mean effective pressures as follows :

$$fmep = imep - bmep - amep - cmep + temp \qquad \ldots (4.5)$$

and

$$imep = gmep - pmep \qquad \ldots (4.6)$$

where, $amep$ = Auxiliaries mean effective pressure

$bmep$ = Brake mean effective pressure

$cmep$ = Mean effective pressure to drive the compressor as a supercharger or scavenging pump

$fmep$ = Friction mean effective pressure corresponding to rubbing losses only

$gemp$ = Gross mean effective pressure

$imep$ = Indicated mean effective pressure

$pmep$ = Pumping mean effective pressure

$temp$ = Mean effective pressure recovered from the exhaust gas in a turbocharger.

If the turbine of a turbocharger is used to run the compressor only and the auxiliary work is ignored, then

$$cmep = temp \quad \text{and } amep = 0$$

$$\therefore \quad femp = imep - bmep \qquad \ldots (4.7)$$

The friction mean effective pressure can be related to engine speed by the following empirical relation.

$$fmep = A + BN + CN^2 \qquad \ldots (4.8)$$

where N = Engine speed

A, B, C = Empirical constants related to a specific engine.

The first term on the right-hand side of equation, constant A, accounts for boundary friction, i.e. metal-to-metal contact which occurs between the piston rings and the cylinder walls particularly at TDC and BDC, and in heavy-loaded bearings of the crankshaft.

The second term of equation, BN, is proportional to engine speed and accounts for the hydraulic shear that occurs between many lubricated components. The shear stress τ_s is given by

$$\tau_s = \mu \frac{du}{dy} \quad \text{. . . (4.9)}$$

where μ = Dynamic viscosity of lubricating oil

$\frac{du}{dy}$ = Velocity gradient between surfaces.

For a given viscosity and geometry, the velocity term *du* is proportional to the engine speed *N*. The third term of equation, CN^2, is proportional to the square of the engine speed. This term accounts for the losses from turbulent dissipation in the intake and exhaust flows. Constants *A*, *B* and *C* depends upon the operating conditions of a given engine.

4.11 Mechanical Friction

All rubbing losses are the result of mechanical friction. It is the sum of resistance to motion of all the engine parts. The friction associated with the engine rubbing surfaces may be divided into the following classes :

1. Hydrodynamic or fluid-film friction
2. Partial-film friction
3. Rolling friction
4. Dry friction

4.11.1 Hydrodynamic or Fluid-film Friction

All hydrodynamic or fluid-film friction is associated with surfaces entirely separated by a film of lubricant. In this case the friction force entirely depends on the lubricant viscosity, which is a measure of the resistance to shear possessed by the oil film. This type of friction is the main component of the mechanical friction losses in an engine.

4.11.2 Partial-film Friction

Partial-film friction is associated with surfaces partially separated by a film of lubricant. In this case, some parts of the rubbing surfaces are lubricated and some parts of the surfaces are in contact. During starting the engine bearing surfaces operate under this condition. However, in normal engine operation there is a very little metallic contact except between the piston rings and cylinder walls for a brief moment at the end of each stroke when the piston velocity is nearly zero. Thus partial-film friction is of little importance and contributes very little to engine friction.

4.11.3 Rolling Friction

The rolling friction is due to the rolling motion between the two surfaces. It is associated with ball-and-roller bearings and with cam-followers and tappet rollers. These bearings have a coefficient of friction which is nearly independent of load and speed. Rolling friction is negligible in comparison to total friction.

4.11.4 Dry Friction

It is not important in engines because some lubricant nearly always remains between the rubbing surfaces, even when an engine is not used for a long period of time. Dry friction can therefore be safely neglected while considering engine friction.

4.12 Mechanical Friction in Major Engine Components

Mechanical friction in some important components of the engine is described in this section.

Answers

1. (a)	2. (a)	3. (a)	4. (b)	5. (d)
6. (c)	7. (a)	8. (b)		

Hints and Explanations:

2. (a)

$$(IP)_n = (BP)_n + FP$$
$$(IP)_{n-1} = (BP)_{n-1} + FP$$
$$(IP)_{1st} = (BP)_{n\ cylinder} - (BP)_{n-1}$$
$$= 9 - 4.25 = 4.75 \text{ kW}$$
$$(IP)_{2nd} = 9 - 3.75 = 5.25 \text{ kW}$$
$$\text{Total IP} = 4.75 + 5.25 = 10 \text{ kW}$$
$$\therefore \quad \eta_m = \frac{BP}{IP} = \frac{9}{10} \times 100 = 90\%$$

Student's Assignments

Q.1 What is ignition? How does it differ from combustion?

Q.2 Explain, with a neat sketch, the working principles of a battery ignition system.

Q.3 Describe, with a neat sketch, the working of magneto ignition system.

Q.4 State the properties of a good lubricant.

Q.5 Why cooling of an IC engine is necessary?

Q.6 Compare the merit and demerits of air and water cooling system.