COMBUSTION AND COMBUSTION CHAMBERS

12.1 INTRODUCTION

Combustion is a chemical reaction in which certain elements of the fuel like hydrogen and carbon combine with oxygen liberating heat energy and causing an increase in temperature of the gases. The conditions necessary for combustion are the presence of combustible mixture and some means of initiating the process. The theory of combustion is a very complex subject and has been a topic of intensive research for many years. In spite of this, not much knowledge is available concerning the phenomenon of combustion.

The process of combustion in engines generally takes place either in a homogeneous or a heterogeneous fuel vapour-air mixture depending on the type of engine.

12.2 HOMOGENEOUS MIXTURE

In spark-ignition engines a nearly homogeneous mixture of air and fuel is formed in the carburettor. Homogeneous mixture is thus formed outside the engine cylinder and the combustion is initiated inside the cylinder at a particular instant towards the end of the compression stroke. The flame front spreads over a combustible mixture with a certain velocity. In a homogeneous gas mixture the fuel and oxygen molecules are more or less, uniformly distributed.

Once the fuel vapour-air mixture is ignited, a flame front appears and rapidly spreads through the mixture. The flame propagation is caused by heat transfer and diffusion of burning fuel molecules from the combustion zone to the adjacent layers of unburnt mixture. The flame front is a narrow zone separating the fresh mixture from the combustion products. The velocity with which the flame front moves, with respect to the unburned mixture in a direction normal to its surface is called the normal flame velocity.

In a homogeneous mixture with an equivalence ratio, ϕ, *(the ratio of the actual fuel-air ratio to the stoichiometric fuel-air ratio)* close to 1.0, the flame speed is normally of the order of 40 cm/s. However, in a spark-ignition engine the maximum flame speed is obtained when ϕ is between 1.1 and 1.2, i.e., when the mixture is slightly richer than stoichiometric.

If the equivalence ratio is outside this range the flame speed drops rapidly to a low value. When the flame speed drops to a very low value, the heat loss from the combustion zone becomes equal to the amount of heat-release due to combustion and the flame gets extinguished. Therefore, it is quite preferable to operate the engine within an equivalence ratio of 1.1 to 1.2 for proper combustion. However, by introducing turbulence and incorporating proper air movement, the flame speed can be increased in mixtures outside the above range.

12.3 HETEROGENEOUS MIXTURE

In a heterogeneous gas mixture, the rate of combustion is determined by the velocity of mutual diffusion of fuel vapours and air and the rate of chemical reaction is of minor importance. Self-ignition or spontaneous ignition of fuel-air mixture, at the high temperature developed due to higher compression ratios, is of primary importance in determining the combustion characteristics.

When the mixture is heterogeneous the combustion can take place in an overall lean mixture since, there are always local zones where ϕ varies between 1.0 and 1.2 corresponding to maximum rate of chemical reaction. Ignition starts in this zone and the flame produced helps to burn the fuel in the adjoining zones where the mixture is leaner. Similarly, in the zones where the mixture is rich the combustion occurs because of the high temperature produced due to combustion initiated in the zones where ϕ is 1.0 to 1.2.

A comprehensive study of combustion in both spark-ignition and compression-ignition engines is given in the following sections.

12.4 COMBUSTION IN SPARK–IGNITION ENGINES

As already mentioned, in a conventional spark-ignition engine, the fuel and air are homogeneously mixed together in the intake system, inducted through the intake valve into the cylinder where it mixes with residual gases and is then compressed. Under normal operating conditions, combustion is initiated towards the end of the compression stroke at the spark plug by an electric discharge. A turbulent flame develops following the ignition and propagates through this premixed charge of fuel and air, and also the residual gas in the clearance volume until it reaches the combustion chamber walls. Combustion in the SI engine may be broadly divided into two general types, viz., normal combustion and abnormal combustion.

12.5 STAGES OF COMBUSTION IN SI ENGINES

A typical theoretical pressure-crank angle diagram, during the process of compression (a→b), combustion (b→c) and expansion (c→d) in an ideal four-stroke spark-ignition engine is shown in Fig.12.1. In an ideal engine, as can be seen from the diagram, the entire pressure rise during combustion takes place at constant volume i.e., at TDC. However, in an actual engine this does not happen. The detailed process of combustion in an actual SI engine is described below.

Sir Ricardo, known as the father of engine research, describes the combustion process in a SI engine as consisting of three stages:

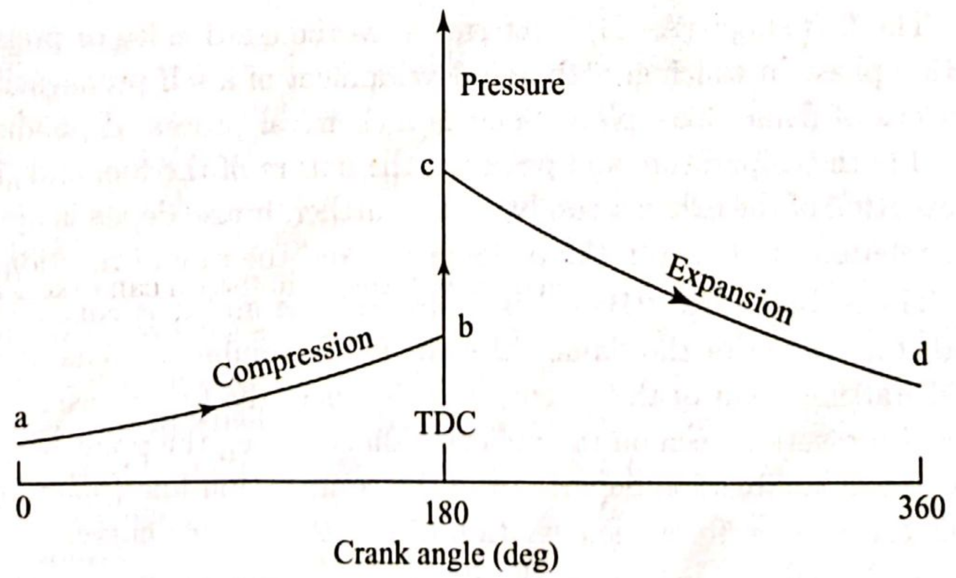


Fig. 12.1 Theoretical p-θ Diagram

The pressure variation due to combustion in a practical engine is shown in Fig.12.2. In this figure, A is the point of passage of spark (say 20°*bTDC*), B is the point at which the beginning of pressure rise can be detected (say 8° *bTDC*) and C the attainment of peak pressure. Thus AB represents the first stage and BC the second stage and CD the third stage.

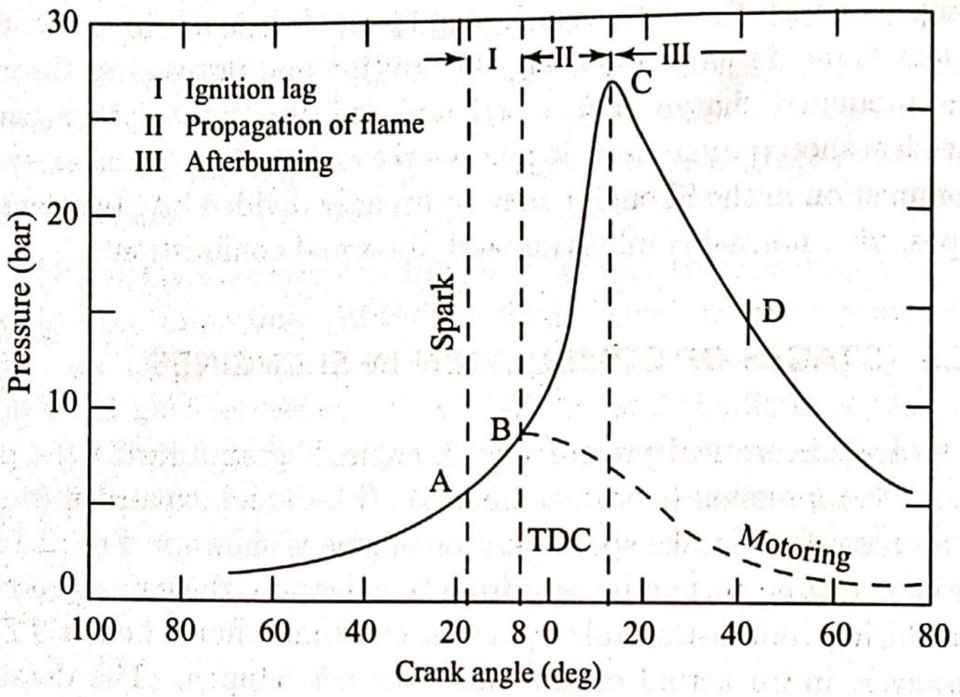


Fig. 12.2 Stages of Combustion in an SI Engine

The *first stage* (A→B) is referred to as the ignition lag or preparation phase in which growth and development of a self propagating nucleus of flame takes place. This is a chemical process depending upon both temperature and pressure, the nature of the fuel and the proportion of the exhaust residual gas. Further, it also depends upon the relationship between the temperature and the rate of reaction.

The *second stage* (B→C) is a physical one and it is concerned with the spread of the flame throughout the combustion chamber. The starting point of the second stage is where the first measurable rise of pressure is seen on the indicator diagram i.e., the point where the line of combustion departs from the compression line (point B). This can be seen from the deviation from the motoring curve.

During the second stage the flame propagates practically at a constant velocity. Heat transfer to the cylinder wall is low, because only a small part of the burning mixture comes in contact with the cylinder wall during this period. The rate of heat-release depends largely on the turbulence intensity and also on the reaction rate which is dependent on the mixture composition. The rate of pressure rise is proportional to the rate of heat-release because during this stage, the combustion chamber volume remains practically constant (since piston is near the top dead centre).

The starting point of the *third stage* is usually taken as the instant at which the maximum pressure is reached on the indicator diagram (point C). The flame velocity decreases during this stage. The rate of combustion becomes low due to lower flame velocity and reduced flame front surface. Since the expansion stroke starts before this stage of combustion, with the piston moving away from the top dead centre, there can be no pressure rise during this stage.

12.6 FLAME FRONT PROPAGATION

For efficient combustion the rate of propagation of the flame front within the cylinder is quite critical. The two important factors which determine the rate of movement of the flame front across the combustion chamber are the *reaction rate* and the *transposition rate.* The *reaction rate* is the result of a purely chemical combination process in which the flame *eats* its way into the unburned charge. The *transposition rate* is due to the physical movement of the flame front relative to the cylinder wall and is also the result of the pressure differential between the burning gases and the unburnt gases in the combustion chamber.

Figure 12.3 shows the rate of flame propagation. In area I, (A→B), the flame front progresses relatively slowly due to a low *transposition rate* and low turbulence. The transposition of the flame front is very little since there is a comparatively small mass of charge burned at the start. The low reaction rate plays a dominant role resulting in a slow advance of the flame. Also, since the spark plug is to be necessarily located in a quiescent layer of gas that is close to the cylinder wall, the lack of turbulence reduces the reaction rate and hence the flame speed. As the flame front leaves the quiescent zone and proceeds into more turbulent areas (area II) where it consumes a greater mass of mixture, it progresses more rapidly and at a constant rate (B→C) as shown in Fig.12.3.

The volume of unburned charge is very much less towards the end of flame travel and so the *transposition rate* again becomes negligible thereby reducing the flame speed. The reaction rate is also reduced again since the flame is entering a zone (area III) of relatively low turbulence (C→D) in Fig.12.3.

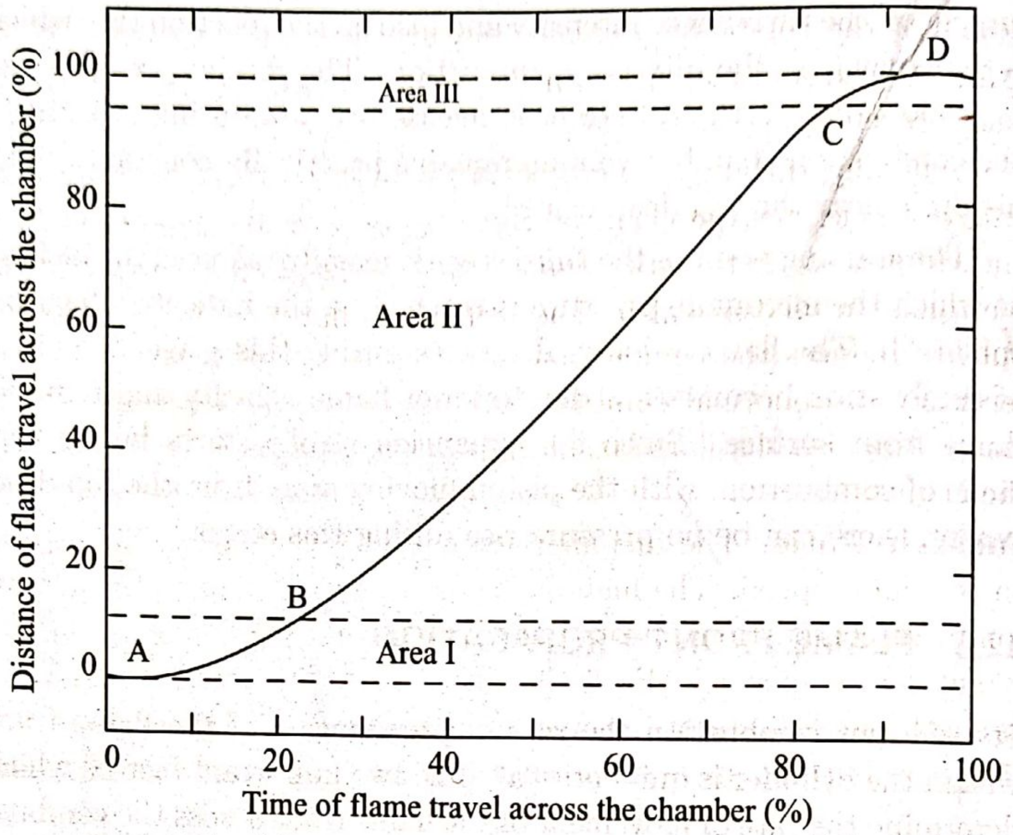


Fig. 12.3 Details of Flame Travel

12.7 FACTORS INFLUENCING THE FLAME SPEED

The study of factors which affect the velocity of flame propagation is important since the flame velocity influences the rate of pressure rise in the cylinder and it is related to certain types of abnormal combustion that occur in spark-ignition engines. There are several factors which affect the flame speed, to a varying degree, the most important being the turbulence and the fuel-air ratio. Details of various factors that affect the flame speed are discussed below.

Turbulence: The flame speed is quite low in non-turbulent mixtures and increases with increasing turbulence. This is mainly due to the additional physical intermingling of the burning and unburned particles at the flame front which expedites reaction by increasing the rate of contact. The turbulence in the incoming mixture is generated during the admission of fuel-air mixture through comparatively narrow sections of the intake pipe, valve openings etc., in the suction stroke. Turbulence which is supposed to consist of many minute swirls appears to increase the rate of reaction and produce a higher flame speed than that made up of larger and fewer swirls. A suitable design of the combustion chamber which involves the geometry of cylinder head and piston crown increases the turbulence during the compression stroke.

Generally, turbulence increases the heat flow to the cylinder wall. It also accelerates the chemical reaction by intimate mixing of fuel and oxygen so that spark advance may be reduced. This helps in burning lean mixtures also. The increase of flame speed due to turbulence reduces the combustion duration and hence minimizes the tendency of abnormal combustion. However, excessive turbulence may extinguish the flame resulting in rough and noisy operation of the engine.

Fuel-Air Ratio: The fuel-air ratio has a very significant influence on the flame speed. The highest flame velocities (minimum time for complete combustion) are obtained with somewhat richer mixture (point A) as shown in Fig.12.4 which shows the effect of mixture strength on the rate of burning as indicated by the time taken for complete burning in a given engine. When the mixture is made

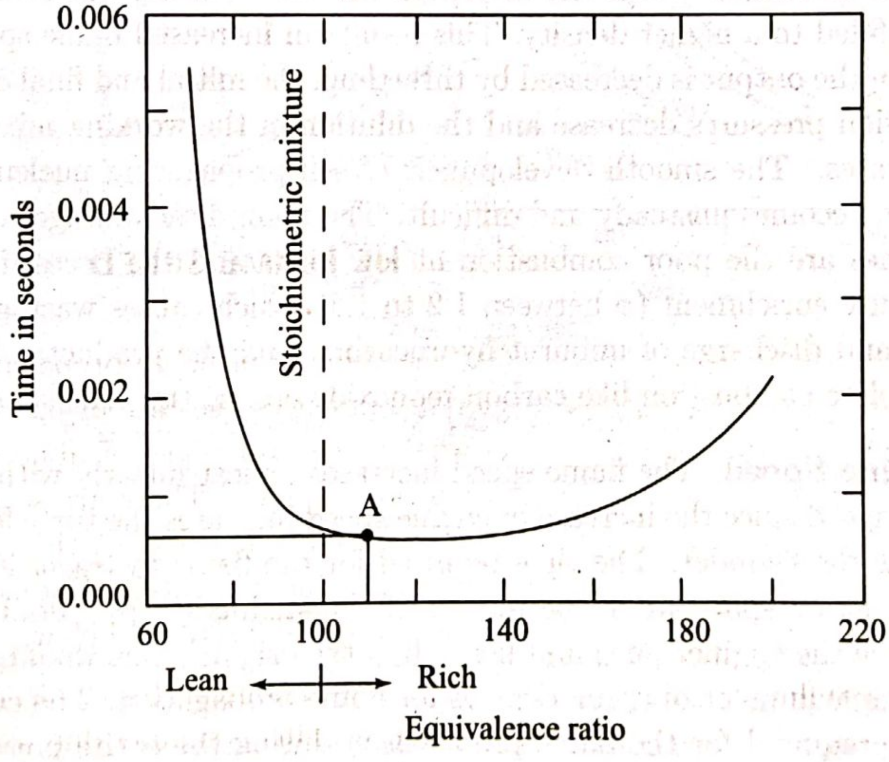


Fig. 12.4 Effect of Mixture Strength on the Rate of Burning

leaner or richer (see point A in Fig.12.4) the flame speed decreases. Less thermal energy is released in the case of lean mixtures resulting in lower flame temperature. Very rich mixtures lead to incomplete combustion which results again in the release of less thermal energy.

Temperature and Pressure: Flame speed increases with an increase in intake temperature and pressure. A higher initial pressure and temperature may help to form a better homogeneous air-vapour mixture which helps in increasing the flame speed. This is possible because of an overall increase in the density of the charge.

Compression Ratio: A higher compression ratio increases the pressure and temperature of the working mixture which reduce the initial *preparation phase* of combustion and hence less ignition advance is needed. High pressures and temperatures of the compressed mixture also speed up the second phase of combustion. Increased compression ratio reduces the clearance volume and therefore increases the density of the cylinder gases during burning. This increases the peak pressure and temperature and the total combustion duration is reduced. Thus engines having higher compression ratios have higher flame speeds.

Engine Output: The cycle pressure increases when the engine output is increased. With the increased throttle opening the cylinder gets filled to a higher density. This results in increased flame speed. When the output is decreased by throttling, the initial and final compression pressures decrease and the dilution of the working mixture increases. The smooth development of self-propagating nucleus of flame becomes unsteady and difficult. The main disadvantages of SI engines are the poor combustion at low loads and the necessity of mixture enrichment (ϕ between 1.2 to 1.3) which causes wastage of fuel and discharge of unburnt hydrocarbon and the products of incomplete combustion like carbon monoxide etc. in the atmosphere.

Engine Speed: The flame speed increases almost linearly with engine speed since the increase in engine speed increases the turbulence inside the cylinder. The time required for the flame to traverse the combustion space would be halved, if the engine speed is doubled. Double the engine speed and hence half the original time would give the same number of crank degrees for flame propagation. The crank angle required for the flame propagation during the entire phase of combustion, will remain nearly constant at all speeds.

Engine Size: The size of the engine does not have much effect on the rate of flame propagation. In large engines the time required for complete combustion is more because the flame has to travel a longer distance. This requires increased crank angle duration during the combustion. This is one of the reasons why large sized engines are designed to operate at low speeds.

12.8 RATE OF PRESSURE RISE

The rate of pressure rise in an engine combustion chamber exerts a considerable influence on the peak pressure developed, the power produced and the smoothness with which the forces are transmitted to the piston. The rate of pressure rise is mainly dependent upon the mass rate of combustion of mixture in the cylinder.

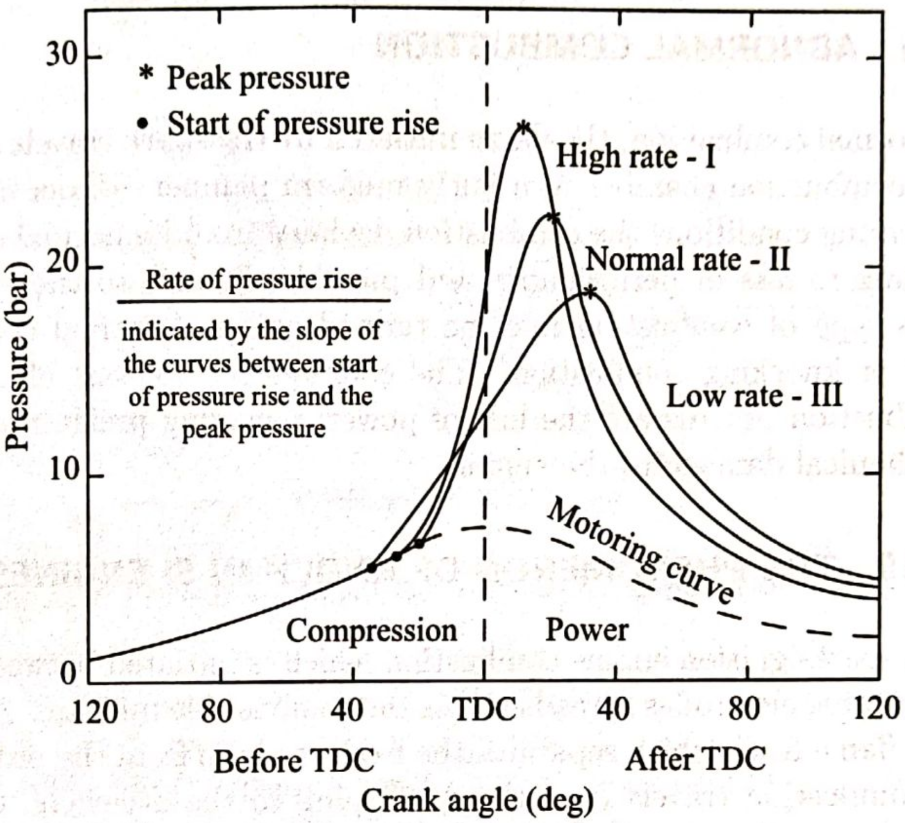


Fig. 12.5 Illustrations of Various Combustion Rates

The relationship between the pressure and the crank angle for three different combustion rates is shown in Fig.12.5. Curve I is for a high, curve II for the normal and curve III for a low rate of combustion. It is clear from the figure that with lower rate of combustion longer time is required for the completion of combustion which necessitates the initiation of burning at an early point on the compression stroke. Also, it may be noted that higher rate of combustion results in higher rate of pressure rise producing higher peak pressures at a point closer to *TDC*. This generally is a desirable feature because higher peak pressures closer to *TDC* produce a greater force acting through a large part of the power stroke and hence, increase the power output of the engine. The higher rate of pressure rise causes rough running of the engine because of vibrations produced in the crankshaft rotation. It also tends to promote an undesirable occurrence known as knocking. A compromise between these opposing factors is accomplished by designing and operating the engine in such a manner that approximately one-half of the maximum pressure is reached by the time the piston reaches TDC. This results in the peak pressure being reasonably close to the beginning of the power stroke, yet maintaining smooth engine operation.

12.9 ABNORMAL COMBUSTION

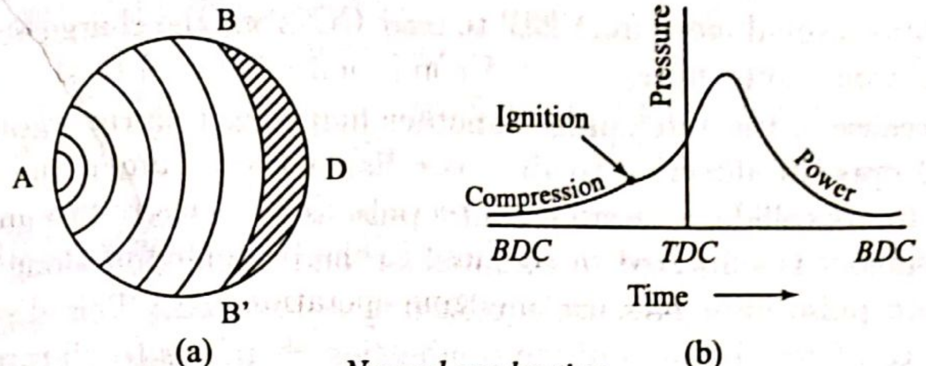
In normal combustion, the flame initiated by the spark travels across the combustion chamber in a fairly uniform manner. Under certain operating conditions the combustion deviates from its normal course leading to loss of performance and possible damage to the engine. This type of combustion may be termed as an abnormal combustion or knocking combustion. The consequences of this abnormal combustion process are the loss of power, recurring preignition and mechanical damage to the engine.

12.10 THE PHENOMENON OF KNOCK IN SI ENGINES

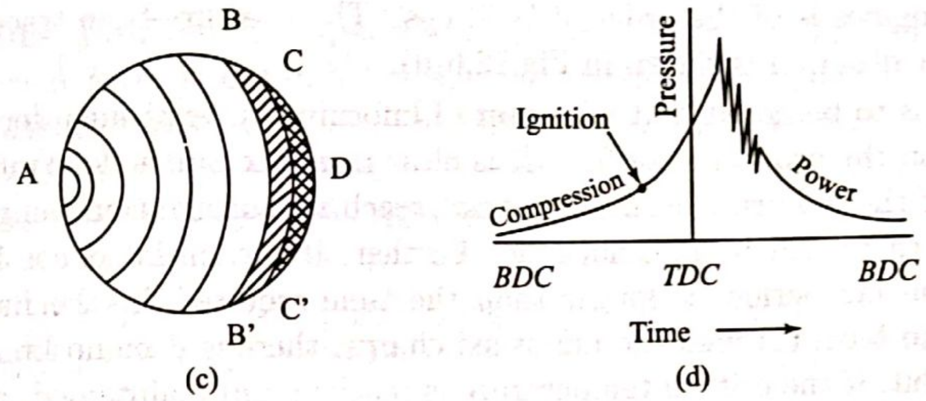
In a spark-ignition engine combustion which is initiated between the spark plug electrodes spreads across the combustible mixture. A definite flame front which separates the fresh mixture from the products of combustion travels from the spark plug to the other end of the combustion chamber. Heat-release due to combustion increases the temperature and consequently the pressure, of the burned part of the mixture above those of the unburned mixture. In order to effect pressure equalization the burned part of the mixture will expand, and compress the unburned mixture adiabatically thereby increasing its pressure and temperature. This process continues as the flame front advances through the mixture and the temperature and pressure of the unburned mixture are increased further.

If the temperature of the unburnt mixture exceeds the self-ignition temperature of the fuel and remains at or above this temperature during the period of preflame reactions (ignition lag), spontaneous ignition or autoignition occurs at various pin-point locations. This phenomenon is called knocking. The process of autoignition leads towards engine knock.

The phenomenon of knock may be explained by referring to Fig.12.6(a) which shows the cross-section of the combustion chamber with flame advancing from the spark plug location A without knock



Normal combustion



Combustion with detonation

Fig. 12.6 Normal and Abnormal Combustion

whereas Fig.12.6(c) shows the combustion process with knock. In the normal combustion the flame travels across the combustion chamber from A towards D. The advancing flame front compresses the end charge BB′D farthest from the spark plug, thus raising its temperature. The temperature is also increased due to heat transfer from the hot advancing flame-front. Also some preflame oxidation may take place in the end charge leading to further increase in temperature. In spite of these factors if the temperature of the end charge had not reached its self-ignition temperature, the charge would not autoignite and the flame will advance further and consume the charge BB′D. This is the normal combustion process which is illustrated by means of the pressure-time diagram, Fig.12.6(b).

However, if the end charge BB′D reaches its autoignition temperature and remains for some length of time equal to the time of preflame reactions the charge will autoignite, leading to knocking combustion. In Fig.12.6(c), it is assumed that when flame has reached the position BB′, the charge ahead of it has reached critical autoignition temperature. During the preflame reaction period if the flame front could move from BB′ to only CC′ then the charge ahead of CC′ would autoignite.

Because of the autoignition, another flame front starts traveling in the opposite direction to the main flame front. When the two flame fronts collide, a severe pressure pulse is generated. The gas in the chamber is subjected to compression and rarefaction along the pressure pulse until pressure equilibrium is restored. This disturbance can force the walls of the combustion chambers to vibrate at the same frequency as the gas. Gas vibration frequency in automobile engines is of the order of 5000 cps. The pressure-time trace of such a situation is shown in Fig.12.6(d).

It is to be noted that the onset of knocking is very much dependent on the properties of fuel. It is clear from the above description that if the unburned charge does not reach its autoignition temperature there will be no knocking. Further, if the initial phase i.e., ignition lag period, is longer than the time required for the flame front to burn through the unburned charge, there will be no knocking. But, if the critical temperature is reached and maintained, and the ignition lag is shorter than the time it takes for the flame front to burn through the unburned charge then the end charge will detonate. Hence, in order to avoid or inhibit detonation, a high autoignition temperature and a long ignition lag are the desirable qualities for SI engine fuels.

In summary, when autoignition occurs, two different types of vibration may be produced. In one case a large amount of mixture may autoignite giving rise to a very rapid increase in pressure throughout the combustion chamber and there will be a direct blow on the engine structure. The human ear can detect the resulting thudding sound and consequent noise from free vibrations of the engine parts. In the other case, large pressure differences may exist in the combustion chamber and the resulting gas vibrations can force the walls of the chamber to vibrate at the same frequency as the gas. An audible sound may be evident.

The impact of knock on the engine components and structure can cause engine failure and in addition the noise from engine vibration is always objectionable.

The pressure differences in the combustion chamber cause the gas to vibrate and scrub the chamber walls causing increased loss of heat to the coolant.

The presence or absence of knocking combustion in engines is often judged from a distinctly audible sound. A scientific method to detect the phenomenon of knocking is to use a pressure transducer.

The output of this transducer is connected, usually, to a cathode ray oscilloscope. Typical pressure-time traces which can be obtained from a pressure transducer are given in Fig.12.6(b) for a normal combustion and in Fig.12.6(d) for knocking combustion.

12.10.1 Knock Limited Parameters

It should be the aim of the designer to reduce the tendency of knocking in the engine. In this connection, certain knock limited parameters are explained. They are:

Knock Limited Compression Ratio: The knock limited compression ratio is obtained by increasing the compression ratio on a variable compression ratio engine until incipient knocking is observed. Any change in operating conditions such as fuel-air ratio or in the engine design that increases the knock limited compression ratio is said to reduce the tendency towards knocking.

Knock Limited Inlet Pressure: The inlet pressure can be increased by opening the throttle or increasing supercharger delivery pressure until incipient knock is observed. An increase in knock limited inlet pressure indicates a reduction in the knocking tendency.

Knock Limited Indicated Mean Effective Pressure: The indicated mean effective pressure measured at incipient knock is usually abbreviated as *Klimep*. This parameter and the corresponding fuel consumption are obviously of great practical interest.

An useful measure of knocking tendency called the performance number, has been developed from the concept of knock limited indicated mean effective pressure. This number is defined as the ratio of *Klimep* with the fuel in question to *Klimep* with iso-octane when the inlet pressure is kept constant. This performance number is related to octane number and one of the advantages of this is that it can be applied to fuels whose knocking characteristics are superior to that of iso-octane, i.e., it extends the octane scale beyond 100.

Further simplification on the use of performance number requirements is done by introducing the concept of relative performance number, *rpn*, which is defined as:

$$rpn = \frac{\text{Actual Performance number}}{\text{Performance number corresponding to the imep of 100}}$$

12.11 EFFECT OF ENGINE VARIABLES ON KNOCK

From the discussion on knock in the previous section, it may be seen that four major factors are involved in either producing or preventing knock. These are the temperature, pressure, density of the unburned charge and the time factors. Since, the effect of temperature, pressure and density are closely interrelated, these three are consolidated into one group and the time factors into another group.

12.11.1 Density Factors

Any factor in the design or operation of an engine which tends to reduce the temperature of the unburned charge should reduce the possibility of knocking by reducing the temperature of the end charge for autoignition. Similarly, any factor which reduces the density of the charge tends to reduce knocking by providing lower energy release. Further, the effect of the following parameters which are directly or indirectly connected with temperature, pressure and density factors on the possibility of knocking is discussed below.

Compression Ratio: Compression ratio of an engine is an important factor which determines both the pressure and temperature at the beginning of the combustion process. Increase in compression ratio increases the pressure and temperature of the gases at the end of the compression stroke. This decreases the ignition lag of the end gas and thereby increasing the tendency for knocking. The overall increase in the density of the charge due to higher compression ratio increases the preflame reactions in the end charge thereby increasing the knocking tendency of the engine. The increase in the knocking tendency of the engine with increasing compression ratio is the main reason for limiting the compression ratio to a lower value.

Mass of Inducted Charge: A reduction in the mass of the inducted charge into the cylinder of an engine by throttling or by reducing the amount of supercharging reduces both temperature and density of the charge at the time of ignition. This decreases the tendency of knocking.

Inlet Temperature of the Mixture: Increase in the inlet temperature of the mixture makes the compression temperature higher thereby, increasing the tendency of knocking. Further, volumetric efficiency will be lowered. Hence, a lower inlet temperature is always preferable to reduce knocking. It is important that the temperature should not be so low as to cause starting and vaporization problems in the engine.

Temperature of the Combustion Chamber Walls: Temperature of the combustion chamber walls play a predominant role in knocking. In order to prevent knocking the hot spots in the combustion chamber should be avoided. Since, the spark plug and exhaust valve are two hottest parts in the combustion chamber, the end gas should not be compressed against them.

Retarding the Spark Timing: By retarding the spark timing from the optimized timing, i.e., having the spark closer to TDC, the peak pressures are reached farther down on the power stroke and are thus of lower magnitude. This might reduce the knocking. However, the spark timing will be different from the MBT timing. This will affect the brake torque and power output of the engine.

Power Output of the Engine: A decrease in the output of the engine decreases the temperature of the cylinder and the combustion chamber walls and also the pressure of the charge thereby lowering mixture and end gas temperatures. This reduces the tendency to knock.

12.11.2 Time Factors

Increasing the flame speed or increasing the duration of the ignition ignition lag or reducing the time of exposure of the unburned mixture to autoignition condition will tend to reduce knocking. The following factors, in most cases, reduce the possibility of knocking.

Turbulence: Turbulence depends on the design of the combustion chamber and on engine speed. Increasing turbulence increases the flame speed and reduces the time available for the end charge to attain autoignition conditions thereby decreasing the tendency to knock.

Engine Speed: An increase in engine speed increases the turbulence of the mixture considerably resulting in increased flame speed, and reduces the time available for preflame reactions. Hence knocking tendency is reduced at higher speeds.

Flame Travel Distance: The knocking tendency is reduced by shortening the time required for the flame front to traverse the combustion chamber. Engine size (combustion chamber size), and spark plug position are the three important factors governing the flame travel distance.

Engine Size: The flame requires a longer time to travel across the combustion chamber of a larger engine. Therefore, a larger engine has a greater tendency for knocking than a smaller engine since there is more time for the end gas to autoignite. Hence, an SI engine is generally limited to size of about 150 mm bore.

Combustion Chamber Shape: Generally, the more compact the combustion chamber is, the shorter is the flame travel and the combustion time and hence better antiknock characteristics. Therefore, the combustion chambers are made as spherical as possible to minimize the length of the flame travel for a given volume. If the turbulence in the combustion chamber is high, the combustion rate is high and consequently combustion time and knocking tendency are reduced. Hence, the combustion chamber is shaped in such a way as to promote turbulence.

Location of Spark Plug: In order to have a minimum flame travel, the spark plug is centrally located in the combustion chamber, resulting in minimum knocking tendency. The flame travel can also be reduced by using two or more spark plugs in case of large engines.

12.11.3 Composition Factors

Once the basic design of the engine is finalized, the fuel-air ratio and the properties of the fuel, particularly the octane rating, play a crucial role in controlling the knock.

Fuel-Air Ratio: The flame speeds are affected by fuel-air ratio. Also the flame temperature and reaction time are different for different fuel-air ratios. Maximum flame temperature is obtained when $\phi \approx 1.1$ to 1.2 whereas $\phi = 1$ gives minimum reaction time for autoignition.

Figure 12.7 shows the variation of knock limited compression ratio with respect to equivalence ratio for iso-octane. The maximum tendency to knock takes place for the fuel-air ratio which gives minimum reaction time as discussed earlier. Thus the most predominant factor is the reaction time of the mixture in this case. In general except at rich end, the behaviour in the engine follows the same pattern as the fuel-air ratio versus reaction time discussed earlier. The drop in *Klimep* at very rich end is caused by large drop in thermal efficiency.

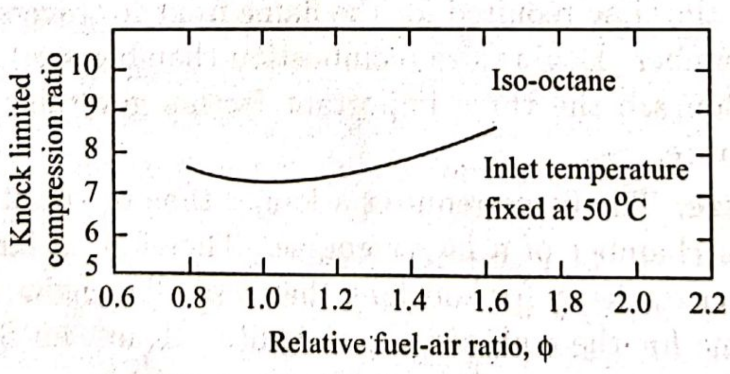


Fig. 12.7 Effect of Equivalence Ratio on Knock Limited Compression Ratio

Octane Value of the Fuel: A higher self-ignition temperature of the fuel and a low preflame reactivity would reduce the tendency of knocking. In general, paraffin series of hydrocarbon have the maximum and aromatic series the minimum tendency to knock. The naphthene series comes in between the two. Usually, compounds with more compact molecular structure are less prone to knock. In aliphatic hydrocarbons, unsaturated compounds show lesser knocking tendency than saturated hydrocarbons, the exception being ethylene, acetylene and propylene.

Table 12.1 gives the general summary of variables affecting the knock in an SI engine and shows whether the various factors can be controlled by the operator.

12.12 COMBUSTION CHAMBERS FOR SI ENGINES

The design of the combustion chamber for an SI engine has an important influence on the engine performance and its knocking tendencies. The design involves the shape of the combustion chamber, the location of spark plug and the location of inlet and exhaust valves. Because of this importance, the combustion chamber design has been a subject of considerable amount of research and development in the last fifty years. It has resulted in the raising of the compression ratio of the engine from 4 before the first world war period to 11 in the present times with special combustion chamber designs and suitable antiknock fuels. The important requirements of an SI engine combustion chamber are to provide high power output with minimum octane requirement, high thermal efficiency and smooth engine operation.

Combustion chambers must be designed carefully, keeping in mind the following general objectives.

12.12.1 Smooth Engine Operation

The aim of any engine design is to have a smooth operation and a good economy. These can be achieved by the following:

Moderate Rate of Pressure Rise: The rate of pressure rise can be regulated such that the greatest force is applied to the piston as closely after *TDC* on the power stroke as possible, with a gradual decrease in the force on the piston during the power stroke. The forces must be applied to the piston smoothly, thus limiting the rate of pressure rise as well as the position of the peak pressure with respect to *TDC*.

Table 12.1 *Summary of Variables Affecting Knock in an SI Engine*

Increase in variable	**Major effect on unburned reduce charge**	**Action to be taken to knocking**	**Can operator usually control?**
Compression ratio	Increases temperature & pressure	Reduce	No
Mass of charge inducted	Increases pressure	Reduce	Yes
Inlet temperature	Increases temperature	Reduce	In some cases
Chamber wall temperature	Increases temperature	Reduce	Not ordinarily
Spark advance	Increases temperature & pressure	Retard	In some cases
A/F ratio	Increases temperature & pressure	Make very rich	In some cases
Turbulence	Decreases time factor	Increase	Somewhat (through engine speed)
Engine speed	Decreases time factor	Increase	Yes
Distance of flame travel	Increases time factor	Reduce	No

Reducing the Possibility of Knocking: Reduction in the possibility of knocking in an engine can be achieved by,

(i) Reducing the distance of the flame travel by centrally locating the spark plug and also by avoiding pockets of stagnant charge.

(ii) Satisfactory cooling of the spark plug and of exhaust valve area which are the source of hot spots in the majority of the combustion chambers.

(iii) Reducing the temperature of the last portion of the charge, through application of a high surface to volume ratio in that part where the last portion of the charge burns. Heat transfer to the combustion chamber walls can be increased by using high surface to volume ratio thereby reducing the temperature.

12.12.2 High Power Output and Thermal Efficiency

The main objective of the design and development of an engine is to obtain high power as well as high thermal efficiency. This can be achieved by considering the following factors:

(i) A high degree of turbulence is needed to achieve a high flame front velocity. Turbulence is induced by inlet flow configuration or squish. Squish can be induced in spark-ignition engines by having a bowl in piston or with a dome shaped cylinder head. Squish is the rapid radial movement of the gas trapped in between the piston and the cylinder head into the bowl or the dome.

(ii) High volumetric efficiency, i.e., more charge during the suction stroke, results in an increased power output. This can be achieved by providing ample clearance around the valve heads, large diameter valves and straight passages with minimum pressure drop.

(iii) Any design of the combustion chamber that improves its antiknock characteristics permits the use of a higher compression ratio resulting in increased output and efficiency.

(iv) A compact combustion chamber reduces heat loss during combustion and increases the thermal efficiency. Different types of combustion chambers have been developed over a period of time. Some of them are shown in Fig.12.8. Brief description of these combustion chambers are given below.

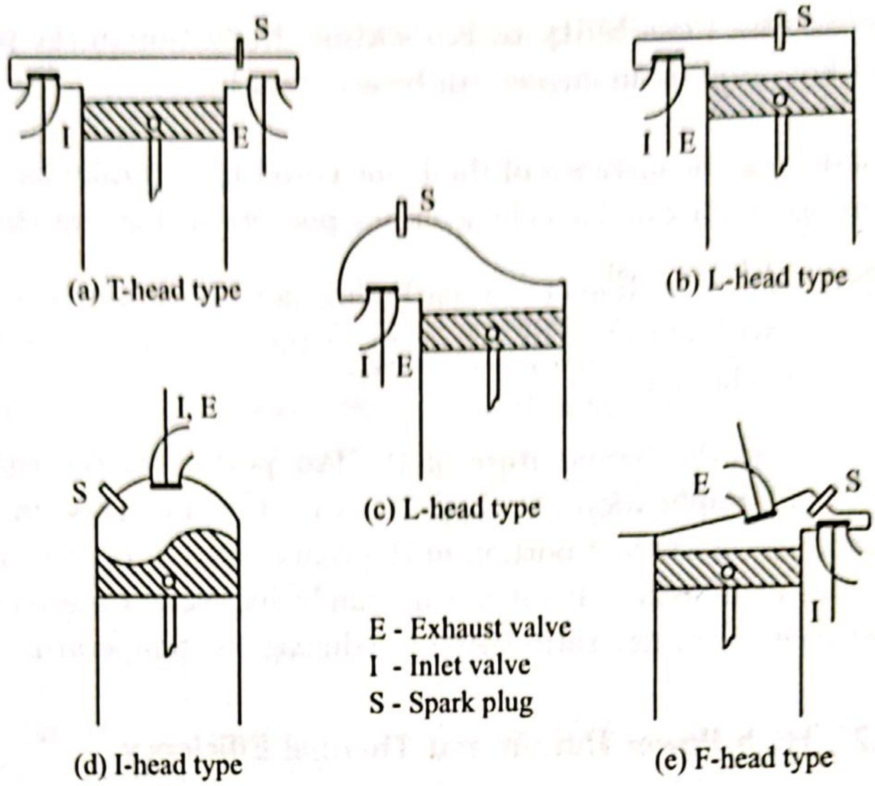


Fig. 12.8 Examples of Typical Combustion Chamber

T-Head Type: The T-head combustion chambers [Fig.12.8(a)] were used in the early stage of engine development. Since the distance across the combustion chamber is very long, knocking tendency is high in this type of engines. This configuration provides two valves on either side of the cylinder, requiring two camshafts. From the manufacturing point of view, providing two camshafts is a disadvantage.

L-Head Type: A modification of the T-head type of combustion chamber is the L-head type which provides the two valves on the same side of the cylinder and the valves are operated by a single camshaft. Figures 12.8(b) and (c) show two types of this side valve engine. In these types, it is easy to lubricate the valve mechanism. With the detachable head it may be noted that the cylinder head can be removed without disturbing valve gear etc. In Fig.12.8(b) the air flow has to take two right angle turns to enter the cylinder. This causes a loss of velocity head and a loss in turbulence level resulting in a slow combustion process.

The main objectives of the Ricardo's turbulent head design, Fig.12.8(c), are to obtain fast flame speed and reduced knock. The main body of the combustion chamber is concentrated over the valves leaving a slightly restricted passage communicating with the cylinder thereby creating additional turbulence during the compression stroke. This design reduces the knocking tendency by shortening the effective flame travel length by bringing that portion of the head which lay over the farther side of the piston into as close a contact as possible with the piston crown, forming a quench space. The thin layer of gas (entrapped between the relatively cool piston and also cooler head) loses its heat rapidly because of large enclosing surface thereby avoiding knocking. By placing the spark plug in the centre of the effective combustion space slightly towards the hot exhaust valve, the flame travel length is reduced.

I-Head Type or Overhead Valve: The I-head type is also called the overhead valve combustion chamber in which both the valves are located on the cylinder head. The overhead valve engine [Fig.12.8(d)] is superior to a side valve or an L-head engine at high compression ratios. Some of the important characteristics of this type of valve arrangement are:

(i) less surface to volume ratio and therefore less heat loss

(ii) less flame travel length and hence greater freedom from knock

(iii) higher volumetric efficiency from larger valves or valve lifts

(iv) confinement of thermal failures to cylinder head by keeping the hot exhaust valve in the head instead of the cylinder block.

F-Head Type: The F-head type of valve arrangement is a compromise between L-head and I-head types. Combustion chambers in which one valve is in the cylinder head and the other in the cylinder block are known as F-head combustion chambers [Fig.12.8(e)]. Modern F-head engines have exhaust valve in the head and inlet valve in the cylinder block. The main disadvantage of this type is that the inlet valve and the exhaust valve are separately actuated by two cams mounted on two camshafts driven by the crankshaft through gears.

12.13 COMBUSTION IN COMPRESSION-IGNITION ENGINES

There are certain basic differences existing between the combustion process in the SI and CI engines. In the SI engine, a homogeneous carburetted mixture of gasoline vapour and air, in a certain proportion, is compressed (compression ratio 6:1 to 10:1) and the mixture is ignited at one place before the end of the compression stroke by means of an electric spark. A single flame front progresses through the air-fuel mixture after ignition.

In the CI engine, only air is compressed through a high compression ratio (16:1 to 20:1) raising its temperature and pressure to a high value. Fuel is injected through one or more jets into this highly compressed air in the combustion chamber. Here, the fuel jet disintegrates into a core of fuel surrounded by a spray envelope of air and fuel particles [Fig.12.9(a)]. This spray envelope is created both by the atomization and vaporization of the fuel. The turbulence of the air in the combustion chamber passing across the jet tears the fuel particles from the core. A mixture of air and fuel forms at some location in the spray envelope and oxidation starts.

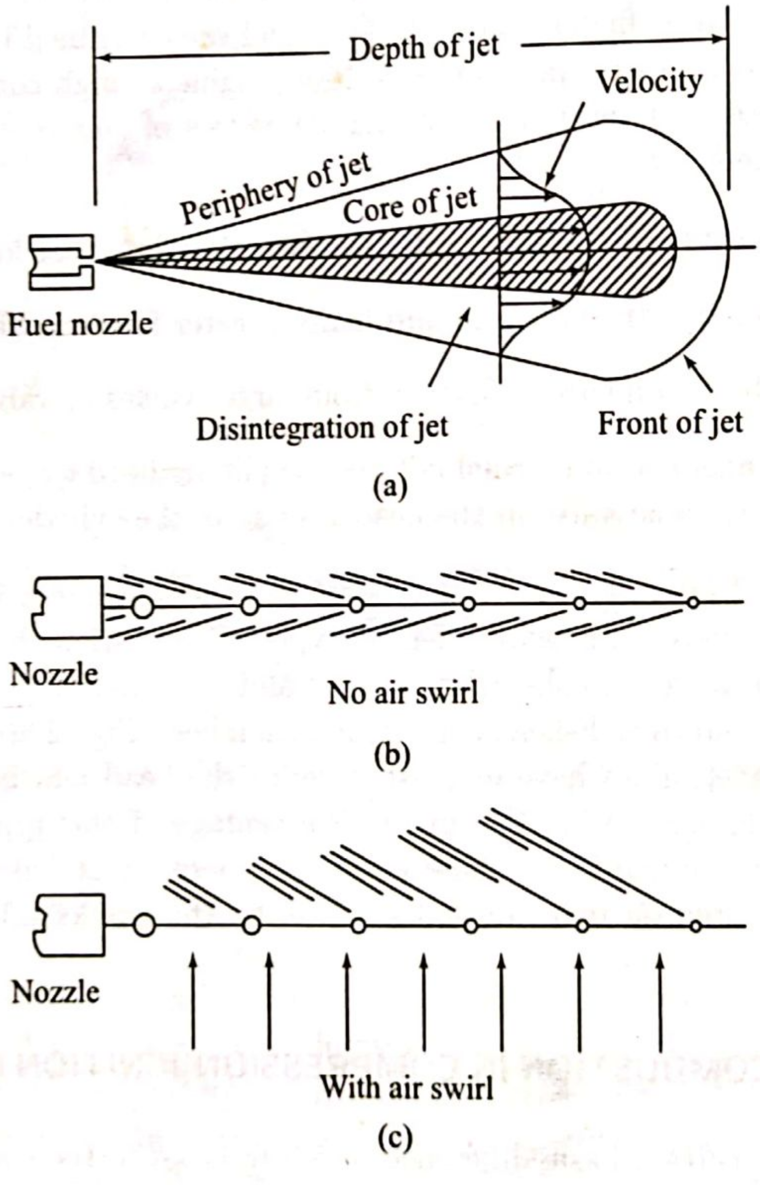


Fig. 12.9 Schematic Representation of the Disintegration of a Fuel Jet

The liquid fuel droplets evaporate by absorbing the latent heat of vaporization from the surrounding air which reduces the temperature of a thin layer of air surrounding the droplet and some time elapses before this temperature can be raised again by absorbing heat from the bulk of air. As soon as this vapour and the air reach the level of the autoignition temperature and if the local A/F ratio is within the combustible range, ignition takes place. Thus, it is obvious that at first there is a certain delay period before ignition takes place.

Since the fuel droplets cannot be injected and distributed uniformly throughout the combustion space, the fuel-air mixture is essentially heterogeneous. If the air within the cylinder were motionless under these conditions, there will not be enough oxygen in the burning zone and burning of the fuel would be either slow or totally fail as it would be surrounded by its own products of combustion [Fig.12.9(b)]. Hence, an orderly and controlled movement must be imparted to the air and the fuel so that a continuous flow of fresh air is brought to each burning droplet and the products of combustion are swept away. This air motion is called the air swirl and its effect is shown in Fig.12.9(c).

In an SI engine, the turbulence is a disorderly air motion with no general direction of flow. However, the swirl which is required in CI engines, is an orderly movement of the whole body of air with a particular direction of flow and it assists the breaking up of the fuel jet. Intermixing of the burned and unburned portions of the mixture also takes place due to this swirl. In the SI engine, the ignition occurs at one point with a slow rise in pressure whereas in the CI engine, the ignition occurs at many points simultaneously with consequent rapid rise in pressure. In contrast to the process of combustion in SI engines, there is no definite flame front in CI engines.

In an SI engine, the air-fuel ratio remains close to stoichiometric value from no load to full load. But in a CI engine, irrespective of load, at any given speed, an approximately constant supply of air enters the cylinder. With change in load, the quantity of fuel injected is changed, varying the air-fuel ratio. The overall air-fuel ratio thus varies from about 18:1 at full load to about 80:1 at no load.

It is the main aim of the CI engine designer that the A/F ratio should be as close to stoichiometric as possible while operating at full load since the mean effective pressure and power output are maximum at that condition. Thermodynamic analysis of the engine cycles has clearly established that operating an engine with a leaner air-fuel ratio always gives a better thermal efficiency but the mean effective pressure and the power output reduce. Therefore, the engine size becomes bigger for a given output if it is operated near the stoichiometric conditions, the A/F ratio in certain regions within the chamber is likely to be so rich that some of the fuel molecules will not be able to find the necessary oxygen for combustion and thus produce a noticeably black smoke. Hence the CI engine is always designed to operate with an excess air, of 15 to 40% depending upon the application. The power output curve for a typical CI engine operating at constant speed is shown in Fig.12.10. The approximate region of A/F ratios in which visible black smoke occurs is indicated by the shaded area.

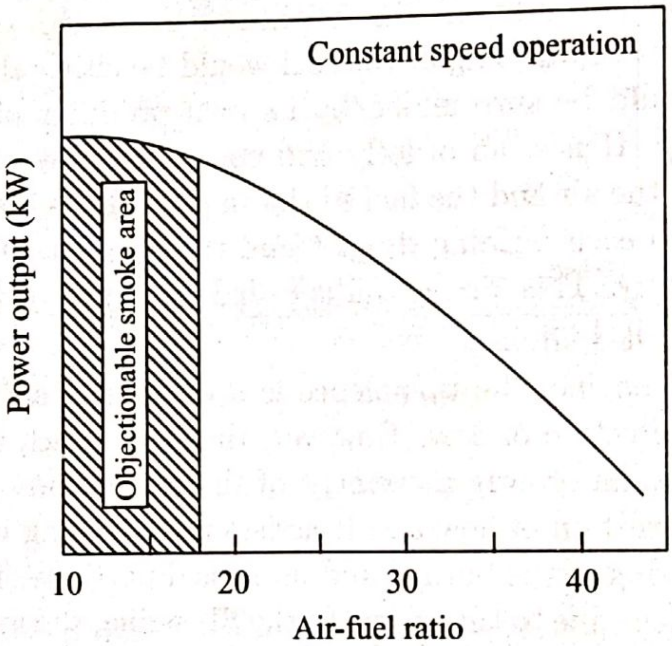


Fig. 12.10 Effect of A/F Ratio on Power Output of a CI Engine

12.14 STAGES OF COMBUSTION IN CI ENGINES

The combustion in a CI engine is considered to be taking place in four stages (Fig.12.11). It is divided into the ignition delay period, the period of rapid combustion, the period of controlled combustion and the period of after-burning. The details are explained below.

12.14.1 Ignition Delay Period

The ignition delay period is also called the preparatory phase during which some fuel has already been admitted but has not yet ignited.

This period is counted from the start of injection to the point where the pressure-time curve separates from the motoring curve indicated as start of combustion in Fig.12.11.

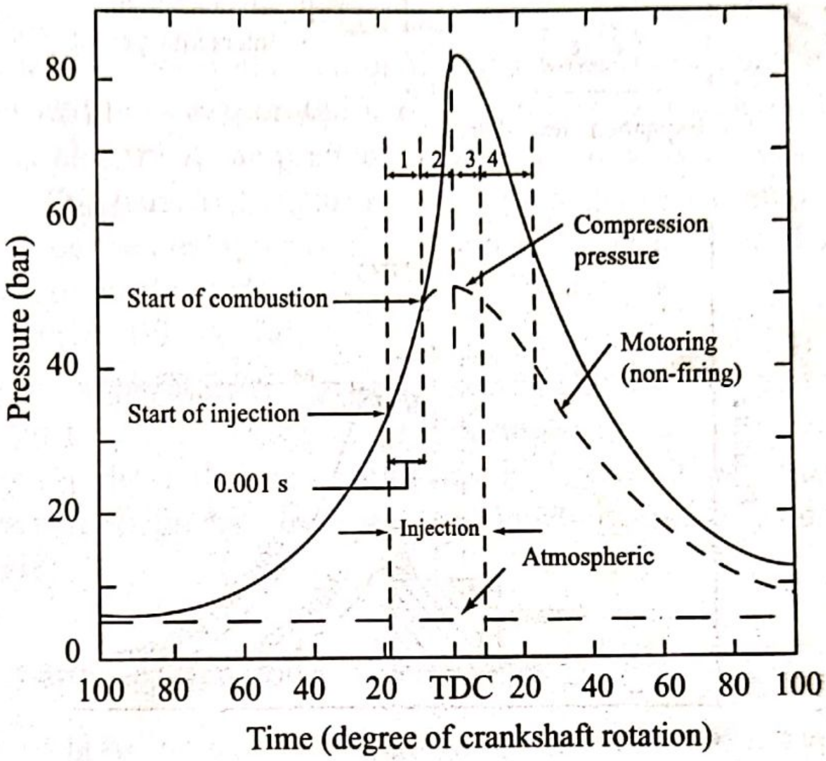


Fig. 12.11 Stages of Combustion in a CI Engine

The delay period in the CI engine exerts a very great influence on both engine design and performance. It is of extreme importance because of its effect on both the combustion rate and knocking and also its influence on engine starting ability and the presence of smoke in the exhaust.

The fuel does not ignite immediately upon injection into the combustion chamber. There is a definite period of inactivity between the time when the first droplet of fuel hits the hot air in the combustion chamber and the time it starts through the actual burning phase. This period is known as the ignition delay period. In Fig.12.12 the delay period is shown on pressure crank angle (or time) diagram between points a and b. Point a represents the time of injection and point b represents the time at which the pressure curve (caused by combustion) first separates from the motoring curve. The ignition delay period can be divided into two parts, the physical delay and the chemical delay.

Physical Delay: The physical delay is the time between the beginning of injection and the attainment of chemical reaction conditions.

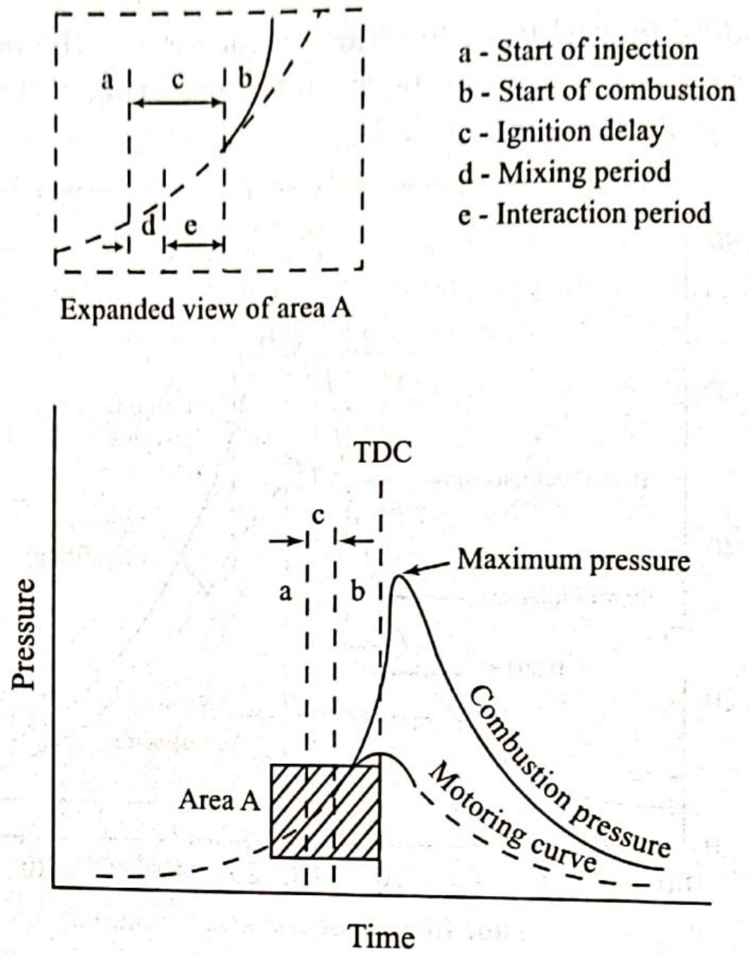


Fig. 12.12 Pressure-Time Diagram illustrating Ignition Delay

During this period, the fuel is atomized, vaporized, mixed with air and raised to its self-ignition temperature. This physical delay depends on the type of fuel, i.e., for light fuel the physical delay is small while for heavy viscous fuels the physical delay is high. The physical delay is greatly reduced by using high injection pressures, higher combustion chamber temperatures and high turbulence to facilitate breakup of the jet and improving evaporation.

Chemical Delay: During the chemical delay, reactions start slowly and then accelerate until inflammation or ignition takes place. Generally, the chemical delay is larger than the physical delay. However, it depends on the temperature of the surroundings and at high temperatures, the chemical reactions are faster and the physical delay becomes longer than the chemical delay. It is clear that, the ignition lag in the SI engine is essentially equivalent to the chemical delay for the CI engine. In most CI engines the ignition lag is shorter than the duration of injection.

12.14.2 Period of Rapid Combustion

The period of rapid combustion also called the uncontrolled combustion, is that phase in which the pressure rise is rapid. During the delay period, the droplets have had time to spread over a wide area and fresh air is always available around the droplets. Most of the fuel admitted would have evaporated and formed a combustible mixture with air. By this time, the preflame reactions would have also been completed. The period of rapid combustion is counted from end of delay period or the beginning of the combustion to the point of maximum pressure on the indicator diagram. The rate of heat-release is maximum during this period.

It may be noted that the pressure reached during the period of rapid combustion will depend on the duration of the delay period (the longer the delay the more rapid and higher is the pressure rise since more fuel would have accumulated in the cylinder during the delay period).

12.14.3 Period of Controlled Combustion

The rapid combustion period is followed by the third stage, the controlled combustion. The temperature and pressure in the second stage is already quite high. Hence the fuel droplets injected during the second stage burn faster with reduced ignition delay as soon as they find the necessary oxygen and any further pressure rise is controlled by the injection rate. The period of controlled combustion is assumed to end at maximum cycle temperature.

12.14.4 Period of After-Burning

Combustion does not cease with the completion of the injection process. The unburnt and partially burnt fuel particles left in the combustion chamber start burning as soon as they come into contact with the oxygen. This process continues for a certain duration called the after-burning period. Usually this period starts from the point of maximum cycle temperature and continues over a part of the expansion stroke. Rate of after-burning depends on the velocity of diffusion and turbulent mixing of unburnt and partially burnt fuel with the air. The duration of the after-burning phase may correspond to 70-80 degrees of crank travel from TDC.

The sequence of the events in the entire combustion process in a CI engine including the delay period is shown in Fig.12.13 by means of a block diagram.

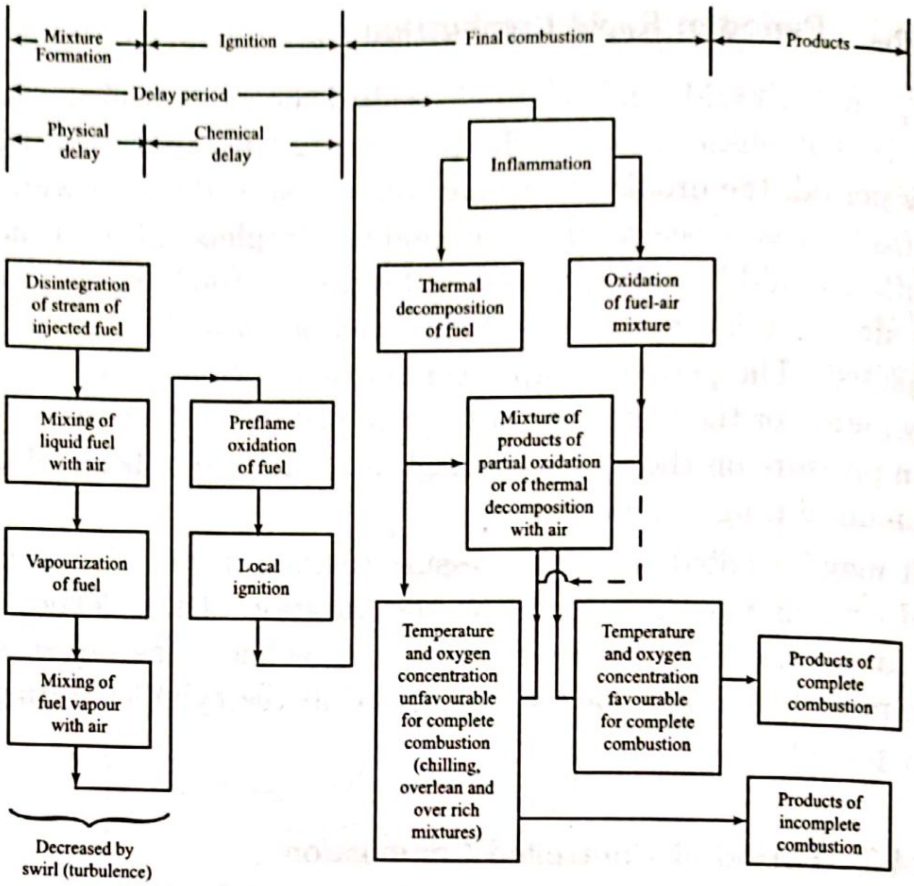


Fig. 12.13 Block Diagram illustrating the Combustion Process in a CI Engine

12.15 FACTORS AFFECTING THE DELAY PERIOD

Many design and operating factors affect the delay period. The important ones are:

(i) compression ratio

(ii) engine speed

(iii) output

(iv) atomization of fuel and duration of injection

(v) injection timing

(vi) quality of the fuel

(vii) intake temperature

(viii) intake pressure

The effect of these factors on the delay period is discussed in detail in the following sections.

12.15.1 Compression Ratio

The increase in the compression temperature of the air with increase in compression ratio evaluated at the end of the compression stroke is shown in Fig.12.14.

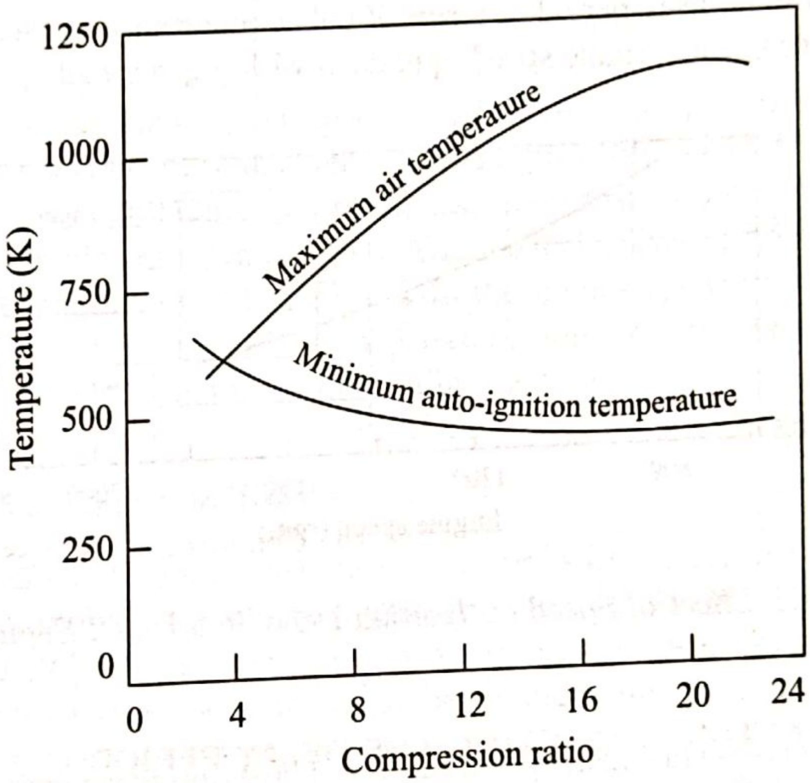


Fig. 12.14 Effect of Compression Ratio on Maximum Air Temperature and Minimum Autoignition Temperature

It is also seen from the same figure that the minimum autoignition temperature of a fuel decreases due to increased density of the compressed air. This results in a closer contact between the molecules of fuel and oxygen reducing the time of reaction. The increase in the compression temperature as well as the decrease in the minimum autoignition temperature decreases the delay period. The peak pressure during the combustion process is only marginally affected by the compression ratio (because delay period is shorter with higher compression ratio and hence the pressure rise is lower).

One of the practical disadvantages of using a very high compression ratio is that the mechanical efficiency tends to decrease due to increase in weight of the reciprocating parts. Therefore, in practice the engine designers always try to use a lower compression ratio which helps in easy cold starting and light load running at high speeds.

12.15.2 Engine Speed

The delay period could be given either in terms of absolute time (in milliseconds) or in terms of crank angle degrees. Fig.12.15 shows the decrease in delay period in terms of milliseconds with increase in engine speed in a variable speed operation with a given fuel.

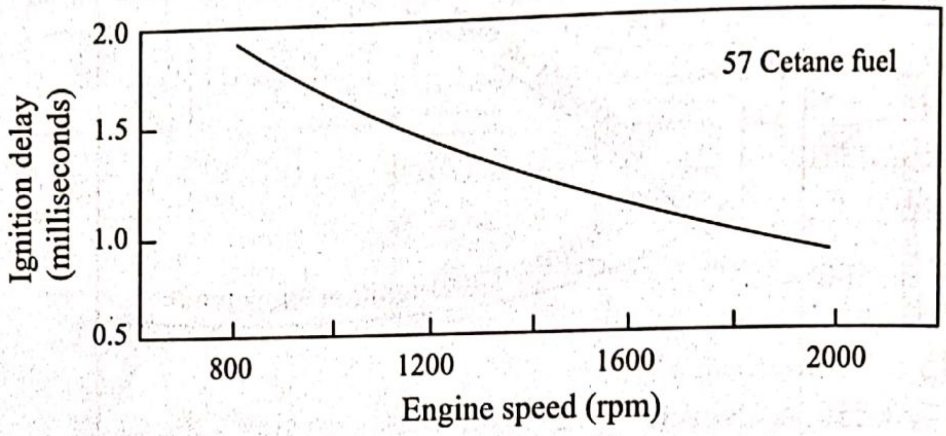


Fig. 12.15 Effect of Speed on Ignition Delay in a Diesel Engine

With increase in engine speed, the loss of heat during compression decreases, resulting in the rise of both the temperature and pressure of the compressed air thus reducing the delay period in milliseconds. However, in degrees of crank travel the delay period increases as the engine operates at a higher rpm. The fuel pump is geared to the engine, and hence the amount of fuel injected during the delay period depends on crank degrees and not on absolute time. Hence, at high speeds, there will be more fuel present in the cylinder to take part in the second stage of uncontrolled combustion resulting in high rate of pressure rise.

12.15.3 Output

With an increase in engine output the air-fuel ratio decreases, operating temperatures increase and hence delay period decreases. The rate of pressure rise is unaffected but the peak pressure reached may be high.

12.15.4 Atomization and Duration of Injection

Higher fuel-injection pressures increase the degree of atomization. The fineness of atomization reduces ignition delay, due to higher surface volume ratio. Smaller droplet size will have low depth of penetration due to less momentum of the droplet and less velocity relative to air from where it has to find oxygen after vapourisation. Because of this air utilization factor will be reduced due to fuel spray path being shorter. Also with smaller droplets, the aggregate area of inflammation will increase after ignition, resulting in higher pressure rise during the second stage of combustion. Thus, lower injection pressure, giving larger droplet size may give lower pressure rise during the second stage of combustion and probably smoother running. Hence, an optimum group mean diameter of the droplet size should be attempted as a compromise. Also the fuel delivery law i.e., change in the quantity of fuel supplied with the crank angle travel will affect the rates of pressure rise during second stage of combustion though ignition delay remains unaffected by the same.

12.15.5 Injection Timing

The effect of injection advance on the pressure variation is shown in Fig.12.16 for three injection advance timings of 9°, 18°, and 27° before TDC. The injected quantity of fuel per cycle is constant. As the pressure and temperature at the beginning of injection are lower for higher ignition advance, the delay period increases with increase in injection advance. The optimum angle of injection advance depends on many factors but generally it is about $20°bTDC$.

12.15.6 Quality of Fuel

Self-ignition temperature is the most important property of the fuel which affects the delay period. A lower self-ignition temperature results in a lower delay period. Also, fuels with higher cetane number give lower delay period and smoother engine operation. Other properties of the fuel which affect the delay period are volatility, latent heat, viscosity and surface tension.

12.15.7 Intake Temperature

Increase in intake temperature increases the compressed air temperature resulting in reduced delay period. However, preheating of the charge for this purpose would be undesirable because it would

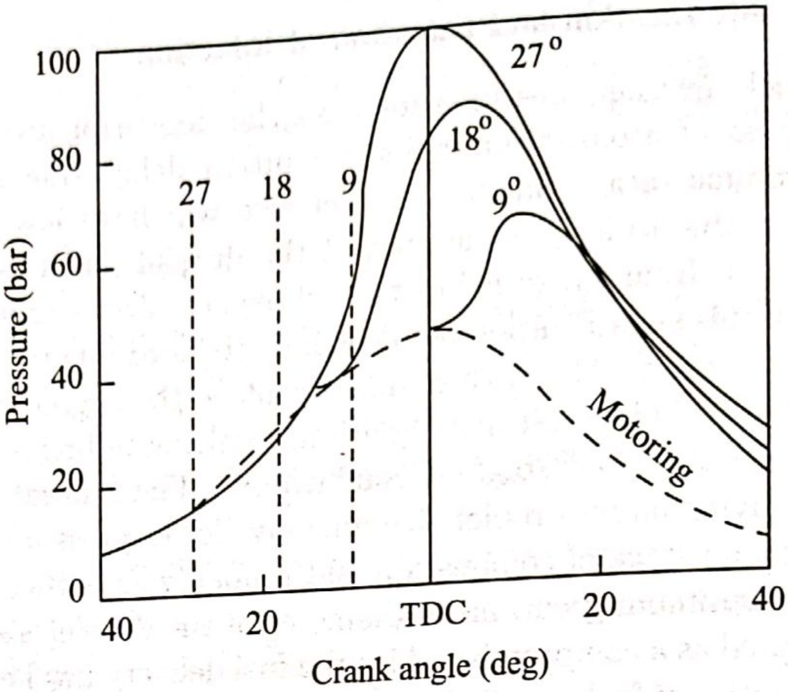


Fig. 12.16 Effect of Injection Timing on Indicator Diagram

reduce the density of air reducing the volumetric efficiency and power output.

12.15.8 Intake Pressure

Increase in intake pressure or supercharging reduces the autoignition temperature and hence reduces the delay period. The peak pressure will be higher since the compression pressure will increase with intake pressure. Table 12.2 gives the summary of the factors which influence the delay period in an engine.

12.16 THE PHENOMENON OF KNOCK IN CI ENGINES

In CI engines the injection process takes place over a definite interval of time. Consequently, as the first few droplets to be injected are passing through the ignition delay period, additional droplets are being injected into the chamber. If the ignition delay of the fuel being injected is short, the first few droplets will commence the *actual burning* phase in a relatively short time after injection and a relatively small amount of fuel will be accumulated in the chamber when *actual burning* commences. As a result, the mass rate of mixture burned will be such as to produce a rate of pressure rise that will exert a smooth force on the piston, as shown in Fig.12.17(a).

Table 12.2 Effect of Variables on the Delay Period

Increases in variable	Effect on Delay Period	Reason
Cetane number of fuel	Reduces	Reduces the self-ignition temperature
Injection pressure	Reduces	Reduces physical delay due to greater surface-volume ratio
Injection timing advance	Reduces	Reduced pressures and temperatures when the injection begins
Compression ratio	Reduces	Increases air temperature and pressure and reduces autoignition temperature
Intake temperature	Reduces	Increases air temperature
Jacket water temperature	Reduces	Increases wall and hence air temperature
Fuel temperature	Reduces	Increases chemical reaction due to better vaporization
Intake pressure (supercharging)	Reduces	Increases density and also reduces autoignition temperature
Speed	Increases in terms of crank angle. Reduces in terms of milliseconds	Reduces loss of heat
Load (fuel-air ratio)	Decreases	Increases the operating temperature
Engine size	Decreases in terms of crank angle. Little effect in terms of milliseconds	Larger engines operate normally at low speeds
Type of combustion chamber	Lower for engines with precombustion chamber	Due to compactness of the chamber

If, on the other hand, the ignition delay is longer, the *actual burning* of the first few droplets is delayed and a greater quantity of fuel droplets gets accumulated in the chamber. When the *actual burning* commences, the additional fuel can cause too rapid a rate of pressure rise as shown in Fig.12.17(b), resulting in a *jamming* of forces against the piston and rough engine operation. If the ignition delay is quite long, so much fuel can accumulate that the rate of pressure rise is almost instantaneous, as shown in Fig.12.17(c). Such a situation produces the extreme pressure differentials and violent gas vibrations known as knocking and is evidenced by audible knock. The phenomenon is similar to that in the SI engine. However, *in the SI engine, knocking occurs near the end of combustion whereas in the CI engine, knocking occurs near the beginning of combustion.*

In order to decrease the tendency of knock it is necessary to start the *actual burning* as early as possible after the injection begins. In other words, it is necessary to decrease the ignition delay and thus decrease the amount of fuel present when the *actual burning* of the first few droplets start.

12.17 COMPARISON OF KNOCK IN SI AND CI ENGINES

It may be interesting to note that knocking in spark-ignition engines and compression-ignition engines is fundamentally due to the autoignition of the fuel-air mixture. In both the cases, the knocking depends on the autoignition lag of the fuel-air mixture. But careful examination of the knocking phenomenon in spark-ignition and the compression-ignition engines reveals the following differences. A comparison of the knocking process in SI and CI engines is shown on the pressure-time diagrams of Fig.12.18.

(i) In spark-ignition engines, the autoignition of the end gas away from the spark plug, most likely near the end of the combustion causes knocking. But in compression-ignition engines the autoignition of the charge causing knocking is at the start of combustion. It is the first charge that autoignites and causes knocking in the compression-ignition engines. This is illustrated in Fig.12.18. It is clear from Fig.12.18 that explosive auto- ignition is more or less over before the peak pressure for the compression-ignition engines. But for spark-ignition engines, the condition for explosive autoignition of the end charge is more favourable after the peak pressure. In order to avoid knocking in spark-ignition engines, it is necessary to prevent

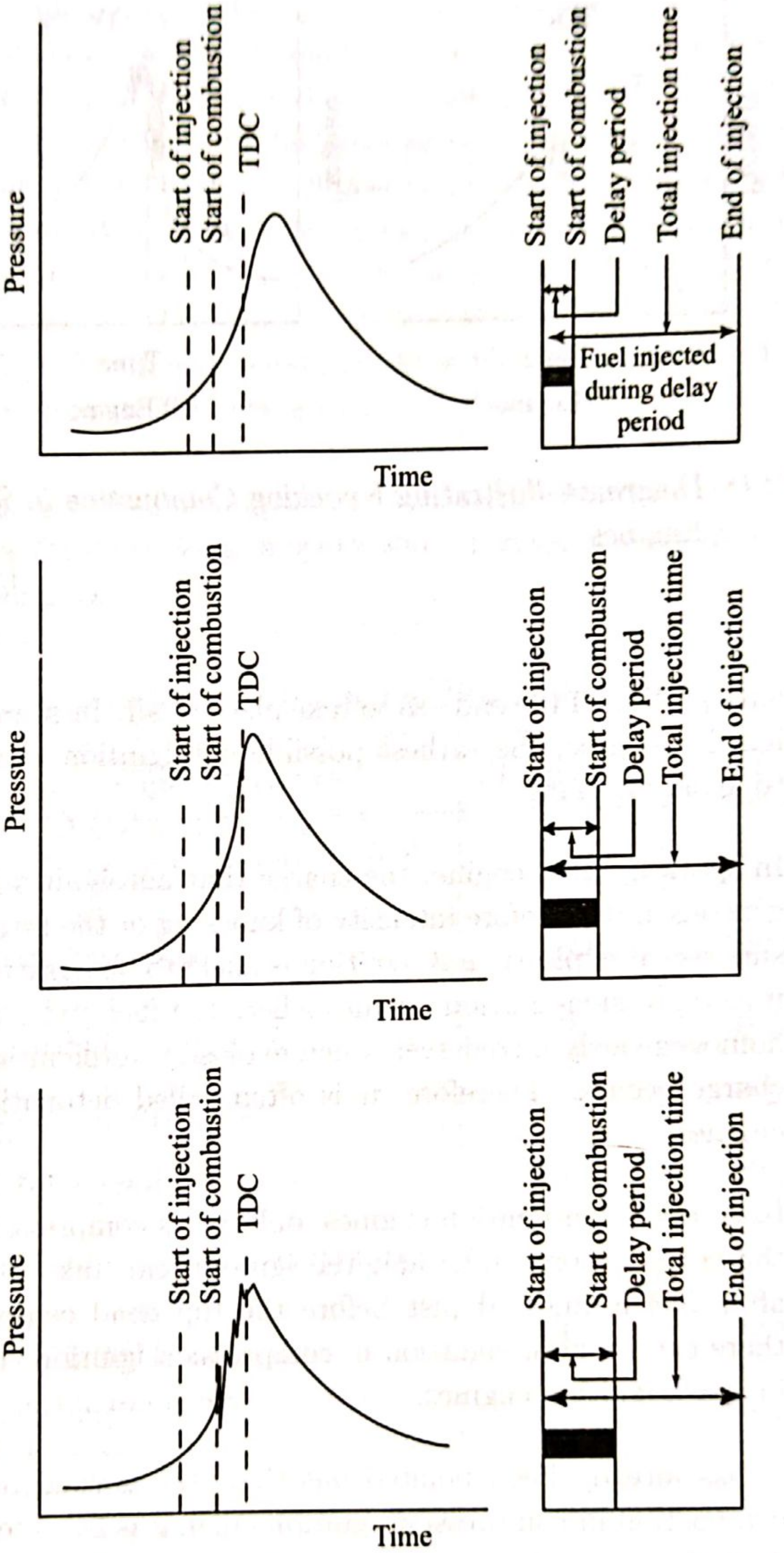


Fig. 12.17 Diagrams illustrating the Effect of Ignition Delay on the Rate of Pressure Rise in a CI Engine

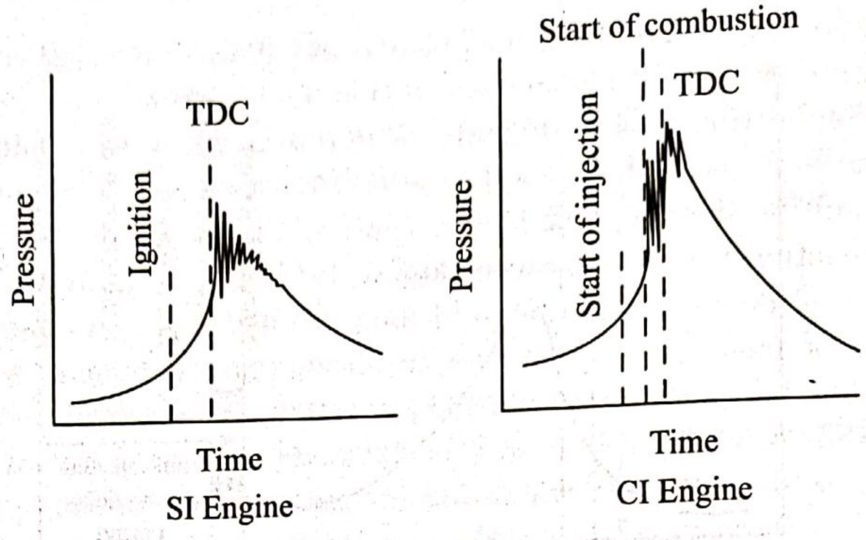


Fig. 12.18 Diagrams illustrating Knocking Combustion in SI and CI Engines

autoignition of the end gas to take place at all. In compression-ignition engine, the earliest possible autoignition is necessary to avoid knocking.

(ii) In spark-ignition engine, the charge that autoignites is homogeneous and therefore intensity of knocking or the rate of pressure rise at explosive autoignition is likely to be more than that in compression-ignition engines where the fuel and air are not homogeneously mixed even when explosive autoignition of the charge occurs. Therefore, it is often called detonation in SI engines.

(iii) In compression-ignition engines, only air is compressed during the compression stroke and the ignition can take place only after fuel is injected just before the top dead centre. Thus there can be no preignition in compression-ignition engines as in spark-ignition engines.

(iv) It has already been pointed out that, the normal process of combustion in compression-ignition engines is by autoignition. And thus normal rate of pressure rise for the first part of the charge for compression-ignition are higher than those for spark-ignition engine, in terms of per degree crank rotation. And normally, audible knock is always present in compression-ignition engine. Thus when the audible noise becomes severe and causes heavy vibrations in the engine, it is said that the engine is knocking. Therefore, it is also a matter of judgement. A definite demarcation between normal combustion and knocking combustion is very difficult. The rate of pressure rise may be as high as 10 bar per degree crank rotation in compression-ignition engines. The factors that tend to increase autoignition reaction time and prevent knock in SI engines promote knock in CI engines. Also, a good fuel for spark-ignition engine is a poor fuel for compression-ignition engine. The spark-ignition fuels have high octane rating 80 to 100 and low cetane rating of about 20, whereas diesel fuels have high cetane rating of about 45 to 65 and low octane rating of about 30.

Table 12.3 gives a comparative statement of various characteristics that reduce knocking in spark-ignition engines and compression-ignition engines.

Table 12.3 Characteristics Tending to Reduce Detonation or Knock

S.No.	Characteristics	SI Engines	CI Engines
1.	Ignition temperature of fuel	High	Low
2.	Ignition delay	Long	Short
3.	Compression ratio	Low	High
4.	Inlet temperature	Low	High
5.	Inlet pressure	Low	High
6.	Combustion wall temperature	Low	High
7.	Speed, rpm	High	Low
8.	Cylinder size	Small	Large

12.18 COMBUSTION CHAMBERS FOR CI ENGINES

The most important function of the CI engine combustion chamber is to provide proper mixing of fuel and air in a short time. In order to achieve this, an organized air movement called the air swirl is provided to produce high relative velocity between the fuel droplets and the air. The effect of swirl has already been discussed in Section 12.13. The fuel is injected into the combustion chamber by an injector having a single or multihole orifices. The increase in the number of jets reduces the intensity of air swirl needed.

When the liquid fuel is injected into the combustion chamber, the spray cone gets disturbed due to the air motion and turbulence inside. The onset of combustion will cause an added turbulence that can be guided by the shape of the combustion chamber. Since the turbulence is necessary for better mixing, and the fact that it can be controlled by the shape of the combustion chamber, makes it necessary to study the combustion chamber design in detail.

CI engine combustion chambers are classified into two categories:

(i) *Direct-Injection (DI) Type*: This type of combustion chamber is also called an open combustion chamber. In this type the entire volume of the combustion chamber is located in the main cylinder and the fuel is injected into this volume.

(ii) *Indirect-Injection (IDI) Type*: In this type of combustion chambers, the combustion space is divided into two parts, one part in the main cylinder and the other part in the cylinder head. The fuel-injection is effected usually into that part of the chamber located in the cylinder head. These chambers are classified further into:

  (a) Swirl chamber in which compression swirl is generated.
  (b) Precombustion chamber in which combustion swirl is induced.
  (c) Air cell chamber in which both compression and combustion swirl are induced.

The details of these chambers are discussed in the following sections.

12.18.1 Direct–Injection Chambers

An open combustion chamber is defined as one in which the combustion space is essentially a single cavity with little restriction from one part of the chamber to the other and hence with no large difference in pressure between parts of the chamber during the combustion process. There are many designs of open chamber some of which are shown in Fig.12.19.

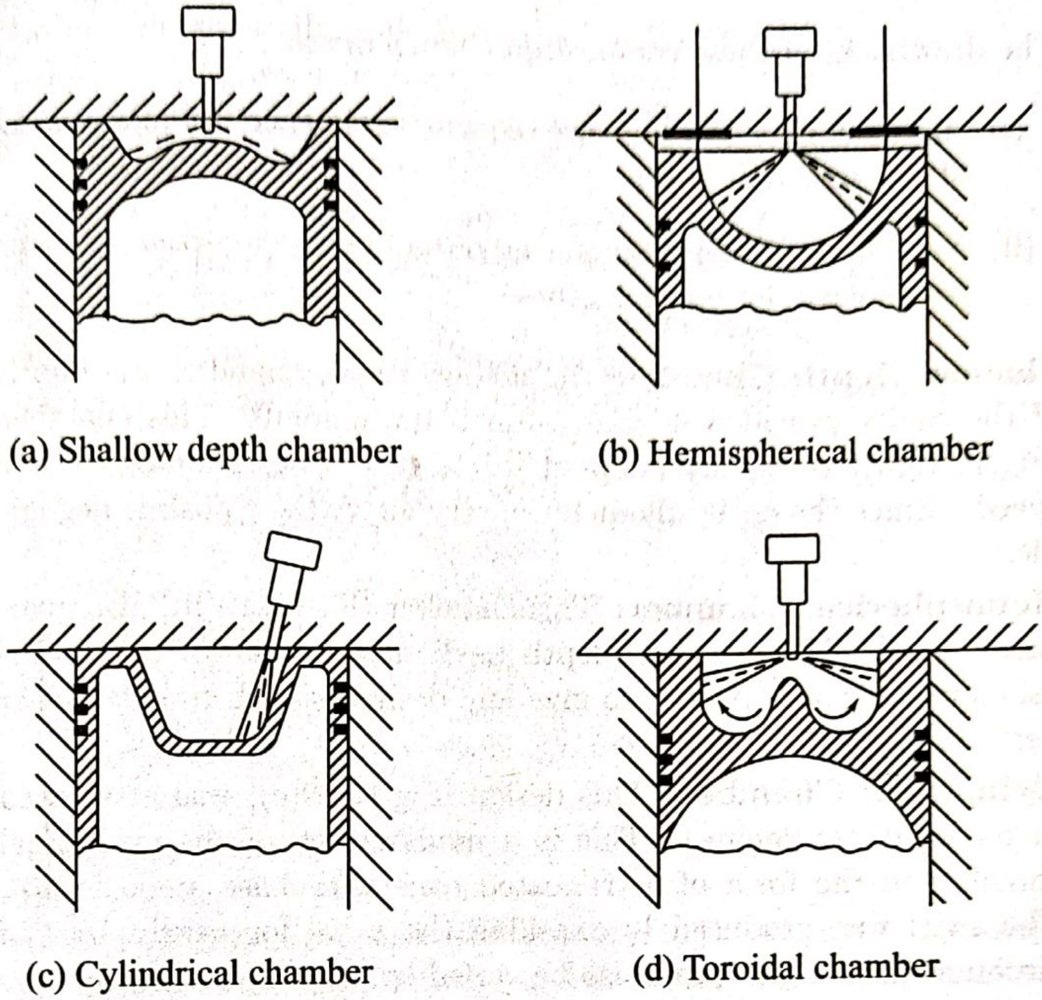


Fig. 12.1J Open Combustion Chambers

In four-stroke engines with open combustion chambers, induction swirl is obtained either by careful formation of the air intake passages or by masking a portion of the circumference of the inlet valve whereas in two-stroke engines it is created by suitable form for the inlet ports. These chambers mainly consist of space formed between a flat cylinder head and a cavity in the piston crown in different shapes. The fuel is injected directly into this space. The injector nozzles used for this type of chamber are generally of multi-hole type working at a relatively high pressure (about 200 bar). The main advantages of this type of chambers are:

(i) Minimum heat loss during compression because of lower surface area to volume ratio and hence, better efficiency.

(ii) No cold starting problems.

(iii) Fine atomization because of multihole nozzle.

The drawbacks of these combustion chambers are:

(i) High fuel-injection pressure required and hence complex design of fuel-injection pump.

(ii) Necessity of accurate metering of fuel by the injection system, particularly for small engines.

Shallow Depth Chamber: In shallow depth chamber the depth of the cavity provided in the piston is quite small. This chamber [Fig.12.19(a)] is usually adopted for large engines running at low speeds. Since the cavity diameter is very large, the squish is negligible.

Hemispherical Chamber: This chamber [Fig.12.19(b)] also gives small squish. However, the depth to diameter ratio for a cylindrical chamber can be varied to give any desired squish to give better performance.

Cylindrical Chamber: This design [Fig.12.19(c)] was attempted in recent diesel engines. This is a modification of the cylindrical chamber in the form of a truncated cone with base angle of 30°. The swirl was produced by masking the valve for nearly 180° of circumference. Squish can also be varied by varying the depth.

Toroidal Chamber: The idea behind this shape [Fig.12.19(d)] is to provide a powerful squish along with the air movement, similar to that of the familiar smoke ring, within the toroidal chamber. Due to powerful squish the mask needed on inlet valve is small and there is better utilisation of oxygen. The cone angle of spray for this type of chamber is 150° to 160°.

12.18.2 Indirect–Injection Chambers

A divided combustion chamber is defined as one in which the combustion space is divided into two or more distinct compartments connected by restricted passages. This creates considerable pressure differences between them during the combustion process.

Swirl Chamber: Swirl chamber consists of a spherical-shaped chamber separated from the engine cylinder and located in the cylinder head (Fig.12.20). Into this chamber, about 50% of the air is transferred during the compression stroke. A throat connects the chamber to the cylinder which enters the chamber in a tangential direction so that the air coming into this chamber is given a strong rotary movement inside the swirl chamber and after combustion, the products rush back into the cylinder through the same throat at much higher

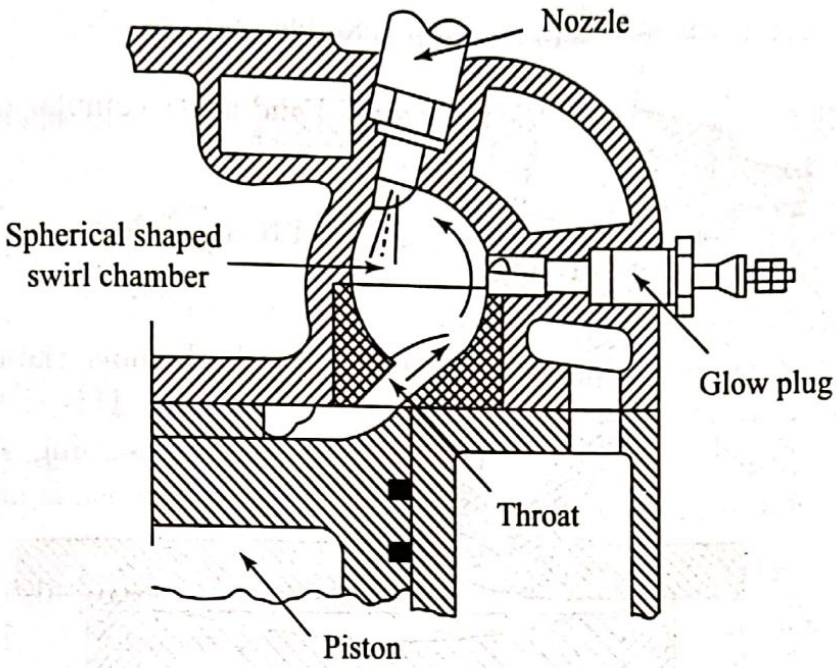


Fig. 12.20 Ricardo Swirl Chamber Comet, Mark II

velocity. This causes considerable heat loss to the walls of the passage which can be reduced by employing a heat-insulated chamber. However, in this type of combustion chambers even with a heat insulated passage, the heat loss is greater than that in an open combustion chamber which employs induction swirl.

This type of combustion chamber finds application where fuel quality is difficult to control, where reliability under adverse conditions is more important than fuel economy. The use of single hole of larger diameter for the fuel spray nozzle is often important consideration for the choice of swirl chamber engine.

Precombustion Chamber: A typical precombustion chamber (Fig.12.21) consists of an antichamber connected to the main chamber through a number of small holes (compared to a relatively large passage in the swirl chamber). The precombustion chamber is located in the cylinder head and its volume accounts for about 40% of the total combustion space. During the compression stroke the piston forces the air into the precombustion chamber. The fuel is injected into the prechamber and the combustion is initiated. The resulting pressure rise forces the flaming droplets together with some air and their combustion products to rush out into the main cylinder at high velocity through the small holes. Thus it creates both strong secondary turbulence and distributes the flaming fuel droplets

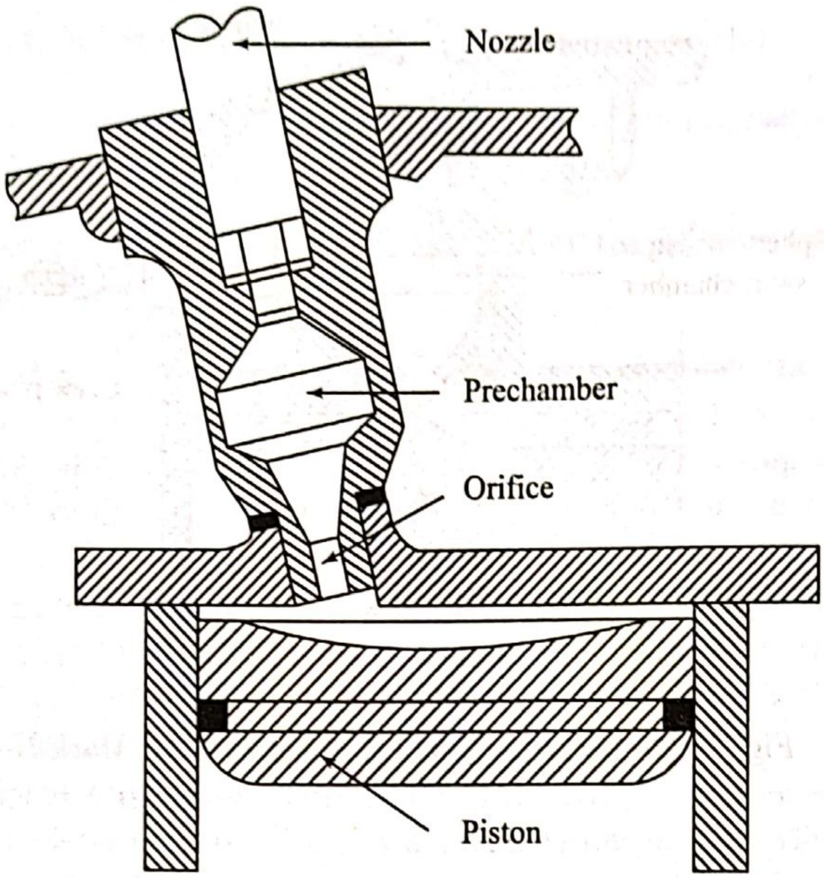


Fig. 12.21 Precombustion Chamber

throughout the air in the main combustion chamber where bulk of combustion takes place. About 80% of energy is released in main combustion chamber.

The rate of pressure rise and the maximum pressure is lower compared to those of open type chamber. The initial shock of combustion is limited to precombustion chamber only. The precombustion chamber has multi-fuel capability without any modification in the injection system because of the temperature of prechamber. The variation in the optimum injection timing for petrol and diesel operations is only 2° for this chamber compared to 8° to 10° in the other designs.

Air-Cell Chamber: In this chamber (Fig.12.22), the clearance volume is divided into two parts, one in the main cylinder and the other called the energy cell. The energy cell is divided into two parts, major and minor, which are separated from each other and from the main chamber by narrow orifices. A pintle type of nozzle injects the fuel across the main combustion chamber space towards the open neck of the air cell.

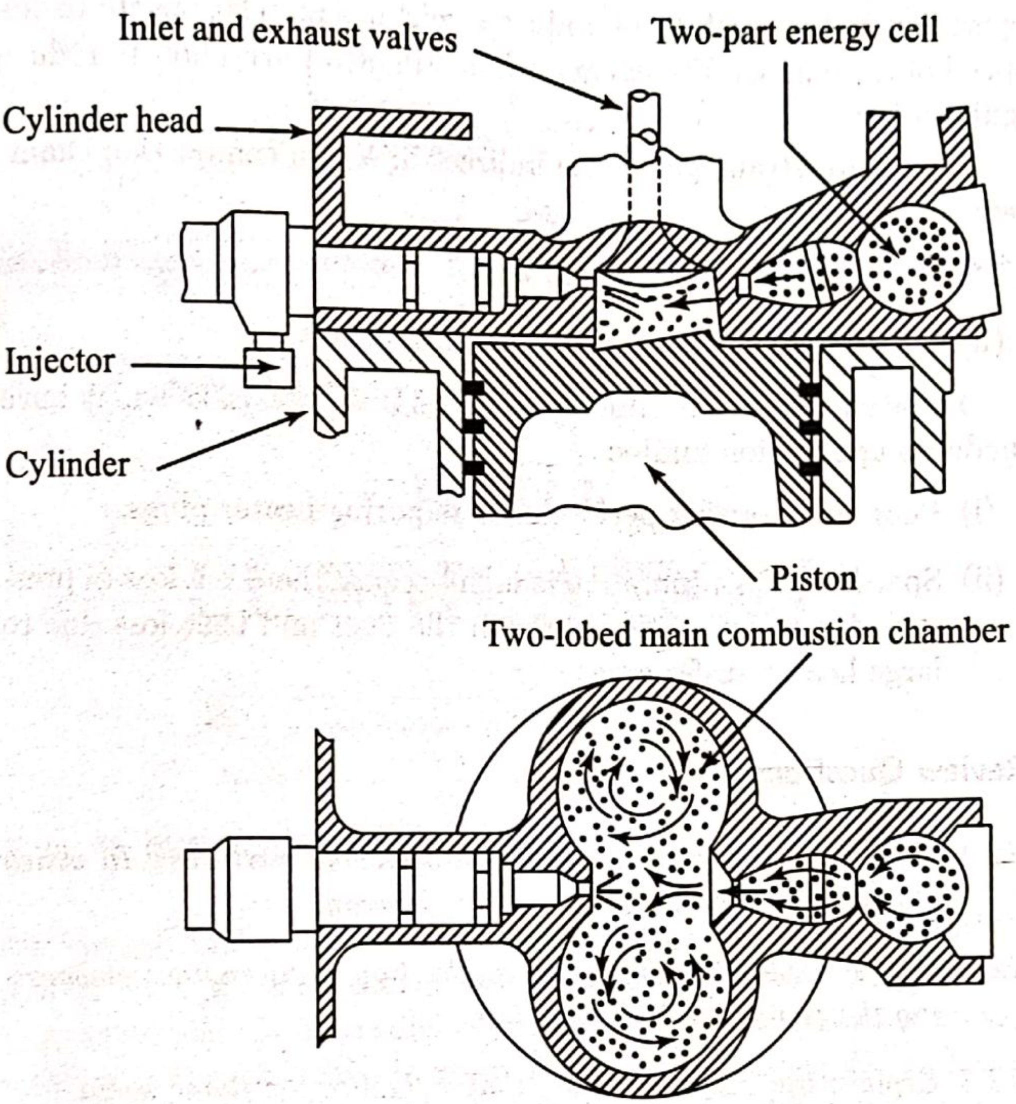


Fig. 12.22 Lanova Air-Cell Combustion Chamber

During compression, the pressure in the main chamber is higher than that inside the energy cell due to restricted passage area between the two. At the *TDC*, the difference in pressure will be high and air will be forced at high velocity through the opening into the energy cell and this moment the fuel-injection also begins. Combustion starts initially in the main chamber where the temperature is comparatively higher but the rate of burning is very slow due to absence of any air motion. In the energy cell, the fuel is well mixed with air and high pressure is developed due to heat-release and the hot burning gases blow out through the small passage into the main chamber. This high velocity jet produces swirling motion in the main chamber and thereby thoroughly mixes the fuel with air resulting in complete combustion. The design is not suitable for variable speed operation as the combustion induced swirl has no relationship to the speed of the engine. The energy cell is designed to run hot, to reduce ignition lag.

The main advantages of the indirect-injection combustion chambers are:

(i) injection pressure required is low

(ii) direction of spraying is not very important.

These chambers have the following serious drawbacks which have made its application limited.

(i) Poor cold starting performance requiring heater plugs.

(ii) Specific fuel consumption is high because there is a loss of pressure due to air motion through the duct and heat loss due to large heat transfer area.

Review Questions

12.1 *What are homogeneous and heterogeneous mixtures? In which engines these mixtures are used? Explain.*

12.2 *Briefly explain the stages of combustion in SI engines elaborating the flame front propagation.*

12.3 *Explain the various factors that influence the flame speed.*

12.4 *What is meant by abnormal combustion? Explain the phenomena of knock in SI engines.*

12.5 *Explain the effect of various engine variables on SI engine knock.*

12.6 *What are the various types of combustion chambers used in SI engines? Explain them briefly.*

12.7 *Bring out clearly the process of combustion in CI engines and also explain the various stages of combustion.*

12.8 *What is delay period and what are the factors that affect the delay period?*

12.9 *Explain the phenomenon of knock in CI engines and compare it with SI engine knock.*

12.10 *Explain with figures various types of combustion chambers used in CI engines.*