Unit 2

INTERNAL COMBUSTION ENGINES (7ME5-11)

SYLLABUS

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1	**Fuel & Combustion:** Combustion in CI & SI engines, Ignition Limits, Stages of combustion, Combustion parameters. Delay period and Ignition Lag, Turbulence and Swirl, Effects of engine variables on combustion parameters, abnormal combustion in CI & SI engines, Detonation & knocking, Theories of detonation, Control of abnormal combustion, Combustion chamber design principles, Types of Combustion chamber.
2	**Alternative Fuels:** Methanol, Ethanol, Comparison with gasoline, Manufacturing, Engine performance with pure Methanol, Ethanol & blends, Alcohols with diesel engine, Vegetable oils, Bio

CHAPTER 2

COMBUSTION IN CI ENGINES

2.1 Introduction

There are certain basic differences existing between the combustion process in SI and CI engines. In the SI engine, a homogenous carbureted mixture of gasoline vapour & 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. After ignition a Single flame front progress through the air-fuel mixture.

In the CI engine only air is compressed through a high compression ratio (16:1 to 20:1) raising its temperature & 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. This spray envelope is created both by the atomization and vaporization of fuel. The turbulence of the air in the combustion chamber passing across the jet tears the fuels particles from the core. A mixture of air & fuel forms at some location in the spray envelope & oxidation starts.

The liquid fuel droplets evaporates by absorbing the latent heat of vaporization from the surrounding air which reduces the temperature of a thin layer of air surrounding the droplets & some time elapse before this temperature can be raised again by absorbing heat from the back of air. As soon as this vapour & the air reach the level of auto ignition temperature & 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 droplet cannot be injected and distributed uniformly throughout the combustion space, the fuel –air mixture is essentially heterogeneous. If the air within the cylinder were motion less under these conditions, there will not be enough oxygen in burning zone & burning of fuel would be either slow or totally fails as it would be surrounded by its own products of combustion. Hence an orderly and controlled movement must be imparted to the air & 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.
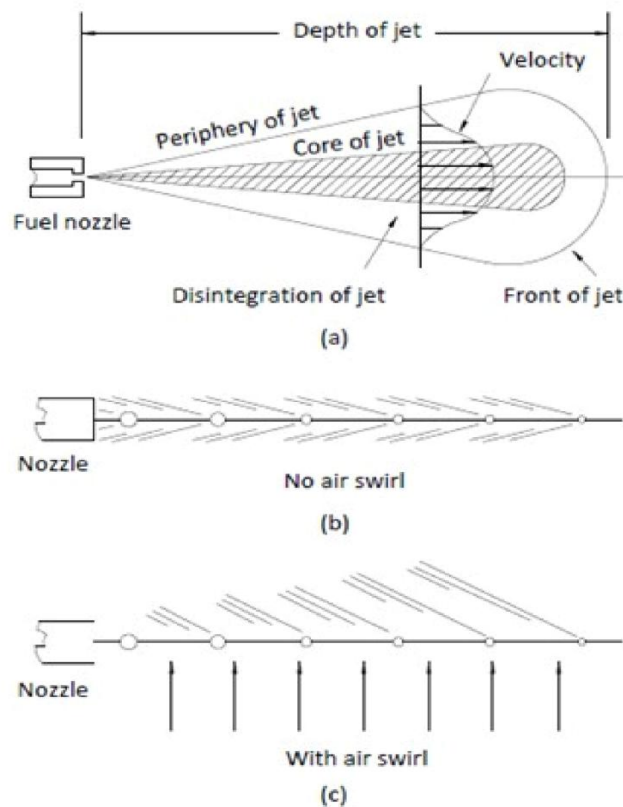

Fig. 2.1: Schematic Representation of the Disintegration of a fuel Jet

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 engine 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 portion 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 where as in the CI engine, ignition occurs at many points simultaneously with consequent rapid lose 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 fuel 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 charged, 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 of combustion chamber should be as close to stoichiometric as possible while operating at full load since the mean effective pressure & power output are maximum at that conditions thermo dynamic analysis of the engine cycles have clearly established that operating an engine with a leaner air-fuel ratio always gives a better thermal efficiency but the mean effective pressure & 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 with in 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 & 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.
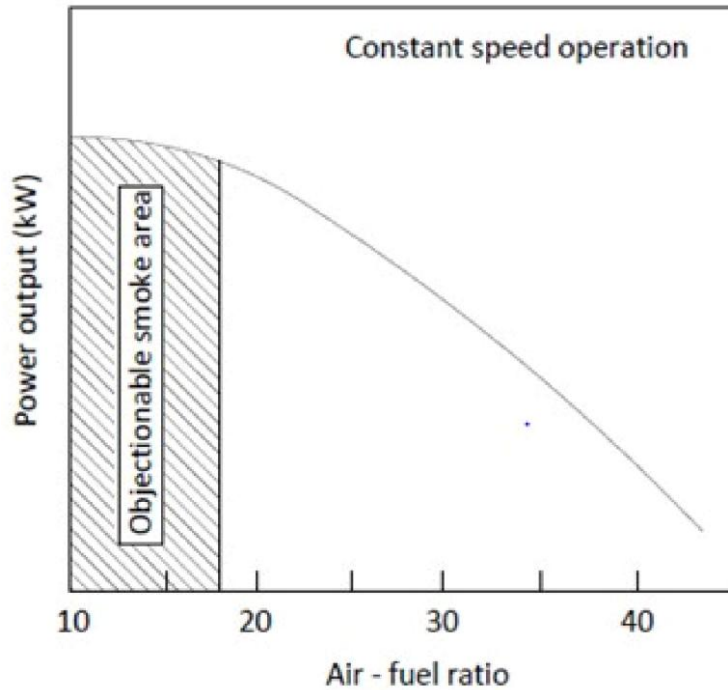
Fig. 2.2: Effect of A/F ratio on Power output of a CI Engine

2.2 Stages of combustion in CI engines

The combustion in CI engine is considered to be taking place in four stages. It is divided into the ignition delay period, the period of rapid combustion, the period of controlled combustion and the period of after burning. Details are as follows:

2.2.1 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 of the point where the pressure time curve separates from the motoring curve indicated as start of combustion in fig.
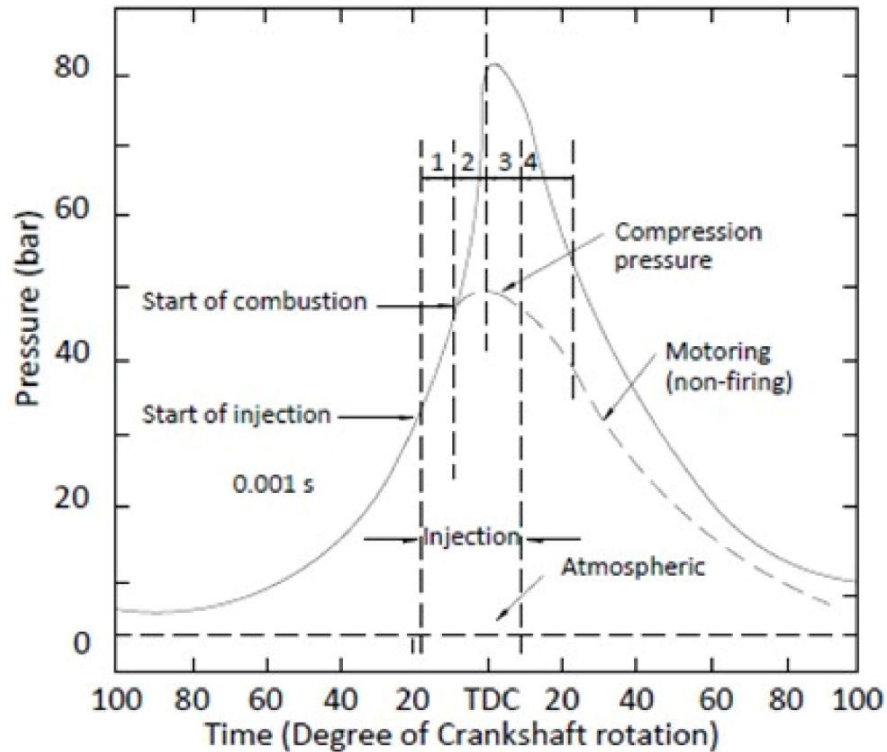
Fig. 2.3: Stages of Combustion in a CI Engine

The delay period in CI engine exerts a very great influence on both engine design & performance. It is of extreme importance because of its effect on the combustion rate, combustion ratio & knocking and also its influence on engine starting ability & 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 & the time it starts through the actual burning phase this period is known as the ignition delay period.

2.2.2 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 & fresh air is always available around the droplets. Most of the fuel admitted would have evaporated & formed a combustible mixture of air. By this time the pre flame reaction 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 the pressure reached during the period of rapid combustion will depends on the duration of delay period, the longer the delay the more rapid & higher is the pressure rise since more fuel would have accumulated in the cylinder during the delay period.

2.2.3 Period of controlled combustion

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

2.2.4 Period of after burning

Combustion does not cease with the completion of the injection process. The un burnt & partially burnt fuel particles left in the combustion chamber start burning as soon as they come into contact with the oxygen. This process continuous 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 expansion stroke.

Rate of after burning depends on the velocity of diffusion & turbulent mixing of unburnt & partially burnt fuel with the air. The duration of the after burning phase may correspond to 70-80 degree of crank travel from TDC.

**2.2.5 Sequence of events in the entire combustion process of CI engine including the delay period**

1.) Delay period or Ignition lag

The first stage of combustion in the CI engine i.e. the delay period exerts a very great influence on both engine design and performance. In fig the delay period is shown on pressure crank angle diagram between points 'a' &'b', point 'a' represents the time at which the pressure curve (caused by combustion) first separate from the compression curve (non-firing & motoring) curve this ignition delay period can be roughly divided into two parts.
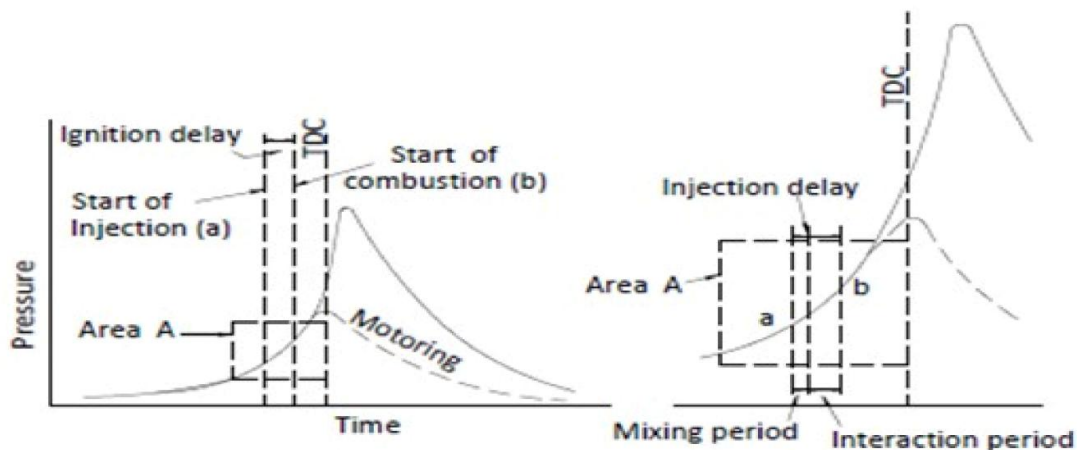
i.) Physical delay

The period of physical delay is the time between the beginning of injection and the attainment of chemical reaction conditions. In the physical delay period the fuel is atomized, vaporized, mixed with air & raised in temperature.
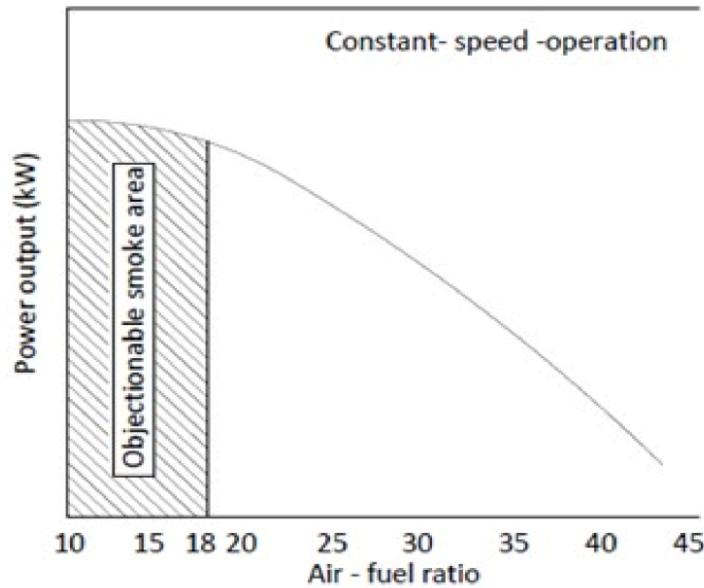
Fig. 2.4: Effect of A/F Ratio on Power Output of a CI Engine

Fig. 2.5: Pressure-Time diagram illustrating delay period

ii.) Chemical Delay

The second part of the delay is called chemical delay in which pro flame reaction starts slowly and then accelerated until local inflammation or ignition rakes place. Generally chemical delay is longer than the physical delay. However it depends on temperature, at high temperature chemical reaction is quicker &

physical delay is longer than chemical delay. The delay period refers to the sum of physical & chemical delay. In most CI engines the ignition delay is shorter than the duration of injection.

The ignition lag of SI engine is basically equivalent to the chemical delay in CI engines. SI engine as the charge consists of homogenous mixture of vaporized fuel & air.

The delay period in CI combustion affects rate of pressure rise and hence knocking it also affects engines start ability.

It is clear that the pressure reached during the second stage will depends on the duration of the delay period. The longer the delay period the more rapid and higher is the pressure rise, since more fuel will be present in the cylinder before the rate of burning comes under control. This may cause rough running and may cause 'diesel knock'. Therefore the diesel engine designer aims to keep the delay period as short as possible, both for smooth running and to maintain control over the pressure changes. But some delay period is necessary otherwise the droplets would not be dispensed in the air for complete combustion. This will result in high smoke & high fuel consumption. In practice, however the delay period is more than required & the designer efforts are always devoted towards shorting it as much as possible.

2.3 Variables affecting delay period

1.) Fuel

The most important property of fuel as far as delay period is concerned is the self-ignition temperature. A lower self-ignition temperature means a wide margin between it and temperature of the compressed air and hence lower delay period. Cetane is a scale for comparing the ignition delay angle of various diesel fuels. A higher cetane number means a lower delay period and smoother engine operations. The cetane number depends on the chemical composition of fuel. The more paraffin hydrocarbons are contained in the fuel, the higher will be its cetane number.

Other properties of fuel which offers delay period are volatility, latent heat, viscosity and surface tension. The volatility & latent heat affect the time taken to form an envelope of vapors the viscosity and surface tension influence the fineness of atomization.

2.) Injection pressure or size of droplet

It seems that in the CI engine in order to achieve complete combustion in the very short time available, the liquid fuel should be injected in the form of droplets of smallest size to obtain largest surface volume ratio. But it should be keep in mind the rate of burning depends primarily upon the rate at which the products of combustion can be removed from the surface & replaced by fresh oxygen i.e. it depends upon the rate at which the burning droplet can move relative to the surrounding air. A smaller droplet will have lesser momentum and hence lesser relative velocity and once its initial velocity is lost it will travel in air with little relative velocity resorting in its practical suffocating by its own products of combustion. Secondly as the pressure rise after ignition depends on the area of inflammation, the smaller the size and greater the number of droplets the larger

will be the aggregate area of inflammation & therefore the greater the uncontrolled pressure rise. The disadvantages are, rate of burning is too slow & hence a compromise is to be struck. As the size of the droplet depends on the injection pressure, it can be said that lower the injection pressure the lower, the rate of pressure rise during the uncontrolled phase & smoother the running.

3.) Injection advance angle

The delay period increases with increase in injection advance angel. The reason for increase in delay period with increase in injection advance angel is that the pressure and temperature are lower when the injection begins. When the injection advance angle are small, the delay period reduces & operation of the engine is smoother, but the power is reduced because larger amount of fuel burns during expansion (after-burning).   The optimum angle of injection advance depends on many factors, but generally it varies between 12^0 To 20^0 before TDC. This would cause peak pressure to occur 10^0 to 15^0 after top dead centre.

The duration of injection and the delivery law i.e. change in the quantity of fuel supplied with the angle of crank travel, also affects the combustion process when duration of injection is decreased with the same fuel delivery per cycle, the delay period remains the same, but the rate of pressure rise increase, since more fuel is supplied into the cylinder by the moment of ignition.

4.) Compression ratio

Increase in compression ratio reduces the delay period as it raises both temperature and density.

Fig 4.6 shows that with increase in compression ratio the temperature of the air increases (curve a). At the same time the minimum auto-ignition temperature decreases due to increased density of the compressed air, resulting in closer contact of the molecules which, thereby, reduces the time of reaction when fuel is injected. As the difference between compressed temperature and the minimum auto-ignition temperature increased, the delay period decreases.

The above theoretical analysis may suggest that in diesel engines the highest possible compression ratio should be used to achieve the lowest delay period.
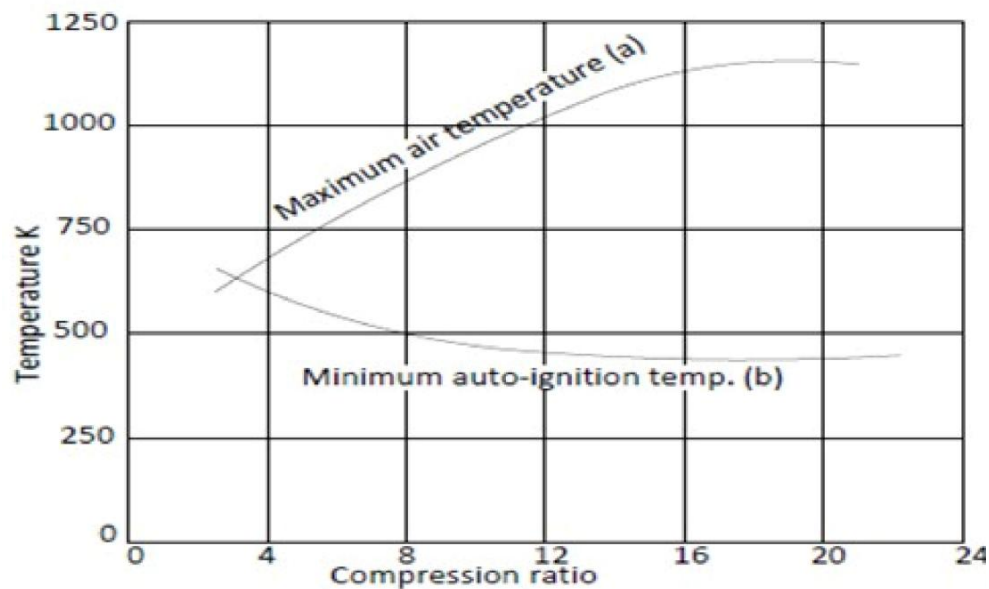
Fig. 2.6: Effect of Compression Ratio on maximum air temperature and minimum auto ignition temperature

However there are practical disadvantages of using very high compression ratios. In CI engines the compression space is already very small and the necessity of providing working clearance between the piston and the cylinder head & around the values compels us to leave thin layers or pockets of air to which the fuel cannot reach with a compression ratio of 16 the unused air is already about 20 percent with increase of compression ratio the unused air would be much more decreasing the volumetric efficiency & power. Another disadvantage of high compression ratio is lower mechanical efficiency due to increase in weight of reciprocating parts. Therefore, in practice the engine designer uses the lowest compression ratio which would satisfy the needs of easy cold starting and light load running at high speeds. Note that this practice is opposite of SI engine design practice where the endeavor is to use highest possible compression ratio, only limited by detonation.

The maximum peak pressure is only marginally affected by the compression ratio, because with higher compression ratio delay period is shorter and therefore the rise of pressure on ignition is lower.

5.) Intake temperature

Increasing the intake temperature would result in increase in the compressed air temperature, which would reduce the delay period. However increasing the intake temperature say by pretesting would be most undesirable because it would reduce the density of air and license volumetric efficiency and power output. This loss would be much greater than the small gain in reduction of delay period. Procreating the air by 100^0C reduces the delay angle by barely 2^0.

6.) Jacket water temperature

Increase in jacket water temperature also increases compressed air temperature and hence delay period is reduced.

7.) Fuel Temperature

Increase in fuel temperature would reduce both physical and chemical delay period.

8.) Intake pressure or supercharging

Increase in intake pressure or supercharging reduces the auto ignition temperature & hence reduces delay periods. Since the compression pressure will increase with intake pressure, the peak pressure will be higher. Also the power output will be more as cylinder will contains more air & hence more fuel can be injected per stroke.

9.) Speed

The delay period can be given either in terms of absolute time or in terms of crank angle rotation. At constant speed, delay time is proportional to delay angle. Hence with reference to constant speed operation it is not necessary to mention whether we mean delay period in terms of millisecond or crank angle. But in variable speed operation delay period many decrease in terms of millisecond but increase in terms of crank angles.

As the engine speed increases, the loss of heat during compression decrease with the result that both the temperature & pressure of the compressed air tend to rise, thus reducing the delay period in milliseconds, as the increase in turbulence however may trend to increase the heat loss in some cases. However, with degrees of crank travel the delay period increases.

Since the amount of fuel injected during delay period depends on crank degrees & not on absolute time because the fuel pump is geared to the engine at high speed there will be more fuel present in the cylinder to take part in the second stage of uncontrolled Combustion, resulting in high rates of pressure rise and high maximum pressures. This factor has caused difficulties in the developments of very high speed CI engine. Very high speed CI engine, therefore required greater angle of injection advance, high ignition quality fuel i.e. high cetane number which gives reduced ignition delay and a special design for combustion chamber.

10.) Air fuel ration

With increase in air fuel ratio (lean mixture) the combustion temperature are lowered & cylinder wall temperature are reduced & hence the delay period increases. The rate of pressure rise is unaffected but the maximum pressure may be looked. With increase in load, air-fuel ratio decrease, operating temperature increase & hence, delay period decreases.

11.) Engine size

The engine size has little effect on the delay period in millisecond. As large engines operates at low rpm because of inertia stress limitations, the delay period in terms of crank angel is smaller & hence less fuel enters the cylinder during delay period. Thus combustion in large slow speed CI engines is smooth.

12.) Type of combustion chamber

Types of combustion chamber as pre-combustion chamber gives shorter delay compared to an open type f combustion chamber.

2.4 Detonation in CI engines

The fuel injection takes place over a definite period. Consequently the first droplets injected are passing through the ignition delay. Additional droplets are being injected into the chamber. If the ignition delay of the injected fuel is small, the first droplets start burning in a relatively short time after injection and relatively small amount of fuel will be accumulated in the chamber. Therefore, the rate of pressure rise will be smooth. But if the delay period is longer, the accumulation of fuel will be larger as the actual burning of the first droplet is delayed.

When actual burning starts, the accumulated fuel and additional fuel injected starts burning and can cause to rapid rate of pressure rise. This rapid rise of pressure cause pulsating combustion and creates heavy noise this type of abnormal combustion is known as detonation. This detonation occurs during the initial period over the delay period when the burning of the first portion of fuel is uncontrolled, thus giving rise to an excessive rate of pressure rise.
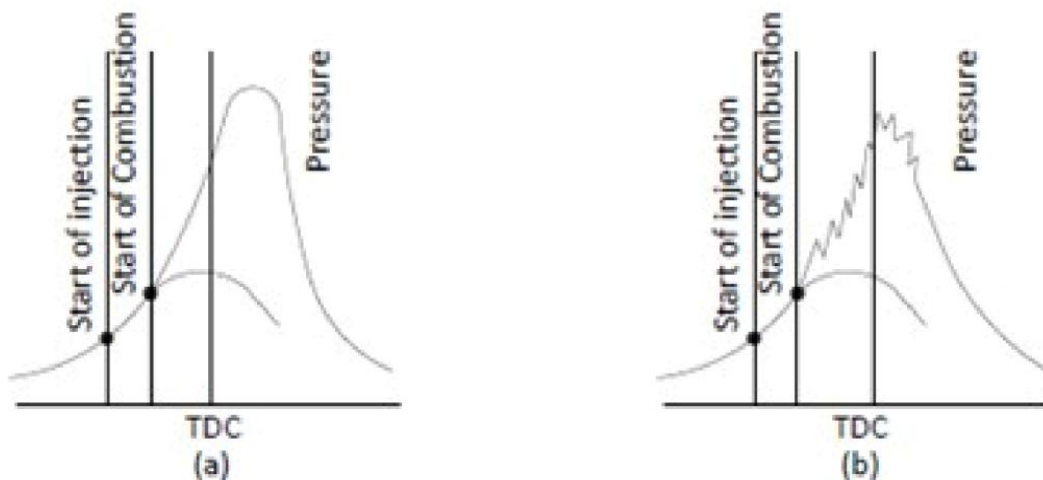
Fig. 2.7: Knocking Combustion in CI and SI Engines

2.4.1 Factors affecting the detonation in CI engines

The factors which influence the delay period also influence the detonation tendency of CI engines as.

1. If the injection of fuel is too far advanced the rate of pressure rise during auto-ignition is very high and cause detonation.
2. Inferior fuels having lower cetane number promote diesel knock but this can be avoided by using better types of fuels.
3. Fuel injection parameters, better combustion chamber design also influence detonation tendency of engine.
4. Initial condition of the air which is at higher temperature or higher pressure, in case of supercharged engine or both influence detonation tendency. Higher pressure & temperature initially reduces detonation tendency.
5. The fuel having longer delay period & higher self-ignition temperature leads to detonation.

With proper design of combustion chamber & injecting the fuel uniformly over a hot surface of the combustion chamber, the detonation cab be avoided.

2.4.2 Controlling the detonation

It the factors which are responsible for the detonation are controlled, then the detonation can be avoided.

The detonation can be controlled by reducing the delay period which is fully responsible for detonation.

1.) Using a better fuel

Higher CN fuel has lower delay period & reduces detonation tendency.

2.) Controlling the rate of fuel supply

It can be reduced by controlling the initial rate of fuel delivery without affecting efficient combustion conditions. A small amount of fuel should be supplied till the combustion starts and then more amount of fuel should be supplied as inside combustion chamber condition is suitable, because of high temperature chamber inside to burn more fuel. In this case, cam shape is so designed which gives low initial injection followed by main injection at higher rate.

3.) Knock reducing fuel injector

This type of injector is developed which can avoid the sudden increase in the pressure rise inside the combustion chamber because of accumulated fuel. In this case, injection pressure of 100 bar is used with a semi-fixable needle value.

Doxford controls detonation by using two injectors slightly out of phase. But a long combustion period reduces the thermal efficiency of the engine.

2.5 Comparing the knocking in SI & CI engines

It is interesting to compare the knocking phenomenon in SI & CI engines. This phenomenon in both engines is fundamentally similar. Both are process of auto ignition subject to the ignition lag characteristics of A/F mixture supplied to the engine.

The differences in knocking phenomenon in both engines are.

1.) In SI engines the knocking occurs near the end of combustion where as in CI engine. This occurs at the beginning of combustion.
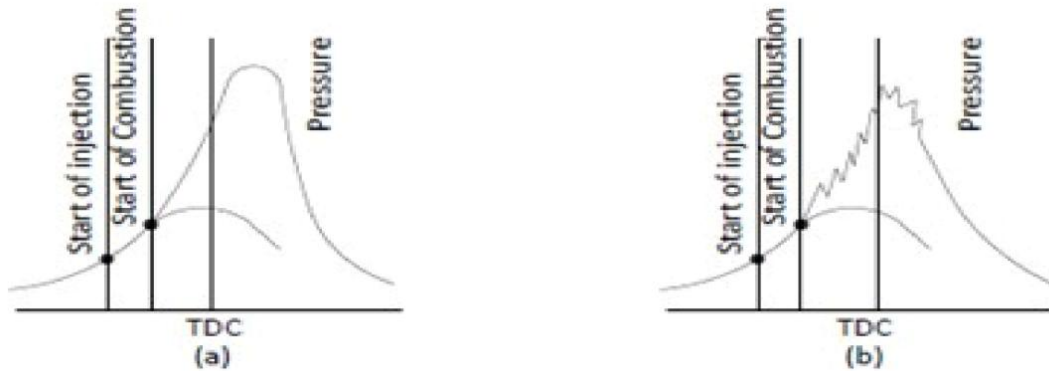
Fig. 2.8: Occurrence of Knocking in SI and CI Engines

2.) The knocking is SI engine takes place in a homogeneous mixture; therefore, the rate of pressure rise and maximum pressure is considerably high. In case of CI engine, the mixture is not homogenous and time the rate of pressure is lower than in SI engine.

3.) The question of pre ignition does not arise in CI engines as the fuels is supplied only near the end of compression stroke.

4.) It is easier to distinguish between knocking & non-knocking operations in SI engine as the human ear easily finds the difference. However in CI engine, the normal ignition is itself by auto ignition and rate of pressure rise under normal operation is considerably higher (10 bar against 2.5bar for SI engines) and cause high noise. The noise level becomes excessive under detonation conditions. Therefore there is no definite distinction between normal & knocking combustion. The knocking in SI engines is because of auto ignition of the last part of the charge. To avoid this, the fuel must have long delay period & high-self ignition

temperature. To avoid knock in CI engine the delay period should be as small as possible & fuel self-ignition temperature should be as low as possible. Because of this dissimilarity in the time of starting of the knock in SI & CI engines, the conditions which reduce the knock tendency in SI engine increase the knock tendency in CI engines the fuels which are better from the points of view of avoiding detonation in SI engines may promote detonation in CI engines, therefore good SI fuels are poor CI fuels in terms of fuel rating, diesel oil with high cetane number (40-60) and low octane number & petrol has high octane number (80-90) & low cetane number (20).

2.6 Combustion chamber design of CI engines

Design of CI engine combustion chamber requires careful consideration for performing smooth operations. Important functions to be performed by CI engine combustion chambers are the following.

- Proper mixing of fuel droplets with the air in a short duration.
- To provide efficient air swill i.e. high relative velocity between the fuel dropouts & air.
- A proper shape so that the effective turbulence may be provided for better atomization.

2.6.1 Types of combustion chamber for CI engines

A large variety of combustion chambers have been developed for high speed diesel engines, but the following types are most common among them.

1.) Open type or direct injection (DI) type or non-turbulent type.

i.) Shallow depth combustion chamber.

ii.) Hemispherical combustion chamber.

iii.) Cylindrical combustion chamber.

iv.) Steroidal combustion chamber.

## 2.) Divided type or indirect injection (IDI) type or turbulent type

i.) Pre combustion chamber type.

ii.) Swill chamber type.

iii.) Air- cell chamber type.

In direct-injection type, the entire combustion chamber is located in main cylinder this is also called open type because the combustion space has a single cavity without restriction or partition.
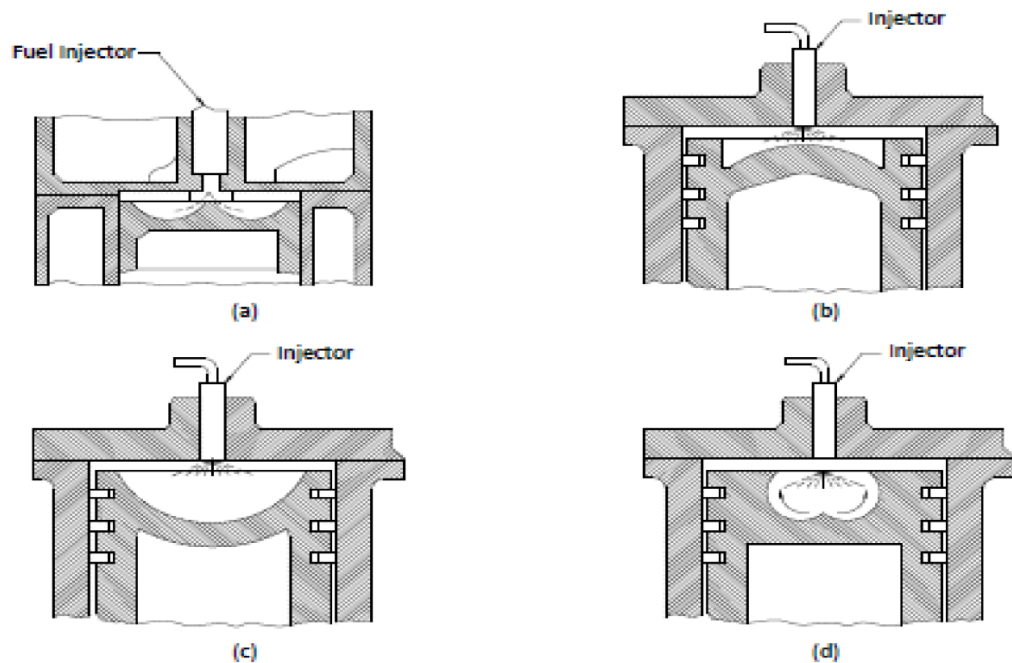
In indirect injection type, the combustion space is divided into two sections, of which one section remains in main cylinder & the other in cylinder head that is way the IDI type combustion chamber are also known as "divided type combustion chamber". The differences in physical shape of different chamber design are displayed in fig.
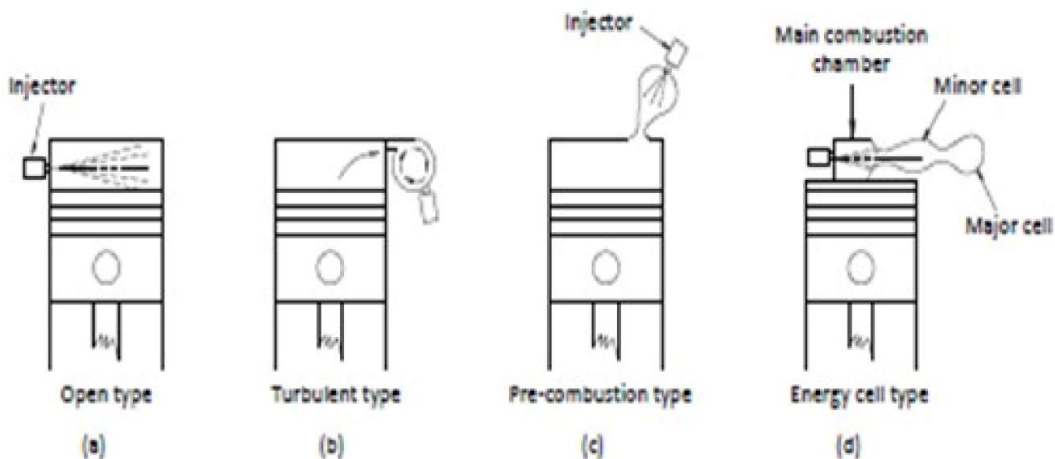
Fig. 2.9: Illustration of commonly used C.I Engine combustion chamber (a) Open type (b) Turbulent type (c) Pre-combustion chamber type, and (d) Energy cell type

2.6.1.1Direct injection type (or open) combustion chamber

In such combustion chambers, the design involves a single cavity without any division or restriction.

Fig. 2.10: Some Designs of Direct injection type (or open) combustion chamber

Therefore, there is not much difference in pressure across the combustion chamber during combustion. In open type combustion chambers, the induction swill is obtained by adopting the following means.

1.) By formation of air intake passages in 4-stroke CI engine.

2.) By masking a portion of the circumference of inlet value in 4-stroke CI engines.

3.) By formation of suitable air ports in 2-stroke CI engines.

1.) Disc type chamber

In this type the injection of diesel is direct into the disc shaped space between the piston & cylinder head. The overhead values are placed vertically in the cylinder head. This type of chamber is used on large but slow speed engines.

2.) Shallow depth type

There due to lower ratio of "surface area to volume" of this chamber, the heat losses & the fuel consumption are lower, however the engines run erratic. Auxiliary starting devices such as hinter plug is not required in them as the fuel injection is of direct types

3.) Steroidal type chamber

In this type, the combustion chamber is formed in the piston crown itself. Due to its shape, it provides a good swill to the injected mixture. The multi-hole injection nozzles are required in such designs such chamber result I a higher combustion efficiency.

Advantages & Disadvantage of Direct injection

Direct- injection combustion chambers have many advantages & few disadvantages some are.

Advantages

1.) Better quality of atomization due to the use of multi-hole nozzles.
2.) No cold starting problems, hence no need of auxiliary starting devices like glow plugs etc.
3.) Loss of heat during compression is minimum owing to a lower surface area to volume ratio.

4.) Efficiency it better.

Disadvantage

1.) Fuel injection pressure is high; therefore related parts are of greater thickness.

2.) Design of fuel-injection pump is complex.

3.) Accuracy is required in metering of the fuel this is more essentially needed for small engines. Hence the control of injection system is complicated.

2.6.1.2 Indirect injection type combustion chambers

These kinds of combustion chambers are constructed such that of combustion space is divided into different compartments.
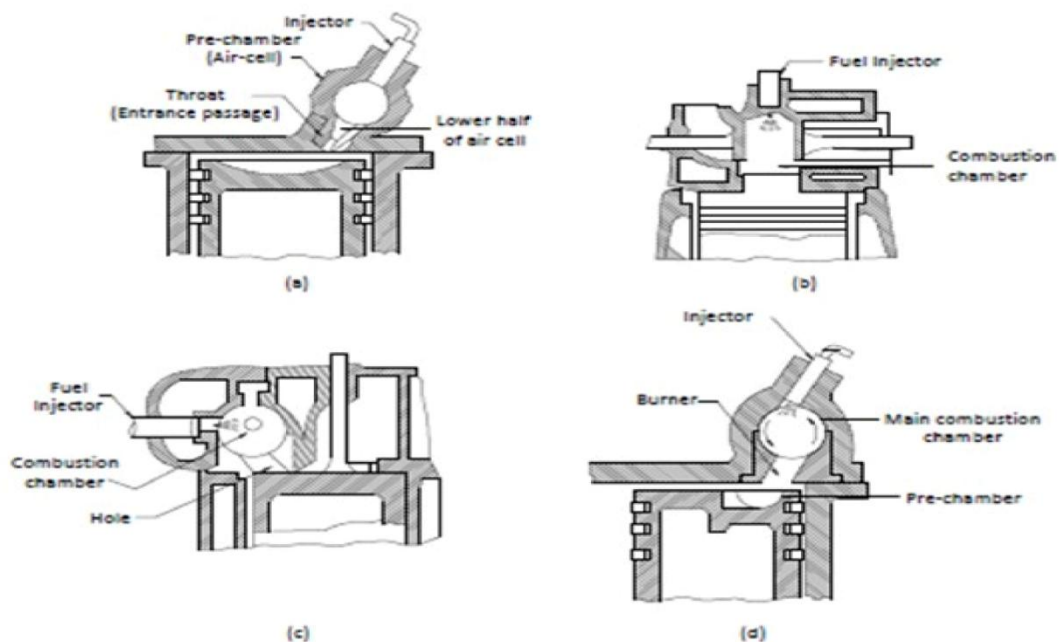
Fig. 2.11: Different type of indirect –injection (or divided) type combustion chambers (a) Swirl Comet type (b) Vortex Type (c) Pre-combustion type (d) Pre-chamber type

The number of compartments may be 2 or more, but two compartments construction is more common. Those divided spaces are connected by restricted passages; therefore substantial pressure difference is created between them during combustion.

The IDI type combustion chambers may be one of the following kinds.

1.) Swirl chamber type: - A compression swirl is generated in it.

1.) Pre combustion chamber type: - A combustion swirl is induced in it.

2.) Air cell chamber type: - Both types' compression swirl & combustion swirl are induced in it.

2.6.1.3 Advantages & Disadvantages of indirect-injection combustion chambers

Advantage

1.) A low fuel injection pressure is required therefore the related parts are not too thick in construction.
2.) An accurate direction of spraying is not essential.
3.) Fuel injection pump is of less complex design.

Disadvantages

1.) Poor cold starting, which necessitates the use of auxiliary starting devices such as glow plugs.
2.) High specific fuel combustion due to loss of pressure, on account of air motion through the duct.
3.) Loss of heat due to large heat transfer area.

2.7 Cold starting problems with CI engines & their remedies

CI engines generally suffer from the problems of easy starting in cold. Even the starting may be difficult in externally cold climate in early regions. In order to ensure easy starting in cold, the requirements of the engines are generally conflicting with each other. However to achieve easy cold starting, the following requirement are incorporated in design & operation.

(1) Compression ratios higher than necessary are used.

(2) A finely atomized fuel jet is directed against the air movement (although this provision causes rough running during normal operation)

(3) Excess supply of fuel is given at starting. However this causes undesired excess smoke & air pollution.

(4) Provision of auxiliary electrical aid is in corporate; amongst these the provision of auxiliary electrical aids is most efficient & commonly adopted.

2.7.1 Speed limits for cold starting

The operational speed of CI engines has an important effect on its cold starting. It should neither be too low nor too high. It is because the engine may not start.

1.) At very low speeds due to

a) High heat losses to the cold walls of cylinder during compression.

b) Greater time available for gas leakage access the piston rings.

2.) At too high speed: due to

a) Less time available for fuel vaporization & preparation of chemically correct mixture.

Hence the engine should be run at optimum speed for trouble free cold starting the optimum speed depends on the following factors.

a) Surface to volume ration of the engine (it controls the heat loss to cylinder walls)

b) Intensity of air swirl (A lower swirl is desired for easier cold starting) and

c) Physical condition of the engine (i.e. the leakage past the values & piston reduces the pressure & temperature of compressed air.)

For an engine in good physical condition, an optimum starting speed of 200-300 rpm is sufficient for the engine of 1000-2000 cc capacity which is provided with sufficiently heavy fly wheel to maintain almost uniform angular vitality throughout the cycle.

2.7.2 Auxiliary cold starting devices

Starting of diesel engines, especially in cold weather may be a troublesome affair. In order to make the engine starting easier, the diesel engines are equipped with certain arrangements. Main amongst them are the following.

1.) Pre-heater (or glow plug :)
2.) Manifold heaters.

CI engines using swirl chambers, air-cells or pre combustion usually require heater plugs to enable a start to be made from cold, unless a very high compression ratio is used.

1. Glow plugs

For easy starting, especially in cold weather, many diesel engines use glow plug the glow plug have electric heating element that become very hot when connected to the battery. In a pre combustion chamber, it is filled close to the fuel-

injection nozzle where the fuel is injected & the combustion start. After combustion, the burning air-fuel mixture streams out of the pre combustion chamber & enters into the main combustion chamber. There it mixes with the air, and combustion is compute.

When the engine is cold & the air temperature is low, the glow plug is turned on to put some heat into the pre combustion chamber. This greatly improves the starting because the fuel is sprayed into air that has been pre heated by the glow plug. On some engines, the glow can be turned on manually if the driver feels the engine needs them. On other such as general motors V-8 diesel used by Chevrolet, olds mobile & Cadillac, the system is semi automatic. A sheathed glow plug is provided in HMs diesel car.

2. Manifold heaters

These are generally used on direct-injection engines where filling of glow plug in combustion chamber is not possible. It consists of an incandescent electric heater of about 150 watt power, which is installed in inlet manifold. A small amount of fuel is fed on to it the intake air passing over this heater picks up heat & also the partially burnt products of combustion. The cold starting is aided by the heat of air as well as the chemical reactivity of partial product of combustion.

2.8 Recent trends in combustion chamber Design

2.8.1. Swirl type combustion chamber

It is a well known fact that the agitation of charge increase with the increasing engine speed, thereby helping to maintain efficient combustion. However the excessive agitation of the charge is undesirable. Since modern engines operate at high compressions, a fair degree of natural ignition of the charge

should be promoted rapidly at that moment, when the charge is directed into the cylinder. This can be easily obtained by providing compression turbulence or induction swirl.

Induction swirl is generated by forcing the incoming charge in a tangential direction into the cylinder. An angle biasing is therefore adopted so that the entering charge is deflected by cylinder walls. Such an arrangement is termed as swirl type combustion chamber. As a consequence of angular momentum imparted to the charge, a beneficial vortex action is set up on the induction stroke which continues during compression stroke. Such combustion chamber has been used on the engine of ambassador Diesel Car.

2.8.2. Stratified charge combustion system

This system allows combustion by forming a rich mixture near spark plug for better ignition ability. In other areas, a leaner mixture is formed. During combustion, the rich mixture spreads outward & moves into the area of leaner mixture which is difficult to ignite. Due to much leaner air-fuel mixture, the amount of pollutants is reduced such charge is known as stratified charge & the engine as stratified- charge engine stratified charge is achieved by providing a swirling motion to the air-fuel mixture when it enters into the cylinder. Turbulence generating pot is another method of centering the combustion. This has been employed in the engines of Toyota Car models the pot helps in spreading the flame rapidly so that a better burning takes place.

2.8.3. M-combustion chamber

This is an open type combustion chamber made in the piston cavity. It is different from other open chamber designs in the since that the spray of fuel impinges upon & spreads over the surface of spherical cavity in the piston. It was

developed by Dr. Meueer of Germany so it is named M-combustion chamber. Since it runs without typical combustion noise of diesel engine, it is also named as 'whisper' engine. Salient features of this combustion chamber are:

1.) Fuel is injected tangentially from a multi-hole nozzle on to the surface of M-chamber in the direction of air swirl.

2.) The rate of energy release is almost the same as the rate of evaporation of fuel.

3.) With M-combustion chamber, although the engine works on diesel cycle yet the combustion characteristics are similar to those of Otto cycle.

Advantage

a) Soot formation is negligible, and smoke level is low
b) Rate of pressure rise is low, and peak pressure is also low.
c) Capability of multi-fuel operation.

Disadvantage

a) Difficult cold starting, hence starting aids are required
b) Low volumetric efficiency.
c) Hydrocarbon emission is high at starting & idling.

COMBUSTION IN SI ENGINES

2.9 Combustion

Burning of fuel in the presence of oxygen is called combustion. It is an exothermic reaction in which the chain of carbons & hydrogen combines with oxygen to give heat as resultant and also some by products.

Some necessary conditions for combustion are:

1) Presence of fuel that can give heat at the time of burning.
2) Presence of oxygen in surrounding where combustion is taking place.
3) Something to initiate the combustion process.
4) Circumstances to make fuel attain their self ignition temperature.

Here in internal combustion engine, the process of combustion takes place inside the cylinder. Process here is mainly depends upon the type of fuel, whether it is heterogeneous or homogeneous.

2.9.1 Homogeneous mixture

Homogeneous mixture is mixture of fuel & air used in combustion process of spark ignition engine. Here homogeneous mixture is prepared outside the engine in carburetor & then forced to enter inside.

Homogeneous mixture is composed of a single phase in which the properties do not change from point to point. The fuel & oxygen molecules are more or less uniformly distributed.

In homogeneous mixture the ratio of actual fuel-air ratio to the stoichiometric ratio is nearly 1.0, with the flame speed of the order of 40 cm/s. however practically the maximum speed of flame is attained when the mixture is slightly richer then stoichiometric.

However with the use of proper air movement, the flame speed can be increased without changing the valve of mixture.

2.9.2 Heterogeneous Mixture

The heterogeneous mixture mainly used in diesel engine or compression ignition engine. In this mixture the rate of combustion is determined by the velocity of mutual diffusion of fuel vapour & air & the rate of chemical reaction is of no major use.

The heterogeneous mixture is composed of more than one phase & also its properties changes with point to point.

2.10 Equivalence ratio & flame speed

Equivalence ratio (ø) is the fraction between the ratio of actual fuel-air to the stoichiometric fuel-air ratio.

2.10.1 For homogeneous mixture

(i) If the equivalence ratio (ø) is nearly 1.0, then the flame will travel with the speed of 40 cm/s.

(ii) for ø, approx to 1.1 to 1.2, the flame speed is maximum.

(iii) for ø greater then 1.2, the flame speed drops drastically. (However we can use turbulence or proper air movement to enhance the speed of flame at these values.)

2.10.2 For heterogeneous mixture

For ø between 1.7 to 1.2, a local zone is been created where the rate of chemical reaction is highest. Ignition starts from here, ø help the remaining fuel to burn.

Here the rate of combustion depends upon the rate of inter-diffusion taking place between fuel & air.

2.11 Combustion in spark ignition engine

In combustion in SI engine the fuel & air are mixed homogeneously outside the cylinder in carburetor, here a proper air-fuel mixture with the desired ratio is formed & atomized. Then this ratio is induced in the cylinder through input valve. Here the mixture is mixed with residual gases already present. After this compression take place, resulting in movement of fuel-air particle as well the temperature gain. Now this mixture is ignited by a single high intensity spark from the spark plug & combustion initiated. Here the spark is a thin thread between the electrodes of spark plug with the temp approx 1000 ^{0}C, the envelope of mixture embarrassing the spark ignite by gaining temperature & flame further propagate to remaining fuel. The rate of flame propagation here is mainly depends upon its own temperature, air movement, temperature of air-fuel mixture & density of fuel in the surrounding.

Here the combustion in spark ignition engine takes place with the help of spherical flame. In starting it is a small nucleus of flame which further increases & burn the fuel present in the cylinder.

In SI engine the combustion of fuel and air mixture takes place in three different stages. The theoretical stages in the combustion in 4 stroke S.I. engine is shown below.
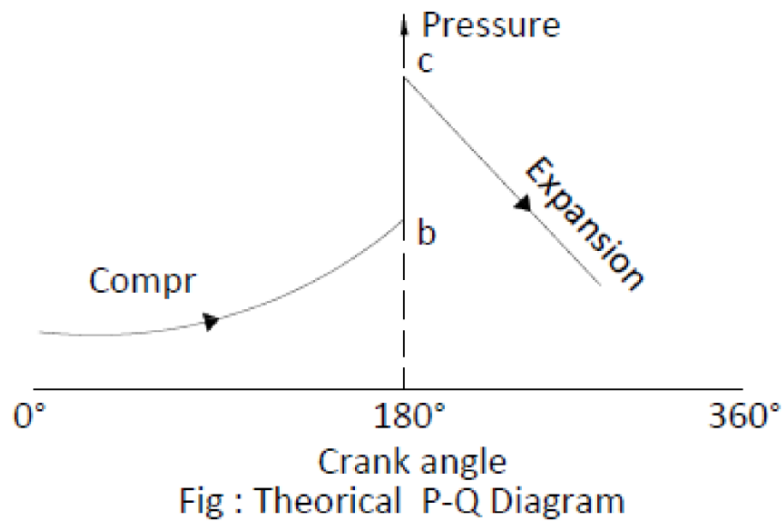
Figure 2.12: Theoretical P-Θ Diagram

But the actual combustion in SI engine is much different from the theoretical concepts.
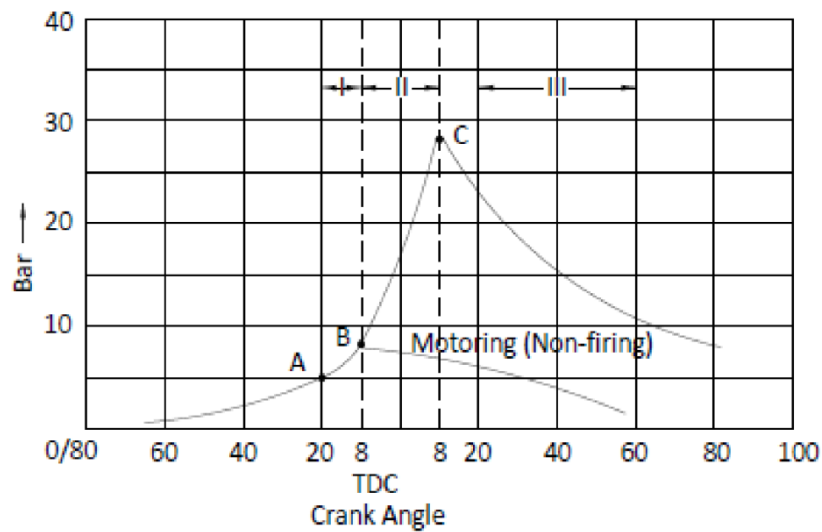
Fig. 2.13: Stages of combustion in SI engine

The stages involve in the actual combustion are.

1) Ignition lag.
2) Flame propagation
3) After burning

Stages of Combustion in SI Engine

I – Ignition Lag

II – Propagation of flame

III – After Burning

2.11.1 Ignition Lag

As we studied till now is the spark ignites when the piston is at top dead center. But actually spark plug gives spark slightly before then that.

This first phase "ignition lag" is actually a time between the point of ignition & point of combustion. As shown in the diagram the spark is timed at "a" & combustion status at point "b" the difference in time between these two is called "Ignition lag" or "preparatory phase"

This phase is a chemical process in which growth & development of a self propagating nucleus of flame takes place. Depending upon

1) Chemical nature of fuel
2) Proportion of exhaust gases
3) Rate of reaction
4) Pressure & temperature at the end of compression stroke.

Here the mixture is sufficiently compressed & heated; a thin thread of flame is suspended between the two electrodes of spark plug. The mixture around this thread get heat up (By gaining latent heat) & started burning in the form of small

nucleus. The surrounding particles of the mixture gain heat from this nucleus & start burning in the form of sphere, here combustion started. If by any means the nucleus doesn't get able to supply heat to the neighboring particle the combustion stops there & motoring takes place.

2.11.2 Propagation of flame

Once the flame formed at point "b", it should be self sustaining & self propagating through the mixture. This sustainability & propagation of flame is only possible when the rate of heat generation (Q_g) due to the burring of mixture is greater than the rate of heat loss (QL) by mixture.

When the difference between these two (Q_H-Q_L) is higher, the rate of flame proportion will be higher, then the complete combustion will be occurred as earliest as possible, which is the foremost requirement of combustion in SI engine.

The flame propagation rate is also depends on the temperature of flame & temperature and density of surrounding mixture as the rate of flame propagation is inversely proportional to these factors.

Weak spark & low compression ratio can results in low rate of flame propagation.

At the beginning after the point "b" because of more heat loss then heat generation, the rate of flame propagation is Quit low. Thus the rate of pressure rise is also low as there is a very little mass burning. Therefore we provide "Angle of Advance" at 30 to 35, if we want to attain the peak pressure at TDC. (Normally the peak pressure is attained at 8 to 10 after TDC.)

The peak pressure is attained at point "c", after this point the pressure started to fall with the fall in the rate of heat generation as the flame reaches the wall in the last part of combustion & cannot compensate for its fall as the expansion started & heat transfer to the walls. Normally the time required for the flame to

travel 95% of chamber length with respect to speed of engine. It is shown in figure when

$$Q_1 = 30^. \quad \text{And A: F} = 13$$
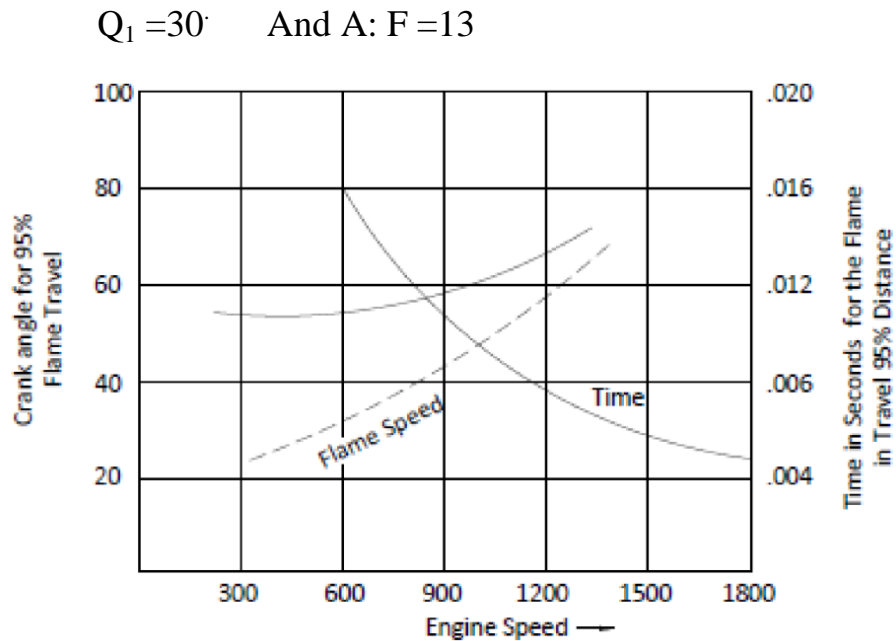
Fig. 2.14: Crank angle v/s Engine speed

The stage I & II are not completely distinct. The starting point of stage-II is measurable as rise in pressure can be seen on P-Q diagram. This is the point where the line of combustion departs from the line of compression.

2.11.3 After Burning

After point "c" represent the end of flame travel, it doesn't mean the flame has gone quenched. In this phase the remaining fuel burns after attaining the peak & this sort of combustion is known as after burning. This sort of thing generally happens when rich mixture is supplied to the engine.

2.12 Effects of engine variables on ignition lag

The very first phase of combustion is not a period of in activity but a chemical process. It depends upon many factors some are.

1) Fuel

Chemical nature of fuel is the foremost factor especially ignition temperature. The fuel with higher ignition temperature will have longer ignition lag as more time will be taken by spark to form & initiate the combustion.

2) Mixture ratio

The mixture ratio which results in maximum temperature will have the smallest ignition lag. This mixture must be somewhat richer in the stoichiometric ratio.
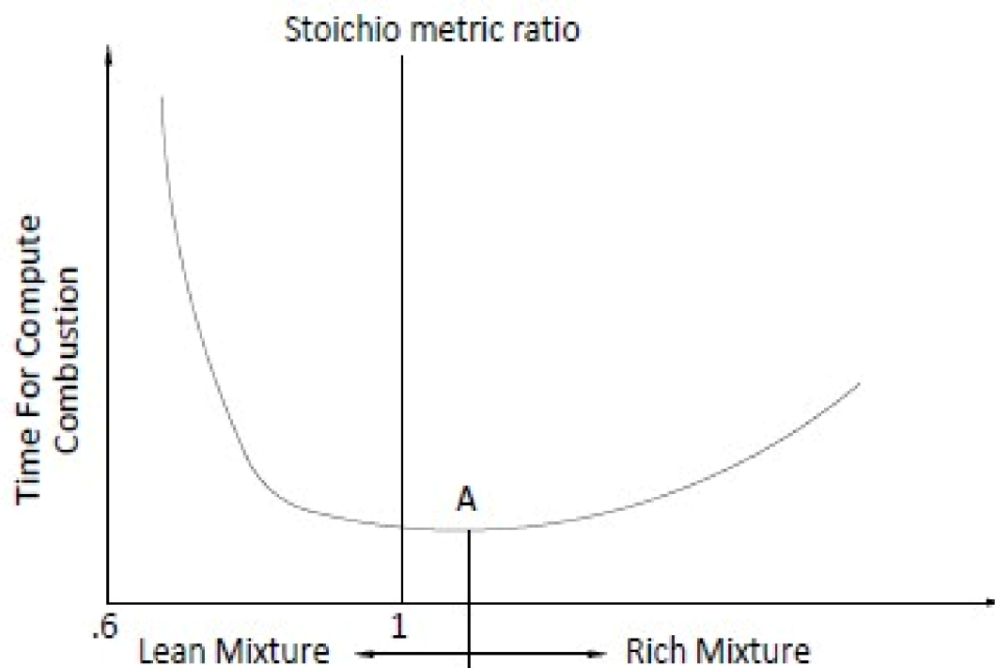
*Fig. 2..15: Combustion time v/s Mixture*

3) Initial temperature & pressure

The effect of increase in suction pressure & temperature is to increase the flame speed. It is so because:

    I)   A more homogenous mixture of air-petrol vapour is formed at higher suction pressure and temperature.

    II)   Density of the charge increases, and

III)   A homogenous mixture helps in increasing the flame speed.

4)   Electrode gap

Whether the nucleus of flame will be established of not, it depends greatly on the electrode gap. It the gap is too small, the nucleus of flame may quench & the range of Air-fuel ratio for the development of flame nucleus may reduced.
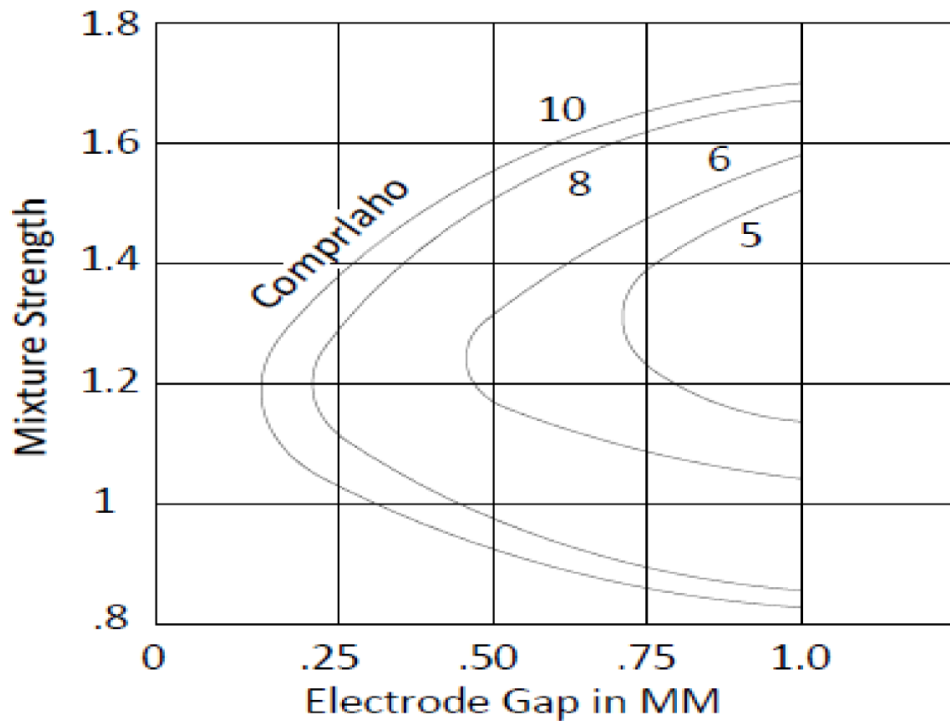
Fig. 2.16: Mixture strength v/s electrode gap

Lower the compression ratio, higher the electrode gap. The voltage required at the spark plug increase with decrease in fuel air ratio & with increase in compression ratio & engine load.

5) Turbulence

Ignition lag is not much affected by turbulence intensity but it has a positive effect on flame speed. Turbulence is directly proportional to engine speed.

As increase in engine speed doesn't affects ignition lag much, as it counted in milliseconds. But it increases the crank angle, hence when measured in degree of crank rotation the ignition lag increase linearly with engine speed.

So however turbulence is important, so some methods to get it properly are

1.) Passage should be narrow at the time of input, as narrow passage result in high pressure, results in good turbulence.

2.) Small & large number of swills in inlet manifolds.

3.) Proper contouring

However excessive turbulence of mixture is harmful, as it increases the heat transfer from the combustion zone & leads to quenching of flame.

6)   Compression ratio

The rate of chemical reaction depends upon the temperature and density of the mixture. With the increase of compression ratio, the mixture of fuel started get dense, which result in collision among the particles, resulting in higher temperature. Higher the temperature shorter the ignition lags.

2.13 Effects of engine variable on flame propagation

The variable those affects the rate of flame propagation are important because the flame velocity influence the rate of pressure use in the cylinder. Several factors which affect flame speed.

1) Fuel – air ratio

The composition of mixture affects the rate of the combustion & rate of heat generation a lot. Normally maximum flame velocity is attain when we use mixture

strength 10% more then stoichiometric ratio. Apart from this lean & rich mixture both have demerits in the case of flame speed.

In lean mixture produce less heat that could result in low flame speed, because of lower flame temperature. Very rich mixture will have incomplete combustion resulting in low flame speed. This in complete combustion manly occurs due to less oxygen present in mixture.
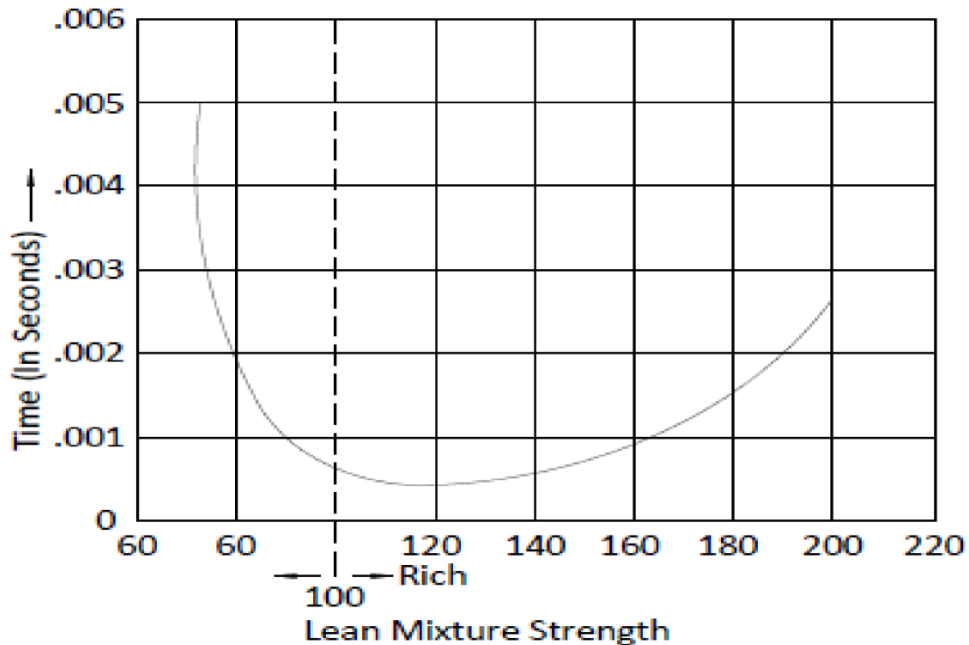
Fig. 2.17: Time v/s Mixture Strength

2) Compression ratio

Higher compression ratios increase the pressure of mixture, which in turn increases the temperature & also reduced the quantity of residual gases. All these favorable conditions reduce the ignition angle. Maximum pressure & indicative mean effective pressure is increased. Here the flame speed will increase.

Compression ratio higher than the desired level will increase the temperature which could increase the tendency of the engine to detonate.

3) Intake temperature & pressure

Increase in intake temperature & pressure increase the flame speed.

4) Engine load

With increase in engine load the cycle pressures increases   hence the flame speed increases. With the decrease in load, power of engine is reduced by throttling. Due to this initial & final pressure also reduces, that in turn increases the dilution of mixture with residual gases, this make flame propagation difficult & unsteady & increases the ignition lag, this difficultly can be overcome by enhancing the mixture with fuel but that increases the phenomena of after burning in expansion stroke. This leads to poor mileage also this will lead to discharge of large amount of pollutant like carbon mono oxide & other poisonous substances.

5) Turbulence

For the non-turbulence mixture the flame speed is very low. A high flame speed can be achieved by high turbulence mixture as it intensify the process of heat transfer & mixing of burnt & un burnt portion in flame front. The turbulence is mainly achieved by intake of mixture by narrow pipe & valves. We can also increase the turbulence by the end of compression by suitable design of cylinder head & piston crown. The degree of turbulence also increases with piston speed. Insufficient turbulence leads to incomplete combustion of fuel resulting in low efficiency also without turbulence time between each explosion will increase that will make high speed engine impossible.

6) Engine Speed

Higher the engine speed, more the piston speed, resulting the high turbulence & more the turbulence more the flame speed. Thus if the engine speed is doubled, the time taken by the flame to cover combustion space will become half.

7) Engine Size

Piston speed is not related to size of engine but only depends upon the design of engine. Hence piston speed will be same for all size of engines. Due to same piston speed, the inlet velocity, the degree of turbulence & flame speed are nearly same in similar engines regardless of the size. However in small engines the flame travel is small & in large engines it is large. Therefore if the engine size is doubled the time required for propagation of flame through combustion space will also be doubled.

8) Rate of pressure rise

As we know that the ignition lag in the first stage in combustion in SI engine. In P.Θ Diagram "a" is the point of spark & "b" indicates the space of pressure rise the pressure rise may occurs at different rates. Accordingly the peak pressure developed, the power produced & smoothness in exerting the force on piston are also different. Different rates & pressure rise are shown in fig, as a function of crank cycle.
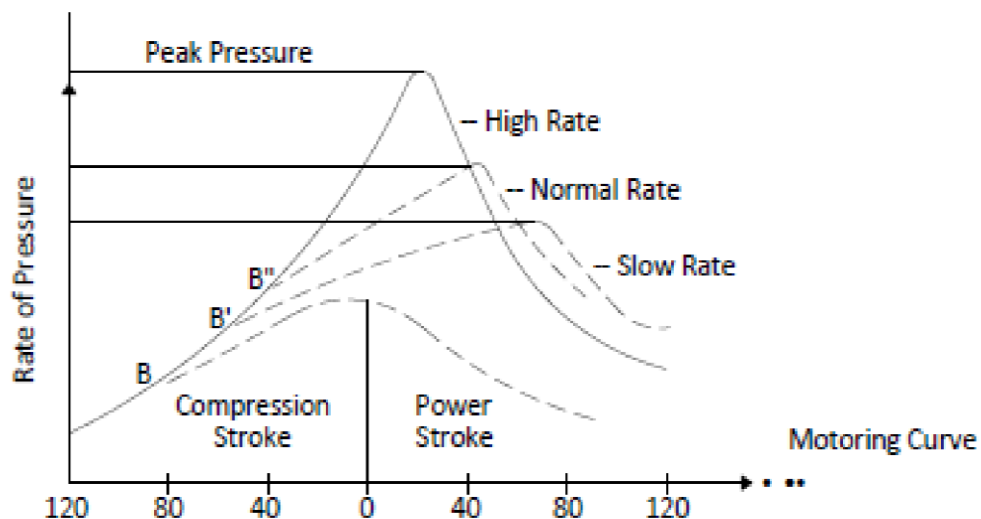
Fig. 2.18: Rate of Pressure

The rate of pressure rise is indicated by the scope of curves I, II & III between start of their pressure rise & peak pressure. This rate mainly depends upon the mass rate of combustion of mixture in the cylinder.

The following observation can be drawn from the figure.

1) When rate of pressure rise is slow, more time is required to compute the combustion. It therefore requires that the burning of fuel should start a little early, as shown by point "B".

2) When rate of pressure rise is high combustion takes place at a higher rate & less time is required for computing the combustion. Also

 a) A higher peak pressure is produced at a point closer to TDC. This is desirable feature as it is responsible for increase in power output of engine.

 b) However, the high rate of pressure rise creates some problems like

 *Rough running of engine

 *Vibrations & jerks produced in crankshaft

 *Occurrence of knocking

Hence, the rate of pressure rise & combustion should neither be slow nor fast, rather it should be medium. Also, the engine design should be accomplished such that a medium rate of pressure rise & combustion takes place.

2.14 Abnormal combustion & its control

Under varying conditions the combustion in SI engine can be termed as

2.14.1 Normal combustion

Here the flame travels in the combustion chamber throughout in fairly uniform manner.

2.14.2 Abnormal combustion

Here the flame travels across the combustion chamber in a deviated manner from normal manner.

The abnormal combustion is also called "knocking combustion". Its consequences are detrimental for the working of the engine these are:

1) Loss of power and of other performances

2) Occurrence of repeated pre-ignition

3) Mechanical damage to the engine.

A mixture of fuel and air can react spontaneously and produce heat by chemical reaction in this absence of flame to initiate the combustion or self-ignition. This type of self-ignition in the absence of flame is known as "Auto Ignition". The temperature at which auto ignition took place is known as self-ignition temperature. The pressure and temperature abruptly increase due to the auto ignition because of sudden release of chemical energy.

This auto ignition leads to abnormal combustion known as detonation which is undesirable because of its bad effect on the engine performance and life as it abruptly increase suddenly large amount of heat energy. In addition to this, knocking put a limit on the compression ratio at which an engine can be operated which directly affects the engine efficiency and output.

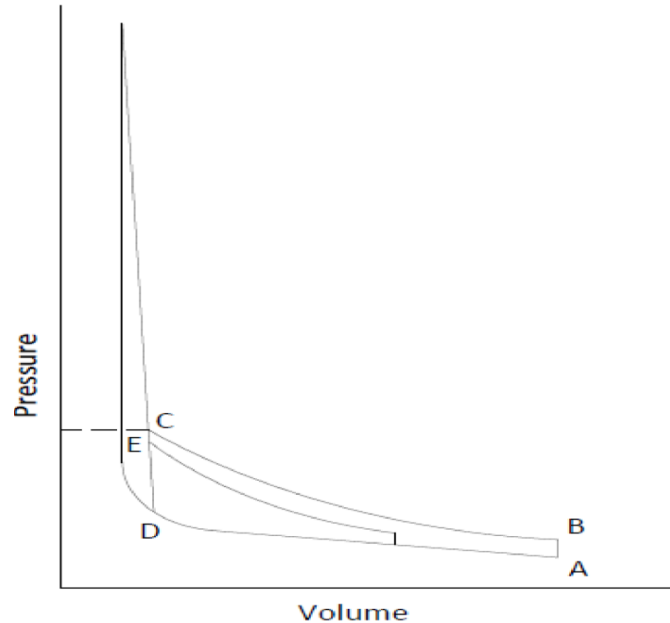The normal combustion and knocking combustion are shown in fig. 3.8.

In normal combustion diagram a normal flame front travels across the combustion chamber from point A to B. The speed of flame is about 30 m/s. As the flame moves towards D, it starts compressing the end change B B'D. Because of this compressing the temperature of the end change started getting high.

Apart from compression, conduction & radiation of the heat is also a factor & reaction in the unburnt charge also help in temperature gain.
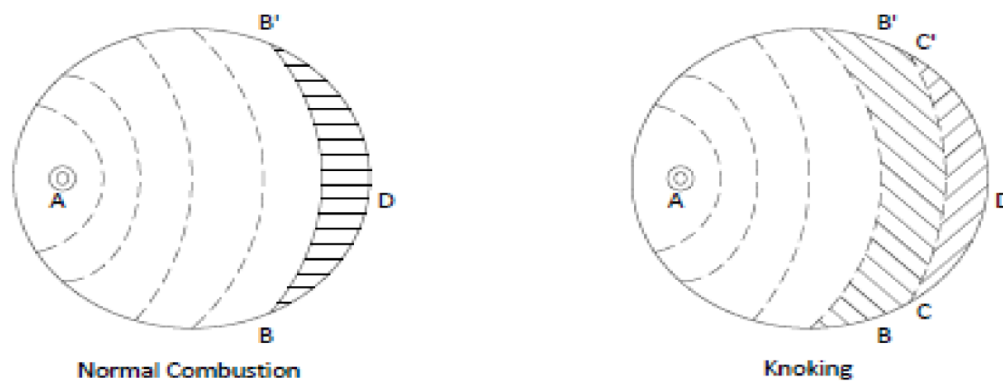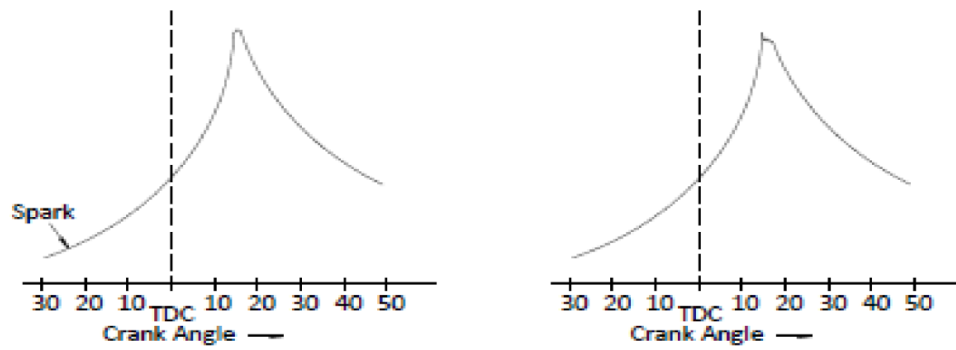
Fig. 2.19 Normal Combustion & Abnormal Combustion

If this end charge doesn't reach to the self ignition temperature, it will not auto ignite. The flame front will reach to BB' & then to D for proper & normal burning of the fuel. The pressure crank diagram for normal combustion is smooth curves. In abnormal combustion, according to diagram the flame is traveling to Point A to Point D the end charge BB'D is compressed & heated by obvious factor. Here because of high temperature the flame is only able to travel till CC', during the ignition Delay period, then the remaining part CC'D will auto ignite & will cause extreme pressure disturbance. In auto ignition the burning is almost instantaneous which result in extremely rapid release of energy causing pressure of end gases rises to 3 to 4 times.

Fig. 2.20: Pressure attained in abnormal Combustion

In the figure ABCD represent the normal cycle, peak pressure at Pc. The last part of charge is compressed form P_B to P_E (HRE $P_E=P_C$) spontaneous ignition of the end gases raises the pressure rapidly from P_E to P_F this large pressure difference give rise to a severe pressure wave which strikes the cylinder walls & set it vibrating, giving rise to high pitched metallic sound.

Knocking or detonation in SI Engine always occurs near the end of combustion.

2.15 FUEL

IC engines use fuels to get energy for their operation. Energy is contained in fuels in the forms of chemical energy. Which on burning converts to heat energy, this heat energy is then transformed into mechanical energy by means of various systems & components of the engine. Since the heat energy is basically derived from fuel, it is essential to know various kinds of fuels, their properties & characteristics. The characteristics of fuels have considerable effect on design &

working of the engine ,they also enhance the combustion, power output & efficiency of the engine. Even more, the fuel characteristics are responsible for creating more or less pollution into atmosphere.
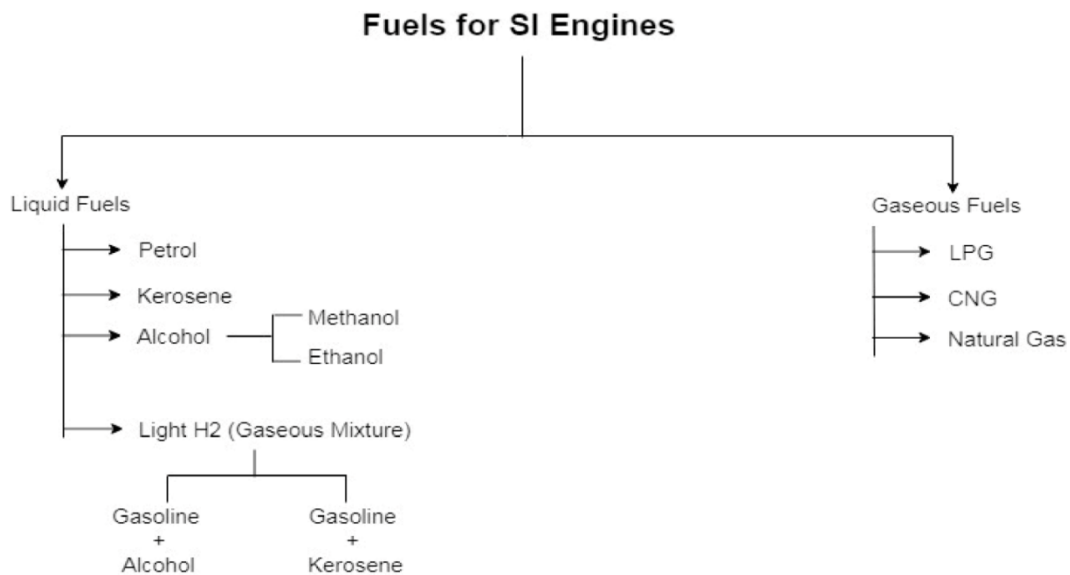
2.15.1 Fuels for SI & CI Engines

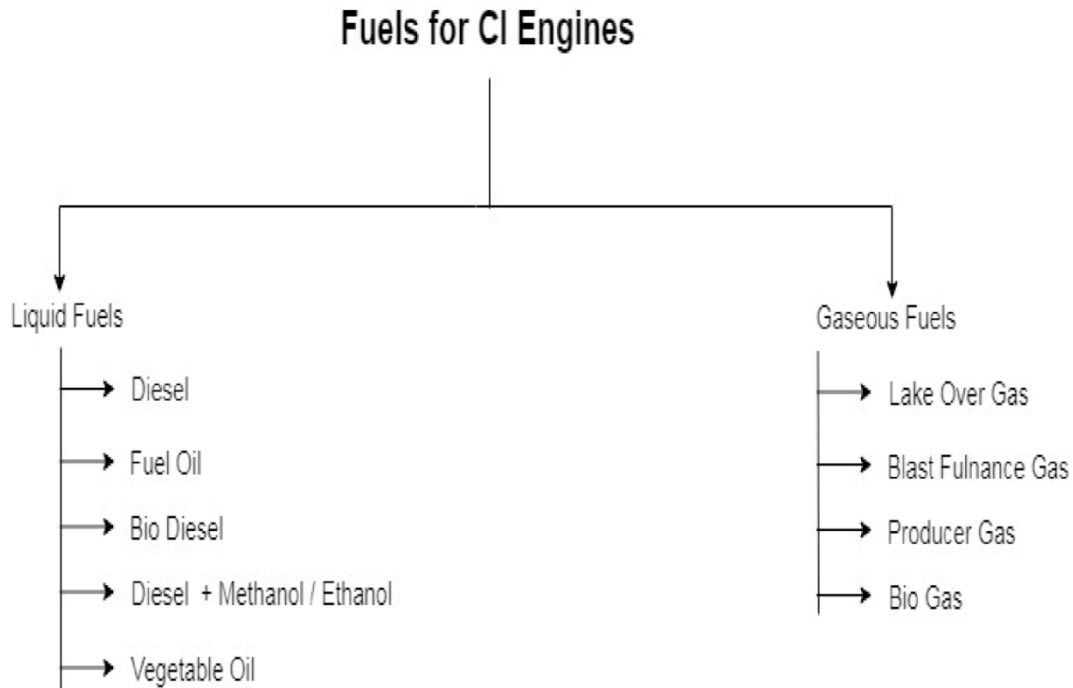IC Engines run on different types of fuels. Broadly they can be classified into following categories.

1.) Solid fuels

2.) Liquid fuels

3.) Gaseous fuels

Here liquid fuels particularly, the petroleum products, the petroleum products, are the most used fuels in IC Engines especially in auto mobiles, aircrafts & marines.

2.15.2 Fuels Categorized for SI engines

Fuels for SI Engines

Liquid Fuels
→ Petrol
→ Kerosene
→ Alcohol ── Methanol
            └ Ethanol
→ Light H2 (Gaseous Mixture)

Gasoline
+
Alcohol

Gasoline
+
Kerosene

Gaseous Fuels
→ LPG
→ CNG
→ Natural Gas

2.15.3 Fuels Categorized for CI Engine

Fuels for CI Engines

Liquid Fuels
→ Diesel
→ Fuel Oil
→ Bio Diesel
→ Diesel + Methanol / Ethanol
→ Vegetable Oil

Gaseous Fuels
→ Lake Over Gas
→ Blast Fulnance Gas
→ Producer Gas
→ Bio Gas

### 2.16 Chemical Structure of petroleum

Automotive fuels are basically derived from petroleum. Petroleum is a natural underground fossil fuel energy resource. It is formed due to dawn position of micro plant on deposited upon the beds of seas, lakes & rivers over a span of million years. The dawn position takes place by the action of bacteria under lack of oxygen & also by catalytic cracking. Petroleum is extracted by digging an oil well under the ground. It is also called crude oil & is not an efficient fuel for use in aircraft, although it can be used as a fuel for other inferior application. Crude oil contains hydro carbons of different types & on their basis these are classified into following types.
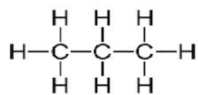
1.   Paraffin's Series

The normal or straight chain paraffin hydro carbons consists of a straight chain molecular structure the general chemical formula for this series is C_nH_{2n+2}. Where n is the number of carbon atoms. The name of each member ends in 'ane' as in methane propane hexane etc. n-propane means normal propane.
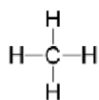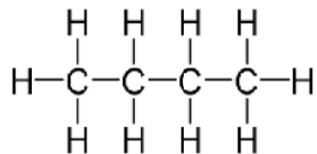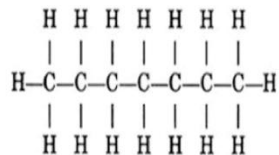
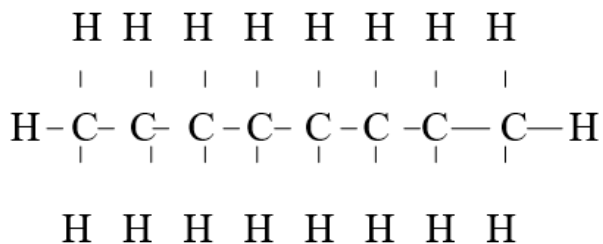*Methane, CH$_4$*   *n – propane, C$_3$H$_8$*

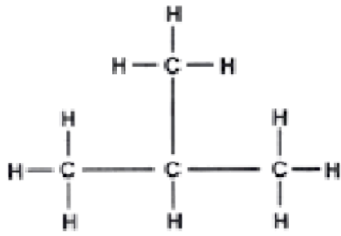*Butane, C$_4$H$_{10}$*   *n-heptane, C$_7$H$_{16}$*
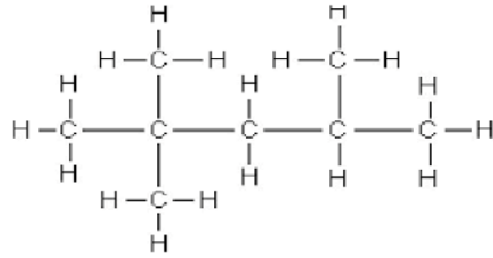
Fig. 2.21: Various paraffin's hydrocarbons

Fig. 2.22: Octane C$_8$H$_{18}$

The valiancy of carbon is fully utilized by single bounds; hence straight chain paraffin's are saturated compounds and are characteristically very stable.

Branch chain or is paraffin has an open chain structure which is branched.


Iso butane C_4H_{10} Iso octane C_3H_{16}

Fig. 2.23: Branch chain

The general formula for is paraffin's is again $C_n H_{2n+2}$. Iso paraffin's are also stable compound and are highly knock resistant when used as SI engine fuel.

2.   Olefin series

Olefins are compound with one or more double banded carbon atoms in a straight chain. Due to double bands these fare capable of citing with other material without displacing hydrogen i.e. they are in saturated compounds. The names of hydro carbons having one double bond end in 'lene' as in ethylene butane etc.
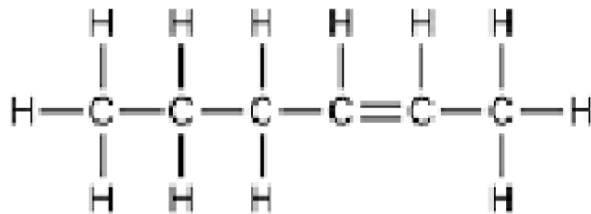
Hexlene, C_6H_{12} (mono-olefin)
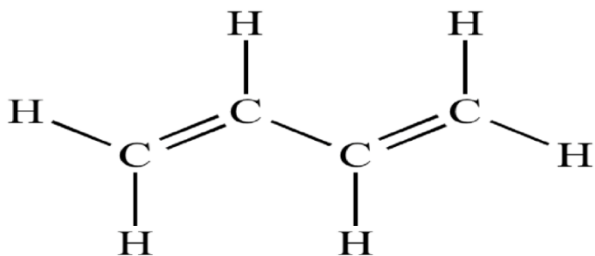
Butadiene, C₄H₆ (Di olefin)

Fig. 2.24: Olefin series

The general formula is C_nH_{2n} for mono olefin (one double bond) & C_nH_{2n-2} for the Di olefin (two-double bonds). Di- olefins are most unstable than mono olefins.

Olefins are common in curtain types of cracked gasoline & these are in consequence readily oxidized in storage to form gummy deposits. Therefore olefin content in certain petroleum product is kept low by specification for example in turbine fuel it is kept less than 3 percent.

3.   Naphthene series

The napthene series has the same chemical formula as the olefins series, C_nH_{2n}, but have greatly different properties the napthene are ring or cycle compounds, where as the olefins are straight chain compound with a double bond connecting two carbon atoms. The napthene are saturated compounds where as olefins are unsaturated.

Cyclo propane C$_3$H$_6$ *Cyclo butane C$_4$H$_8$*
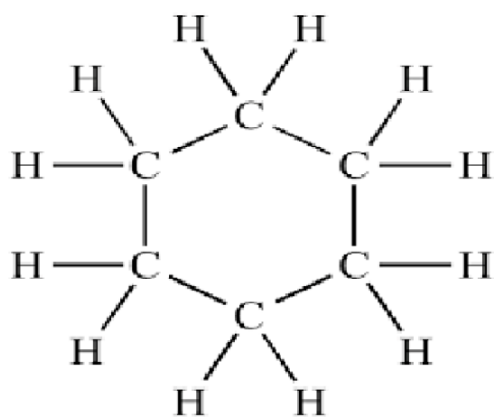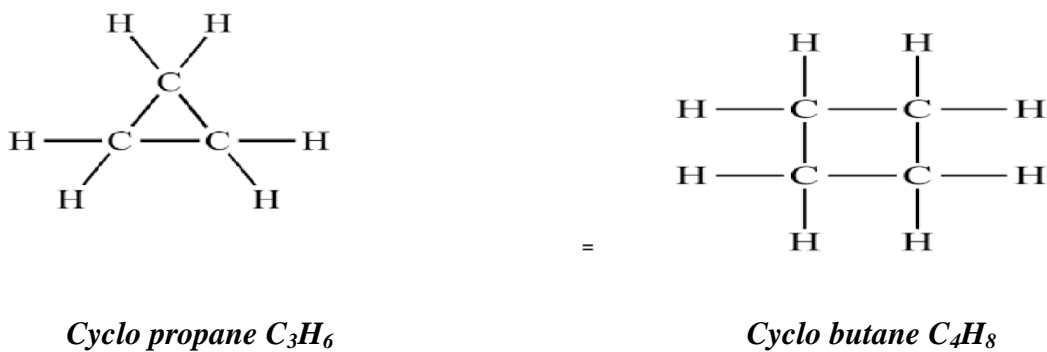
Cyclo hexane C$_6$H$_{12}$

Fig. 2.25: Naphthene Series

4.   Aromatic Series

Aromatics are ring structure compounds having the benzene modules (C$_6$H$_6$) as their central structure. Various aromatic compounds are formed by replacing one or more of the hydrogen atoms of the benzene molecule with an organic radial such as paraffin, napthene & olifins. By adding a methyl group (CH$_3$) benzene is converted to toluene (C$_6$H$_5$CH$_3$) the base for trinitrotoluene, TNT, a well known explosive.

The three double-bonds make aromatics very active and so they are highly unsaturated compounds. Both benzene & toluene are preset to a modest extent in most unaltered gasoline.
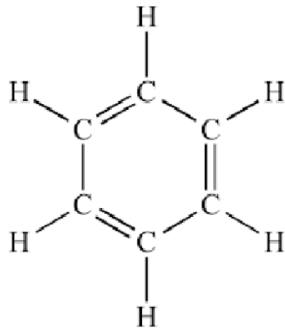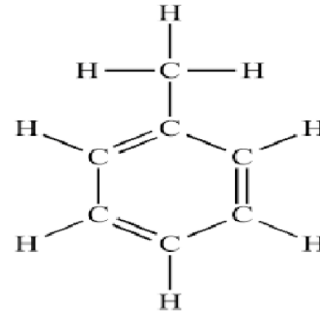
Benzene C₆H₆   **Toluence C₆H₆ CH₃**

Fig. 2.26: Aromatic Series

2.17 Refining Process

The crude oil, as it comes out from the oil wells, contains inpurities such as water, solids & gases consisting mainly of ethane & methane. By simple atmospheric pressure distillation, utilizing the fact that the boiling points of various hydrocarbon increase with an increase in moleculce weight, the crude oil is seprated into gasoline, kerosene, fuel oil or reduced crude oil.

First of all the highest fractions such as butane, propane, ethane etc. which were either standing above the liquid in earth or dissolved in the crude, are obtanined at low tempertuare & form natural gas. Then comes gasoline, naptha kerosene, fuel & gas oils, in order of increasing molecular weight. After distilation of residul of paraffin wax or asphalt depending on the base of the crude is left.

The gasoline demand is much more than that of other petroleum products. the typical yield of a crude is much more heavy material than needed. This led to the development of refinery processes to convert unwanted streams of crude into useable products & to upgrade quality of these streams to crack the larger molecules into smaller molecules having low boiling point as in the gasoline range and in process to polymerize small molecules into larger molecules both having boiling points in the gasoline range. The main refinery procedures are as follows:

2.17.1 Thermal cracking

If large hydrocarbon molecules are heated to a high temperature & pressure they decompose into smaller, lower boiling-point molecules. This process of thermal decomposition is called cracking. The more stable molecules form cracked gasoline & the realtive ones polymerize, forming cracked oil & petroleum coke. Gasoline is the primary final product from the cracking plant.

2.17.2 Catalytic cracking

Catlytic cracking using a catalyst is done at a lower pressure & temperature than the thermal cracking. Due to the catalysis the napthenes are cracked to olifins & paraffins and olifins to isopraffins & thus forming gasoline. Catalytic cracking gives better anti-knock properties to gasoline as compared to thermal cracking.

2.17.3 Polymerization

Polymerization is the process of converting olefins, the unsaturated products of cracking into heavier & stable compounds such as high octane gasoline by the typical reaction.

2.17.4 Alkylation

Alkylation combines an olifin with an iso paraffins to produre a branched chain iso-paraffin of moleculer weight equal to the sum of reactants, in the

pressence of a catalyst. This gives a fuel of very high octane number such as iso octane or iso-pentane.

2.17.4.1 Isomerisition

Isomerisition is the process by which isomers, i.e. compounds having same chemical formula but different properties are produced. isomerisation is used to convert n-butane into iso-butane for alkylation to convet n-pentane & n-hexane into isoparaffins to improve knock rating of highly volatile gasoline's.

Octane rating between 93 & 107 are obtained with 95 percent pure iso-paraffins.

2.17.5 Reforming

Reforming is used to convert low antiknock Quality stocks. It does not increase the total gasoline volume as is the case in cracking polymerisation & alkylation processes.

2.17.6 Blending

Blending is the process of obtaining a product of desired quality by mixing certain products in some suitable porportion.

2.18   Products of Refining Process

1. Natural gas:- Natural gas is found dissolved in petroleum or in huge amount under earth surface in oil & gas bearing areas. Natural gas is made up mainly of the paraffins compound methane, a small amount of propane, ethane, butane & other high hydro carbons plus some nitrogen & oxygen.

2. Liquidified petroleum gas:- propane & butane with some other light hydro carbons after separation from natural gas, if stored under pressure, form

liquid & this is called liquidified petroluem gas. LPG is supplied in containers under pressure.

3. Gasoline:- Gasoline is the lightest liquid petroleum fraction. This is mixture of a number of hydrocarbons.the compostion depends upon the crude oil & refining process. Gasoline lies in specific gravity range 0.70 to 0.78. This covers most of fuels used for spark-ignition engines.

4. Kerosene:- the kerosene is a fraction heavier than gasoline. its boiling range is 150 to 300 ^{0}C & the specific gravity range is 0.78 to 0.85. Kerosene are used in aviation gas turbines, as jet fuel and in lamps & stove.

5. Distillate:- The distillate is slightly heavier than kerosene. these are used as domestic fuels.

6. Diesel oils:- Diesel oils are fuels which lie between kerosene & lubricating oils, these cover a wide range of spceific gravity & boiling point. Boiling range is 200 to 370 ^{0}C. thus form the fuels for compression- ignition system.

7. Fuel Oils:- fuel oils are similar to diesel fuel in specific gravity & distilation range but their composition varies in a range wides than those of diesel fuels. These are used as industrial fuels.

8. Lubricating oils:- Lubricating oils are made up of heavy distillate of petroleum & residual oil. These are used for lubricating purpose.

9. Tar & Asphart:- Tar and Asphart are solid or semi-solid undistilled products of petroleum.

10. Petroleum coke:- Petroleum coke is used as solid industrial fuels.

2.19   Requirements of fuels for spark ignition engines

1. Volatility :- One of the most important characteristics of fuels is its volatility, it is difined as the ability of a fuel to transform itself from liquid to

vapour state at any temperature. Easy starting of engine its behaviour during warming-up & normal operations are depands on volatility of the fuel.

A fuel having high volatility is desirable for easy starting whereas a low volatility fuel is suitable to avoid vapour lock, carburettor icing and storage problems. In practice the fuels of high & low volatilities are blended together in suitable proportions to suit the desired need. Rolatility is given in the unit of vapour pressure & is generally expressed in kgf/cm^2 at a known temperature.

2. High Calorific Value:- it is the heat releasing capacity of a fuel on burning & is expressed in kcal/kg or kj/kg for a gaseous fuel, the calorific value is expressed in kcal/m^3 or kj/m^3. A fuel having high carlorific value is desired. Calorific value of different categories of fuels lies in different ranges.

   Crude   10000-11600 kcal/kg

   Gasolin   11000-11470 kcal/kg

   Diesel   10900-11000 kcal/kg

   Heavy oil   9550 -11500 kcal/kg

3. Low sulphur content :- Much sulpur is likely to corrode cylinder bores, bearing & exhaust systems. Therefore, a good fuel should posses low sulphur content since some of its compounds form sulpherous acid while the other compounds slow down the action causes corrosion while the inaction of head does not help in increasing the "anti-knock" quality of fuel. sulpher content in a good fuel should not exceed 0.1%.

4. Least gum content:- High molecular weight gum is formed due to polymerization of some unstatured hydro carbon at certain temperature or due to oxidation of gasoline or due to condensation of olefin components. Gum is normally soluble in gasoline but it tends to deposit in the carburettor & other components of fuel system as gasoline evaporates.

5. High anti-knock rating:- A high anti-knock value is a desireable property of IC engine fuel for that , the tetraethyl lead and other additives are mixed in petrol.

6. Low Distillation temperature:- It is desired for efficient warm up of the engine. It is also desired to avoid "crankcase dilution" as the gasoline in the cylinder is vapourised by the time, the combustion is over.

7. Vapourization at low temperature:- It is derived for easy starting of the engine. In this regards ability of vapourization of a part of gasoline at room temperature will be more advantageous.

8. Sufficient Vapourization:- It is desired for more uniform distribution of fuel in the cylinder of a multi cylinder engine. Further it also help in achieving better accelaration characteristics as the quality of liquid droplets is reduced in the inlet manifold.

9. High boiling temperature:- This characteristic is required to prevent "Vapour Lock" which due to high rate of vapourization may bring trouble to carburettor metering, or may even stop the fuel flow.

2.20 Requirements of fuel for compressed ignition engine

1. Short ignition lag:- It is desired so that the fuel ignites readily. It also affects the starting & warm –up of engine.

2. Sufficiently high cetane rating:- It is desired in a fuel because high cetane value avoids knock, which is undesired. A cetane number of the value of above 45 is desired.

3. Sufficient Volatility:- It is a well desired quality of fuel for proper mixing & combustion in operating temperature range of the engine.

4. Low self Ignition Temperature:- The quality of fuel is desired for easier starting of the engine. A low self-ignition temperature also demands high volatility & high cetane rating.

5. compute combustibility:- It is desired in the fuel so that the engine exhaust does not contain much smoke & unpleasant odour.

6. Flowable viscosity :- The fuel should neither be too viscous, nor flowable. It should be just able to flow through the fuel system under lowest operating temperature of the engine.

7. Low Sulphur ash and residue contents:-   These are essentially required in the fuel to avoid corrosion & wear of the engine parts before & after combustion.

8. Reasonable pour points:- Pour points is the temperature at which the fuel in a 15mm, diameter tube inclined at 45^0, doesnot change its convex surface in the course of 1minute. A resonable pour point allows easy flow of fuel under all conditions of engine operation.

9. High Flash point:- Flash point is the temperature at which the vapours of fuel mixed with the air ignite in contact with the flame. A fuel having flash point more than 150^0C is disired.

10. High fire point:- It is the higher temperature at which the fuel vapours continue to burn, when brought in content with a flame. Fire point is always higher than the flash point by about 30 to 45^0C. A good fuel should posses a high fire point.

2.21 Fuel additives

Commercial automotive fuels used to run the engines, are not just the gasoline & gas oils they are prepared by binding different refinery gasoline and additives. This is done to obtain appropriate quality of fuel having a desired

octane number, rolatility, stablity & anti-knock qualities.Requirement of good additives:-

To serve the desired purpose in a better manner, the additives must posses certain basic qualities some are.

1. It should be effective in resisting the engine knock.
2. It should be easily soluble in fuels under all conditions.
3. It should be stable in storage & also during reactions.
4. It should be capable of easier vapourisation at higher temperature.
5. It should be free from unwanted deposits such as sulphur, gum etc.
6. Its solubity in water should be minimum.

2.21.1 Blending constituents

Commercial petrol is prepared by binding various types of gasoline , some are.

1. "Straight run gasoline" is obtained by distillation at atmospheric pressure.
2. "Trermally cracked gasoline" is found from high temperature & high pressure cracking of heavier petroleum fration remaining after straight run gasoline.
3. "Natural gasoline" is obtained by compressing natural gas taken out of the oil well.
4. "polymer gasoline" is the product formed due to the reactions between certain hydrocarbons existing in the gases formed after distillation, cracking & reforming processes.
5. "Alkylate" is the product of reactions between unlike hydrocarbon gases formed after distillation, cracking & reforming processes.

Straight run & thermally cracked gasolines are blended in larger proportion as they are cheap. Other types of gasolines are blended in smaller proportion to improve certain characteristics in petrol.

2.21.2 Additive compounds

Additives are chemical compounds which are mixed in blended petrol to impart certain specific properties in petrol. They may be hydrocrabons, non-hydrocarbons, organic or in some important additives are

1. Benzol
2. Ethyl Alchol
3. Tetra ethyl lead
4. Tetra methyl lead

"Tetra ethyl lead" is an important anti-knock additive. Its chemical formula is $(C_2H_5)_4$ pb. It is a heavy liquid with density of 1700kg/m^3 & boiling point of 200 ^{0}C. It is soluble in gasoline its addition neither changes the reaction, nor affics the rate of energy libreation. However it delays auto ignition & allows it to occur at a higher temperature. Main advantage of its use as additive is to increase the octane rating of petrol.

"Tetra methyl lead" is used as additive sometimes instead of tetra ethyl lead its chemical formula provides very effictive protection to fuel against engine knock.

2.22 Rating of fuels

Normally fuels are rated for their anti knock qualities. The rating of fuels is done by definig two parameters cetane number and octane number for gasoline & diesel oil resp.

2.22.1 Rating of SI engine fuels

Resistance to knocking is an extermely important characteristic of fuel for SI engines. These fuels differ widely in their ablity to resist knock depending on their chemical composition. A satisfactory rating method for comparing the antiknock qualities of the various fuels has been established. In addition to the chemical characteristics of hydrocarbon in the fuel, other operating parameter such as fuel-air ratio, ignition timing, dilution, engine speed, shape of the combustion chamber, ambient conditions, compression ratio etc. after the tendency to knock in the engine cylinder. Therefore, in order to determine the knock resitance characteristes of the fuel, the engine & its operating variables must be fixed at standard values.

According to a standard practice, the anti knock value of an SI engine fuel is determined by comparing its antiknock property with a mixutre of two reference fuels, iso-octane (C_3H_3) & normal heptane (C_7H_{16}). Iso octane chemically being a very good antiknock fuel, is arbitrartly assigned a rating of 100 octane number. Normal heptane (C_7H_{16}), on the other hand has very poor antiknock qualties & is given a rating of octane number. The Ocatane number of fuel is defined as the percntage, by volume of iso-octane in a mixure of iso octane & normal heptane which exactly matches the knocking intensity of the fuel in a standard engine under a set of standard operating conditions.

The addition of certain compounds to iso-octane produces fuels of greater antiknock quality. The antiknock effectiveness of tetra ethyl lead, for the some quantity of lead added, decrease as the total content, of lead in the fuel increase.

Further more, earth octane number at the higher range of the octane scale will produre greater antiknock effect compared to the same unit at the lower end of the scale.

From the performance number, Pn

Octane number $= 100 + \dfrac{Pn-100}{3}$

The approximate relative engine performance & the units of scale (Designed for non-liner variations) are known as performance number, P_n.

2.22.2 Rating of CI engine fuels

In compression-ignition engines, the knock resitance depends on chemical charcteristics as well as on the operating & design conditions of the engines. Therfore, the knock rating of a diesel fuel is found by comparing the fuel under prescribed conditions of operation in a special engine with primary, reference fuels. The reference fuels are normal cetane, $C_{16}H_{34}$, which is arbitrarily assigned a centane number of 100 & alpha methyl naphtalene, $C_{11}H_{10}$, with an assigned cetane mumber of 0. Cetane number of a fuel is defined as the percentage by volume of normal centane & α-methyl napthalene which has the same ignition characteristes as the test fuel when combustion is carried out in a standard engine under specified operating conditions. Since ignition delay is the primary factor in controlling the intial auto ignition in CI engines, it is reasonable to conclude the knock should be directly related to the ignition delay of the fuel. Knock resistance property of oil can be improved by adding small quantities of compounds like anyl nitrate, ethyl nitrate or other.

2.23 Some new fuels for IC engine

In a new vehicle, the fuel injector, carburettor, fuel intake valves & combustion chamber are free from deposits. But over the time, carbon deposits lead to accumulate on all parts, impending the vehcile performance.

All new generation cars are fitted with multi-port fuel injectors to accurately deliver petrol in the form of any dropouts to clean burning.

Because of narrow fuel passages, injectors are highly sensitive to the smallest amount of deposits. These deposits can affect the spray pattern & reduce the fuel flow affecting fuel economy, decreasing power & increasing emission levels.

Intake valves are subject to more deposits that operate at higher tempertaure. combustion chamber deposits tends to increase the octane number requirement, resulting in knocking, thereby causing engine damage.

The present speed fuel has a capacity to remove existing deposits & further prevent the formation of new deposits. speed is blended with multi-functional additves that effectively remove harmful deposits from all parts but also ensure that your engine remains deposits free at all times performing as good as new engine.

The deposits in fuel injector or carburettor intake values and combustion chamber increase emission clearly indicating the relationship between increased deposits & decreased emission. Since speed removes deposits & reduces emission keeping the engine clear. The effect is same for carburettor or injector systems.

Some benefits of speed over conventional gasoline.

1. Maintains the peak performance of the engine
2. Reduces emission level
3. Lowers maintenance cost
4. Extends life of catalytic convertor
5. Easy starting
6. Maximum power
7. Maximum acceleration
8. Eliminates engine knocking

2.24 Alcohols as substitute fuel for IC engines

Due to global energy crisis & continous increase in petroum prices, the scientists are in search of new fuel to replace conventional fuels used for IC engines.

Among all fuels, alcohols are considered most promising fuels for future. Alcohols are of two types, ethanol (C_2H_5OH) & methanol (CH_3OH) which can be produced from sugarcane waste and many other agriculture products. India has a vast potentia for alcohol production & it is necessary to take this ahead to maximum level in national interest.

2.25 Ethanol as alternative fuel

Ethanol as a transport fuel has been attracting a lot of attention because, it is seen as a relatively cheap non-petroleum based fuels. It is produced to a large extent from biomass, which aids in agriculture economy by creating a stable market for it. ethanol being a pure compounds has fixed set of phyical as well as chemical properties. This is in contrast to petrol & diesel which are mixture of hydrocarbons.
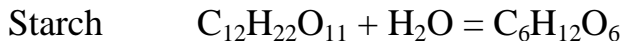
2.25.1 Production of ethanol (C_2H_5OH)

We can produce ethanol form various sources , are

1. Manufacture from saccharine material

$$C_{12}H_{22}O_{11} + H_2O = C_6H_{12}O_6 + C_6H_{12}O_6$$
$$C_6H_{12}O_6 = 2C_2H_5OH + 2LO_2$$
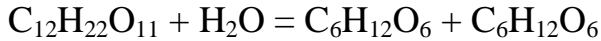
2. Manufacture from Starch Material

Starch $\quad C_{12}H_{22}O_{11} + H_2O = C_6H_{12}O_6$

(Naltose) (Dextrose)

In this process, starchy material are first converted ito fermentable sugar. This is done by distatic conversion by means of malt process or by acid hydrolysis.

3. Manufacture from Cellulose Material

   a.) From wood:- cellulose wood is hydrolysed into simple sugar by means of dilute acid at high temperature or by concentrated acid at low temperature. Similar, cellulose agricultural waste & straws can be used in the place of wood.

   b.) From surphite waste liquid from paper manufacture :- waste liquor contains 2 to 3.5% of sugar out of which 65% is fermentable, all acid in the liquor are removed by addition of calcuim. Then fermenlation is carried out by special yeast. Generally 1% of liquor is converted into alcohol.
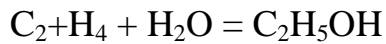
4. From hydrocarbon gases:-

   a.) Hydration of ethylene:-

   $$C_2H_4 + H_2SO_4 = C_2H_5\ HSO_4$$
   $$2C_2H_5H\ SO_4 = (C_2H_5)_2\ SO_4$$
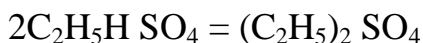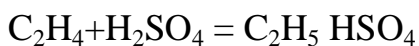
These products ethyl sulpheric acid & diethyl sulphate when treated with water give ethanol.

$$C_2H_5.HSO_4 + H_2O = C_2H_5OH + H_2SO_4$$

$$(C_2H_5)_2 SO_4 + 2H_2O = 2C_2H_5OH + H_2SO_4$$
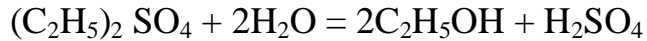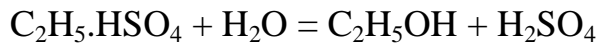
b.) By direct hydration:-

$$C_2+H_4 + H_2O = C_2H_5OH$$

This type of conversion is very little as reaction is exothermic. This method of production is not suitable for mass production.

2.26 Advantages of alcohol fuel engines compared with gasoline engines

1. The alcohols have higher heat of vapourisation. As the liquid fuel evaporates in the air stream being charged to the air allowing more mass to be enter into cylinder. This increase the power produced from the given engine size. High latent heat of vapourisation leads to higher volumetic efficiency & provides good internal cooling.

2. The high octane numbers of alcohols compared to petrol means higher compression ratios can be used, which results in higher engine efficiencies & higher power form the engines.

3. Ethanol burns faster than petrol allowing more uniform and efficient torque development. Both alcohols have wides flammablity limits when needed to maximise power by injecting more fuel per cycle.

4. Alcohols also have lower exhaust emissions than gasoline engines except for aldehydes. Both alcohlos have lower carbon to hydrogen ratio than petrol & diesel & they produce less CO_2. For the same power output, the CO_2 produced by ethanol fired engine is about 80% of the petrol the fuels burn

with lower flame temperature than petrol & less NOx formation occus. The low percentage in both case more or less remains same.

5. Also contamination of water in alcohols is less dangerous than petrol or diesel because alcohols are less toxic to human & has a recognizable taste.

6. The alcohols can also be blended with gasoline to form so called gashol & widely used in USA.

7. Ethyl Alcohol as a fuel offers the advantage of great safety by the propertise of its low degree of volatility & higher flash point.

8. The major problem faced with ethanol is the corrosion & special metals should be used for the engine parts to avoid corrosion.

Alcohols are considered as clean burning renewable alternative fuels which can come to our result to meet the duel challenge of vehicular fuel oil scareity and fouling of the enviroment by exhaust emissions.

2.27 Methanol

Methanol behaves much like petroleum & So, it can be stored & shifted in the same manner. It is more flexible fuel than hydrocarbon fuels permitting wide variation form ideal A:F ratios. It has relatively good combustion charateristcs compared to hydrocarbon fuels. Its wide inflamablity limits & higher flames speeds have showed higher thermal efficiency and lesser exhaust emission compared with petrol engines.

Methanol can be used directly or mixed with gasoline. By mixing it can improve the fuel economy by 5% to 13%, Decreses the CO emission by 14% to 70% & can reduce the exhaust temperature by 1 to 9%.

Some important features of methanol fuel are:-

1. The specific heat consumption with methanol as fuel is 50% less than petrol.

2. Exhaust CO & HC are decreased continously with blends containing higher and higher percentage of methanol. But exhaust aldehyde concentration shows a reverse trends.

3. No wear of engine components is encountered with methanol as fuel while there is an improvement in engine peak power and reduction in smoke density & no concentration in exhaust. The availablity of methanol from indigenous shows, ease of handling, low emission & high thermal efficency obtainable with its use, make it a logical alternative fuel for vehicles.

2.27.1 Production of Methanol

Methanol can be produced by resources that are abundanct world wide as load, natural gas, oil shell, farm waste, etc.

But methanol from natural gas is unlikely to provide large green house benefit, not more than 10% reduction in emissions with quite optimistic assumptions. It is not considered as a main raw material to produce methanol.

2.27.2 Advantages of Methanol

1.) 1% methanol in petrol is used to prevent freezing of fuel in winter.

2.) Butanol alcohol is used as an octane improving agent.

3.) Because of its brilliant anti knock property, it is much suitable for SI engines.

4.) Iso propyl alcohol is used as anti icing agent in carburattor.

5.) Addition of methanol causes evaporation at much faster rate than pure gasoline below its B.P.

6.) It is also observed with tests, methanol emits less amount of CO_2 and other polluting gases as compared to gasoline fueled vehicles there fore methanol

use maintains good air quality. For higher compression ratio, it is possible to receive higher level of no. But low flame temperature and latest heat of vaporization tend to decrease no emissions the over all effect is lower level of no emissions.

2.28 Hydrogen as a future fuel

Hydrogen has a very low density. In its liquified form, its density is one tenth that of gasoline . But it poses no ignition problems owing to the wide range of A/F ratios possible.

Hydrogen in comparison to the other proposed alternatives seems to provide the most satisfactory answer to the problem in hand. Hydrogen has almost in-exhaustible natural sources in water. Also hydrogen on combustion produces only water & no emissions whose toxic effects are trivial in comparision to the obnoxious contents of the exhaust gases of other fuels.

2.28.1Production of Hydrogen

1. Electrolysis of water:- in this method, electrical energy is used to break water into the H_2 & O_2.
2. Thermal Decomposition of water:- In this method heat at high temperature is used to thermally decompose water into H_2 & O_2
3. Thermochemical method:- This method is considered potentially most promising as it depends on complex series of interaction between the primary energy, water and some specific chemicals to produce hydrogen at temperature substantially lower than thermal decomposition. The chemical used are recyclable.

4. Photo bi-analysis:- in this process, action of certain catalysts to produce H_2 form water by use of direct sunlight at ambient temperature.though,it appears attractive, the present efficiency of production is only 1%.   We can also produce hydrogen "on-board" by

1. Directly engine coupled to DC gernerator.
2. Air Disc DC Generator.

2.28.2 Advantages of H_2 as fuel

1. It burns CO times faster, so can be used in high speed engines.
2. Hydrogen ignition limits are much wider than gasoline. So it can burn easily & give considerably higher efficiency.
3. Hydrogen has high self-ignition temperature but very little energy required to ignite it.
4. It has clean exhaust.
5. Exhaust heat can be used to extract H_2 from the hydride reducing the load on engine.

2.29   Some other fuels for future

1. Biogas
2. Produces gas
3. Biomass generated gas
4. LPG & LNG
5. Compressed natural gas
6. Coal gas
7. Non ediable vegetable oils