

CHAPTER SEVEN

COMBUSTION PROCESS IN SI ENGINES

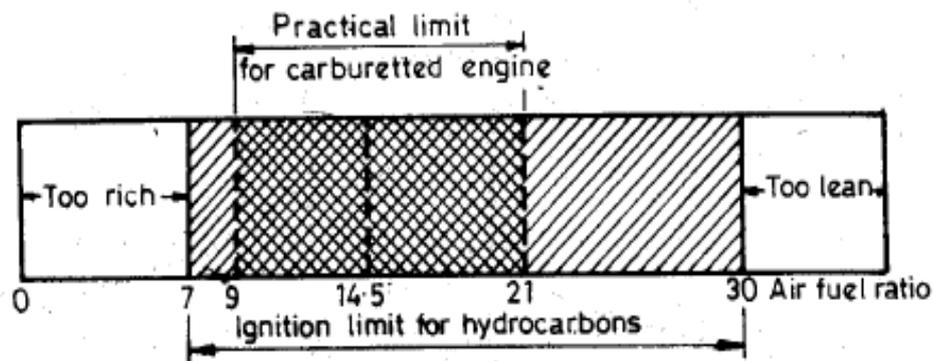
Combustion may be defined as a relatively rapid chemical combination of hydrogen and carbon in fuel with oxygen in air resulting in liberation of energy in the form of heat. Following conditions are necessary for combustion to take place:

1. The presence of combustible mixture
2. Some means to initiate mixture
3. Stabilization and propagation of flame in Combustion Chamber

In S I Engines, carburetor supplies a combustible mixture of petrol and air and spark plug initiates combustion.

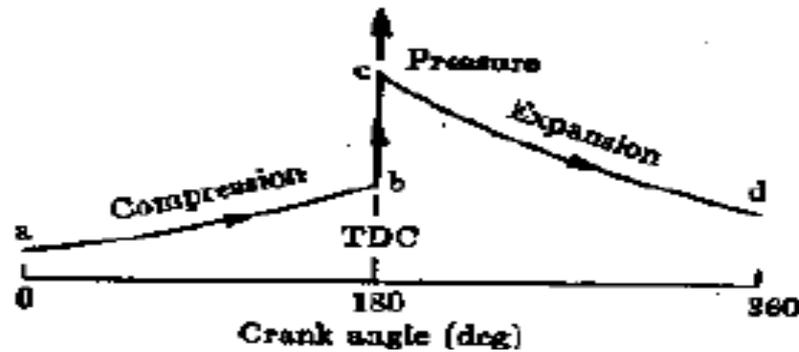
Ignition Limits

Ignition of charge is only possible within certain limits of fuel-air ratio. Ignition limits correspond approximately to those mixture ratios, at lean and rich ends of scale, where heat released by spark is no longer sufficient to initiate combustion in neighboring unburnt mixture. For hydrocarbons fuel the stoichiometric fuel air ratio is 1:15 and hence the fuel air ratio must be about 1:30 and 1:7.



Theories of Combustion in SI Engine

Combustion in SI engine may roughly is divided into two general types: Normal and Abnormal (knock free or knocking). Theoretical diagram of pressure crank angle diagram is shown in figure below. (a → b) is compression process, (b → c) is combustion process and (c → → d) is an expansion process. In an ideal cycle it can be seen from the diagram, the entire pressure rise during combustion takes place at constant volume i.e., at TDC. However, in actual cycle this does not happen.



Richard Theory of Combustion:

Sir Ricardo, known as father of engine research describes the combustion process can be imagined as if it is developing in two stages:

1. Growth and development of a self-propagating nucleus flame. (Ignition lag)
2. Spread of flame through the combustion chamber

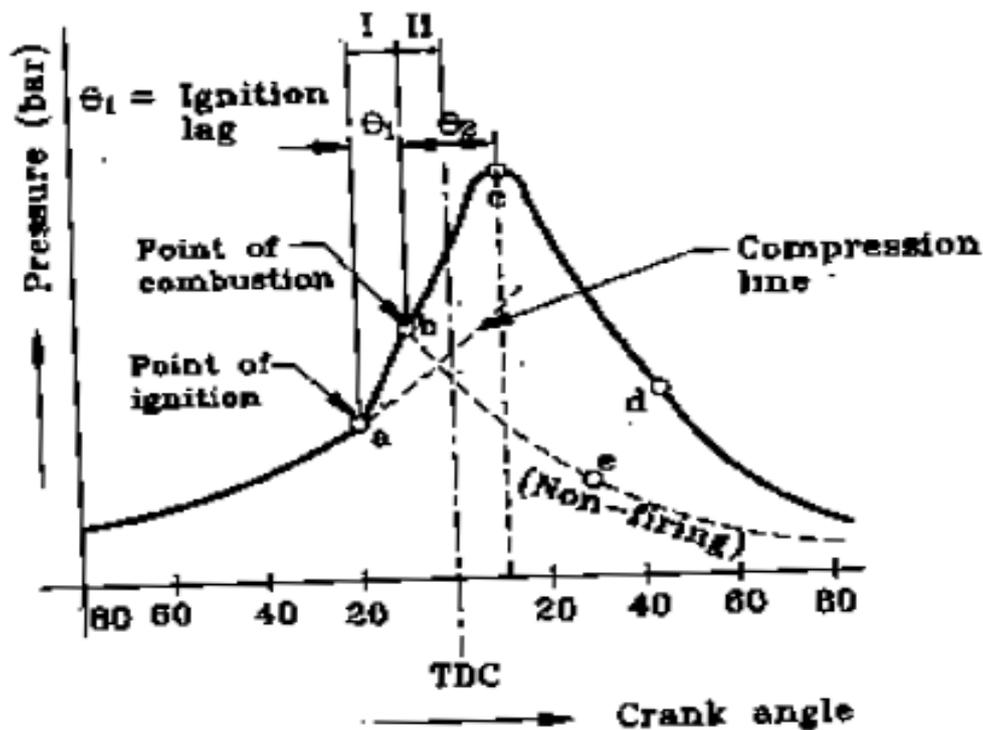
Three Stage of Combustion:

According to Ricardo, There are three stages of combustion in SI Engine as shown

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

1. Ignition lag stage:

There is a certain time interval between instant of spark and instant where there is a noticeable rise in pressure due to combustion. This time lag is called IGNITION LAG. Ignition lag is the time interval in the process of chemical reaction during which molecules get heated up to self ignition temperature, get ignited and produce a self propagating nucleus of flame. The ignition lag is generally expressed in terms of crank angle (θ_1). The period of ignition lag is shown by path (a-b). Ignition lag is very small and lies between 0.00015 to 0.0002 seconds. An ignition lag of 0.002 seconds corresponds to 35 deg crank rotation when the engine is running at 3000 RPM. Angle of advance increase with the speed. This is a chemical process depending upon the nature of fuel, temperature and pressure, proportions of exhaust gas and rate of oxidation or burning.



2. Flame propagation stage:

Once the flame is formed at “b”, it should be self sustained and must be able to propagate through the mixture. This is possible when the rate of heat generation by burning is greater than heat lost by flame to surrounding. After the point “b”, the flame propagation is abnormally low at the beginning as heat lost is more than heat generated. Therefore pressure rise is also slow as mass of mixture burned is small. Therefore, it is necessary to provide angle of advance (30-35) degrees, if the peak pressure to be attained (5-10) degrees after TDC. The time required for crank to rotate through an angle (θ_2) is known as combustion period during which propagation of flame takes place.

3. After burning:

Combustion will not stop at point “c” but continue after attaining peak pressure and this combustion is known as after burning. This generally happens when the rich mixture is supplied to engine.

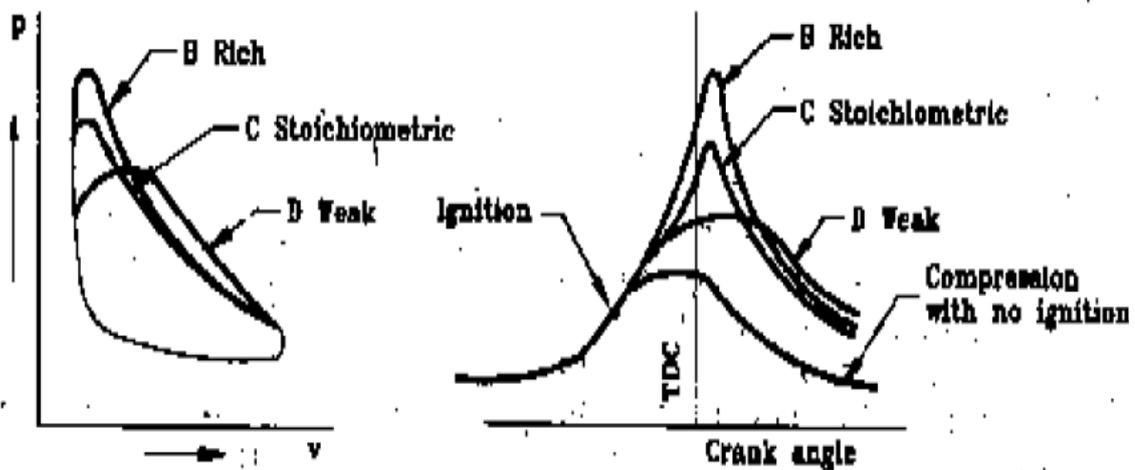
Factors Affecting the Flame Propagation:

Rate of flame propagation affects the combustion process in SI engines. Higher flame propagation velocities can achieve higher combustion efficiency and fuel economy. Unfortunately flame velocities for most of fuel range between [10-30] (m/second).

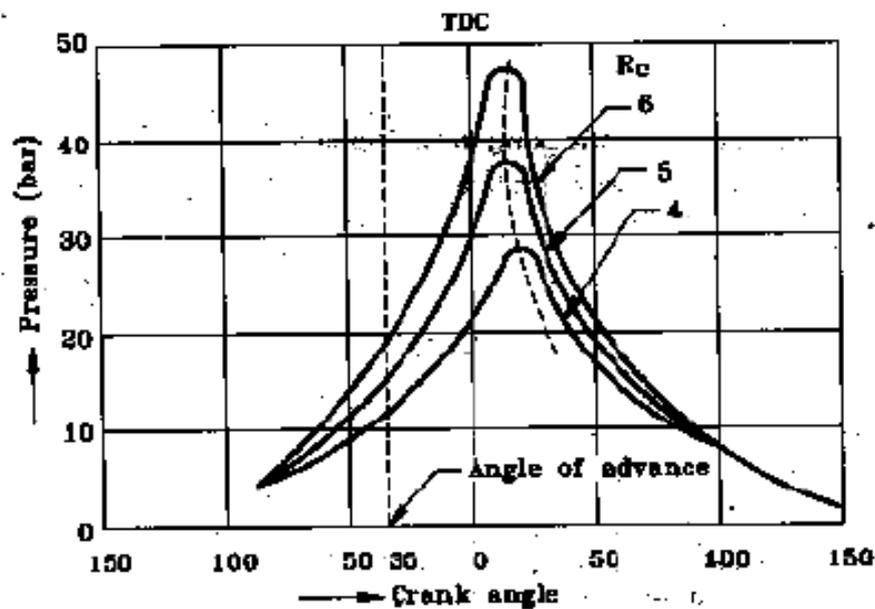
The factors that affect the flame propagations are:

1. Air fuel ratio
2. Compression ratio
3. Load on engine
4. Turbulence and engine speed
5. Other factors

1. **A/F ratio**: The mixture strength influences the rate of combustion and amount of heat generated. The maximum flame speed for all hydrocarbon fuels occurs at nearly 10% rich mixture. Flame speed is reduced both for lean and as well as for very rich mixture. Lean mixture releases less heat resulting lower flame temperature and lower flame speed. Very rich mixture results incomplete combustion ($C-C\alpha$) instead of $C\alpha$, and also results in production of less heat and flame speed remains low. The effects of (A/F) ratio on P-v diagram and P- α diagram are shown below, (where α is crank angle):



2. **Compression ratio**: The higher compression ratio increases the pressure and temperature of the mixture and also decreases the concentration of residual gases. All these factors reduce the ignition lag and help to speed up the second phase of combustion. The maximum pressure of the cycle as well as mean effective pressure of the cycle with increase in compression ratio. Figure below shows the effect of compression ratio on pressure (indirectly on the speed of combustion) with respect to crank angle for same (A/F) ratio and same angle of advance. Higher compression ratio increases the surface to volume ratio and thereby increases the part of the mixture which after-burns in the third phase.



3. **Load on Engine**: With increase in load, the cycle pressures increase and the flame speed also increases. In S.I. engine, the power developed by an engine is controlled by throttling. At lower load and higher throttle, the initial and final pressure of the mixture after compression decrease and mixture is also diluted by the more residual gases. This reduces the flame propagation and prolongs the ignition lag. This is the reason, the advance mechanism is also provided with change in load on the engine. This difficulty can be partly overcome by providing rich mixture at part loads but this definitely increases the chances of afterburning. The after burning is prolonged with richer mixture. In fact, poor combustion at part loads and necessity of providing richer mixture are the main disadvantages of S.I engines which causes wastage of fuel and discharge of large amount of CO with exhaust gases.

4. **Turbulence** : Turbulence plays very important role in combustion of fuel as the flame speed is directly proportional to the turbulence of the mixture. This is because, the turbulence increases the mixing and heat transfer coefficient or heat transfer rate between the burned and unburned mixture. The turbulence of the mixture can be increased at the end of compression by suitable design of the combustion chamber (geometry of cylinder head and piston crown). Insufficient turbulence provides low flame velocity and incomplete combustion and reduces the power output. But excessive turbulence is also not desirable as it increases the combustion rapidly and leads to detonation. Excessive turbulence causes to cool the flame generated and flame propagation is reduced. Moderate turbulence is always desirable as it accelerates the chemical reaction, reduces ignition lag, increases flame propagation and even allows weak mixture to burn efficiently.

A) Engine Speed:

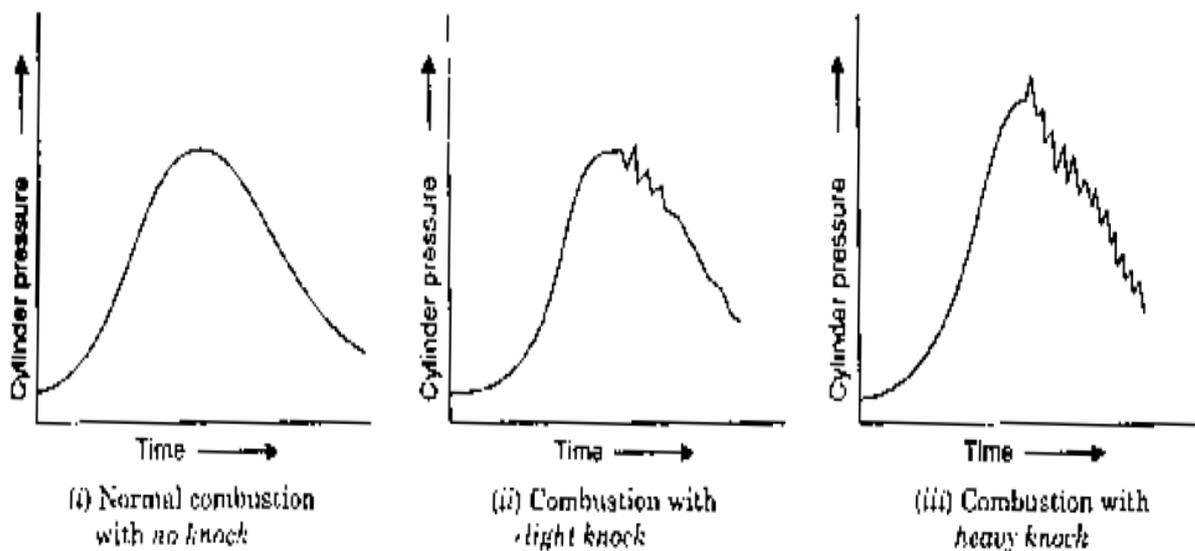
The turbulence of the mixture increases with an increase in engine speed. For this reason, the flame speed almost increases linearly with engine speed. If the engine speed is doubled, flame to traverse the combustion chamber is halved. Double the original speed and half the original time give the same number of crank degrees for flame propagation. The crank angle required for the flame propagation, which is main phase of combustion will remain almost constant at all speeds. This is an important characteristics of all petrol engines.

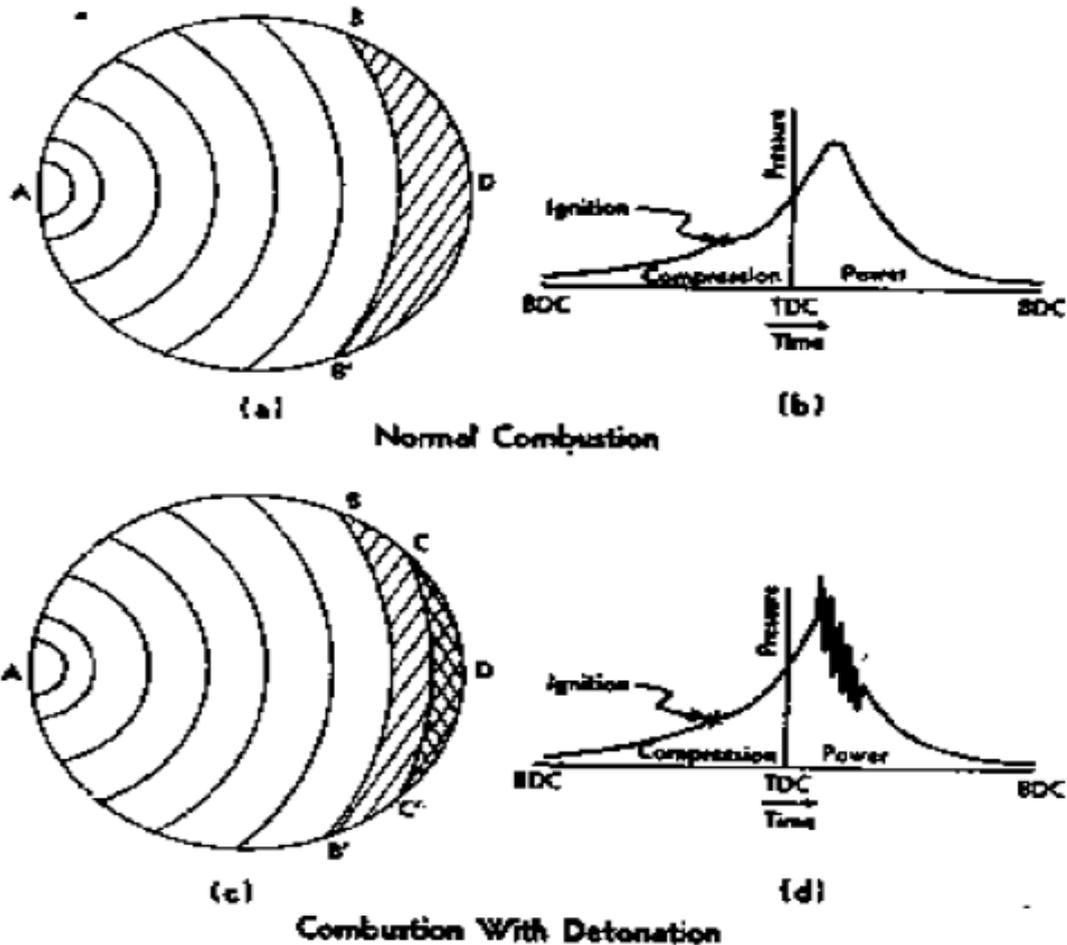
B) Engine Size:

Engines of similar design generally run at the same piston speed. This is achieved by using small engines having larger RPM and larger engines having smaller RPM. Due to same piston speed, the inlet velocity, degree of turbulence and flame speed are nearly same in similar engines regardless of the size. However, in small engines the flame travel is small and in large engines large. Therefore, if the engine size is doubled the time required for propagation of flame through combustion space is also doubled. But with lower RPM of large engines the time for flame propagation in terms of crank would be nearly same as in small engines. In other words, the number of crank degrees required for flame travel will be about the same irrespective of engine size provided the engines are similar.

5. **Other Factors**: Among the other factors, the factors that increase the flame speed are supercharging of the engine, spark timing and residual gases left in the engine at the end of exhaust stroke. The air humidity also affects the flame velocity but its exact effect is not known. Anyhow, its effect is not large compared with (A/F) ratio and turbulence.

A) ***PHENOMENON OF KNOCKING IN SI ENGINE***: Knocking is due to auto ignition of end portion of unburned charge in combustion chamber. As the normal flame proceeds across the chamber, pressure and temperature of unburned charge increase due to compression by burned portion of charge. This unburned compressed charge may auto ignite under certain temperature condition and release the energy at a very rapid rate compared to normal combustion process in cylinder. This rapid release of energy during auto ignition causes a high-pressure differential in combustion chamber and a high-pressure wave is released from auto ignition region. The motion of high-pressure compression waves inside the cylinder causes vibration of engine parts and pinging noise and it is known as knocking or detonation. This pressure frequency or vibration frequency in SI engine can be up to 5000 Cycles per second.

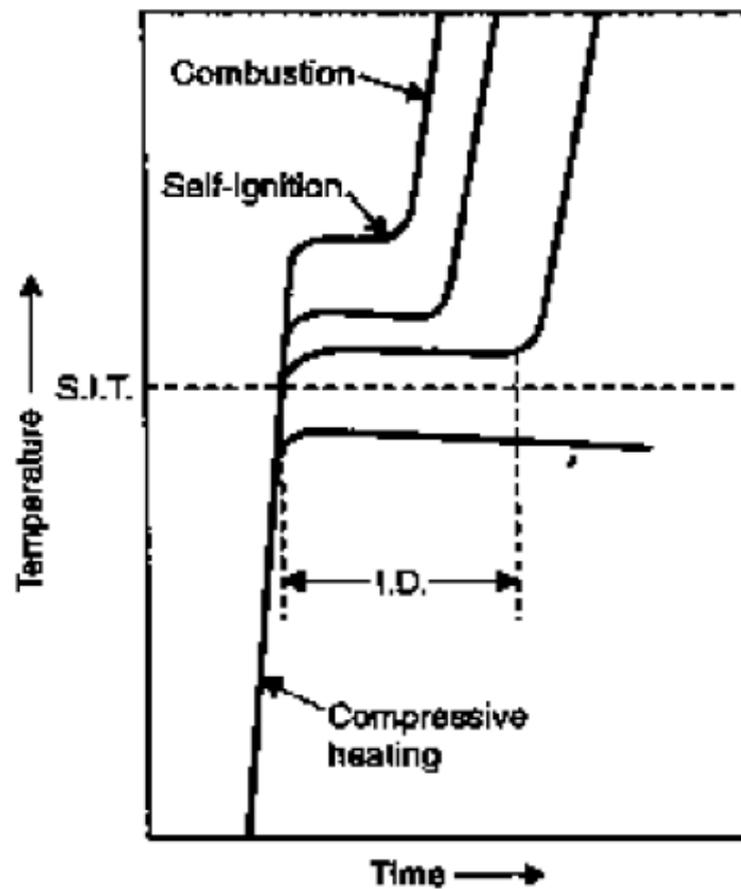




Detonation is undesirable as it affects the engine performance and life, as it abruptly increases sudden large amount of heat energy. It also put a limit on compression ratio at which engine can be operated which directly affects the engine efficiency and output.

B) AUTO IGNITION: A mixture of fuel and air can react spontaneously and produce heat by chemical reaction in the 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 the self-ignition takes place is known as self-igniting temperature. The pressure and temperature abruptly increase due to auto-ignition because of sudden release of chemical energy. This auto-ignition leads to abnormal combustion known as detonation which is undesirable because its bad effect on the engine performance and life as it abruptly increases sudden large amount of heat energy. In addition to this knocking puts a limit on the compression ratio at which an engine can be operated which directly affects the engine efficiency and output. Auto-ignition of

the mixture does not occur instantaneously as soon as its temperature rises above the self-ignition temperature. Auto-ignition occurs only when the mixture stays at a temperature equal to or higher than the self-ignition temperature for a “finite time”. This time is known as delay period or reaction time for auto-ignition. This delay time as a function of compression ratio is shown in adjacent figure. As the compression ratio increases, the delay period decreases and this is because of increase in initial (before combustion) pressure and temperature of the charge. The self-ignition temperature is a characteristic of fuel air mixture and it varies from fuel to fuel and mixture strength to mixture - strength of the same fuel.



S.I.T. → Self-ignition temperature

I.D. → Ignition delay

C) PRE –IGNITION: Pre-ignition is the ignition of the homogeneous mixture of charge as it comes in contact with hot surfaces, in the absence of spark . Auto ignition may overheat the spark plug and exhaust valve and it remains so hot that its temperature is sufficient to ignite the charge in next cycle during the compression stroke before spark occurs and this causes the pre-ignition of the charge. Pre-ignition is initiated by some overheated projecting part such as the sparking plug electrodes, exhaust valve head, metal corners in the combustion chamber, carbon deposits or protruding cylinder head gasket rim etc. pre-ignition is also caused by persistent detonating pressure shockwaves scoring away the stagnant gases which normally protect the combustion chamber walls. The resulting increased heat flow through the walls, raises the surface temperature of any protruding poorly cooled part of the chamber, and this there fore provides a focal point for pre-ignition.

Effects of Pre-ignition

- It increase the tendency of denotation in the engine
- It increases heat transfer to cylinder walls because high temperature gas remains in contact with for a longer time
- Pre-ignition in a single cylinder will reduce the speed and power output
- Pre-ignition may cause seizer in the multi-cylinder engines, only if only cylinders have pre-ignition

Effects of Detonation

The harmful effects of detonation are as follows:

1. Noise and Roughness: Knocking produces a loud pulsating noise and pressure waves. These waves which vibrates back and forth across the cylinder. The presence of vibratory motion causes crankshaft vibrations and the engine runs rough.

2. Mechanical Damage:

(a) High pressure waves generated during knocking can increase rate of wear of parts of combustion chamber. Sever erosion of piston crown(in a manner similar to that of

marine propeller blades by capitation), cylinder head and pitting of inlet and outlet valves may result in complete wreckage of the engine.

(b) Detonation is very dangerous in engines having high noise level. In small engines the knocking noise is easily detected and the corrective measures can be taken but in aero-engines it is difficult to detect knocking noise and hence corrective measures cannot be taken. Hence severe detonation may persist for a long time which may ultimately result in complete wreckage of the piston.

3. Carbon deposits: Detonation results in increased carbon deposits.

4. Increase in heat transfer: Knocking is accompanied by an increase in the rate of heat transfer to the combustion chamber walls.

The increase in heat transfer is due to two reasons:

- The minor reason is that the maximum temperature in a detonating engine is about 150°C higher than in a non-detonating engine, due to rapid completion of combustion
- The major reason for increased heat transfer is the scouring away of protective layer of inactive stagnant gas on the cylinder walls due to pressure waves. The inactive layer of gas normally reduces the heat transfer by protecting the combustion and piston crown from direct contact with flame.

5. Decrease in power output and efficiency. Due to increase in the rate of a detonating engine decreases.

6. Pre-ignition: The increase in the rate of heat transfer to the walls has yet another effect. It may cause local overheating, especially of the sparking plug, which may reach a temperature high enough to ignite the charge before the passage of spark, thus causing pre-ignition. An engine detonating for a long period would most probably lead to pre-ignition and this is the real danger of detonation.

EFFECT OF ENGINE OPERATING VARIABLES ON THE ENGINE

KNOCKING DETONATION

The various engine variables affecting knocking can be classified as:

- *Temperature factors*
- *Density factors*
- *Time factors*
- *Composition factors*

(A) TEMPERATURE FACTORS

Increasing the temperature of the unburned mixture increase the possibility of knock in the SI engine We shall now discuss the effect of following engine parameters on the temperature of the unburned mixture:

- ☒ ***RAISING THE COMPRESSION RATIO***: Increasing the compression ratio increases both the temperature and pressure (density of the unburned mixture). Increase in temperature reduces the delay period of the end gas, which in turn increases the tendency to knock.
- ☒ ***SUPERCHARGING***: It also increases both temperature and density, which increase the knocking tendency of engine
- ☒ ***COOLANT TEMPERATURE***: Delay period decreases with increase of coolant temperature , decreased delay period increase the tendency to knock
- ☒ ***TEMPERATURE OF THE CYLINDER AND COMBUSTION CHAMBER WALLS***: The temperature of the end gas depends on the design of combustion chamber. Sparking plug and exhaust valve are two hottest parts in the combustion chamber and uneven temperature leads to pre-ignition and hence the knocking.

(B) DENSITY FACTORS

Increasing the density of unburnt mixture will increase the possibility of knock in the engine. The engine parameters that affect the density are as follows:

- ☒ Increased compression ratio increase the density
- ☒ Increasing the load opens the throttle valve more and thus the density
- ☒ Supercharging increase the density of the mixture
- ☒ Increasing the inlet pressure increases the overall pressure during the cycle. The high-pressure end gas decreases the delay period, which increase the tendency of knocking.

- ✘ Advanced spark timing: quantity of fuel burnt per cycle before and after TDC, position depends on spark timing. The temperature of charge increases by increasing the spark advance and it increases with rate of burning and does not allow sufficient time to the end mixture to dissipate the heat and increase the knocking tendency.

(C) TIME FACTORS

Increasing the time of exposure of the unburned mixture to auto-ignition conditions increase the possibility of knock in SI engines.

- ✘ Flame travel distance: If the distance of flame travel is more, then possibility of knocking is also more. This problem can be solved by combustion chamber design, spark plug location and engine size. Compact combustion chamber will have better anti-knock characteristics, since the flame travel and combustion time will be shorter. Further, if the combustion chamber is highly turbulent, the combustion rate is high and consequently combustion time is further reduced; this further reduces the tendency to knock.
- ✘ Location of sparkplug: A spark plug that is centrally located in the combustion chamber has minimum tendency to knock, as the flame travel is minimum. The flame travel can be reduced by using two or more spark plugs.
- ✘ Location of exhaust valve: The exhaust valve should be located close to the spark plug so that it is not in the end gas region; otherwise, there will be a tendency to knock.
- ✘ Engine size: Large engines have a greater knocking tendency because flame requires a longer time to travel across the combustion chamber. In SI engine therefore , generally limited to 100mm
- ✘ Turbulence of mixture decreasing the turbulence of the mixture decreases the flame speed and hence increases the tendency to knock. Turbulence depends on the design of combustion chamber and one engine speed.

(D) COMPOSITION

The properties of fuel and A/F ratio are primary means to control knock:

(a) **Molecular Structure**: The knocking tendency is markedly affected by the type of the fuel used. Petroleum fuels usually consist of many hydrocarbons of different molecular structure. The structure of the fuel molecule has enormous effect on knocking tendency. Increasing the carbon-chain increases the knocking tendency and centralizing the carbon atoms decreases the knocking tendency. Unsaturated hydrocarbons have less knocking tendency than saturated hydrocarbons.

Paraffins

- ☒ Increasing the length of carbon chain increases the knocking tendency.
- ☒ Centralizing the carbon atoms decreases the knocking tendency.
- ☒ Adding methyl group (CH₃) to the side of the carbon chain in the centre position decreases the knocking tendency.

Olefins

Introduction of one double bond has little effect on anti-knock quality but two or three double bond results less knocking tendency except C₂ and C₃

Napthenes and Aromatics

- ☒ Napthenes have greater knocking tendency than corresponding aromatics.
- ☒ With increasing double-bonds, the knocking tendency is reduced.
- ☒ Lengthening the side chains increases the knocking tendency whereas branching of the side chain decreases the knocking tendency.

(b) **Fuel-air ratio**: The most important effect of fuel-air ratio is on the reaction time or ignition delay. When the mixture is nearly 10% richer than stoichiometric (fuel-air ratio = 0.08) ignition lag of the end gas is minimum and the velocity of flame propagation is maximum. By making the mixture leaner or richer (than F/A 0.08) the tendency to knock is decreased. A too rich mixture is especially effective in decreasing or eliminating the knock due to longer delay and lower temperature of compression.

(c) **Humidity of air**: Increasing atmospheric humidity decreases the tendency to knock by decreasing the reaction time of the fuel.

Effect of engine variables on Knocking in SI engine

1. Compression ratio: The pressure and temperature at the end of compression increases with increase in compression ratio. This in turn increases the maximum pressure during the combustion and creates a tendency to knock
2. Supercharging: increase the temperature and density of mixture and thus the tendency to knock is increased.
3. Turbulence: decreasing the turbulence of mixture decreases the flame speed and hence increase the tendency to knock
4. Octane rating of fuel : higher the octane number, less the tendency to knock. Parafins have maximum tendency to knock and aromatic series have minimum tendency to knock .

Factors that limits the compression ratio in petrol engine

In petrol engine we use the mixture of air and petrol and thermal efficiency of petrol engine increase with increase in compression ratio. However, the value of compression ration is limited by phenomenon of knocking. The pressure and temperature at the end of compression increases with increase in compression ratio. This in turn increases the maximum pressure during the combustion and creates a tendency to knock. Thus Higher compression ratio, higher is the tendency to knock, therefore the value of compression ratio in petrol engine is limited to 6 to 10. Compression ratio can be marginally improved by using fuel with Tetra-ethyl lead. TEL delays the auto ignition allows it to occur at higher temperature and thus reduces knocking. The use of TEL is now in disfavor because of atmospheric pollution (lead is toxic and has serious environmental and health hazards).

KNOCK RATING OF SI ENGINE FUELS (OCTANE NUMBER)

The tendency to detonate depends on composition of fuel. Fuel differ widely in their ability to resist knock. The property of fuel that describes how fuel will or will not self ignite is called the OCTANE NUMBER. It is defined as the percentage of Isooctane by volume in a mixture of Isooctane and n-heptane, which exactly matches the knocking tendency of a given fuel, in a standard fuel under given standard operating conditions. The rating of a particular SI fuel is done by comparing its antiknock

performance with that of standard reference fuel that is usually combination of Isooctane and nheptane. Isooctane (C_8H_{18}) which has a very high resistance to knock and therefore it is arbitrarily assigned a rating of (100 octane number). N-heptane (C_7H_{16}) which is very prone to knock and therefore given a zero value.

For example: Octane number 80 means that the fuel has same knocking tendency as mixture of 80% isooctane and 20% n-heptane (by volume basis).

A fuel having an octane number of 110 means fuel has the same tendency to resist as a mixture of 10 cc of Tetra ethyl lead (TEL) in one U.S gallon of Isooctane.