UNIT – 2

Fuels
Basic requirement of I.C. Engine fuels, requirement of an ideal gasoline, structure of petroleum, effect of fuel structure on combustion, volatility of liquid fuels, effect of volatility on engine performance for starting, vapour lock,acceleration, percolation, carburetor icing, and crank case dilution.
Combustion
Determination of stoichiometric air fuel ratio, fuel-air and exhaust gas analysis for a given combustion process.Combustion in S.I. and C.I. engines, Detonation,Pre-ignition , Knocking, Antiknock rating of fuels Octane number, critical compression ratio, HUCR, performance number, Cetane number. Dopes

University Questions:

1) **What are the two basic requirements of an I. C. Engine fuel? (Nov-Dec 2008)**
2) **Discuss the effect of fuel structure on:**
    - **Knocking**
    - **Volatility and**
    - **Heating value of fuel**
3) **Discuss the effect of volatility on the following; (May 2010)**
    - **Vapor lock and**
    - **Carburetor icing**
4) **Discuss the use of LPG as SI engine fuel**
5) **Explain the terms in brief: i) Vapor lock ii) Carburator Icing iii) Critical compression ratio iv) Performance number**
6) **What is performance number? Define.**
7) **Describe stages of combustion in a CI Engine with the help of pressure crank angle diagram and discuss the variable affecting delay period.**
8) **Describe knocking combustion in an SI engine. What action can be taken with regards to following variable in order to reduce the possibility of knocking. Justify your answer by reasons:**
    i) **Compression ratio,**
    ii) **Spark timing**
    iii) **Engine speed**
    iv) **Engine size**
9) **Define Stoichiometric (chemically correct) air fuel ratio.**
10) **What are the requirements of petrol engine fuel and diesel engine fuel ?**
11) **Explain the stages of combustion in CI Engine with the help of pressure crank angle (p-θ) diagram.**
12) **What is Octane number and how it is found? What is the difference between preignition and knocking ?**
13) **Explain the difference between detonation and preignition. Define octane number and cetane number.**
14) **Explain with suitable sketches the combustion phenomena in SI engines and explain the three stages of combustion in SI engine.**
15) **Explain the knocking combustion in SI, CI engines with the help of pressure-crank angle diagram. 7 marks**

Fuel:-Fuel is a Chemical substance which evolves heat energy when it undergoes combustion process.

They are classified into solid, liquid and gaseous fuels.

1. Solid fuels (ex. Steam engine)

Disadvantages:

a) Handling, storage and feeding problems,
b) Disposing off, the solid residue or ash after combustion.

2. Gaseous Fuels

Adv. a) It mixes more homogeneously with air and eliminate the distribution and starting problems that are encountered with liquid fuels

Disadv. a) Storage and handling problems

b) Hence they are commonly used for stationary power plants located near the source of availability of the fuel.

3. Liquid Fuels

Liquid fuels overcome the disadvantages of both solid and liquid fuels.

Types of liquid fuels are: Benzyl, alcohol and petroleum products

BASIC REQUIREMENTS FOR AN I.C.E. FUEL ARE:-

1. Fuels must take as little time during combustion process in the cylinder so that maximum amount of heat energy must be released during this period.
2. Above requirement must be fulfilled as long as required. Longer operations result in the formation of deposits and many side effects such as wear, etc. It should not left behind gummy deposits after combustion.
3. The Products of combustion should not be harmful when they are exhausted to atmosphere.
4. It must be easy starting under different ambient conditions and must be reliable.

REQUIREMENTS OF AN IDEAL GASOLINE (Petrol engine fuel):-

1. It should mix readily with air
2. It must be knock resistant
3. It should not pre-ignite easily
4. It should not decrease the volumetric efficiency
5. It must have high C.V.
6. It should be easy to handle
7. It must be cheap and should be easily available
8. It must be clean and produce no corrosion
9. It should not form gum and varnish.

REQUIREMENTS OF A GOOD DIESEL (Diesel engine fuel):-

1. It should be satisfactorily handled and stored (means Flash point, Fire point, Viscosity, Cloud point and Pour point)

- **a) Flash point:** Flash point is the temperature at which a flammable liquid will produce a mixture of its vapor and air which will ignite to give a visible flash by contact with an open flame. Diesel should have agreeable flash point.
- **b) Fire point:** Fire point is the temperature at which the flash will sustain itself as a steady flame for at least five seconds. Diesel should have Fire point near to the boiling point of it.
- **c) Viscosity:** Viscosity of fuel is a measure of its resistance to flow. Diesel should have proper viscosity, which is important in lubrication, pumping and spraying of it in the combustion chamber. Viscosity should be low to permit bulk flow in pumping and high enough to do necessary lubrication.
- **d) Cloud point:** The temperature below which the wax content of the petroleum oil separates out in the form of a solid is called Cloud point. Such waxy solid can clog fuel lines and fuel filters.
- **e) Pour point:** It is the temperature below which the entire mass of the fuel freeze and the cause flow of fuel impossible. Pour point is 5 to 10°C below the cloud point.

2. It should be burnt smoothly, completely and efficiently: (following parameter play a role in combustion of diesel)
   - **a) Volatility:** The boiling range of Diesel varies from initial boiling point of 220°C to 390°C with 50% evaporation (measure of volatility) at 270°C. The normal range of 10% evaporation point is 204-250°C and that for 95% point is 320 to 385°C.
   - **b) Ignition quality:** For a Diesel fuel smooth spontaneous ignition at relatively low temperature is essential.
   - **c) Cetane rating:** The cetane rating of Diesel fuel is a measure of its ability to autoignite quickly when it is injected into the compressed and heated air in the engine. A Good diesel engine fuel is a bad gasoline engine fuel. Diesel fuels have typical cetane rating of 40-60 while high octane fuels as gasoline which are difficult to autoignite have cetane numbers of about 10 to 20 indicating their poor suitability as a diesel fuel.
3. **Cleanliness:** This is very important for a diesel fuel. Even a small amount of dust can affect engine operation as the plunger of the fuel injection pump is lapped to tolerance of 0.00025mm.
4. **Sulphur:** A high sulphure content in diesel fuel causes corrosion, wear of engine parts, especially the cylinder wear, and tends to increase the rate of sticky and sludge like deposits.

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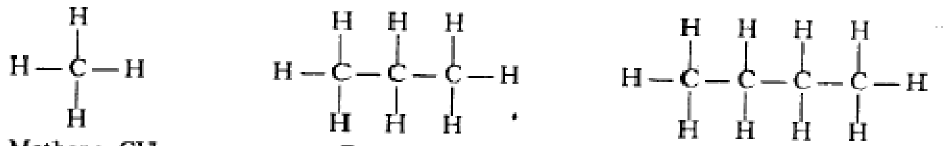
STRUCTURE OF PETROLEUM:-

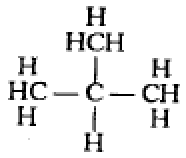
The constituents of crude petroleum are classified in four main groups.

(a) ***Paraffin's (C_nH_{2n+2}):-*** The normal or straight chain paraffin HC consists of a straight molecular structure.

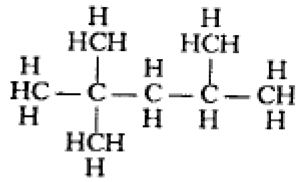


Methane, CH_4 n-Propane, C_3H_8 Butane, C_4H_{10}

Branch chain or iso-paraffins have an open chain structure.



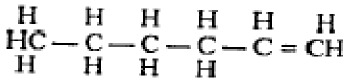
(a) Iso-butane, C_4H_{10}



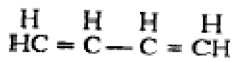
(b) Iso-octane, C_8H_{18}

*Iso-paraffins are stable compounds and are highly knock resistant when used as S.I. Engine Fuels.

(b) ***Olefin Series (C_nH_{2n}):-*** These compounds have more of double bonded carbon atoms in a straight chain. They are unsaturated compounds

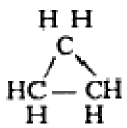


(a) Hexlene, C_6H_{12} (mono-olefin)

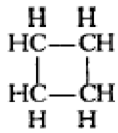


(b) Butadiene, C_4H_6 (diolefin)

(c) ***Napthene Series (C_nH_{2n}):-*** Napthene Series has the same chemical formula as the olefin series. There are ring or cyclic compounds

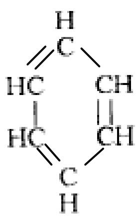


(a) Cyclopropane, C_3H_6



(b) Cyclobutane, C_4H_8

(d) ***Aromatic Series:-*** These are ring structure compounds having the benzene molecule (C_6H_6) as central structure.



Benzene, C_6H_6

EFFECT OF FUEL STRUCTURE ON COMBUSTION

1. EFFECT OF FUEL STRUCTURE ON ANTIKNOCK QUALITY OF FUEL OR KNOCKING:

Normal paraffins show the **poorest antiknock quality** when used in an SI engine. But the antiknock quality improves with the increasing number of carbon atoms and the compactness of the molecular structure. The Aromatics offer the best resistance to knocking in SI Engines.

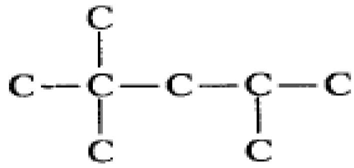
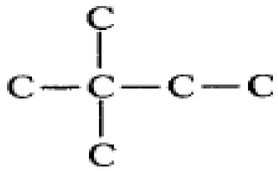
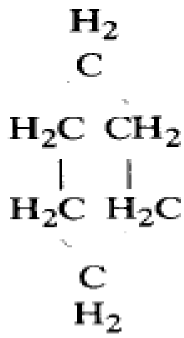
For CI Engine the order is reversed i.e., the normal paraffins are the best fuels and aromatics are the least desirable.

Knocking was affected by the structure of the fuel. Knocking is proportional to the amount of un-burnt and gas which undergoes auto – ignition.

Hence n-heptane which is prone to knock is converted into other partially oxidized hydrocarbon derivatives more than isooctane.

In general, hydrocarbons of extended chain like structure oxidise easily and knock readily and hard, while those of clustered structure oxidise less easily and do not knock so readily. Thus,

n-heptane C—C—C—C—C—C—C— and

n-octane C—C—C—C—C—C—C—C— falls in the knocking class while iso-octane  and triptane  are definitely knock-resistant. Ring compounds, the naphthenses and aromatics differ somewhat. Cyclohexane  is

-only moderately knocking.

2. **EFFECT OF FUEL STRUCTURE ON BOILING TEMPERATURE OF FUEL:**

As the number of atoms (carbon) in the molecular structure increases, the boiling temperature increases. Thus fuels with fewer atoms in the molecule tend to be more volatile.

3. **EFFECT OF FUEL STRUCTURE ON HEATING VALUE:**

The heating value generally increases as the proportion of hydrogen atoms to carbon atoms in the molecule increases due to the higher heating value of hydrogen than carbon. Thus, paraffins have the highest heating value and the aromatics the least.

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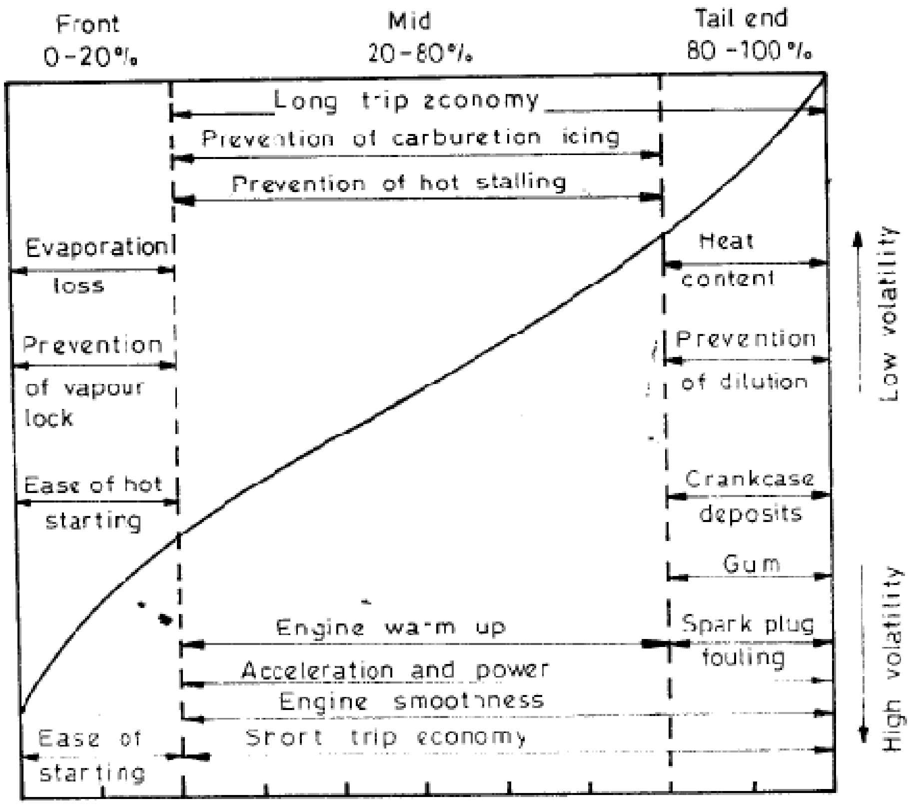
Volatility of Liquid Fuels:- "The volatility of a liquid is its tendency to evaporate (go from a liquid to a gaseous state) under given set of conditions".

Distillation Curve:- If a fuel is heated at a steadily increasing temperature and the percentage of fuel evaporated is plotted against temperature then a curve is obtained is called "Distillation Curve:.

EFFECT OF VOLATILITY ON (PETROL) ENGINE PERFORMANCE:

Engine performance parameters are as follows:

1) Cold and hot starting
2) Vapor lock
3) Acceleration and power
4) Engine Warm up
5) Engine Acceleration, Smoothness and fuel economy
6) Carburator icing
7) Dilution or Crankcase Dilution
8) Deposits and spark plug fouling
9) Evaporation loss



FRONT-END VOLATALITY

i. Cold Starting:-

At the time of starting, a rich enough mixture must be supplied near the spark plug to ignite easily. A mixture of 12:1 is the fastest burning mixture and most suitable for starting.

At low ambient temperatures (cold conditions), only a small portion of the fuel fed into combustion chamber evaporates and forms a very lean mixture. This mixture falls out of combustible range and no ignition of fuel takes place. Therefore choke is used to reduce the air quantity to make the mixture within the combustible range. [8:1 to 20:1]

An air fuel mixture ratio of 12:1 is the fastest burning mixture most suitable for starting.

The main cause of cold starting is non availability of sufficient-fuel-evaporation. Hence a **more volatile fuel** at front end is desirable to avoid cold starting problem.

ii. Hot Starting:-

When an Engine is shutdown after running for long time (4-5 hours, especially in summer), due to heat from other hot parts of the engine, the fuel present in the fuel pump, fuel links and carburetor bowl evaporates. If the ventilation is not proper, the vapour goes into intake manifold, when the engine is started. And the mixture in the combustion chamber will be too rich and it can't be ignited. This is Hot Starting.

If the front end volatility of the fuel is high, the amount of evaporation is more and increases the problem of hot starting because the mixture formed will be too rich. Hence to avoid hot starting problem; the fuel must have **Low volatility** at the front end.

This phenomenon, where it is impossible to start an engine specially during hot days, when it has been stopped for a short time after a long fast run is called "**Percolation**".

It can be avoided by proper placement and design of the fuel system.

iii. Vapour Lock:-

Vapour Lock, occurs when a too lean mixture is supplied to the engine. The fuel pump should handle both liquids and vapours. If the amount of fuel evaporated in the fuel system is very high, then pump supplies vapour and very little liquid fuel to the engine. This results in very weak (lean) mixture which cannot maintain the engine output.

It causes uneven running of an engine, stalling while idling and difficult starting when hot or momentary stalling when running. It occurs at a range of vapour-liquid ratio of 24 to 36.

The volatility should be maintained low to prevent Vapour lock. It can be reduced by keeping the fuel system away from heat, by improving the vapour handling capacity and by limiting the fuel contents of propare and butanes lesser. Propane and Butane have boiling points of 40°C and 0°C, respectively, which limits the front end volatility of the fuel.

MID-RANGE VOLATILITY

iv. Engine Warm up:- When an engine is first started it does not respond as rapidly to changes in operating conditions as it does after some time. This interval is called Engine Warm-Up (EWU) period. This is related to mid range volatility. The ASTM 50% is used as indication of warm up performance of fuel.

v. Engine Acceleration, Smoothness & Fuel economy:- The acceleration of an engine depends upon its ability to deliver suddenly to the intake of an extra supply of fuel-air mixture in a sufficiently vaporized form to burn quickly. A good acceleration occurs with an A/F ratio of 12:1.

For power & smoothness of operation correct fuel air ratio should be used. The **lower mid range** and **tail end** volatility help in good mixture distribution and hence good fuel economy.

vi. Carburettor Icing:- Due to vaporization of gasoline in the carburetor there is a drop in the temperature of the carburetor body, and if the humidity is higher than 75% and air temperature lower than 10^{o}C, water condenses out of air and freezes on carburetor.

This results in poorer economy. This ice formation restricts the air path and the engine stalls (stand, stop or pause) due to the richness of mixture and can even stop completely due to air starvation. This freezing is dependent upon the cooling effect exerted by fuel evaporation. High volatile fuel which evaporates rapidly gives the greater amount of cooling and increases carburetor icing. Low volatile decreases the rate of evaporation and prevents the carburetor icing, but it will effect cold starting of the engine.

Activities like Di-propylene Glycol (DPG) are used to overcome this problem.

TAIL-END VOLATALITY

vii. Crankcase Dilution:-If the **tail end volatility has too high evaporation temperatures**, this part of the fuel will not be completely vaporized and carried as fuel droplets into the Combustion Chamber. These droplets get across the piston rings into the crankcase where it dilutes the oil and decreases viscosity. It also washes away the lubricating oil film on cylinder walls.

Crankcase dilution is more at low engine operating temperatures like cold weather, stop-and-go driving conditions.

The tendency of the fuels to cause the dilution of lubrication oils is related to ASTM 90% temperature.

viii. Varnish and Sludge Deposits: Certain types of **high boiling hydrocarbons** contribute to varnish and sludge deposition inside an engine. These deposits cause piston ring plugging and sticking and valve sticking problems. It results in poor operation and poor fuel economy.
Lower the tail end volatility lesser are the amounts of such high boiling hydrocarbons.

ix. Spark plug fouling:- Some **high boiling Hydrocarbons** form deposits leading to spark plug fouling. To avoid this, the tail end volatility should be low.

x. Evaporation loss: Evaporation loss from the storage tanks and carburetor depends on the **vapor pressure** which is a function of fraction components and initial temperature. These losses can be as high as **10 to 12%** which not only decreases the fuel economy, but also increases knocking tendency as the lighter fractions have lesser knocking tendencies (SI Engine).

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Stoichiomatric A/F Ratio (Chemically Correct Ratio):-It is a mixture of Air and fuel which contains sufficient of oxygen for complete combustion of the fuel. It is 12:1 (A:F).

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COMBUSTION EQUATIONS

Combustion of Hydrogen.

$2H_2 + O_2 \rightarrow 2H_2O$

$2H_2 + O_2 + (79/21)N_2 \rightarrow 2H_2O + (79/21)\ N_2$ (Considering N_2)

Combustion of Carbon Complete

$C + O_2 \rightarrow CO_2$

$C + O_2 + (79/21)\ N_2 \rightarrow CO_2 + (79/21)\ N_2$ (Considering N_2)

In incomplete Combustion.

$2C + 2O_2 \rightarrow 2CO + CO_2$

Highest useful compression Ratio (HUCR) (or) **Critical compression Ratio (CCR)** :- The HUCR is the highest compression ratio at which a fuel can be used **without detonation (knocking/self ignition)** in a specified test Engine (SI Engine) under specified operating conditions.

Rating of SI Engine Fuels (Octane Number)

"Octane number of a fuel is defined as the percentage volume of iso-octane in a mixture of iso-octane and n-heptane, which exactly matches the knocking intensity of fuel (petrol) in a standard engine, under a set of similar standard operating conditions."

The addition of certain compounds i.e. Tetra ethyl lead to iso-octane produces fuels of greater antiknock quality.

Octane Number - It indicates the performance of the fuel against "Knocking"

1) In this, the performance of unknown gasoline is compared with that of a series of reference fuels consisting of mixtures of iso-octane (C_8H_{18}) and n-heptane (C_7H_{16}).
2) Iso-octane has a very lesser tendency to knock and hence its Octane Number of 100.
3) n–heptane has a very high tendency to knock and its Octane Number of 'Zero'.
4) These fuels are known as the **Primary Reference Fuels** (**PRF**).
5) The Octane Number of an unknown fuel is defined as the percentage of iso-Octane in the PRF that gives the same knock intensity as that of test fuel (say gasoline).
6) It a gasoline that gives the same knock intensity as 90% PRF then its Octane Number is 90.
   Octane Number = 100 + (PN-100)/3

Research Octane Number:- Octane Number determined by Research Test is termed as Research Octane Number (RON)

Motor Octane Number:- Octane Number determined by motor method is termed as Motor Octane Number (MON)

Sensitivity:- The difference between RON and MON is called sensitivity. Highest the sensivity the poorer its performance. **Sensitivity = RON – PON**

Performance Number (PN):-

It is the ratio of the knock limited indicated mean effective pressure (klimep) of test fuel to knock limited indicated mean effective pressure of iso Octane.

$$PN = \frac{\text{Klimep of test fuel}}{\text{Klimep of Iso - Octane.}}$$

PN of iso – Octane is 100

Advantages of High – Octane Fuel:-

1. The engine can be operated at high compression Ratio hence higher efficiency can be achieved without detonation.
2. The engine can be supercharged to high output without knocking.
3. Optimum sport advance may be employed which increases power and efficiency.

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Note: Octane rating of Petrol (gasoline) is 80-84.
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Cetane Number:-

"The Cetane number of a fuel is defined as the percentage volume of normal cetane in a mixture of normal cetane ($C_{16}H_{34}$) and alpha-methyl naphthalene ($C_{11}H_{10}$), which has the same ignition characteristics (ignition delay) as the test fuel (Diesel) when combustion is carried out in a standard test engine, under similar specified operating conditions."

The cetane Rating of a diesel fuel is a measure of its ability to auto-ignite quickly when it is injected into the compressed and heated air in the engine.

The knock rating of a diesel fuel is found by comparing the fuel under prescribed conditions of operation in a special test engine with primary reference fuels, Normal Cetane, ($C_{16}H_{34}$) and alpha methyl nepthalene ($C_{11}H_{10}$) with an assigned cetane number of zero.

$$CN = \frac{104 - ON}{2.75}$$

Note: Cetane rating of Diesel is 40-45.

Knock resistance property of diesel fuel can be improved by adding small quantities of compounds like **Amyl nitrate, ethyl nitrate or ether**.

Additives (or) Dopes :- These are substances which improve combustion performance of fuels.

Antiknock Additives:- Which reduce the knocking.
Ex.:- Tetra-Ethyl Lead, Tetra-Methyl Lead (in SI engine) and Amyl nitrate, ethyl nitrate or ether in case of CI engines.

(NOTE:- Do all the Numerical that are discussed in the class.)

LPG AS A SI ENGINE FUEL:

LPG consists of hudrocarbons of such volatility that they exist as gases under atomospheric conditions, but can be readily liquefied under pressure. Methane and ethane are too volatile for easy liquefaction, so LPG mostly consists of propane and to some extend butane. The largest use of LPG at present is as domestic and industrial fuel. However, there is an increasing trend to use LPG as a motor fuel.

Advantages of LPG:

1) It is cheaper than gasoline
2) It is highly knock-resistant and does not pre-ignite easily.
3) It gives better (inlet) manifold distribution and mixes easily with air.
4) Crankcase oil dilusion is small, resulting in increased engine life.
5) Residue and oil contamination is small as it burns cleanly and completely.

Disadvantages of LPG:

1) It is suitable only for higher compression ratio engines
2) It reduces the volumetric efficiency due to its high heat of vaporization.
3) Handling has to be done under pressure of about 18 bar.
4) Its characteristic odour is faint, so leakage can not be easily detected.
5) Its motor octane number is undesirably low and the road sensitivity is very high.
6) Response to blending is very poor.

A trend to use LPG as a main fuel in dual-fuel engine is in progress nowadays.

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Combustion:- It is defined as a relatively rapid chemical combination of carbon and Hydrogen in the fuel with the O_2 in the air resulting is liberation of heat energy.

Conditions - 1. Presence of a combustible mixture.
2. Some means of initiation of combustion.
3. Stabilization & propagation of flame in Combustion Chamber

Ignition Limits:-

The ignition of the charge is only possible within certain limits fuel air ratio. These are called ignition limits. The flame will propagate only if the temperature of the burnt gases exceeds approx. 1500 k in case of Hydro Carbon mixture to achieve this temperature, the relative fuel air ratio must be between 0.5 and 2.1

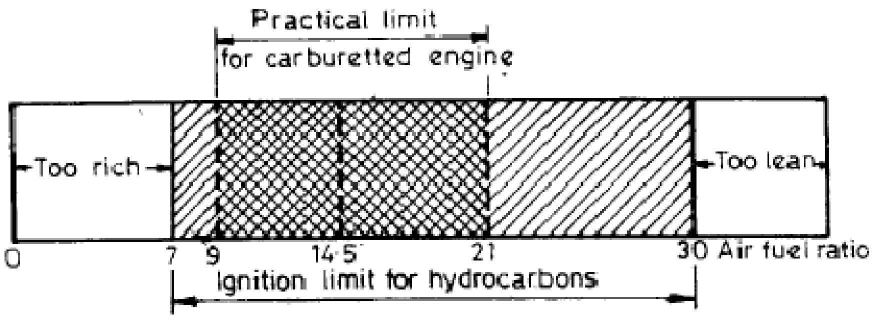

Fig. 5.1. Ignition limits for hydrocarbons.

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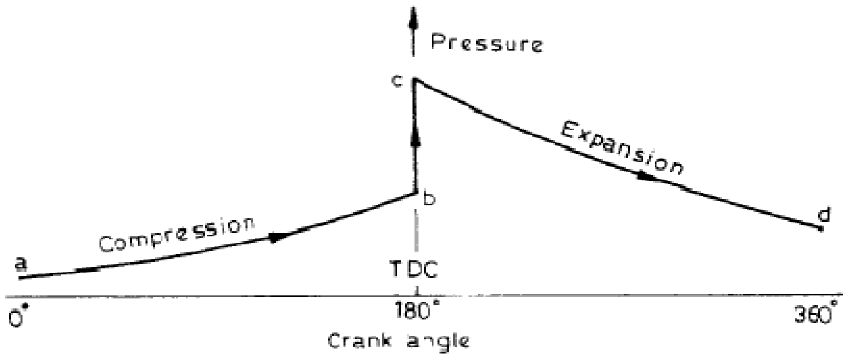
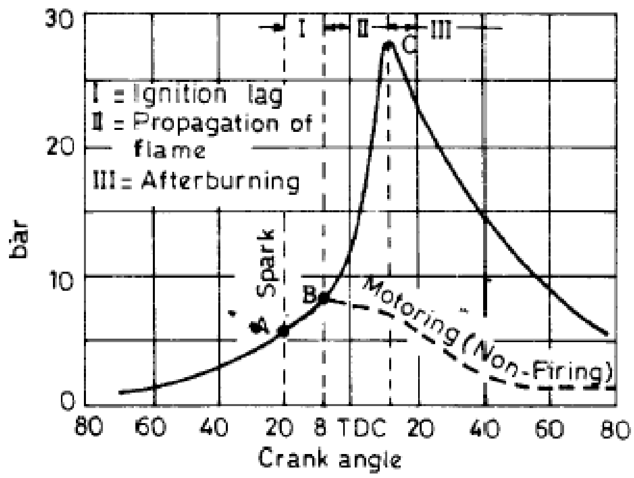
Combustion Phenomenon is S.I. Engine:-

The combustion is S.I. Engine will take place with help of spark. The speed of flame front depends primarily upon the temperature of the flame front and secondarily on temperature and density of surrounding envelope.

"Sir Ricardo" describes the combustion process is S.I. Engine in three stages.





i. **The First Stage (A–B):-** This is referred as the ignition lag or preparation phase is which growth and development of a self propagating Nucleus of flame takes place. This process depends upon temperature, pressure, the nature of the fuel and on the exhaust residual gas.

ii. **The Second stage (B – C):-** It is a physical one. It depends upon the speed of the flame throughout the Combustion Chamber. It starts at a point where the first measurable rise of pressure is seen. In this stage flame propagates at a certain velocity. The rate of pressure rise is proportional to the rate of heat release. It ends at a point where the pressure is maximum.

iii. **Third Stage (C – D):-**The flame velocity decreases during this stage. The rate of combustion is low due to low flame velocity and reduced flame front surface. And there is no pressure rise in this stage.

The point C indicates end of flame travel, but it does not follow that at this point the whole of the heat of the fuel has been liberated. But some amount of heat is still released due to chemical adjustments due to reassociation etc. This is called "After Burning".

Effect of Engine Variables on Ignition Lag (IL)

i. **Fuel:-** It depends on the chemical nature of the fuel. The higher the self- ignition temperature of the fuel, the longer the Ignition Lag.

ii. **Mixture Ratio:-** The IL is the smallest for the mixture ratio which gives maximum temperature. The mixture should be slightly richer than Chemically Correct Ratio (CCR).

iii. **Initial Temperature & Pressure:-** The IL decreases with an increase in the temperature and pressure at the time of spark.

iv. **Electrode Gap:-** If the gap is too small, quenching of the flame nucleus may occur and the range of F/A Ratio for development of Flame nucleus may be reduced. The lower the Compression Ratio (CR), the highest the electrode gap.

v. **Turbulence:-** It is not much affected by Turbulence. The turbulence is directly proportional to speed the IL increases almost linearly with the engine speed.

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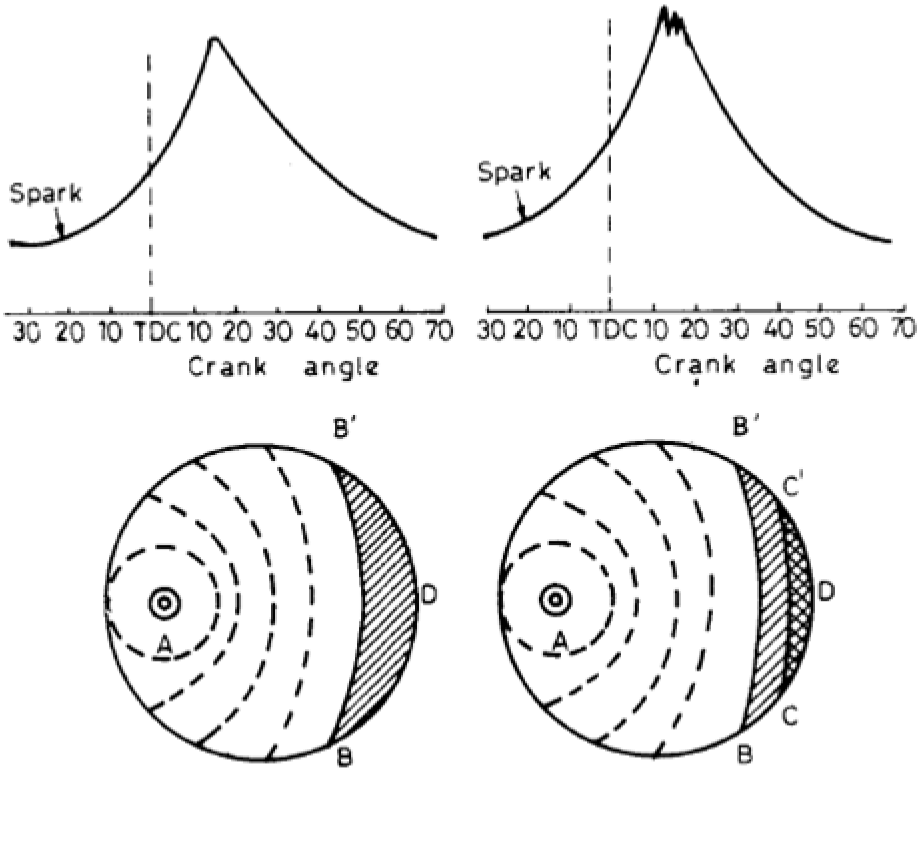
Knocking (or) Detonation process in S.I. Engine:-

Due to Abnormal combustion process in SIE, a very sudden rise of pressure during combustion takes place accompanied by metallic hammer like sound, which is called Knocking.



(a) Normal combustion (b) Detonation or knock

Combustion in the spark-ignition engine.

Knocking-

In Normal Combustion the flame propagates from A with a velocity of 65 to 30 m/sec. The advancing flame front compresses the end charge BB'D. The temperature of end charge is increased due to above compression and also due to heat which is radiated from flame front. "If the increased temperature is less than the auto ignition temperature of the end charge then there will be no abnormal combustion and also no knocking".

If the temperature of end charge is equal to or more than auto ignition temperature then the end charge undergoes pre flame reactions called ignition delay. If the time required for flame front at BB' to reach D is less than this ignition delay then there will be 'No Knocking'.

If the time required for flame front at BB' to reach D is more than the ignition delay. Then flame can reach CC' only [with in ignition delay] and the end charge at D produces a flame(upon completion of ignition delay) from opposite side which leads to abnormal combustion. Due to this abnormal combustion a very sudden rise in pressure (150 bar – 200 bar) takes place. This large pressure differential give rise to a severe pressure wave which strikes the cylinder wall and sets it vibrating giving rise to a characteristic high pitched metallic "pitching" or ringing sound as if a stroke struck by a light hammer. This phenomenon is known as knocking or detonation.

Factors Affecting Knocking:-

1. **Compression Ratio:-** Increase in compression ratio increases both temperature and pressure of end charge. Increase is temperature reduces the delay period. Hence the tendency of knock increases.
2. **Raising the inlet temperature:-** Raising the inlet temperature decreases delay period hence the tendency of knock increases.
3. **Spark Timing:-** When spark is advanced, the piston has to compress the burning gas due to this both temperature and pressure are increased. This reduces the delay period. Hence the tendency of knocking increases.
4. **Location of Spark Plug:-** If it is centrally located in the combustion chamber then it reduces the tendency of knock because the flame travel is minimum.
5. **Engine Size:-**The delay period is not very much affected by the size of the cylinder. However larger the size, longer the flame travel, hence the tendency of knocking increases with size.
6. **Engine Speed:-**In a lower speed engines, longer is the flame travel to reach the end charge which increases the time for pre flame reactions. Hence the tendency of knock increases.
7. **Fuel – Air Ratio:-** It plays important effect on the ignition delay. When the mixture is 10% rich than theoretical Air fuel ratio; the ignition delay is maximum and the velocity of flame propagation is maximum. But the former effect(maximum ignition delay) predominates the later effect(maximum velocity of flame propagation) and increases the tendency of knock. A too rich mixture is especially effective is decreasing the knock due to longer delay.
8. **Combustion Chamber Design:-** The more the compact the Combustion Chamber(CC), the better will be its anti knock characteristics, since the flame travel and combustion time will be shorter.

Pre ignition increases the time losses and reduces the net work output. Compression of burning gases raises the temperature more and more which causes the pre ignition to occur earlier and earlier in the cycle.

In the limit pre ignition would ignite the incoming charge and power produced will be reduced to zero and the engine would stop.

Pre ignition inhibitors:- Water is a very effective inhibitor. Commercial Alcohol reduces the pre ignition. Lead has a small effect in inhibiting pre ignition.

Effects of Knocking:-

1. **Noise and Roughness:-** Mild knock is seldom audible and not harmful. When knock intensity increases a loud pulsating noise is produced and vibrates the cylinder. This causes crankshaft vibrations and engine runs rough.

2. **Mechanical Damage:-** Knocking increases the rate of wear. Erosion of piston crown may happen. The cylinder head and valves may also be pitted.

   In large high duty engines (aero engines) the knocking may result in complete "Wreckage of the piston".

3. **Carbon Deposits:-** Knocking increases carbon deposits.

4. **Power output and efficiency:-** Due to increase in the rate of heat transfer, the power and efficiency decreases.

5. **Increase in heat Transfer:-**

   Knocking increases the rate of heat transfer. Due to knocking the maximum temperature in chamber is about 150^{o}C higher than the normal engine. The higher the temperature difference, more the rate of heat transfer.

   Due to knocking a high pressure wave is produced, which cleans the protective layer which is stagnant on the cylinder walls. This increases rate of heat transfer because cylinder walls are in direct contact with the flame.

6. **Pre – ignition:-**

   If the ignition occurs before the passage of the spark, then the ignition is called pre-ignition.

   It is caused by an overheated spot which may occur at the spark plug, combustion chamber deposits or Exhaust valves. Mostly it is the spark plug which may reach a temperature (if > 1100^{o}C) high enough to ignite the charge before the passage of spark.

   The overheating of the above occurs if an engine is knocking for a long time and this is the real danger of knocking. However, the pre-ignition may also occur due to reasons other than the knocking.

Effect: The effect of pre-ignition is same as ignition (Spark) advance. The additional negative work done by the piston during compression stroke because of already burning gases. This produces higher peak pressures and temperature in the cylinder. This increases pressure and temperature of and charge (BB'D) and hence leads to knocking.

"That means knocking could read to pre-ignition and pre-ignition leads to knocking. Thus a circle is formed, with one leading to other until all the power is lost".

Theories of Detonation (or) Knocking:–

The phenomenon of knocking was explained by following theories. They are –

(a) **The Auto-ignition Theory:-** The temperature of end charge (BB'D) increases due to compression of the flame from and heat radiated from the flame front. If the temperature is below than self-ignition temperature then the end charge may not auto-ignite and there will be no knocking.

If the temperature of end charge is equal to auto-ignition temperature, the charge will auto-ignite after ignition delay. During the delay period, some chemical reactions occur which are called pre flame reactions; after this it gives rise to a flame. During pre flame reactions, extensive decomposition of the fuel produces aldehydes, peroxides, hydrogen peroxide and free radicals. The energy released by these reactions and presence of active chemical substances greatly accelerates the chemical reactions and leads to auto-ignition.

(b) **Detonation Theory:-**According to this a true detonating pressure wave is formed by pre flame reactions which causes explosive auto-ignition. This wave would travel through the chamber at about twice the sonic velocity and compress the gases to very high pressure.

(c) **General Concept:-** According to this, when a fuel under goes pre flame reactions, the flame velocity may up to 150-400 m/sec. The accelerating flame passes through the end gas and causes explosion of the end gas.

Control of Detonation (or) Knocking:–

The knocking can usually be controlled (or) even stopped by the following manipulations.

1. Increasing the R.P.M.
2. Retarding the spark
3. Reducing pressure in inlet manifold.
4. Making the ratio too lean or too rich preferably the later option.
5. Water injection:- This increases the delay period as well as reduces the flame temperature.

The following are design features which reduces knock.

1. Use of lower compression ratio
2. Increasing turbulence
3. Relocating spark plug (or) use of two or more spark plugs
4. Proper design of combustion chamber to reduce flame length and temperature of end gas.
5. Use of high octane fuel
6. By adding dopes.

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Combustion in C.I. Engine:–

In the CI Engine, air alone is compressed through a large compression ratio (12:1 to 22:1). During compression stroke, the pressure of air is increased to (30-40 bar) and temperature increased up to (450^{o}C – 500^{o}C).The high pressure fuel (110 – 200 bar) whose pressure was increased by fuel pump was injected into high pressure combustion chamber. Each minute droplet as it enters chamber is quickly surrounded by an envelope of its own vapour. To evaporate the liquid, latent heat is taken from the surrounding air which reduces the temperature of a thin layer of air surrounding droplet and some time will be elapsed before this temperature can be raised again by extracting heat from the main bulk of air.

As soon as temperature of this vapour and air in contact with it is reached to auto-ignition temperature and if the air fuel air ratio is within combustible range, ignition takes place. Once ignition has taken place and a flame is established, the heat required for further evaporation will be supplied from the combustion. The vapour would be burning as fast as it can find fresh oxygen.

Delay Period of Ignition Lag (C.I. Engine) –

The ignition delay period in C.I. Engines divided into two parts.

(1) **Physical Delay:-**The period of physical delay is the time between the beginning of injection and the attainment of chemical reactions conditions. In this period, the fuel is atomized, vaporized, mixed with air and raised in temperature.

(2) **Chemical Delay:-** During this delay pre flame reactions take place within the charge and ignition takes place.

Generally chemical delay is longer than the physical delay. It depends upon temperature. At high temperatures physical delay longer than chemical delay.

The delay period in C.I. Engines is sum of physical and chemical delays.

Difference between S.I. Engine and C.I. Engine ignition lag –

The ignition lag of S.I. Engine is only of chemical delay and there is no physical delay.

In fact the ignition lag of S.I. Engine is basically equivalent to the chemical delay of C.I. Engine.

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Combustion phenomenon in C.I. Engine [Combustion stages] –

Sir Ricardo considered C.I. Engine combustion as taking place in three district stages.

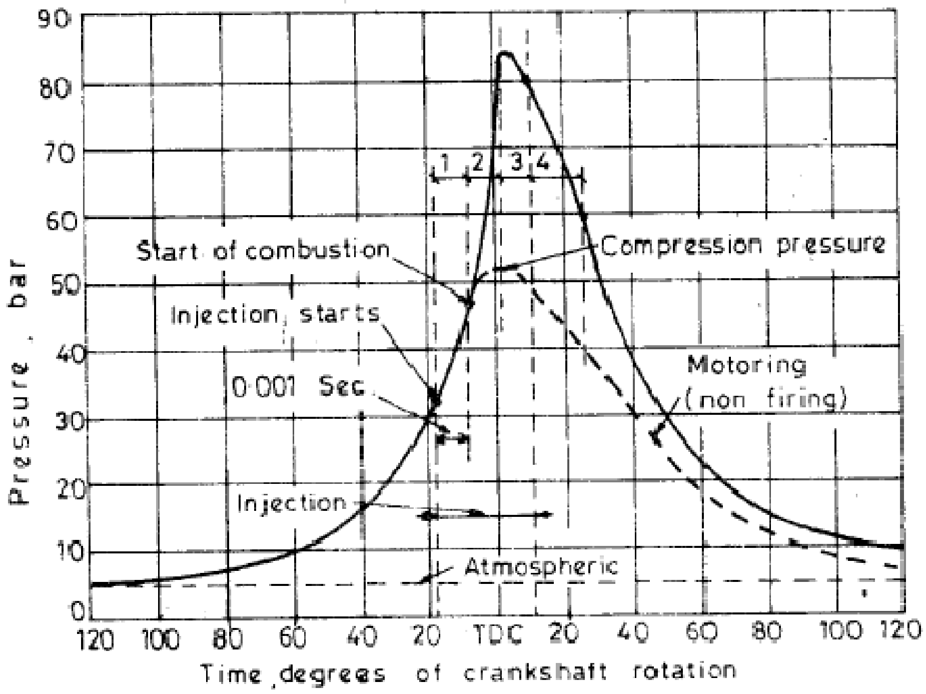

Figure - Stages of Combustion in the C.I. Engine

I. **First Stage (1-2):-** This stage is **ignition delay period**. During this some fuel is already admitted but no ignition takes place. This stage is counted when fuel injection starts. It is a preparation phase.

II. **Second Stage (2-3):- Rapid or uncontrolled combustion –**

In this stage the pressure rise is rapid because during the delay period, the fuel droplets have had enough time to spread over a wide area and are surrounded by fresh air all around them. This stage is counted from the end of delay period to the point of maximum pressure. About one third of heat is evolved during this period.

III. **Third Stage (3-4) Controlled Combustion-**

At the end of second stage the temperature and pressure are so high that the fuel droplets injected during this stage, burn almost as they enter and further pressure rise takes place in a controlled manner. This is assumed to end at maximum cycle temperature. About 70 to 80% heat from fuel is evolved during this stage.

The above three stages proposed by “Ricardo” and a fourth stage can be added. This stage may not be present is all cases.

IV. **Fourth Stage (After Burning):-** Theoretically, the combustion process completed after the third stage. Because of poor distribution of the fuel, combustion continues during the part of expansion stroke. This burning is called after burning and this is last stage. At the end of this, total heat (95-97%) of fuel evolved and remaining 3 to 5% of heat of un-burnt fuel goes into exhaust.

Variables Affecting Delay Period:-

1. **Fuel:–** The delay period depends on the self-ignition temperature of the fuel. The lower the self-ignition temperature lower will be the delay period.

2. **Injection pressure (or) size of droplet:–**The lower the injection pressure, the lower the rate of pressure rise during the uncontrolled phase.

3. **Injection Advance Angle:–**The delay period increases with increase in injection advance. The reason is that the pressures and temperatures are lower when the injection begins.

4. **Compression Ratio:–**Increase in compression ratio reduces the delay period as it raises temperature.

5. **Intake temperature:–**Increase in intake temperature increases the compressed air temperature which reduces the delay period.

6. **Jacket Water Temperature:–** Increase in 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 periods. And delay period reduces.

8. **Intake Pressure (or) Supercharging:–** Increase in intake pressure reduces the auto-ignition temperatures and hence reduces delay period.

9. **Speed:–**As the speed increases, the loss of heat during compression decreases, with this both the temperature and pressure of the compressed air tend to rise, thus reducing the delay period in milliseconds.

10. **Air Fuel Ratio:–**With increase in Air-fuel ratio (leaner) the combustion temperatures are lowered and hence delay period increases.

    With the increase in load, air-fuel ratio decreases and increases temperature and the delay period decreases.

11. **Engine Size:–**The engine size has little effect on the delay period. The large engines operate at low RPM because of stress limitations, the delay period is smaller.

12. **Type of Combustion Chamber:–**The delay period is lower if the engine contains pre-combustion chamber.

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Diesel Knock –

If the delay period in C.I. Engine is long, a large amount of fuel will be injected and accumulated in the chamber. The auto-ignition of this large amount of fuel may cause high rate of pressure rise and high maximum pressure which may cause knocking.

A long delay period not only increases the amount of fuel but also improves homogeneity of the fuel-air mixture. The chemical preparedness for explosive type ignition is similar to knocking in S.I. Engines.

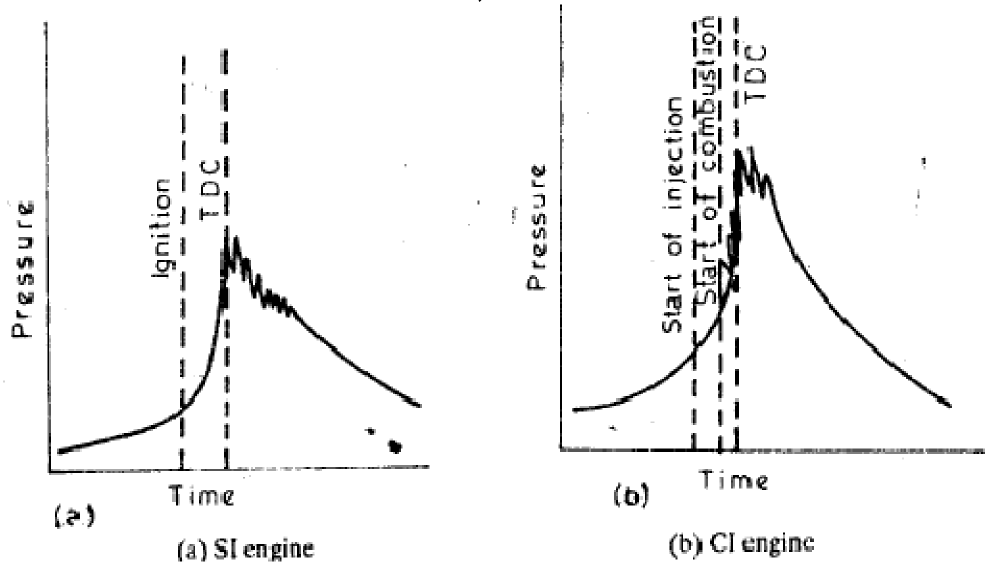

Figure - Detonation in the S.I. Engine compared with knocking in the C.I. Engine

Differences in the Knocking of S.I. and C.I. Engine –

1. In the S.I. Engine, the knocking occurs near the end of combustion.

   In the C.I. Engine, the knocking occurs near the beginning of combustion.

2. The rise in pressure in S.I. Engine due to knocking is at high.

   The rise in pressure in C.I. Engine due to knocking is lower than S.I. Engine.

3. Knocking is S.I. Engine may lead to pre ignition, but there is no chance of pre ignition in C.I. Engine.

4. It is easy to distinguish between knocking and non-knocking operation in S.I. Engine.

   It is very difficult to identify the knocking in C.I. Engine.

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Que. It is important to note that factors that tend to reduce detonation in the S.I. Engine increase knocking in C.I. Engine and vice-versa – justify the above.

Ans. The detonation of knocking in the S.I. Engine is due to auto-ignition of the end charge. to reduce the knocking is S.I. Engine, the fuel must have a high self ignition temperature and a long delay period.

The detonation of knocking in the C.I. Engine is due to late auto-ignition of the charge during ignition delay period. To reduce the knocking in C.I. Engine, the fuel must have a low self ignition temperature and a short ignition delay period.

Table – Factors tending to reduce knocking in SI and CI Engine.

S.No.	Factors	SI engine	CI engine
1.	Self-ignition temperature of fuel	High	Low
2.	Time lag or delay period for fuel	Long	Short
3.	Compression ratio	Low	High
4.	Inlet temperature	Low	High
5.	Inlet pressure	Low	High
6.	Combustion chamber wall temperature	Low	High
7.	Speed	High	Low
8.	Cylinder size	Small	Large

From the above it is clearly indicating that the factors that tend to reduce detonation in the S.I. Engine increase knocking in C.I. Engine and vice-versa.

It is clear from the above that, a good C.I. Engine fuel is a bad S.I. Engine fuel and a good S.I. Engine fuel is a bad C.I. Engine fuel.

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