COMBUSTION MODES AND FLAME TYPES

Premixed flames:
• If the fuel and oxidizer are essentially uniformly mixed together, the flame is designated as **premixed**.

• The conventional spark-ignition flame is thus a premixed unsteady turbulent flame, and the fuel-air mixture through which the flame propagates is in the gaseous state.

Diffusion flames:
• If the reactants are not premixed and must mix together in the same region where reaction takes place, the flame is called a **diffusion flame**.

• The diesel engine combustion process is predominantly an unsteady turbulent diffusion flame, and the fuel is initially in the liquid phase.
Combustion is defined as a 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 SI Engines, carburetor supplies a combustible mixture of petrol and air and spark plug initiates combustion.
The fuel and air are homogeneously mixed together in the intake system.

Inducted through the intake valve into the cylinder where it mixes with residual gases and is then compressed.

Combustion is initiated towards the end of the compression stroke at the spark plug by an electric discharge.

A flame develops and propagates through this premixed charge of fuel and air and also the residual gas in the clearance volume until it reached the combustion chamber wall.

Combustion is divided into Normal and abnormal combustion.
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 neighbouring unburnt mixture. For hydrocarbons fuel the stoichiometric fuel air ratio is 1:15 and the ignition limit is 1:30 and 1:7 (Fuel – Air)
THEORIES OF COMBUSTION IN SI ENGINE

Combustion in SI engine may be roughly divided into two general types: Normal and Abnormal (knock free or Knocking).

In the diagram, a to b is compression process, b to c is combustion process and c to d is the 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.
- In actual cycle this does not happen.
According to Sir Ricardo, (father of engine research) 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
COMBUSTION PROCESS IN SI ENGINES

STAGE OF COMBUSTION

There are three stages of combustion in SI Engines,

1. Ignition lag
2. Flame propagation
3. After burning
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.
COMBUSTION PROCESS IN SI ENGINES

Ignition lag

- During ignition lag, molecules get heated up to self ignition temperature (chemical reactions), get ignited and produce a self propagating nucleus of flame.
- The ignition lag is generally expressed in terms of crank angle ($\theta_1$).
- The period of ignition lag is shown by path A to B.
- Ignition lag lies between 0.0015 to 0.002 seconds.
- An ignition lag of 0.002 second corresponds to 35° 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

- Once the flame is formed, 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 the heat lost by flame to surrounding.
- After the point “B”, the flame propagation is slow at the beginning as heat lost is more than heat generated.
- Pressure rise is slow as mass of mixture burned is small.
- Therefore it is necessary to provide angle of advance 30 to 35°, if the peak pressure is to be attained 5-10° ATDC.
- The time required for the crank to rotate through an angle $\theta_2$ is known as combustion period during which propagation of flame takes place.
COMBUSTION PROCESS IN SI ENGINES

3. After burning

- Combustion will not stop at point “C” but continue after attaining peak pressure and this combustion is known as after burning.
Two important factors which determine the rate of movement of the flame front across the combustion chamber are the Reaction rate and Transposition rate.

Reaction rate is the result of a purely chemical combination process in which the flame eats its way into the unburned charge.

Transposition rate is due to the physical movement of the flame front relative to the cylinder wall and is also the result of the pressure differential between the burning gases and the unburnt gases in the combustion chamber.
COMBUSTION PROCESS IN SI ENGINES
FLAME FRONT PROPAGATION

Details of Flame Travel
Flame Velocity

Normal laminar flame velocity versus Relative air fuel ratio for petrol-air mixtures
Area I, (A→B)

- Flame front progresses relatively **slow** due to a low transposition rate and low turbulence.
- Transposition rate is low because there is a comparatively small mass of charge burned at the start.
- There is a lack of turbulence due to spark plug is located close to the cylinder wall (i.e. in quiescent layer of gas).
- Thus turbulence reduce the reaction rate, thus the flame speed is reduced.
COMBUSTION PROCESS IN SI ENGINES
FLAME FRONT PROPAGATION

Area II, (B→C):

- The flame leaves the quiescent zone and proceeds into more turbulence area (area II).
- Flame consumes a greater mass of mixture, it progresses more rapidly and at a constant rate.

Area III, (C→D):

- Transposition rate again becomes negligible.
- As the volume of unburned charge is very less towards the end of flame travel, the flame speed is reduced.
- Reaction rate also reduced since the flame enter into low turbulence zone.
1. **Fuel-air ratio**: When the mixture is made leaner or rich, the velocity of flame diminishes.
COMBUSTION PROCESS IN SI ENGINES

Effect of Engine Variables on Flame Propagation

2. **Compression ratio**: The speed of combustion increases with increase of CR. The increase in CR results in increase in temperature which increases the tendency of the engine to detonate.

3. **Intake temperature & pressure**: Increase in intake temperature and pressure increases the flame speed.
COMBUSTION PROCESS IN SI ENGINES
Effect of Engine Variables on Flame Propagation

4. **Engine load:** As the load on the engine increases, the cycle pressure increases and hence the flame speed increases.

5. **Turbulence:** The flame speed is low in non-turbulent mixture. Turbulent motion intensifies the processes of heat transfer and mixing of the burnt and unburnt portions in the flame front. These two factors cause the velocity of turbulent flame to increase in proportion to the turbulent velocity.
COMBUSTION PROCESS IN SI ENGINES

Effect of Engine Variables on Flame Propagation

6. **Engine speed:** The flame speed increases almost linearly with engine speed. The crank angle required for flame propagation, which is the main phase of combustion, will remain almost constant at all speeds.

7. **Engine size:** The number of crank degrees required for flame travel will be about the same irrespective of engine size, provided the engines are similar.
COMBUSTION PROCESS IN SI ENGINES

RATE OF PRESSURE RISE:

- The rate of pressure rise in the combustion chamber influences the peak pressure developed, the power produced and smoothness in operation.
- The rate of pressure rise is mainly dependent upon the rate of combustion of mixture.
- P-θ diagram for three different combustion rates is shown in the figure.
  1) Curve I ➔ High combustion rate.
  2) Curve II ➔ Normal combustion rate.
  3) Curve III ➔ Low combustion rate.
COMBUSTION PROCESS IN SI ENGINES

RATE OF PRESSURE RISE

Illustrations of Various Combustion Rates
COMBUSTION PROCESS IN SI ENGINES

RATE OF PRESSURE RISE

High combustion rate (Curve I)

- High rate of combustion results in high rate of pressure rise.
- It produces higher peak pressures at a point closer to TDC.
- This is desirable because high peak pressure closer to TDC produce more force acting through larger part of the power stroke, increasing the power output of the engine.
- Higher rate of pressure rise causes rough running of the engine because of vibrations produced in the crank shaft. This tends to knocking.
COMBUSTION PROCESS IN SI ENGINES

RATE OF PRESSURE RISE

Normal combustion rate (Curve II)

- A compromise between these opposing factors is accomplished by designing and operating the engine approximately one-half of the maximum pressure is reached by the time the piston reaches TDC.

- This result in the peak pressure being reasonably close to the TDC, yet maintaining smooth engine operation.
COMBUSTION PROCESS IN SI ENGINES

RATE OF PRESSURE RISE

Low combustion rate (Curve III)

- Low rate of combustion requires long time to complete combustion.
- It initiates the burning at an early point on the compression stroke and the peak pressure occurs very late.
- This will result in poor power output of the engine.
COMBUSTION PROCESS IN SI ENGINES

Factors affecting normal combustions in S.I. engines

1. **Induction pressure.** Less induction pressure - ignition lag increases - ignition must be advanced - vacuum control

2. **Engine speed.** Speed increases - constant time ignition lag needs more crank angle - ignition must be advanced - Centrifugal advance

3. **Ignition timing.** Ignition too early - peak pressure will occur too early and work done falls. Ignition too late - peak pressure will be low and work done falls. Combustion is not complete when exhaust valve opens and the valve may also burn.
COMBUSTION PROCESS IN SI ENGINES

Factors affecting normal combustions in S.I. engines

4. **Mixture strength**. Stoichiometric ratio should give best combustion. Dissociation demands a slightly rich mixture necessary for maximum work transfer.
COMBUSTION PROCESS IN SI ENGINES

Factors affecting normal combustions in S.I. engines

5. **Compression ratio.** Increase in compression ratio - increases the maximum pressure and the work transfer.

6. **Combustion chamber.** The combustion chamber Design - short flame path to avoid knock - promote optimum turbulence.

7. **Fuel choice.** Calorific value and enthalpy of vaporization affects the temperatures achieved.
Ignition lag is not a period of inactivity but is the duration of pre-flame reactions.

The ignition lag in terms of crank angles is 10° to 20° and in terms of time, 0.0015 to 0.002 sec.

1. **Fuel.** Ignition lag depends on chemical nature of fuel. The higher the self-ignition temperature of fuel, longer the ignition lag.

2. **Mixture ratio.** Ignition lag is the smallest for the mixture ratio which gives the maximum temperature. This mixture ratio is slightly richer than stoichiometric ratio.
COMBUSTION PROCESS IN SI ENGINES
EFFECT OF ENGINE VARIABLES ON IGNITION LAG

3. Initial temperature and pressure.
   - Ignition lag is reduced if the initial temperature and pressure are increased.
   - These can also be increased by increasing the compression ratio.

4. Turbulence. Ignition lag is not much affected by the turbulence.
COMBUSTION PROCESS IN SI ENGINES

WHY SPARK ADVANCE?

- In order to obtain maximum power from an engine, the compressed charge (burning) must deliver maximum pressure at a time when the piston is about to start the expansion stroke.
- Since there is an ignition lag, the spark must take place before the piston reaches T.D.C. on its compression stroke, i.e., the spark timing is advanced.
- Usually the spark advance is about 15° BTDC.
COMBUSTION PROCESS IN SI ENGINES

FACTORS AFFECTING IGNITION TIMING

1. Engine speed.
   ➢ If an engine has an ignition advance of $\theta^\circ$ and operating speed of $n$ rps,
   ➢ Time available for initiation of combustion $= \frac{\theta}{360n}$ sec.
   ➢ If the engine speed is increased to $2n$ rps, then in order to have the same time available for combustion, an ignition advance for $2\theta^\circ$ is required.
   ➢ As the engine speed is increased, it will be necessary to advance the ignition progressively.
2. **Mixture strength.**
- In general rich mixtures burn faster.
- If the engine is operating with rich mixtures the spark timings must be retarded, i.e., the number of crank angle BTDC at the time of ignition is decreased and the spark occurs closer to TDC.
3. **Part-load operation.**
   - Part-load operation of a spark-ignition engine is affected by throttling the incoming charge.
   - Due to throttling a small amount of charge enters the cylinder, and the dilution due to residual gases is also greater.
   - In order to overcome the problem of exhaust gas dilution and the low charge density, at part-load operation the spark advance must be increased.
COMBUSTION PROCESS IN SI ENGINES

FACTORS AFFECTING IGNITION TIMING

4. **Type of fuel.** Ignition delay will depend upon the type of fuel used in the engine. For maximum power and economy a slow burning fuel needs a higher spark advance than a fast burning fuel.
COMBUSTION PROCESS IN SI ENGINES

ABNORMAL COMBUSTION

There are two combustion abnormalities,

1. **Pre or Post ignition**
   - This is the ignition of the mixture by incandescent carbon particles in the chamber.
   - This will have the effect of reducing the work transfer.

2. **Knock**
   - This is a complex condition with many facets.
   - Knock occurs when the unburnt portion of the gas in the combustion chamber is heated by combustion and radiation so that its temperature becomes greater than the self ignition temperature.
COMBUSTION PROCESS IN SI ENGINES

ABNORMAL COMBUSTION

Contd......

- If normal combustion is not completed before the end of the induction period then a simultaneous explosion of the unburnt gas will occur.
- This explosion is accompanied by a detonation wave which will be repeatedly reflected from the cylinder walls setting up a high frequency resonance which gives an audible noise.
- The detonation wave causes excessive stress and also destroys the thermal boundary layer at the cylinder walls causing overheating.
Pre-ignition is the ignition of the homogeneous mixture in the cylinder, before the timed spark occurs, caused by the local overheating of the combustible mixture.

- For premature ignition of any local hot-spot to occur in advance of the timed spark on the combustion stroke it must attain a temperature of 700 – 800°C.
- Pre-ignition is initiated by some overheated projecting part such as the sparking plug electrode, exhaust valve head, metal corners in the combustion chamber, carbon deposits or protruding cylinder head gasket rim etc.
The initiation of ignition and the propagation of the flame front from the heated hotspot is similar to that produced by the spark-plug when it fires, the only difference between the hot-spot and spark plug is their respective instant of ignition.

The spark plugs provides a timed and controlled moment of ignition whereas the heated surface forming the hot-spot builds up to the ignition temperature during each compression stroke and therefore the actual instant of ignition is unpredictable.
COMBUSTION PROCESS IN SI ENGINES

A – Normal Combustion
B – Detonation
C – Pre-Ignition
Ignition created by pre-ignition extends the total time the burnt gases remain in the cylinder and increases the heat transfer to the chamber walls, resulting in the self-ignition temperature occurring earlier and earlier on each successive compression stroke.

Peak cylinder pressure (which occurs at 10°-15° ATDC) will progressively advance towards TDC where the cylinder pressure and temperature are maximum.
COMBUSTION PROCESS IN SI ENGINES

PRE-IGNITION

- The accumulated effects of an extended combustion time, rising peak cylinder pressure and temperature cause the mixture to attain self-ignition temperature much ahead of TDC.

- Peak cylinder pressure will now take place BTDC so that negative work will be done in compressing the combustion products.
COMBUSTION PROCESS IN SI ENGINES

PRE-IGNITION

Cylinder pressure variation with Pre-Ignition
COMBUSTION PROCESS IN SI ENGINES

ABNORMAL COMBUSTION

- Normally, the flame initiated by the spark travels across the combustion chamber in a uniform manner.
- Under certain operating conditions, the combustion deviates from its normal course leading to loss of performance and possible damage to the engine.
- This type of combustion is termed as Abnormal combustion or knocking combustion.
- The consequences of abnormal combustion process are the loss of power, recurring pre-ignition and mechanical damage to the engine.
COMBUSTION PROCESS IN SI ENGINES
NORMAL & ABNORMAL COMBUSTION

(a) Normal combustion
(b) Normal combustion process
(c) Combustion with detonation
(d) Combustion with detonation process
COMBUSTION PROCESS IN SI ENGINES
NORMAL & ABNORMAL COMBUSTION
COMBUSTION PROCESS IN SI ENGINES
NORMAL & ABNORMAL COMBUSTION

Autoignition theory holds when fuel-air mixture in the end-gas region is compressed to sufficiently high p and T, the fuel oxidation process - starting with the preflame chemistry and ending with rapid energy release - can occur spontaneously in parts or all of the end-gas region.

Detonation theory postulates that under knocking conditions, advancing flame front accelerates to sonic velocity and consumes the end-gas at a rate much faster than would occur with normal flame speeds.
COMBUSTION PROCESS IN SI ENGINES

PROCESS OF DETONATION OR KNOCKING

Refer Fig c and d.

- Flame advances from the spark plug location A.
- This flame front compresses the end charge BB’D farthest from the spark plug raising its temperature.
- The temperature of the end charge also increases due to heat transfer from the hot advancing flame front.
- Some preflame oxidation may take place in end charge leading to further increase in its temperature.
COMBUSTION PROCESS IN SI ENGINES

PROCESS OF DETONATION OR KNOCKING

- If the end charge reaches its auto-ignition temperature and remains for some time to complete the preflame reactions, the charge will auto-ignite leading to knocking combustion.
- During the preflame reaction period the flame front could move from BB’ to CC’, and the knock occurs due to auto-ignition of the charge ahead of CC’.
- Here we have combustion unaccompanied by flame, producing a very high rate of pressure rise.
The ‘intensity of detonation’ will depend mainly upon the amount of energy contained in the ‘end-mixture’ and the rate of chemical reaction which releases it in the form of heat and a high intensity pressure-wave. Thus, the earlier in the combustion process the detonation commences, the more unburnt end-mixture will be available to intensify the detonation. As little as 5 per cent of the total mixture charge when spontaneously ignited will be sufficient to produce a very violent knock.
COMBUSTION PROCESS IN SI ENGINES

SYMPTOMS WHICH CAN HELP TO IDENTIFY THE KNOCK

- Metallic sound in harmony with engine firing
- Sound comes out after long running
- Sound disappears at idle speed
- Drastic drop in fuel efficiency
- Drop in power output
- Engine run with high temperature and noise
COMBUSTION PROCESS IN SI ENGINES

KNOCK – Damaged Components
SI Engine Combustion Chamber
Combustion Chamber

• In diesel and gasoline engines the enclosed space where the combustion of the fuel takes place is called the combustion chamber.

• It is an enclosed volume bound between the cylinder head and the top of the piston.

• The layout and the shape of the combustion chamber depend on the profile of the piston top, the shape of the cylinder head, the location and the arrangements of the inlet and exhaust valves, and the spark plugs.
Combustion Chamber

• The design of the combustion chamber influences the performance of the engine and its anti-knock properties.

• The layout and shape of the combustion chamber has a bearing on the thermal efficiency and performance as well, thus different types of combustion chambers have been designed and used over the years (and still the research is on).

• It must be noted that the design of the combustion chamber is different for the spark ignition and compression ignition engines.
Basic requirements of a good combustion Chamber

- High Power Output
- High thermal efficiency and low specific fuel consumption
- Smooth engine operation
- Reduced exhaust pollutants
High Power Output

- A high compression ratio
- A little rich mixture
- Good Turbulence
- Large inlet valve to achieve good Volumetric Efficiency
- Streamline flow in order to reduce the pressure drop and to increase the volumetric efficiency further
High thermal efficiency and low specific fuel consumption

- A high compression ratio
- A small heat loss during combustion, which means a small surface to volume ratio and a compact shape
- Faster fuel burning process
- A little lean mixture
Smooth engine operation

• A moderate rate of pressure rise during combustion

• Absence of knock, which in turn means,
  – A compact combustion chamber to reduce flame travel distance
  – Proper location of spark plug, exhaust valve and their cooling
Reduced exhaust pollutants

Exhaust pollutants can be reduced by designing a combustion chamber that produces a faster burning rate of fuel. A faster burning chamber with its shorter burning time permits operation with higher EGR, which reduces NOx in the exhaust gas without substantial increase in HC emissions.

• Locating the spark plug to a most central position within a compact combustion chamber
• Using two spark plugs
• Increasing the in-cylinder gas motion by creating swirl during the induction process or during the latter stages of compression
Principle of Combustion Chamber Design

No matter what new innovation the automobile companies claim to have made or any new radical design developed, the principles of combustion chamber design are the same:

• The inlet valve should be as large as possible to achieve a high volumetric efficiency.

• The length the flame has to travel should be as short as possible to avoid detonation of the charge. This would involve the design of the combustion chamber, the location of the spark plugs, and installation of multiple spark plugs to start multiple flame fronts.

• Hot spots that can cause pre-ignition should be avoided by cooling and the location of the spark plug and the exhaust valve. A smaller area of the exhaust valve would offer less chance of hot spots. The small area can be compensated by increasing the
Principle of Combustion Chamber Design

• An optimum degree of turbulence should be provided so that the velocity of the flame propagation is the highest. This would decrease the combustion time and increase the thermal efficiency.

• Cooling has to be optimum, a high degree of cooling would reduce the thermal efficiency and low cooling could lead to pre-ignition or material failure.

• The surface to volume ratio should be least so that loss of heat is avoided and we can get a high thermal efficiency.

• According to the grade of the fuel used the highest compression ratio should be used to increase the thermal efficiency.

• Scavenging must be efficient to reduce exhaust gas dilution.
COMBUSTION CHAMBER DESIGN PRINCIPLES

1. High Volumetric Efficiency

- More charge per stroke and a proportionate increase in power output
- Effective valve open area, which depends on valve diameter and lift
- To reduce pumping losses, valve head should be large (Valve size depends upon head geometry)
2. Minimum path of Flame Travel

- Determined by location of spark plug and shape of the combustion chamber
- A compact CC reduces flame travel
- With a little turbulence, this reduces the time of combustion and minimises the burning time losses.
- Minimum flame travel distance also reduces the knocking tendency
- SI engine cylinder bore is limited to 100mm
3. Provision of minimum heat loss zone around the spark plug

- This ensures good initial combustion conditions
- The spark plug is placed near the exhaust valve to reduce heat loss at the first phase of combustion
- Surface to volume ratio should be minimum
4. Reduced rate of pressure rise

- The second phase of combustion zone should be designed to give a reduced rate of pressure rise to avoid knocking and to avoid excessive shocks on the crankshaft.
5. Provision of a suitable quench region

• Quench region is provided at the farthest distance of flame travel so that cooling of the air-fuel mixture during the most likely knocking period occurs.

• This can be achieved by making the surface to volume ratio high at this location.

• Keeping the cool inlet valve at this location also helps.
6. Maximum Thermal Efficiency

• Maximum thermal efficiency can be achieved by using the highest compression ratio possible for that fuel for smooth engine operation without knocking tendency under all operating conditions.
7. Short combustion time or Fast burn

- This is a very important point to be considered
- Short combustion duration can be achieved by creating turbulence.
- Turbulence helps lean combustion, thus reducing air pollution
- Proper air movement can be created by positioning the inlet valve suitably
**Combustion Chamber Types**

T Head Combustion Chamber: This was used in Ford famous model T car. It was however very successful as it had two cam shafts and the prone to detonation even at a low compression ratio of 4:1. In this T head combustion chamber both the inlet and the exhaust valves are located at the opposite types of the combustion chamber. This type of combustion chamber was common as it those days the fuel available was of octane rating about 45 and highly prone to self igniting. A far and isolated exhaust valve lead to fewer self ignitions.
I Head Combustion Chamber: These were also called Side Valve Combustion Chambers or Flat-heads, and both the inlet and the exhaust valves were placed on side of the engine together. This type of the engine was easier to manufacture and the maintenance was also easy as the complete valve block could be removed for overhaul. However it was prone to detonation as large flame length was large and the air had to take two right turns to reach the combustion space resulting in less turbulence.
F Head Combustion Chamber: In this type of combustion chamber one valve is located in the side pockets and the other is located in the cylinder head. The F head type engine was better than the T head engine but the valve operating mechanism was a bit complicated.
• This is a modification of T head combustion chamber. In this type, both inlet and exhaust valves are provided on the same side of the cylinder and are opened by tappets actuated by a single camshaft.

• It is easy to lubricate the valve mechanism with a detachable head. Cylinder head can be removed for cleaning without disturbing the valves.
HEMI Design

- Exhaust valve
- Exhaust port
- Intake valve
- Spark plug
- Intake port
- Combustion chamber
- Piston
What is a Hemispherical Combustion Chamber

A hemispherical combustion chamber, also known as the HEMI, has a combustion chamber in the shape of a half sphere. The hemispherical combustion chamber has an advantage of cross flow design that allows the engine to breathe better. The hemispherical engines are in use from the early 1900’s and were widely used. The newer style hemispherical combustion chamber is not a true hemisphere but a partial hemisphere. This modification is to give some turbulence to the engine.
**What is a Hemispherical Combustion Chamber**

- The hemispherical combustion chamber generates more power as the air does not have to turn at right angles and the resistance to its motion is less. However, emission problems are more on a hemispherical combustion chamber and hence the new HEMI are only partially hemispherical. The key advantage of a hemispherical combustion chamber is that its surface area to volume ratio is the least in the category compared to other designs like flat head, wedge heads, etc. and therefore they have a superior thermal efficiency than other engines. Also, as the valves are located cross-wise, the valves can be made large resulting in better scavenging or breathing of the engine.
THANK YOU