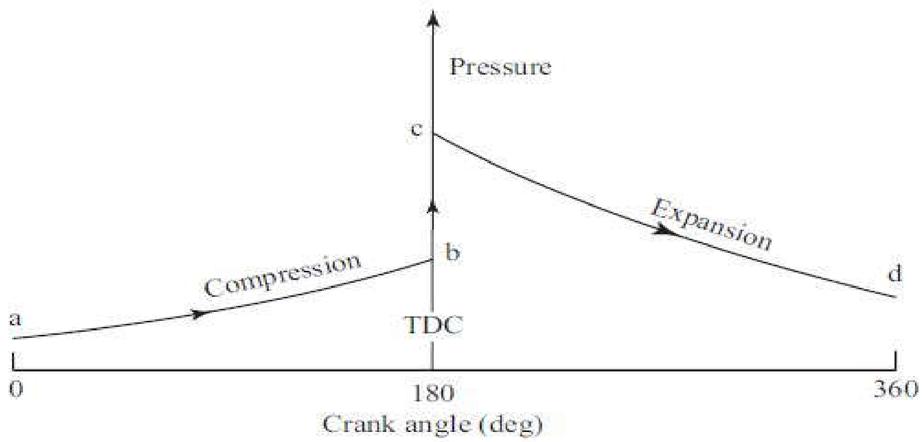
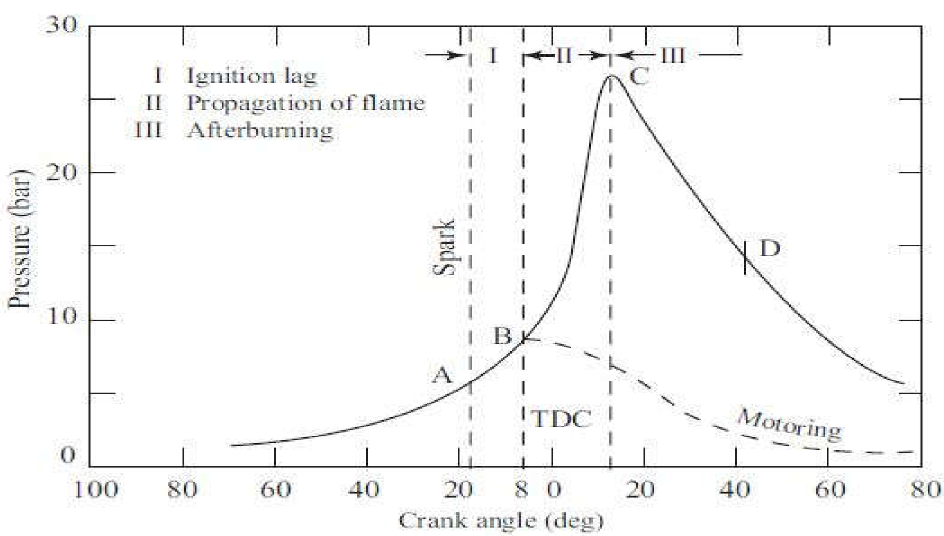
Combustion is a chemical reaction in which certain elements of the fuel like hydrogen and carbon combine with oxygen liberating heat energy and causing an increase in temperature of the gases.
The process of combustion in engines generally takes place either in a homogeneous or a heterogeneous fuel vapour-air mixture depending on the type of engine.

COMBUSTION IN SPARK–IGNITION ENGINES:

Combustion in the SI engine may be broadly divided into two general types, viz., normal combustion and abnormal combustion.
The Pressure-crank angle diagram, during the process of compression (a→b), combustion (b→c) and expansion (c→d) in an ideal four stroke spark-ignition engine is shown in Fig.



Theoretical p-θ diagram



Stages of combustion in an SI engine

The detailed process of combustion in an actual SI engine is described below.
In this figure, A is the point of passage of spark (say 20^{o} bT DC), B is the point at which the beginning of pressure rise can be detected (say 8^{0} bT DC) and C the attainment of peak pressure. Thus AB represents the first stage and BC the second stage and CD the third stage.

On the basis of Recardo experiment, there are three stages of combustion in SI engine as given below:

1. Preparation phase
2. Flame propagation phase
3. After burning

1. Preparation Phase

- The preparation phase is also called a period of ignition lag. This is the first stage in the combustion stages in SI engines. According to the experiment, there is some time interval between the first spark given to the mixture (at point A) and the first flame appears out of the mixture. This time interval is known as ignition lag and it is represented on the above map as period AB. Due to this combustion, there is a clear rise in cylinder pressure.
- This ignition lag represents the preflame reaction.
- During the AB period, the angle changed by the crank between points A and B is known as the ignition delay angle.
- This first phase or preparation phase in stages of combustion in SI engines depends upon the different factors such as the temperature of fuel, pressure, molecular structure of fuel, density and air-fuel ratio in the combustion chamber.

2. Flame Propagation Phase

- When the first flame appears after the spark at point B, this flame travels surrounding and burns the fuel in different layers. This fuel burning rate and flame speed are noticeably low and there is a small but steady pressure rise in the combustion chamber.
- This burning of air and fuel in the combustion chamber continues further and it causes a continuous rise in pressure and temperature. It releases heat energy in the combustion chamber which is transferred from burned to unburned charge. The speed of flame propagation is becoming very high in the range of 15 to 35 m/s.
- The second phase i.e. flame propagation phase starts when the pressure in the combustion chamber starts rising at point B and the phase ends when the highest pressure is achieved in the cylinder at point C on ($P - \theta$) diagram.
- Curve BC on the diagram represents the rate of pressure rise. The rate of heat transfer to the cylinder walls is very low at the beginning of the flame propagation phase. This stage is one the most important stage in the stages of combustion in SI engine.

3. After Burning

- We attained point C in the second stage of the combustion. But, it does not represent the completion of the combustion of the mixture. Because of the continuous burning of the remaining fuels in the cylinder and reassociation of dissociated gases in the combustion chamber.
- During the expansion stroke, the combustion of air and fuel mixture continues after point C. This phase is called after burning. After burning represents the third stage of combustion in SI engine up to point D on ($P - \theta$) diagram.
- During after burning phase, flame velocity reduces to a certain level. This was the last phase of the stages of combustion in SI engine.

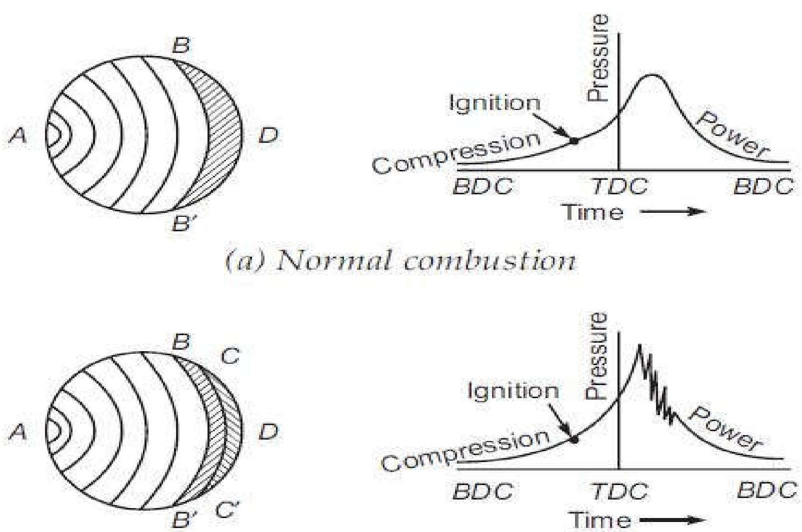
Note:

Motoring curve is Cylinder pressure Vs crank angle curve, which is observed when no firing occurs into the cylinder that means the pressure which build inside the cylinder is basically due to the compression of the fresh air charge going into the cylinder.

Detonation in SI Engine

(Detonation or knocking)

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. Denotation 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) Combustion with detonation

Normal combustion and detonation in SI engine

****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 it's 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.

****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 therefore 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

****Effect 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 vibrate 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 cavitation), 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 heat transfer the power output as well as efficiency of a detonating engine decreases.
6 Pre-ignition: 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.

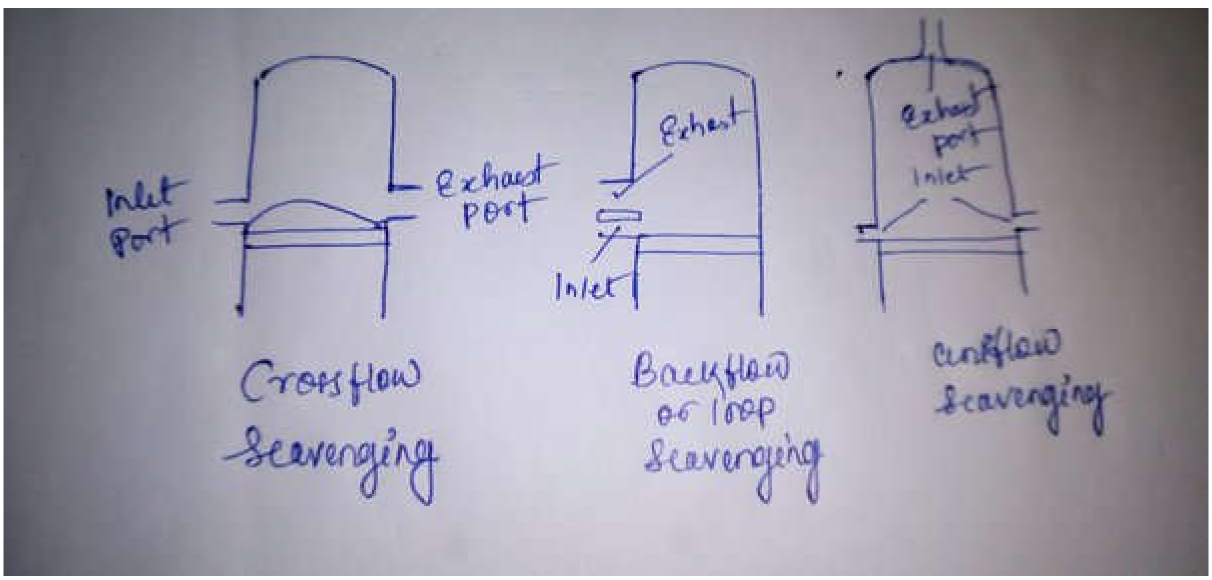
Scavenging:

Scavenging is the process of removing burnt gases out of the combustion chamber for filling the chamber with fresh charge for the subsequent cycle in internal combustion engine. The basic types of scavenging are

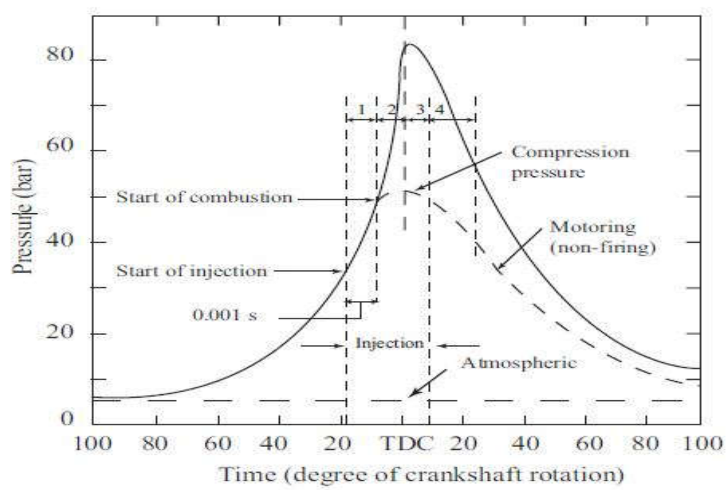
1. **Crossflow Scavenging-** The inlet and exhaust ports are present on the opposite side of the cylinder.

2. **Backflow or loop Scavenging-** The inlet and exhaust port are present on the same side of the cylinder.

3. **Uniflow Scavenging-** Inlets are present either in one or both side of the cylinder and the exhaust is present on the top of the cylinder.



***Stages of combustion in CI engine:**



Stages of combustion in a CI engine

There are four different stages of combustion in CI engine where proper combustion of air and fuel takes place as follows:

1. Ignition Delay Period
2. Period of Uncontrolled Combustion
3. Period of Controlled Combustion
4. After Burning

1. Ignition Delay Period

- At this first stage of combustion in the CI engine, the fuel from the injection system sprayed in the combustion chamber in the form of a jet. Due to atomization and vaporization, this fuel disintegrates at the core which is surrounded by a spray of air and fuel particles.
- In this vaporization process, the fuel gets heat from the compressed and hot surrounding air.
- After completion of the vaporization process, the *preflame reaction* of the mixture in the combustion chamber starts. During the preflame reaction, pressure into the cylinder starts increasing with the release of energy at a slow rate.
- This preflame reaction starts slowly and then speeds up until the ignition of the fuel takes place. You can see this process at point C on the diagram.
- This time interval between the starting of the fuel injection and the beginning of the combustion is called the ***delay period***. This delay period can further be divided into two parts – Physical delay and chemical delay.
- The period between the time of injection of the fuel and its achievement of self-ignition temperature during vaporization is called physical delay.

- When physical delay completes, the time interval up to the fuel ignites and the flame of the combustion appears is called chemical delay.

If this delay period performs longer than usual, then we can here knocking in CI engine.

2. Period of Uncontrolled Combustion

This is the second stage of combustion in the CI engine. After the above-mentioned delay period is over, the air and fuel mixture will auto-ignite as they have achieved their self-ignition temperature.

The mixture of air and fuel in CI engines is heterogeneous unlike homogeneous in the SI engines. Due to this heterogeneous mixture, flames appear at more than one location where the concentration of the mixture is high.

When the flame formed the mixture in the other low concentration starts burning by the propagation of flames or due to auto-ignition, because of the process of heat transfer.

The accumulated fuel during the delay is now started burning at an extremely rapid rate. It causes a rise in in-cylinder pressure and temperature. So, the higher the delay period, the higher would be the rate of pressure rise.

During this stage, you can't control the amount of fuel burning, that's why this period is called a *period of uncontrolled combustion.*

3. Period of Controlled Combustion

When the accumulated fuel during the delay period completely burned in the period uncontrolled combustion, the temperature and pressure of the mixture in the cylinder are so high that new injected fuel from the nozzle will burn rapidly due to the presence of sufficient oxygen in the combustion chamber.

That's the reason we can control the rise of pressure into the cylinder by controlling the fuel injection rate. Therefore, this period of combustion is called a period of controlled combustion

4. After Burning

This is the last stage out of the four stages of combustion in CI engine.

Naturally, the combustion process is completed at the point when the maximum pressure is obtained in the combustion chamber at point E as shown in the figure.

Practically, the burning of the fuel in the combustion chamber remains to continue during the expansion stroke. The main reason behind it is the *reassociation of dissociated gases* and unburnt fuel.

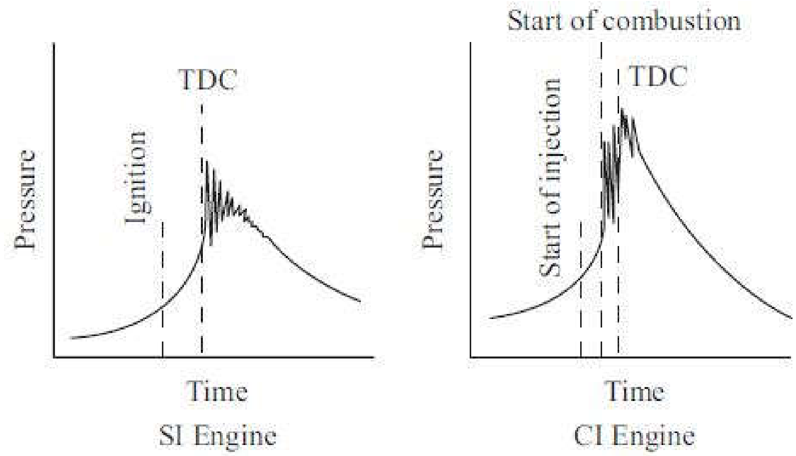
Therefore, this last phase of combustion is called After Burning.

Knocking in CI engines:

- In spark ignition engines (SI engines), at the end part of the gas, if flame speed and delay period are low in the combustion chamber, produce detonation in SI engine. In the case of the CI engine, it was the first part of the gas which causes the Knocking in CI engine and rough running of the engine.
- In CI engines, when fuel is injected in the combustion chamber and combustion occurs by the way of the auto ignition system. When the period of injection of fuel is long, an excess amount of fuel starts to inject in the combustion chamber. Then there is a large amount of fuel accumulates in the combustion chamber due to longer injection of fuel or delay period.
- When there is uncontrolled combustion, the amount of fuel accumulated in the combustion chamber suddenly explodes. It increases the rate of pressure rise in the

combustion chamber and ultimately high pressure. This high rate of pressure rise in the internal combustion engine is equivalent to a sudden increase in load on the engine.

- Also high and increasing pressure of gases in the chamber affects the whole engine structure during the pressure equalization process. Due to this, you will hear a thudding sound from the engine, the same sound is called Knock or Knocking in CI engine.
- From the above explanation, we can conclude that the knocking in CI engines occurs if the delay period of injection is longer than the usual condition.



Diagrams illustrating knocking combustion in SI and CI engines