

Module – III Combustion

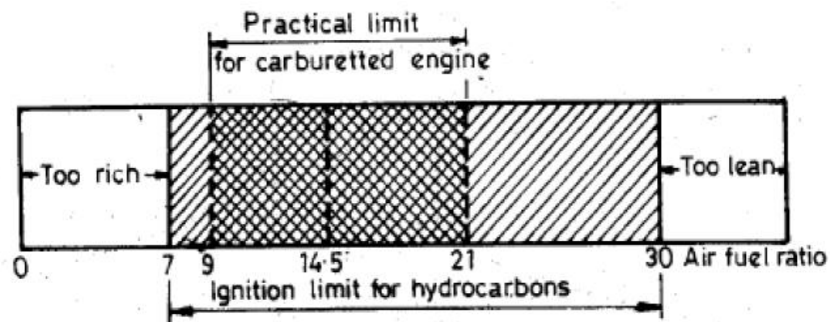
Combustion may be defined as a relatively rapid chemical combination of hydrogen and carbon in fuel with oxygen in air resulting in liberation of energy in the form of heat. Following conditions are necessary for combustion to take place:

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

In SI 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.



Stages of SI engine combustion

In SI engine homogeneous mixture of vaporised fuel, air and residual gases is ignited by a single intense and high temperature spark between the spark plug electrode (electrodes exceeds 10,000 °C) and generate pre-flame which spreads to envelope of mixture for combustion.

Three stages of combustion in SI engine are,

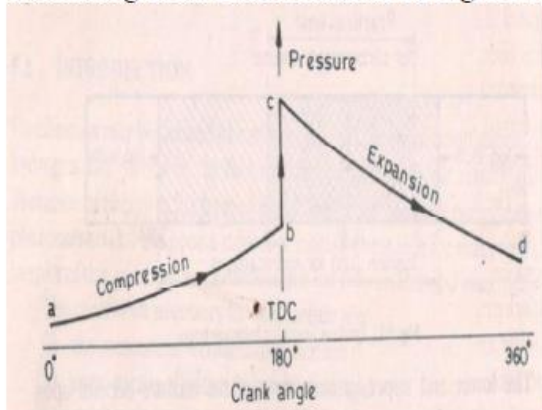


Fig. 24. Theoretical p-θ diagram

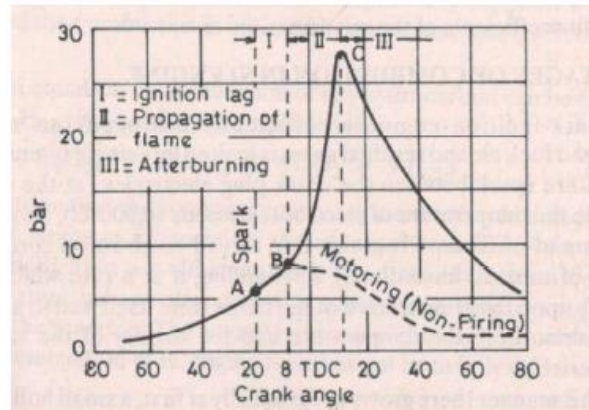


Fig. 25. Stages of combustion in SI engine

I-Ignition lag or preparation phase (AB):

- growth and development of a semi propagating nucleus of flame
- chemical process depending upon the nature of the fuel, upon both temperature and pressure, the proportion of the exhaust gas, and also upon the temperature coefficient of the fuel, that is, the relationship of oxidation or burning
- point A shows the passage of spark and point B is the first rise of pressure
- ignition lag is generally expressed in terms of crank angle
- Ignition lag is very small and lies between 0.00015 to 0.0002 seconds
- 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

II-propagation of flame (BC):

- Period from the point B where the line of combustion departs from the compression line to point C, the maximum rise of pressure in P- θ diagram
- flame propagates at the constant velocity
- Heat transfer to the cylinder wall is low
- rate of heat release depends upon the turbulence intensity and reaction rate

III-After burning (CD):

- After point C, the heat release is due to the fuel injection in reduced flame front after the starts of expansion stroke
- no pressure rise during this period

***Effect of engine variables on Ignition lag**

Fuel: High self-ignition temperature of fuel longer the ignition lag.

Mixture ratio: mixture richer than the stoichiometric ratio provide shorter ignition lag

Initial temperature and pressure: increasing the intake temperature and pressure, increasing the compression ratio, chemical reaction rate and retarding the spark all reduce the ignition lag

Electrode gap: lower the compression ratio and higher the electrode gap is desirable

-voltage required at the spark plug electrode to produce spark is found to increase with decrease in fuel-air ratio and with increase in compression ratio and engine load

Turbulence: directly proportional to engine speed

-engine speed does not affect much ignition lag measured in milliseconds

-but ignition lag increases linearly with engine speed when measured in degree crank angle

-spark advance is desirable in higher engine speed

***Effect of engine variables on flame propagation**

Rate of flame propagation affects the combustion process in SI engines. Higher combustion efficiency and fuel economy can be achieved by higher flame propagation velocities. Unfortunately flame velocities for most of fuel range between 10 to 30 m/second.

The factors which 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 and also results in production of less heat and flame speed remains low.

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 above 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 SI 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.

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 characteristic of all petrol engines.

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 which 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.

***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.

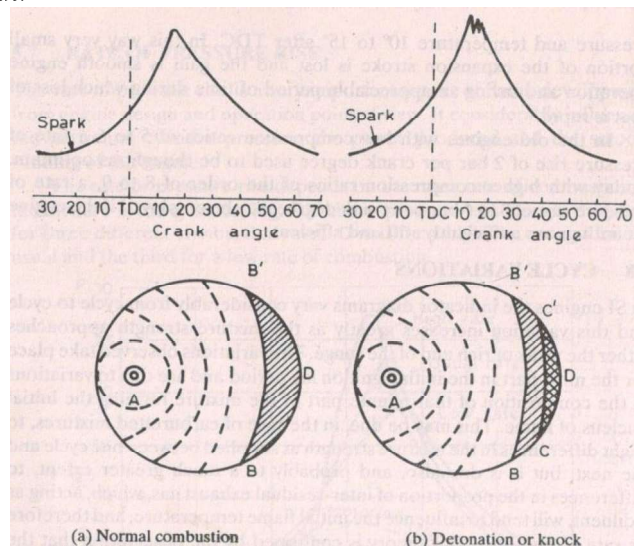


Fig. 26. Detonation in SI engine

***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 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.

***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.

***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 SI engine, 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 which 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 which 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 :

(i) Molecular Structure: The knocking tendency is markedly affected by the type of the fuel used. Petroleum fuels usually consist of many hydro-carbons 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.

-Centralising the carbon atoms decreases the knocking tendency.

-Adding methyl group (CH 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 C and C

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.

(ii) 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.

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

*SI engine combustion chamber

- (a) T-head combustion chamber: 2 cam shaft, prone to detonation, average octane number 45-50
- (b) I-head or side valve combustion chamber:
 - lack of turbulence
 - extremely sensitive to ignition timing
 - prone to detonation
- (c) F-head combustion chamber:
 - Compromise between I-head and L-head

*Stages of combustion in CI engine

1. Ignition delay period:

The period between the start of fuel injection into the combustion chamber and the start of combustion is termed as ignition delay period. The start of combustion is determined from the change in slope on p- θ diagram or from heat release analysis of the p- θ data, or from luminosity detector in experimental conditions. Start of injection can be determined by a needle-lift indicator to record the time when injector needle lifts off its seat. Start of combustion is more difficult to determine precisely. It is best identified from the change in slope of heat release rate, determined from cylinder pressure data. In DI engines ignition is well defined, in IDI engines ignition point is harder to identify

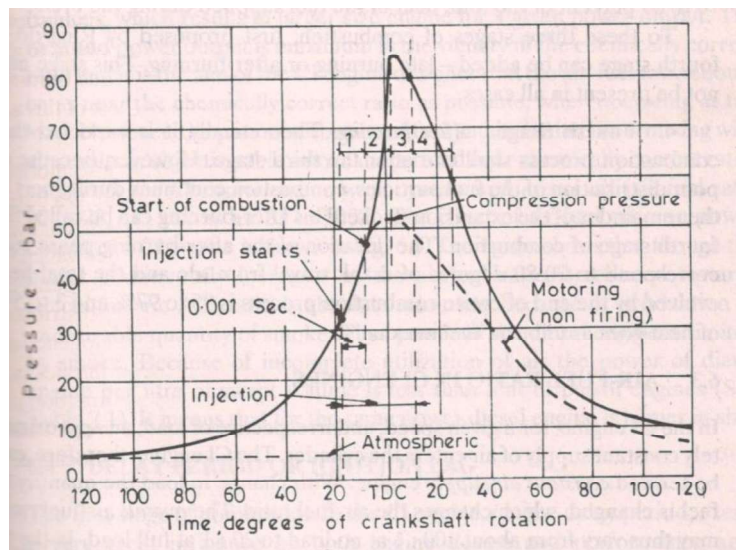


Fig. 27. Stages of combustion in CI engine

Both physical and chemical processes must take place before a significant fraction of the chemical energy of the injected liquid is released.

Physical processes are fuel spray atomization, evaporation and mixing of fuel vapour with cylinder air.

Good atomization requires high fuel-injection pressure, small injector hole, optimum fuel viscosity, high cylinder pressure (large divergence angle).

Rate of vaporization of the fuel droplets depends on droplet diameter, velocity, fuel volatility, pressure and temperature of the air.

Chemical processes similar to that described for auto ignition phenomenon in premixed fuel-air, only more complex since **heterogeneous reactions** (reactions occurring on the liquid fuel drop surface) also occur.

Chemical delay is more effective for the duration of the ignition delay period.

Ignition delay period is in the range of

0.6 to 3 ms for low-compression ratio DI diesel engines,

0.4 to 1 ms for high-compression ratio, turbocharged DI diesel engines,

0.6 to 1.5 ms for IDI diesel engines

2. Rapid or uncontrolled or pre-mixed combustion phase:

Combustion of the fuel which has mixed with air within flammability limits during ignition delay period occurs rapidly in a few crank angle degrees - high heat release characteristics in this phase. If the amount of fuel collected in the combustion chamber during the ignition delay is much - high heat release rate results in a rapid pressure rise which causes the diesel knock.

For fuels with low cetane number, with long ignition delay, ignition occurs late in the expansion stroke - incomplete combustion, reduced power output, poor fuel conversion efficiency. If the pressure gradient is in the range $0.4 - 0.5 \text{ MPa}/^\circ\text{CA}$, engine operation is not smooth and diesels knock starts. This value should be in the range 0.2 to $0.3 \text{ MPa}/^\circ\text{CA}$ for smooth operation (max allowable value is $1.0 \text{ MPa}/^\circ\text{CA}$) of the engine.

3. Controlled or diffusion combustion phase:

Once the fuel and air which is pre-mixed during the ignition delay is consumed, the burning rate (heat release rate) is controlled by the rate at which mixture becomes available for burning. The rate of burning in this phase is mainly controlled by the mixing process of fuel vapour and air. Liquid fuel atomization, vaporization, pre flame chemical reactions also affect the rate of heat release.

Heat release rate sometimes reaches a second peak (which is lower in magnitude) and then decreases as the phase progresses. Generally it is desirable to have the combustion process near the TDC for low particulate (soot) emissions and high performance (and efficiency).

4. After burning or late combustion phase:

Heat release rate continues at a lower rate into the expansion stroke -there are several reasons for this: a small fraction of the fuel may not yet burn, a fraction of the energy is present in soot and fuel-rich combustion products and can be released. The cylinder charge is non-uniform and mixing during this phase promotes more complete combustion and less dissociated product gases. Kinetics is slower.

*** Variables affecting delay period**

(i) Cetane number

Both physical and chemical properties of the fuel are important. Ignition quality of the fuel is defined by its cetane number. Straight chain paraffinic compounds (normal alkanes) have

highest ignition quality, which improves as the chain length increases. Aromatic compounds, alcohols have poor ignition quality.

-Cetane number can be increased by ignition-accelerating additives like organic peroxides, nitrates, nitrites and various sulphur compounds. Most important (commercially) is alkyl nitrates – about 0.5% by vol in a distillate fuel increase CN by 10.

-Normal diesel fuel has CN of 40 to 55 (high speed 50 – 60, low speed 25 – 45)

(ii) Injection timing

-At normal operating conditions min ignition delay (ID) occurs with start of injection at 10 to 15 °CA BTDC

-Cylinder temperature and pressure drops if injection is earlier or later (high at first but decrease as delay proceeds)

(iii) Injection quantity (load)

-Reducing engine load changes AFR, cools down the engine, reduces wall temperatures, reduces residual gas temperatures and increase ID

-Droplet size, injection velocity and rate Ignition quality within practical limits do not have significant effect on ID

-Increase in injection pressure produces only modest decrease in ID Injector nozzle diameter

-effects of droplet size but has no significant effect on ID

(iv) Intake air temperature and pressure

-Reducing intake air T and p increase ID

-Strong dependence of ID on charge temperature below 1000 K – above this value effect of intake air conditions is not significant.

(v) Engine speed

Increase in engine speed increases the air motion and turbulence, reduces ID time slightly (in ms), in terms of CA degrees ID increases almost linearly.

-A change in engine speed, changes “temp~time” and “pressure~time” relationships

(vi) Combustion chamber design

-Spray impingement on the walls effect fuel evaporation and ID increase in compression ratio, increase p and T and reduces ID

-Reducing stroke volume, increase surface area to volume ratio, increase engine cooling and increase ID

(vii) Swirl rate

-Change of evaporation rate and air-fuel mixing - under normal operating conditions the effect is small.

-At start-up (low engine speed and temperature) more important, high rate of evaporation and mixing is obtained by swirl

(viii) Oxygen concentration

Residual gases reduce O₂ concentration and reducing oxygen concentration increases ID

***Diesel knock**

-CI engine detonation occurs in the beginning of combustion

-In CI engine the fuel and air are imperfectly mixed and hence the rate of pressure rise is normally cause audible knock. Rate of pressure rise may reach as high as 10 bar/°CA

- High engine vibration is the symptoms of knocking
- no pre-ignition or premature ignition as like SI engine

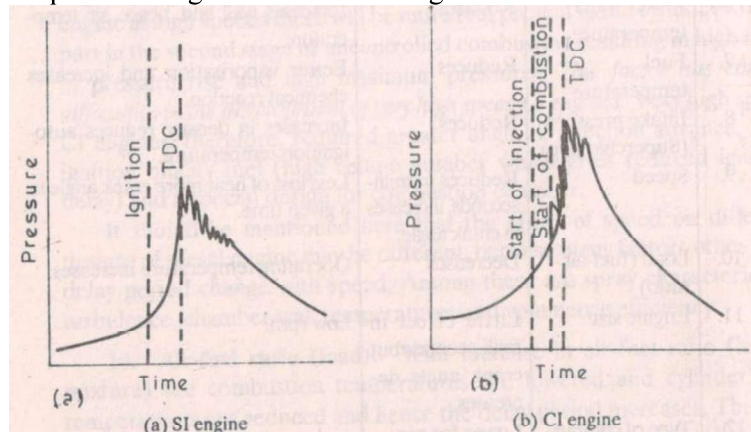


Fig. 28. Detonation in SI and CI engine

***Combustion chamber**

(i) According to the swirl of air

- (a) Induction swirl or open chamber or non-turbulent chamber
- (b) Compression swirl
- (c) Combustion induced swirl

(ii) According to speed of the engine

(a) Low speed engine ($n < 1500$ rpm):

- Shallow, swirl-less combustion chambers
- Direct, multi-jet fuel injection

(b) Medium speed engine ($n = 1500-3000$ rpm):

- Deep combustion chambers with intensive swirl of charge
- Direct injection of atomised fuel

(c) high speed engine ($n = 3000-5000$ rpm):

- Pre-chambers (sectional combustion chambers)
- Indirect injection of fuel into the pre-chamber