APPLIED THERMODYNAMICS

Internal Combustion Engines
(Module III)

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List of Topics

1. Internal Combustion Engine – Components, Nomenclature and Classifications
2. Basic Engine Cycle and Engine Kinematic Analysis
3. Engine Operating Characteristics
4. Thermodynamic Analysis of Air Standard Cycles
5. Valve Timing Diagram and Fuel – Air Cycle
6. Thermochemistry and Fuel Characteristics
7. Combustion Phenomena in Engines
8. Heat Transfer Analysis in Engines
9. Exergy Analysis and Engine Emission/Pollution

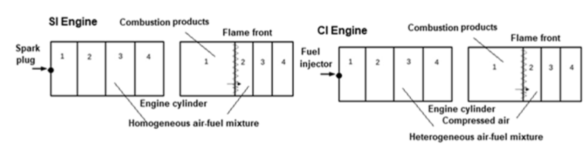
Lecture 7

Combustion Phenomena in Engines

- Homogeneous Mixture Combustion
- Heterogeneous Mixture Combustion
- Combustion Mechanism in SI Engines
- Combustion Mechanism in CI engines

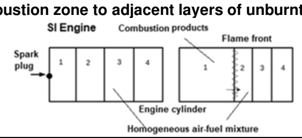
Homogeneous Mixture Combustion

- The combustion mechanism in an engine is a complex process which is understood through correlation of broad operating parameters such as pressure, temperature, fuel, knock characteristics and engine speed.
- The conditions necessary for the combustion are the presence of combustible mixture with some means of ignition process.
- The process of combustion in engines takes place either in a homogeneous or a heterogeneous fuel vapour-air mixture depending on type of engine.



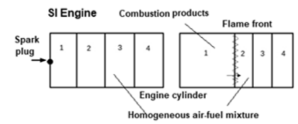
Homogeneous Mixture Combustion

- In SI engines, a nearly homogeneous mixture of air and fuel is formed in the carburetor which is outside the engine cylinder. The combustion is initiated inside the cylinder through a spark-plug ignition at a particular instant towards end of compression stroke.
- A flame-front is generated that spreads over the combustible mixture (with fuel and oxygen molecules uniformly distributed) with certain velocity. Typically, the flame-front is visualized as an imaginary partition that separates fresh mixture from combustion products.
- The velocity with which flame-front moves with respect to the unburnt mixture in a direction normal to the surface is called as normal flame velocity.
- The flame propagation is caused by heat transfer and diffusion of burning fuel molecules from combustion zone to adjacent layers of unburnt mixture.



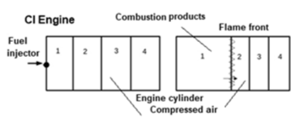
Homogeneous Mixture Combustion

- The conditions necessary for the combustion are the presence of combustible mixture with some means of ignition process.
- Ideally, for homogeneous mixture with equivalence ratio close to stoichiometric value, the flame speed is observed as 0.4 m/s. The maximum flame speed is observed for rich mixture (equivalence ratio 1.1 to 1.2).
- When the flame speed drops to a low value (lower equivalence ratio), the heat loss from combustion zone becomes equal to amount heat release due to combustion and the flame gets extinguished.
- By incorporating turbulence and incorporating proper air movement, the flame speed can be increased in mixture outside above range.



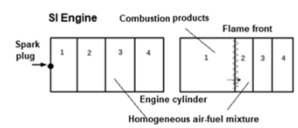
Heterogeneous Mixture Combustion

- The rate of combustion is determined by the velocity of mutual diffusion of fuel vapours and air while rate of chemical reaction is of minor importance.
- Self ignition or spontaneous ignition of fuel-air mixture at high temperature due to high CR is the prime importance of combustion characteristics.
- With heterogeneous mixture of varying equivalence ratio (1 to 1.2) in local zones, combustion can be initiated with overall lean fuel. The ignition can start with fuel-rich zone and the flame produced by this process, helps to burn the fuel in the adjoining zones where the mixture is leaner.
- In the zones where the mixture is rich, the combustion occurs because of high temperature produced due to initiation of the combustion.
- This is the mechanism of combustion phenomena in CI engine which is different from SI engine.



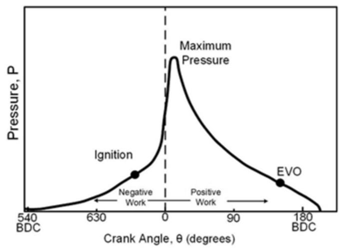
Combustion Mechanism in SI Engines

- In an SI engine, the combustion ideally consists of an exothermic subsonic flame progressing through premixed air-fuel mixture which is locally homogeneous.
- The spread of flame front is increased by induced turbulence and swirl in the cylinder. The right combination of fuel and operating characteristics is such that 'knock' is avoided.
- There are three broad regions for SI engine combustion process:
  - ➢ Ignition and flame development
  - ➢ Flame propagation
  - ➢ Flame termination



Combustion Mechanism in SI Engines

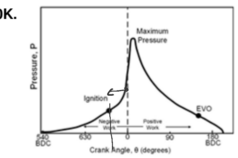
- Cylinder pressure in the combustion chamber of an SI engine can be plotted as a function of crank angle.
- The increase in pressure rise is very slow after ignition during the flame development period.
- This result in a slow pressure force increase on the piston and a smooth engine cycle. The maximum pressure occurs 5° to 10° aTDC.



Combustion Mechanism in SI Engines

Ignition and flame development

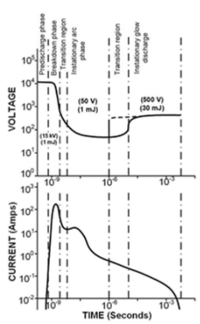
- The flame development is generally considered as the consumption of first 5% of air-fuel mixture. During this period, the ignition occurs and the combustion process starts with a little noticeable pressure rise. No useful work is produced.
- The combustion is initiated by an electric discharge across the electrodes (separated by a gap 0.7-1.7 mm) of a spark plug anywhere from 10-30° bTDC.
- The high temperature plasma discharge between electrodes ignites the fuel-air mixture in its vicinity and the combustion spreads outwards.
- The flame can be detected at about 6° crank rotation after spark plug firing. As an estimate, the applied voltage potential is about 25-40 kV with a maximum current of 200 amps, lasting for about 10^{-9}s. The peak temperature is about 60000K and the spark lasts for about 1ms with average temperature of 6000K.



Combustion Mechanism in SI Engines

Ignition and flame development

- Spark plug voltage and current as a function of time for ignition in a typical SI engine.
- A stoichiometric air-fuel mixture requires about 0.2 mJ of energy to ignite self-sustaining combustion.
- Normal quasi-steady-state temperature of spark plug electrodes between firing is about 650-700°C.
- Maximum voltage can be greater than 40,000 volts, with a maximum current on the order of 200 amps lasting for about 10^{-8} seconds.
- The total energy delivered during one discharge is generally about 30 to 50 mJ.



Combustion Mechanism in SI Engines

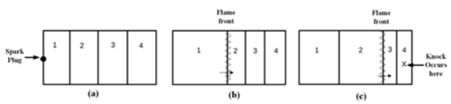
Flame propagation

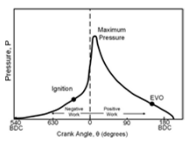
- After the combustion process is well established by flame development, the induced turbulence, swirl and squish, additionally provide a flame propagation speed 10-times faster than it were a laminar flame front moving through a stationary gas mixture. Moreover, the ideal spherical flame front greatly distorted and spread by these motion.
- During this period, the bulk of fuel-air mixture (around 80-90%) is burnt and the pressure in the cylinder is significantly increased, providing the force to produce work in the expansion stroke.
- All useful work produced in the engine cycle is the result of flame propagation period of the combustion process.
- The burnt gases behind the flame front are hotter than the unburnt gases with all of them about same pressure. It decreases the density of burnt gases and expands them to occupy greater percent of total combustion volume.

Combustion Mechanism in SI Engines

Flame propagation

- SI engine combustion chamber schematically visualized as long hollow cylinder with the spark plug located at left end.
  - (a) Mass of air-fuel is equally distributed as spark plug is fired to start combustion
  - (b) As flame front moves across chamber, unburned mixture in front of flame is compressed into smaller volume.
  - (c) Flame front continues to compress unburned mixture into smaller volume, which increases its temperature and pressure.
  - (d) If compression raises temperature of end gas above SIT, self ignition and knock can occur.

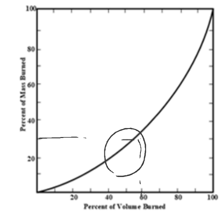


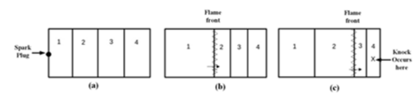


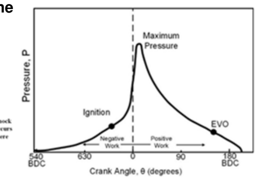
Combustion Mechanism in SI Engines

Flame propagation

- From the figure, it can be seen that when 30% of gas mass is burnt, they already occupy 60% of total volume. Subsequently, they compress about 70% of mixture that is not yet burned into 40% of total volume and their temperature rises through compressive heating.
- During this period, the bulk of fuel-air mixture (around 80-90%) is burnt and the pressure in the cylinder is significantly increased, providing the force to produce work in the expansion stroke.



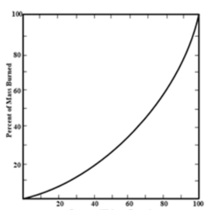


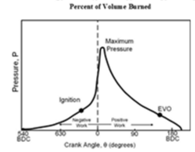


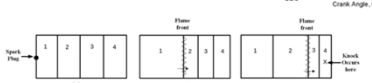
Combustion Mechanism in SI Engines

Flame propagation

- All useful work produced in the engine cycle is the result of flame propagation period of the combustion process.
- The burnt gases behind the flame front are hotter than the unburnt gases with all of them about same pressure. It decreases the density of burnt gases and expands them to occupy greater percent of total combustion volume.
- When the flame moves through the combustion chamber, it travels through an environment of increase of pressure and temperature that causes the chemical reaction time to decrease at increased speed of flame.



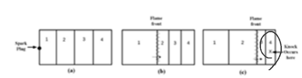


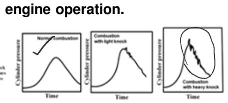


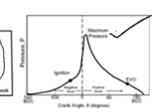
Combustion Mechanism in SI Engines

Flame propagation

- The radiation (at about 3000K) emitted from flame reaction zone, boost up the further heat for all charges in the combustion chamber, reaching a maximum at the end of combustion process.
- Ideally, the two-third air-fuel mixture should be burnt at TDC and almost completely at about 15ºaTDC so that the maximum pressure and temperature occurs 5-10ºaTDC.
- It is expected to have maximum pressure rise about 240 kPa per degree engine rotation desirable for smooth transfer force on piston face.
- A lesser pressure rise (i.e. slower combustion) rate lowers thermal efficiency and danger for knock. So, the combustion process is a compromise between highest thermal efficiency and a smooth engine cycle with some loss in efficiency.
- Actual cycle does not really follow a constant volume process as approximated in Otto cycle. A true constant volume combustion would result pressure curve an infinite upward slope at TDC, resulting rough engine operation.



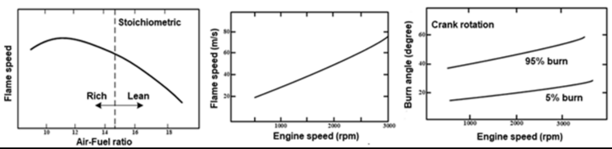




Combustion Mechanism in SI Engines

Flame propagation

- The flame speed increases with engine speed due to higher turbulence and swirl. The flame speed also depends on air-fuel ratio. Lean mixtures have slower flame speed while slightly rich mixtures have fastest speed at equivalence ratio of 1.2. Exhaust residuals and recycle gases normally slows down the flame speed. As the engine speed increases, the intensity of turbulence, swirl, squish and tumble increases resulting faster flame speed.
- If ignition occurs too early, cylinder pressure will increase to undesirable level (waste of work during compression) and late ignition will not lead to higher peak pressure (with loss of work in power stroke).



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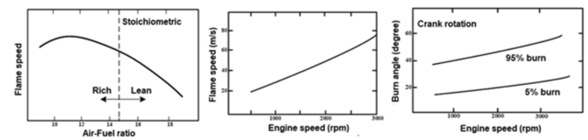
Combustion Mechanism in SI Engines

Flame propagation

- "Burn angle" is another parameter, that quantifies the angle through which the crankshaft turns during the flame propagation mode (typically, 25°: ignition at 10°bTDC and complete combustion at 15°aTDC).
- The increase in angle of ignition and flame development period (5 % burn) is mainly due to due to constant spark ignition process in real time.
- During flame propagation (5% to 95% burn), both combustion and engine speed increases resulting fairly constant burn angle.



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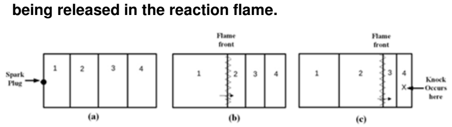
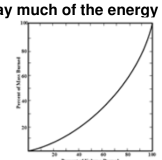
Combustion Mechanism in SI Engines

Flame termination

- The final 5% of air-fuel mass burns as flame termination period during which the pressure quickly drops indication completion of combustion process.
- The flame front has reached almost extreme corner of combustion chamber.
- At this point, the piston has already moved away from TDC while combustion chamber volume has increased only of the order of 10-20% of clearance volume.
- Thus, the last end mass of air and fuel will react in a very small volume at the corners of combustion chamber along its wall at reduced rate.
- There are two main cause of reduced rate of reaction near the wall; firstly, the stagnant boundary layer dampens out the induced turbulence of gas mixture; secondly, the metal walls act as heat sink and conducts away much of the energy being released in the reaction flame.





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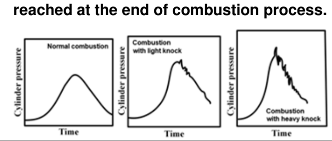
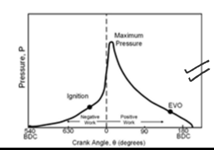
Combustion Mechanism in SI Engines

Flame termination

- The cylinder pressure tapers off slowly towards zero during flame termination. Thus, the forces transmitted to the piston slows down resulting in smooth engine operation.
- Self ignition may occur in the end gas in front of flame front, resulting 'knock'. It is mainly because, the temperature of unburnt gases could rise, reaching a maximum in the last end of the gas. Since, the flame front moves slowly at this time, the gases are not consumed during ID period and self-ignition occur.
- Maximum power of the engine is obtained when it operates with very slight self-ignition and knock occurs at the end of combustion i.e. knock could provide additional pressure boost after the maximum pressure and temperature is reached at the end of combustion process.





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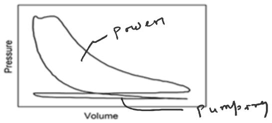
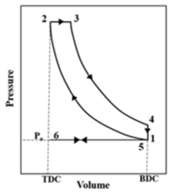
Combustion Mechanism in CI Engines

- Combustion in CI engine is quite different from that of SI engine (where the flame front moves through a locally homogeneous mixture). The combustion phenomena is an unsteady occurring simultaneously at many stops in a very non-homogeneous mixture at a rate controlled by fuel injection.
- Air intake to the engine is un-throttled, while the engine torque and power output controlled by the amount of fuel injected per cycle. The pressure in the intake manifold is consistently close to atmospheric pressure which means the pump work loop of engine cycle is very small.
- The net work output is saved for CI engine as compared with SI engine operation at part-throttled condition. It implies better thermal efficiency as compared with SI engine.





$$W_{net} = W_{gross} - W_{pump} \approx W_{gross}$$

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Combustion Mechanism in CI Engines

- Only air is contained in the cylinder during compression stroke for which higher CRs (around 12 to 24) can be incorporated.
- Although, CI engines have higher fuel conversion efficiencies, but they are operated with quite lean mixture (equivalence ratio of 0.8). It means less brake power output for a given engine displacement.
- Fuel is injected into the cylinder late in the compression stroke by one or more fuel injectors located in each cylinder for about 20° crank rotation (starting at 15°bTDC and ending at 5°aTDC) with ignition delay fairly constant.
- Thus, a high injection velocity of the fuel is required so that the fuel can spread throughout the cylinder, cause it to mix with the air.
- After injection, the fuel must go through the series of events of proper combustion process:
  - Atomization → Vapourization → Mixing→ Self ignition → Combustion

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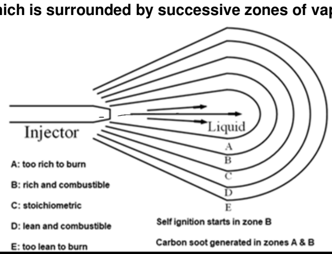
Combustion Mechanism in CI Engines

Atomization

- The fuel drops released from the injector, break into very small droplets. The typical nozzle diameter of fuel injector is 0.2 mm to 1 mm and velocity of fuel leaving the nozzle is 100–200 m/s. The fuel droplet diameter is about 10 µm.
- The atomization process becomes quicker and efficient if the original droplet size emitted by the injector is very small.
- Fuel jets from the injector of CI engine has air-fuel vapour zones around the inner liquid core which is surrounded by successive zones of vapour.



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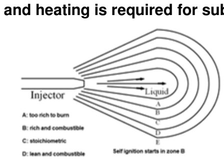
Combustion Mechanism in CI Engines

Vaporization

- The small liquid fuels evaporate to form vapour and it occurs very quickly due to hot air temperature in compression process. Hence, the minimum compression ratio for CI engines are kept at 12.
- About 90% fuel gets vaporized during 1ms after injection. As the first fuel evaporates, the immediate surroundings are cooled by evaporative cooling. It affects greatly the subsequent evaporation.
- Near the core region of fuel jet, the combination of high fuel concentration and evaporative cooling causes adiabatic saturation of fuel. Hence, the evaporation stops in this region.
- Additional mixing and heating is required for subsequent fuel drop evaporation.



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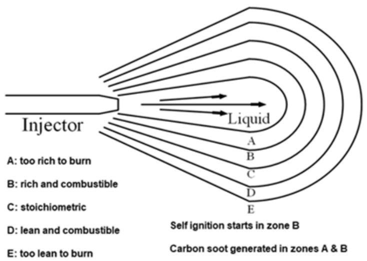
Combustion Mechanism in CI Engines

Mixing

- The fuel vapours must mix with air to form a combustible mixture within desired range of equivalence ratio (0.8 to 1.8).
- Mixing mechanism adds swirl and turbulence of high fuel injection velocity with air in the cylinder.
- Hence, there is non-homogeneous distribution of air-fuel ratio around the injected fuel jet.



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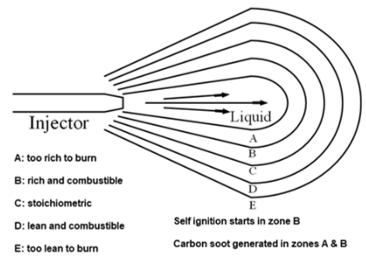
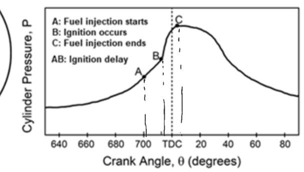
Combustion Mechanism in CI Engines

Self-Ignition

- The mixture self ignites at about 8ºbTDC (6º- 8º after start of injection).
- Actual combustion is preceded by secondary reactions, including breakdown of large hydrocarbon molecules into smaller species with oxidation.
- The reactions caused by high temperature air are exothermic and further rises air temperature in the immediate local vicinity. It leads to sustained actual combustion process.





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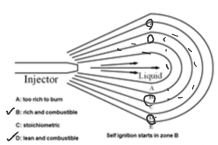
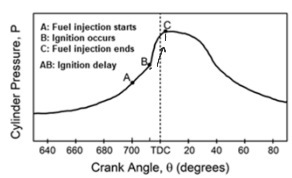
Combustion Mechanism in CI Engines

Combustion

- At this state, about 75-95% of fuel in the combustion chamber is in vapour state. There is non-homogeneous air-fuel mixture at different regions (A to E) in the combustion chamber at varied equivalence ratio (1.8 to 0.8).
- The combustion starts through self-ignition simultaneously at many locations in slightly rich zone (1 to 1.5) of fuel jet (typically zone 'B').
- Multiple flame fronts spreading from many self-ignition sites quickly consume all gas mixtures at correct air-fuel ratio and subsequently move to other regions where self-ignition is not possible. It produces very quick rise in pressure and temperature as shown in figure (B to C).





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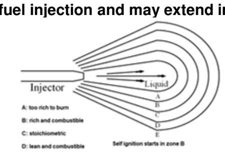
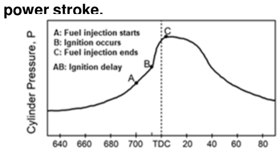
Combustion Mechanism in CI Engines

Combustion

- The higher temperature and pressure reduces vaporization time and ignition delay time. Since liquid fuel particles are continuously injected, the reduction of these times, additionally generates more self-ignition points in the combustion chamber.
- After initial start of combustion, the rest of combustion process is controlled by the rate at which fuel can be injected, atomized, vapourized and mixed into proper air-fuel mixture. The path B-C can be controlled by the rate of combustion and fuel injection rate.
- The combustion lasts for about 40º-50º of engine rotation, much longer than the 20º of fuel injection and may extend into the power stroke.





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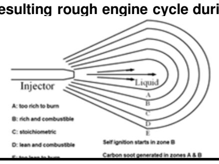
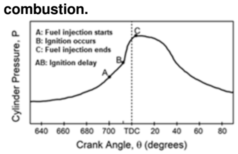
Combustion Mechanism in CI Engines

Combustion

- The pressure remains high until the piston is at 30°-40° aTDC. About 60% of the fuel is burnt in one-third combustion time. The burning rate increases with engine speed so that the 'burn angle' remains constant. In the main part of the combustion process, 10-35% of fuel vapour in the cylinder is combustible.
- The average engine speed strongly correlates with inverse of stroke length. Thus, the average piston speed in all engines is in the range of 5–20 m/s. So, the combustion process is generally favoured to cater these speed ranges.
- If the cetane number of fuel is too low, the greater amount of fuel will be injected during ignition delay time.
- In such case, the additional fuel will cause pressure at point 'B' to increase at faster rate, resulting rough engine cycle during combustion.





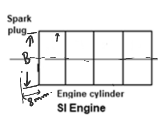
Combustion Mechanism in CI Engines

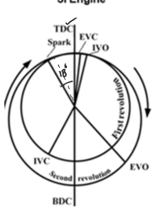
Direct injection (DI) vs Indirect injection (IDI)

- Large but slow engines have adequate real time for fuel injection, atomization, vaporization and mixing of fuel for combustion to occur for about 40°-50° of engine rotation. These engines have large open chambers without need of high swirls. Higher injection pressures gives fuel jets of very high velocity. Penetration of jets reaches across large combustion chambers and assists mixing of fuel with air. Such engines are known as "DI engines". They have higher BTE because of slower speed, reduced friction/heat losses, lower combustion chamber surface area-to-volume ratio. These engines require higher CR with greater heat loss. Thus, starting of a cold DI engine is very difficult.
- Small CI engines operate much higher speeds and thus need high swirl to enhance the speed of vaporization and mixing of fuel. It has to occur at about 10 times faster so that combustion duration can be mapped in the range of 40°-50° of engine rotation. These are "IDI engines" that has provisions of divided chambers with provision of secondary fuel injection. So, the IDI engines can operate with lower injection pressures with lower fuel jet velocities.

Numerical Problems

Q1. The spark plug is fired at 18° bTDC in an engine running at 1800 rpm. It takes 8° of engine rotation to start combustion and get into flame propagation mode. The flame termination occurs at 12° aTDC. The bore diameter is 80 mm and the spark plug is 8 mm offset to from the centreline of the cylinder. Calculate the effective flame speed.





Soln

$V_f = \frac{D}{t}$ $\quad D = \frac{B}{2} + 8 = 48\ mm.$

Spark plug: 18° bTDC.

Combustion start: 8° crank ⇒ 10° bTDC.

Flame termination: 12° aTDC

Flame propagation → 22° engine rotation

$$t = \frac{(22/360)\ rev}{\left(\frac{1800}{60}\right) rev/s} = 0.00204\ s.$$

$$V_f = \frac{\left(\frac{48}{1000}\right)}{0.00204} = 23.5\ m/s$$

Numerical Problems

Q2. Referring to Q1, the speed of the engine is increased to 3000rpm to enhance turbulence and swirl. So, the flame front speed increases linearly at the rate 0.85 times the engine rpm. The flame development after spark plug firing takes 8° of engine rotation. Calculate the advancement of ignition timing for flame termination at 12° aTDC.

Soln

$N_1 = 1800\ rpm$ $\quad N_2 = 3000\ rpm.$

$V_{f1} = 23.5\ m/s.$ $\quad V_{f2} \propto 0.85\ N.$

$\Rightarrow \frac{V_{f2}}{V_{f1}} = 0.85\left(\frac{N_2}{N_1}\right). \Rightarrow V_{f2} = 33.3\ m/s.$

$t = \frac{D}{V_{f2}} = \frac{0.048\ m}{33.3\ m/s} = 0.00144\ s.$

$\theta = 360 \times t \times N = 360 \times 0.00144 \times 3000 = 25.92°.$

Q.1 spark plug firing 18° bTDC

termination – 12° aTDC, 8° start of combustion.

propagation → 13.92° bTDC

Spark plug → 21.92° bTDC

⇒ Advancement of ignition timing = 3.92°

Numerical Problems

Q3. A diesel engine has a compression ratio of 18 and operates on a air-standard dual cycle at 2400 rpm. The fuel injection starts at 20ºbTDC and the combustion starts at 7ºbTDC. The combustion lasts for 42ºof engine rotation. The ratio of connecting rod length to crankshaft offset is 3.8. Calculate the ignition delay and fuel cut-off ratio.

Soln (i) Fuel injection $\rightarrow$ 20^0 bTDC.

Start of comb. $\rightarrow$ 7^0 bTDC.

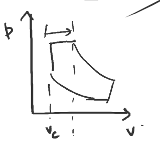
ID = 13^0 crank rotation.

$\Downarrow$

$$ID = \frac{(13/360)\ rev}{(2400/60)\ rev/s}.$$

$\boxed{ID = 9\ ms.}$

(ii) Fuel cut off ratio, $\beta = \frac{V}{V_{TDC}} = \frac{V}{V_c}$.



Recall engine kinematics.

$$\beta = 1 + \frac{1}{2}(r_c - 1)\left[R + 1 - \cos\theta - \sqrt{R^2 - \sin^2\theta}\right]$$

$r_c = 18$ $\quad \theta = 42 - 7 = 35^0$

$R = 3.8$ $\quad \boxed{\beta = 2.9}$

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THANK YOU

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