Combustion in SI engine

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Effect of Engine Variables on Ignition Lag

Nature of Fuel
- Higher the self-ignition temperature of the fuel, longer is the ignition lag.

Mixture ratio
- Ignition lag is smallest for the mixture ratio which gives the maximum temperature.

Electrode gap
- If gap is too small quenching of flame nucleus may occur but if it too large spark intensity reduced
- Lower compression ratio requires higher electrode gap

Initial temperature and pressure
- Increasing the intake temperature, pressure & the compression ratio and retarding the spark, reduces the ignition lag.

Turbulence
- Excessive turbulence of the mixture in the area of spark plug is harmful.
Spark and Flame Propagation

- Spark discharge is at -30° & flame is visible first at -24°.
- Blue light is emitted most strongly from the flame front.
- At TC, flame diameter ≈ 2/3 of cylinder bore.
- Flame reaches the farthest cylinder wall at 15° ATC, but combustion continues for another 10°.
- The afterglow comes from the gases behind the flame as these are compressed to the highest temperatures attained in the cylinder (at about 15° ATC) while the rest of the charge burns.

Features of SI engine combustion process

- Pressure reaches a maximum after TDC but before the cylinder charge is fully burned,
- The pressure continues to decreases as the cylinder volume continues to increase during the remainder of the expansion stroke.

Cylinder pressure for five consecutive cycles in a spark-ignition engine as a function of crank angle. Ignition timing 30 degree BTC, wide open throttle, 1044 rev/min, φ = 0.98
Features of SI engine combustion process

- **Volume fraction enflamed** curves rise more steeply than the **mass fraction** burned curves, because the density of the unburned mixture ahead of the flame is about four times the density of the burned gases behind the flame.
- Some unburned mixture (25% by mass) still to burn behind the visible front to the flame; even when the entire combustion chamber is fully enflamed.

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Features of SI engine combustion process

- If the **start of the combustion process** is progressively **advanced before TDC**, the compression stroke work transfer increases.
- If the **end of the combustion process** is progressively delayed by retarding the spark timing the peak cylinder pressure occurs later in the expansion stroke and is reduced in magnitude.
- These changes reduce the expansion stroke work transfer from the cylinder gases to the piston.
- The optimum timing which gives the maximum brake torque called maximum brake torque or **MBT**.

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(a) Cylinder pressure versus crank angle for over advanced spark timing (109°, MBT timing 30°), retarded timing (10°). (b) Effect of spark advance on brake torque at constant speed and (A/F), at wide-open throttle. MBT is maximum brake torque timing.
Features of SI engine combustion process

- The optimum spark setting will depend on the following:
  - Rate of flame development and propagation,
  - the length of the flame travel path across the combustion chamber, and
  - the flame termination process after it reaches the wall.

- Empirical rules for relating the mass burning profile and maximum cylinder pressure to crank angle at MBT timing are often used.
- For example, with optimum spark timing:
  - maximum pressure occurs at about 16 deg. after TDC,
  - half the charge is burned at about 10 deg. after TC.

Analysis of Cylinder Pressure Data

Pressure volume data from a firing SI engine on both a linear p-V and a log p-log V diagram.
Analysis of Cylinder Pressure Data

- Effect of heat transfer, crevices and leakage can be explicitly incorporated into cylinder pressure data analysis using a “heat release” approach based on 1st law of thermodynamics.

\[ \delta Q_{ch} = dU_s + \delta Q_{ht} + \delta W + \sum h_i \ dm_i \quad \text{...(6)} \]

- Change in sensible energy of the charge \(dU_s\) is separated form that due to change in composition
- Term \(\delta Q_{ch}\) represents chemical energy released by combustion
- Work done is piston work and is equal to \(p \ dV\)
- \(\delta Q_{ht}\) is heat transfer to the chamber walls.

![Open system boundary for combustion chamber for heat-release analysis](image)

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Analysis of Cylinder Pressure Data

- Assuming that \(U_s\) is given by \(mu(T)\), where \(T\) is the mean charge temperature and \(m\) is the mass within the system boundary, then

\[ dU_s = mc_v(T) \ dT + m(T) \ dm \quad \text{...(7)} \]

- Substituting for \(dU_s\) and \(dm (= dm_{cr} = dm)\), above equation becomes,

\[ \delta Q_{ch} = mc_v \ dT + (h' - u)dm_{cr} + p \ dV + \delta Q_{ht} \quad \text{...(8)} \]

- \(dm_{cr} > 0\) when flow is out of the cylinder into the crevice
- \(dm_{cr} < 0\) when flow is from the crevice to the cylinder
- \(h'\) is evaluated at cylinder conditions when \(dm_{cr} > 0\) and at crevice conditions when \(dm_{cr} < 0\)
- use of the ideal gas law (neglecting the change in gas constant \(R\)) with Eq. 8 then gives

\[ \delta Q_{ch} = \left(\frac{c_v}{R}\right) V \ dp + \left(\frac{c_v}{R} + 1\right) p \ dV + (h' - u + c_v T) \ dm_{cr} + \delta Q_{ht} \quad \text{...(9)} \]

*Equation 9 can be used in several ways.*
Analysis of Cylinder Pressure Data

- **Net heat release**: When the heat or energy release term $\delta Q_{ah}$, is combined with the heat-transfer and crevice terms, the combination is termed as net heat release.

- It is equal to the first two terms on the right-hand side of Eq. 9, and represent the *sensible energy change and work transfer to the piston*.

- While *heat losses* during combustion are a small fraction of the fuel energy (10 to 15 percent), the distributions of heat release and heat transfer with crank angle are different; heat transfer becomes more important as the combustion process ends and average gas temperatures peak.

- The convective heat-transfer rate to the combustion chamber walls:

\[
\frac{dQ_{hm}}{dt} = Ah_c(T - Tw)
\]

Where,  

- $A$ is the chamber surface area,
- $T$ is the mean gas temperature,
- $T_w$ is the mean wall temperature, and
- $h_c$ is the heat-transfer coefficient

Results of heat release analysis showing the effects of heat transfer, crevice and combustion efficiency.

- Lowest curve is net heat release,

- Addition of heat transfer and crevice models give chemical energy release and

- Curve at the top is mass of the fuel in combustion chamber times its lower heating value.

- The difference between final value of $Q_{ah}$ and $(m_f Q_{LHV})$ is equal to the combustion inefficiency.
Flame-development angle $\Delta \theta_d$
- The crank angle interval between spark discharge and the time when a small but significant fraction of the cylinder mass has burned or fuel chemical energy has been released.
- Usually, this fraction is 10%, though other fractions such as 1 and 5 percent have been used.

Rapid-burning angle $\Delta \theta_b$
- Crank angle interval required to burn the bulk of the charge.
- Interval between the end of flame development stage and the end of the flame propagation process.
- Usually, the mass fraction burned or energy release fraction of 90%.
Combustion Process Characterization

- Overall burning angle $\Delta \theta_o$
- The duration of the overall burning process.
- It is the sum of $\Delta \theta_d$ and $\Delta \theta_b$

Flame structure and speed

- Critical parameters necessary for engine optimization are:
  - Engine combustion flame as it develops from the spark discharge,
  - Flame speed at which it propagates across the combustion chamber, and charge motion,
  - Charge composition and
  - Chamber geometry,
**Flame structure and speed**

Experimental observation:
- Approximately spherical development of flame from the vicinity of the spark plug.
- Geometry of combustion chamber and spark plug govern the flame front surface area.

Larger the surface area greater the mass of fresh charge that cross the surface and enters the flame zone.

- The center plug location gives twice the flame area of side flame geometry and burn about twice as fast.

- Mixture burning rate is highly influenced by the engine speed.

**Ignition System in SI Engines**

**Spark Plug**
- Ignition system has to transform battery voltage of 12 V to 8-20 kV and has to deliver the voltage to the right cylinder, at the right time.
- About 0.2 mJ of energy is required to ignite a stoichiometric mixture at normal engine operating conditions.
- Over 3 mJ is required for a rich or lean mixture.
- Ignition systems deliver 30 to 50 mJ of electrical energy.
- Fundamental requirements of the ignition source:
  - A high ignition voltage to break down in the spark-gap,
  - A low source impedance or steep voltage rise,
  - A high energy capacity to create a spark kernel of sufficient size,
  - Sufficient duration of the voltage pulse to ensure ignition,
Ignition System in SI Engines

For the mixture to be ignited:
(a) *Spark energy must be higher* than the minimum energy of ignition of the mixture,
(b) *Distance between electrodes* should be larger than the extinguishing distance for a given mixture,
(c) *Local gradient of velocity* should be smaller than the critical for a given mixture.

**Improvement of spark ignition effectiveness**
1. Energy of spark generated by spark-plug is not enough to ignite the lean mixtures
2. To improve the effectiveness of spark-ignition of lean mixtures we can:
   - Use 2- spark-plug systems (twin-spark),
   - Increase of ignition energy by:
     - Increasing spark energy
     - Laser ignition
   - Increase the distance between electrodes
Combustion in CI Engine

- Combustion in a CI engine is quite different from that of an SI engine. While combustion in an SI engine is essentially a flame front moving through a homogeneous mixture, combustion in a CI engine is an unsteady process occurring simultaneously in many spots in a very non-homogeneous mixture controlled by fuel injection.

- Air intake into the engine is unthrottled, with engine torque and power output controlled by the amount of fuel injected per cycle.

- Only air is contained in the cylinder during compression stroke, and a much higher compression ratios (12 to 24) are used in CI engines.

- In addition to swirl and turbulence of the air, a high injection velocity is needed to spread the fuel throughout the cylinder and cause it to mix with the air.

- Fuel is injected into the cylinders late in the compression stroke by one or more injectors located in each cylinders. Injection time is usually about 200° of crankshaft rotation (150 bTDC and 50 aTDC).
Combustion in CI Engine

- In a CI engine the fuel is sprayed directly into the cylinder and the fuel-air mixture ignites spontaneously. These photos are taken in CI engine conditions with swirl air flow.

In Cylinder Measurements

- This graph shows the fuel injection flow rate, net heat release rate and cylinder pressure for a direct injection CI engine.
Four Stages of Combustion in CI Engines

The combustion process proceeds by the following stages:

- **Ignition delay (ab)** - fuel is injected directly into the cylinder towards the end of the compression stroke. The liquid fuel atomizes into small drops and penetrates into the combustion chamber. The fuel vaporizes and mixes with the high-temperature high-pressure air.

- **Premixed combustion phase (bc)** - combustion of the fuel which has mixed with the air to within the flammability limits (air at high-temperature and high-pressure) during the ignition delay period occurs rapidly in a few crank angles.
Four Stages of Combustion in CI Engines

- **Mixing controlled combustion phase (cd)** — after premixed gas consumed, the burning rate is controlled by the rate at which mixture becomes available for burning. The rate of burning is controlled in this phase primarily by the fuel-air mixing process.

- **Late combustion phase (de)** — heat release may proceed at a lower rate well into the expansion stroke (no additional fuel injected during this phase). Combustion of any unburned liquid fuel and soot is responsible for this.

![Combustion Diagram](image)

Types of diesel combustion chamber

- Diesel engines are divided into two basic categories according to their combustion chamber design:

1. **Direct-injection (DI) engines**, which have a single open combustion chamber into which fuel is injected directly.

2. **Indirect-injection (IDI) engines**, where the chamber is divided into two regions and the fuel is injected into the “prechamber” which is connected to the main chamber (situated above the piston crown) via a nozzle, or one or more orifices.

- IDI engine design are only used in the smallest engine sizes.

- Within each category there are several different chamber geometry, air-flow, and fuel-injection arrangements.
Application of various types of combustion chamber

- For very-large engines (stationary power generation) which operate at low engine speeds, the time available for mixing is long so a direct injection quiescent chamber type is used (open or shallow bowl in piston).

- As engine size decreases and engine speed increases, increasing amounts of swirl are used to achieve fuel-air mixing (deep bowl in piston).

- For small high-speed engines used in automobiles, chamber swirl is not sufficient, indirect injection is used where high swirl or turbulence is generated in the pre-chamber during compression and main products / fuel blowdown and mix with chamber air.

Types of CI Engines

Direct injection: quiescent chamber

Direct injection: swirl in chamber

Indirect injection: turbulent and swirl pre-chamber
Direct-Injection Systems

- In the largest-size engines, where mixing rate requirements are least stringent, quiescent direct-injection system of the type shown in fig. are used.

![Diagram of Direct-Injection Systems](image1)

**FIGURE 10-1**
Common types of direct-injection compression-ignition or diesel engine combustion systems: (a) quiescent chamber with multihole nozzle typical of larger engines; (b) bowl-in-piston chamber with swirl and multihole nozzle; (c) bowl-in-piston chamber with swirl and single-hole nozzle. (b) and (c) used in medium to small DI engine size range.

Indirect-Injection Systems

- Inlet generated air swirl, despite amplification in the piston cup, has not provided sufficiently high fuel-air mixing rated for small high-speed diesel such as those used in automobiles.
- Indirect-injection or divided chamber engine systems have been used instead where the vigorous charge motion required during fuel-injection is generated during the compression stroke.
- Two broad classes of IDI systems can be defined: (1) swirl chamber systems and (2) prechamber systems as shown in fig.

![Diagram of Indirect-Injection Systems](image2)

**FIGURE 10-2**
Two common types of small indirect-injection diesel engine combustion system: (a) swirl prechamber; (b) turbulent prechamber.
Comparison of different combustion systems

<table>
<thead>
<tr>
<th>System</th>
<th>Direct Injection</th>
<th>Indirect Injection</th>
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<tbody>
<tr>
<td></td>
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Combustion Photographs in an engine

- Direct Injection quiescent chamber
- Direct Injection multi-hole nozzle swirl in chamber
- Direct Injection single-hole nozzle swirl in chamber
- Indirect injection swirl pre-chamber
Thanks