Combustion in SI Engines

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ME 401: Internal Combustion Engines

Stages of SI Engine Flame Propagation

At the end of compression stroke, an electrical discharge initiates the combustion process; a flame develops from the kernel created by spark discharge and propagates across the cylinder to the walls. At the walls, flame is quenched as heat transfer & destruction of active species at the wall become the dominant processes.

Spark discharge is at -30° & flame is visible first at -24°.
Nearly circular flame propagates outward from the spark plug location. Irregular shape of turbulent flame front is apparent. 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°.
At about 10° ATC, additional radiation - initially white, turning to pinky-orange - centred at the spark plug location is evident. These 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.

Essential Features of Combustion Process

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Flame Development & Propagation

° Combustion normally begins at the spark plug where the molecules in and around the spark discharge is activated to a level where reaction is self-sustaining. This level is achieved when the energy released by combustion is slightly greater than the heat loss to the metal & gas surroundings.

° Initially, flame speed is very low as the reaction zone must be established, and heat loss to the spark plug is high as it is located near the cold walls. During this period, pressure rise is also small because the mass of mixture burned is small.

° Unburned gas ahead of flame front, and the burned gas behind the flame front, are raised in temperature by compression, either by a moving piston or by heat transfer from advancing flame.

° In the final stage, flame slows down as it approaches the walls of the combustion chamber (from heat loss & low turbulence) and is finally extinguished (wall quenching).

° Volume fraction en-flamed \((V_f/V)\) curves rise more sharply than mass fraction \((x_b)\). In the large part, this is due to \(\rho_u \approx 4\rho_b\).

° Flame development and propagation vary, cycle- by-cycle: shape of \(P = \theta, V_f = \theta & x_b = \theta\) curves for each cycle differ significantly.

° Three key factors to influence the cycle-by-cycle variation:
  1. Variation is gas motion in the cylinder during combustion,
  2. Variation in the amounts of fuel, air, and recycled exhaust gas.
  3. Variation in mixture composition within the cylinder each cycle - especially near the spark plug - due to variations in mixing between air, fuel, recycled exhaust gas, and residual gas.

° Experimental evidences suggest 4 distinct phases in combustion:
  1. Spark ignition
  2. Early flame development
  3. Flame propagation
  4. Flame termination

° During combustion, cylinder pressure rises due to release of fuel’s chemical energy.

° As \(\rho_u \approx 4\rho_b\), gas expansion compresses unburned mixture ahead of flame & displaces it towards the walls, and burned gases are pushed towards the spark plug.

° Elements of unburned mixture which burn at different times have different pressure and temperature just prior to combustion and thus end up at different thermodynamic states after combustion.

\[\Rightarrow\] Thermodynamic state & composition of burned gas is non-uniform within cylinder.
Combustion Process Characterization

- **Flame-development angle**, $\Delta \theta_d$: crank angle interval between spark discharge and the time when a small but significant fraction of the cylinder mass ($\approx 10\%$) has burned.
- **Rapid-burning angle**, $\Delta \theta_b$: crank angle interval required to burn the bulk of the charge, interval between end of flame development ($x_b = 10\%$) & end of flame propagation ($x_b = 90\%$).
- **Overall burning angle**, $\Delta \theta_o$: $\Delta \theta_o = \Delta \theta_d + \Delta \theta_b$

Characteristic features of the heat release curve of a SI engine are initial small slope region beginning with spark ignition, followed by a region of rapid growth, and then a more gradual decay. The pattern is generally represented by a Wiebe function:

$$x_b(\theta) = 1 - \exp \left[-a \left(\frac{\theta - \theta_s}{\theta_d}\right)^n\right]$$

- $\theta_s$: start of combustion
- $\theta_d$: duration of heat release
- $n$: Weibe form factor
- $a$: Weibe efficiency factor

$a = 5$ & $n = 3$ have been reported to fit well with experimental data.

Spark Timing & MBT

- Combined duration of the flame development & propagation process is typically between 30 and 90°. Combustion starts before the end of the compression stroke, continue through the early part of the expansion stroke, and ends after the point in the cycle at which the peak cylinder pressure occurs.
- If the start of the combustion process is progressively advanced before TC, the compression stroke work transfer increases.
- If the end of the combustion process is progressively delayed by retarding the spark timing, peak cylinder pressure occurs later in the expansion stroke and is reduced in magnitude. These changes reduce the expansion stroke work transfer.
- The optimum timing which gives the maximum brake torque (MBT), occurs when the magnitudes of these two opposing trends just offset each other.

Empirical rules with MBT timing:

1. the maximum pressure occurs at around 5 to 10° after TC
2. half the charge is burned at about 10° after TC.

In practice, the spark is often retarded to give a 1 or 2% reduction in brake torque from the maximum value.
In logP-logV diagram:

- Compression & expansion processes are straight line.
- Start of combustion & end of combustion are identified by departure of curve from straight line.
- Compression & expansion processes are given by a relation:

\[ PV^n = \text{constant} \quad n = 1.3(\pm 0.05) \]

Knock in SI Engines

Knock is the name of the noise transmitted through the engine structure when essentially spontaneous ignition of a portion of end-gas – the fuel, air, residual gas, mixture ahead of the flame front – occurs. When knock takes place, there is an extremely rapid release of much of the chemical energy in the end-gas, causing very high local pressures and the propagation of pressure waves of substantial amplitude across the combustion chamber.

Abnormal Combustion: Knock & Surface Ignition

- Normal combustion: A combustion process which is initiated solely by a timed spark and in which the flame front moves completely across the combustion chamber in a uniform manner at a normal velocity.
- Abnormal combustion: A combustion process in which a flame front may be started by hot combustion - chamber surfaces either prior to or after spark ignition, or a process in which some part or all of the charge may be consumed at extremely high rates.

- Spark Knock:
  - A knock which is recurrent and repeatable in terms of audibility. It is controllable by the spark advance; advancing the spark increases the knock intensity and retarding the spark reduces the intensity.

- Surface ignition:
  - Surface ignition is ignition of the fuel-air charge by any hot surface other than the spark discharge prior to the arrival of the normal flame front. It may occur before the spark ignites the charge (pre-ignition) or after normal ignition (post-ignition).

The abnormal combustion phenomena are of concern because:

- when severe, they can cause major engine damage;
- even if not severe, these are objectionable source of noise.

Surface Ignition

Surface ignition is the ignition of the fuel-air premixture by a hot spot on the combustion chamber walls such as an overheated valve or spark plug, or glowing combustion chamber deposit: i.e. any means other than the normal spark discharge. Following the surface ignition, a turbulent flame develops at each surface-ignition locations and starts to propagate across the chamber in an analogous manner to what occurs in normal knock.
When spark is advanced, burning gas is compressed by the raising piston and therefore temperature (& densities) are radically increased. Thus knock is encouraged by the advanced spark timings and relieved by retarding spark timings.

To prevent knock in the SI engine the end gas should have:
- A low temperature
- A low density
- A long-ignition delay
- A non-reactive composition

When engine conditions are changed, the effect of the change may be reflected by more than one of the above variables. For example, an increase in compression ratio will increase both the temperature and density of unburned mixture.

Increasing the temperature of the unburned mixture by any of the following factors will increase the possibility of SI engine knock:
- Raising the compression ratio
- Raising the inlet air temperature
- Raising the coolant temperature
- Raising the temperatures of the cylinder and chamber walls
- Advancing the spark timing.

The temperature of the exhaust valve is relatively high and therefore it should be located near the spark plug and not in the end-gas region.

Opening the throttle does not appreciably change the gas temperatures when the air-fuel ratio is constant. However, total energy release is proportional to the mass of the mixture in the cylinder, and therefore opening the throttle tends to raise wall temperatures and raise mixture & end-gas temperatures.
Time Factors in SI Knock Reduction

Increasing the time of exposure of the unburned mixture to autoigniting conditions by any of the following factors will increase the possibility of SI engine knock:
- Increasing the distance the flame has to travel in order to traverse the combustion chamber
- Decreasing the turbulence of the mixture and thus decreasing the flame speed
- Decreasing engine speed: thus decreasing the turbulence of the mixture and increasing the time available for preflame reactions

★ If the chamber width is great, the end-gas may have time to reach a self-ignition temperature and pass through the ignition delay period before the flame has completed its travel.

Composition Factors in SI Knock Reduction

The properties of the fuel and fuel-air ratio are the primary means for controlling knock, once the compression ratio and engine dimensions are selected. The possibility of knock is decreased by
- Increasing the octane rating of the fuel
- Either rich or lean mixtures
- Stratifying the mixture so that the end gas is less reactive
- Increasing the humidity of the entering air.

★ A rich/lean mixture is effective in reducing knock because of:
- the longer delay
- the lower combustion temperature