Combustion in SI Engines

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ME 417: Internal Combustion Engines

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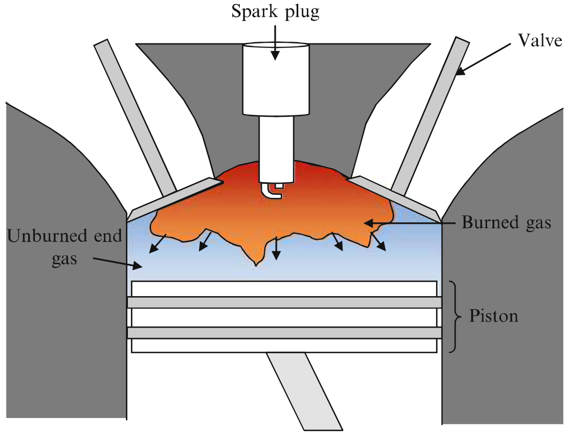
Essential Features of Combustion Process



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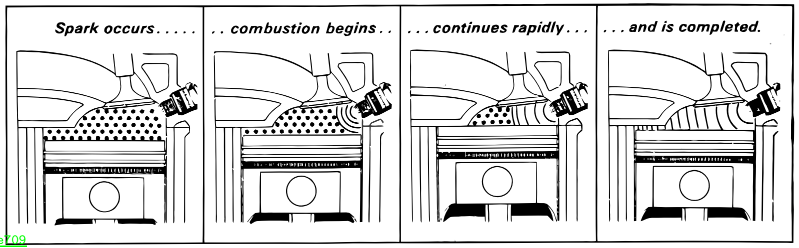

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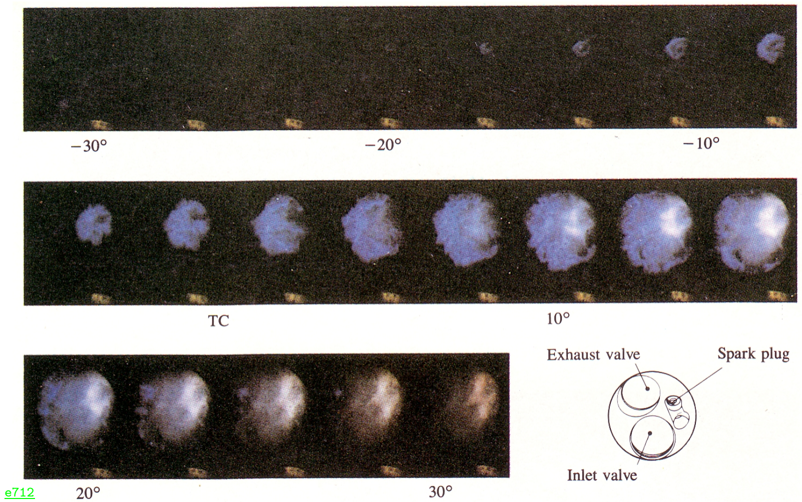
- At the end of compression stroke, an electrical discharge initiates the combustion process; a flame develops from the *kernel* created by spark discharge and propagates across the cylinder to the walls. At the walls, flame is *quenched* as heat transfer and destruction of active species at the wall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



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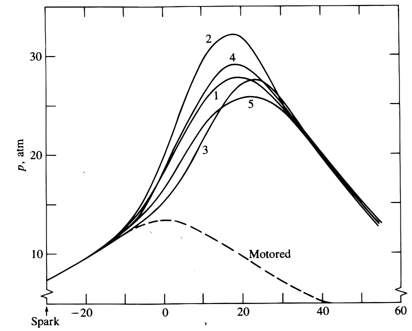
Images of a SI Engine Combustion Process

Observations:

- Spark discharge is at -30°, and 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 (Top Centre), flame diameter ≈ 2/3 of cylinder bore.
- Flame reaches the farthest cylinder wall at 15° ATC (After Top Centre), 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.



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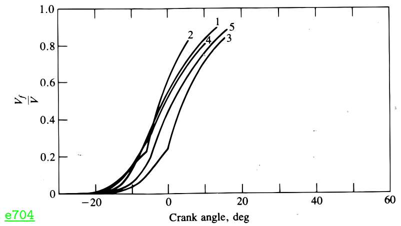

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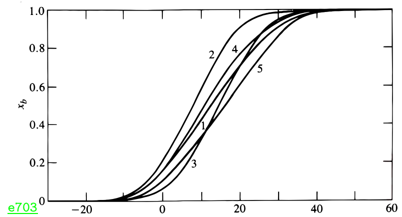

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- Volume fraction en-flamed (V_f/V) curves rise more sharply than mass fraction (x_b). In the large part, this is due to $\rho_u \simeq 4\rho_b$.
- Flame development and propagation vary, cycle- by-cycle: shape of P *vs.* θ, $\frac{V_f}{V}$ *vs.* θ and x_b *vs.* θ curves for each cycle differ significantly.
- Three key factors to influence the **cycle-by-cycle variation**:
  1. Variation in 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.
- Experiments suggest **4 distinct phases** in SIE combustion:
  1. Spark ignition
  2. Early flame development
  3. Flame propagation
  4. Flame termination

Flame Development and Propagation

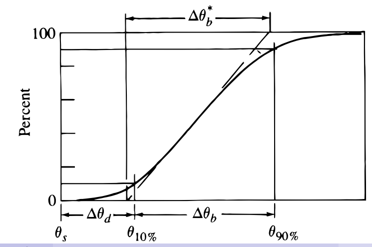
- Combustion normally begins at the spark plug where the molecules in and around the spark discharge is activated to a level where reaction is self sustaining. It is achieved when the energy released by combustion is slightly greater than the heat loss to the metal and gas surroundings.
- Initially, flame speed is low as the reaction zone must be established, and the 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 and low turbulence) and is finally extinguished (wall quenching).

- During combustion, cylinder pressure rises due to release of fuel's chemical energy.
- As $\rho_u \simeq 4\rho_b$, gas expansion compresses unburned mixture ahead of flame and displaces it towards the walls.
- 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 and 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 ($\simeq$ 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, $\Delta\theta_o$**: $\Delta\theta_o = \Delta\theta_d + \Delta\theta_b$



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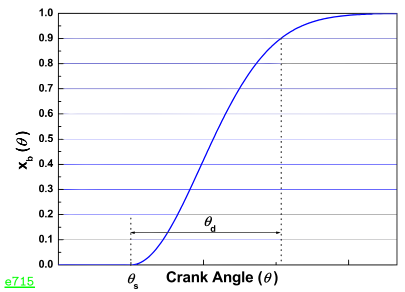
Characteristic features of the heat release curve of a SI engine are initial small slope region beginning with spark ignition, followed by a region of rapid growth, and then a more gradual decay. The pattern is generally represented by a **Wiebe function**:



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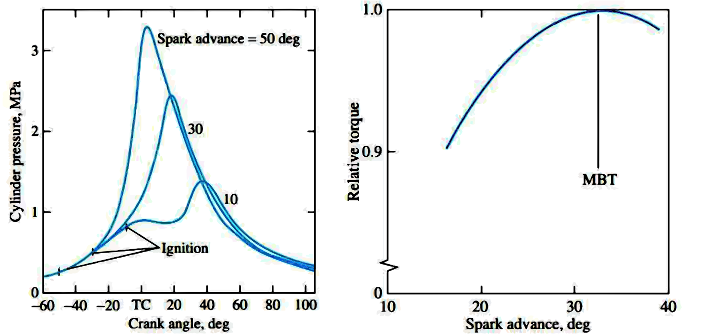
$$x_b(\theta) = 1 - \exp\left[-a\left(\frac{\theta - \theta_s}{\theta_d}\right)^n\right]$$

θ_s : start of combustion
θ_d : duration of heat release
n : Weibe form factor
a : Weibe efficiency factor

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

Spark Timing and MBT

- 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.



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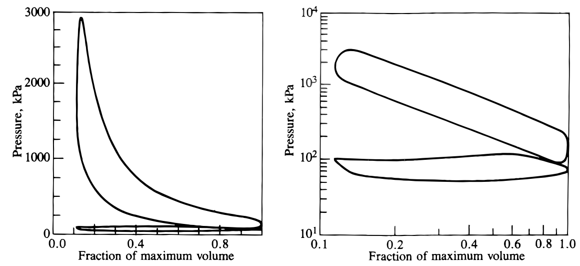
Empirical rules with MBT timing:

1. the maximum pressure occurs at around 5 to 10° after TC
2. half the charge is burned at about l0° after TC.

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

Pressure-Volume Diagram of SI Engine



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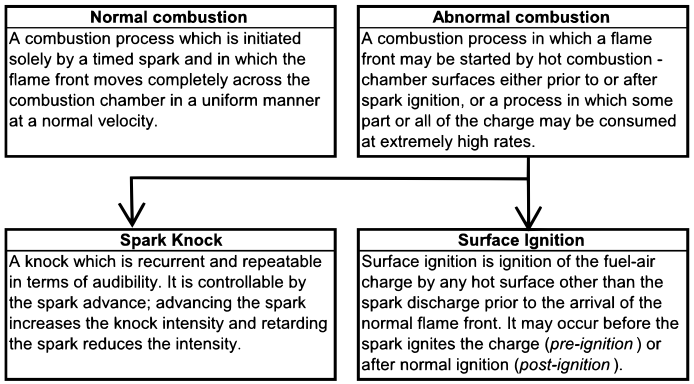
In logP-logV diagram:

- 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:

$$PV^n = constant \qquad n = 1.3 \pm 0.05$$

Abnormal Combustion: Knock and Surface Ignition



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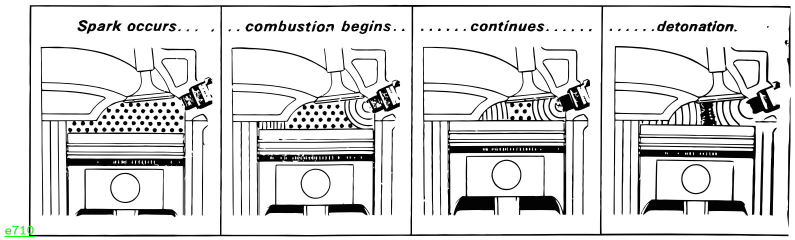
The abnormal combustion phenomena are of concern because:

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

Spark Knock or Knock



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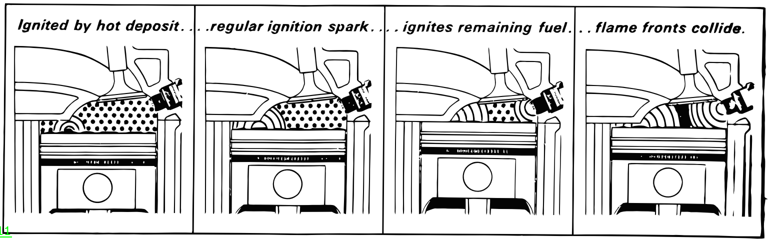
Knock is the name of the noise which happens if essentially spontaneous ignition occurs at a portion of end-gas – the fuel, air, residual gas, mixture ahead of the flame front. With knocking, there is an extremely rapid release of much of the chemical energy in the end-gas, causing very high local pressures and the propagation of pressure waves of substantial amplitude across the combustion chamber.

Surface Ignition



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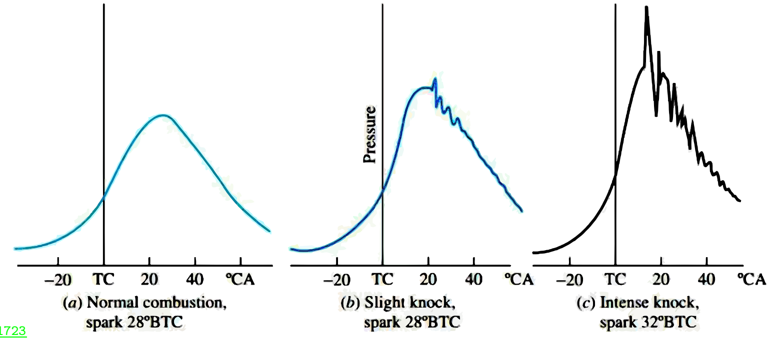
Surface ignition is the ignition of the fuel-air premixtrue by a hot spot on the combustion chamber walls such as an overheated valve or spark plug, or glowing combustion chamber deposit: i.e. any means other than the normal spark discharge. Following the surface ignition, flames develops at various surface-ignition locations and start to propagate across the chamber in an analogous manner to what occurs in normal knock.



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When spark is advanced, burning gas is compressed by the raising piston and therefore temperature (and densities) are radically increased. Thus knock is encouraged by the advanced spark timings and relieved by retarding spark timings.

Reduction of knock in SI engines

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.

Temperature Factors in SI Knock Reduction

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.

★ 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.

Density Factors in SI Knock Reduction

Increasing the density of unburned mixture by any of the following will **increase** the possibility of SI engine knock:

- Opening the throttle (increasing the load)
- Supercharging the engine
- Advancing the spark timing

★ 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 temperature, and mixture & end-gas temperatures.

Time Factors in SI Knock Reduction

Increasing the time of exposure of the unburned mixture to auto-igniting 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
  - increasing the time available for pre-flame reactions

★ If the chamber width is great, the end-gas may have time to reach a self-ignition temperature and pass though 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

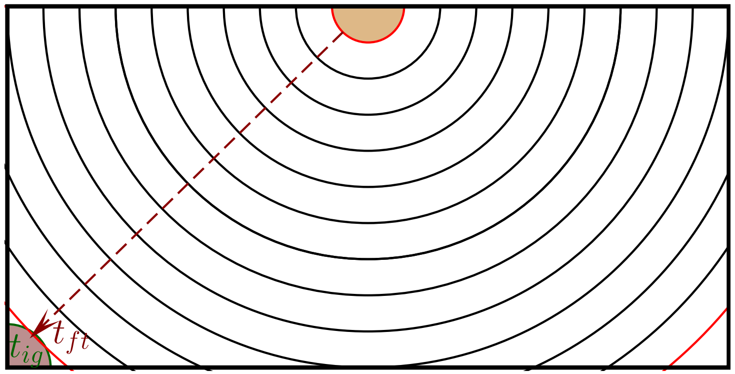
- Increasing the octane rating of the fuel
- Either rich or lean mixtures
- Stratifying the mixture so that the end gas is less reactive
- Increasing the humidity of the entering air.

★ A rich/lean mixture is effective in reducing knock because of:

- the longer delay
- the lower combustion temperature

$t_{ft} \equiv$ flame travel time

$t_{ig} \equiv$ ignition delay time



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- $t_{ig} > t_{ft}$: No self ignition of end gas, and no knock.
- $t_{ig} < t_{ft}$: Self ignition of end gas before the arrival of flame, and therefore leads to knocking.