Combustion in IC Engines
Flame Propagation in SI Engine

After intake the fuel-air mixture is compressed and then ignited by a spark plug just before the piston reaches top center.

The turbulent flame spreads away from the spark discharge location.

\[ N = 1400 \text{ rpm} \]
\[ P_i = 0.5 \text{ atm} \]
In-cylinder Parameters

$T_u$ – unburned gas temperature
$T_{b,e}$ – early burning gas elements
$T_{b,l}$ – late burning gas elements
Flame Development

**Flame development angle** $\Delta \theta_d$ – crank angle interval during which flame kernel develops after spark ignition.

**Rapid burning angle** $\Delta \theta_b$ – crank angle required to burn most of mixture

**Overall burning angle** - sum of flame development and rapid burning angles
Mixture Burn Time versus Engine Speed

The time for an overall burn is:

\[ t_{90\%} = \frac{\Delta \theta_{90\%}}{N \cdot \left( \frac{\text{min}}{60\text{s}} \right) \cdot \left( \frac{360^\circ}{\text{rev}} \right)} \]

For a typical value of 50 crank angles for the overall burn

<table>
<thead>
<tr>
<th>N (rpm)</th>
<th>t_{90%}(ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard car at idle</td>
<td>500</td>
</tr>
<tr>
<td>Standard car at max power</td>
<td>4,000</td>
</tr>
<tr>
<td>Formula car at max power</td>
<td>19,000</td>
</tr>
</tbody>
</table>

Note: To achieve such high engine speeds a formula car engine has a very short stroke and large bore.
**Mixture Burn Time vs Engine Speed**

How does the flame burn all the mixture in the cylinder at high engine speeds?

The piston speed is directly proportional to the engine speed, $u_p \sim N$

The turbulent intensity increases with piston speed, $u_t \sim \frac{1}{2} U_p$

The turbulent burning velocity is proportional to the turbulent intensity $U_t \sim u_t$, -- at higher engine speeds the turbulent flame velocity is also higher: less time is needed to burn the entire mixture

\[ f = 1.0 \]
\[ P_i = 0.54 \text{ atm} \]
Spark at 30° BTC

![Graph showing combustion duration vs engine speed]
Heat Losses During Burn

During combustion the cylinder volume is very narrow.

In order to reduce the heat loss want burn time to be small (high flame velocity) accomplished by either increasing

a) laminar burning velocity, or
b) turbulence intensity.

Highest laminar burning velocity is achieved for slightly rich mixtures; for iso-octane maximum \( U_f \approx 26 \text{ cm/s} \) at \( f=1.13 \) (we use for equivalence ratio \( \phi \) instead of \( f \))
Optimum Fuel/Air (F/A) Composition

Maximum power is obtained for a F/A≈1.1 since this gives the highest burning velocity and thus minimum heat loss.

Best fuel economy is obtained for a F/A that is less than 1.0.
Spark Timing

Spark timing relative to TC affects the pressure development and thus the \textit{imep} and power of the engine.

To center the combustion around TC the mixture should be ignited before TC.

The overall burning angle is between 40 to 60°, depending on engine speed.
Maximum Brake Torque Timing

If combustion starts too early, then work is done against piston; if it is too late then peak pressure is reduced.

The optimum spark timing which gives the maximum brake torque, called **MBT timing** occurs when these two opposite factors cancel.

Engine at WOT, constant engine speed and A/F
Effect of Engine Speed on Spark Timing

The overall burn angle (about 90% of fuel burn) increases with engine speed. A larger spark advance is required to accommodate this.
Effect of Throttle on Spark Timing

✓ At part-throttle the residual gas fraction increases, and since residual gas represents a diluent it lowers the laminar burning velocity.

✓ Because of lower burning velocity overall burn angle increases, so the increase spark advance is needed.

✓ At idle, where the residual gas fraction is very high, the burn time is very long and thus a long overall burn angle which requires more spark advance.

✓ In modern engines the onboard computer sets the spark advance based on information about the throttle position, intake manifold pressure and engine speed.
Abnormal Combustion in SI Engine - Knock

Knock is the term used to describe a pinging noise emitted from a SI engine undergoing abnormal combustion.

The noise is generated by shock waves produced in the cylinder when unburned gas ahead of the flame auto-ignites.
Observation window for photography

Spark plug

Intake valve

Exhaust valve

Knock cycle

Normal cycle

Observation window for photography
Engine Damage From Severe Knock

Damage to the engine is caused by a combination of high temperature and high pressure during knocking combustion.
**Knock**

As the flame propagates away from the spark plug the pressure and temperature of the unburned gas increases.

Under certain conditions the end-gas can autoignite and burn very rapidly producing a shock wave

The end-gas autoignites after a certain *induction time* is dictated by the chemical kinetics of the fuel-air mixture.

If the flame burns all the fresh gas before autoignition in the end-gas can occur then knock is avoided.

Therefore knock is a potential problem when the burn time is long!
Computer Modeling of Knocking combustion

Normal combustion N=9
knocking combustion N=14_v6_6
Knock suppressed N=14_v9_12
Velocity distribution in the cylinder for N=15 v6_6_vel before knock (simulation)
Pressure in the cylinder – no (very mild) knock (simulation)
Pressure in the cylinder – knock (simulation)
Kinetics

The high temperature mechanisms include some parts of unburned hydrocarbons (approx. 70%) and corresponding parts of O₂ and CO. The simplest and the most effective way is using two-step “global” scheme of chemical kinetic for the oxidation process.

\[ C_nH_{2n+2} + \frac{2n + 1}{2} O_2 = n \cdot CO + (n + 1)H_2O \quad CO + \frac{1}{2}O_2 = CO_2 \]

\[
\frac{d[C_nH_{2n+2}]}{dt} = -A_n \exp\left(\frac{E_{ln}}{RT}\right)\left[C_nH_{2n+2}\right]^\beta\left[O_2\right]^\alpha
\]

\[
\frac{d[CO_2]}{dt} = B_{CO_2} \exp\left(-\frac{E_{CO_2}}{RT}\right)[CO][O_2]^{0.25}[H_2O]^{0.5} - C_{CO_2} \exp\left(-\frac{E_{CO_2}}{RT}\right)[CO_2]
\]
Induction times – calculated for the conditions of a rapid compression machine
Autoignition onset calculated using “Shell model”
Consequence of images of flame front propagating in tube
$L = 240L_f = 4.8\text{cm}, \ R = 30L_f = 0.6\text{cm}.$

\[ U_f = U_{f0} \left( \frac{T_i}{300K} \right)^{2.18} \left( \frac{P_i}{1\text{atm}} \right)^{-0.16} \]

$L_f = (0.19-0.21) \times 10^{-4} \text{m}$
Temperature variation near the end wall, after $t = 6$ msec
Temperature profile at the initial time of autoignition (approx. 8.5ms)
Hot spot formation
Flame with “switched-off” low-temperature kinetics
Flame propagation without heat losses to the cylinder walls

\[ \text{CAD} = 16.8^\circ \]
Flame propagation with heat losses to the cylinder walls - enhanced convection

CAD = 16.8°
Pressure trace 1 – knocking combustion (N=14)
Calculated flow field in an engine cylinder
Knock Mitigation Using Spark Advance

Spark advance set to 1% below MBT to avoid knock

\[
\text{X} \quad \text{crank angle corresponding to borderline knock}
\]

\[
\text{---} \quad 1\% \text{ below MBT}
\]
Fuel Knock Scale

To provide a standard measure of a fuel’s ability to resist knock, a scale has been devised in which fuels are assigned an octane number ON.

The octane number determines whether or not a fuel will knock in a given engine under given operating conditions.

By definition, normal heptane (n-C$_7$H$_{16}$) has an octane value of zero and iso-octane (C$_8$H$_{18}$) has a value of ON=100.

The higher the octane number, the higher the resistance to knock.

Blends of these two hydrocarbons define the knock resistance of intermediate octane numbers: e.g., a blend of 10% n-heptane and 90% iso-octane has an octane number of 90.

A fuel’s octane number is determined by measuring what blend of these two hydrocarbons matches the test fuel’s knock resistance.
Octane Number Measurement

Two methods have been developed to measure ON using a standardized single-cylinder engine developed under the auspices of the Cooperative Fuel Research Committee in 1931.

The CFR engine is 4-stroke with 3.25” bore and 4.5” stroke, compression ratio can be varied from 3 to 30.

<table>
<thead>
<tr>
<th></th>
<th>Research</th>
<th>Motor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inlet temperature (°C)</td>
<td>52</td>
<td>149</td>
</tr>
<tr>
<td>Speed (rpm)</td>
<td>600</td>
<td>900</td>
</tr>
<tr>
<td>Spark advance (°BTC)</td>
<td>13</td>
<td>19-26 (varies with r)</td>
</tr>
<tr>
<td>Coolant temperature (°C)</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>Inlet pressure (atm)</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>Humidity (kg water/kg dry air)</td>
<td>0.0036 - 0.0072</td>
<td></td>
</tr>
</tbody>
</table>

Note: In 1931 iso-octane was the most knock resistant HC, now there are fuels that are more knock resistant than iso-octane.
Octane Number Measurement

Testing procedure:

- Running the CFR engine on the test fuel at both research and motor conditions.
- Slowly increase the compression ratio until a standard amount of knock occurs as measured by a magnetostriction knock detector.
- At that compression ratio run the engines on blends of n-heptane and isooctane.
- ON is the % by volume of octane in the blend that produces the stand. knock

- The antiknock index which is displayed at the fuel pump is the average of the research and motor octane numbers:

  \[
  \text{Antiknock index} = \frac{\text{RON} + \text{MON}}{2}
  \]

- The motor octane number is always higher because it uses more severe operating conditions: higher inlet temperature and more spark advance.

- The automobile manufacturers specify the minimum fuel ON that will resist knock throughout the engine’s operating speed and load range.
Knock Characteristics of Various Fuels

<table>
<thead>
<tr>
<th>Formula</th>
<th>Name</th>
<th>Critical $r$</th>
<th>RON</th>
<th>MON</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH$_4$</td>
<td>Methane</td>
<td>12.6</td>
<td>120</td>
<td>120</td>
</tr>
<tr>
<td>C$_3$H$_8$</td>
<td>Propane</td>
<td>12.2</td>
<td>112</td>
<td>97</td>
</tr>
<tr>
<td>CH$_4$O</td>
<td>Methanol</td>
<td>-</td>
<td>106</td>
<td>92</td>
</tr>
<tr>
<td>C$_2$H$_6$O</td>
<td>Ethanol</td>
<td>-</td>
<td>107</td>
<td>89</td>
</tr>
<tr>
<td>C$<em>8$H$</em>{18}$</td>
<td>Isooctane</td>
<td>7.3</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Blend of HCs</td>
<td>Regular gasoline</td>
<td></td>
<td>91</td>
<td>83</td>
</tr>
<tr>
<td>n-C$<em>7$H$</em>{16}$</td>
<td>n-heptane</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

For fuels with antiknock quality better than octane, the octane number is:

$$\text{ON} = 100 + 28.28T / \left[ 1.0 + 0.736T + (1.0 + 1.472T - 0.035216T^2)^{1/2} \right]$$

where $T$ is milliliters of tetraethyl lead per U.S. gallon
Fuel Additives

Chemical additives are used to raise the octane number of gasoline.

The most effective antiknock agents are lead alkyls;
(i) Tetraethyl lead (TEL), $(\text{C}_2\text{H}_5)_4\text{Pb}$
(ii) Tetramethyl lead (TML), $(\text{CH}_3)_4\text{Pb}$

In 1959 a manganese antiknock compound known as MMT was introduced to supplement TEL (used in Canada since 1978).

About 1970 low-lead and unleaded gasoline were introduced over toxicological concerns with lead alkyls (TEL contains 64% by weight lead).

Alcohols such as ethanol and methanol have high knock resistance.

Since 1970 another alcohol methyl tertiary butyl ether (MTBE) has been added to gasoline to increase octane number. MTBE is formed by reacting methanol and isobutylene.
Effect of Fuel-air Dilution

If the fuel-air mixture is leaned out with excess air or is diluted with increasing amounts of residual gas or exhaust gas recycle burn time increases and the cycle-by-cycle fluctuations in the combustion process increases.

Eventually a point is reached where engine operation becomes unstable. This point defines the engine’s stable operating limit.

With no or little dilution combustion occurs prior to the exhaust valve opening consistently cycle after cycle.

With increasing dilution first in a fraction of the cycles the burns are so slow that combustion is only just completed prior to the exhaust valve opening.

As dilution increases further, in some cycles combustion is not complete prior to the exhaust valve opening and flame extinguishment before all the fuel is burned. Finally misfire cycles start to occur where the mixture is not ignited.

As the dilution is further increased the proportion of partial burns and misfires increase to a point where the engine no longer runs.
Effect of Fuel-air Dilution

Leaner mixture needs more spark advance since burn time longer - Set spark timing for maximum brake torque (MBT).

Along MBT curve increasing excess air we reach partial burn limit when not all cycles result in complete burn and then ignition limit - misfires start to occur.
**CI Engine combustion**

In a CI engine the fuel is sprayed directly into the cylinder - the fuel-air mixture ignites spontaneously.

These photos are taken under CI engine conditions with swirl air flow

- **0.4 ms after ignition**
- **3.2 ms after ignition**
- **3.2 ms after ignition**
- **Late in combustion process**
In Cylinder Measurements

This graph shows the fuel injection flow rate, net heat release rate and cylinder pressure for a direct injection CI engine.
CI Engine Combustion

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.

*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.
Four Stages of CI Engines Combustion
**CI Engine Types**

*Two basic categories of CI engines:*

i) **Direct-injection** – have a single open combustion chamber into which fuel is injected directly

ii) **Indirect-injection** – chamber is divided into two regions and the fuel is injected into the “pre-chamber” which is connected to the main chamber via an orifice, or one or more orifices.

- 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 products/fuel blowdown and mix with main chamber air.
Types of CI Engines

Direct injection:
- quiescent chamber
- swirl in chamber

Indirect injection:
- turbulent and swirl pre-chamber
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
Combustion Characteristic

Combustion occurs throughout the chamber over a range of equivalence ratios dictated by the fuel-air mixing before and during the combustion phase.

Most of the combustion occurs under very rich conditions within the head of the jet, which results in production a considerable amount of solid carbon (soot).
**Ignition Delay**

- Ignition delay is defined as the time (or crank angle interval) from when the fuel injection starts to the onset of combustion.

- 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 diam., 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 autoignition phenomenon in premixed fuel-air, only more complex since **heterogeneous reactions** (reactions occurring on the liquid fuel drop surface) also occur.
**Fuel Ignition Quality**

- The ignition characteristics of the fuel affect the ignition delay.

- The ignition quality of a fuel is defined by its **cetane number** CN.

- For *low* cetane fuels the ignition delay is long and most of the fuel is injected before autoignition and rapidly burns, under extreme cases this produces an audible knocking sound referred to as “diesel knock”.

- For *high* cetane fuels the ignition delay is short and very little fuel is injected before autoignition, the heat release rate is controlled by the rate of fuel injection and fuel-air mixing – smoother engine operation.
Cetane Number

✓ The method used to determine the ignition quality in terms of CN is analogous to that used for determining the antiknock quality using the ON.

✓ The cetane number scale is defined by blends of two pure hydrocarbon reference fuels.

✓ By definition, isocetane (heptamethylnonane, HMN) has a cetane number of 15 and cetane (n-hexadecane, C_{16}H_{34}) has a value of 100.

✓ In the original procedures a-methylnaphtalene (C_{11}H_{10}) with a cetane number of zero represented the bottom of the scale.

✓ The higher the CN the better the ignition quality, i.e., shorter ignition delay.

✓ The cetane number is given by:

\[
CN = (\% \text{ hexadecane}) + 0.15 (\% \text{ HMN})
\]
**Cetane Number Measurement**

The method to measure CN uses a standardized single-cylinder engine with variable compression ratio.

The operating condition is:

- Inlet temperature (°C) 65.6
- Speed (rpm) 900
- Spark advance (°BTC) 13
- Coolant temperature (°C) 100
- Injection pressure (MPa) 10.3

With the engine running at these conditions on the test fuel, the compression ratio is varied until combustion starts at TC, ignition delay period of 13°.

The above procedure is repeated using blends of cetane and HMN. The blend that gives a 13° ignition delay with the same compression ratio is used to calculate the test fuel cetane number.
Cetane versus Octane Number

The octane number and cetane number of a fuel are inversely correlated.

Gasoline is a poor diesel fuel and vice versa.
Factors Affecting Ignition Delay

**Injection timing** – At normal engine conditions the minimum delay occurs with the start of injection at about 10-15 BTC.

The increase in the delay time with earlier or later injection timing occurs because of the air temperature and pressure during the delay period.

**Injection quantity** – For a CI engine the air is not throttled so the load is varied by changing the amount of fuel injected.

Increasing the load (bmeP) increases the residual gas and wall temperature which results in a higher charge temperature at injection which translates to a decrease in the ignition delay.

**Intake air temperature and pressure** – an increase in ether will result in a decrease in the ignition delay, an increase in the compression ratio has the same effect.