Spark discharge characteristics

Fig. 9-39
Schematic of voltage and current variation with time for conventional coil spark-ignition system.
Flame Kernel Development (SAE Paper 880518)

- Single cycle flame sequence
  - Flame from 4 consecutive cycles at fixed time after spark
  - $\lambda=1$, $\theta_{spk}=40^\circ$ BTC, 1400 rpm, vol. eff. = 0.29

Energy associated with Spark Discharge, Combustion and Heat Loss

- Cycle 1
- Cycle 2
- Cycle 3
- Cycle 4

Graph showing energy release over time after spark onset
Ignition and Flame Development Process

1. Spark discharge creates a high temperature plasma kernel which expands rapidly (1mm, 100 μs).

2. The hot reactive gas at the outer edge of this kernel causes the adjacent fuel-air mixture to ignite, creating an outward propagating flame which is almost spherical.

3. As the flame grows larger, the flame surface is distorted by the turbulence of the fluid motion. A wrinkled laminar flame results.

4. Because of the significant surface area enhancement by the wrinkling, the locally laminar “turbulent” flame burns rapidly.

Schematic of entrainment-and-burn model

Fig. 14-12
**SI engine flame propagation**

**Entrainment-and-burn model**

Rate of entrainment:

\[
\frac{dm_e}{dt} = \rho_u A_f S_L + \rho_u A_f u_T \left(1 - e^{-t/\tau_b}\right)
\]

- Laminar diffusion through flame front
- Turbulent entrainment

Rate at which mixture burns:

\[
\frac{dm_b}{dt} = \rho_u A_f S_L + \frac{m_e - m_b}{\tau_b}; \quad \tau_b = \frac{\ell_T}{S_L}
\]

- Laminar frontal burning
- Conversion of entrained mass into burned mass

Critical parameters: \(u_T\) and \(\ell_T\)

---

**SI Engine design and operating factors affecting burn rate**

1. **Flame geometry:**
   - The frontal surface area of the flame directly affects the burn rate. This flame area depends on flame size, combustion chamber shape, spark plug location and piston position.

2. **In-cylinder turbulence during combustion:**
   - The turbulence intensity and length scale control the wrinkling and stretching of the flame front, and affect the effective burning area. These parameters are determined largely by the intake generated flow field and the way that flow changes during compression.

3. **Mixture composition and state:**
   - The local consumption of the fuel-air mixture at the flame front depends on the laminar flame speed \(S_L\). The value of \(S_L\) depends on the fuel equivalence ratio, fraction of burned gases in the mixture (residual plus EGR), and the mixture temperature and pressure.
Cycle-to-cycle variations

Fig. 9-31
Measured cylinder pressure and calculated gross heat-release rate for ten cycles in a single-cylinder SI engine operating at 1500 rpm, Φ = 1.0, MAP = 0.7 bar, MBT timing 25°BTC

Cycle-to-cycle change in combustion phasing
SI ENGINE CYCLE-TO-CYCLE VARIATIONS

Phases of combustion
1. Early flame development
2. Flame propagation
3. Late stage of burning

Factors affecting SI engine cycle-to-cycle variations:
(a) Spark energy deposition in gas (1)
(b) Flame kernel motion (1)
(c) Heat losses from kernel to spark plug (1)
(d) Local turbulence characteristics near plug (1)
(e) Local mixture composition near plug (1)
(f) Overall charge components - air, fuel, residual (2, 3)
(g) Average turbulence in the combustion chamber (2, 3)
(h) Large scale features of the in-cylinder flow (3)
(i) Flame geometry interaction with the combustion chamber (3)

Cycle distributions

Very Slow-burn cycles

Charge and combustion duration variations

Partial burn – substantial combustion inefficiency (10-70%)
Misfire – significant combustion inefficiency (>70%)
(No definitive value for threshold)
Knock

Processes
• Auto-ignition
• Rapid heat release
• Pressure oscillation

Consequences
• Audible noise
• Damage to combustion chamber in severe knock

How to “burn” things?
Reactants → Products

Premixed
• Premixed flame
  – Examples: gas grill, SI engine combustion
• Homogeneous reaction
  – Fast/slow reactions compared with other time scale of interest
  – Not limited by transport process
• Detonation
  – Pressure wave driven reaction

Non-premixed
• Diffusion flame
  – Examples: candle, diesel engine combustion
SI engine Combustion

Normal combustion
• Spark initiated premixed flame

Abnormal combustion
• Pre-ignition (“diesel”)
  – Ignition by hot surfaces or other means
• End gas knock (“spark knock”)
  – Compression ignition of the not-yet-burned mixture (end gas)
  – Affected by spark timing

Heat release rate and pressure wave
• When acoustic expansion is not fast enough to alleviate local pressure buildup due to heat release, pressure wave develops

\[
\dot{q} = \text{Heat release per unit volume over sphere of radius } R \\
a = \text{Sound speed} \\
\text{Criterion for setting up pressure wave:} \\
\dot{q} \geq \frac{3\gamma \cdot a \cdot p}{\gamma - 1 \cdot R}
\]
Pressure oscillations observed in engine knock

Single cylinder engine, 381 cc displacement; 4000 rpm, WOT

Acoustic modes

Spectrogram of 4 valve engine knock pressure data
(2L I-4 engine; CR=9.6)

Calculated acoustic frequency of modes by FEM

SAE Paper 980893
Steps to Audible Knock

Heavy Knock/ detonation

- Rapid combustion of stoichiometric mixture at compressed condition
  - Approximately constant volume
  - Local P ~ 100 to 150 bar
  - Local T > 2800°K
- High pressure and high temperature lead to structural damage of combustion chamber
Knock originates in the extremely rapid release of much of the fuel chemical energy contained in the end-gas of the propagating turbulent flame, resulting in high local pressures. The non-uniform pressure distribution causes strong pressure waves or shock waves to propagate across and excites the acoustic modes of the combustion chamber.

When the fuel-air mixture in the end-gas region is compressed to sufficiently high pressures and temperatures, the fuel oxidation process — starting with the pre-flame chemistry and ending with rapid heat release — can occur spontaneously in parts or all of the end-gas region.

Most evidence indicates that knock originates with the auto-ignition of one or more local regions within the end-gas. Additional regions then ignite until the end-gas is essentially fully reacted. The sequence of processes occur extremely rapidly.
Knock chemical mechanism

CHAIN BRANCHING EXPLOSION

Chemical reactions lead to increasing number of radicals, which leads to rapidly increasing reaction rates

<table>
<thead>
<tr>
<th>Chain Initiation</th>
<th>Formation of Branching Agents</th>
</tr>
</thead>
<tbody>
<tr>
<td>RH + O₂ → ·R + HO₂</td>
<td>R·O₂ + RH → ROOH + ·R</td>
</tr>
<tr>
<td></td>
<td>R·O₂ → R·CHO + R·O</td>
</tr>
<tr>
<td>Chain Propagation</td>
<td>Degenerate Branching</td>
</tr>
<tr>
<td>·R + O₂ → R·O₂, etc.</td>
<td>ROOH → R·O + ·OH</td>
</tr>
<tr>
<td></td>
<td>R·CHO + O₂ → R·CO + HO₂</td>
</tr>
</tbody>
</table>

Ignition delay for primary reference fuels

(Adapted from data of Fieweger et al, C&F 109)
Ignition delay kinetics

Propagation
\[ R + O_2 \rightarrow RO_2 \]
\[ RO_2 \rightarrow ROOH (\text{isomerization}) \]
\[ ROOH + O_2 \rightarrow OOROHH \]
\[ OOROHH \rightarrow O=ROOH + OH \]

Degenerate Branching
\[ O=ROOH \rightarrow O=RO + OH \]

Initiation
\[ RH + O_2 \rightarrow R + HO_2 \]

Low temperature

Branching agent (hydroperoxyl carbonyl species)

High temperature

Branching agent (hydrogen peroxide)

Livengood and Wu integral

\[ 1 = \int_0^t \frac{dt}{\tau(p(t), T(t))} \]

NTC regime
Temperature high enough to shift formation of RO_2 to H_2O_2, but not high enough for H_2O_2 decomposition

Low temperature

Temperature high enough to shift formation of RO_2 to H_2O_2, but not high enough for H_2O_2 decomposition

High temperature

5th Combustion Symposium, 1954
FUEL FACTORS

• The auto-ignition process depends on the fuel chemistry.

• Practical fuels are blends of a large number of individual hydrocarbon compounds, each of which has its own chemical behavior.

• A practical measure of a fuel's resistance to knock is the octane number. High octane number fuels are more resistant to knock.

Types of hydrocarbons
(See text section 3.3)

PARAFFINS

Butane
The carbon atoms in paraffins are held together chemically by single bonds. Paraffins have the general formula \( \text{C}_n\text{H}_{2n+2} \) with "n" indicating the number of carbon atoms.

OLEFINs

cis-2-Butene
Olefins are similar to paraffins, but they have two fewer hydrogen atoms and contain one double bond between two of the carbon atoms. Olefins have the general formula \( \text{C}_n\text{H}_{2n} \). They rarely occur naturally in crude oil, but are formed in the refining process. Olefins may also be cyclic, resembling a naphthene with a double bond.

NAPHTHENES

Cyclohexane
Naphthenes are also called "cycloparaffins," because the carbon atoms are arranged in a ring structure—usually of five or six carbon atoms. If all the carbon atoms are held together by single bonds, naphthenes have the same general formula as olefins, \( \text{C}_n\text{H}_{2n} \).

NAPHTHENES

Cylohexane

Cyclopentane

 iso-Octane

 AROMATICS

 Benzene
Aromatics are odorless, ring-type hydrocarbons. The carbon atoms are joined by "aromatic" bonds, which are actually hybrids of single and double bonds.

ISOmers

There is one more thing you should know about paraffins and olefins. Paraffins with four or more carbon atoms can exist in more than one form. Butane, with four carbon atoms, is the simplest member of the paraffins in which it is possible to form two or more distinctly different chemical structures using the same number of hydrogen and carbon atoms. These variations are called isomers. For example, normal octane is a straight-chain hydrocarbon. It has 8 carbon and 18 hydrogen atoms and it looks like this:

\[
\text{H}_2\text{C} - \text{C} - \text{CH}_2 - \text{CH}_2 - \text{CH}_2 - \text{CH}_2 - \text{CH}_2 - \text{CH}_2 - \text{CH}_2 - \text{H}
\]

iso-Octane

Isomers do not have the same properties. Isooctane is less likely to knock than normal octane—it has an RON of 100, compared to only 95 for its straight-chain cousin. Not surprisingly, it has become a standard for rating the performance of a gasoline.
Knock tendency of individual hydrocarbons

Critical compression ratio for incipient knock at 600 rpm and 450 K coolant temperature for hydrocarbons

Fig 9-69

Fuel anti-knock rating
(See table 9.6 for details)

- Blend primary reference fuels (iso-octane and normal heptane) so its knock characteristics matches those of the actual fuel.
- Octane no. = % by vol. of iso-octane
- Two different test conditions:
  - Research method: 52°C (125°F) inlet temperature, 600 rpm
  - Motor method: 149°C (300°F) inlet temperature, 900 rpm
Octane Requirement Increase


ACS Vol. 36, #1, 1991
Knock control strategies

1. Provide adequate cooling to the engine
2. Use intercooler on turbo-charged engines
3. Use high octane gasoline
4. Anti-knock gasoline additives
5. Fuel enrichment under severe condition
6. Use knock sensor to control spark retard so as to operate close to engine knock limit
7. Fast burn system
8. Gasoline direct injection
Anti-knock Agents

Alcohols
Methanol \( \text{CH}_3\text{OH} \)
Ethanol \( \text{C}_2\text{H}_5\text{OH} \)
TBA (Tertiary Butyl Alcohol) \( (\text{CH}_3)_3\text{COH} \)

Ethers
MTBE (Methyl Tertiary Butyl Ether) \( (\text{CH}_3)_3\text{COCH}_3 \)
ETBE (Ethyl Tertiary Butyl Ether) \( (\text{CH}_3)_3\text{COC}_2\text{H}_5 \)
TAME (Tertiary Amyl Methyl Ether) \( (\text{CH}_3)_2(\text{C}_2\text{H}_5)\text{COCH}_3 \)

Adiabatic cooling of gasoline/ethanol mixture

Preparing a stoichiometric mixture from air and liquid fuel

Note that evaporation stops when temperature drops to dew point of the fuel in vapor phase.
Sporadic Pre-ignition (super-knock)

- Phenomenon observed at very high load (18-25 bar bmep)
- Sporadic occurrence (one event every 10's of thousands of cycles)
- Each event may be one or more knocking cycles
- Mechanism not yet defined (oil, deposit, …?)

SI Engine Knock

1. Knock is most critical at WOT and at low speed because of its persistence and potential for damage. Part-throttle knock is a transient phenomenon and is a nuisance to the driver.

2. Whether or not knock occurs depends on engine/fuel/vehicle factors and ambient conditions (temperature, humidity). This makes it a complex phenomenon.

3. To avoid knock with gasoline, the engine compression ratio is limited to approximately 12.5 in PFI engines and 13.5 in DISI engines. Significant efficiency gains are possible if the compression ratio could be raised. (Approximately, increasing CR by 1 increases efficiency by one percentage point.)

4. Feedback control of spark timing using a knock sensor is increasingly used so that SI engine can operate close to its knock limit.