Presentation contents

Engine combustion regimes
- SI Engines, turbulent premixed combustion
- CI Engines, turbulent mixing controlled combustion
- New regimes: HCCI, RCCI, Dual Fuel

SI and CI Engine Fuels, alternative fuels
- SI Engine fuels
- CI Engine fuels
- Alternative fuels

Reactivity
Fuel discussion and Outlook
Engine Combustion Regimes

SI Engines, turbulent premixed combustion
CI Engines, turbulent mixing controlled combustion
New regimes in LTC area: HCCI, RCCI, Dual Fuel, PPC
SI engines, turbulent premixed combustion

Turbulence driven flame propagation controls combustion

Physics in main role in combustion and in the charge preparation

CI engines, turbulent mixing controlled combustion

Fuel spray induced mixing controls the combustion.

Spray physics in a big role

New combustion regimes

- Homogenous Charge Compression Ignition (HCCI)
- Reactivity Controlled Compression Ignition (RCCI)
- Dual Fuel Combustion (DF)
- Partially Premixed Combustion (PPC)

Low Temperature Combustion (LTC) idea is for common for all of these.

Engine combustion regimes

- Diesel combustion
  - controlled heat release (mixing)
  - controlled combustion timing
  - wide load range
  - high efficiency (relative to SI)
  - NOx and PM emissions

- Spark ignition (SI) combustion
  - controlled heat release (flame propagation)
  - controlled combustion timing
  - wide load range
  - three-way catalyst
  - low efficiency (relative to diesel)

Gurpreet Singh
DOE, USA
Dual Fuel Combustion

Figure: Wärtsilä
Dual Fuel Combustion

Argonne video:

https://www.youtube.com/watch?v=WvISTEeckto

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Fuels and engine combustion

- SI and CI combustion has been largely influenced by crude oil properties

- Striving away from crude oil based fuel gives us a new degree of freedom

- New combustion regimes with a new set of engine parameters could be chosen for alternative fuels
Petroleum distillation tower

<table>
<thead>
<tr>
<th>Fraction</th>
<th>Number of carbons</th>
<th>Boiling point range</th>
<th>Uses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heats</td>
<td>1–4</td>
<td>0–30°C</td>
<td>Bottled and natural gas</td>
</tr>
<tr>
<td>Naphthas</td>
<td>5–10</td>
<td>30–180°C</td>
<td>Gasoline</td>
</tr>
<tr>
<td>Kerosenes</td>
<td>10–16</td>
<td>180–260°C</td>
<td>Kerosene for home heaters, jet fuel</td>
</tr>
<tr>
<td>Gas oils</td>
<td>16–60</td>
<td>260–350°C</td>
<td>Diesel fuel, feedstock for cracking</td>
</tr>
<tr>
<td>Lubricants</td>
<td>&gt;60</td>
<td>350–575°C</td>
<td>Motor oil, feedstock for cracking</td>
</tr>
<tr>
<td>Fuel oil</td>
<td>&gt;70</td>
<td>&gt;490°C</td>
<td>Candles, fuel oil for ships and power stations</td>
</tr>
<tr>
<td>Asphalt</td>
<td>&gt;80</td>
<td>&gt;580°C</td>
<td>Roofing tar, road tar</td>
</tr>
</tbody>
</table>

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SI Engine Fuels

Easy mixing with air
Resistance for autoignition
SI engine fuels

- Lower heating value LHV
- Density
- Viscosity
- Vapor pressure
- Heat of evaporation
- Molar mass
- Oxygen content
- Reactivity resistance i.e. low reactivity
- Octane Number (ON)
- Gasoline Carbon Number = 4-12
CI engine fuels

Easy injection with high momentum and good spray formation for efficient mixing of fuel vapor and air

Good ignitability: high reactivity
CI engine fuels

Lower heating value LHV
Density
Viscosity
Vapor pressure
Heat of evaporation
Molar mass
Oxygen content
Reactivity: high reactivity
Cetane Number (CN)
Diesel Oil Carbon Number = 15–19
RCCI and DF fuels

- Low reactivity ”SI engine like” fuel like is the main fuel and it is premixed. High reactivity ”CI engine like” fuel is sprayed and act as the combustion initiating fuel.

- In RCCI the combustible mixture with two fuels is made before combustion starts = early injection of high reactivity fuel. DF combustion is clearly started by the high reactivity spray = late injection.

- Many fuel combinations will work out, even SI fuels with very low ignitability will be applicable aslo very lean premixed charges would be applicable.

- Reactivity of fuels play a new role.
No single index for reactivity

- Octane Number - autoignition resistance
- Cetane Number - ignitability
- Various Indexes
- CCAI for heavy fuel
- Flammability
- IQT
Octane Number


CFR Octane Rating Unit
**Octane Number measurement**

<table>
<thead>
<tr>
<th></th>
<th>Research method</th>
<th>Motor method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inlet temperature</td>
<td>50°C</td>
<td>149°C</td>
</tr>
<tr>
<td>Inlet pressure</td>
<td>Atmospheric</td>
<td></td>
</tr>
<tr>
<td>Humidity</td>
<td>0.0036-0.0072 kg/kg dry air</td>
<td></td>
</tr>
<tr>
<td>Coolant temperature</td>
<td></td>
<td>100°C</td>
</tr>
<tr>
<td>Engine speed</td>
<td>600 rpm</td>
<td>900 rpm</td>
</tr>
<tr>
<td>Spark advance</td>
<td>13° BTC (constant)</td>
<td>19-26° BTC (varies with compression ratio)</td>
</tr>
<tr>
<td>Air /fuel ratio</td>
<td>Adjusted for maximum knock</td>
<td></td>
</tr>
</tbody>
</table>
This is not knocking

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What is knocking?

Sudden local heat release is the cause of knocking.

This results in pressure waves oscillating in the cylinder.

Flame front is proceeding at speed c. 20 m/s, pressure wave is proceeding at the speed out sound.
Cetane Number

Cetane Number - Autoignition quality of fuel

The proportion (in % by volume) of n-hexadecane (cetane) in the mixture of n-hexadecane and α-methyl naphthalene. Cetane Number ↑, the fuel’s tendency to ignite ↑.

Test apparatus

CFR Cetane Rating Unit
Cetane Number measurements

Intake air temperature  65.6° C
Injection pressure  10.3 MPa
Coolant temperature  100° C
Engine speed  900 rpm
Injection timing  13° BTC (constant)
Compression ratio  Adjusted to the same ignition delay
Flammability of fuels

Main parameters
- Flash point
- Autoignition temperature
- Flammability limits
Flash point

Flash point is the lowest temperature at which fuel vapor can be ignited by externally supplied ignition.

Determination of flash point -- Pensky-Martens closed cup method
Autoignition temperature

Autoignition temperature is the lowest temperature at which the fuel will spontaneously ignite without an external source of ignition.

Autoignition temperature apparatus
## Flammability of the fuels

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Flash point (°C)</th>
<th>Autoignition Temperature (°C)</th>
<th>Flammability limits (Vol. %)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Lean (Lower)</td>
</tr>
<tr>
<td>Gasoline</td>
<td>-(40~45)</td>
<td>260-460</td>
<td>1.4</td>
</tr>
<tr>
<td>Diesel</td>
<td>50-90</td>
<td>230-254</td>
<td>0.6</td>
</tr>
<tr>
<td>Ethanol</td>
<td>13</td>
<td>423</td>
<td>3.3</td>
</tr>
<tr>
<td>Methanol</td>
<td>11</td>
<td>464</td>
<td>5.5</td>
</tr>
</tbody>
</table>
A new reactivity measure would be desirable to replace

- Octane Number - autoignition resistance
- Cetane Number - ignitability
- Various Indexes
- CCAI for heavy fuel
- Flammability
- IQT
Fuel discussion

- Some CI fuel alternatives
- Some SI fuel alternatives

- Fuels for RCCI and DF?
Some CI fuel alternatives

1. ”Biodiesel” = Fatty Acid Methyl Ester (FAME). Typical example is Rape Seed Methyl Ester (RME)

2. Renewable Diesel: Paraffinic high Cetane Number fuels like Hydrotreated Vegetable Oil (HVO) or Gas to Liquid (GTL) diesel fuel through Fischer-Tropsch process

3. Straight Vegetable Oil (SVO)

4. BioDME
Some CI fuel alternatives

- HVO
- FAME

Fossil diesel fuel:
- Isoparaffins
- Normal paraffins
- Naphthenes
- Aromatics
- Polvaromatics

Fatty acid methyl esters
Some CI fuel alternatives

1. "Biodiesel" = Fatty Acid Methyl Ester (FAME), LVH 38 MJ/kg, density 880 kg/m³, viscosity 4.5 mm²/s @ 40 C, high CN
2. Renewable Diesel: Paraffinic diesel fuel from synthesis or hydrotreatment C15 ... C18, LHV 44 MJ/kg, density 780 kg/m³, viscosity 3 mm²/s @ 40 C, very high CN, Carbon number 15...18
3. Straight Vegetable Oil (SVO), High density 900 kg/m³ and very high viscosity 70 mm²/s @ 20 C (Rapeseed Oil), low ignitability CN -, acid value
4. DME close to LPG, but high reactivity = good diesel fuel
PM and Soot

\[ d = 50 \text{ nm} \]
\[ \text{Coagulation} \]
\[ \text{Surface growth and coagulation} \]
\[ \text{Particle inception} \]
\[ \text{Particle zone} \]

\[ d = 0.5 \text{ nm} \]

\[ \text{Molecular zone} \]

\[ \text{Premixed fuel and oxidizer} \]
Some SI fuel alternatives

1. Ethanol
2. Methanol
3. Higher Alcohols
4. BioGas

Knocking resistance and short heat release key to high efficiency and high power density.
Outlook 1

- Fuel physical properties are important in the charge preparation and mixing process.
- Chemical fuel properties and kinetics are the most important in ignition.
- Combustion is dominated by chemical or physical properties depending on the combustion regime. However, the combustion circumstances (phi-T) has great influence.
- Emissions are dependent to some extent on fuel chemical composition properties, but to a large extent on the combustion circumstances (phi-T)
Outlook 2

- Engine configuration have been dominated by crude oil based fuel properties. However, we should take more freedom to engine combustion development.
- Certain fuel would need a dedicated combustion regime and carefully chosen engine parameters to reach high efficiency and low emissions. "Drop in" fuels mean often heavy compromises. Fuel flexibility would need flexible engines.
- Fuel reactivity is a key issue in the promising new combustion regimes: RCCI and DF-combustion. These new regimes could give us possibilities for even higher efficiencies and still minimum emissions.
References

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and many more …
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