Mechanism of Enhanced Late-Cycle Soot Oxidation

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Project Description

Lund University
- Division of Combustion Engines
- Division of Fluid Mechanics

Politecnico di Milano

Volvo GTT

Volvo Cars

Scania
In Compression Ignition (CI) engines the efficiency and soot emissions are linked to the level of mixing.

- Mixing is controlled by turbulence
- Large scale motions
  - Swirl
  - Tumble
  - Squish
- Shear stresses created by spray
- Piston motion

Increasing the level of mixing will enhance the late-cycle oxidation
Experimental observations

Effect of injection pressure on the late-cycle soot oxidation

Experimental results from an optical engine
Measured at swirl number 1.7
Swirl number is defined as the ratio of air rotational velocity around cylinder center axis and engine rotational crankshaft velocity

Experimental observations

- As the injection pressure increases from 500 to 2000 bar, the soot oxidation is affected
- Despite the increase in maximum soot value, the final soot at late-cycle is drastically reduced
- Effect of turbulence generated by spray?
  - According to these measurements the turbulence of the spray dies within about 5 CAD
  - Energy stored in the large scale motion?
Experimental observations

Mean kinetic Energy at different swirl numbers

Experimental results from an optical engine
Measured at swirl number 1.7
Experimental observations

Comparing swirl number 6.4 to swirl number 1.7

- Higher kinetic energy is stored in the flow due to the spray at higher swirl number
- Effect of injection pressure is pronounced at higher swirl number
- Doubling of the injection pressure increases the mean kinetic energy by 50% during expansion (red and light blue curve) for higher swirl number
- Despite this differences
  - The injection pressure increased late-cycle soot oxidation for both swirl numbers
Experimental cases

The experimental cases considered in this study are from an open-bowl, heavy duty direct ignition engine.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal compression ratio</td>
<td>15.9</td>
</tr>
<tr>
<td>RPM</td>
<td>1200</td>
</tr>
<tr>
<td>Bore diameter</td>
<td>131.0 mm</td>
</tr>
<tr>
<td>Stroke</td>
<td>158 mm</td>
</tr>
<tr>
<td>Clearance (Nominal)</td>
<td>1.0 mm</td>
</tr>
<tr>
<td>Injection hole size</td>
<td>212 µm</td>
</tr>
<tr>
<td>Injection pressure</td>
<td>1500 bar</td>
</tr>
<tr>
<td>Number of holes</td>
<td>6</td>
</tr>
</tbody>
</table>
Experimental cases

Details of the operating condition for the simulated cases; SOI: Start of injection, EOI, End of injection, $\lambda_{cyl}$: In cylinder air to fuel ratio, CO$_2$ ratio: ratio between in cylinder CO$_2$ and stoichiometric CO$_2$, HL: High Load, LL: Low Load.

<table>
<thead>
<tr>
<th>Load</th>
<th>100%</th>
<th>100%</th>
<th>25%</th>
<th>25%</th>
</tr>
</thead>
<tbody>
<tr>
<td>SOI (CAD)</td>
<td>355</td>
<td>355</td>
<td>357</td>
<td>357</td>
</tr>
<tr>
<td>EOI (CAD)</td>
<td>378</td>
<td>377</td>
<td>363.8</td>
<td>363.5</td>
</tr>
<tr>
<td>Mass injected (mg)</td>
<td>48.86</td>
<td>46.67</td>
<td>13.17</td>
<td>13.19</td>
</tr>
<tr>
<td>CO$_2$ ratio</td>
<td>0.232</td>
<td>0.191</td>
<td>0.198</td>
<td>0.291</td>
</tr>
<tr>
<td>Intake temp. (K)</td>
<td>404</td>
<td>404</td>
<td>390</td>
<td>390</td>
</tr>
<tr>
<td>$\lambda_{cyl}$</td>
<td>1.17</td>
<td>1.3</td>
<td>1.49</td>
<td>1.74</td>
</tr>
</tbody>
</table>
To understand the effect of swirl number and in-cylinder flow motions in the late cycle oxidation of soot, a sweep over swirl number, injection pressure and start of injection is performed.

<table>
<thead>
<tr>
<th>Case reference</th>
<th>Load</th>
<th>Swirl Nr.</th>
<th>$\Delta P_{inj}$</th>
<th>$\Delta SOI$</th>
</tr>
</thead>
<tbody>
<tr>
<td>HL1S0SOI0</td>
<td>100%</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>HL1S0SOI0Pinjm50</td>
<td>100%</td>
<td>0</td>
<td>-50%</td>
<td>0</td>
</tr>
<tr>
<td>HL1S0SOI0Pinjp50</td>
<td>100%</td>
<td>0</td>
<td>+50%</td>
<td>0</td>
</tr>
<tr>
<td>HL1S05SOI0</td>
<td>100%</td>
<td>0.5</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>HL1S17SOI0</td>
<td>100%</td>
<td>1.7</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>HL1S34SOI0</td>
<td>100%</td>
<td>3.4</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>HL1S34SOI0Pinjm50</td>
<td>100%</td>
<td>3.4</td>
<td>-50%</td>
<td>0</td>
</tr>
<tr>
<td>HL1S34SOI0Pinjp50</td>
<td>100%</td>
<td>3.4</td>
<td>+50%</td>
<td>0</td>
</tr>
<tr>
<td>HL1S34SOIm3</td>
<td>100%</td>
<td>3.4</td>
<td>0</td>
<td>-3</td>
</tr>
<tr>
<td>HL1S34SOIp3</td>
<td>100%</td>
<td>3.4</td>
<td>0</td>
<td>+3</td>
</tr>
<tr>
<td>HL2S0SOI0</td>
<td>100%</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>HL2S17SOI0</td>
<td>100%</td>
<td>1.7</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>HL2S17SOIm3</td>
<td>100%</td>
<td>1.7</td>
<td>0</td>
<td>-3</td>
</tr>
<tr>
<td>HL2S17SOIp3</td>
<td>100%</td>
<td>1.7</td>
<td>0</td>
<td>+3</td>
</tr>
<tr>
<td>HL2S34SOI0</td>
<td>100%</td>
<td>3.4</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>LL1S0SOI0</td>
<td>25%</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>LL1S17SOI0</td>
<td>25%</td>
<td>1.7</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>LL1S17SOIm3</td>
<td>25%</td>
<td>1.7</td>
<td>0</td>
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<td>25%</td>
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<td>0</td>
<td>+3</td>
</tr>
<tr>
<td>LL1S34SOI0</td>
<td>25%</td>
<td>3.4</td>
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<tr>
<td>LL2S0SOI0</td>
<td>25%</td>
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<td>0</td>
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</tr>
<tr>
<td>LL2S05SOI0</td>
<td>25%</td>
<td>0.5</td>
<td>0</td>
<td>0</td>
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<td>LL2S17SOI0</td>
<td>25%</td>
<td>1.7</td>
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<td>25%</td>
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<td>0</td>
<td>0</td>
</tr>
<tr>
<td>LL2S34SOIm3</td>
<td>25%</td>
<td>3.4</td>
<td>0</td>
<td>-3</td>
</tr>
<tr>
<td>LL2S34SOIp3</td>
<td>25%</td>
<td>3.4</td>
<td>0</td>
<td>+3</td>
</tr>
</tbody>
</table>
Base-line case, Temperature
Pressure traces
Heat release rates

![Graph showing heat release rates for different cases](image)

**Results**

Heat release rates for studied cases are presented in the graph. The graph compares heat release rates for various conditions, demonstrating the impact of different parameters on heat release efficiency.
Soot

Background
Introduction
Studied cases
Results
Acknowledgement

Hesam Fatehi

March 12, 2018
Effect of swirl number on soot

![Graph showing the effect of swirl number on soot production](image_url)
Effect of swirl on NOx
Kinetic energy
Vorticity fields of no swirl and high swirl

HL1 S=0  CAD: 365

HL1 S=3.4  CAD: 365
Vorticity fields of no swirl and high swirl

HL1 S=0

HL1 S=3.4
Vorticity fields of no swirl and high swirl

HL1 S=0

HL1 S=3.4
Vorticity fields of no swirl and high swirl

HL1 S=0

HL1 S=3.4
Vorticity fields of no swirl and high swirl

HL1 S=0

HL1 S=3.4
Vorticity fields of no swirl and high swirl

HL1 S=0

HL1 S=3.4
Soot distribution

HL1 S=0
CAD: 370.000000

HL1 S=3.4
CAD: 370.000000
Soot distribution

HL1 S=0

CAD: 374.0000000

HL1 S=3.4

CAD: 374.0000000
Soot distribution

HL1 S=0
HL1 S=3.4
Soot distribution

HL1 S=0

CAD: 385.000000

HL1 S=3.4

CAD: 394.000000
Temperature Field

HL1 S=0

HL1 S=3.4

CAD: 365

CAD: 365
Temperature Field

HL1 S=0

HL1 S=3.4

CAD: 370

CAD: 370
Temperature Field

HL1 S=0

HL1 S=3.4
Temperature Field

HL1 S=0

HL1 S=3.4

CAD: 380

CAD: 380
Temperature Field

HL1 S=0

HL1 S=3.4
Temperature Field

HL1 S=0

HL1 S=3.4
Air entrainment

To quantify the effect of swirl number on the combustion behaviour, the mixture in the cylinder is divided to three groups:

- where equivalence ratio is less than 0.35 → lean
- where equivalence ratio is between 0.35 and 2 → flameable
- where equivalence ratio is greater than 2 → rich
Air entrainment
Large scale structures

To see the large structure of the flow in the context of mixing:

**The relative motion of the flow field to the oxidisers concentration**

\[ \alpha_{O2} = u \cdot \nabla Y_{O2} \quad \text{and} \quad \alpha_{OH} = u \cdot \nabla Y_{OH} \]

The positive values of these fields represent the depletion of oxidisers towards the higher concentrations (red colors)

The negative values represents the mixing of oxidisers into the fuel rich regions (blue colors)
Large scale structures

HL1 S=0

HL1 S=3.4
Large scale structures

HL1 $S=0$

HL1 $S=3.4$
Correlation between the scalar dissipation rate and soot oxidation
Scalar dissipation rate is normalized by its maximum value
Scalar dissipation rate and soot oxidation

HL1 S=0

HL1 S=3.4
Scalar dissipation rate and soot oxidation

HL1 S=0

HL1 S=3.4
Scalar dissipation rate and soot oxidation

HL1 S=0

HL1 S=3.4
Thank you!

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Questions?