Optical-Engine Study of a
Low-Temperature Combustion Strategy
Employing a Dual-Row, Narrow-Included-Angle Nozzle
and Early, Direct Injection of Diesel Fuel

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Motivation

- Early direct-injection (DI), high-efficiency clean-combustion (HECC) strategies are attractive at moderate loads.

- Why do emissions increase for early-DI strategies that use diesel fuel, when they don’t for a gasoline-like fuel (iso-octane)?

Source: Hwang, Dec, and Sjöberg, SAE 2007-01-4130, Fig. 10
**Experimental Approach:**

*Use Sandia Compression-ignition Optical Research Engine (SCORE)*

<table>
<thead>
<tr>
<th>Research engine</th>
<th>1-cyl. Cat 3176</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injector type</td>
<td>Caterpillar HEUI® A</td>
</tr>
<tr>
<td>Injector model</td>
<td>HIA-450</td>
</tr>
<tr>
<td>Bore</td>
<td>125 mm</td>
</tr>
<tr>
<td>Stroke</td>
<td>140 mm</td>
</tr>
<tr>
<td>Piston bowl diameter</td>
<td>90 mm</td>
</tr>
<tr>
<td>Piston bowl depth</td>
<td>16.4 mm</td>
</tr>
<tr>
<td>Squish height</td>
<td>1.5 mm</td>
</tr>
<tr>
<td>Swirl ratio</td>
<td>0.59</td>
</tr>
<tr>
<td>Displacement per cyl.</td>
<td>1.72 liters</td>
</tr>
<tr>
<td>SCORE comp. ratio</td>
<td>11.8:1</td>
</tr>
</tbody>
</table>

- **15-hole, dual-row nozzle**
  - All orifices 103 μm in diameter
  - 10 orifices in outer row
    - 70° included angle
  - 5 orifices in inner row
    - 35° included angle
High-Speed Optical Diagnostics

- **Spray visualization**
  - Mie (elastic) scattering from liquid-fuel droplets
  - Illumination from high-intensity discharge lamps

- **Natural luminosity (NL)**
  - Signal dominated by incandescence from hot soot

- **Spatially integrated natural luminosity (SINL)**
  - SINL is time-resolved measure of NL
  - Single-element detector
  - Sensitive from 400 – 1070 nm

- **...plus apparent heat release rate (AHRR) and emissions**
Operating Conditions – Baseline

- Baseline condition
  - Constant parameters
    - Speed = 1200 rpm
    - Fuel = #2 ULSD, 45.9 cetane, 34.8 wt% aromatics
  - Swept parameters
    - Start of injection (SOI) = -39.5°
    - Load = 4.82 bar gross IMEP
    - Equivalence ratio = 0.39
    - EGR = 50%
    - Intake temperature = 42 °C
    - Intake pressure = 1.42 bar (abs.)
    - Injection pressure = 142 MPa

- EGR simulated using N₂ and CO₂ addition to match X_{O₂} and c_p of intake mixture with real EGR
### Operating Conditions – Sweep Matrix

<table>
<thead>
<tr>
<th></th>
<th>Injection Timing [°ATDC]</th>
<th>Injection Pressure [MPa]</th>
<th>( \Phi ) [-]</th>
<th>EGR [%]</th>
<th>Intake Temp. [°C]</th>
<th>Load gIMEP [bar]</th>
<th>Boost [bar]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Baseline Condition</strong></td>
<td>-39.5</td>
<td>142</td>
<td>0.39</td>
<td>50</td>
<td>42</td>
<td>4.82</td>
<td>1.418</td>
</tr>
<tr>
<td><strong>Injection Timing Sweep</strong></td>
<td>-69.5 to -29.5</td>
<td>142</td>
<td>0.39</td>
<td>46.6 to 50.2</td>
<td>42</td>
<td>4.82</td>
<td>1.418</td>
</tr>
<tr>
<td><strong>Injection Pressure Sweep</strong></td>
<td>-36.3 to -39.5</td>
<td>47, 95, 142</td>
<td>0.39</td>
<td>50</td>
<td>42</td>
<td>4.82</td>
<td>1.418</td>
</tr>
<tr>
<td><strong>Equivalence Ratio and Boost Sweep</strong></td>
<td>-39.5</td>
<td>142</td>
<td>0.24 to 0.58</td>
<td>50</td>
<td>42</td>
<td>4.82</td>
<td>2.060 to 1.132</td>
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<tr>
<td><strong>EGR and Boost Sweep</strong></td>
<td>-39.5</td>
<td>142</td>
<td>0.39</td>
<td>30 to 70</td>
<td>42</td>
<td>4.82</td>
<td>1.188 to 1.949</td>
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<tr>
<td><strong>Intake Temperature and Boost Sweep</strong></td>
<td>-39.5</td>
<td>142</td>
<td>0.39</td>
<td>32 to 62</td>
<td>4.82</td>
<td>1.373 to 1.508</td>
<td></td>
</tr>
<tr>
<td><strong>Intake Temperature and Equivalence Ratio</strong></td>
<td>-39.5</td>
<td>142</td>
<td>0.39 to 0.41</td>
<td>50</td>
<td>32 to 62</td>
<td>4.82</td>
<td>1.418</td>
</tr>
<tr>
<td><strong>Load and Boost Sweep</strong></td>
<td>-39.5</td>
<td>142</td>
<td>0.39</td>
<td>50</td>
<td>42</td>
<td>3.82 to 5.83</td>
<td>1.203 to 1.629</td>
</tr>
</tbody>
</table>
Early Injections Lead to Liquid Fuel Impinging on Piston Top

SOI = -69.5° ATDC

SOI = -29.5° ATDC

Absolute gross indicated efficiency is ~3% lower than for conventional operation at a similar load
Sometimes Pool Fires Are Observed in Areas Where Liquid Fuel Impinged...

SOI = -69.5° ATDC

Cylinder-Window View

Piston-Window View
...But Sometimes Little or No Evidence of Pool Fires Is Observed

SOI = -39.5° ATDC

Cylinder-Window View

Piston-Window View

Bottom of piston bowl

Reflection from top of bowl-rim window

ID of piston bowl
Pool-Fire Activity (i.e., Peak SINL) Is Separate from the Main Heat-Release Event

Main heat-release event produces little SINL, and peak SINL occurs after majority of heat-release has ended.
Pool-Fire Activity (i.e., Peak SINL) Is Correlated with Emissions

Data from all two-parameter sweeps
A Hypothesis to Explain How Fuel Films, Emissions, and Efficiency Are Linked

- If a bright, luminous pool fire is formed:
  - Fuel-rich regions are producing soot
  - Near-stoichiometric regions around rich regions are producing NO\(_x\)
  - Radiative coupling between flame and fuel-film causes film to more-completely vaporize and burn, yielding lower HC and CO emissions

- If a bright, luminous pool fire is not formed:
  - Hot soot is not being produced in locally richer regions
  - NO\(_x\) may or may not be produced in non-luminous regions, since don’t expect to see soot luminosity from regions with \(\phi < 2\)
  - Lack of radiative heating from flame means incomplete fuel-film vaporization and higher HC and CO emissions

- Non-optimal phasing, incomplete combustion \(\rightarrow\) lower efficiency

- Either way, fuel films lead to problems with emissions and efficiency!
Summary

- Liquid-fuel impingement on in-cylinder surfaces can lead to formation of fuel films
  - Incomplete combustion → lower efficiency
  - Pool fires

- Fuel films can have a strong effect on emissions
  - If they ignite, stoichiometric-to-rich combustion can produce excessive soot and NO\textsubscript{x}
  - If they don’t fully react, can produce elevated HC and CO emissions

- Looking on the bright side
  - Since significant emissions and fuel-consumption increases come from fuel films, eliminating them could enable much-improved performance
  - In-cylinder charge motion and/or a higher-volatility fuel could help

For more information, see SAE 2008-01-2400