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Experimental study of primary atomisation in the near-nozzle region of diesel fuel sprays

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Centre for Automotive Engineering
University of Brighton

14th, July, 2015, Research Workshop
Introduction

1. Objectives
2. Operating conditions
3. Spray A injector
4. Experimental setup
5. Image processing and analysis
6. Results
7. Conclusions
Objectives- Engine Combustion Network

**Experimental Objectives**

- Focus on the near nozzle region within first 10 mm
- Concentrate on non-vaporizing experiments

- Provide boundary conditions for initializing the simulations for both Spray A and Spray B
  - Nozzle geometry
  - Rate of injection
  - Needle lift & off-axis motion
  - Injection pressure vs. time

- Provide data for validation for both Spray A and Spray B
  - Liquid mass distribution at nozzle exit and in the spray region
  - Droplet sizes
  - Qualitative physics to understand the spray processes
  - Liquid penetration

- Assess the uncertainties for all of these parameters
### Operating conditions

<table>
<thead>
<tr>
<th>Exp. Priority</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxygen</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temperature [K]</td>
<td>900</td>
<td>800</td>
<td>1000</td>
<td>1200</td>
<td>700</td>
<td>950</td>
</tr>
<tr>
<td>Density [kg/m³]</td>
<td>22.8</td>
<td>15.2</td>
<td>7.6</td>
<td>45.6</td>
<td>30.4</td>
<td>-</td>
</tr>
<tr>
<td>Inj. Pressure [bar]</td>
<td>1500</td>
<td>1000</td>
<td>500</td>
<td>2000</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Fuel</td>
<td>n-dodecane</td>
<td>n-heptane</td>
<td>77% n-dodecane, 23% m-xylene</td>
<td>50% n-dodecane, 50% iso-octane</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Inj. Duration [ms]</td>
<td>1.5</td>
<td>4</td>
<td>0.5/0.5 dwell/0.5</td>
<td>0.3/0.5 dwell/1.2</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Nozzle</td>
<td>0.090 mm, axial hole</td>
<td>3-hole, 145 angle, Spray B</td>
<td>0.2 mm Spray C</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

**Spray A standard**
- 0%, 15%
- 900 K
- 22.8 kg/m³
- 1500 bar
- n-dodecane
- 1.5 ms
- 0.090 mm, axial hole

**Spray B**
- 13%
- 1000 K
- 7.6 kg/m³
- 500 bar
- 77% n-dodecane, 23% m-xylene
- 0.5/0.5 dwell/0.5
- 0.2 mm Spray C

**Spray C**
- 19%
- 1200 K
- 45.6 kg/m³
- 2000 bar
- 50% n-dodecane, 50% iso-octane
- 0.3/0.5 dwell/1.2
- -

### Fuel temperature at nozzle
- 363 K (90°C) → 403 K (130°C)

### Common rail
- GM Part number 97303659
- Common rail volume/length: 22 cm³/28 cm
- Distance from injector inlet to common rail: 24 cm
- Tubing inside and outside diameters: Inside: 2.4 mm. Outside: 6-6.4 mm.
- Fuel pressure measurement: 7 cm from injector inlet / 24 cm from nozzle

### Legend
- **Completed**
- **In progress**
- **Not met**
Spray A injector

- **Injector: Spray A.2 nozzle #201.02**
  - From second batch of Spray A injectors, purchased by IFPEN (Malbec et al. 2013 [papers.sae.org/2013-24-0037](papers.sae.org/2013-24-0037))
  - New STL file for #201.02 generated by University of Bergamo (Prof. Santini)

<table>
<thead>
<tr>
<th>Injector Serial #</th>
<th>Exit diameter [μm]</th>
<th>K-factor</th>
<th>Inlet radius [μm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>201.02</td>
<td>93.9</td>
<td>1.8</td>
<td>30</td>
</tr>
</tbody>
</table>

X-ray μCT
(University of Bergamo)

Optical microscopy
(University of Brighton)
Experimental setup – Rapid compression machine

- Reciprocating RCM based on Ricardo Proteus (2 stroke engine)
- Operated at 500 rpm
- TDC conditions: 5 MPa, 720 K
- Quiescent air motion at start of injection (no swirl)
- 3 optical accesses
- Multiple injection strategy/injection frequency

Temperature at TDC was computed by Ricardo WAVE by fitting measured ICP with simulated ICP (WAVE)
Experimental setup – Fuel temperature control

Instrumented Siemens injector was used to measure injector tip temperature

- Measured tip temperature: 195-220 °C
- ECN target 90 °C
- Injector cooling was needed

Injector tip and fuel channel temperatures

![Diagram of the injector setup with temperature measurements](image)
Experimental setup – Fuel temperature control

Fuel line temperature as a function of time for cooled and uncooled injectors

- Directly cooled injector stem
- $\Delta T$ tip $\approx$ 80-100 °C
- $130 <$ Tip temperature $<$ 135 °C for 120 min
Experimental setup – High-speed video

Microscope working distance 95 - 122 mm
Microscope NA = 0.156 - 0.20
Microscope DOF = 0.01 - 0.02 mm
Experimental setup – Long distance microscopy

Shadowgraphy setup based on Crua et al. (2015) Fuel 157 doi.org/4F3

- New camera: 29 megapixel (4400x6600 pixels) dual-frame
- Scale factor: 0.56 µm/pixel (2.46x3.70 mm)
- MTF at 10%: 250 cycles/mm → 2 µm object
Test conditions for long-distance microscopy

<table>
<thead>
<tr>
<th>Test condition</th>
<th>Spray A</th>
<th>Spray B</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1500 bar</td>
<td>1500 Bar</td>
</tr>
<tr>
<td></td>
<td>1000 bar</td>
<td>1000 bar</td>
</tr>
<tr>
<td></td>
<td>500 bar</td>
<td>500 bar</td>
</tr>
</tbody>
</table>

- Acquired ~7,400 dual-frame images for Spray A (815 GB)
- Data set covers $x = 0$ to 8 mm ($y = \pm 1.2$ mm; $z = \pm 10$ µm)

- Currently processing for droplet size distributions
- Still need to process velocity fields, and acquire Spray B data
Image processing

1. Convolution with wavelet
2. Threshold at 30% of intensity range
3. Measure droplet’s projected area
4. Calculate eq. diameter $d = \sqrt{A/\pi}$
5. Correct diameters based on NIST-calibrated target (1.9 to 101.6 µm)
Algorithm correctly identifies many of the small liquid structures (left of figure below), without producing significant false positives in blurred regions (right of figure below).
Results: Start of injection – 1500 bar

- Vapour emerges with vortex ring motion
- Followed by liquid jet and droplets
- Droplets present at liquid interface
Results: 0.5 ms after start of injection – 1500 bar

- Droplets visible at spray periphery
- Surrounded by vaporised fuel

- Pressure waves often visible along spray periphery.
- Not expected to occur for multi-hole nozzles, but could affect Spray A droplet formation, mixing and optical resolution.


Results: Steady-state phase 1500 bar

- 1,575 images => 619,756 droplets
- Droplet data merged into 50x50 $\mu$m$^2$ bins
- Droplet count: 200-1000 droplets/bin
- SMD in the optically-thin periphery of the spray is 6 – 8 $\mu$m
Results: Steady-state phase – 1500 bar

Statistics for x = 1, 2, 4, 6 ±0.25 mm (y = ±1.2 mm; z = ±10 µm) from orifice
Analysis – Comparison between 500 and 1500 bar

- Marginally larger SMD at 500 bar, compared to 1500 bar, especially after 6 mm
- Asymmetrical distributions observed in both cases (SMD, drop count, median diameter)
Results: End of injection – 1500 bar

• Large variations in
  – droplet position
  – droplet size
  – droplet shape
Conclusions

- Droplet size distributions measured in near-nozzle, optically-thin ($\approx 100 \, \mu m$), regions
- Droplet sizes appear normally distributed, and independent of radial position
- Processed data available for ECN4

Comparison with simulations

- Data processing is ongoing: can still produce new droplet binning, locations, etc…

Future plans

- Spray B in progress, expected to be completed after ECN4 meeting (September 2015)
- Velocimetry data (Sprays A and B)
- Droplet shape analysis for end of injection (Sprays A and B)
- All raw & processed data will be made public to promote comparison with simulations, and development of new image analysis techniques
Acknowledgments

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BP Global Fuels Technology

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