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Measurement of droplet sizes in the near-nozzle region of an ECN Spray A injector

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Centre for Automotive Engineering
University of Brighton

23rd, September, 2015, UnICEG- The Universities’ Internal Combustion Engines Group
Optical Diagnostics and Sensors applied to IC Engines
Introduction

1. Objectives
2. Operating conditions
3. Spray A injector
4. Experimental setup
5. Image processing and analysis
6. Results
7. Conclusions
### 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>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5</td>
<td></td>
<td>4</td>
<td>2</td>
<td>7</td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td>Spray A standard</td>
<td>0%, 15%</td>
<td>900</td>
<td>22.8</td>
<td>1500</td>
<td>n-dodecane</td>
<td>1.5</td>
<td>0.090 mm, axial hole</td>
</tr>
<tr>
<td>2</td>
<td>21%</td>
<td>800</td>
<td>15.2</td>
<td>1000</td>
<td>n-heptane</td>
<td>4</td>
<td>3-hole, 145 angle, Spray B</td>
</tr>
<tr>
<td>3</td>
<td>13%</td>
<td>1000</td>
<td>7.6</td>
<td>500</td>
<td>77% n-dodecane, 23% m-xylene</td>
<td>0.5/0.5 dwell/0.5</td>
<td>0.2 mm Spray C</td>
</tr>
<tr>
<td>4</td>
<td>19%</td>
<td>1200</td>
<td>45.6</td>
<td>2000</td>
<td>50% n-dodecane, 50% iso-octane</td>
<td>0.3/0.5 dwell/1.2</td>
<td>-</td>
</tr>
<tr>
<td>5</td>
<td>17%</td>
<td>700</td>
<td>30.4</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>6</td>
<td>11%</td>
<td>950</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>7</td>
<td>-</td>
<td>850</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>8</td>
<td>-</td>
<td>1100</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>9</td>
<td>-</td>
<td>750</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

**Legend**

- **Completed**
- **In progress**
- **Not met**

**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
**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

Fuel channel thermocouple
Tip thermocouple

Injector tip and fuel channel temperatures

working range
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 $^\circ$C
- 130$^\circ$C $<$ Tip temperature $<$ 135 $^\circ$C for 120 min
Experimental setup – High-speed video

- Common rail GM (part number 97303659)
- Fuel pressure measurement point
- High-speed camera or high resolution dual frame camera
- K2 DistaMax™ long-distance microscope system
- Light source
- Rapid compression machine
- ECN Spray A coordinate system

Graph showing penetration length vs. time for different conditions:
- Bright 201.02 vapour
- IFPEN 201.02 vapour
- IFPEN 201.02 liquid
Shadowgraphy setup based on Crua et al. (2015) *Fuel* 157 [doi.org/4F3](https://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 \(\Rightarrow\) 2 µm object

![Experimental setup – Long distance microscopy](image-url)
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

### Test conditions for long-distance microscopy

<table>
<thead>
<tr>
<th></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>

<table>
<thead>
<tr>
<th></th>
<th>Spray A</th>
<th>Spray B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Start of injection</td>
<td>acquired,</td>
<td>in progress</td>
</tr>
<tr>
<td>SOI+0.5ms</td>
<td>completed</td>
<td>not planned</td>
</tr>
<tr>
<td>End of injection</td>
<td>processed</td>
<td>in progress</td>
</tr>
</tbody>
</table>

![Diagram of injection system]
Image processing

1. Convolution with wavelet
2. Threshold at 30% of intensity range
3. Measure droplet’s projected area
4. Calculate eq. diameter \( d = \sqrt{\frac{A}{\pi}} \)
5. Correct diameters based on NIST-calibrated target (1.9 to 101.6 µm)
Image processing (0.5 ms after start of injection)

- 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
- Liquid tip becomes more defined (coalescence)
- 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 $\Rightarrow 619,756$ droplets
- Droplet data merged into $50 \times 50 \mu m^2$ bins
- Droplet count: 200-1000 droplets/bin
- SMD in the optically-thin periphery of the spray is $6 – 8 \mu m$

Median diameter $= 5.8 \mu m$
Results: Steady-state phase – 1500 bar

Statistics for $x = 1, 2, 4, 6 \pm 0.25$ mm ($y = \pm 1.2$ mm; $z = \pm 10$ 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 (≈ 100 µm), 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
- 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

**Equipment**

EPSRC Engineering Instrument Pool

BP Global Fuels Technology

**Funding**

BP Global Fuels Technology

EPSRC (grant EP/K020528/1)