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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
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>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>
</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>
</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>
</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>
</tr>
<tr>
<td>5</td>
<td>17%</td>
<td>700</td>
<td>30.4</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>
</tr>
<tr>
<td>7</td>
<td>-</td>
<td>850</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>
</tr>
<tr>
<td>9</td>
<td>-</td>
<td>750</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

*Fuel temperature at nozzle: 363 K (90°C) → 403 K (130°C)*

### Legend

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

- **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)
  - 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
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

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

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**Graph:**
- **Penetration length (mm)** vs **Time (μs)**
  - Bright 201.02 vapour
  - IFPEN 201.02 vapour
  - IFPEN 201.02 liquid
Experimental setup – Long distance microscopy


- 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></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>
<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>

- 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
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
- 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

Pressure wave spacing: 100 to 150 µm
Clusters of droplets surrounded by vapour
Optically thin region ~100 µm
Results: Steady-state phase 1500 bar

- 1,575 images => 619,756 droplets
- Droplet data merged into 50x50 µm² bins
- Droplet count: 200-1000 droplets/bin

- SMD in the optically-thin periphery of the spray is 6 – 8 µm
Results: Steady-state phase – 1500 bar

Statistics for $x = 1, 2, 4, 6 \pm 0.25 \text{ mm}$ ($y = \pm 1.2 \text{ mm}; z = \pm 10 \mu\text{m}$) 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**

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BP Global Fuels Technology

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EPSRC (grant EP/K020528/1)