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

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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>4</th>
<th>2</th>
<th>7</th>
<th>3</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
• **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
Experimental setup – Fuel temperature control

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

- Directly cooled injector stem
- $\Delta T \text{ tip} \approx 80\text{-}100\,^\circ\text{C}$
- $130 < \text{Tip temperature} < 135\,^\circ\text{C}$ for 120 min

Fuel channel temperature, $^\circ\text{C}$

- uncooled
- cooled

ECN target

Time, min

0 20 40 60 80 100 120

Refrigerated bath circulator
Experimental setup – High-speed video

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

Penetration length vs. time graph:

- Brighto 201.02 vapour
- IPEN 201.02 vapour
- IPEN 201.02 liquid

- **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
Acquired ~7,400 dual-frame images for Spray A (815 GB)

- Data set covers $x = 0$ to $8$ mm ($y = \pm 1.2$ mm; $z = \pm 10 \ \mu m$)

- 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)

12bit raw image  Wavelet filter
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 => 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

Median diameter = 5.8 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

**Funding**

BP Global Fuels Technology

EPSRC (grant EP/K020528/1)