Topic 2: Droplet and liquid size measurements in the near-nozzle region

Cyril Crua*, V. Stetsyuk, G. de Sercey – University of Brighton
S. Som, C. Powell, A. Kastengren – Argonne National Laboratory
Droplet size measurements by long-distance microscopy
- University of Brighton: Cyril Crua, Viacheslav Stetsyuk, Guillaume de Sercey

Droplet size measurements by Ultra-Small Angle X-ray Scattering
- Argonne National Laboratory: Chris Powell, Alan Kastengren

Atomization and mixing at elevated conditions
- University of Brighton: Cyril Crua
- Sandia National Laboratories: Julien Manin, Lyle Pickett
Overview

1. Objectives
2. Measurement techniques
3. Spray A measurements
4. Comparison with Spray B
5. Effect of gas pressure and temperature
6. Experimental conclusions and future directions
Use USAXS to probe average droplet size
- Measure number of x-rays scattered as a function of angle
- Slope of curve depends on the shape of the scatterers (rod, plate, sphere)
- Absolute magnitude of the scattering depends on the surface area of the scatterers
- Measured density using radiography
- Can determine Sauter Mean Diameter (diameter of a sphere with the same volume/surface area ratio)
- Measurements are pathlength integrated, space-resolved, and time-averaged over the steady-state period of injection
- Beam size: 100×500 µm
Shadowgraphy setup based on Crua et al. (2015) *Fuel* 157 [doi.org/4F3](https://doi.org/4F3)

- Record shadowgraphs of the sprays
- We measure droplet size and (when possible!) velocity by image processing
- Camera: dual-frame 29 megapixel (ROI = 4400×6600 pixels)
- Scale factor: 0.56 µm/pixel (ROI = 2.46×3.70 mm)
- Resolution: 2 µm at 10% contrast (at optimum conditions)
- Space and time-resolved measurements
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### Injector Spray A #210679

### Some deviations from the standard ‘Spray A’ conditions

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<td>0.5/0.5 dwell/0.5</td>
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<td>0.3/0.5 dwell/1.2</td>
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**Legend**
- Completed
- Not met

- Fuel temperature at nozzle: 338K (65°C) instead of 363 K (90°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
- Accuracy of the measurements is +/- 20% at each measurement location.
- The measurements for this particular injector (Spray A) provide much smaller droplets than previous USAXS measurements (~ 4 µm): Cavitation?
Parametric variations for optical dropsizing

- Injector Spray A #201.02 (Malbec et al. 2013 [papers.sae.org/2013-24-0037])
- Some deviations from the standard ‘Spray A’ conditions

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Fuel temperature at nozzle
- 403 K (130°C) instead of 363 K (90°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
Results – 0.5 ms after start of injection

- Droplets are visible in the optically-thin region of spray periphery, but challenging to measure:
  - Surrounded by density gradients, vaporised fuel, and shock/pressure waves
- Advanced image processing algorithms identifies many of the small liquid structures, without producing significant false positives in blurred parts of the image (lower left figure)

Optically-thin region is narrow, and generally limited to the high-shear and entrainment regions.

Pressure waves are often visible along the spray periphery.

How do they affect droplet formation, mixing and optical resolution?
Droplet sizes appear normally distributed, and somewhat independent of radial position.

- SMD reduces with axial distance.
- Is the optically-thin region dominated by droplets that can be entrained by small-scale eddies in the shear layer?
- If so, then we should expect larger droplets in the centreline than in the shear layers.
• LDM and USAXS give different SMD results at 1, 4 and 6 mm

• This may be real, or partially due to differences between the techniques:
  • USAXS is pathlength-integrated and time-averaged; LDM is space and time-resolved.
  • LDM cannot measure droplets smaller than 2-3µm, so the SMD is biased towards large droplets. The size of droplets may also be overestimated due to low contrast and motion blurring.

• These results represent our best efforts, and they may change as calibration and analysis methods improve. We believe these LDM measurements are an upper limit for the SMD.
Qualitative comparison with Spray B

- During ‘steady state’ (0.5ms after SOI) Spray B appears broadly similar to Spray A
- Droplets are visible in the optically-thin region of spray periphery
  - Also surrounded by density gradients, vaporised fuel, and shock/pressure waves

- Droplet size distributions to be processed soon but, qualitatively, the shear layer structures appear similar to Spray A
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Effect of gas conditions on atomization

**Atomization and classical evaporation**
- Droplets can be seen in the shear layer and at the end of injection
- Droplets deform/oscillate, ligaments converge into spheres
- Droplets diameters progressively reduce, with vapour trails

**Atomization and miscible mixing**
- Cannot resolve droplets in shear layers
- Breakup is observed with droplets visible at the end of injection
- Droplets deform/oscillate, ligaments converge into spheres
- Droplets suddenly spread out and vaporize

n-hexadecane into 900 K, 79 bar, 30.4 kg/m³

n-hexadecane into 1200 K, 107 bar, 30.4 kg/m³
Effect of operating conditions on surface tension

**700 K  Surface tension & classical evaporation**
- Droplet remains spherical, with sharp interface
- Progressive mass transfer from liquid to gas

**1000 K  Surface tension & deformation-accelerated evaporation?**
- Rapid transition from spheroid into stretched fluid
- Disintegration process is initiated at the *wake side* of the droplet

**1200 K  Surface tension initially followed by evaporation and miscible mixing**
- Fluid stretches without a clearly elastic behaviour
- Mixing of two fluids with different densities
n-heptane No significant sign of surface tension
   – Transition to miscible fluid within 500 μm of the nozzle exit

n-dodecane Surface tension initially followed by evaporation and miscible mixing
   – Significant droplet oscillations and deformations
   – Mixes with surrounding gas through a single-phase two-fluid mixing process

n-hexadecane Evaporation followed by miscible mixing
   – Significant droplet oscillations and deformations
   – Disintegration also at the wake side
   – But into three separate chunks of fluid
- Manin et al. (2014) Fuel
  - surface tension criteria
  - transition between atomization and diffusion-controlled mixing

- New results for \( n \)-heptane, \( n \)-dodecane, \( n \)-hexadecane
  - more reliable data \( \Rightarrow \) improved confidence
  - some surface tension at all conditions for \( n \)-dodecane and \( n \)-hexadecane
  - some surface tension for most conditions for \( n \)-heptane
  - transition from classical evaporation to miscible mixing
New findings

- Atomisation and surface tension
  - Evidence of surface tension for all diesel engine-relevant conditions
  - Under certain conditions surface tension appeared negligible and liquid breakup inexistent

- Droplet size distributions
  - Measured in near-nozzle, optically-thin and optically-dense, regions
  - LDM droplet sizes appear normally distributed, and independent of radial position

- Secondary breakup has not been directly observed (limitation of our instruments?)

Near future

- These results represent our best efforts, and **they may change** as calibration and analysis methods improve
- We believe these LDM measurements are an **upper limit** for the ‘true’ SMD of Spray A
- We may need to move away from mean droplet size parameters, unless our instruments can resolve *all* droplet sizes:
  - PDF and droplet count distributions would allow selective, and more detailed, comparisons between experiments and simulations
Towards a better understanding of atomization for both Spray A and Spray B

- **Droplet size distributions**
  1. Time evolution of droplet size distributions (including start & end of injection)?
  2. Need space-resolved data and simulations, especially radial distributions
  3. Need quantification of droplet shapes to better estimate their surface area

- **Shear layer dynamics**
  1. Does local turbulence affect radial droplet size distributions through spatial ‘filtering’?
  2. Need measurements and simulations for vortex size and velocity profiles

- **Boundary conditions**
  1. How do fuel properties influence size and shape distributions?
  2. How does fuel temperature influence size and shape distributions?

- **Physics of atomization**
  1. How do internal flow differences between Spray A and B affect breakup?
  2. Is atomization a single stage breakup process? (or do we need better diagnostics)?