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Original Citation

Stetsyuk, V., Crua, C., de Sercey, G. and Turner, J. (2015) Measurement of droplet sizes in the near-nozzle region of an ECN Spray A injector. In: Optical Diagnostics and Sensors applied to IC Engines (UnICEG meeting), 23rd September 2015, University of Oxford. (Submitted)

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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

EPSRC
Pioneering research and skills

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

ECN 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

Exp. Priority	5	1	4	2	7	3	6
	Oxygen	Temperature [K]	Density [kg/m^3]	Inj. Pressure [bar]	Fuel	Inj. Duration [ms]	Nozzle
Spray A standard	0%, 15%	900	22.8	1500	n-dodecane	1.5	0.090 mm, axial hole
2	21%	800	15.2	1000	n-heptane	4	3-hole, 145 angle, Spray B
3	13%	1000	7.6	500	77% n-dodecane, 23% m-xylene	0.5/0.5 dwell/0.5	0.2 mm Spray C
4	19%	1200	45.6	2000	50% n-dodecane, 50% iso-octane	0.3/0.5 dwell/1.2	-
5	17%	700	30.4	-	-	-	-
6	11%	950	-	-	-	-	-
7	-	850	-	-	-	-	-
8	-	1100	-	-	-	-	-
9	-	750	-	-	-	-	-

Fuel temperature at nozzle	363 K (90°C) ➔ **403 K (130°C)**
Common rail	GM Part number 97303659
Common rail volume/length	22 cm^3/28 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

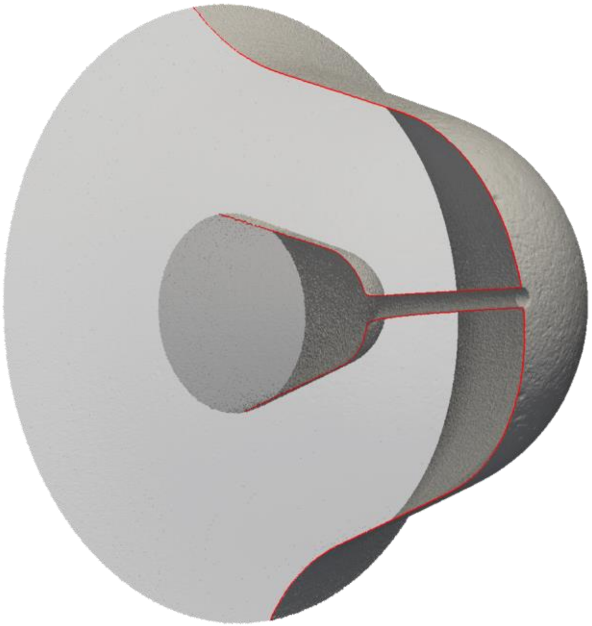
Legend

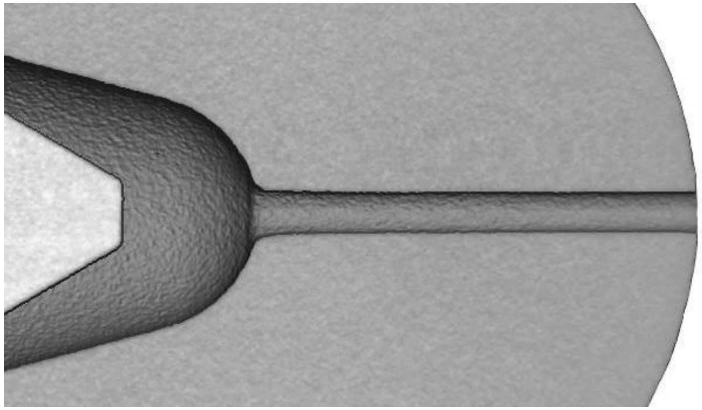
- Completed
- In progress
- Not met

Spray A injector

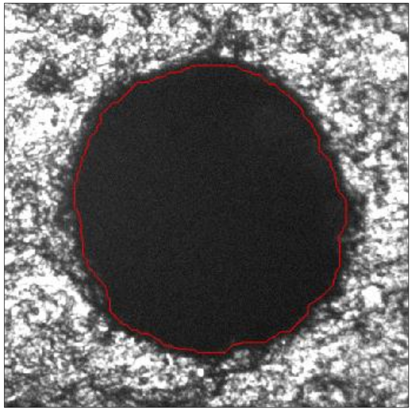
- Injector: **Spray A.2 nozzle #201.02**
  - From second batch of Spray A injectors, purchased by IFPEN (Malbec et al. 2013 papers.sae.org/2013-24-0037)
  - New STL file for #201.02 generated by University of Bergamo (Prof. Santini)

Injector Serial #	Exit diameter [μm]	K-factor	Inlet radius [μm]
201.02	93.9	1.8	30





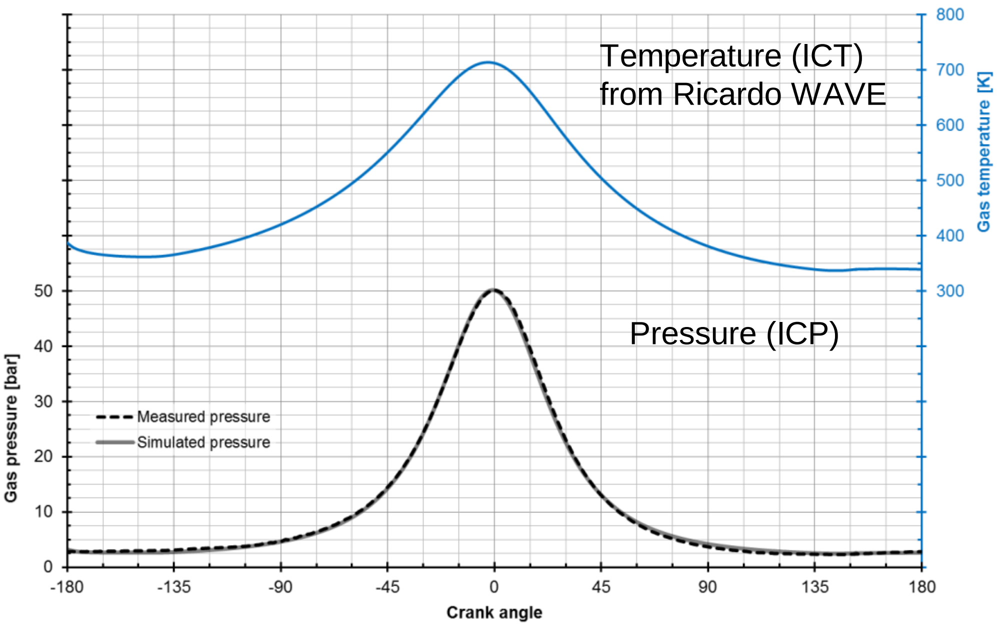
X-ray μCT
(University of Bergamo)

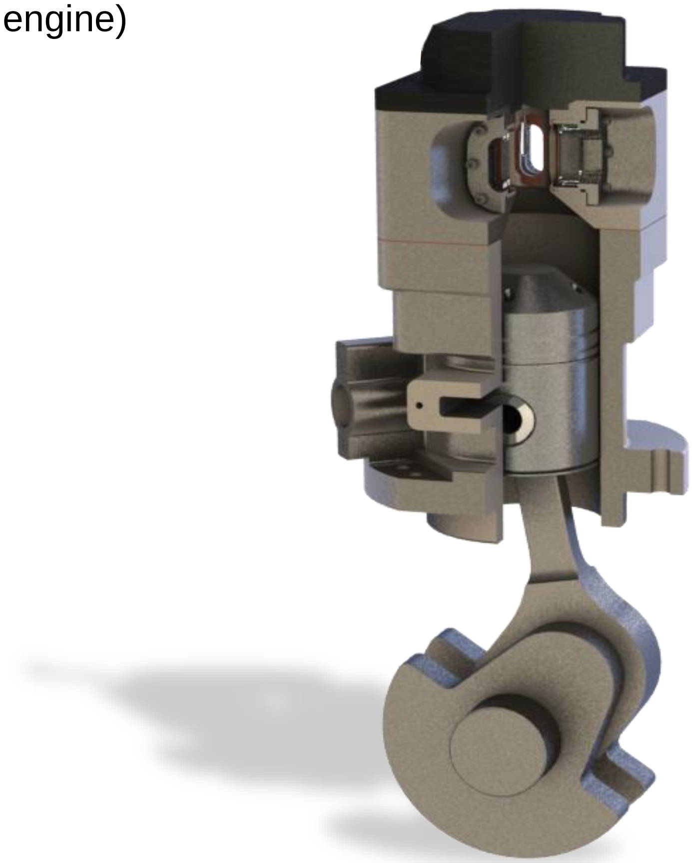


Optical microscopy
(University of Brighton)

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



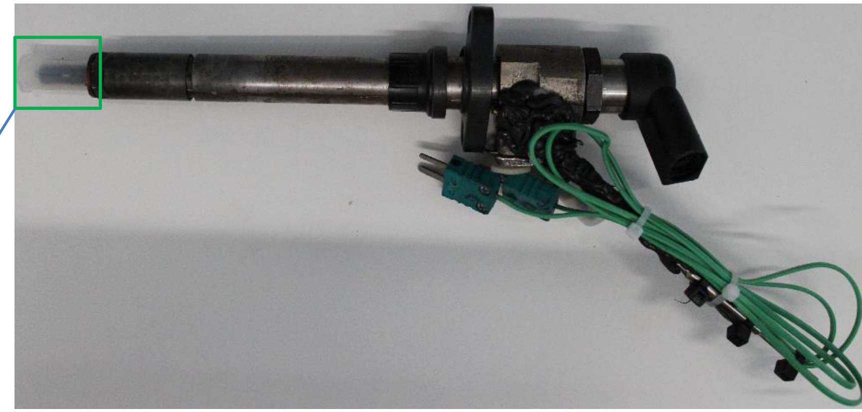


Temperature at TDC was computed by Ricardo WAVE by fitting measured ICP with simulated ICP (WAVE)

Experimental setup – Fuel temperature control

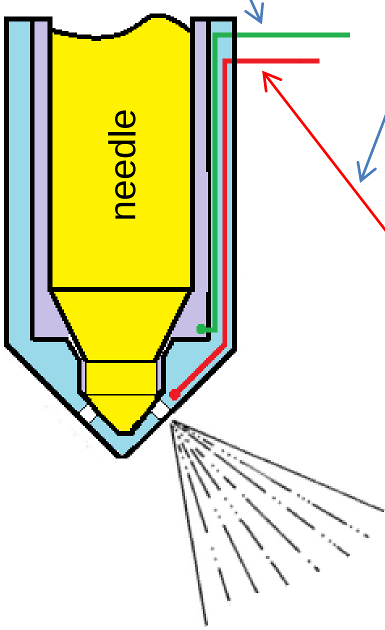
Instrumented Siemens injector was used to measure injector tip temperature

- Measured tip temperature: 195-220 ^{o}C
- ECN target 90 ^{o}C
- Injector cooling was needed

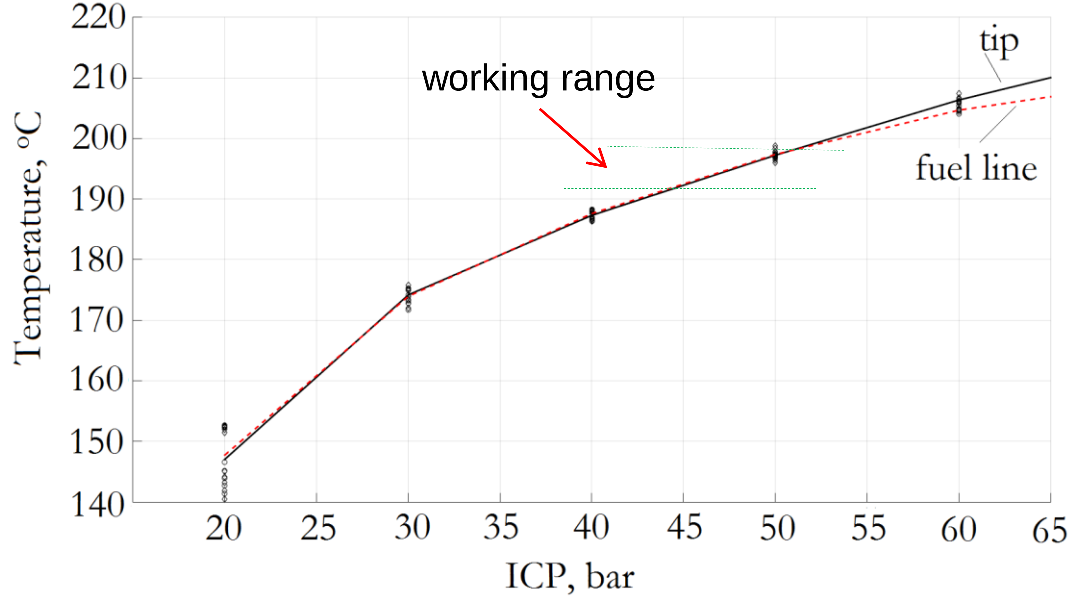


Fuel channel thermocouple

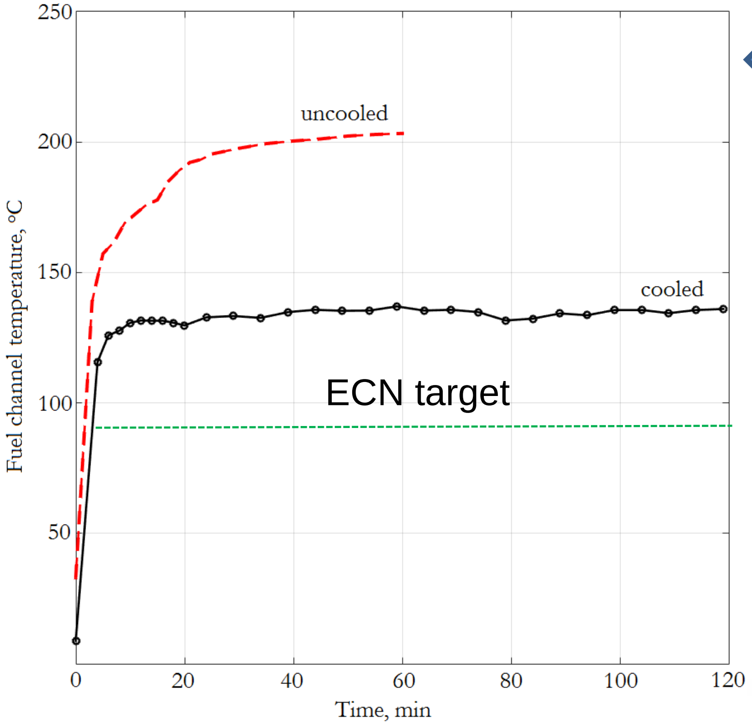
Tip thermocouple



Injector tip and fuel channel temperatures

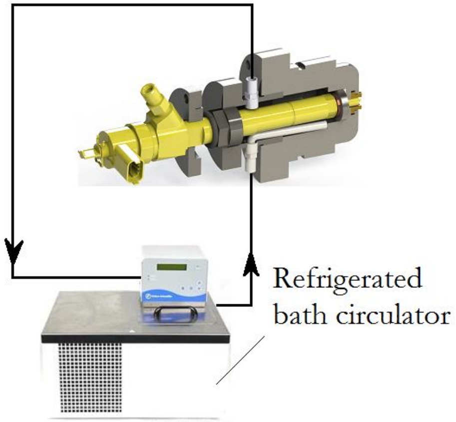


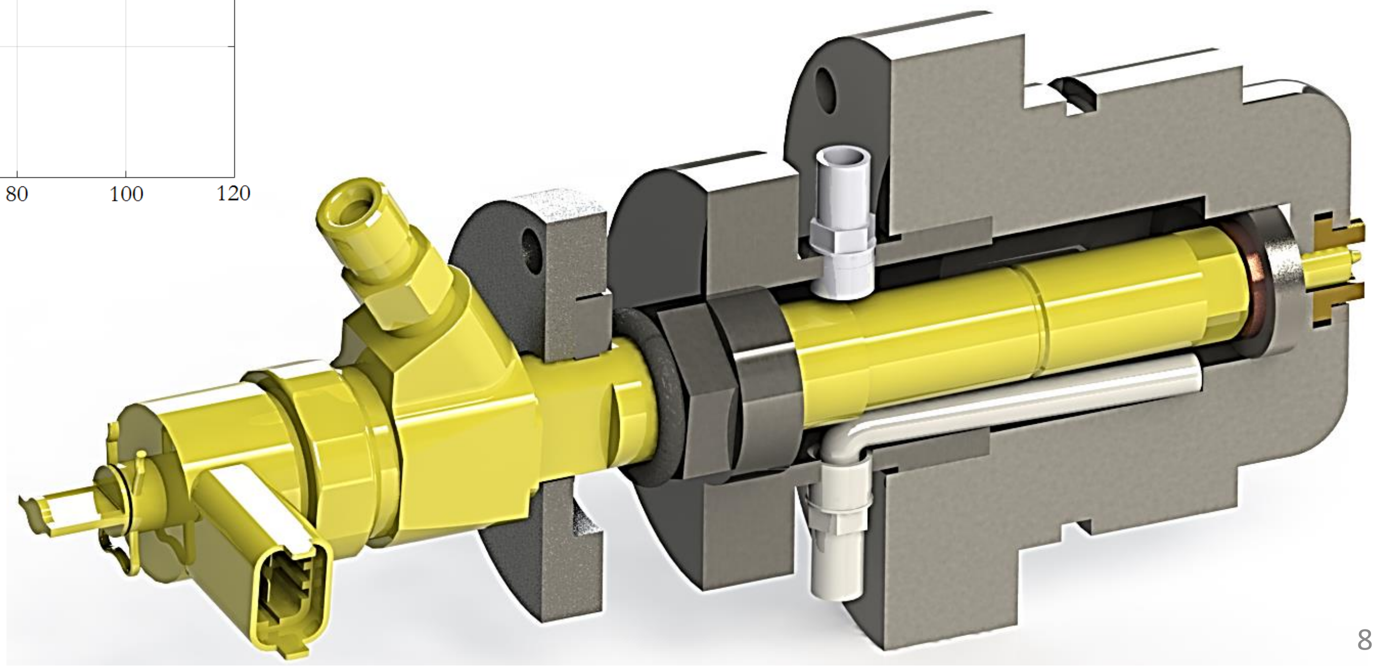
Experimental setup – Fuel temperature control



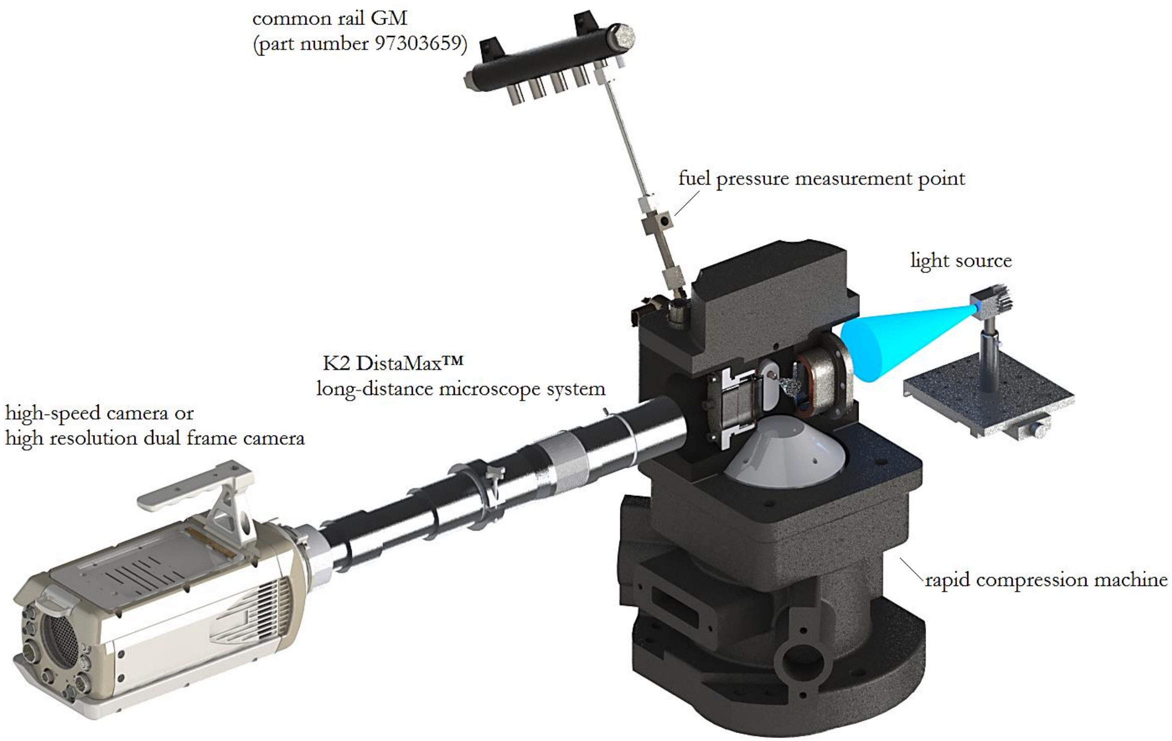
Fuel line temperature as a function of time for cooled and uncooled injectors

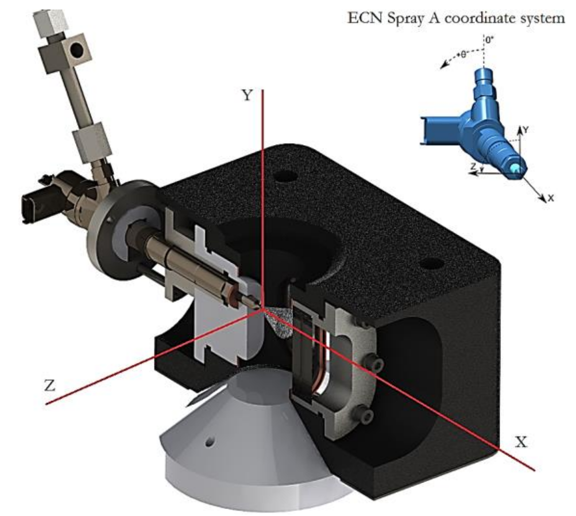
- Directly cooled injector stem
- ΔT tip ≈ 80-100 °C
- 130< Tip temperature < 135 °C for 120 min

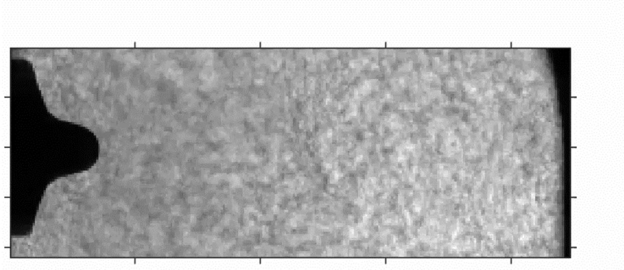


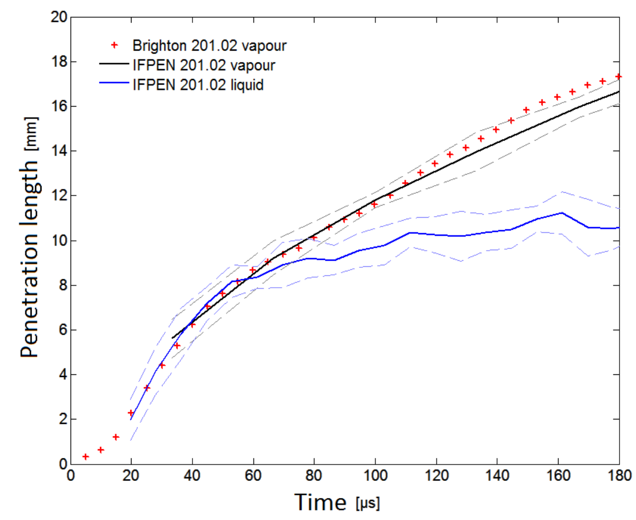


Experimental setup – High-speed video





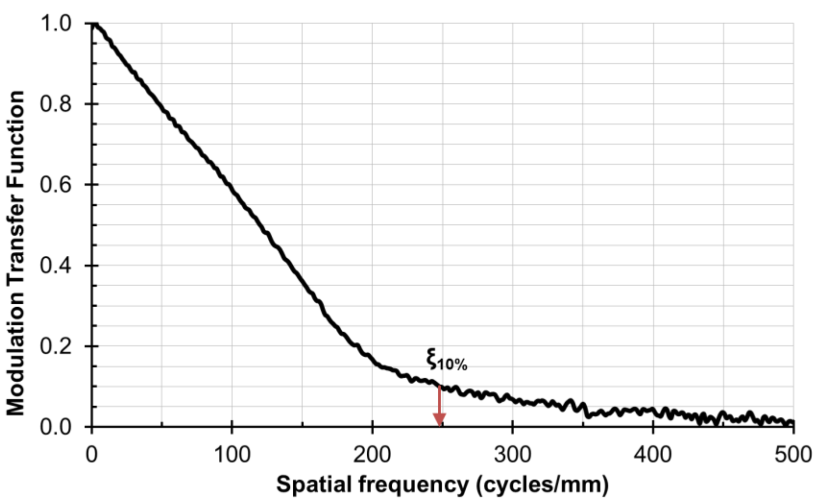


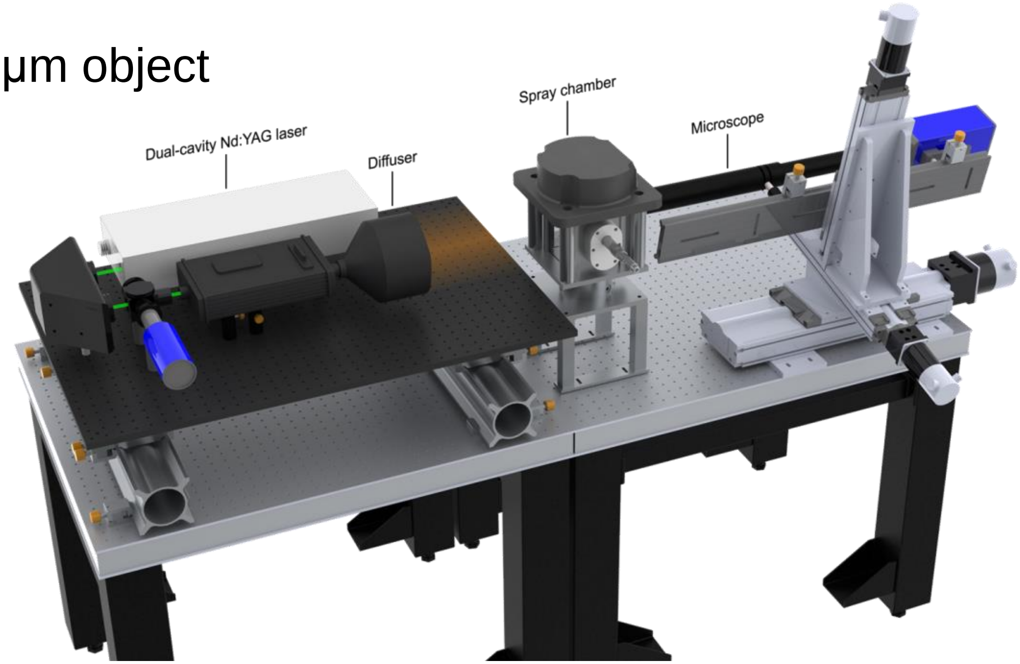


Experimental setup – Long distance microscopy

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>
<tr><th></th><th colspan="3">Spray A</th><th colspan="3">Spray B</th></tr>
<tr><td></td><td>1500 bar</td><td>1000 bar</td><td>500 bar</td><td>1500 Bar</td><td>1000 bar</td><td>500 bar</td></tr>
<tr><td>Start of injection</td><td colspan="3">acquired,</td><td rowspan="3">in progress</td><td rowspan="3">not planned</td><td rowspan="3">in progress</td></tr>
<tr><td>SOI+0.5ms</td><td>completed</td><td>being</td><td>completed</td></tr>
<tr><td>End of injection</td><td colspan="3">processed</td></tr>
</table>

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

➔ Currently processing for droplet size distributions

➔ Still need to process velocity fields, and acquire Spray B data

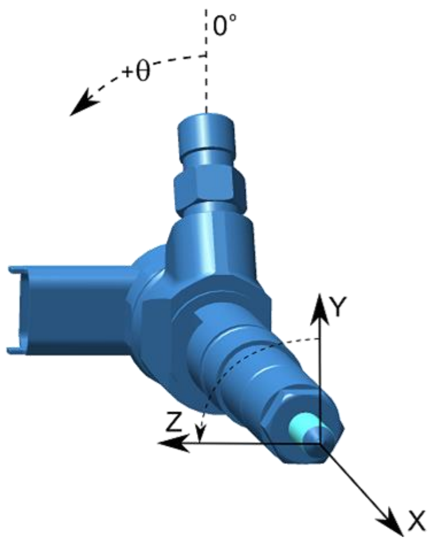
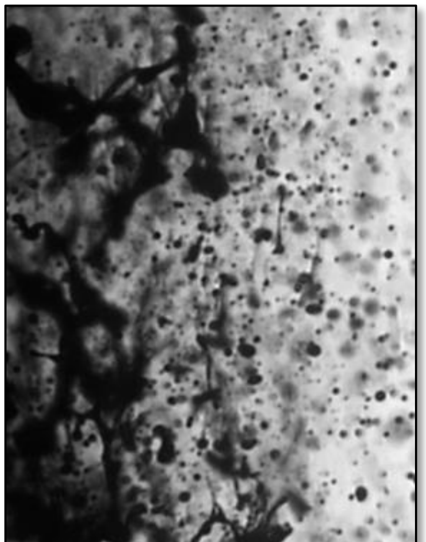
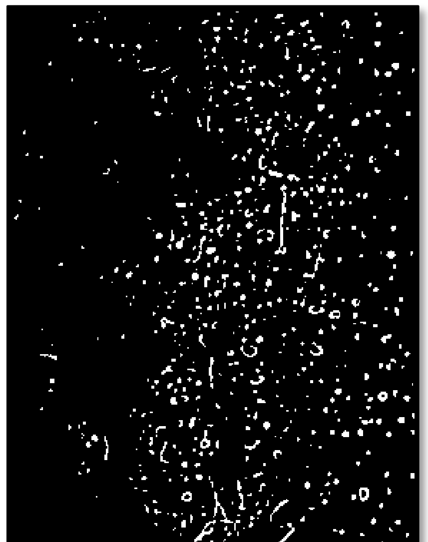


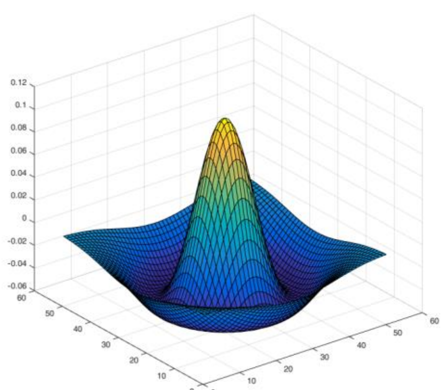
Image processing



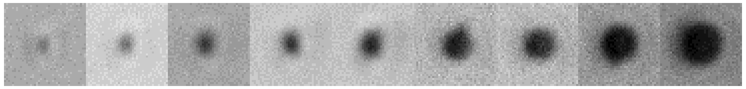
12bit raw image



Wavelet filter



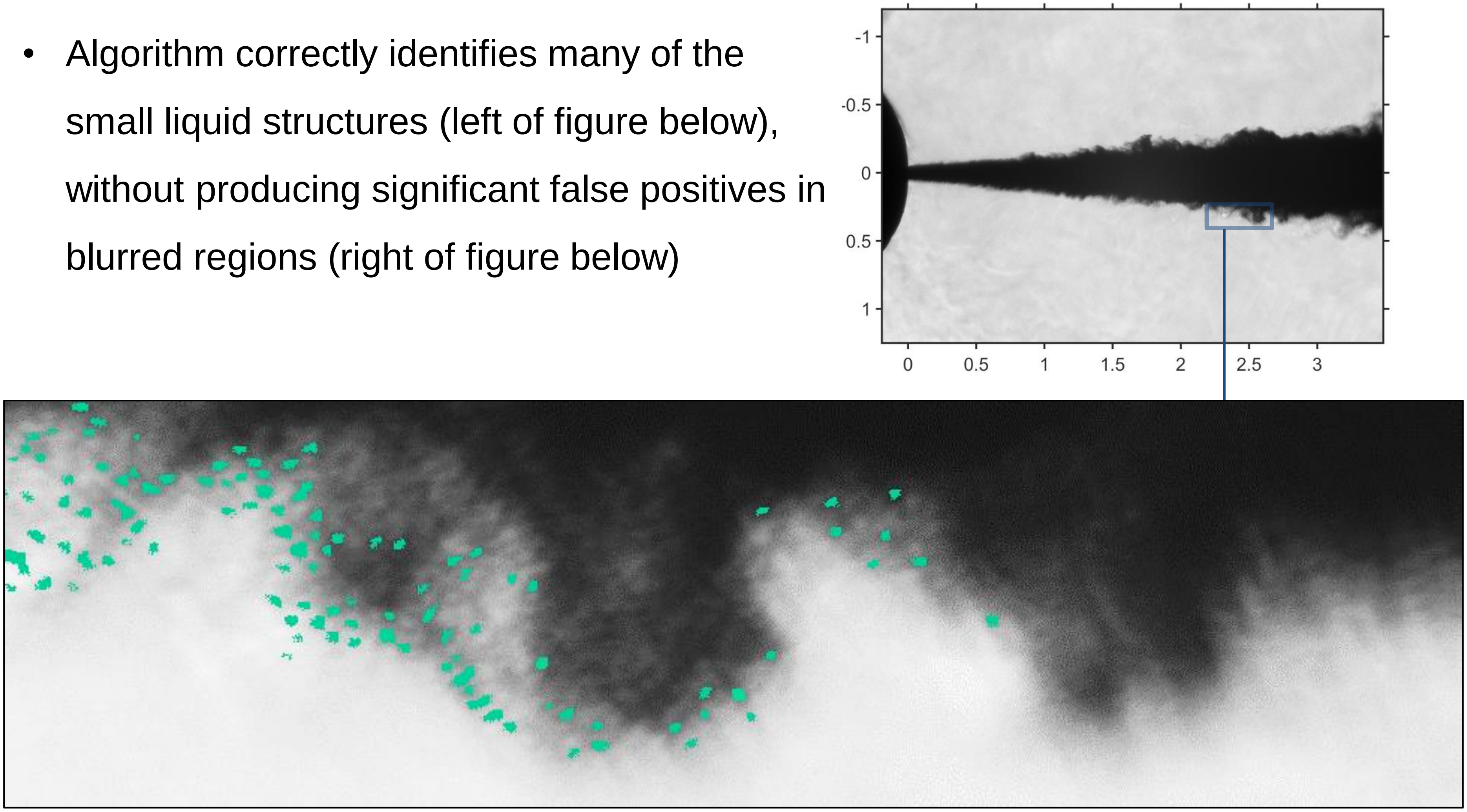
1. Convolution with wavelet
2. Threshold at 30% of intensity range
3. Measure droplet's projected area
4. Calculate eq. diameter $\mathrm{d} = \sqrt{\mathrm{A}/\pi}$
5. Correct diameters based on NIST-calibrated target (1.9 to 101.6 μm)



1.9 3.1 3.7 4.8 5.9 7.0 7.6 8.8 10.1

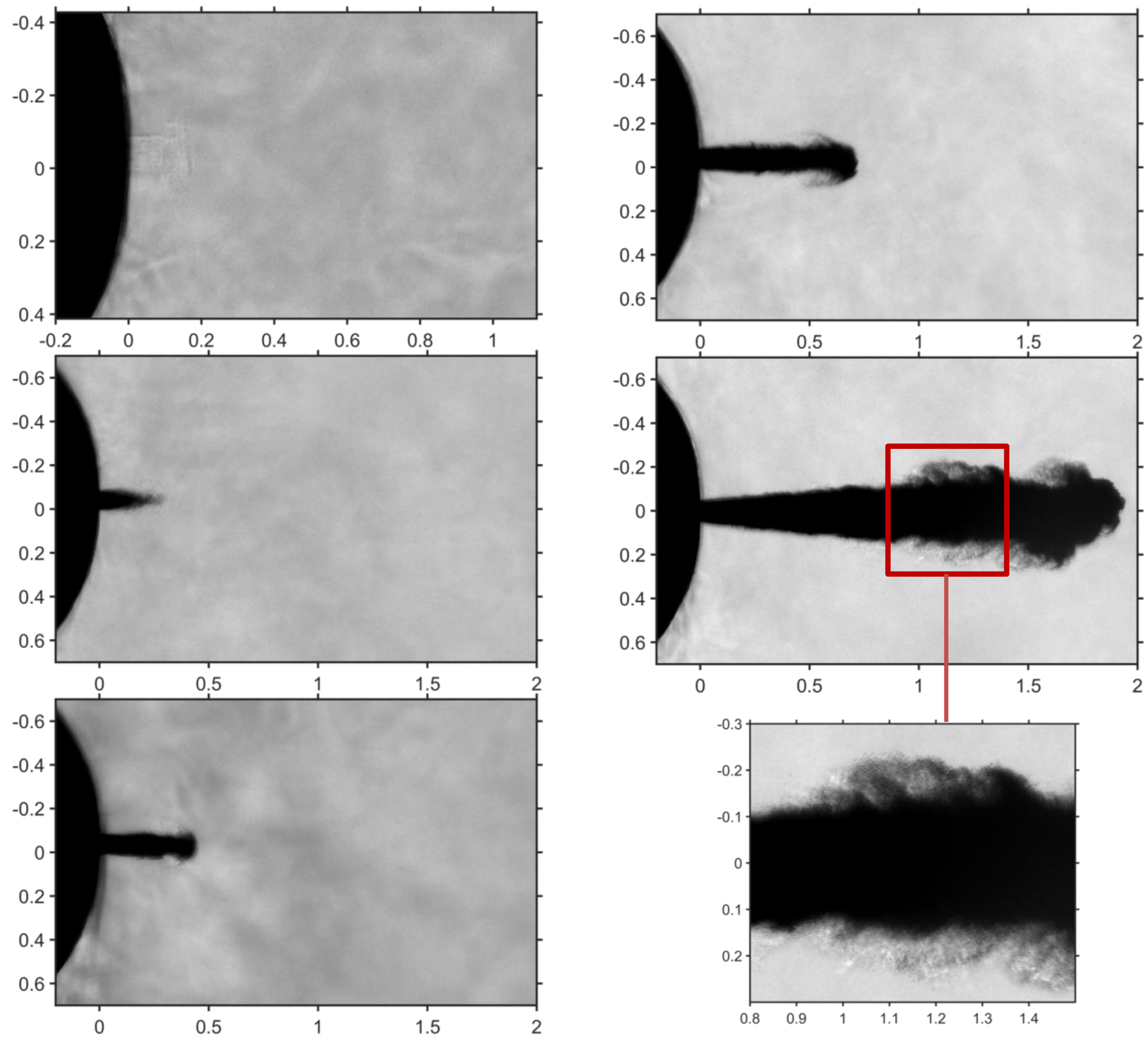
Image processing (0.5 ms after start of injection)

- 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)



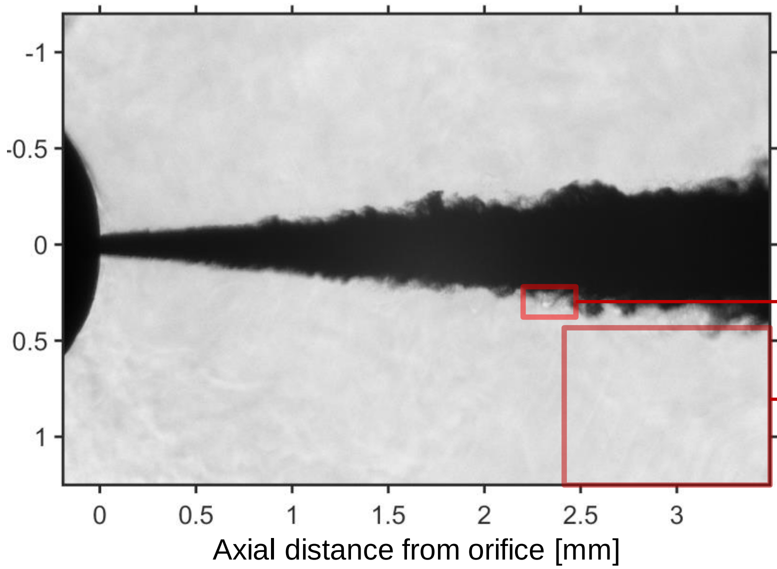
Results: Start of injection – 1500 bar

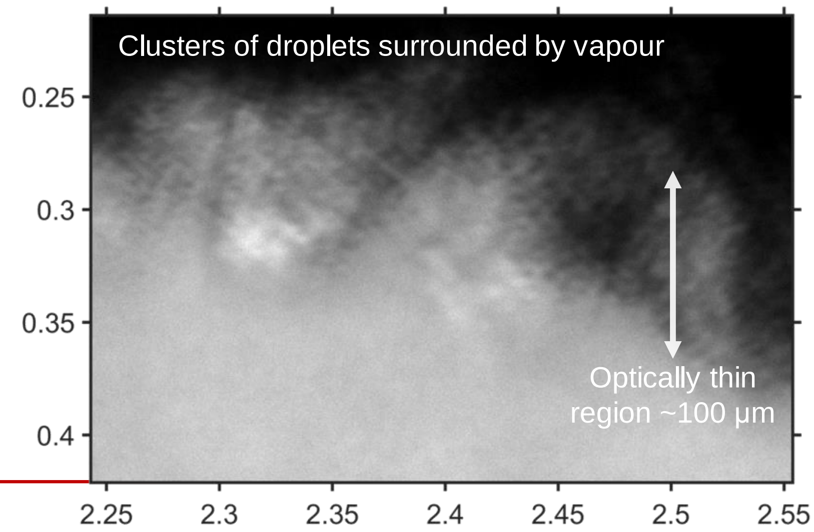
- Vapour emerges with vortex ring motion
- Followed by liquid jet and droplets
- Liquid tip becomes more defined (coalescence)
- Droplets present at liquid interface

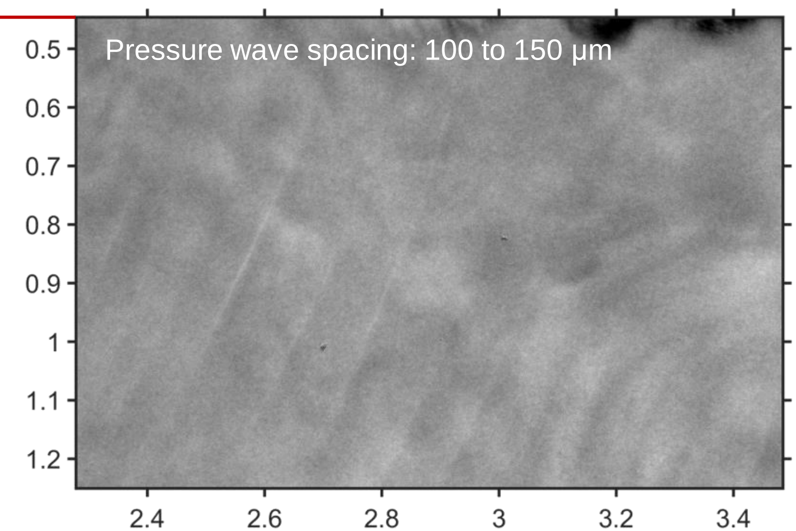


Results: 0.5 ms after start of injection – 1500 bar

- Droplets visible at spray periphery
- Surrounded by vaporised fuel

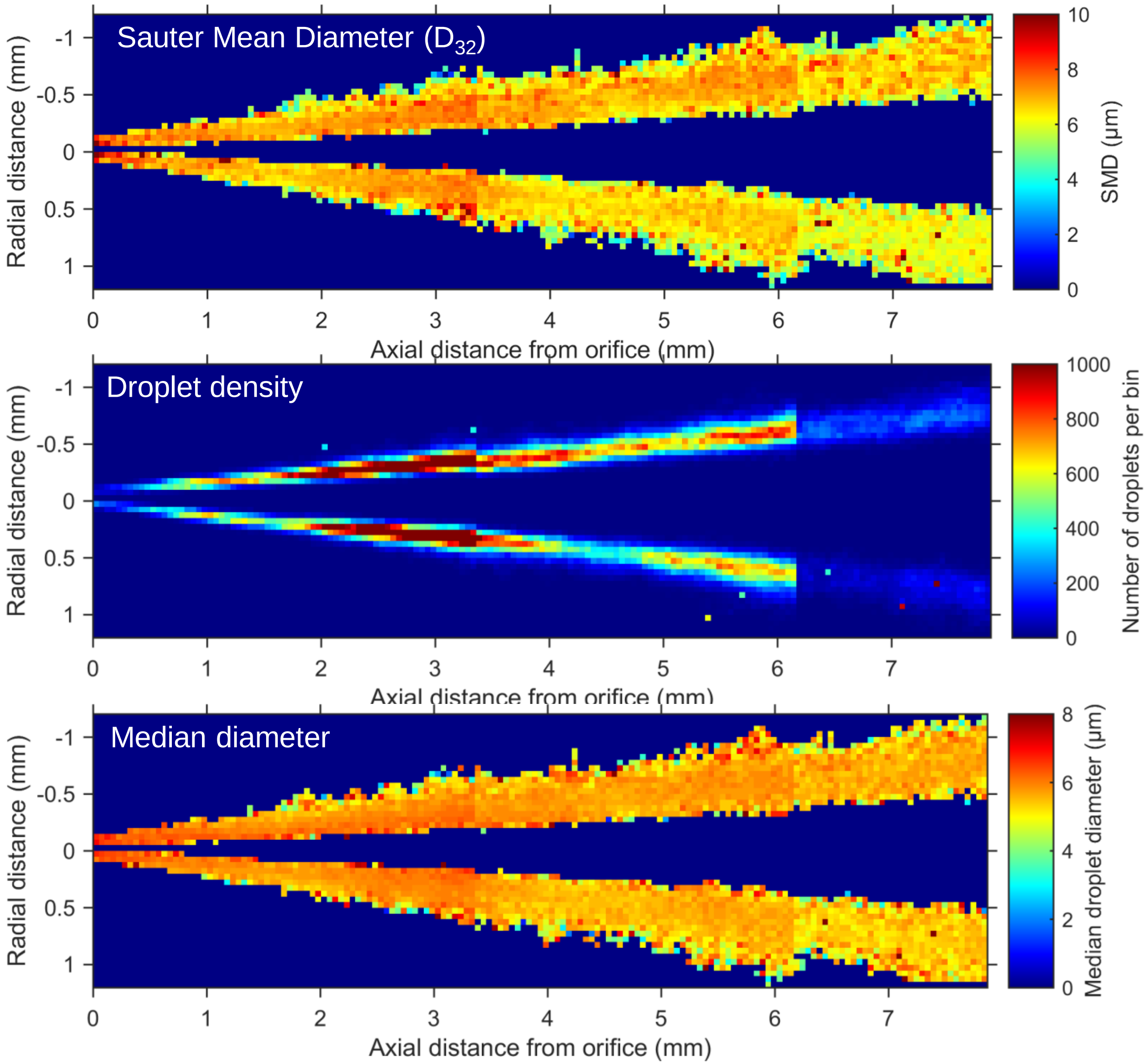




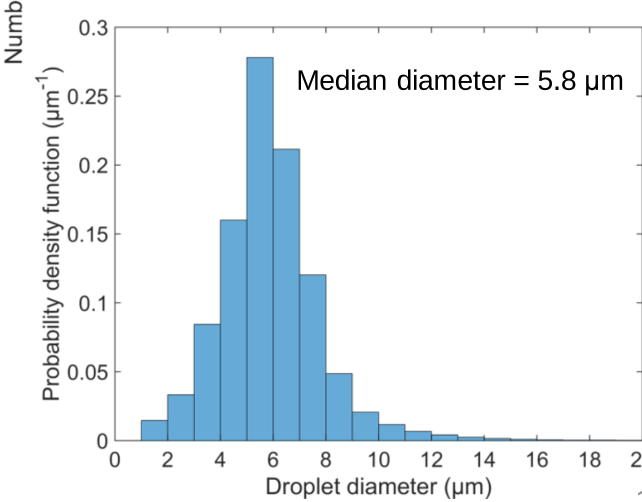


- Pressure waves often visible along spray periphery.
- Not expected to occur for multi-hole nozzles, but could affect Spray A droplet formation, mixing and optical resolution

Results: Steady-state phase 1500 bar

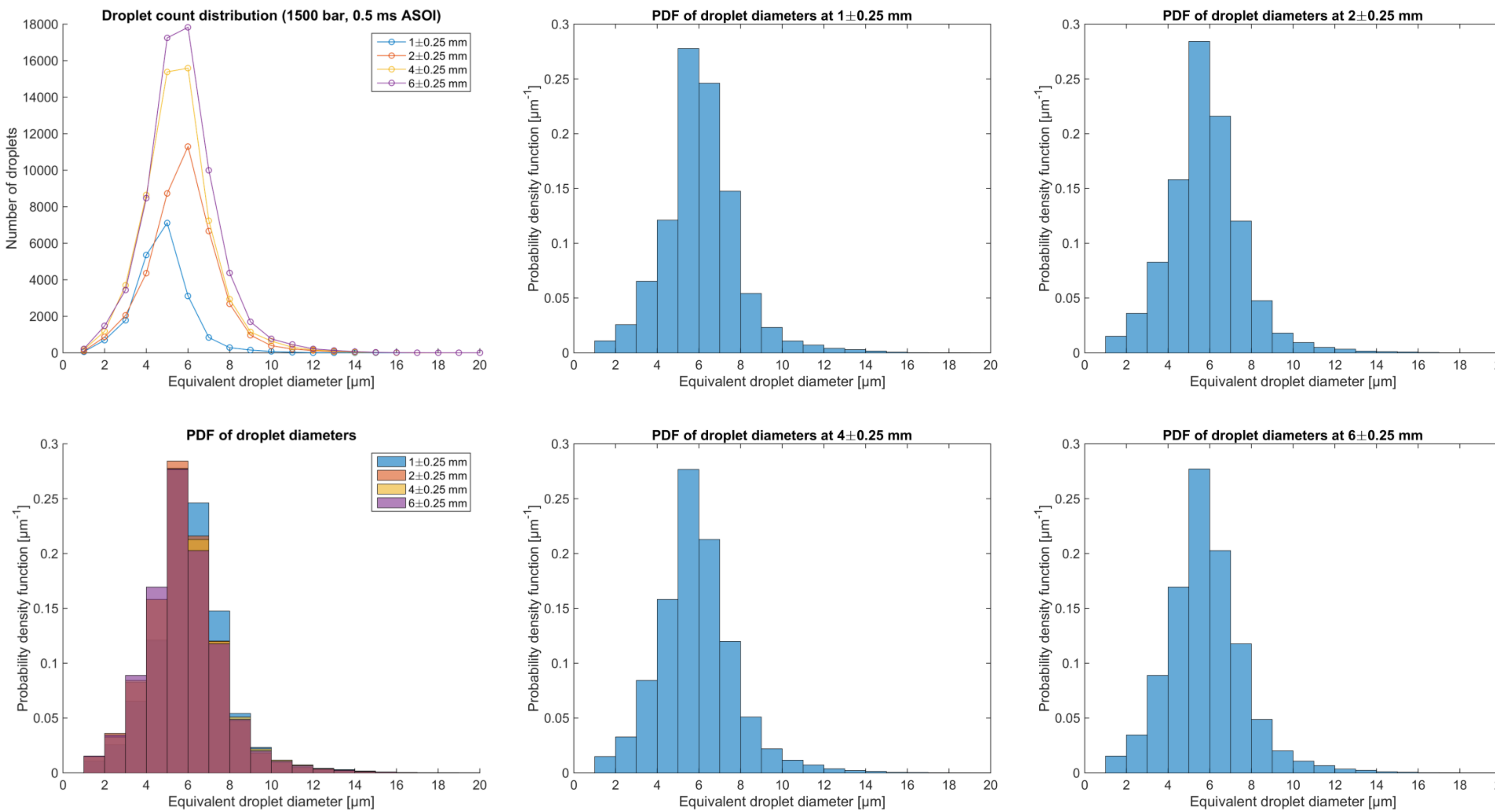


- 1,575 images => 619,756 droplets
- Droplet data merged into 50x50 μm^2 bins
- Droplet count: 200-1000 droplets/bin
- SMD in the optically-thin periphery of the spray is 6 – 8 µm

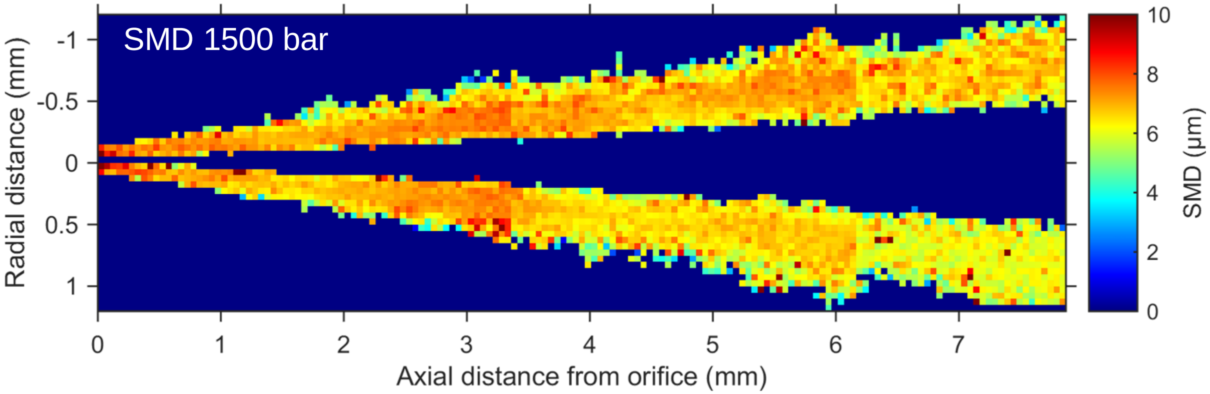


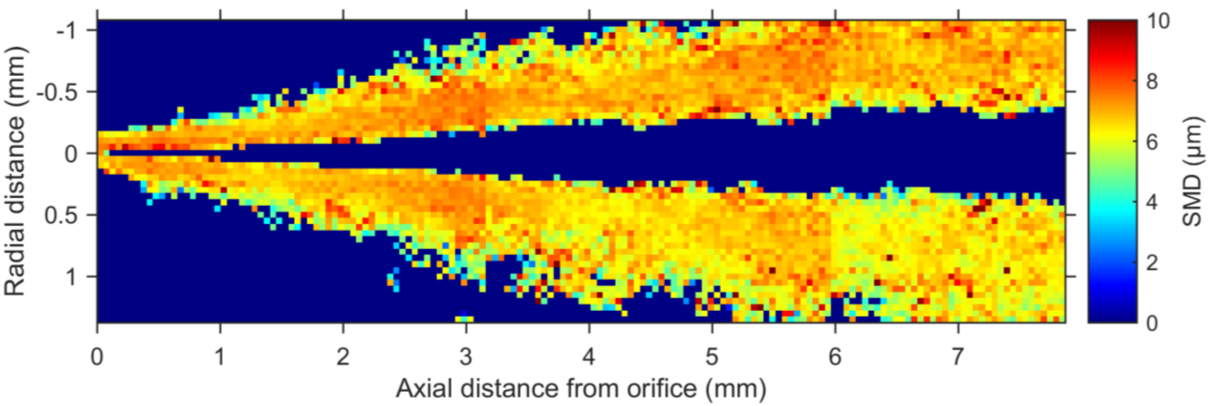
Results: Steady-state phase – 1500 bar

Statistics for x = 1, 2, 4, 6 ±0.25 mm (y = ±1.2 mm; z = ±10 μm) from orifice



Analysis – Comparison between 500 and 1500 bar

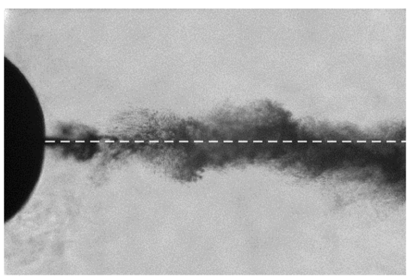


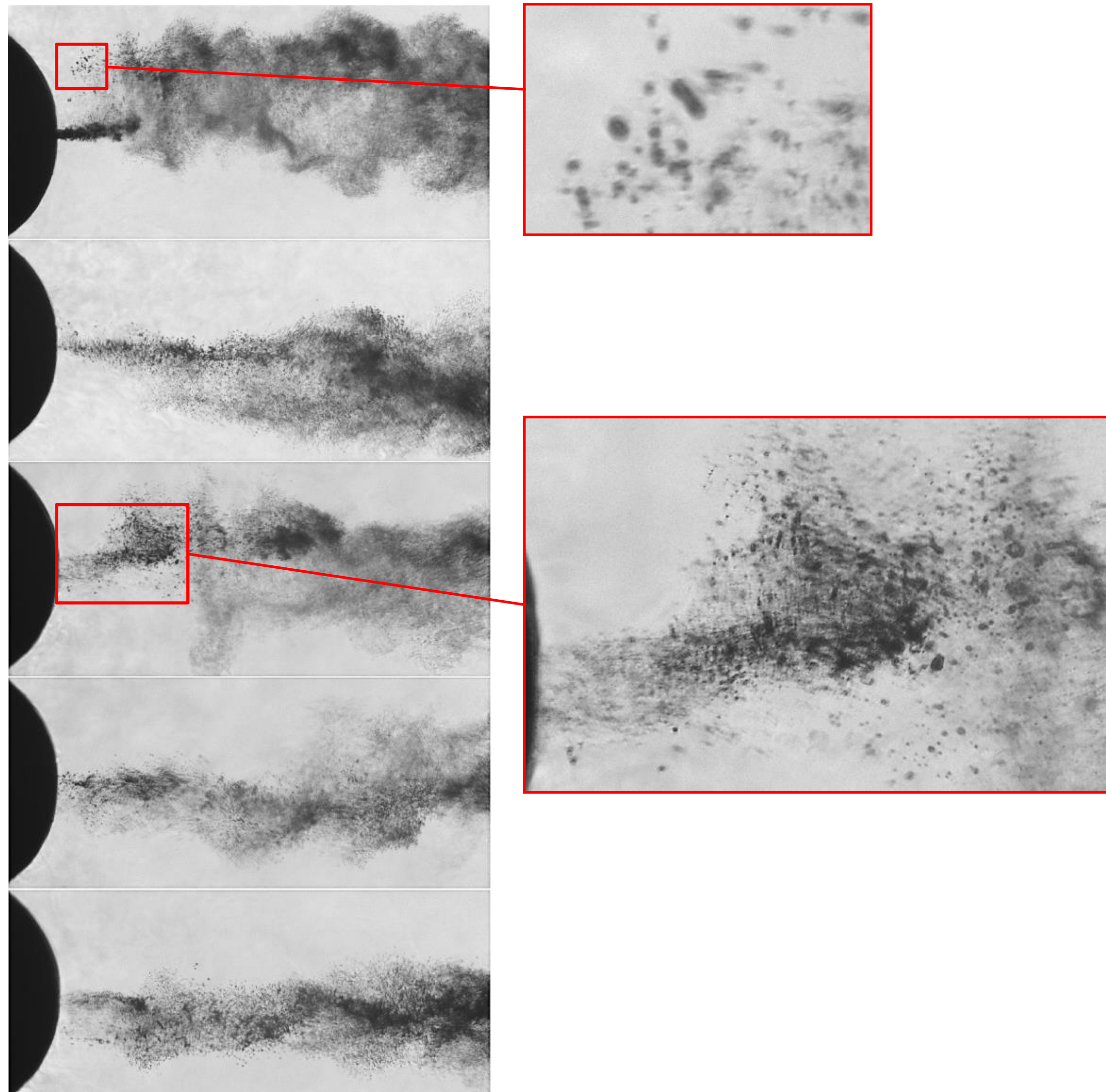


- Marginally larger SMD at 500 bar, compared to 1500 bar, especially after 6 mm
- Asymmetrical distributions observed in both cases (SMD, drop count, median diameter)

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 (≈ 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)