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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

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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/m³]	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

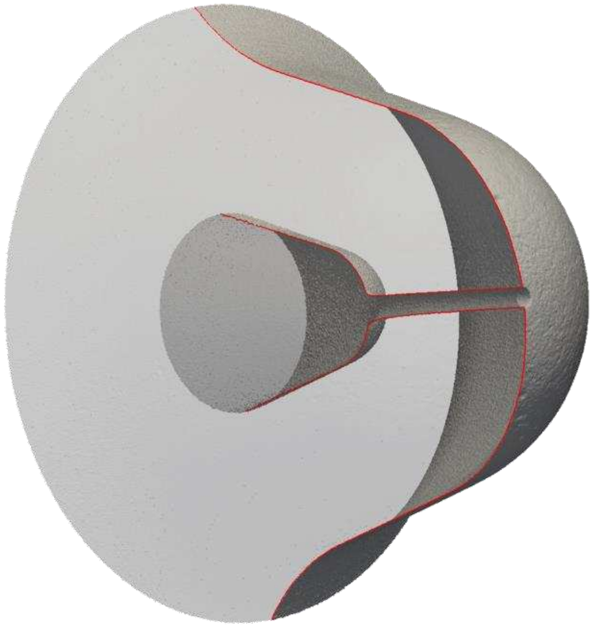
Legend

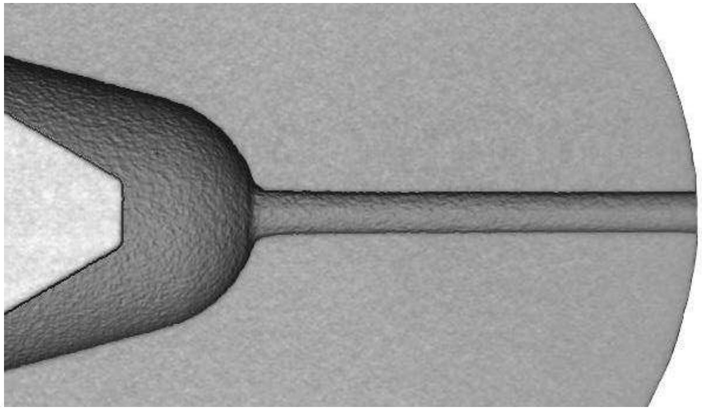
- Completed
- In progress
- Not met

Spray A injector

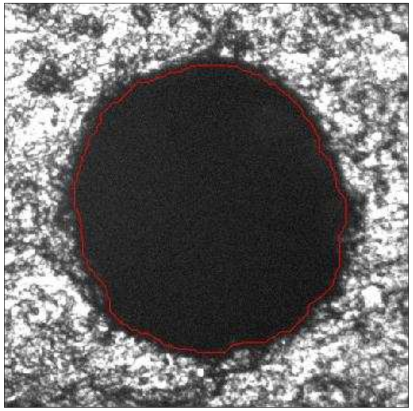
- Injector: **Spray A.2 nozzle #201.02**
  - From second batch of Spray A injectors, purchased by IFPEN (Malbec et al. 2013 papers.sae.org/2013-24-0037)
  - ➢ New STL file for #201.02 generated by University of Bergamo (Prof. Santini)

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





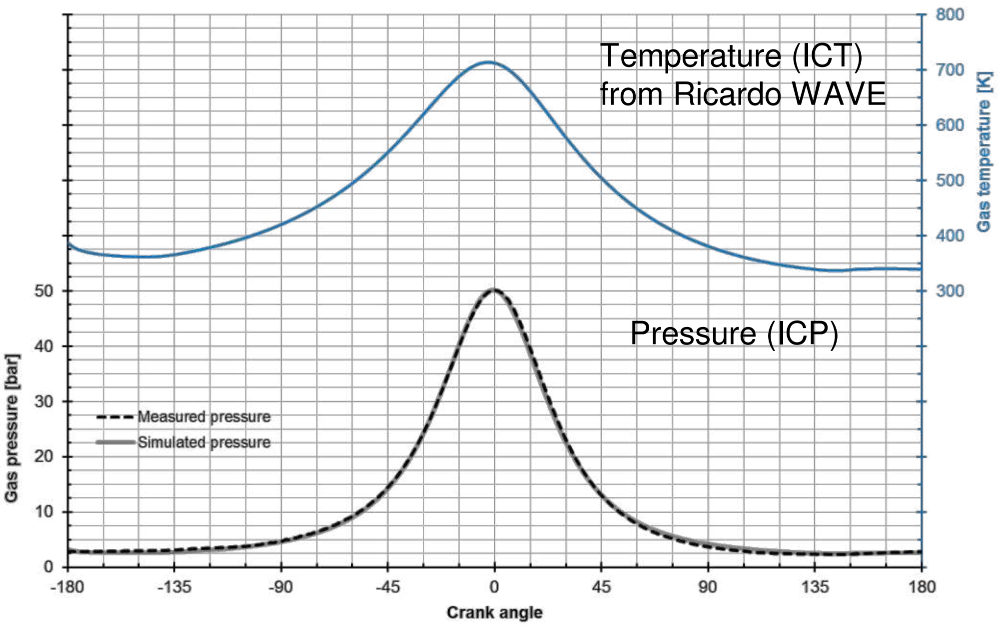
X-ray µCT
(University of Bergamo)

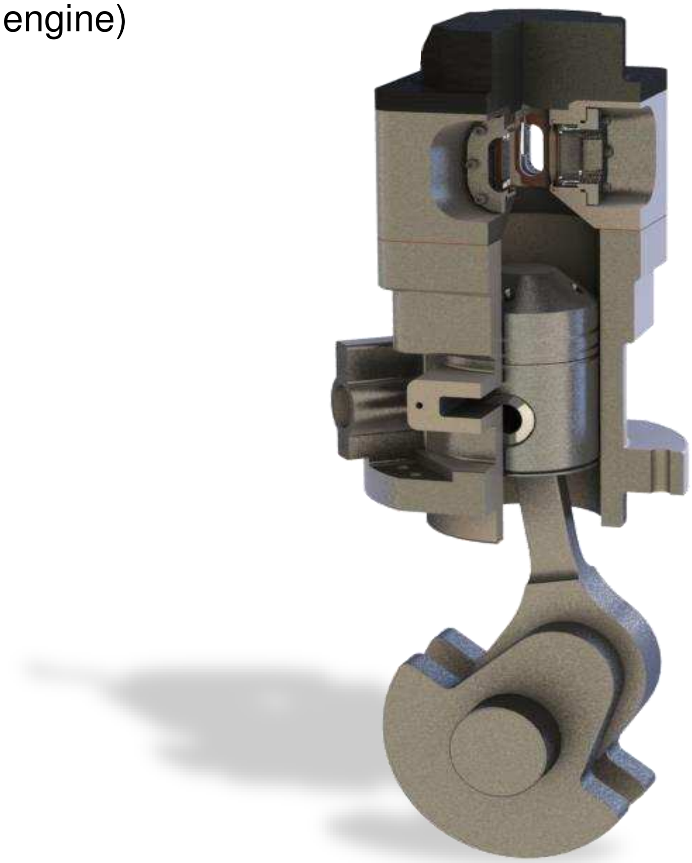


Optical microscopy
(University of Brighton)

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

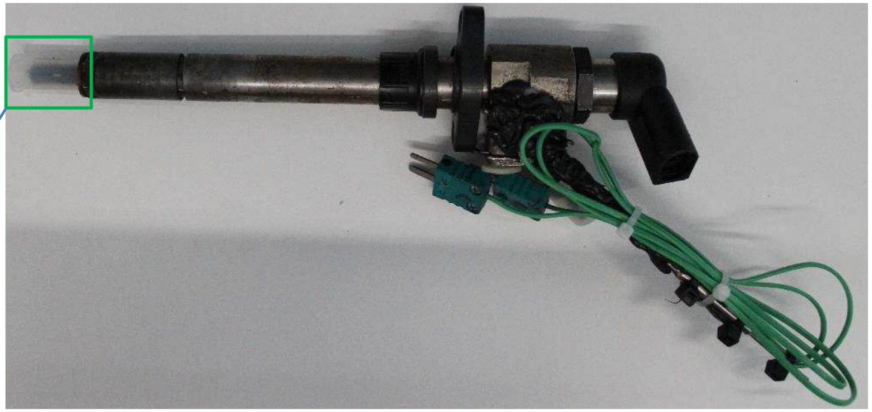




Temperature at TDC was computed by Ricardo WAVE by fitting measured ICP with simulated ICP (WAVE)

Experimental setup – Fuel temperature control

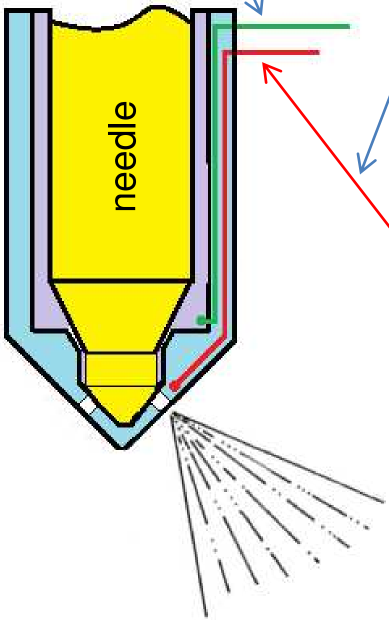
Instrumented Siemens injector was used to measure injector tip temperature



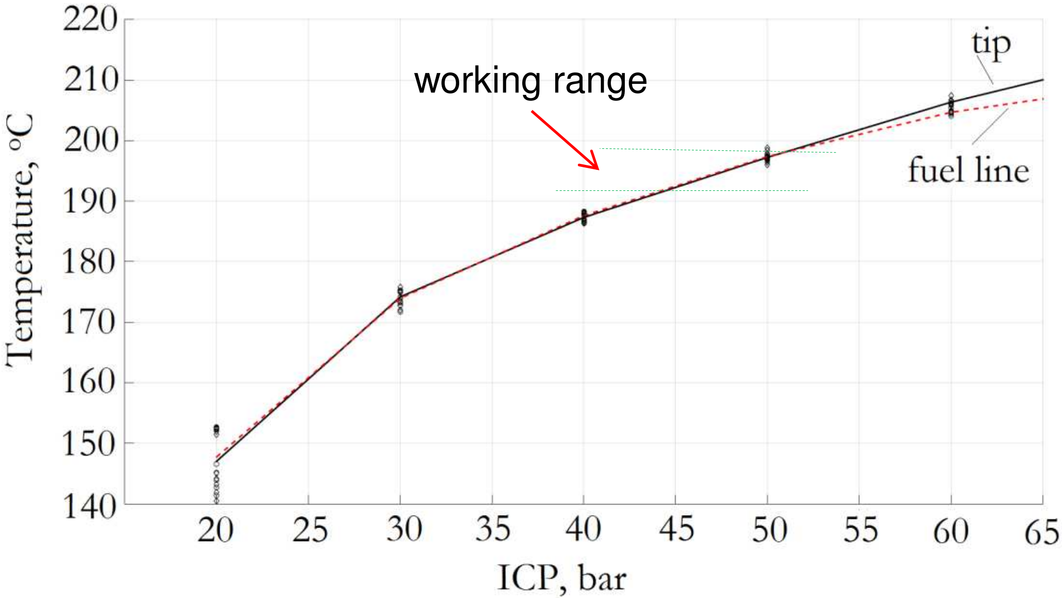
- Measured tip temperature: 195-220 °C
- ECN target 90 °C
- Injector cooling was needed

Fuel channel thermocouple

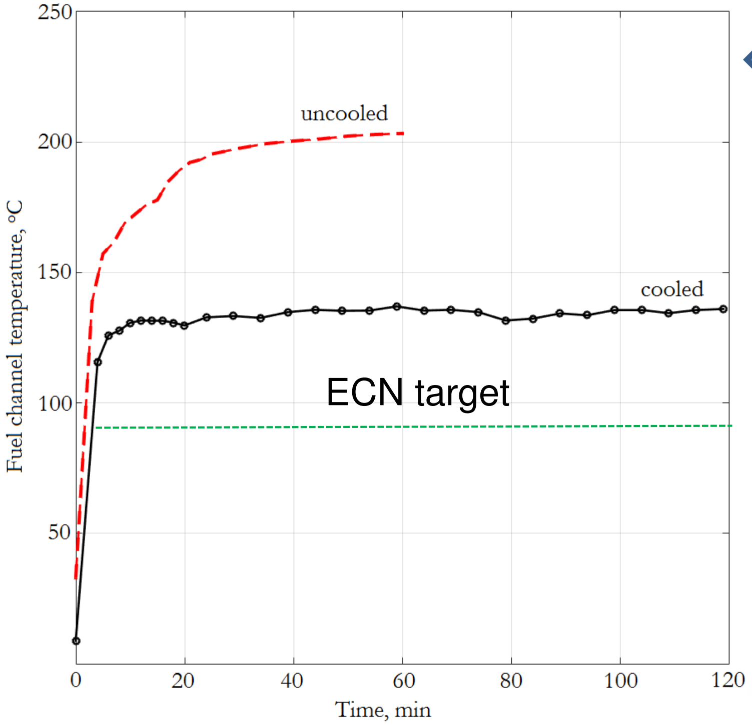
Tip thermocouple



Injector tip and fuel channel temperatures

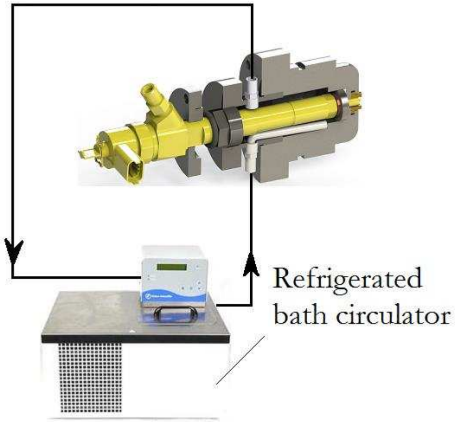


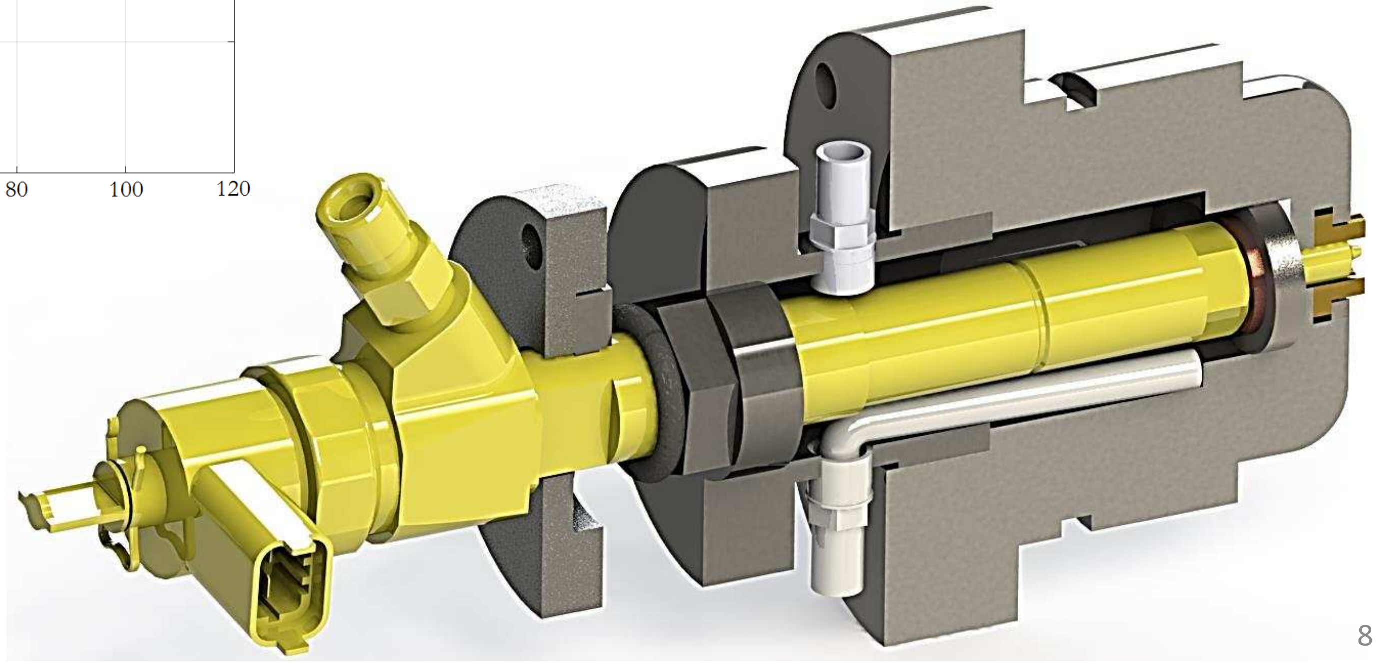
Experimental setup – Fuel temperature control



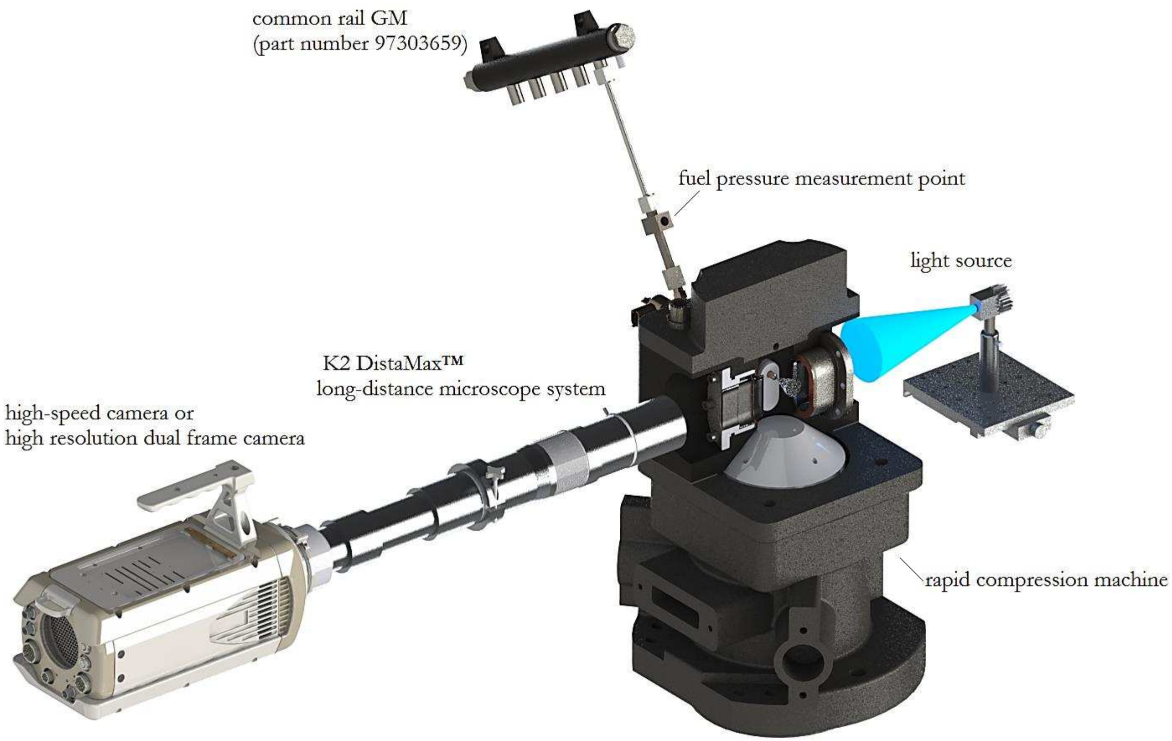
Fuel line temperature as a function of time for cooled and uncooled injectors

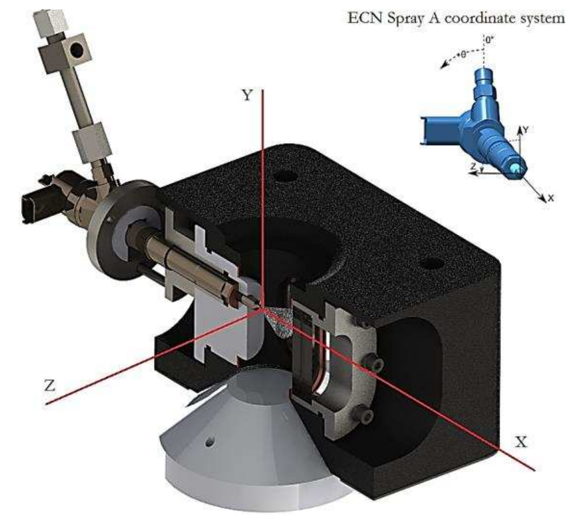
- Directly cooled injector stem
- ΔT tip ≈ 80-100 °C
- 130< Tip temperature < 135 °C for 120 min

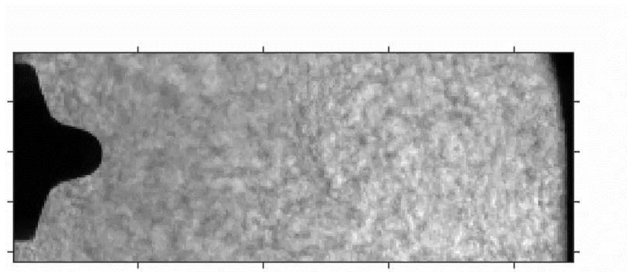


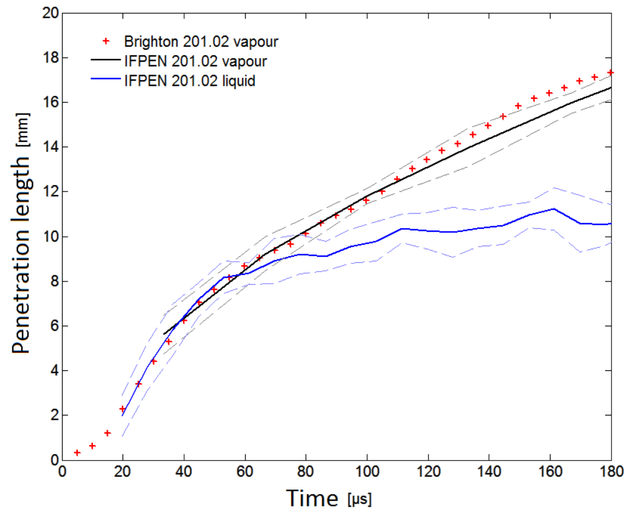


Experimental setup – High-speed video





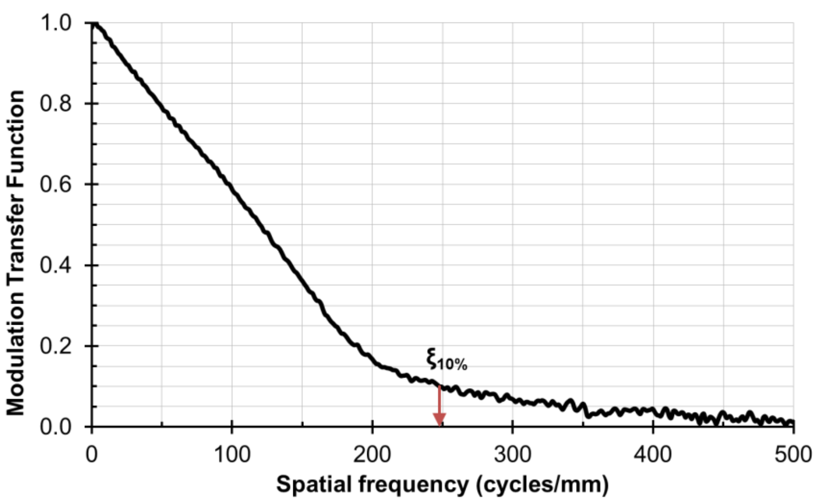


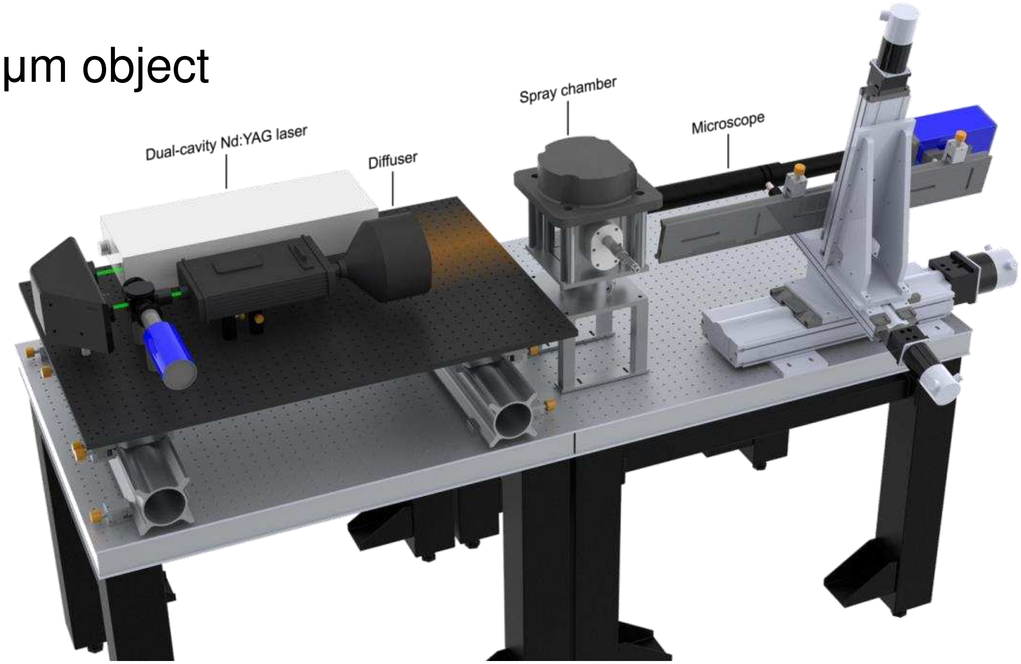


Experimental setup – Long distance microscopy

Shadowgraphy setup based on Crua et al. (2015) *Fuel* 157 doi.org/4F3

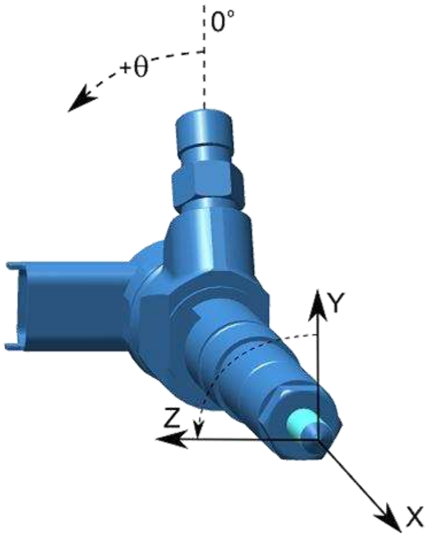
- New camera: 29 megapixel (4400x6600 pixels) dual-frame
- Scale factor: 0.56 µm/pixel (2.46x3.70 mm)
- MTF at 10%: 250 cycles/mm ➔ 2 µm object





Test conditions for long-distance microscopy

	Spray A			Spray B		
	1500 bar	1000 bar	500 bar	1500 Bar	1000 bar	500 bar
Start of injection		**acquired,**		**in progress**	**not planned**	**in progress**
SOI+0.5ms	**completed**	**being**	**completed**			
End of injection		**processed**				

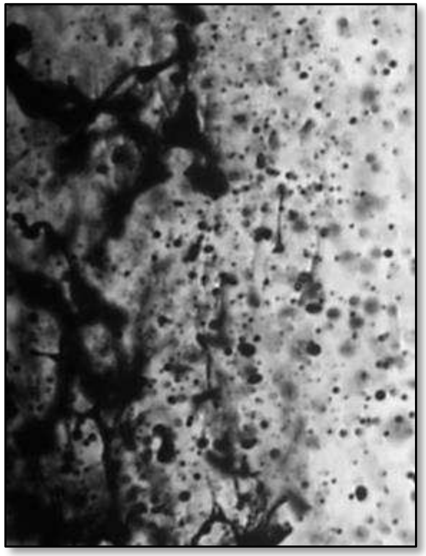


- Acquired ~7,400 dual-frame images for Spray A (815 GB)
- Data set covers x = 0 to 8 mm (y = ± 1.2 mm; z = ±10 μm)

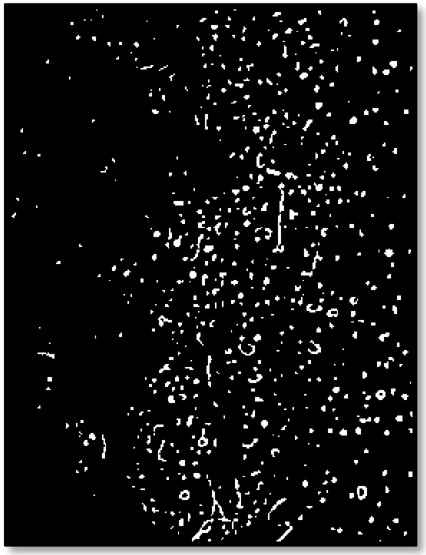
➔ Currently processing for droplet size distributions

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

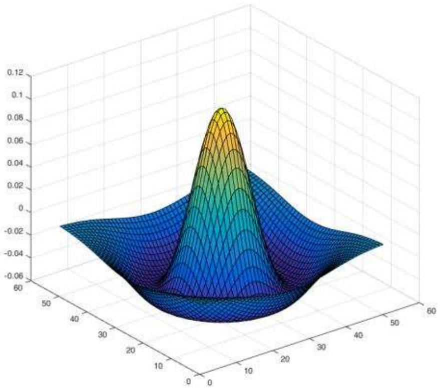
Image processing



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)

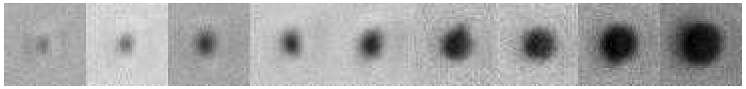
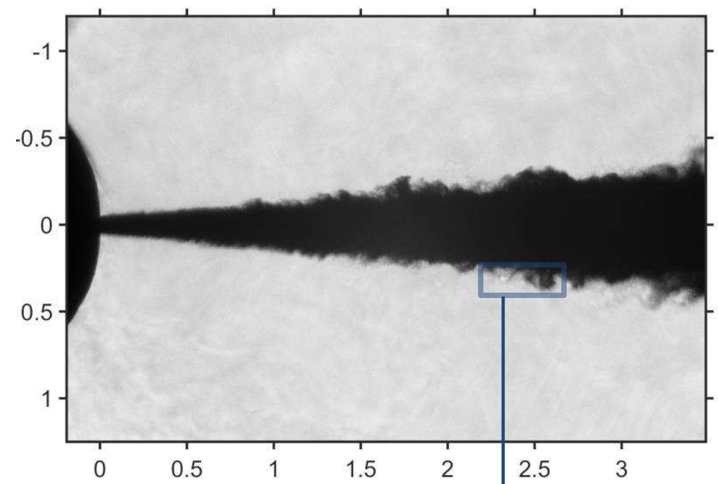
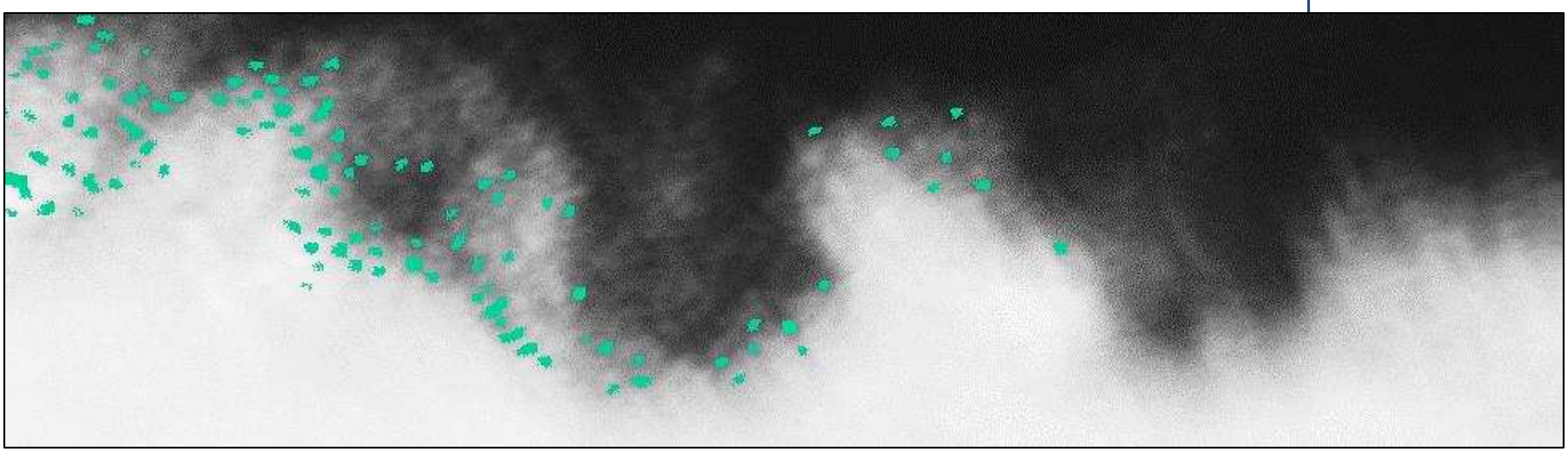


Image processing (0.5 ms after start of injection)

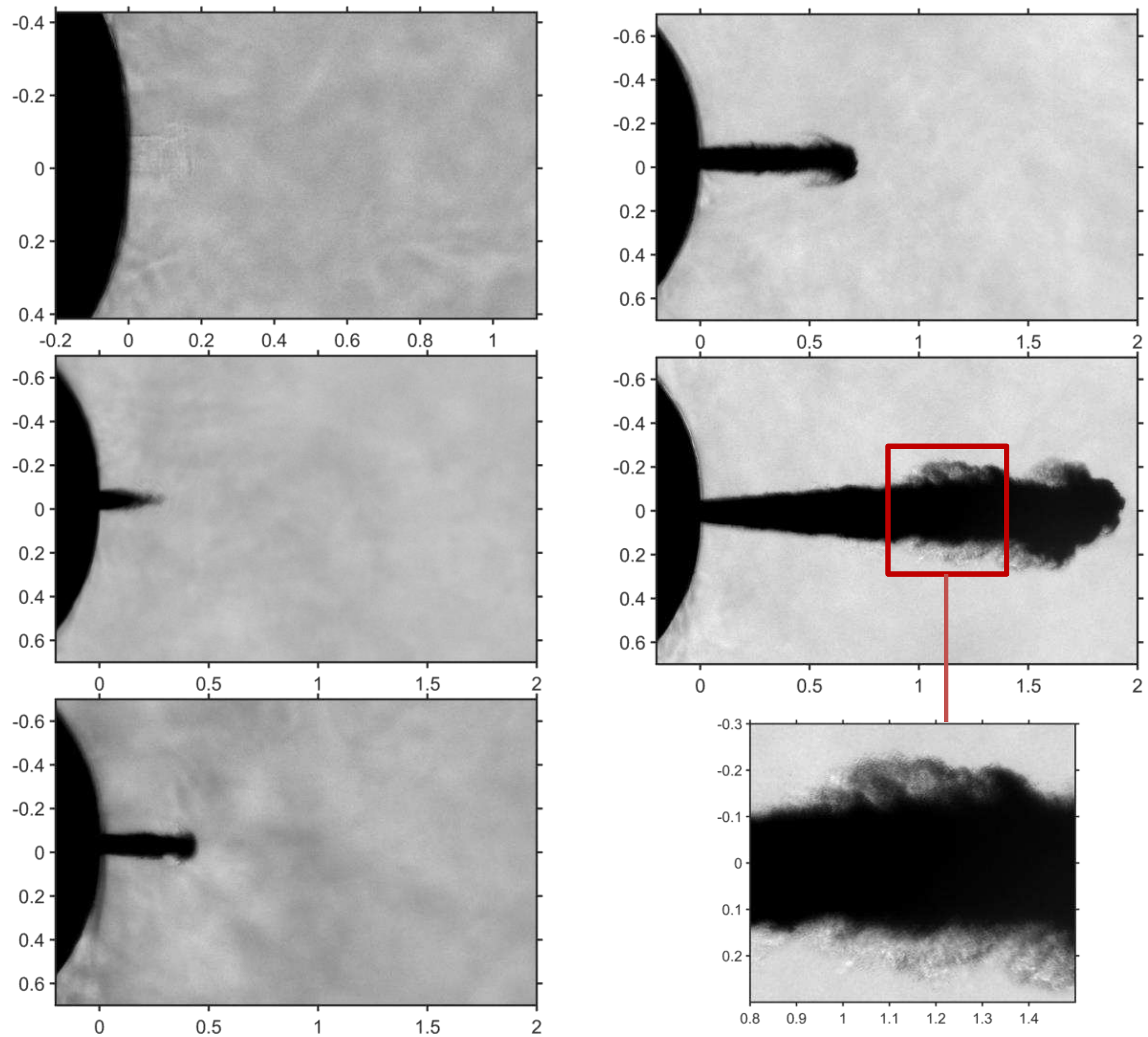
- Algorithm correctly identifies many of the small liquid structures (left of figure below), without producing significant false positives in blurred regions (right of figure below)





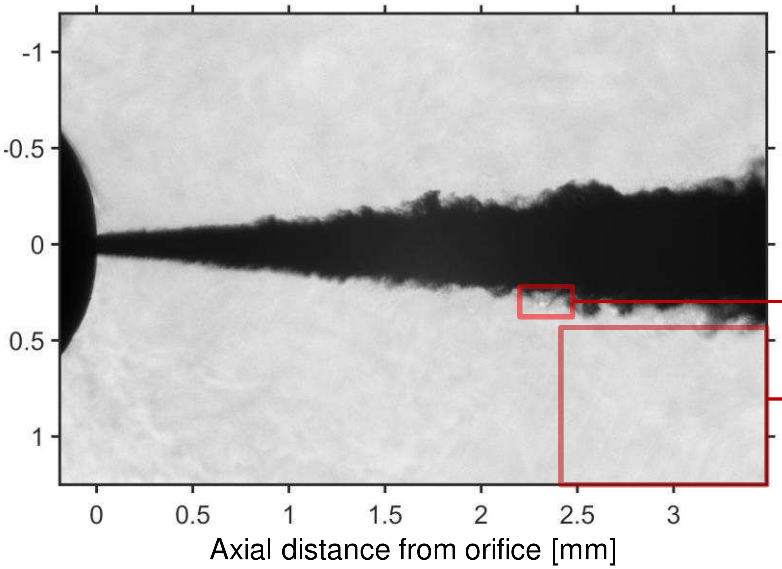
Results: Start of injection – 1500 bar

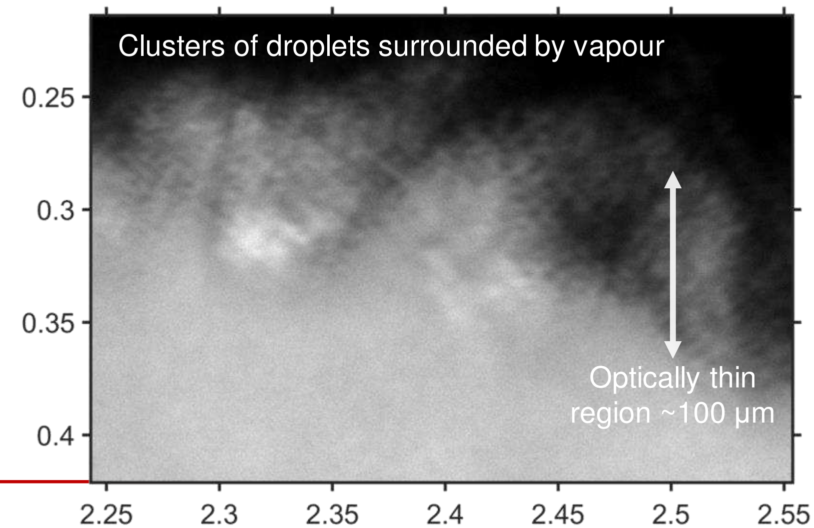
- Vapour emerges with vortex ring motion
- Followed by liquid jet and droplets
- Liquid tip becomes more defined (coalescence)
- Droplets present at liquid interface

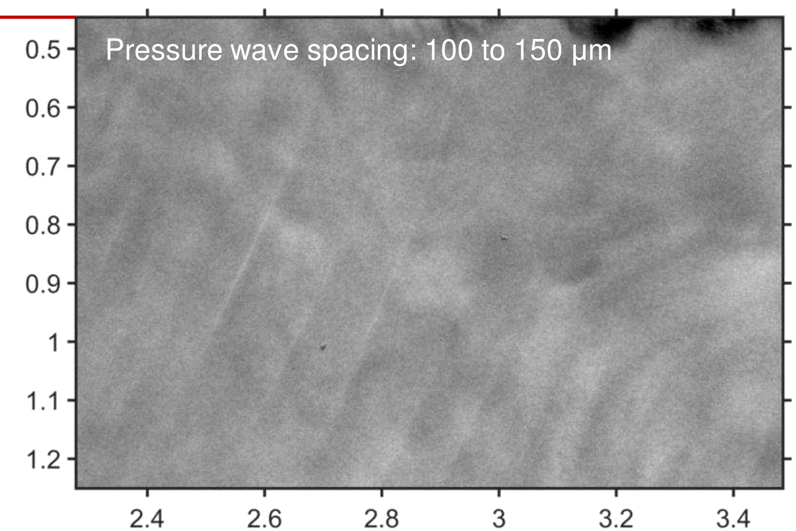


Results: 0.5 ms after start of injection – 1500 bar

- 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

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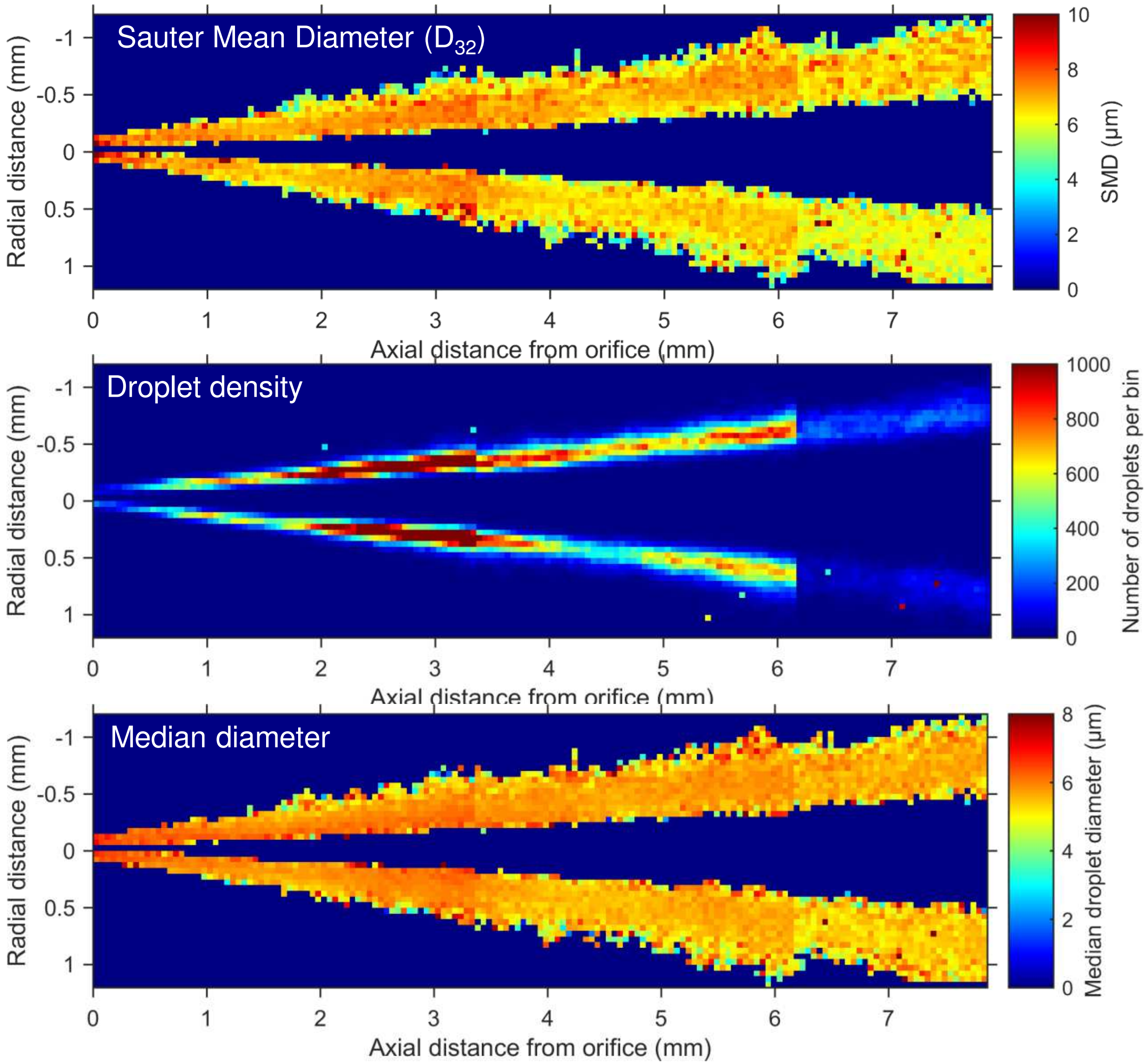
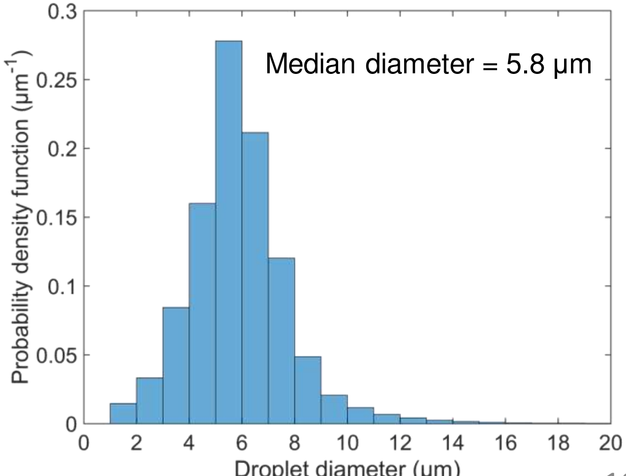
Results: Steady-state phase 1500 bar



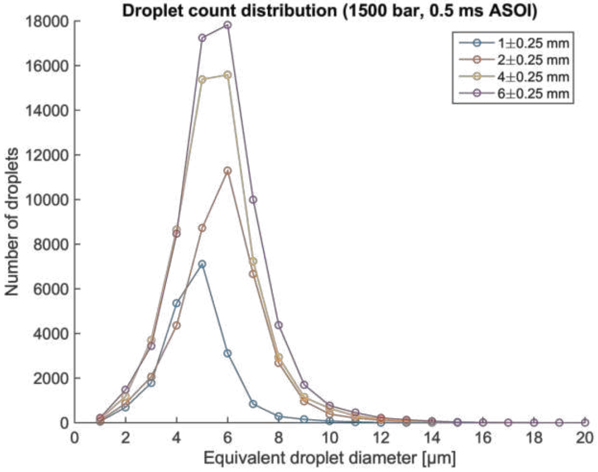
- 1,575 images => 619,756 droplets
- Droplet data merged into 50x50 μm^2 bins
- Droplet count: 200-1000 droplets/bin

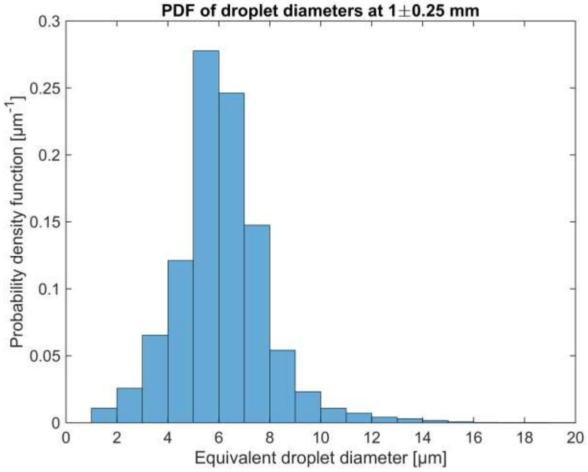
- SMD in the optically-thin periphery of the spray is 6 – 8 μm

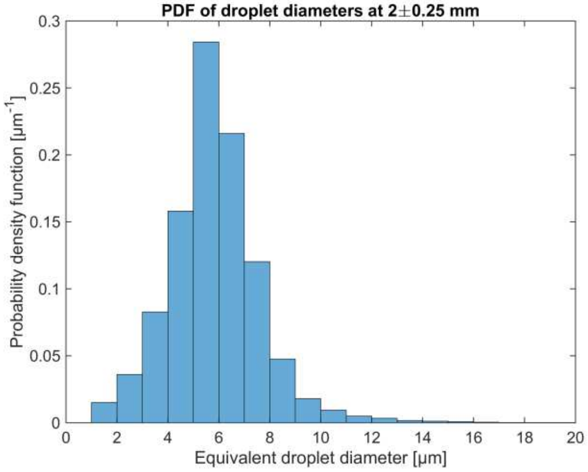


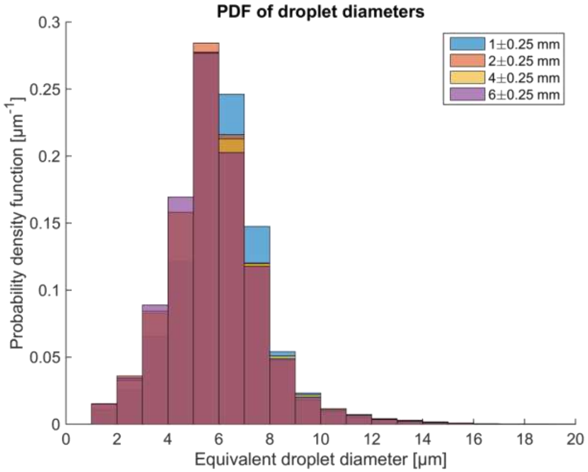
Results: Steady-state phase – 1500 bar

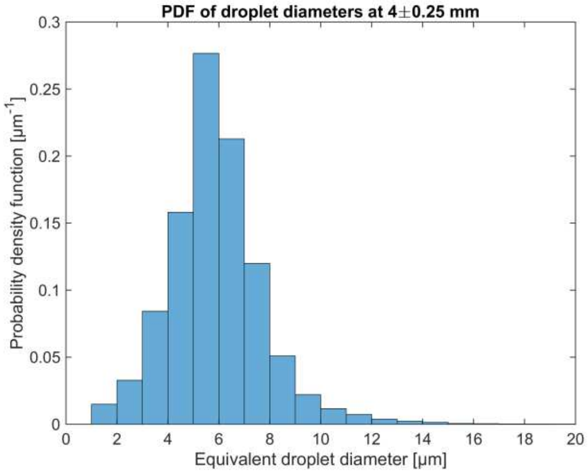
Statistics for x = 1, 2, 4, 6 ±0.25 mm (y = ±1.2 mm; z = ±10 μm) from orifice

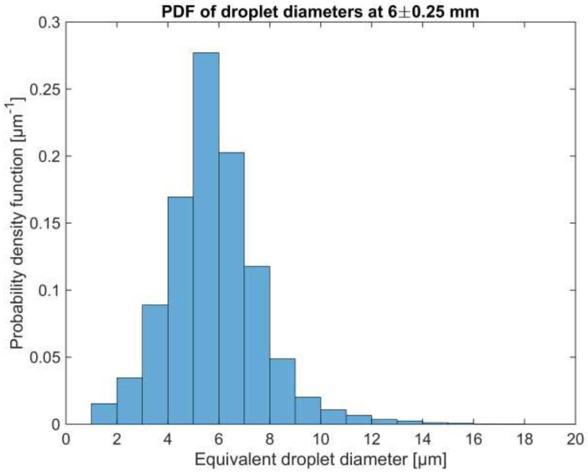




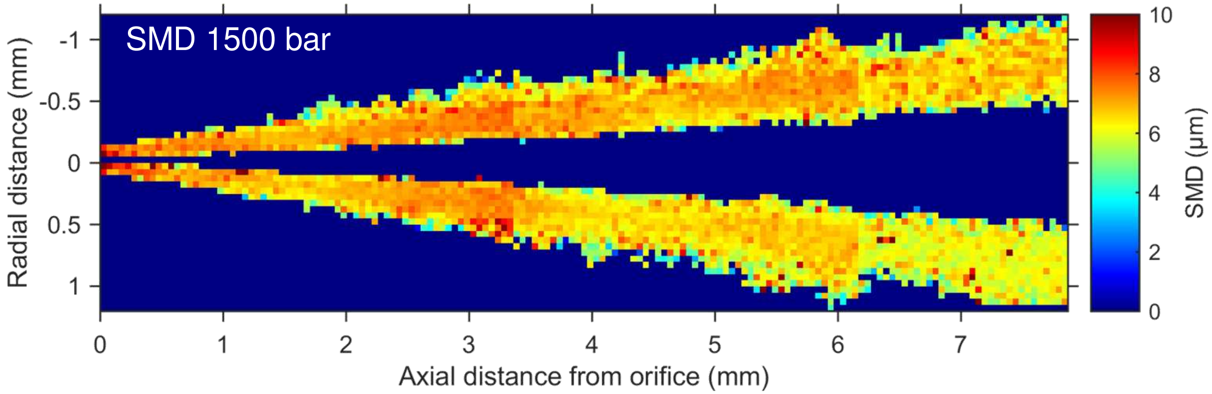




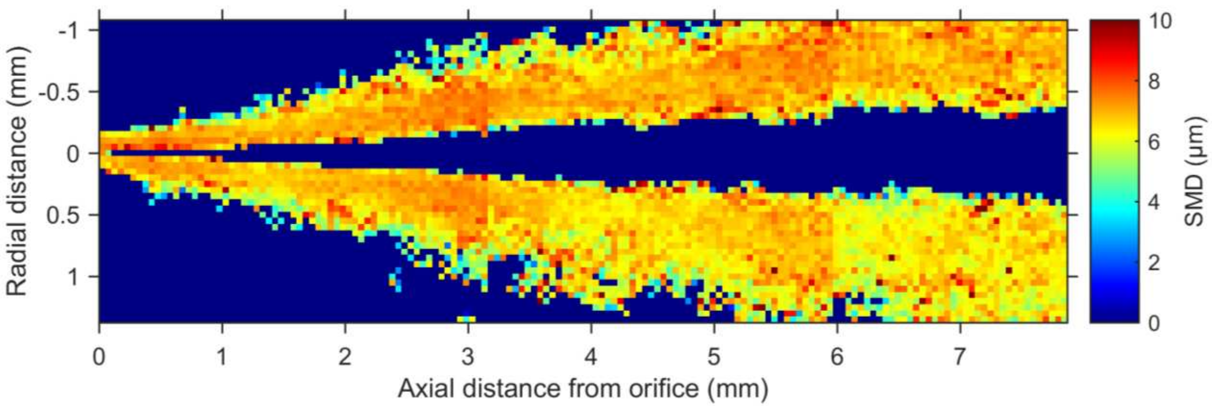




Analysis – Comparison between 500 and 1500 bar



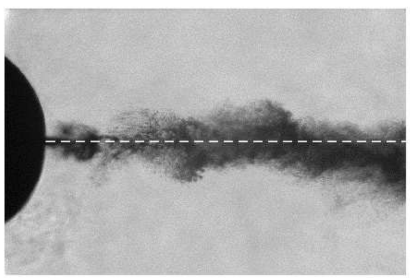
- Marginally larger SMD at 500 bar, compared to 1500 bar, especially after 6 mm

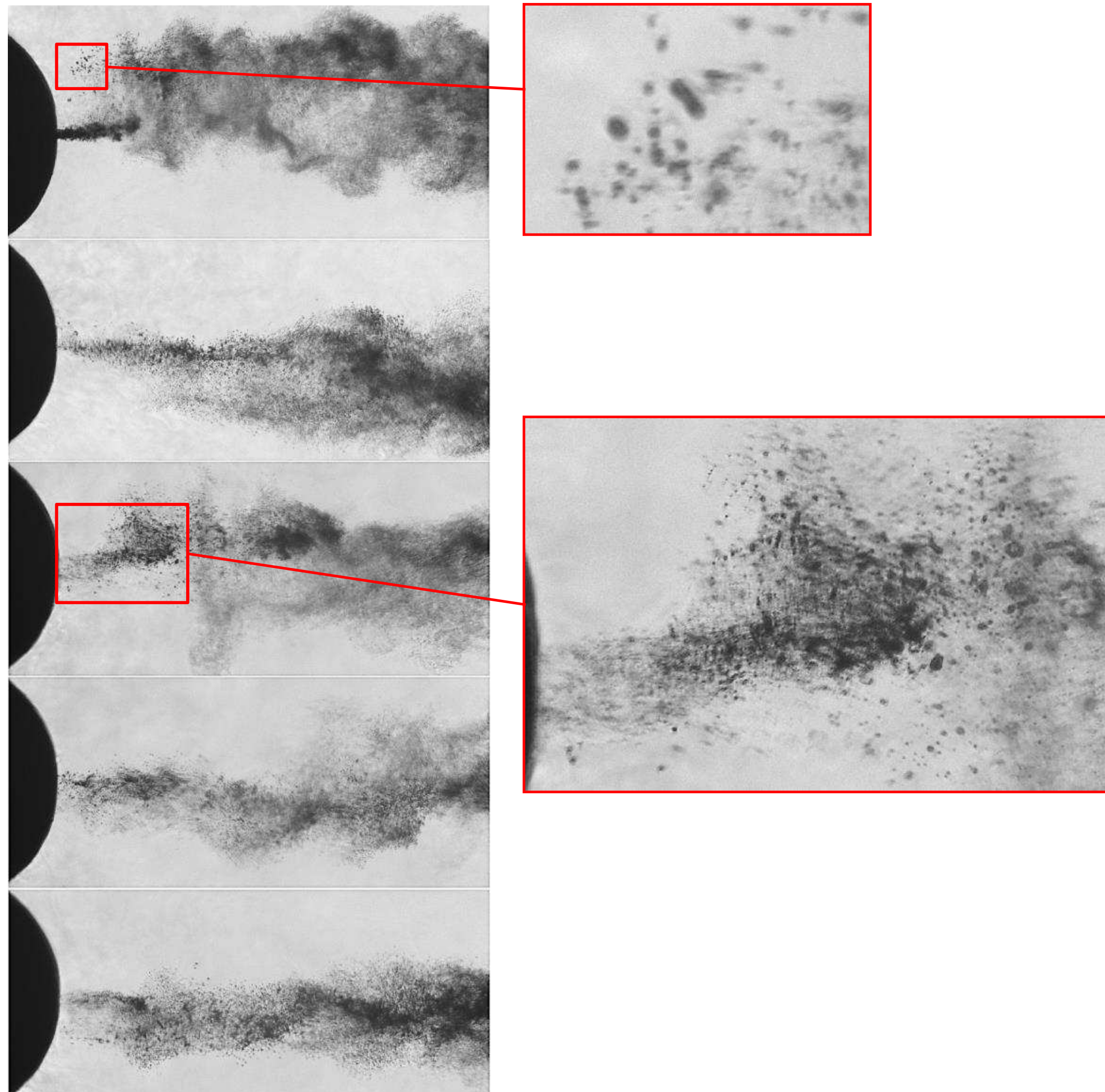


- Asymmetrical distributions observed in both cases (SMD, drop count, median diameter)

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

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BP Global Fuels Technology

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