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

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Contributors

- Droplet size measurements by long-distance microscopy
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- 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

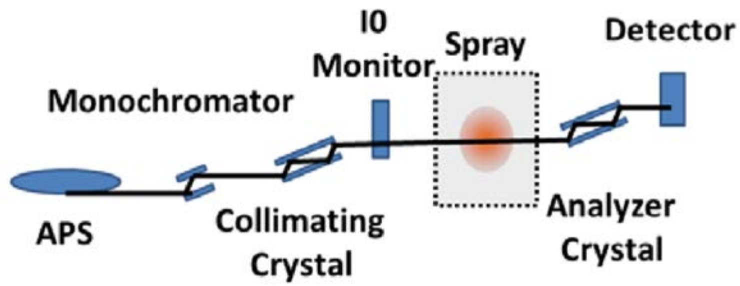
Overview

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

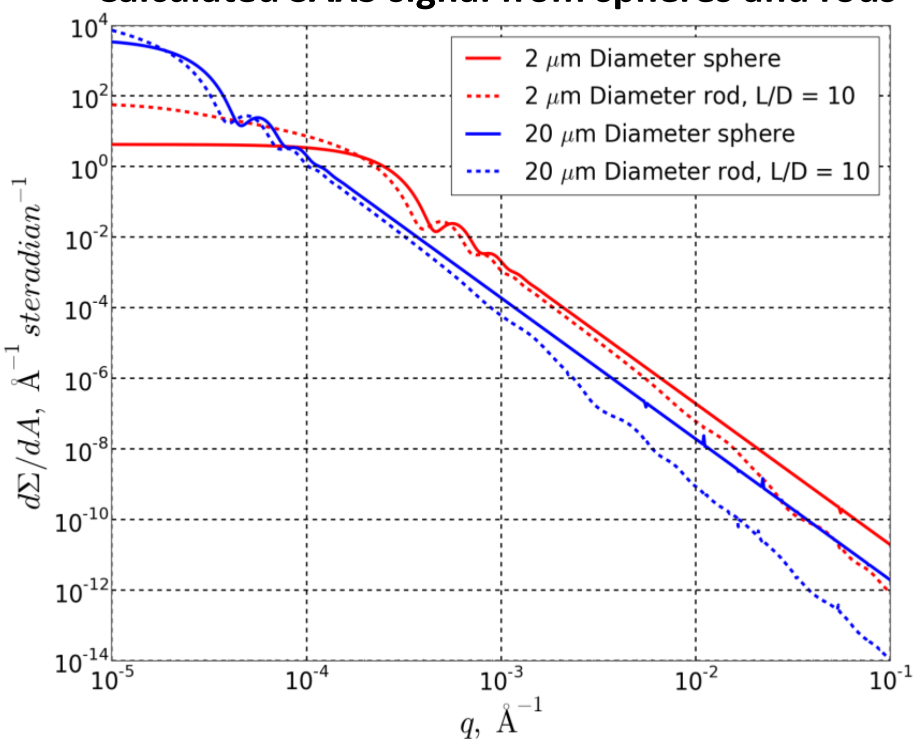
Ultra-Small Angle X-ray Scattering (Argonne)

USAXS setup based on Powell et al. (2013) *ILASS Americas*

- 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



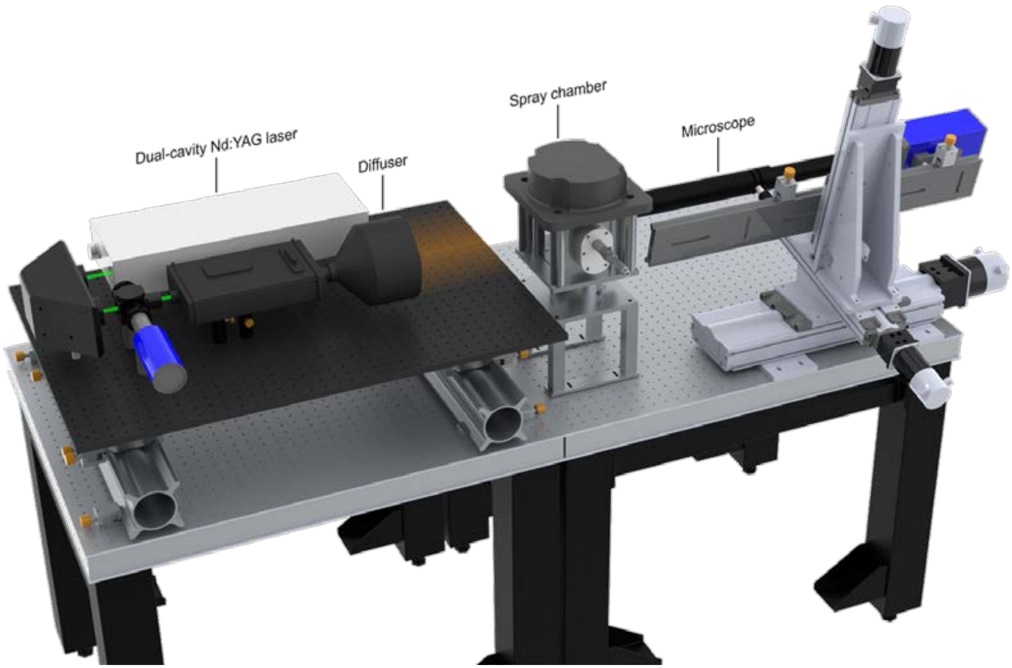
Calculated SAXS signal from spheres and rods

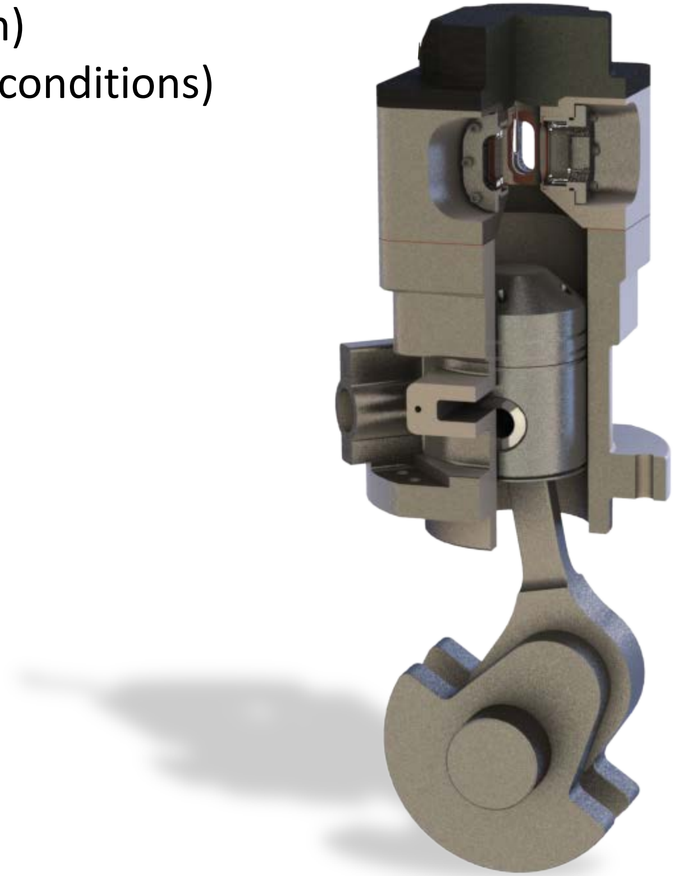


Long distance microscopy (Brighton)

Shadowgraphy setup based on Crua et al. (2015) *Fuel* 157 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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3. **Spray A measurements**
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Parametric variations for USAXS

- Injector Spray A #210679
- Some deviations from the standard 'Spray A' 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%	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	-	-	-	-	-
	-	300	-	-	-	5	-

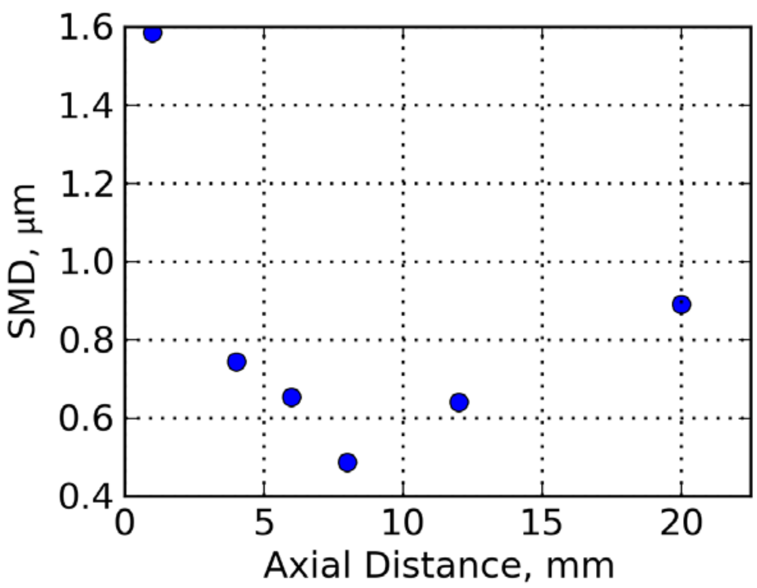
Fuel temperature at nozzle	338K (65°C) instead of 363 K (90°C)
Common rail	GM Part number 97303659
Common rail volume/length	22 cm^3/28 cm
Distance from injector inlet to common rail	24 cm
Tubing inside and outside diameters	Inside: 2.4 mm. Outside: 6-6.4 mm.
Fuel pressure measurement	7 cm from injector inlet / 24 cm from nozzle

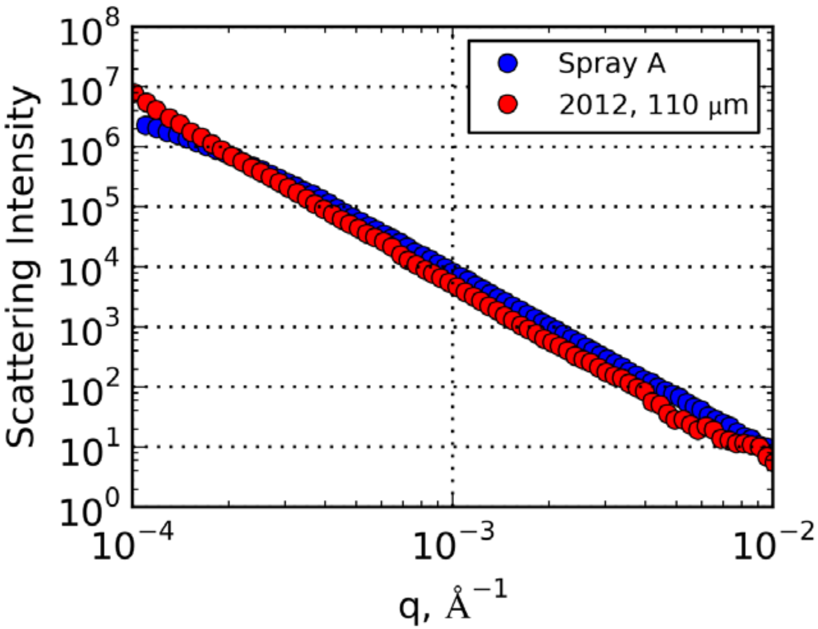
Legend

Completed
Not met

Ultra-small angle x-ray scattering measurements

- 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

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	-	-	-	-	-

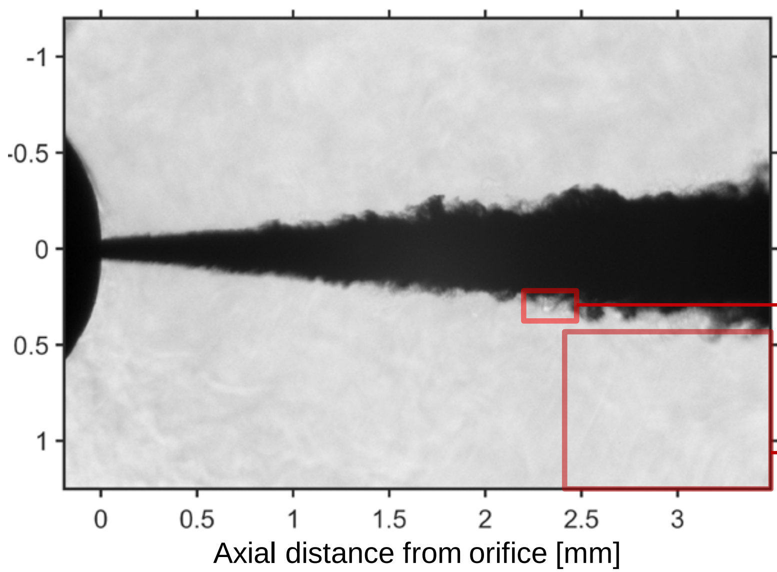
Fuel temperature at nozzle	403 K (130°C) instead of 363 K (90°C)
Common rail	GM Part number 97303659
Common rail volume/length	22 cm^3/28 cm
Distance from injector inlet to common rail	24 cm
Tubing inside and outside diameters	Inside: 2.4 mm. Outside: 6-6.4 mm.
Fuel pressure measurement	7 cm from injector inlet / 24 cm from nozzle

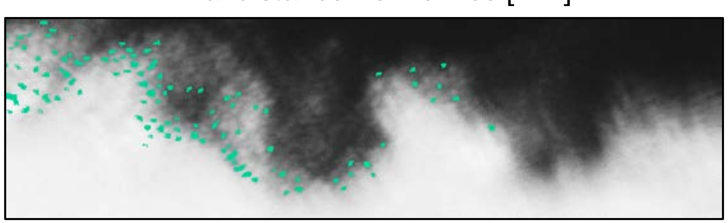
Legend

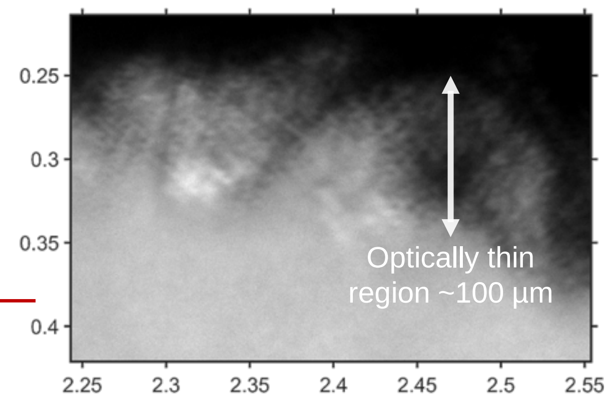
- Completed
- In progress
- Not met

Results – 0.5 ms after start of injection

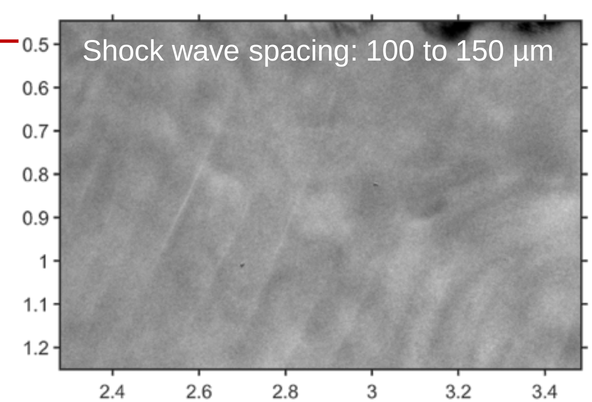
- Droplets are visible in the optically-thin region of spray periphery, but challenging to measure:
  - Surrounded by density gradients, vaporised fuel, and shock/pressure waves
- Advanced image processing algorithms identifies many of the small liquid structures, without producing significant false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

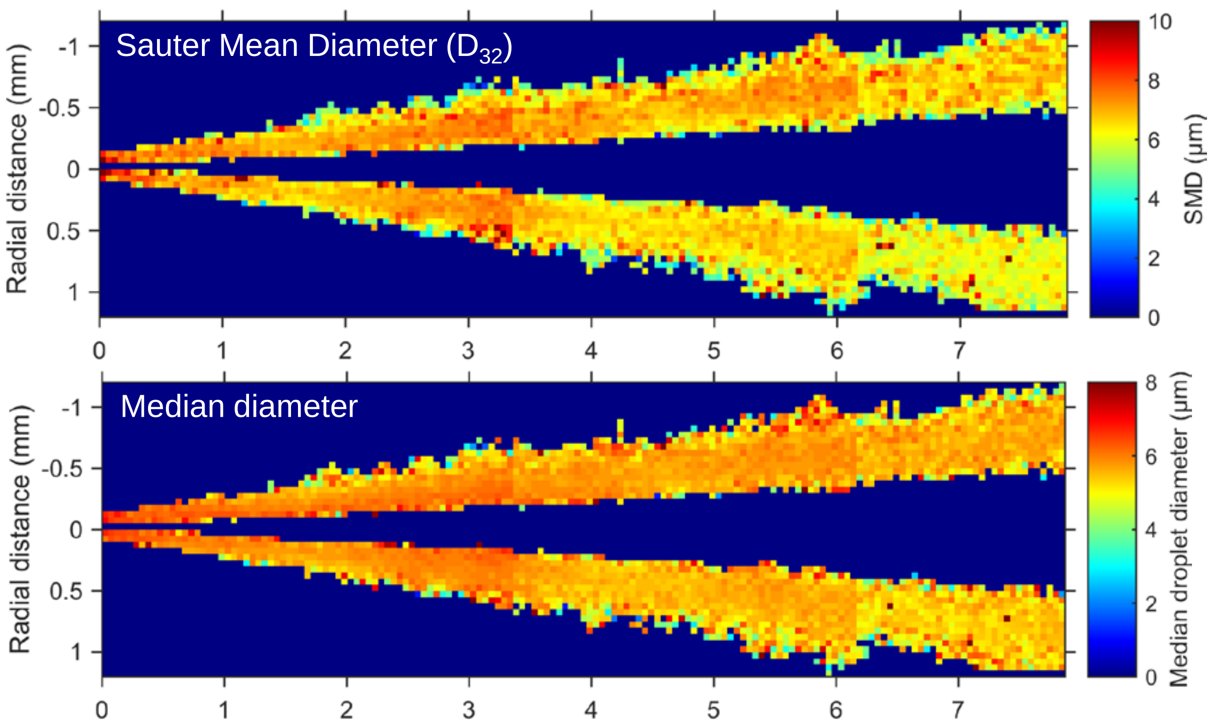


Pressure waves are often visible along the spray periphery.

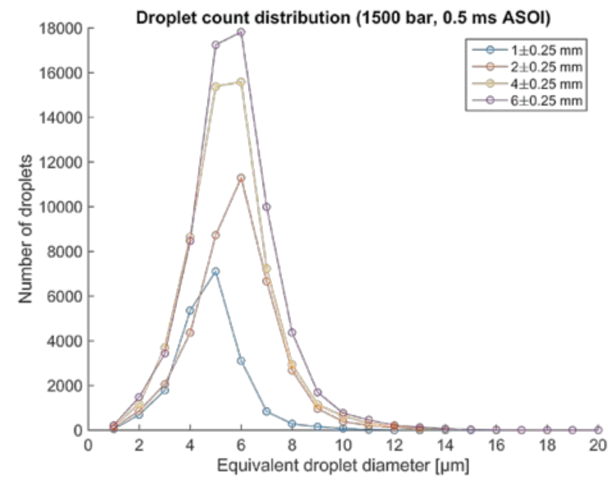
How do they affect droplet formation, mixing and optical resolution?

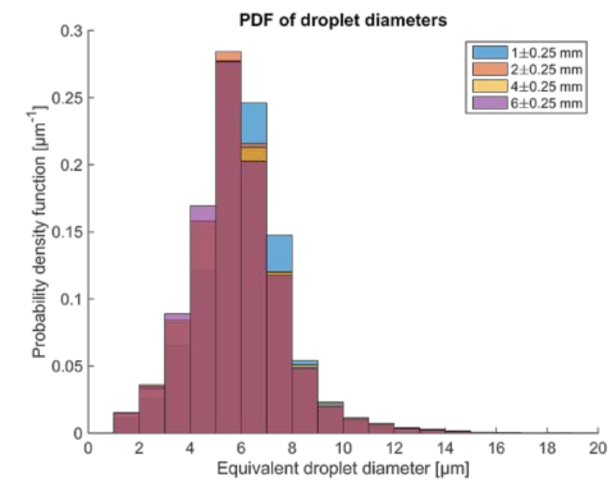
Droplet size distributions

- ❖ 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.



Statistics for x = 1, 2, 4, 6 ±0.25 mm (y = ±1.2 mm; z = ±0.01 mm)

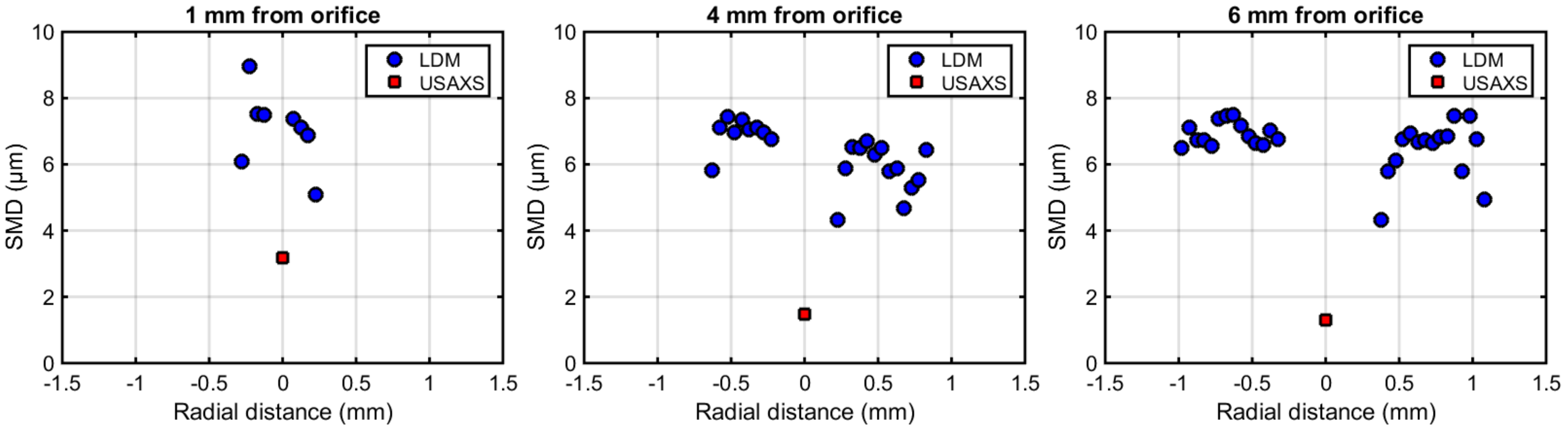




Comparison of LDM and USAXS for Spray A

- 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.

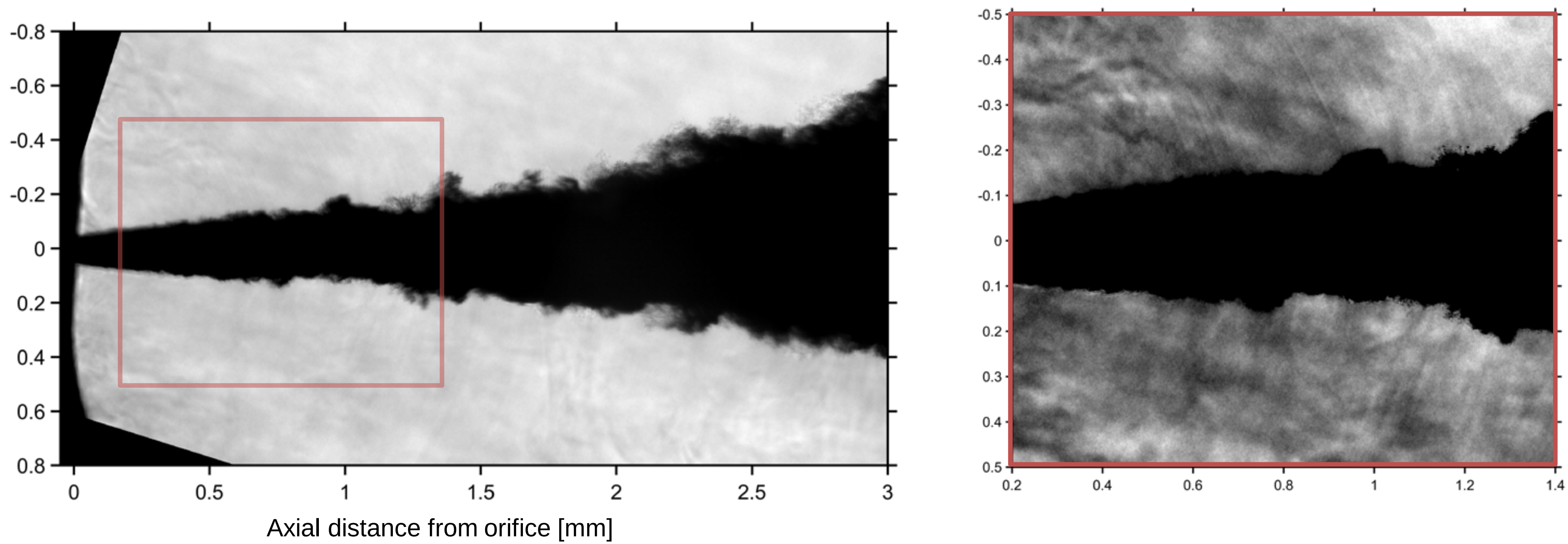
- These results represent our best efforts, and **they may change** as calibration and analysis methods improve. We believe these LDM measurements are an **upper limit** for the SMD.



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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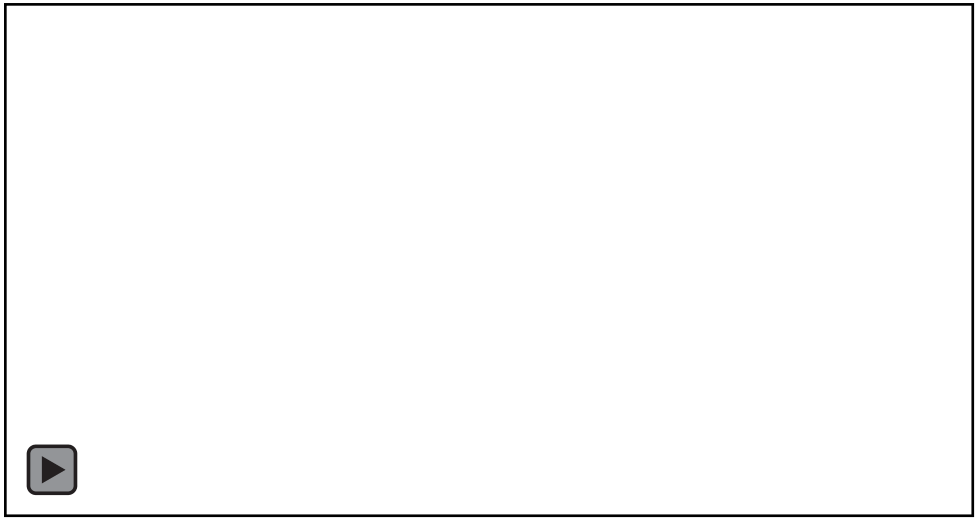
Effect of gas conditions on atomization

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

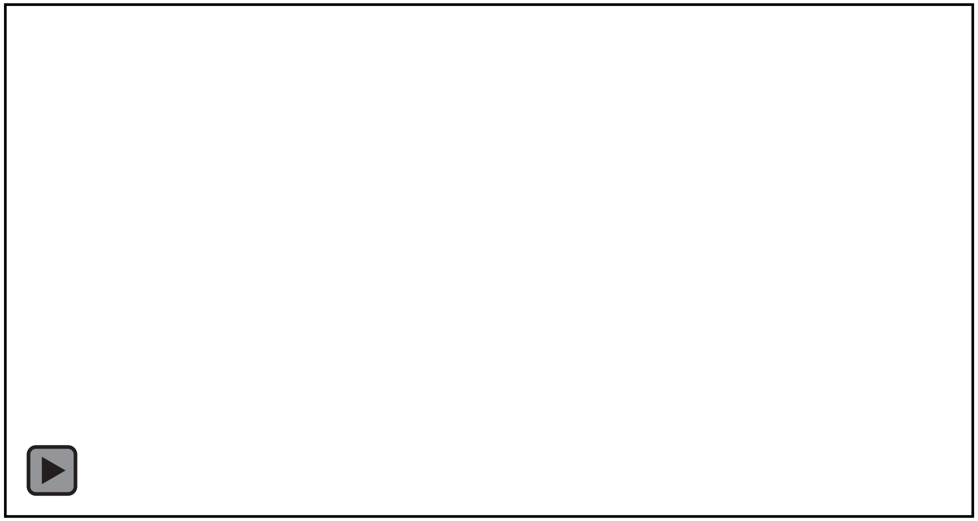
n-hexadecane into **900 K**, 79 bar, 30.4 kg/m^3



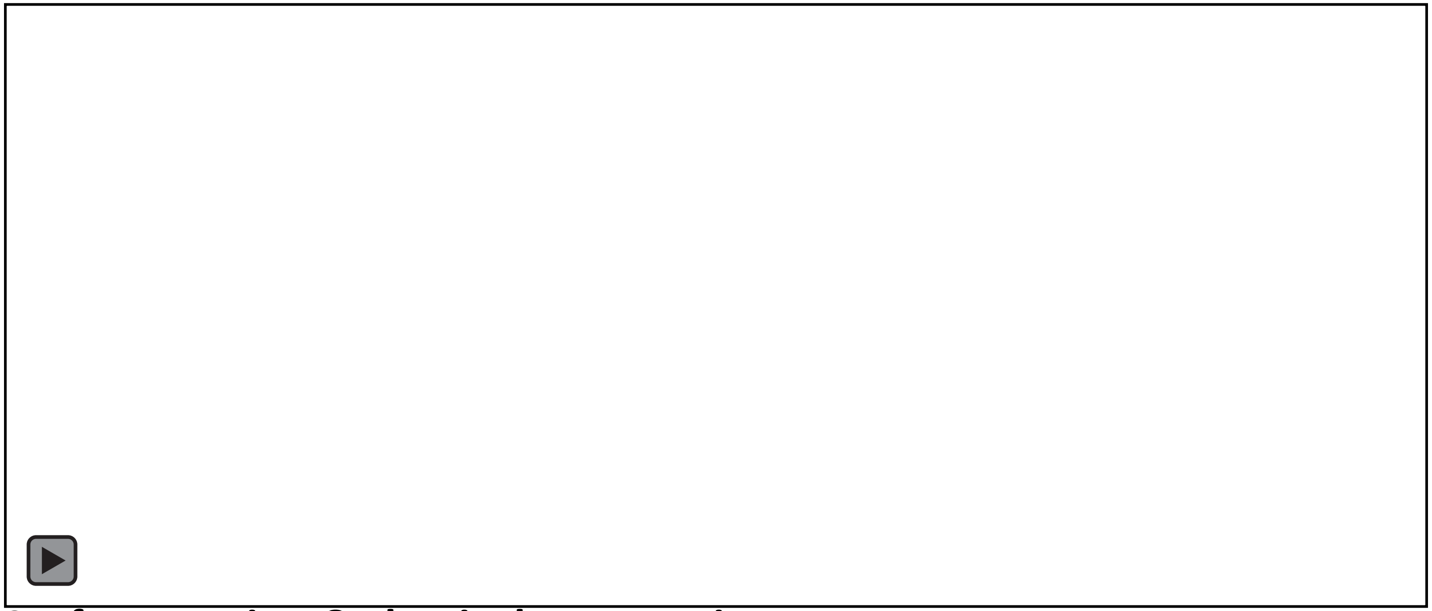
Atomization and miscible mixing

- 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 **1200 K**, 107 bar, 30.4 kg/m^3



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

Effect of fluid properties on surface tension at 1200 K

***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

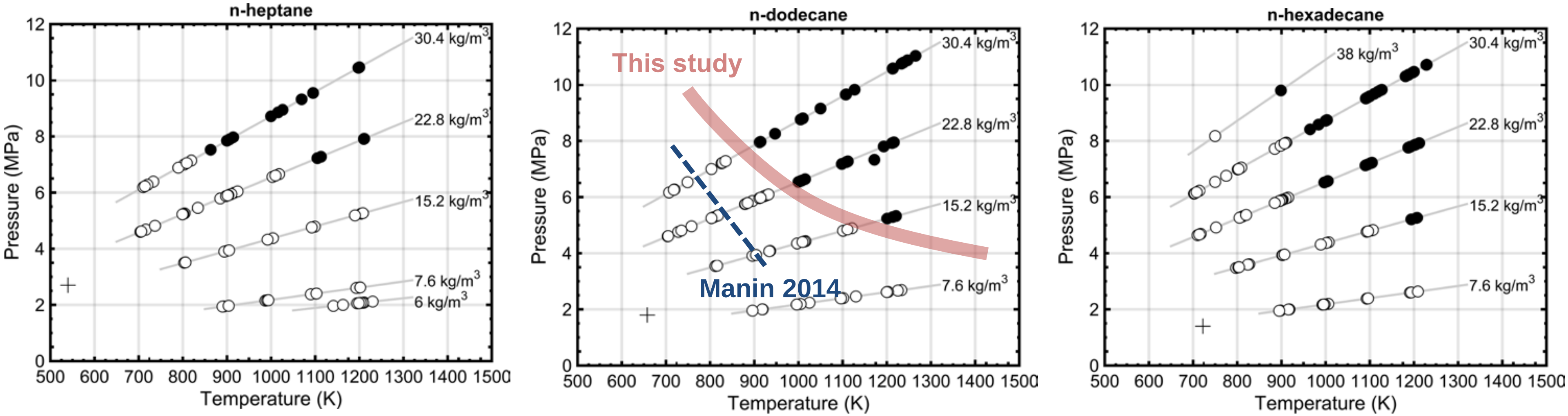
***n*-hexadecane** **Evaporation followed by miscible mixing**

- Significant droplet oscillations and deformations
- Disintegration also at the *wake side*
- But into *three* separate chunks of fluid

Effect of fuel properties

- 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 ➔ 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



Experimental conclusions

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

To ECN5 and beyond

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)?