'Joint workshop Combustion & Sprays SIGs'

Special interest Group Meeting – London, Mon 8th April 2019

Manufacture, Characterization, and Stability Limits of an Additive Manufactured Prefilming Air-Blast Atomizer

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FLEXIS is part funded by the European Regional Development Fund through the Welsh Government.

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Background and Previous Studies

- Research group led by Professor Phil Bowen, previously worked for Shell Research at Thornton Research Centre studying very large multi-phase explosion hazards after the Piper-Alpha disaster in the North Sea, before joining the Energy Group at Cardiff School of Engineering in 1994.

- Based at the Gas Turbine Research Centre, the former UK Defence Evaluation Research Agency (DERA) national gas turbine combustion research facility relocated from Farnborough (Pyestock) to Port Talbot. Now sits within Cardiff's 'Energy Systems' University Research Institute.

- Carry out fundamental and applied research on alternative / hazardous fuels, elevated pressure and temperature combustion.

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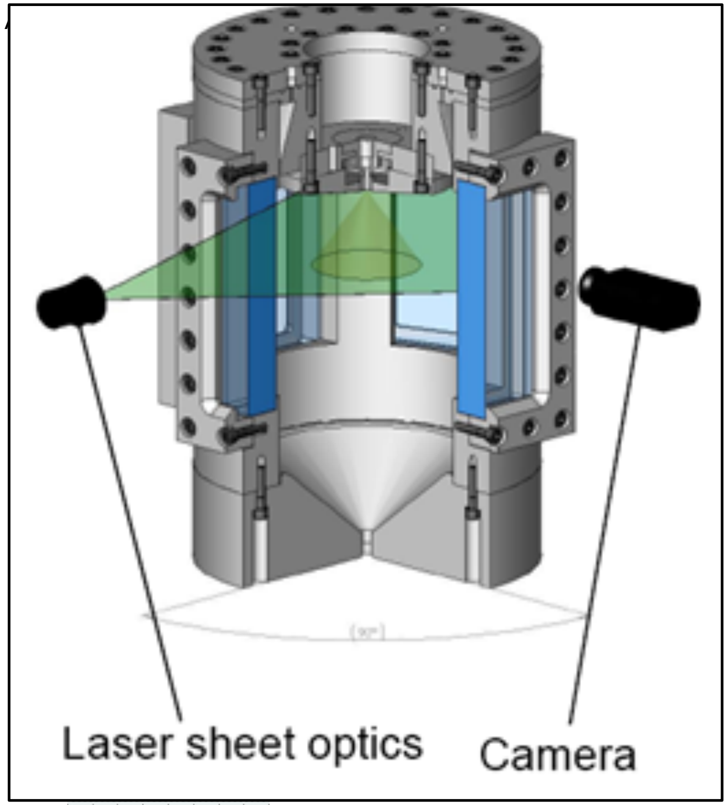
Manufacture, Characterization, and Stability Limits of an Additive Manufactured Prefilming Air-Blast Atomizer

Background and Previous Studies – Automotive Sprays

- Worked with Ricardo to develop techniques for characterisation of automotive injectors.
- Collaborative research has spanned over 15 years and included 5 PhD research projects.
- Capable of analysing sprays delivered into in-cylinder environments
  (P ≈ 15 barg, T≈ 220 to 400 K).
- Studies carried out for variety of fuel blends, with injector rail pressures above 200 barg.
- Spray is characterised through mixture of time resolved high speed imaging, planer laser and PDA laser diagnostics.



Pressurised Injector Test Chamber

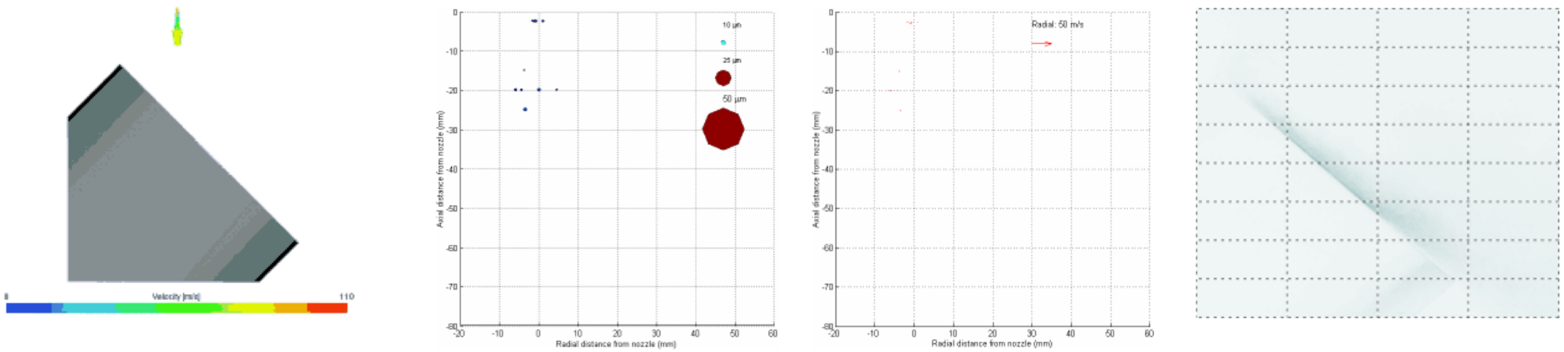
Sample Spray Characterisation Results

Manufacture, Characterization, and Stability Limits of an Additive Manufactured Prefilming Air-Blast Atomizer

Background and Previous Studies – Automotive Sprays

- Investigated effect of impingement on droplet sizing and fuel film formation.
- Experimental work and subsequent CFD model development were critical in the introduction of GDI technology in automotive industry.
- Automotive studies are in effect **far more straightforward than mist hazard quantification**; as injectors are precisely engineered to produce desired spray under controlled delivery conditions, fuels properties are also tightly controlled by legislation.

Air Density = 4.76 kg.m^{-3}, Air Temp. = Atmos, Piston Temp. = 150 °C



Comparison of CFD Predictions and Experimental Measurements

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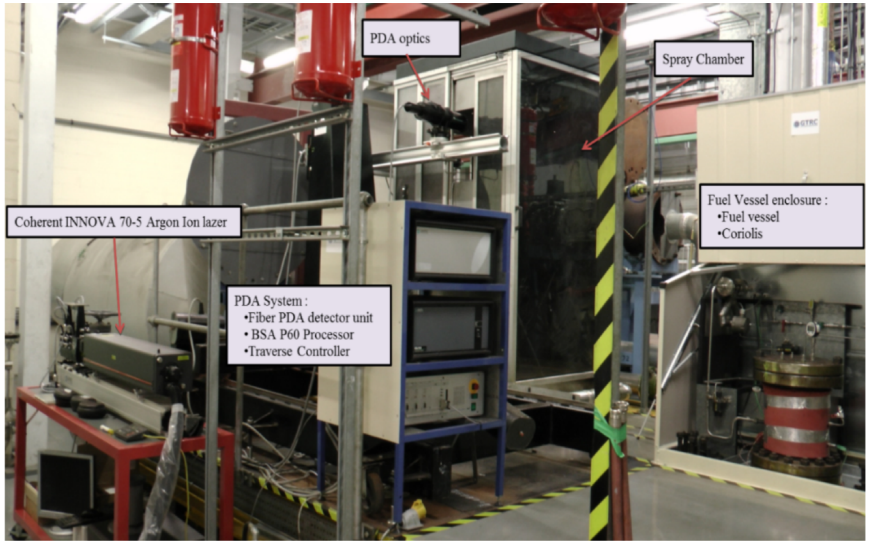
Manufacture, Characterization, and Stability Limits of an Additive Manufactured Prefilming Air-Blast Atomizer

Background and Previous Studies – Mist Explosion Hazards

- 1.2 x 1.2 x 2.5m spray chamber for study of down-fired liquid releases.
- 25 barg liquid pressure vessel or 345 barg accumulator for supply.
- Remotely operated pneumatic control valves
- Logging of Mass flow (Coriolis meter), liquid and ambient pressure and temperature.
- Equipment fully ATEX compliant with inbuilt fire suppression.
- Suitable for spray characterisation and ignition trials.



Large Scale Spray Chamber / Test Fuel Properties

Physical Properties	Liquid			
	Kerosene JETA1	Hydraulic Oil (Mobil DTE)	LFO Ambient (class E)	LFO preheated 70°C
Density (kgm^{-3})	800	870	930	880
Kinematic Viscosity (mm^2/sec)	3.5 (15 °C)	111 (20 °C)	169.8 (at 24 °C)	18 (at 70 °C)
Dynamic Viscosity (Kgm^{-1}s^{-1})	0.0028	0.09657	0.158	0.01584
Surface Tension (kgs^{-2})	0.026	0.03328	0.03317	0.03148
Flashpoint (°C)	38	223	81	81

Background and Previous Studies – Mist Explosion Hazards

Liquid: JET-A1 Kerosene
Nozzle: D=1 mm, L=2 mm
Location: y-axis =300 mm,
x-axis=5.52 mm
Pressure (bar g): 20.48
Flowrate (g/s): 28.69
Liquid Temperature (°C) : 17.6
Ambient Temperature (°C) : 20
Ignition System: ≈ 1 J-15Hz

Liquid: JET-A1 Kerosene
Nozzle: D=1mm, L=2 mm
Location: y-axis =600 mm,
x-axis= 107.04 mm
Pressure (bar g): 15.66
Flowrate (g/s): 24.95
Liquid Temperature (°C) :17.5
Ambient Temperature (°C) : 19.8
Ignition System: ≈ 1 J-15Hz

Liquid: JET-A1 Kerosene
Nozzle: D=1 mm, L=2 mm
Location: y-axis = 1500 mm,
x-axis= 105 mm
Pressure (bar g): 11.45
Flowrate (g/s) :21.12
Liquid Temperature (°C) :19.9
Ambient Temperature (°C) : 16.2
Ignition System: ≈ 1 J-15Hz

Liquid: JET-A1 Kerosene
Nozzle: D=1 mm, L=2 mm
Location: y-axis = 900 mm,
x-axis= 35 mm
Pressure (bar g): 5.22
Flowrate (g/s):14.44
Liquid Temperature (°C) : 17.6
Ambient Temperature (°C) :14.07
Ignition System: ≈ 1 J-15Hz

Sample Ignition Trial Results

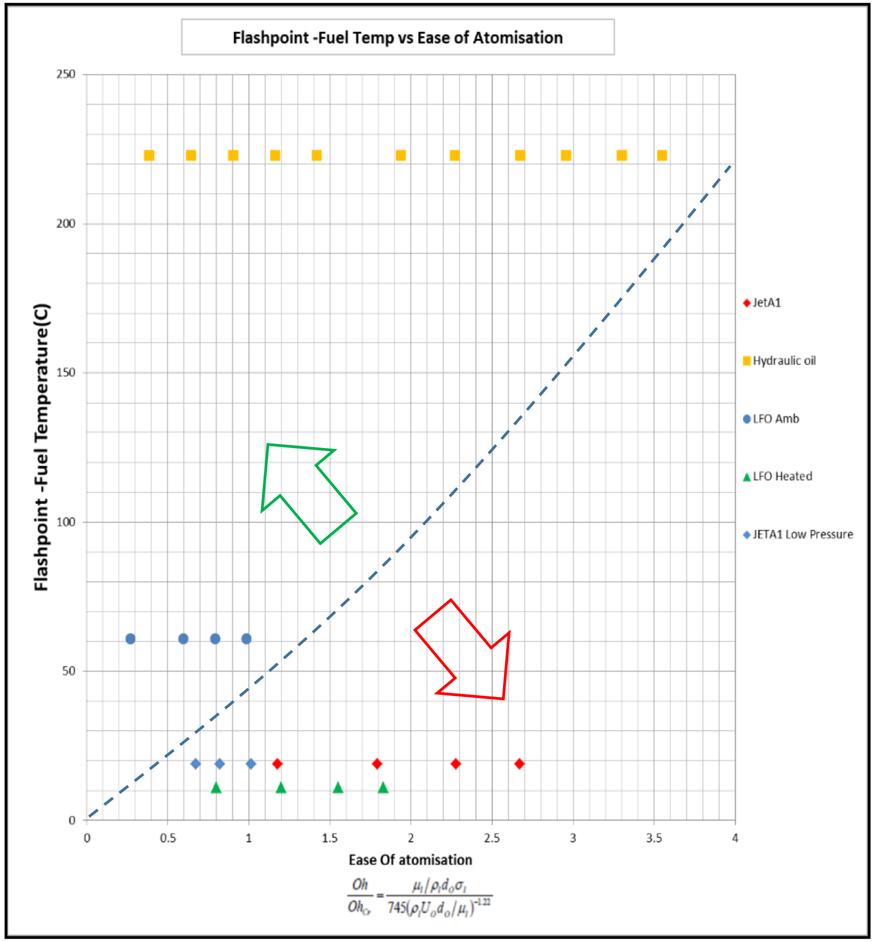
Manufacture, Characterization, and Stability Limits of an Additive Manufactured Prefilming Air-Blast Atomizer

Background and Previous Studies – Mist Explosion Hazards

- Need to take into account fuel conditions on mist ignitability
- Possible relationship Oh vs (Flashpoint – Fuel Temp) used
- Can broadly separate successful ignitions from “safe” conditions
- Ignition requires presences of:
  - Droplets below MID
  - Sufficient droplet numbers

- Transition region still needs to be defined.

- Future work includes expanding to include additional fuels and more realistic orifice shapes.



MISTS JIP Results / Initial Fuel Classification

Swansea University Prifysgol Abertawe
Cardiff University Prifysgol Caerdydd
University of South Wales Prifysgol De Cymru
Prifysgol Aberystwyth University
Prifysgol Bangor University
TATA
Neath Port Talbot County Borough Council
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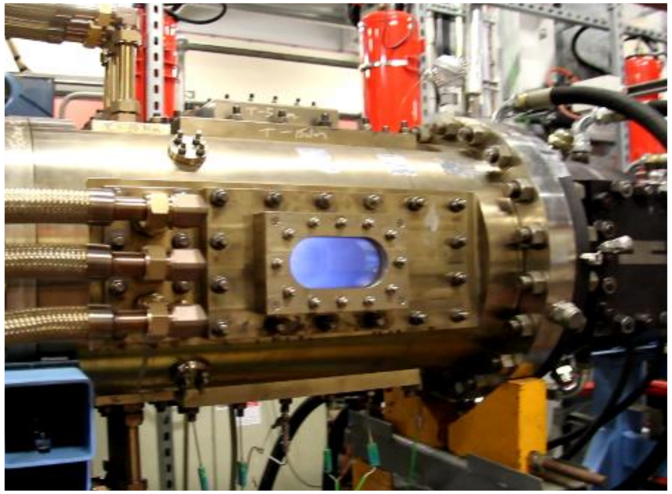
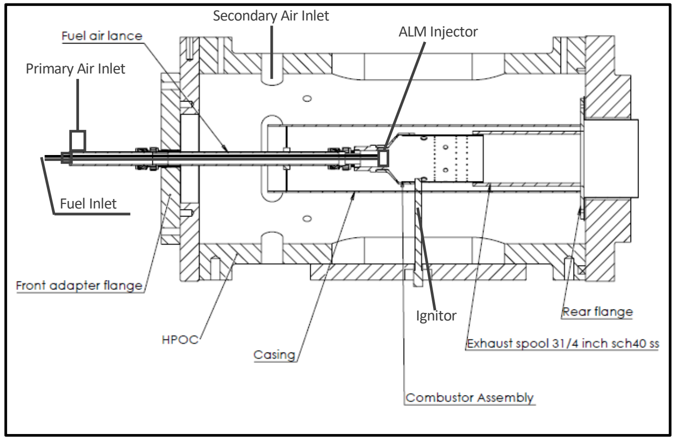
Development of Air-Blast Atomizer – Design and Manufacture

- Main combustion test apparatus at GTRC is the High Pressure Optical Casing (HPOC).
- Max operating capability: < 16 bar absolute
  < 5kg/s air flow
  < 900 K inlet temp
- Typical operation: < 9 bar absolute
  < 250 g/s air flow
  < 575 K inlet temp



HPOC Pressure Casing

- To further develop facility - requirement to develop our own Rich burn, Quick-mix, Lean burn combustor to sit alongside our Generic Swirl burner.
- Previous studies carried out with liquid fuels have primarily utilised “Delavan” style nozzles.
- To be representative of industrial RQL combustors, requirement for suitably scale air-blast atomizer.



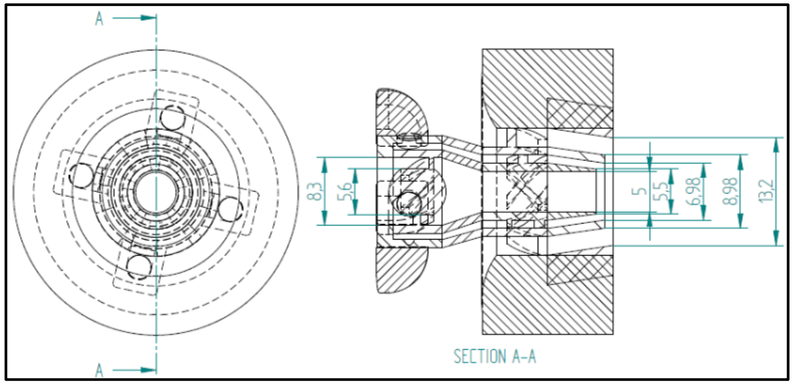
Schematic of RQL Burner in HPOC

Development of Air-Blast Atomizer – Design and Manufacture

- Design concept chosen for prototype nozzle is that of the Parker Hannifin Corporation.
- Fuel delivery annuli positioned between a centrally located co-rotating air outlet and a secondary counter-rotating outer air channel [1].

- Design utilises swirl vane in the fuel and air channels, angled at 45 degrees [2].
- Comparatively large outer air cross sectional area used to increase swirl strength and flow recirculation.
- Air flow path area at nozzle exit 80-90% of that through swirl vane [3].

[1] doi.org/10.2514/2.5568
[2] doi.org/10.1115/GT2006-91156
[3] United States Patent 3980233



Prefilming Airblast Atomizer Prototype Design / Specification

	Inner Air	Fuel	Outer Air
Vane Thickness (mm)	1	1.2	1.2
Swirl Description	Helical	Front facing Helical	Helical
Swirl Angle	45° Clockwise	45° Clockwise	45° Anti- clockwise
Swirl chord Length (mm)	5.75	7.6	5.75
N° of Vanes	5	5	5
Swirl Di (mm)	8.3	7	11
Swirl Do (mm)	5.6	9	15.6
Orifice Di (mm)	-	5.5	8.98
Orifice Do (mm)	5	6.98	13.2
Inlet CSA no vanes (mm^2)	29.48	25.13	96.10
Inlet CSA including vanes (mm^2)	22.73	19.13	82.30
Blockage Ratio (%)	77.10	76.3	85.6
Orifice CSA (mm^2)	19.63	14.51	73.51
Constriction Ratio (%)	86.40	75.82	89.32

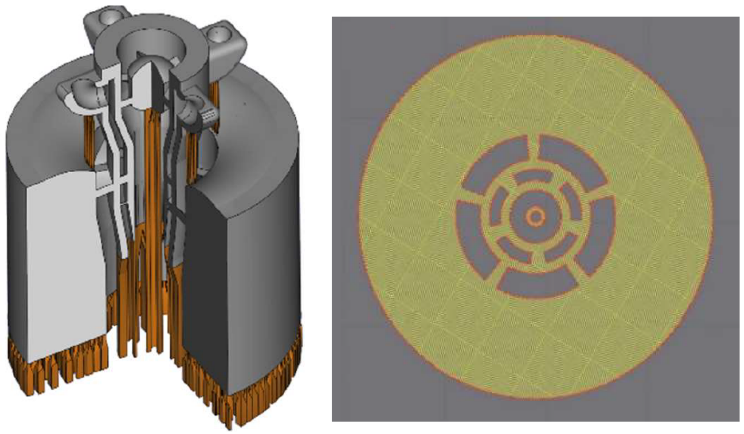
Development of Air-Blast Atomizer – Design and Manufacture

- Selective Laser Melting Additive Manufacturing Technique chosen to produce prototype design.

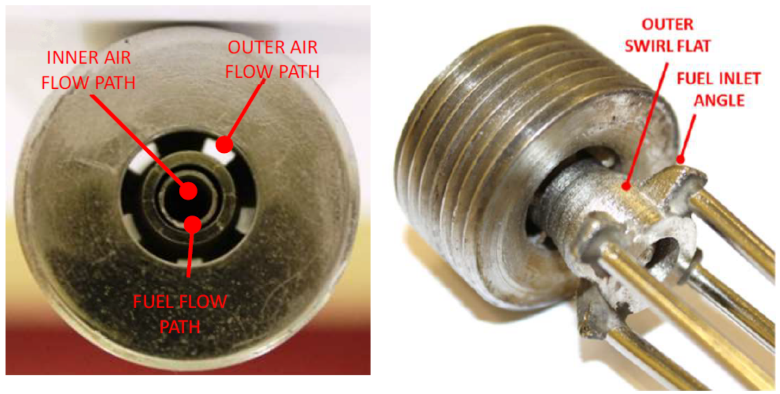
- A Renishaw AM250 SLM machine, incorporating a modulated Ytterbium fibre laser was used.

- The recommended process parameters were used:
  200 W laser power
  110 µm hatch distance
  50 µm powder layer
  6 µm point distance
  50 µs exposure time
  67° layer rotation

- Predicted surface roughness (Ra) values with process parameters used 15 – 45 µm.



Injector Design with support structures, layer scan path



ALM Injector Prototype

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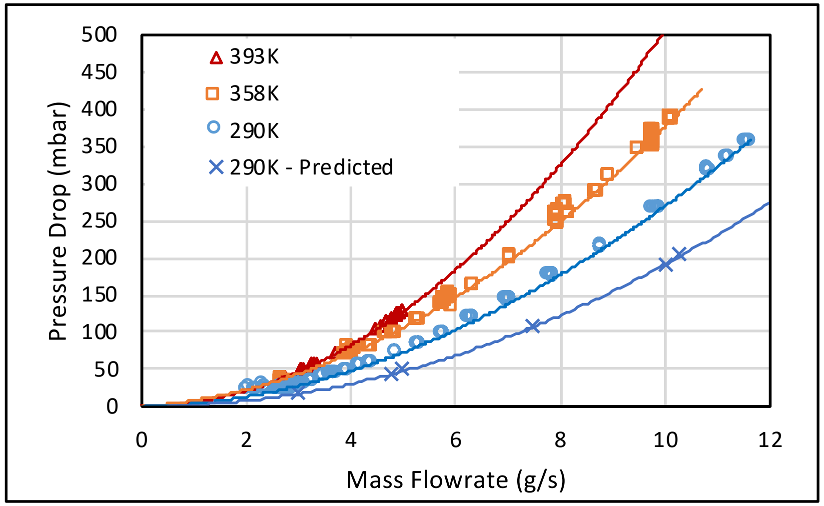
Development of Air-Blast Atomizer – Performance

- Pressure drop for air-flow across the nozzle measured for range of mass flows.
- Values compared to that calculated based upon designs geometry.
- Measured losses approximately 30 % higher than that predicted.

- **Pressure loss for fuel channels not measured.**



Pressure Drop vs Air Mass Flow

Measured Manufacturing Tolerances

	Diameter (mm)			Central position	
Flow Path location	Measured	CAD	error (%)	x-Dev (mm)	y-Dev (mm)
Inner Air Outlet	4.75	5	-5.00	0.00	0.00
Fuel Inner	5.70	5.5	3.58	0.01	0.00
Fuel Outer	6.74	6.98	-3.47	0.00	-0.03
Outer Air Inner	9.06	8.98	0.94	-0.05	-0.08
Outer Air Outer	13.22	13.2	0.14	0.07	0.12

- Manufacturing tolerance issues were observed, particularly with concentricity of the exit annuli.

- Measured sample Ra values:
  Flat surfaces - 12.3 µm ± 3.0 µm
  Angled surfaces - 26.2 µm ± 9.7 µm

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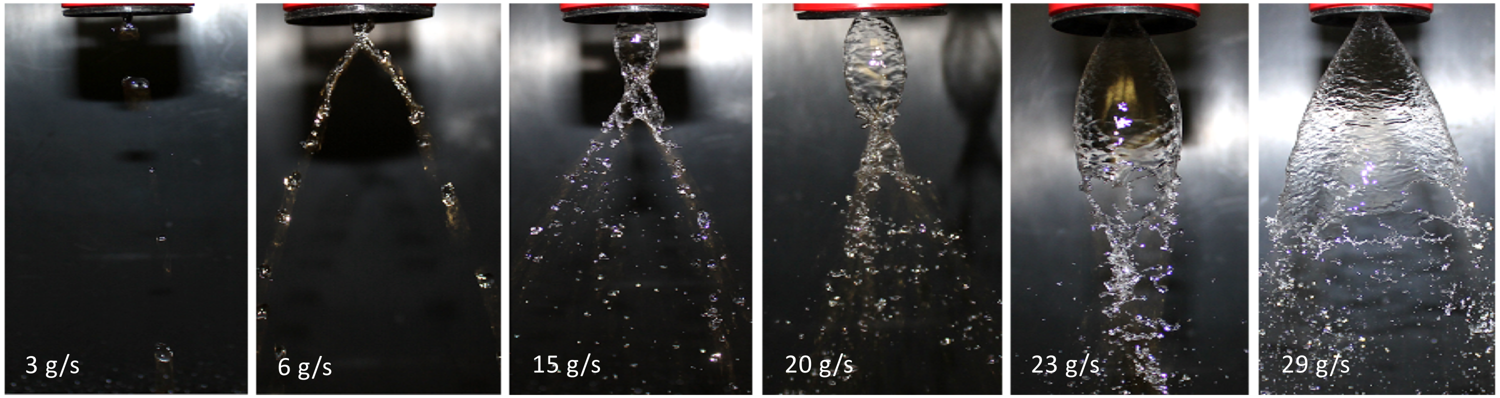
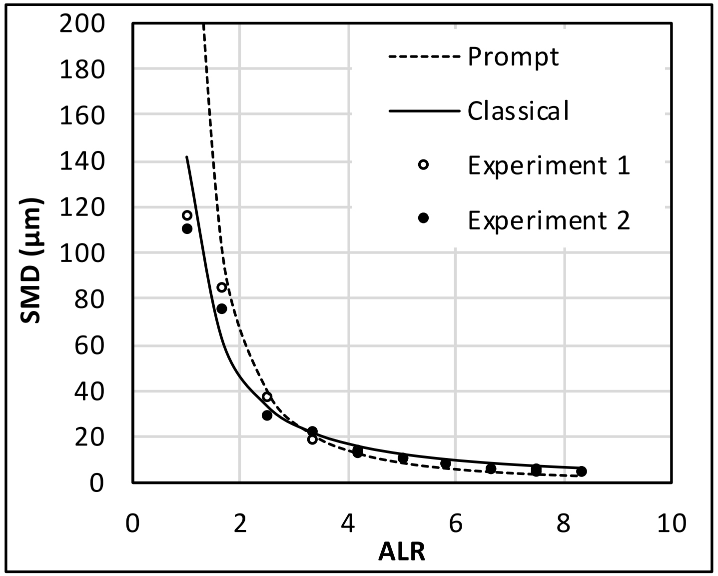
Development of Air-Blast Atomizer – Performance



Development of spray in swirling pre-filming atomiser at increasing water mass flow rates



Measured and Predicted SMD with Varying ALR

- Manufacturing imperfections not seen to impact prefilming sheet development.
- Typical hollow cone spray development observed with “rim”, “wave” and “perforated-sheet” sheet disintegration evident.

- Laser diffraction measurements of resultant spray compared favourably with “Prompt” and “Classical” correlations from literature.

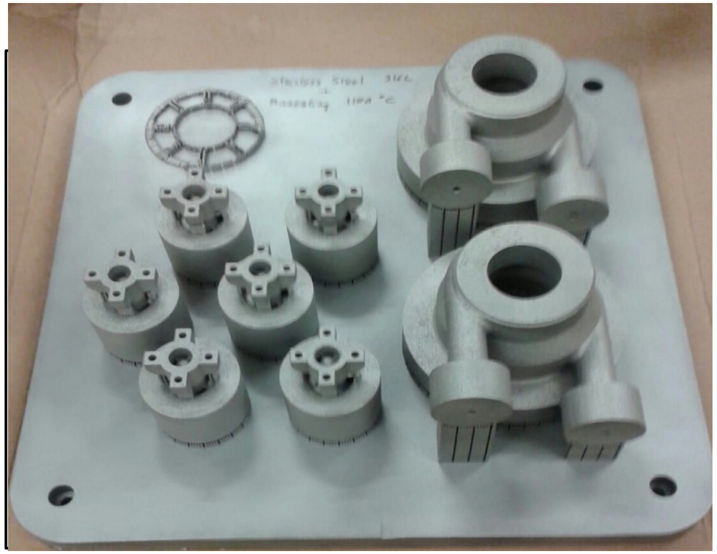
Manufacture, Characterization, and Stability Limits of an Additive Manufactured Prefilming Air-Blast Atomizer

Development of Air-Blast Atomizer – Combustion Testing

- Preliminary ignition and stability trials undertaken at GTRC within HPOC.
- Experimental work has been carried out at ambient and elevated pressures (up to 2.5 bara).

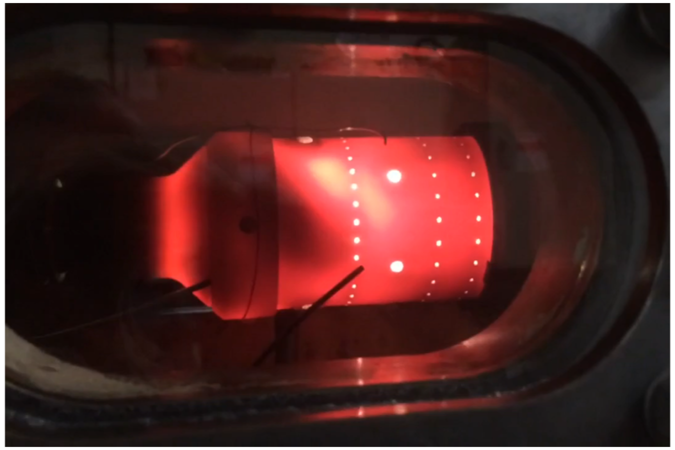
- Development work on variations to design continuing.

Unconfined Jet-A1 combustion



Preliminary Ignition and Stability Trial Results

Further Nozzle Prototypes



RQL Jet-A1 combustion

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Conclusions and Future Work

- A scaled, representative air-blast atomiser has been designed and manufactured from 316L stainless steel using Additive Manufacturing.

- Typical surface roughness (Ra) values of between 12 and 26 µm were measured for the nozzle, future work is looking at parameter control and post-processing of critical surfaces.

- The flow characteristics of the nozzle were typical of an air-blast atomizer, with liquid breakup flow structures consistent with that seen in literature. The measured pressure drop across the atomizer was higher than that expected, suggesting surface roughness tolerances are significant.

- Initial combustion trials were positive, with a stable flame observed and maintained at ambient and elevated pressures.

- Subsequent studies will introduce full optical access and examine variations in design; with the option to rescale atomizer for different combustor operating conditions and fuel specifications.

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