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School of Mechanical and Industrial Engineering

Water jet interaction with free supersonic air jet

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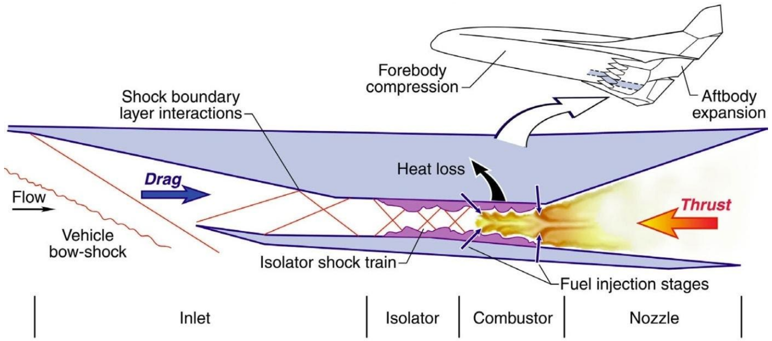
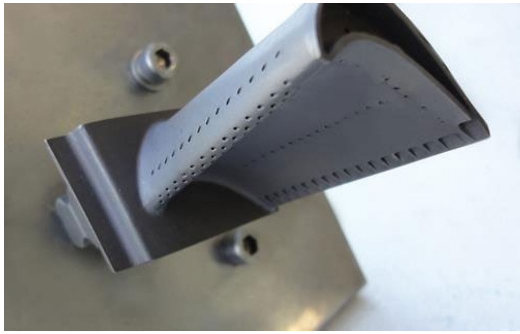
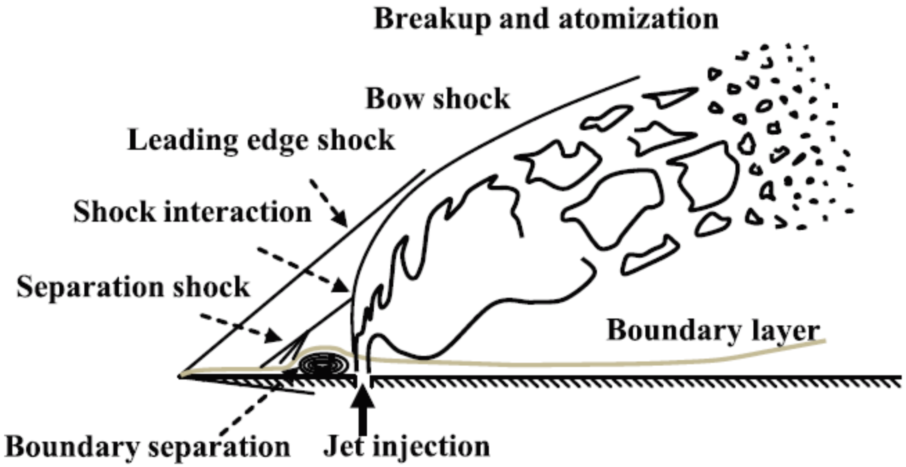
Research supported by: LaSPACE & LSU Board of Regents

Motivation

- Traditional Jet-In-Crossflow (JICF) has been studied extensively for subsonic and supersonic flows

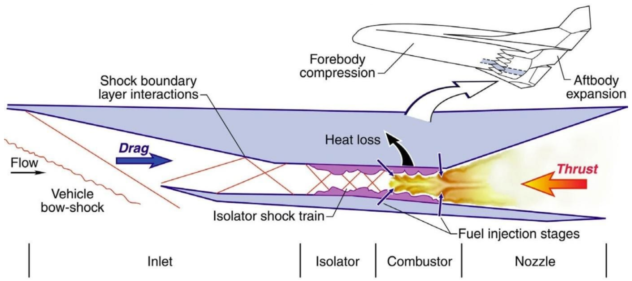


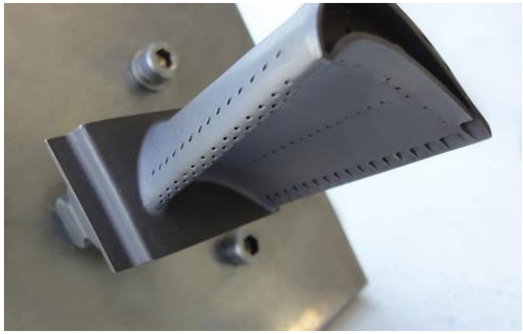


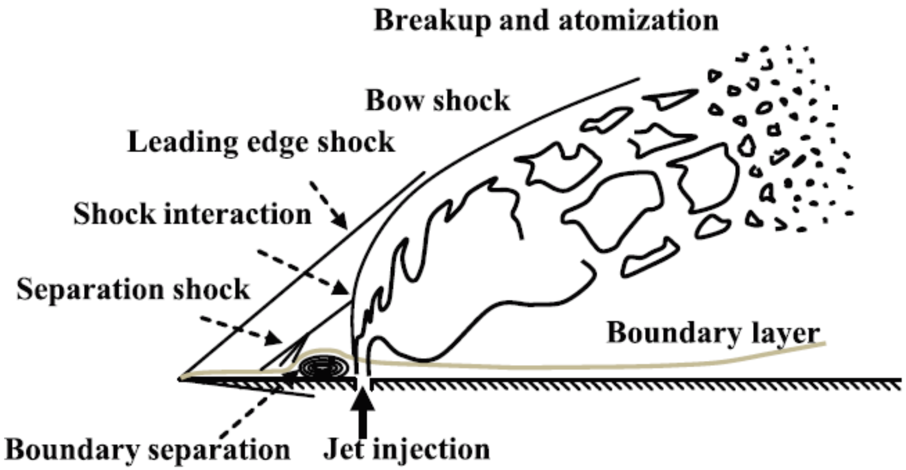


Motivation

- Jet injection into







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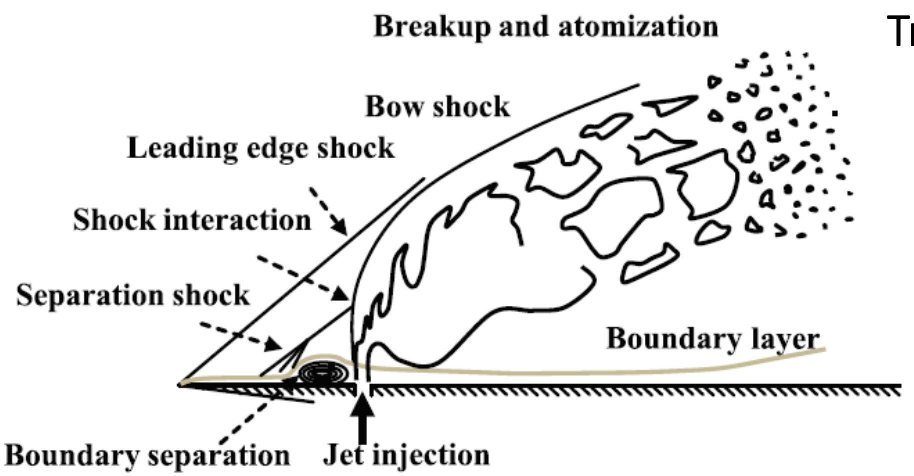
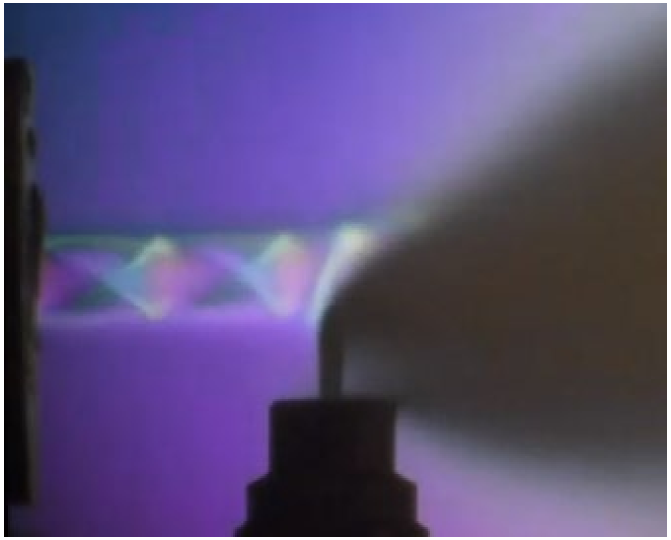
Project Motivation



Traditional JICF



- We seek to examine the key differences in breakup behavior between liquid injection into a continuous supersonic flow and injection into a discontinuous flow.

Liu, H., Guo, Y., & Lin, W. (2016). Numerical simulations of transverse liquid jet to a supersonic crossflow using a pure two-fluid model. Advances in Mechanical Engineering, 8(1), 1687814016629341.

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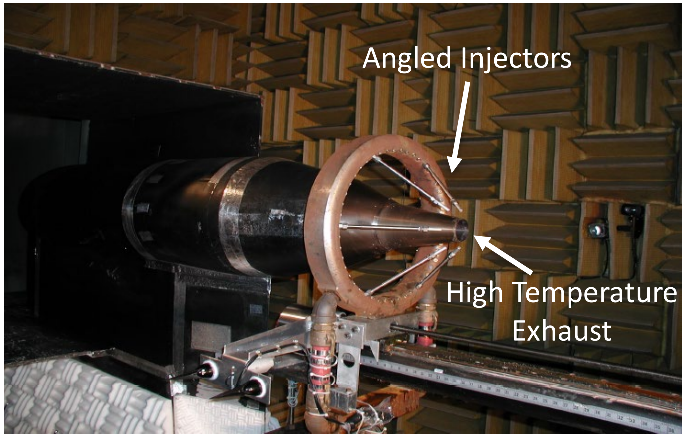
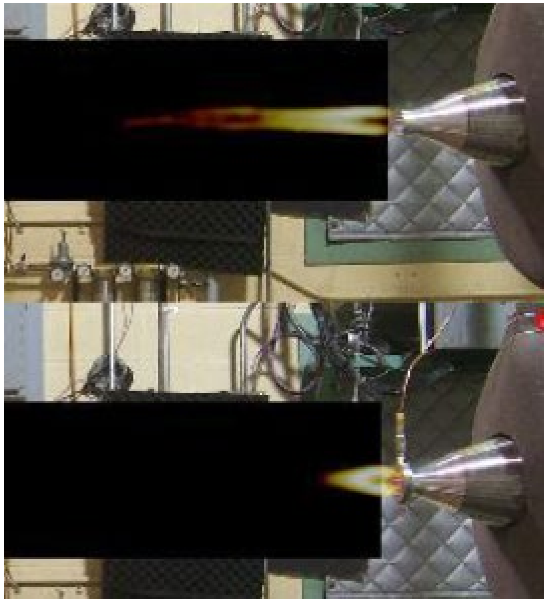
Noise Reduction in Free Jets



- Focused on minimizing noise production in mixing layer between free jet and ambient

Norum, T. D. (n.d.). Reductions in Multi-component Jet Noise by Water Injection. American Institute of Aeronautics and Astronautics.



No liquid injection

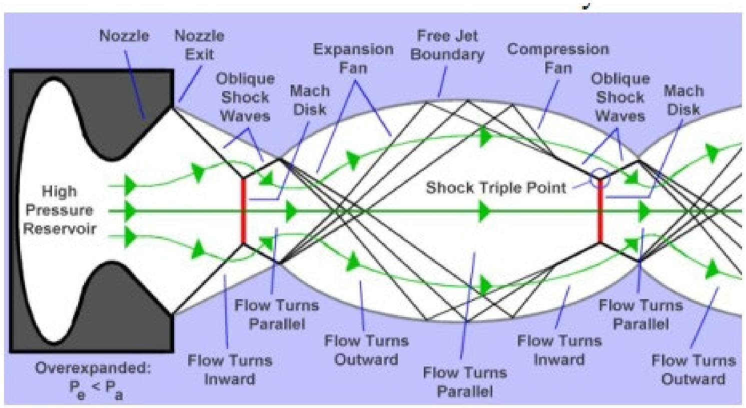
With liquid injection

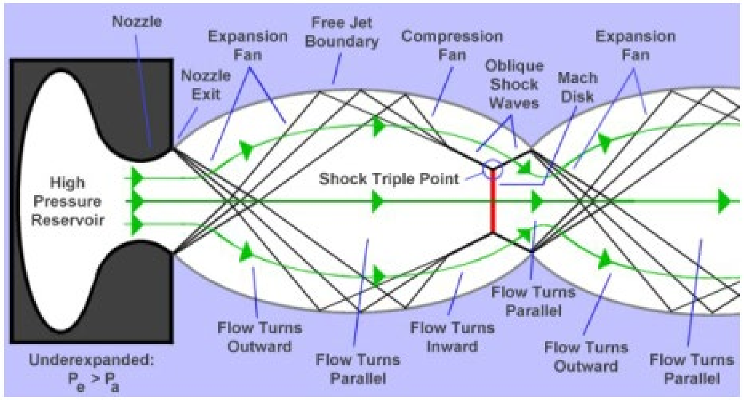
- Focused on minimizing noise production by breaking up internal shock structure and locating sound source locations

Zaman, K., & Podboy, G. (2010, June). Effect of microjet injection on supersonic jet noise. In 16th AIAA/CEAS Aeroacoustics Conference (p. 4022).

Previous work lacks examination of primary breakup regime and liquid penetration distance, <u>that is the focus of the current work</u>

Introduction to Supersonic Jets





Aerospaceweb. Available online: http://www.aerospaceweb.org/question/propulsion/q0224.shtml; (accessed on 14 August 2015).

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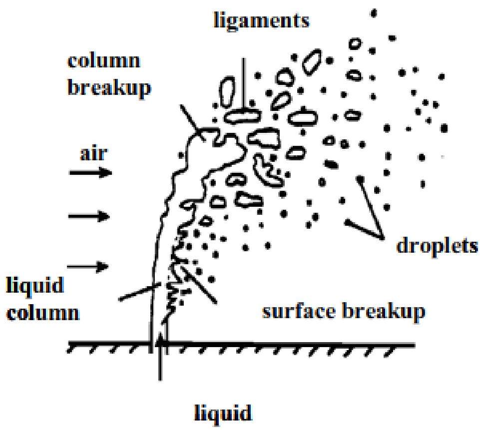
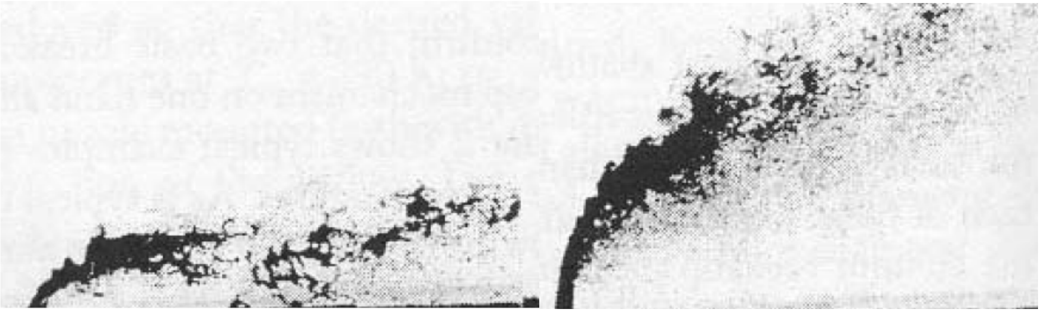
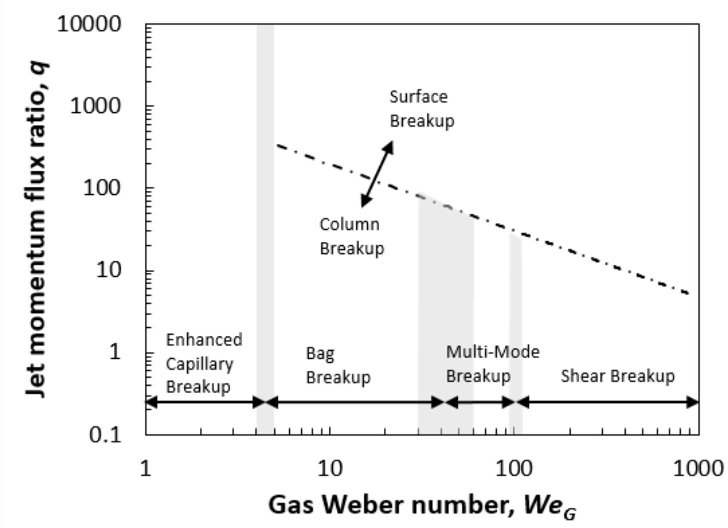
Liquid Jet Primary Breakup in JICF







$$We_G = \frac{\rho_g v_g^2 D_l}{\sigma} \qquad \mathrm{Re_D} = \frac{\rho v D_l}{\mu} \qquad \mathrm{Oh} = \frac{\mu}{\sqrt{\rho \sigma D_l}} = \frac{\sqrt{We}}{Re}$$

$$q = \frac{\rho_l v_l^2}{\rho_g v_g^2} \qquad q = \frac{P_l D_l}{P_g D_g}$$

Madabhushi, R. K., Leong, M. Y., & Arienti, M. (2006, May). ON THE BREAKUP REGIME MAP OF LIQUID JET IN CROSSFLOW. Paper presented at 19th Annual Conference on Liquid Atomization and Spray Systems, Toronto, Canada.

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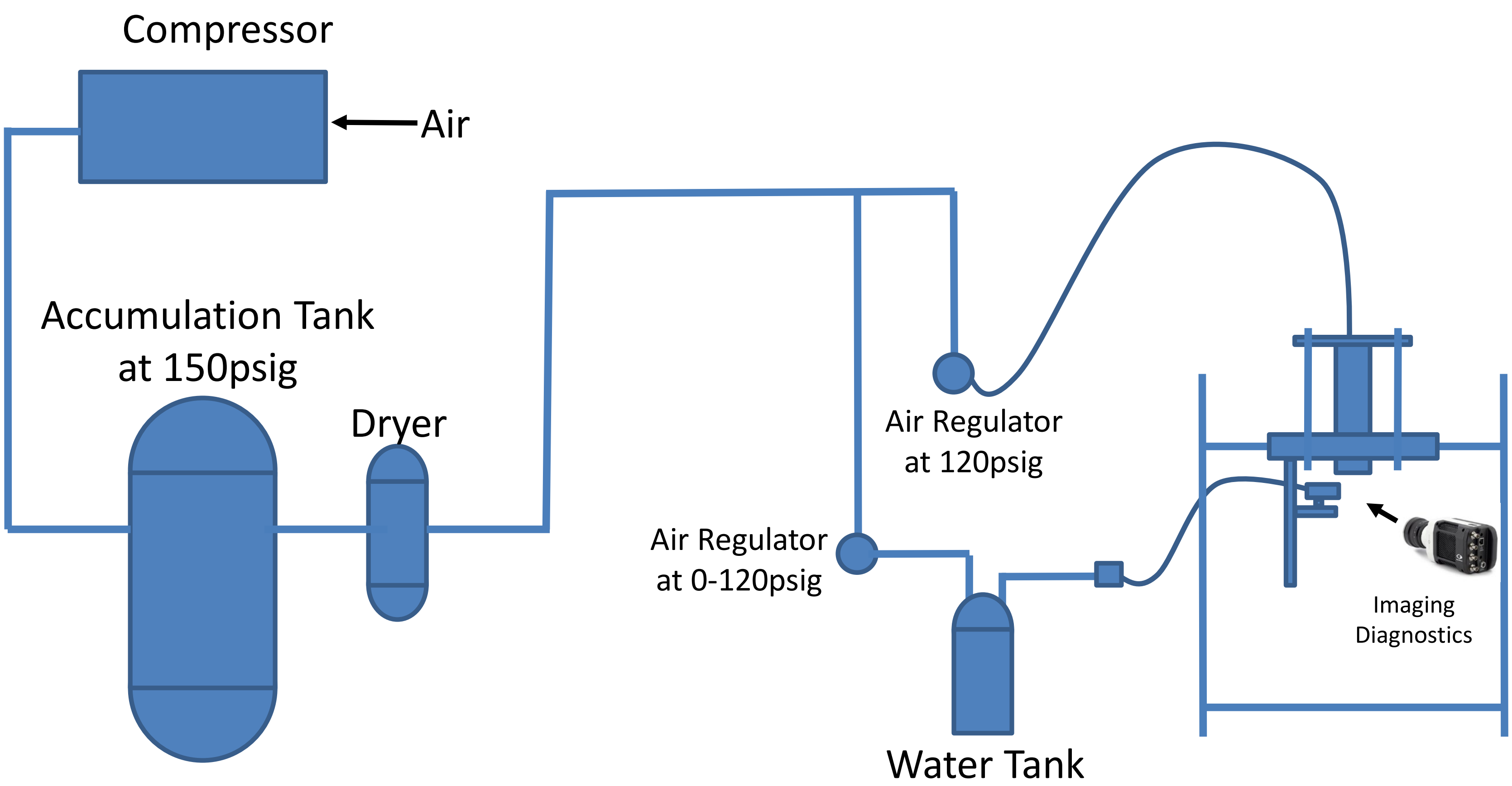
Cold Flow Test Rig Overview



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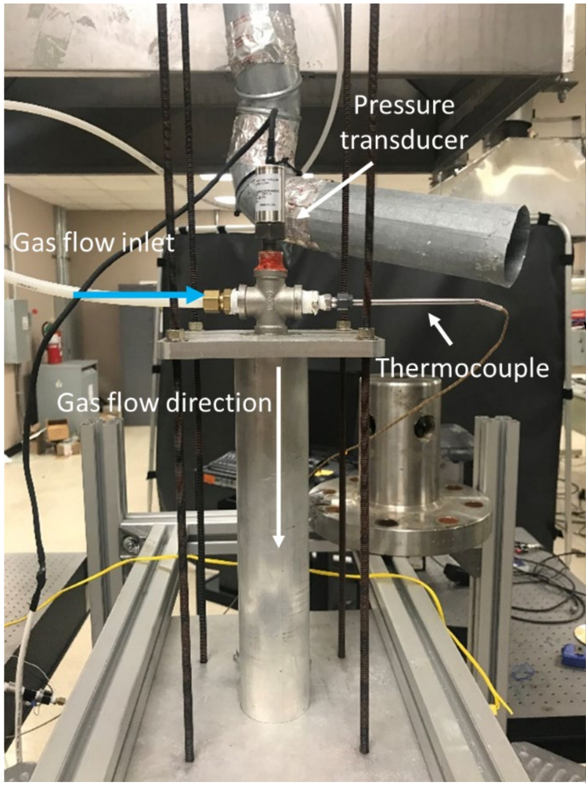
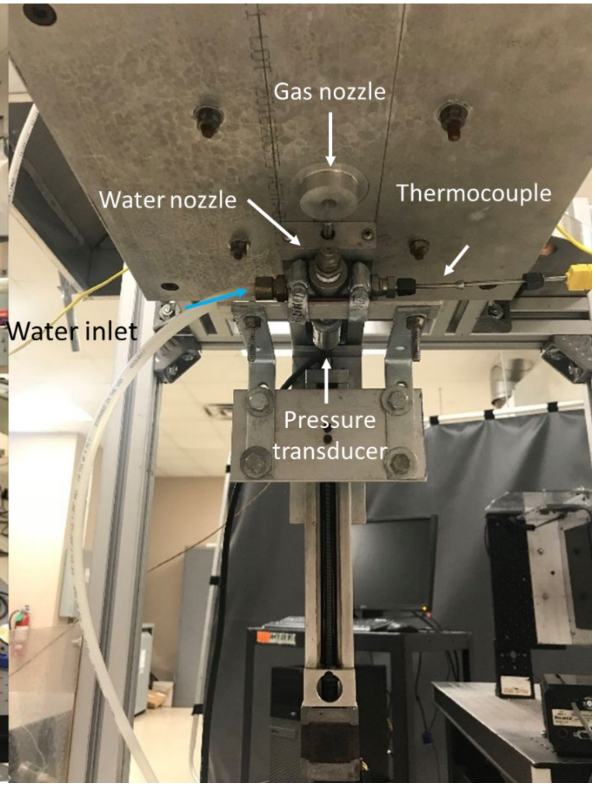
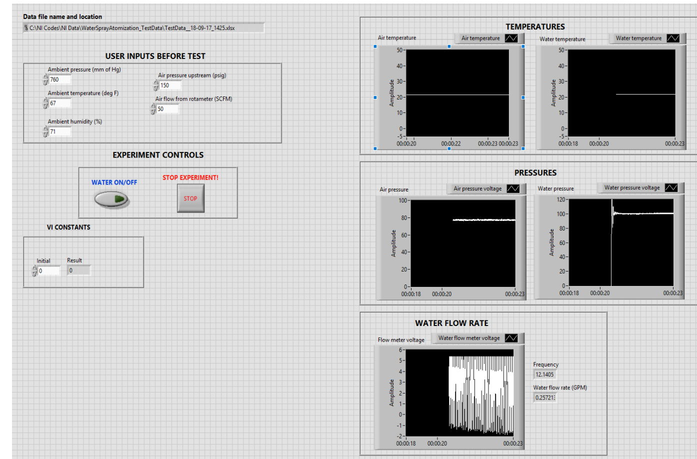
Stand Configuration and Measurement

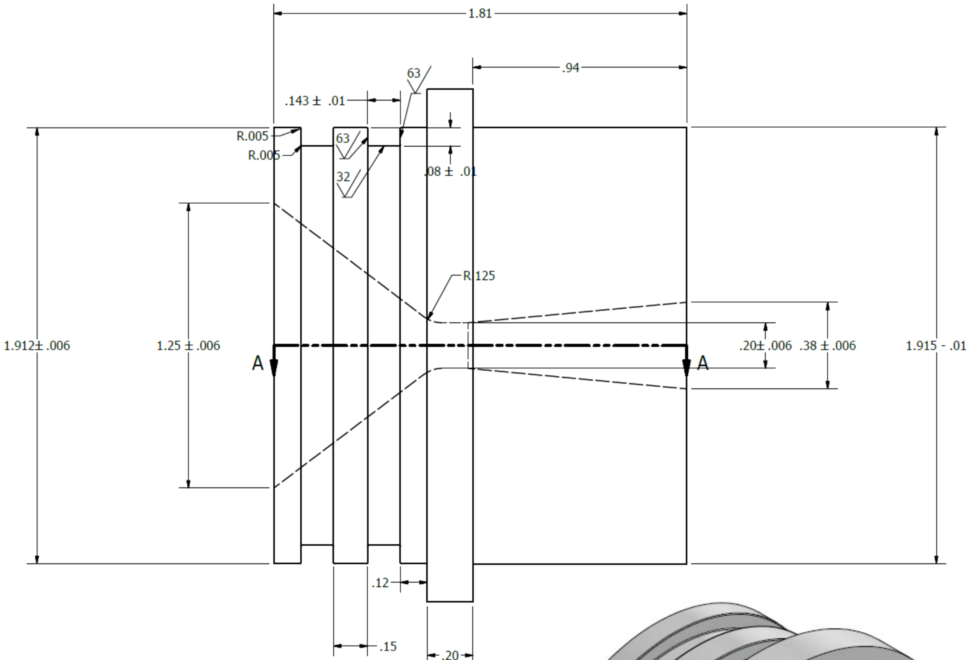


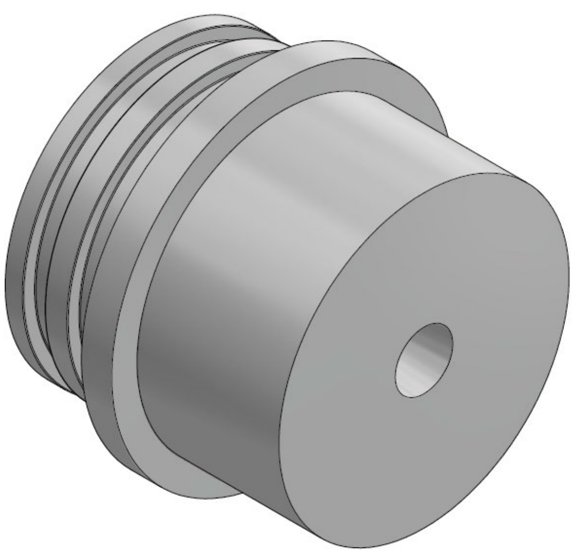




- After ambient conditions are entered, data for each run is stored during operation and immediately stored.

Nozzle Design





- Air is supplied to the chamber at a constant flow rate of 54SCFM at a static pressure of 73psig measured in a 3/8” SCH40 pipe section for all test cases
- Water back pressure is varied from 20-100psig and nozzle diameters of 0.06”, 0.04”, and 0.03” are examined

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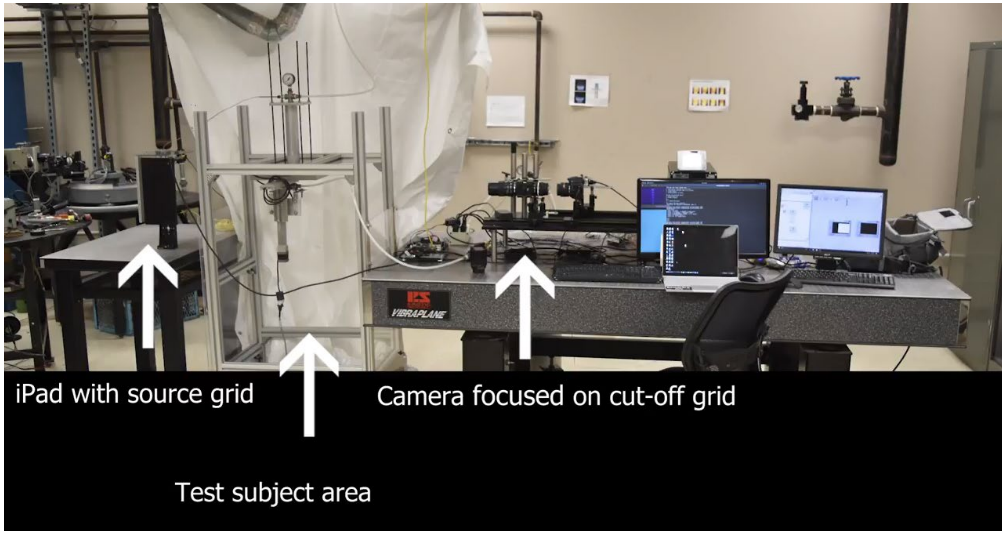
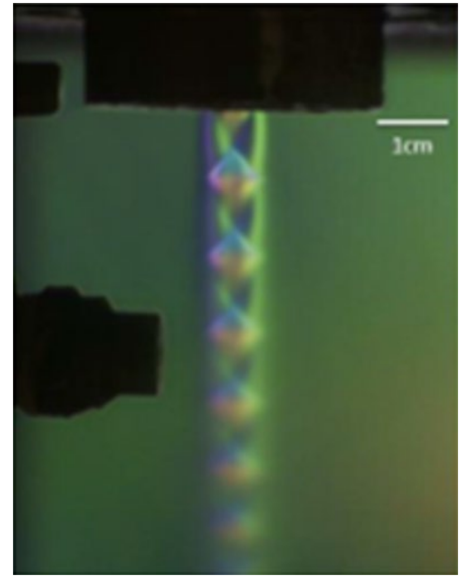
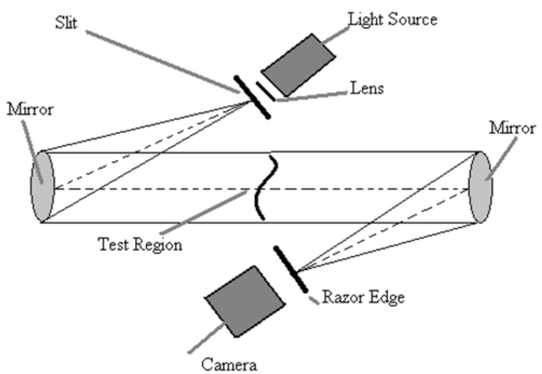
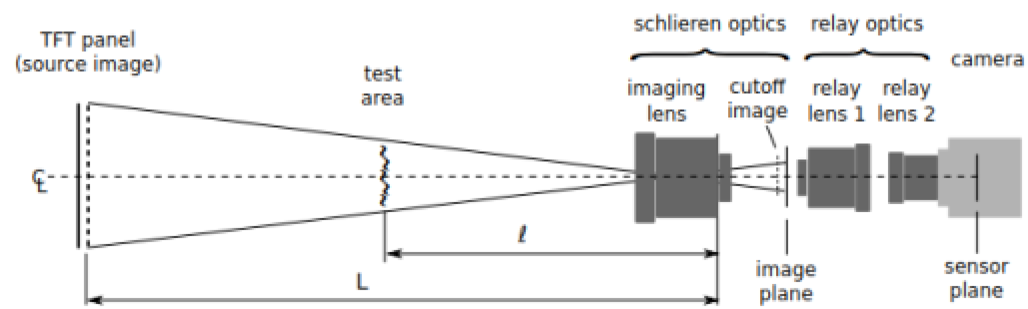
Focusing Color Schlieren (FCS)









Schoegl, I., Pisano, AJ, & Sedky, G. (2016). Development of a compact focusing color schlieren technique. In 54th AIAA aerospace sciences meeting, San Diego, CA, USA, AIAA (Vol. 1765).

Fillingham, Patrick & Murali, Harikrishnan & Novosselov, Igor. (2017). Non-Dimensional Parameter for Characterization of Wall Shear Stress from Underexpanded Axisymmetric Impinging Jets. Journal of Fluids Engineering. 139. 10.1115/1.4037035.

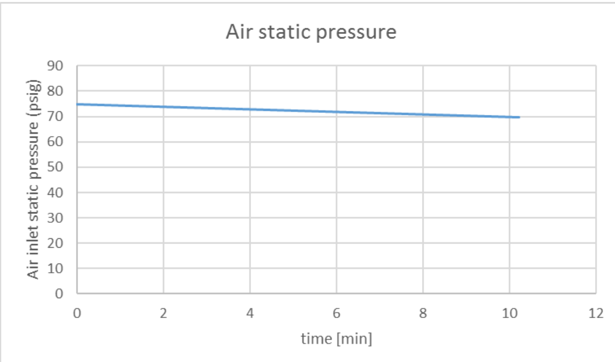
Volume Illuminated High-Speed Video

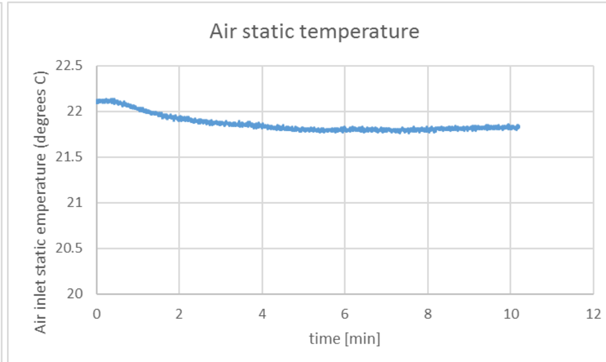
- 500W halogen bulb placed ~5m away at ~10° angle provides diffuse indirect light source

- Photron SA3 high-speed camera
- 60-200,000fps
  - 20,000fps used for primary breakup imaging
  - 2,000fps used for penetration imaging
- 54mm lens @ f/1.4

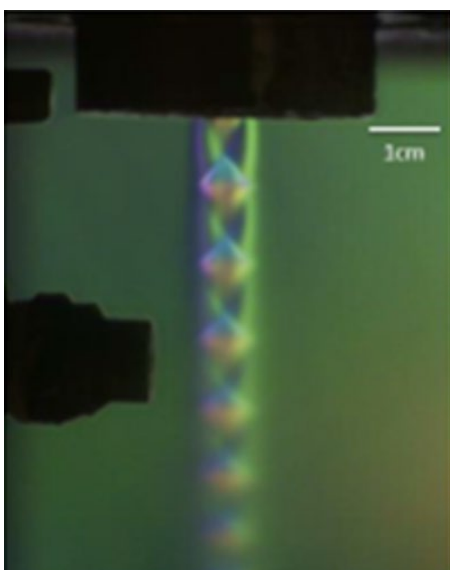
https://www.techimaging.com/products/legacy/legacy-high-speed/product/photron-fastcam-sa3

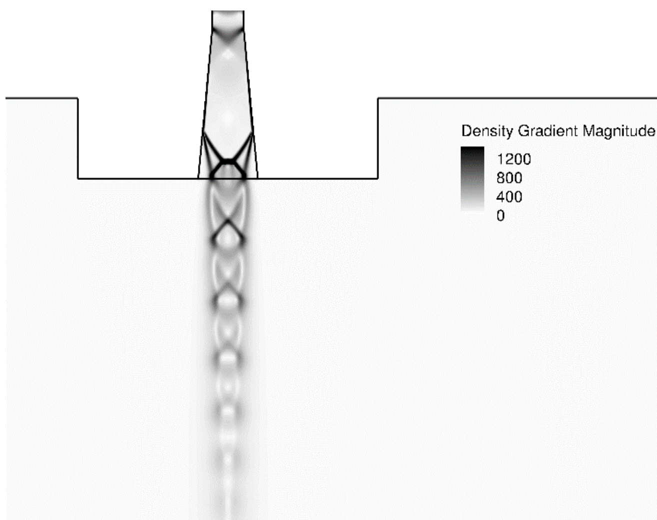
Gas Phase Characterization

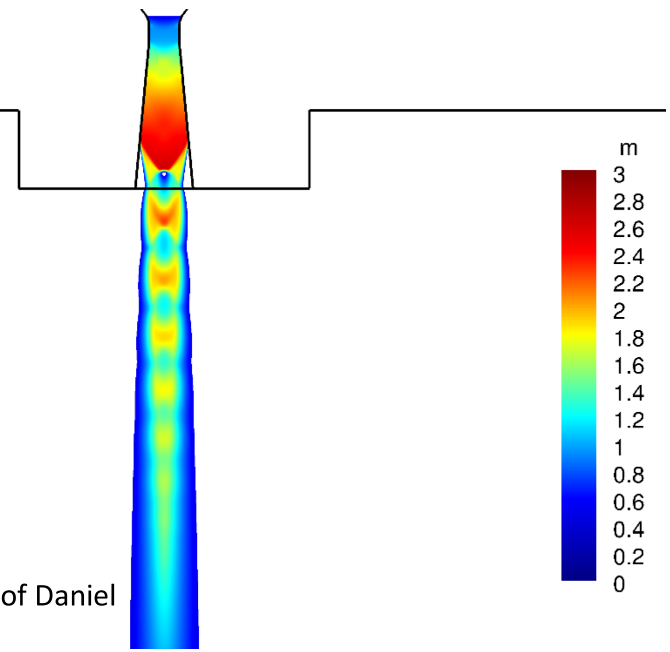




- Good agreement between CFD and experiment for shock structure and inlet conditions
- Threshold of 5mins combined run time for each tank was set to keep tank pressure deviation <5%







CFD results courtesy of Daniel Allgood, NASA SSC

Liquid Phase Characterization

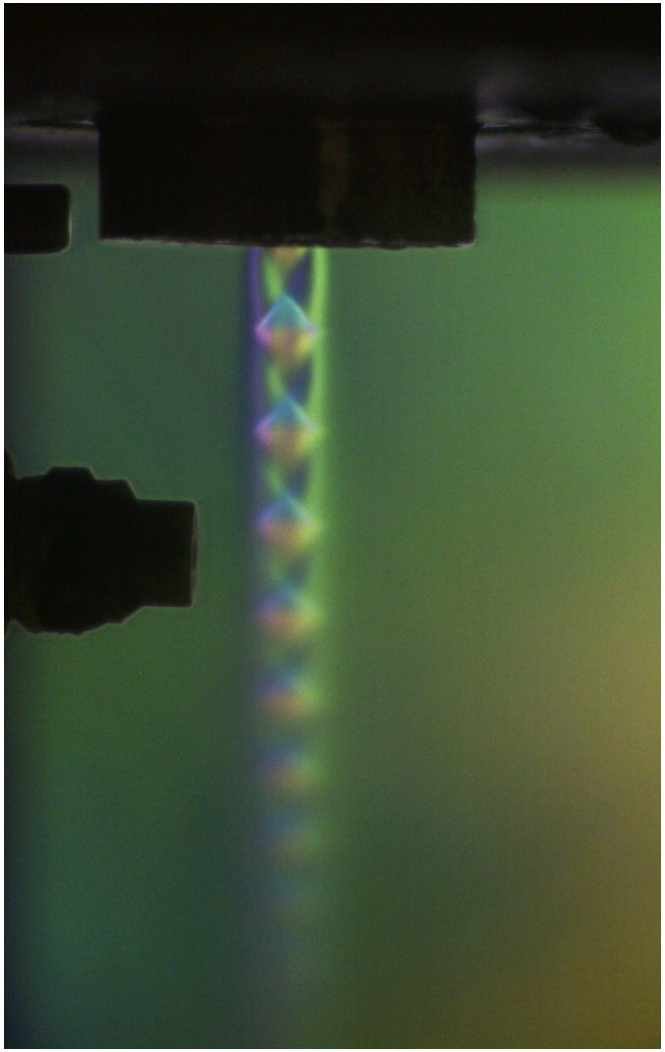
Nozzle 1 D=.06”	We=6138	Oh=.0032							
Injection Pressure [psig]	20	30	40	50	60	70	80	90	100
Measured Flowrate [GPM]	0.4753	0.593	0.693	0.791	0.865	0.918	1.00	1.05	1.12
Measured Velocity [m/s]	16.44	20.51	23.97	27.35	29.91	31.75	34.58	36.31	38.73
Calculated Velocity [m/s]	16.63	20.37	23.52	26.30	28.81	31.12	33.26	35.28	37.19
% Error	1.18	-0.67	-1.86	-3.87	-3.70	-1.99	-3.82	-2.84	-3.99
q	0.624	0.937	1.249	1.561	1.873	2.185	2.497	2.810	3.122
Re_D	24064	29472	34032	38049	41680	45020	48128	51048	53810

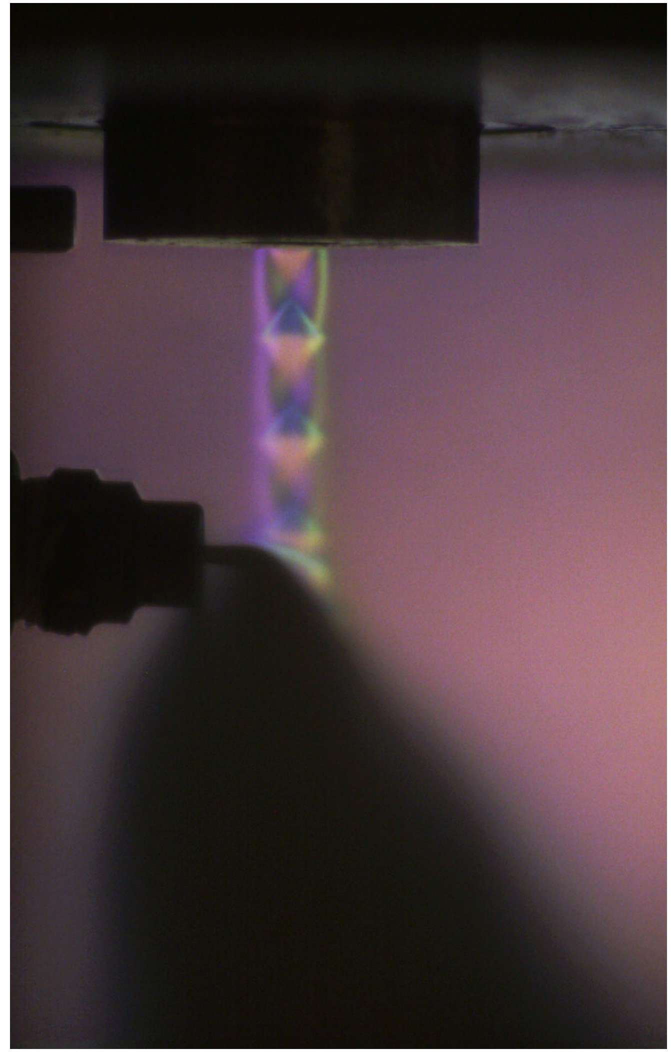
$$v = \frac{C_D}{\sqrt{1-\beta^2}}\sqrt{\frac{2\Delta P}{\rho}}$$

Shape factor

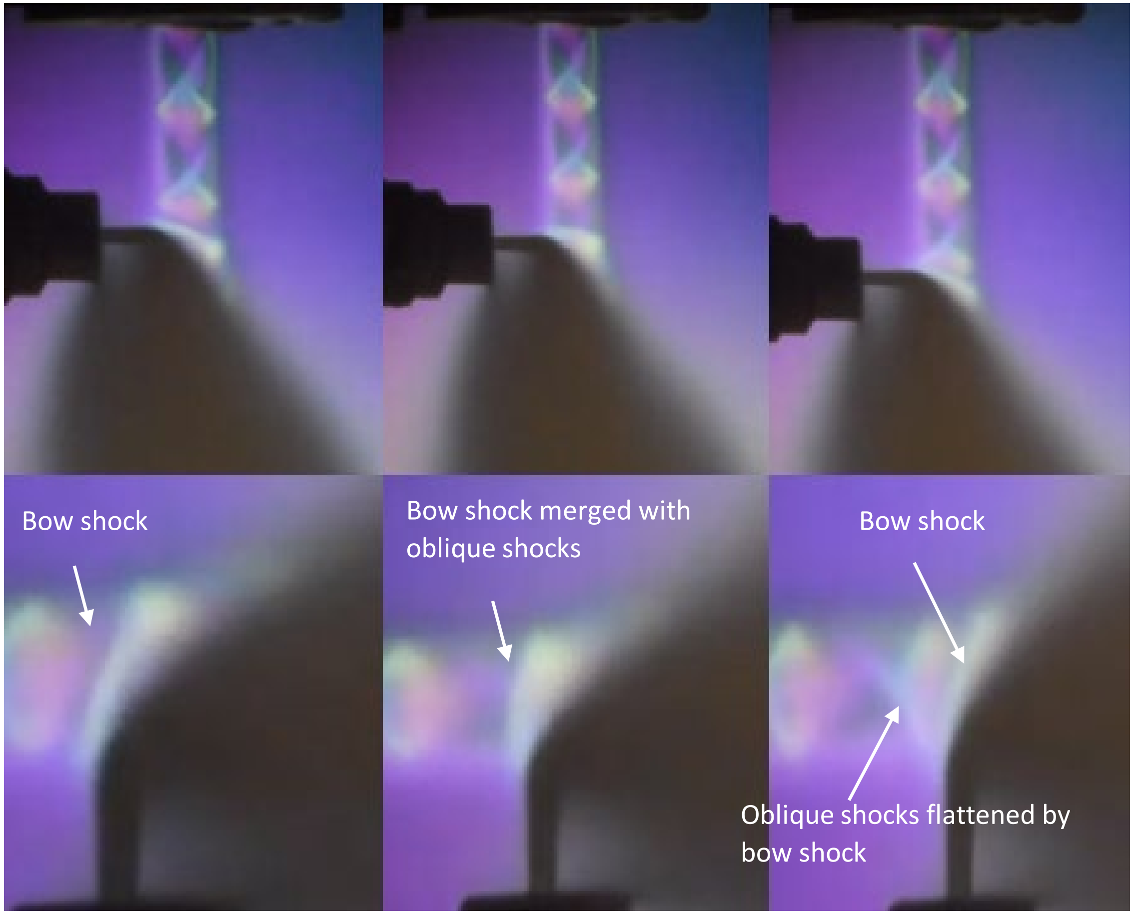
- Flow tests were completed on nozzle 1 to confirm velocity measurements, these were used on all other nozzles

Shock Structure





Shock Structure



Nozzle 1, q=1.873

- Shock structure differs from traditional jet in crossflow due to presence of internal Mach diamonds

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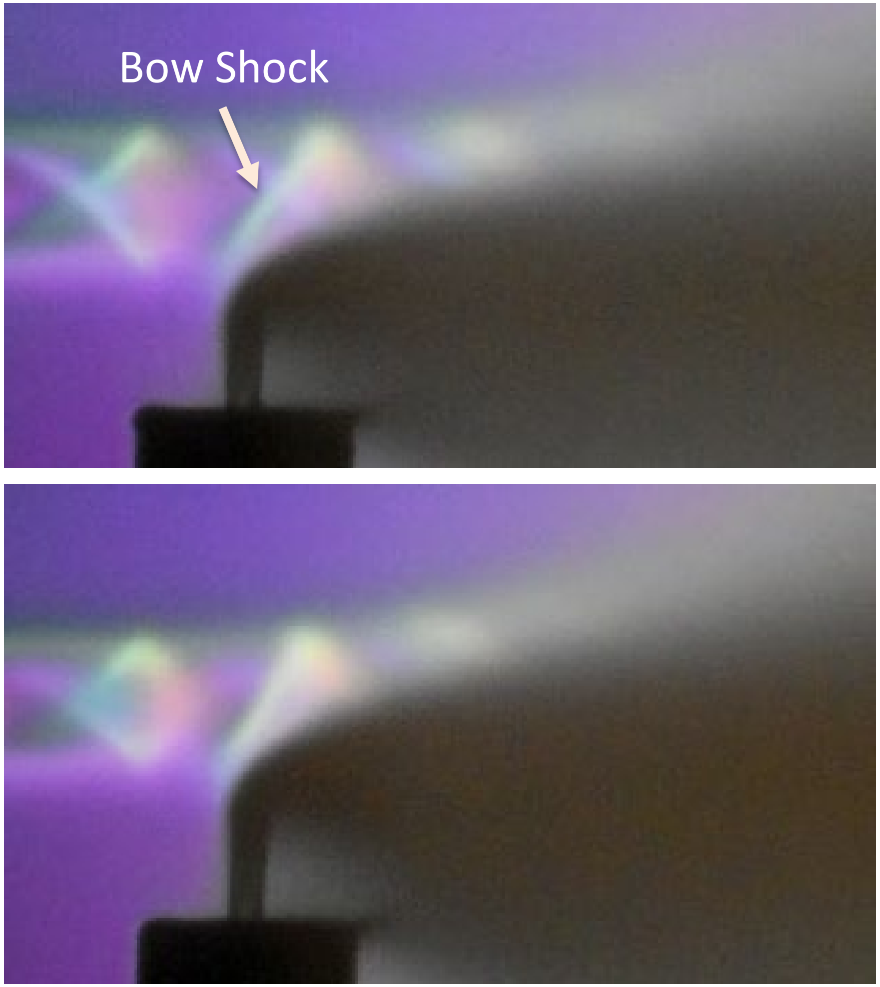
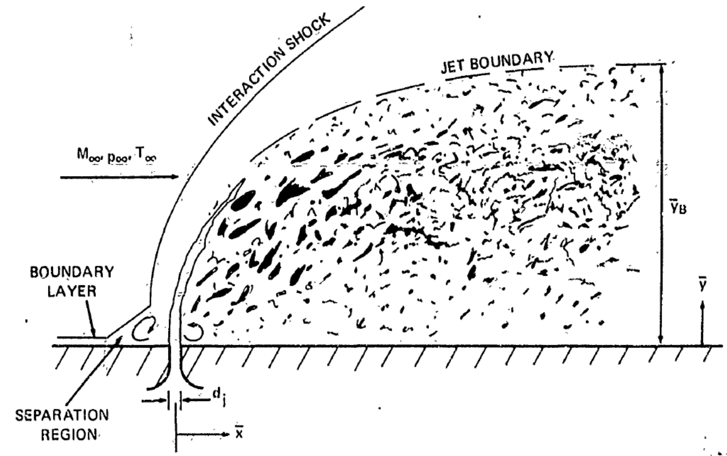
Shock Structure



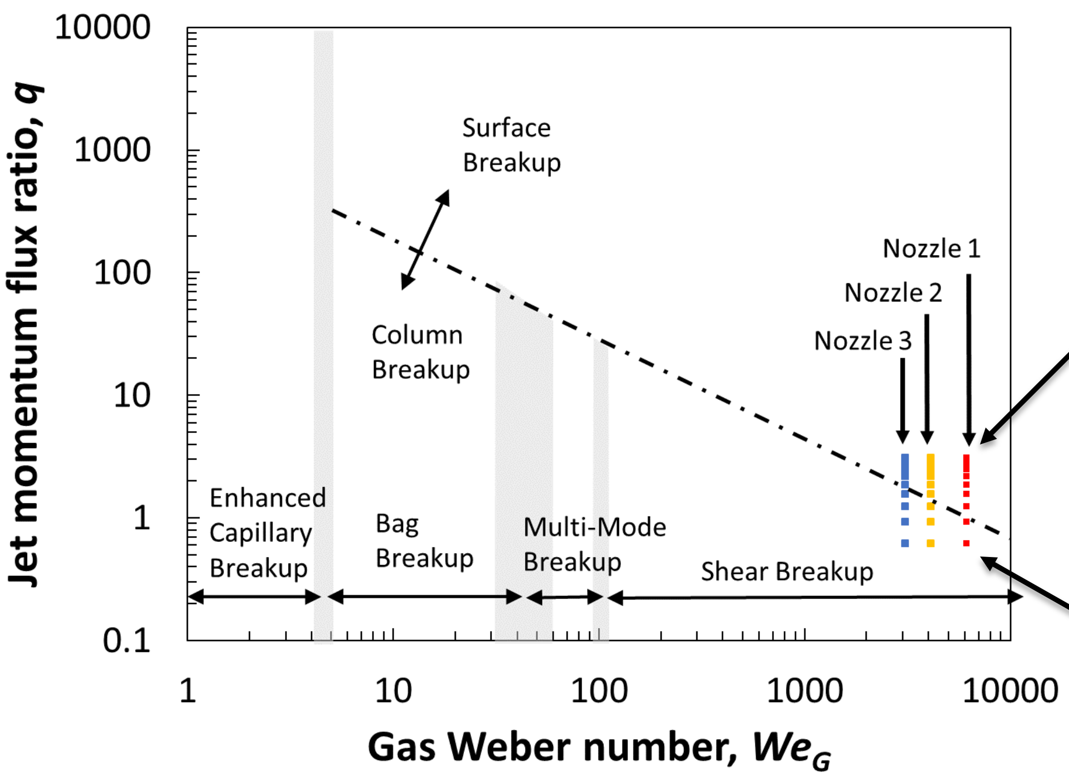
Nozzle 1, q=0.624 (top), q=0.937 (bottom)

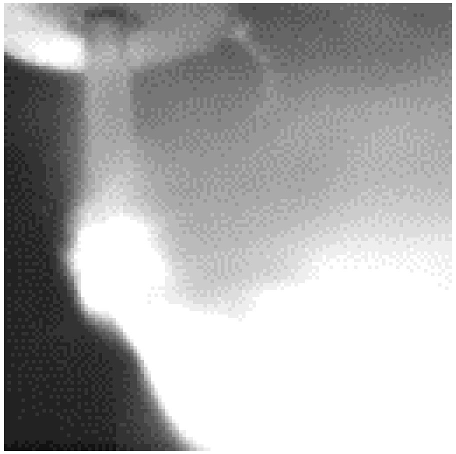


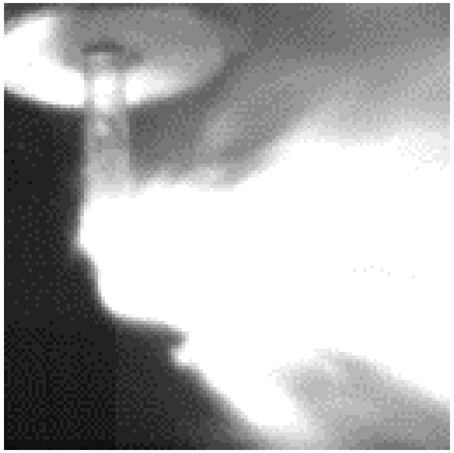
Yates, C. (1971). Liquid injection into supersonic airstreams. In 7th Propulsion Joint Specialist Conference (p. 724).

- No presence of separation region or shock interaction
- Visible signs of flow turning

Primary Liquid Breakup







Nozzle 1, q=3.122 (top), q=0.624 (bottom)

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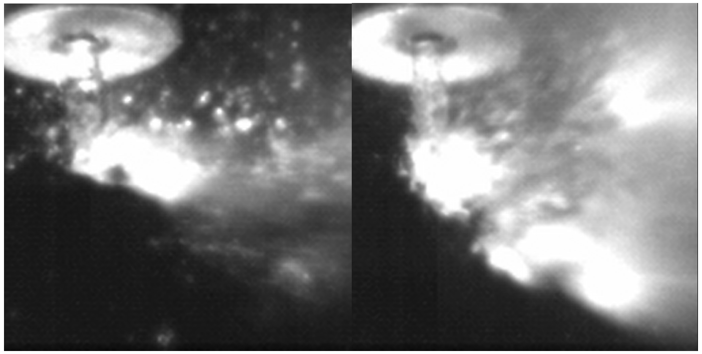
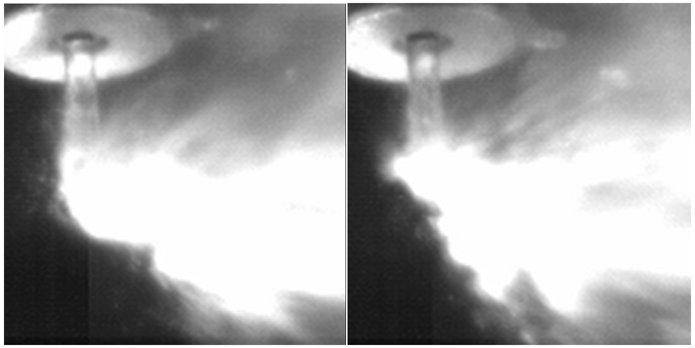
Primary Liquid Breakup



- Low momentum ratio characterized by strong shearing of coherent liquid jet, no long ligaments of fluid extend to secondary breakup section



- High momentum ratio characterized by surface stripping/tearing. This allows for extension of fluid ligaments prior to secondary breakup

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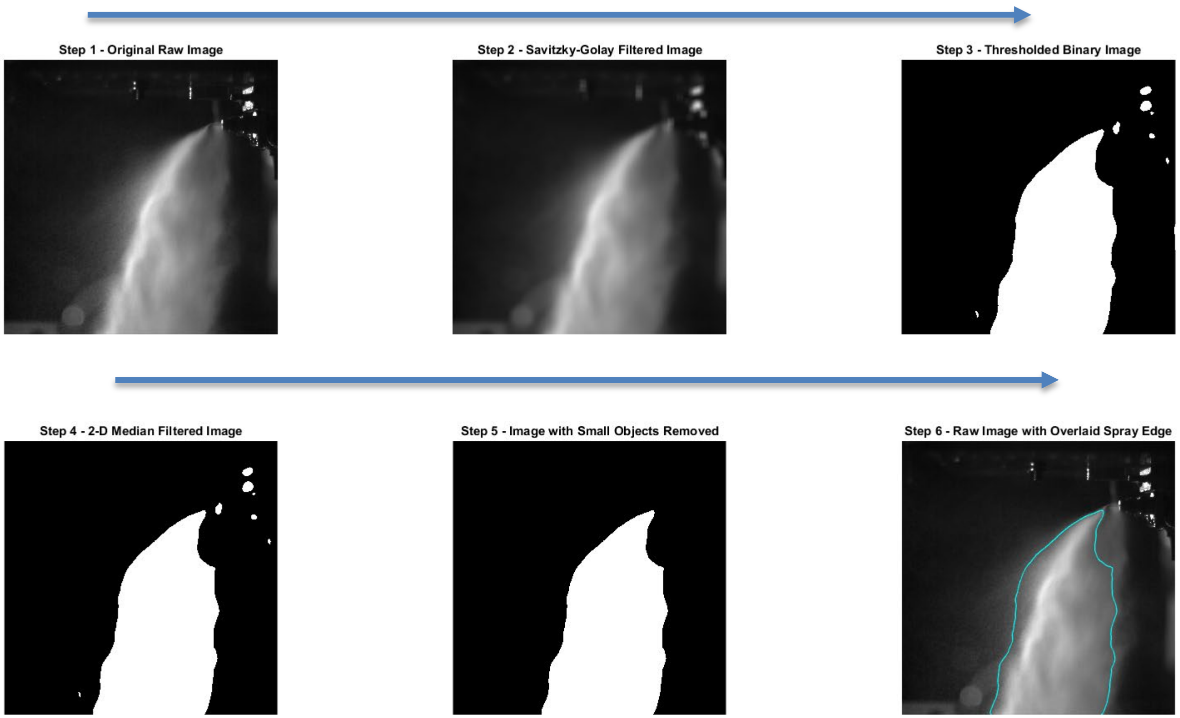
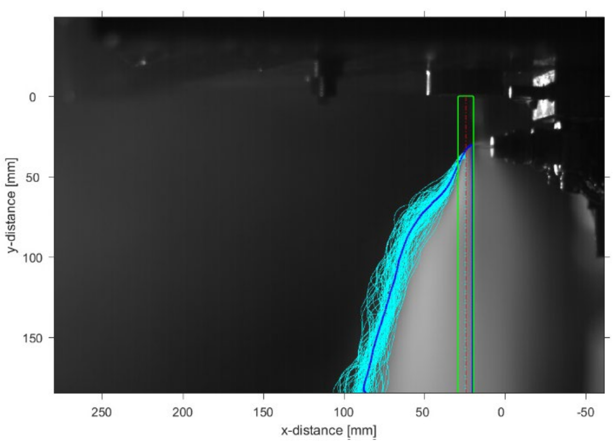
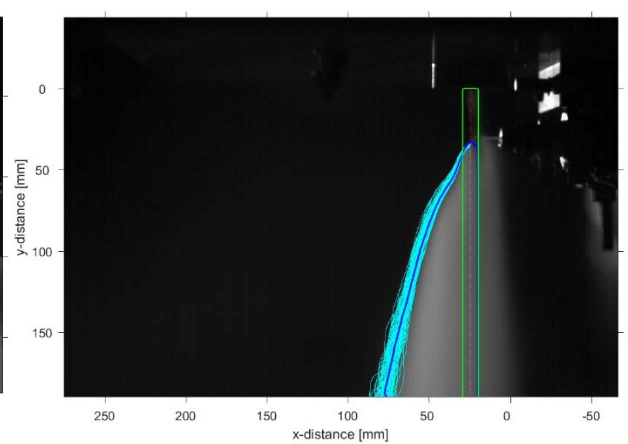
Spray Edge Penetration/Detection







- Edge location is important indicator of dominant flow phase, is an important parameter of study for CFD validation

- More prominent edge variation at higher momentum ratios

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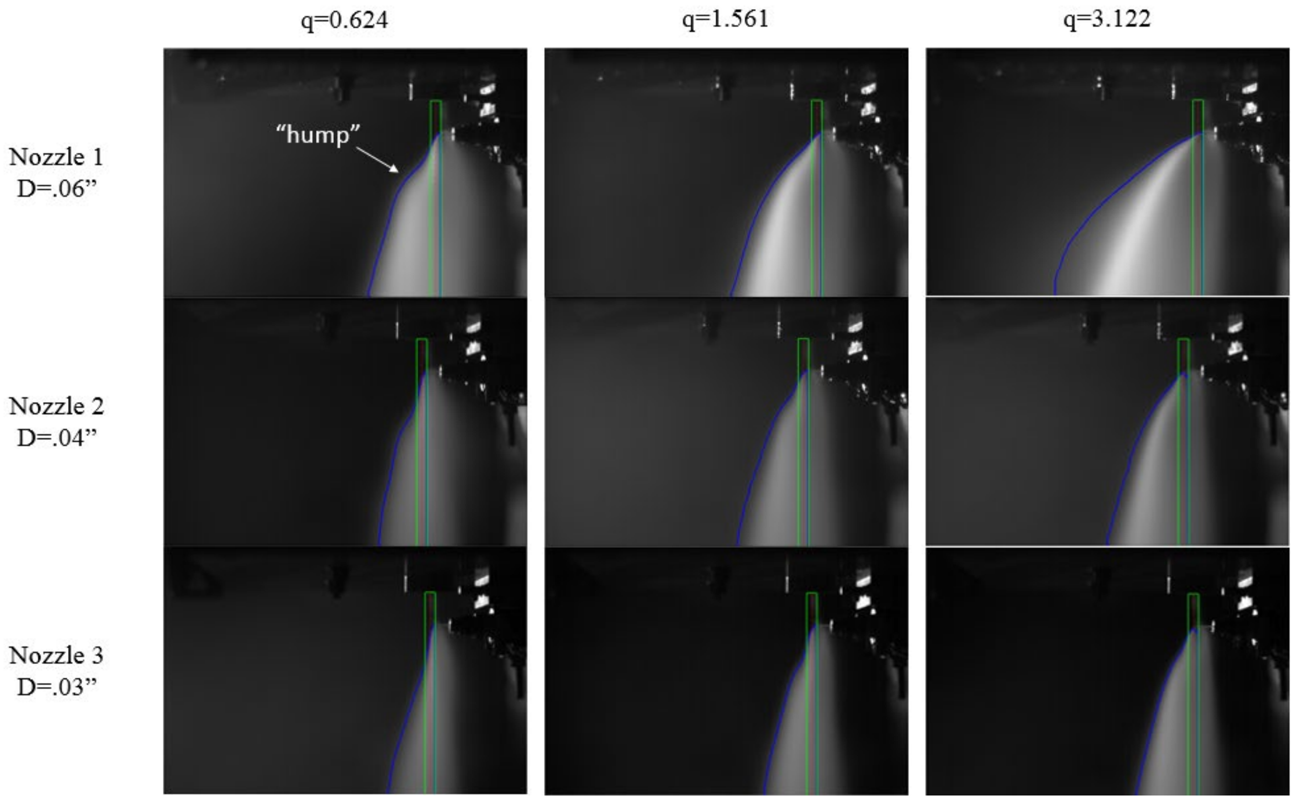
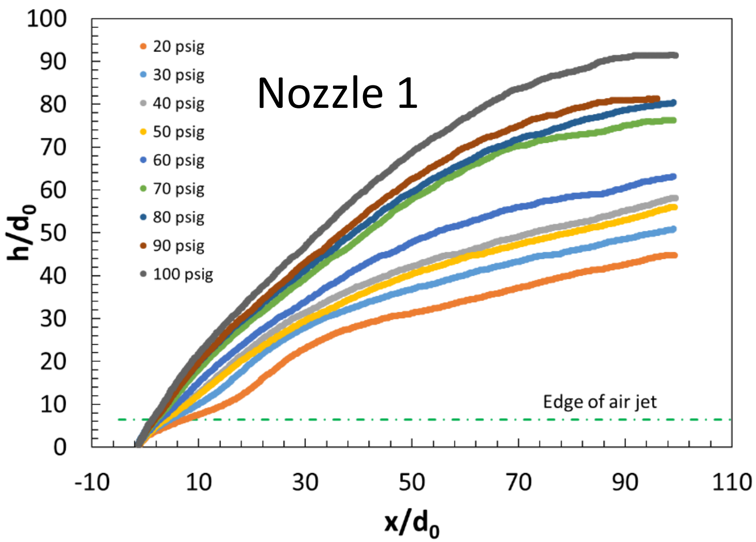
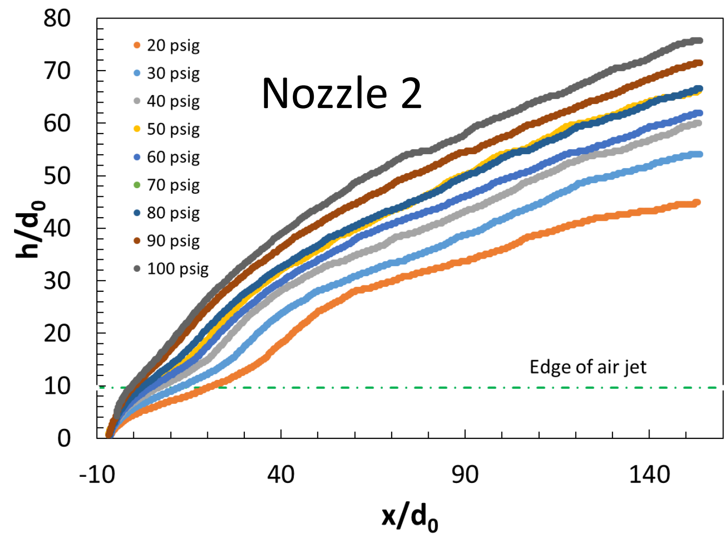
Average Spray Location

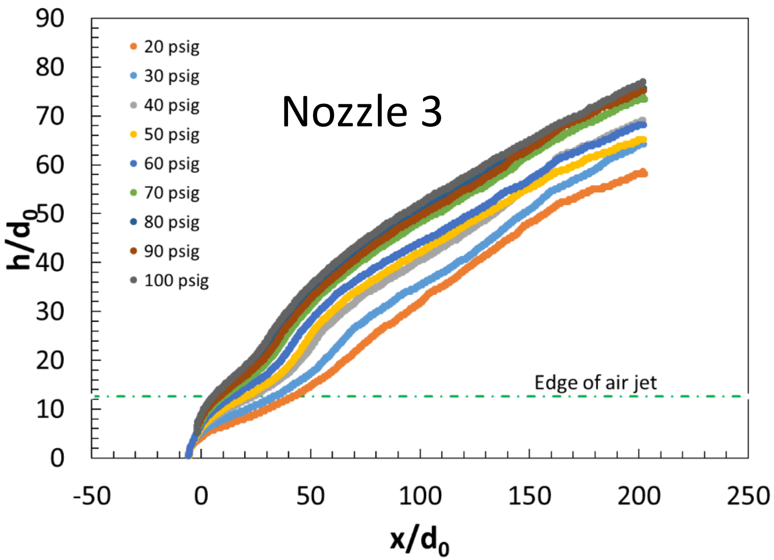


- Clear strong dependence on diameter ratio
- Appearance of region of sudden vapor phase expansion, more prevalent at lower momentum ratios and smaller diameter ratio

Global Spray Penetration







- Less variation at smaller diameter ratio

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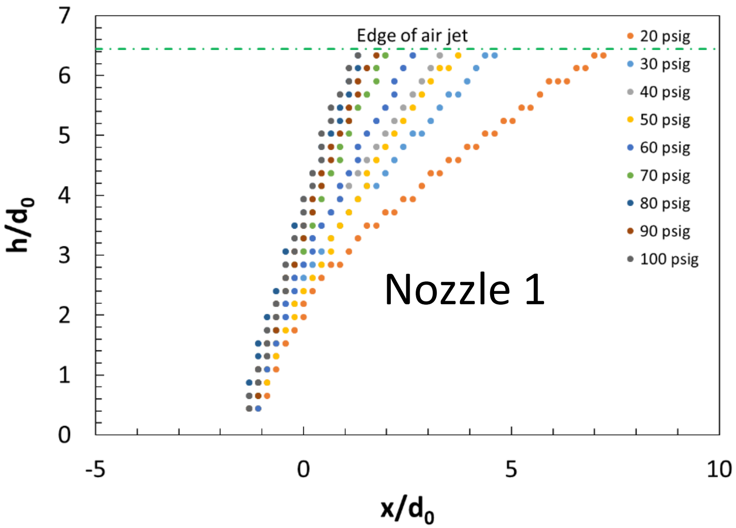
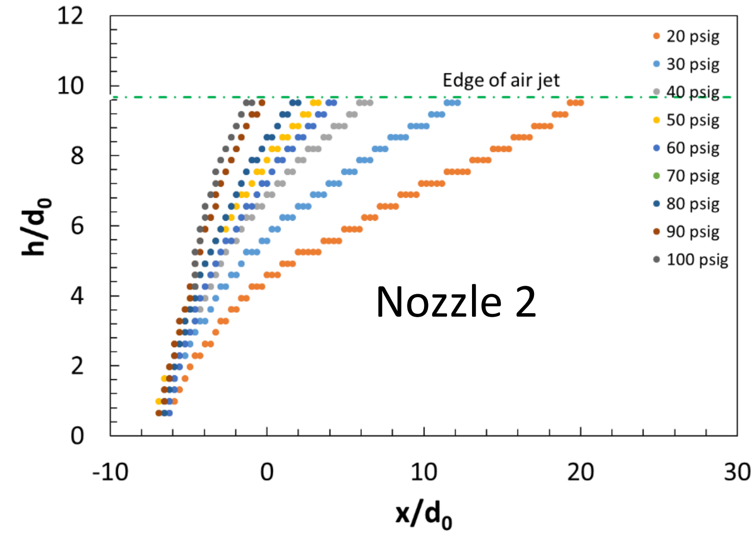
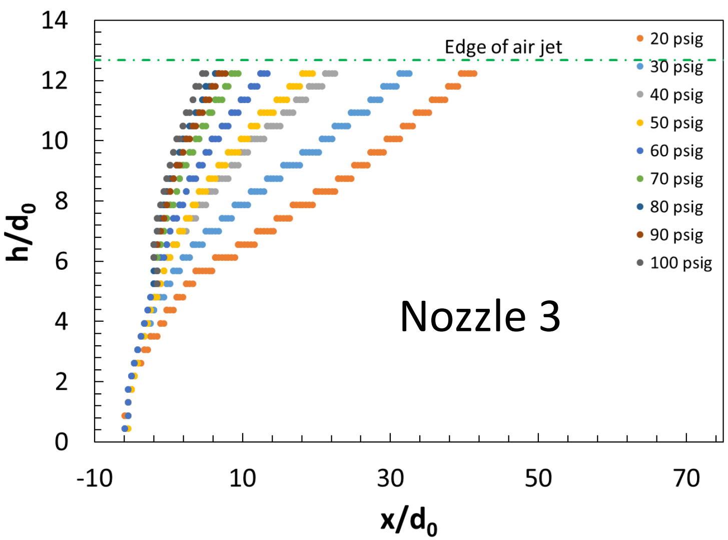
Local Gas Phase Spray Penetration







- More variation at smaller diameter ratio, can better be compared with existing empirical correlations

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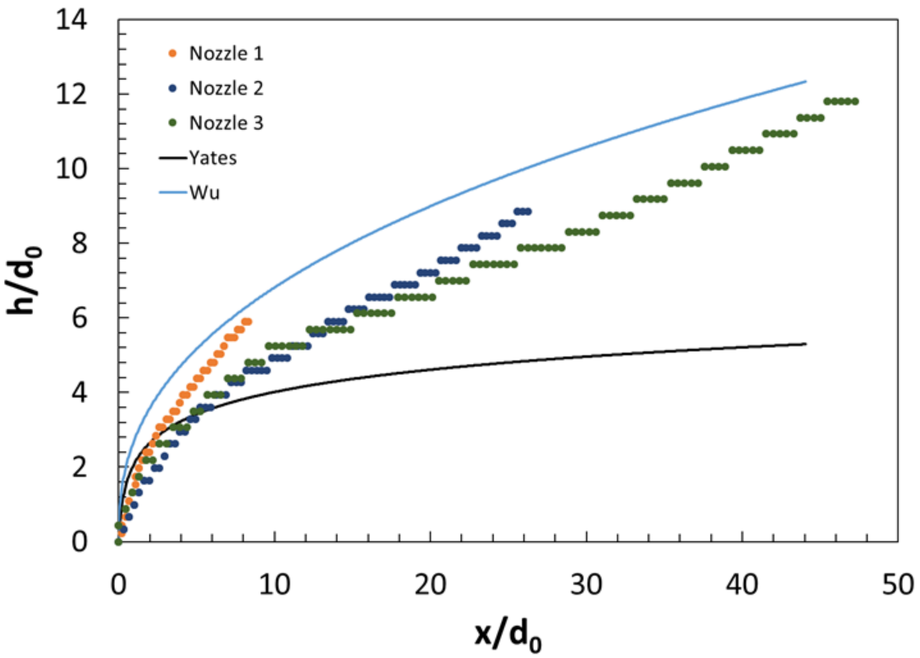
Local Gas Phase Spray Penetration



- More variation at smaller diameter ratio, can better be compared with existing empirical correlations

Conclusions and Future Work

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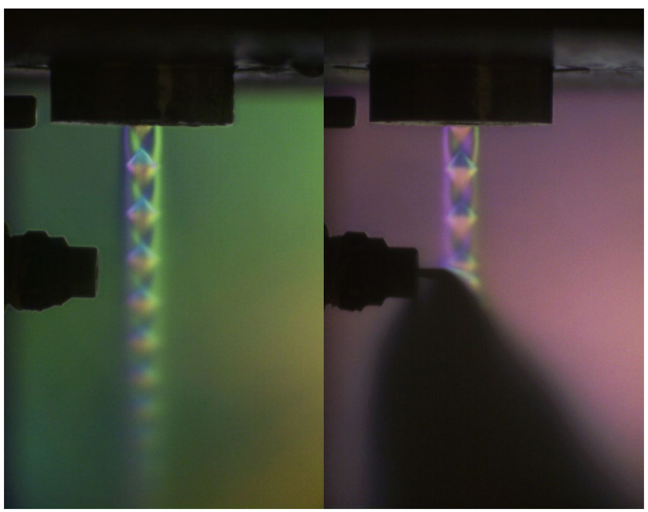
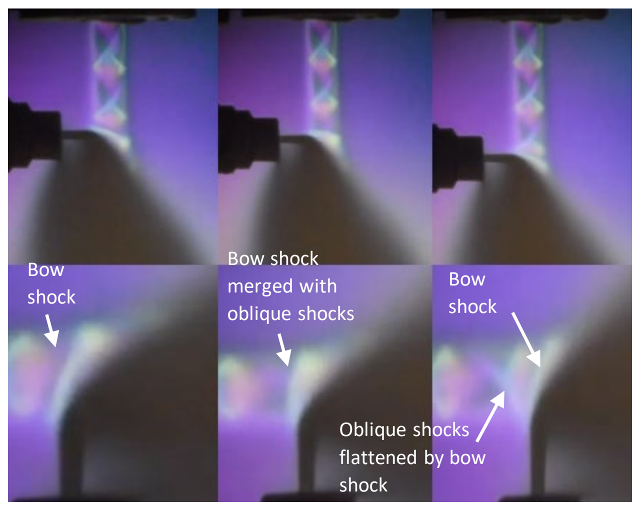
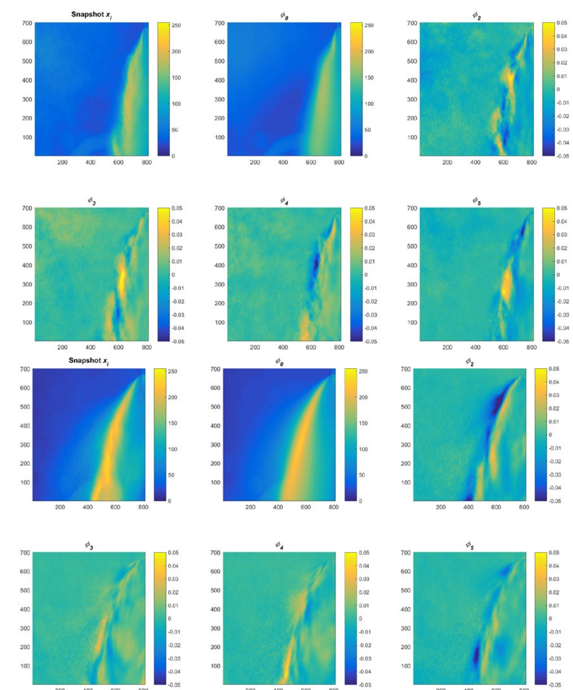
Conclusions

- Successfully constructed cold flowing test stand capable of steady operation
  - Characterized gas and liquid phases
- Showed qualitative characteristics for gas phase shockwave structure at varied injection locations
  - Lack of separation shockwave and locations of subsonic flow not present in traditional JICF
- Examined primary breakup region in context of traditional JICF regime diagram, extended to higher Weber number
  - Used POD to extract primary modes which agree with literature







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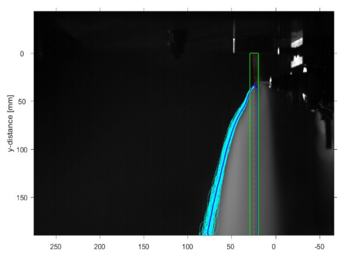
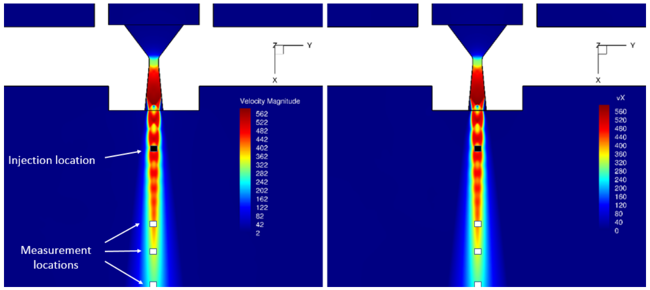
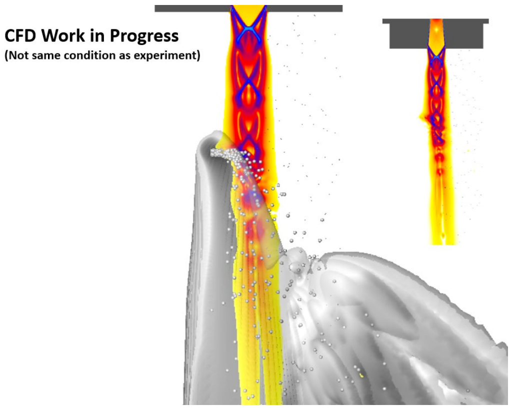
Conclusions

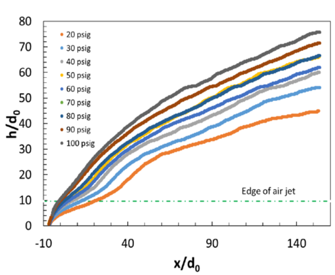
- Spray edge detection yielded results for spray penetration globally and locally in projected gas phase boundary
  - Global results vary heavily from correlations for traditional JICF
  - Strong Dependence on jet diameter ratio is shown
- PDPA was used to gain statistical information about liquid droplet size and velocity downstream
  - Centerline data showed large deviation from expected gas phase velocity. This is likely due to large expected droplet size and turning of the gas flow.
- Preliminary CFD work shows significant flow weakening and turning downstream of liquid injection.

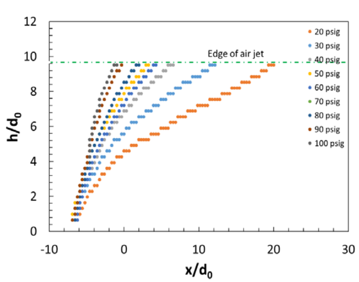


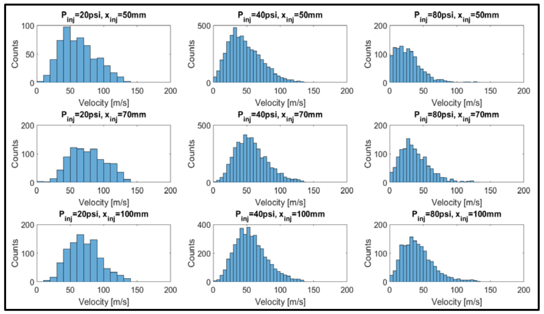




CFD results courtesy of Daniel Allgood, NASA SSC

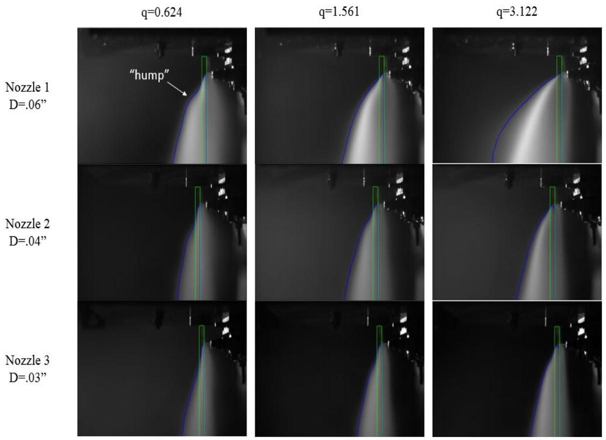


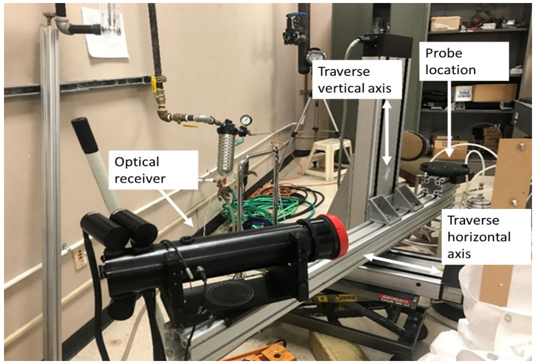


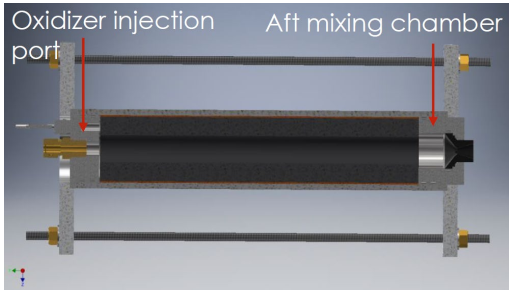


Future Work

- Further explore the dependency on diameter ratio
  - Development of a new correlation or physical parameter for momentum ratio should be determined
- Expand PDPA measurements to two components and map spray behavior in 2D
  - Will allow for better identification of mean spray path after gas phase flow turning and facilitate CFD validation
- Test and characterize hybrid rocket to supply combusting gas flow
  - Will allow for better matching of physical properties to those at SSC
  - Many of the diagnostics used already can again be applied







LOVE PURPLE
LIVE GOLD