



# Effect of Chamber Backpressure on Swirl Injector Fluid Mechanics

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# Outline

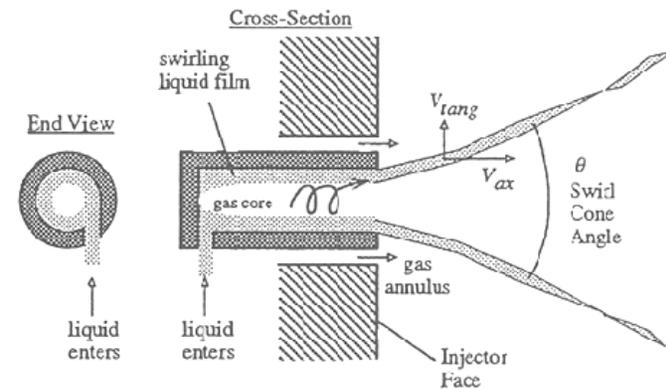
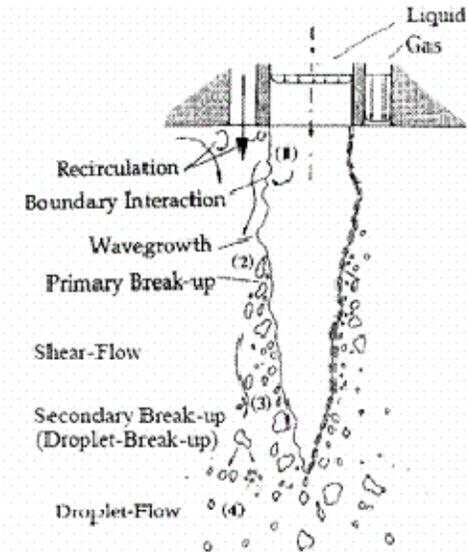


- Background
- Objective
- Results
- Conclusions/Discussion

# Background

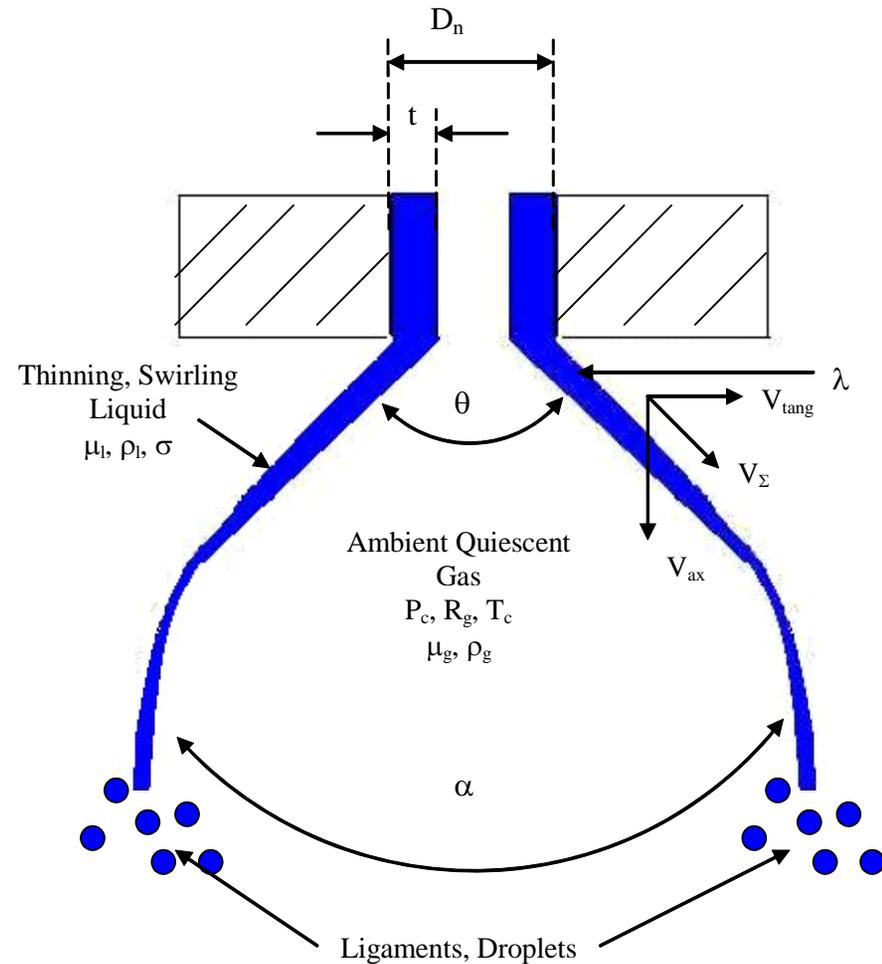
- A common propellant combination used for high thrust generation is GH<sub>2</sub>/LOX.
  - Historical GH<sub>2</sub>/LOX injection elements have been of the shear-coaxial type.
  - Element type has a large heritage of research work to aid in element design.
- The swirl-coaxial element, despite its many performance benefits, has a relatively small amount of historical, LRE-oriented work to draw from.
  - Design features of interest are grounded in the fluid mechanics of the liquid swirl process itself, are based on data from low-pressure, low mass flow rate experiments.

• There is a need to investigate how high ambient pressures and mass flow rates influence internal and external swirl features.



# Objective

- Determine influence of varying liquid mass flow rate and ambient chamber pressure on the intact-length fluid mechanics of a liquid swirl element





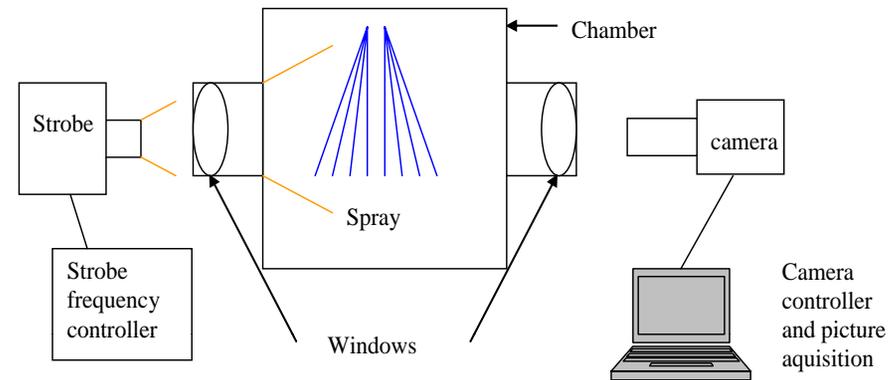
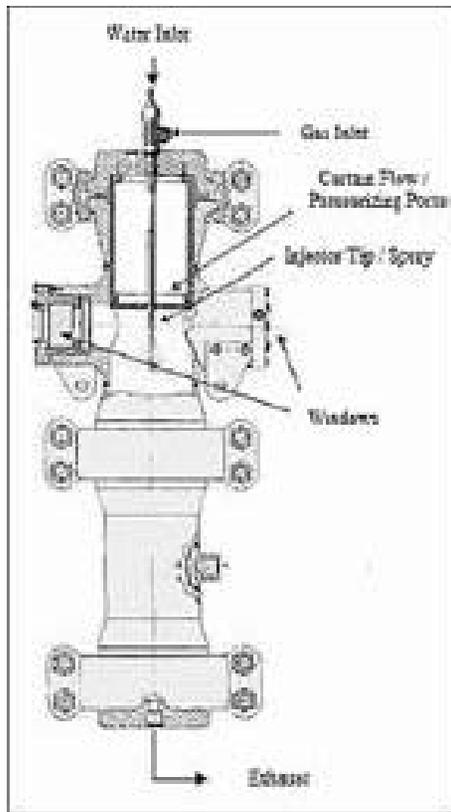
# Cold Flow Facility

- Water/Nitrogen Injector Spray Test Rig (WNIST)
  - Simulates LOX/gaseous fuel by H<sub>2</sub>O/GN<sub>2</sub>
  - Ambient chamber pressure set up to 1400 psia by additional GN<sub>2</sub> feed lines
  - H<sub>2</sub>O mass flow rates up to 1 lbm/s
  - Real-time controllable backpressure, flow rates, and gas temperature



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# Cold Flow Facility



- Cameras:
  - Kodak digital still camera: 4500 x 3000 pix
  - Phantom video camera: 512 x 512 pix; 4000 frames/sec
- Light Source:
  - High intensity strobe
  - 500 W Halogen Light



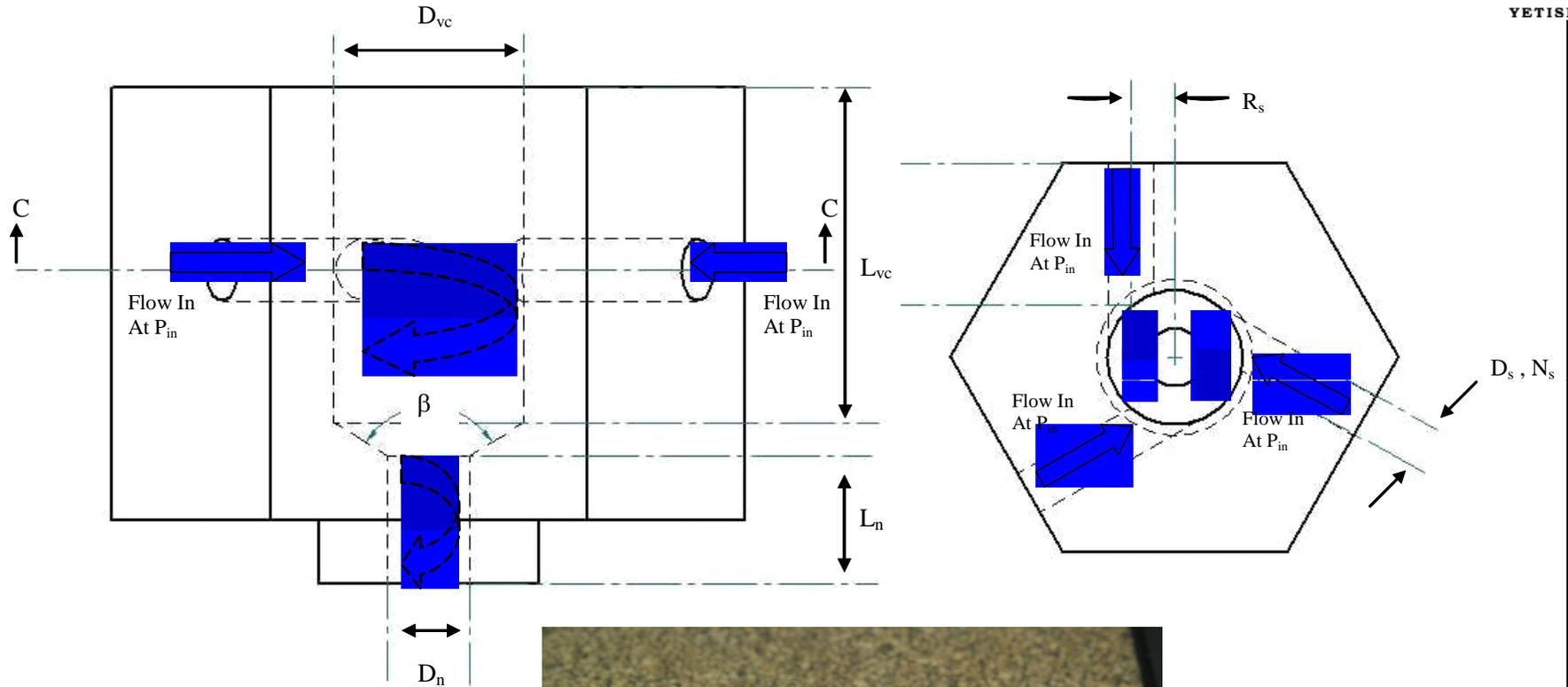
# Diagnostic Methods

- Metering of:
  - Upstream liquid static pressure
  - Chamber pressure
  - Liquid mass flow rates
  - Fluid temperatures
- Spray Profile through Shadowgraph Imaging
  - Inner film thickness profile
  - External spray boundary and cone angle



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# Swirl Element





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## Swirl Element Cont.

- Inner flow structure seen by clear acrylic section
- Similar acrylic section used with squared bottom for external spray features





# Design Methodology

- Doumas & Laster gives relations between swirl features via experimental work
  - Incorporates friction effects
  - No chamber pressure influences
  - No information about off-design mass flow rate operation
- Bazarov gives relations between swirl features via analytical approach
  - Can incorporate friction effects
  - No ambient pressure influences



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# Swirl Element Design Parameters

Parameter	Bazarov Prediction	Doumas & Laster Prediction
Mass Flow Rate (kg/s)	0.09	0.09
Free Cone Spray Angle (deg)	49	52
Pressure Drop at Design Flow (MPa)	1.72	2.09
Discharge Coefficient	0.463	0.414
Film Thickness (mm)	0.43	0.40
Orifice Diameter (mm)	1.58	1.58
Orifice to Centerline Radius (mm)	1.55	1.55
Vortex Chamber Diameter (mm)	3.35	3.35
Orifice Length (mm)	3.73	N/A
Vortex Chamber length (mm)	3.91	N/A
Nozzle Diameter (mm)	2.08	2.08
Nozzle Length (mm)	16.05	N/A



# Inner Film Thickness Videography

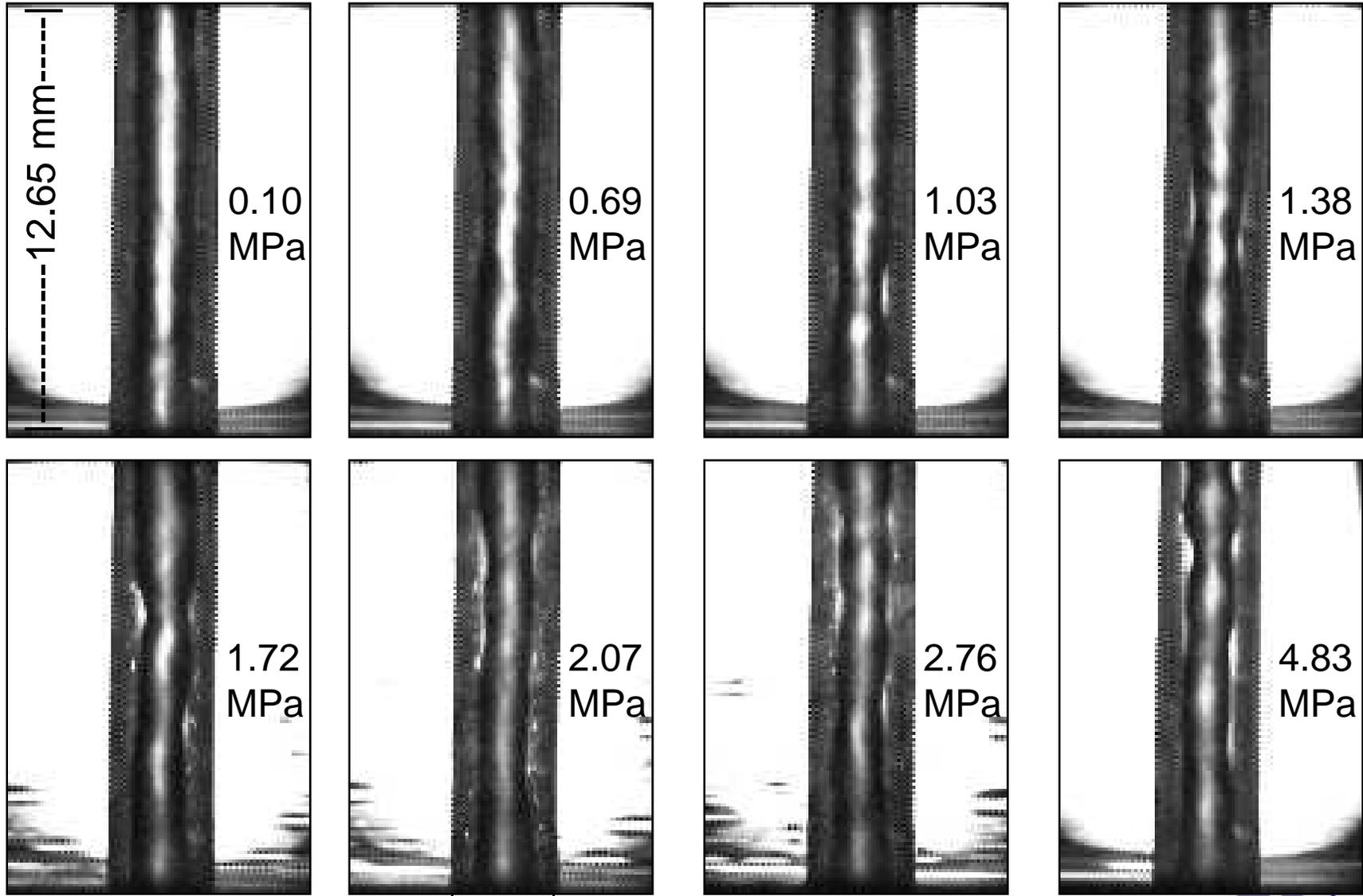


- Show movies of internal flow at full flow rate and chamber pressure of:
  - 0.10 MPa
  - 0.69 MPa
  - 1.03 MPa
  - 1.38 MPa
  - 1.72 MPa
  - 2.07 MPa
  - 2.76 MPa
  - 4.83 MPa



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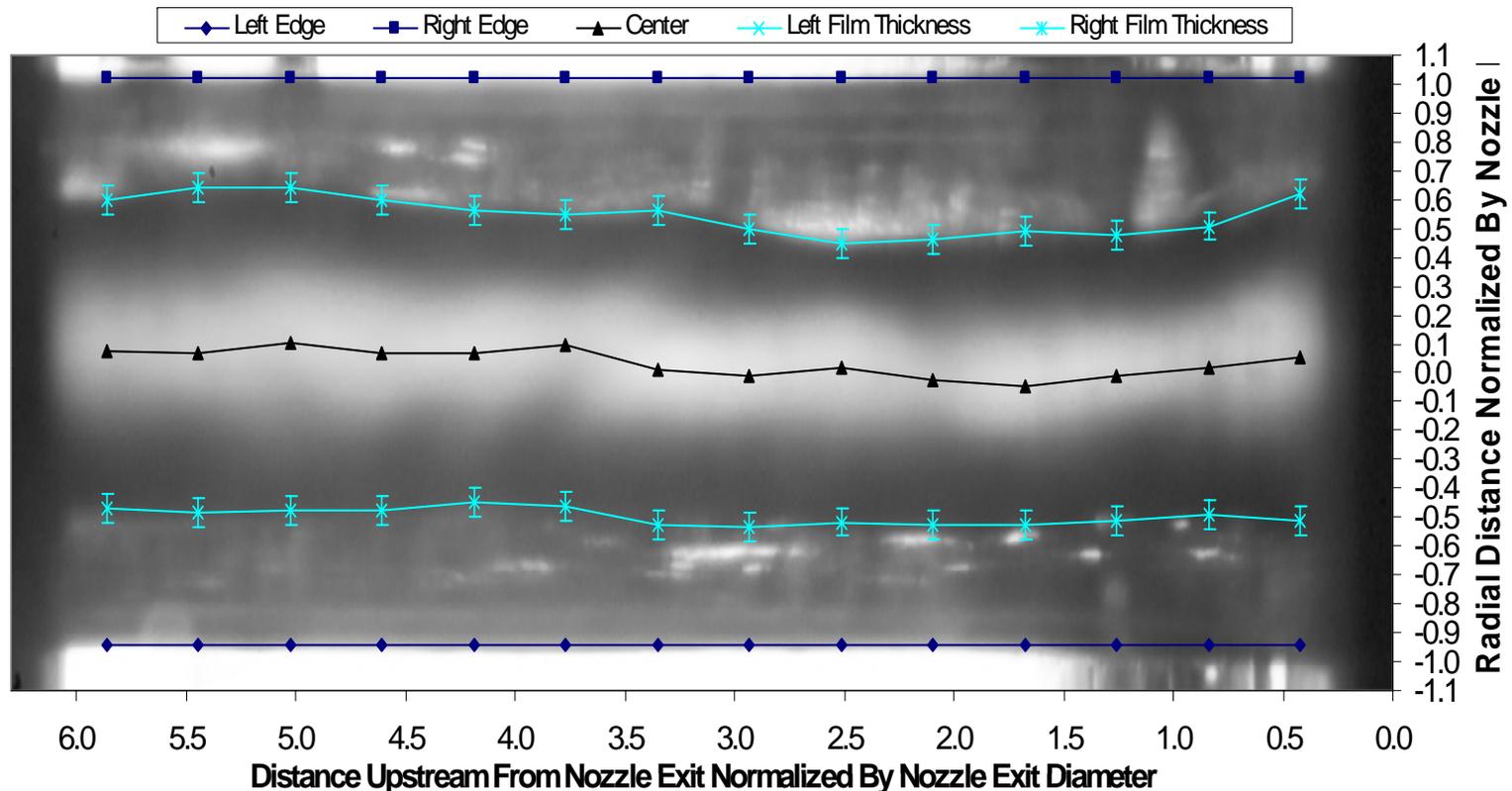
# Inner Film Thickness Profiles



2.08 mm



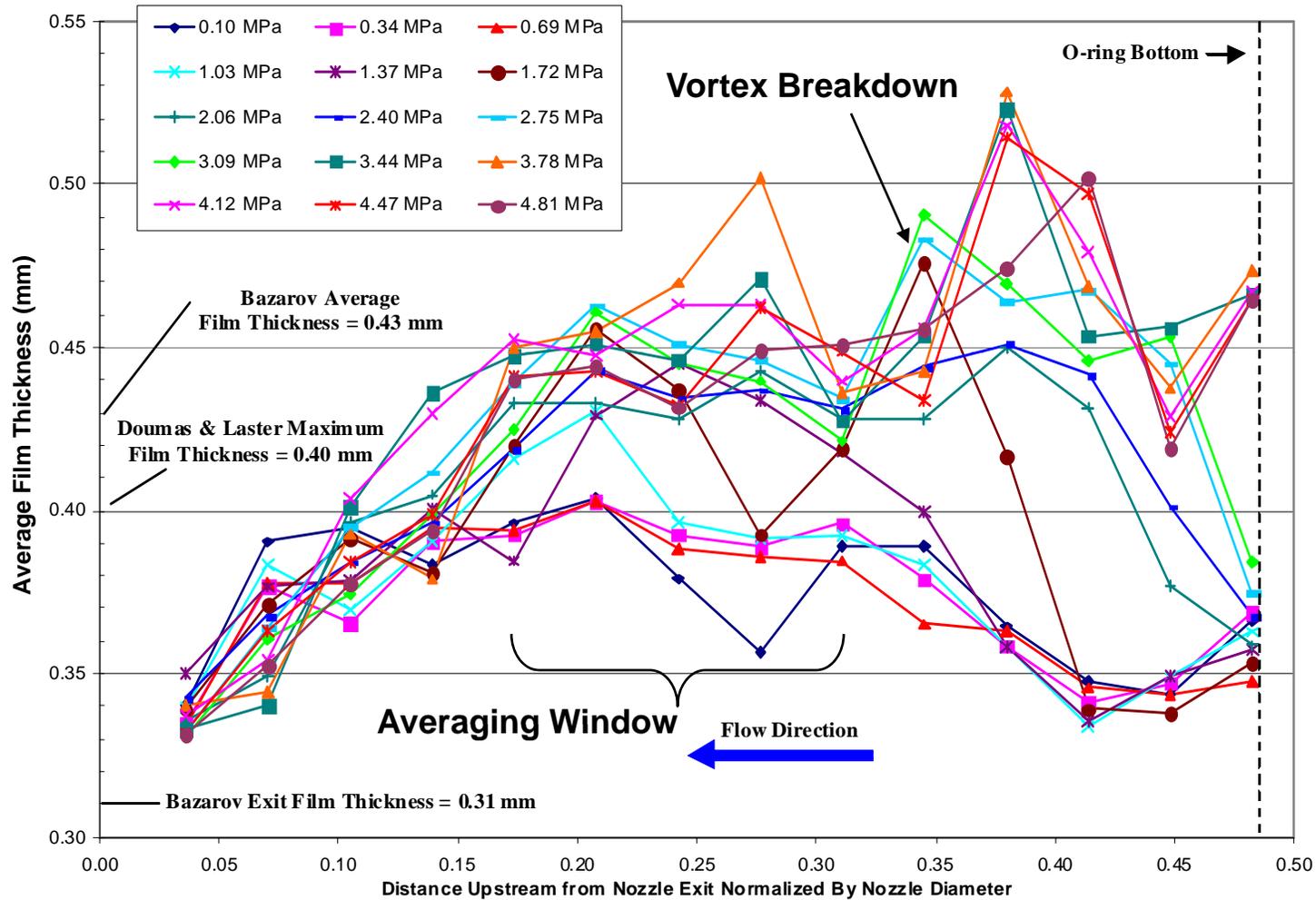
# Spatial Film Thickness



- Corrected for optical effects
- Both left and right sides profiles measured and used to find average film thickness profile



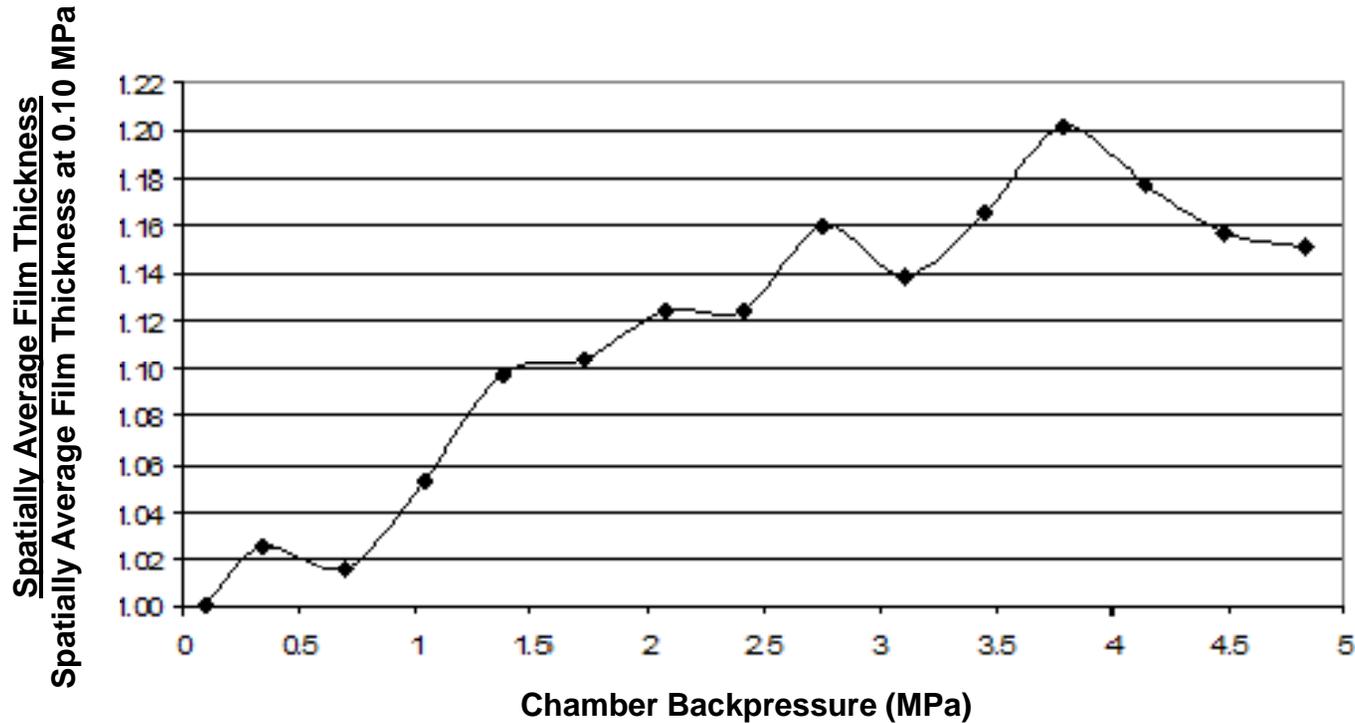
# Inner Film Thickness Quantification



- Fixed design mass flow rate, varying chamber pressures.



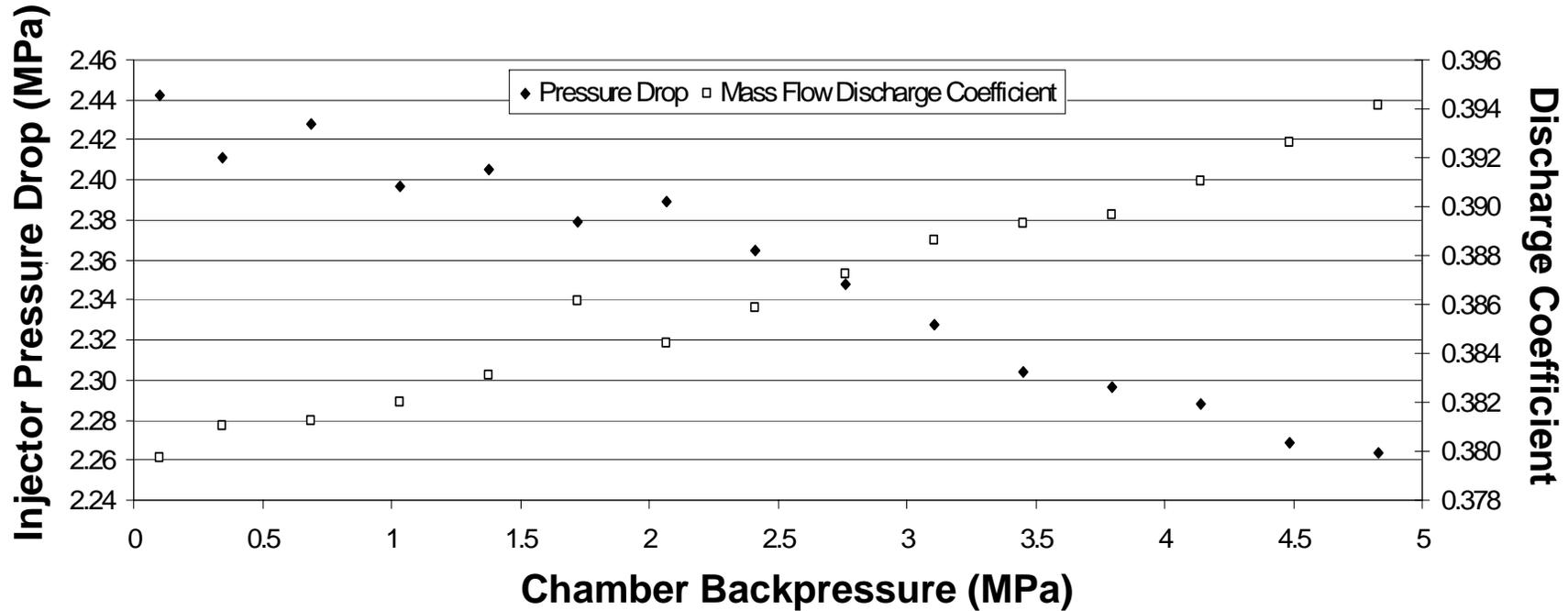
# Average Film Thickness Variation



- Presence of hydraulic jump in flow distorts film thickness and induces susceptibility of flow to disturbances.
- For the same mass flow rate, increases in film thickness will raise the discharge coefficient and lower the issuing spray angle



# Injector Pressure Drop and Discharge Coefficient at 0.09 kg/s

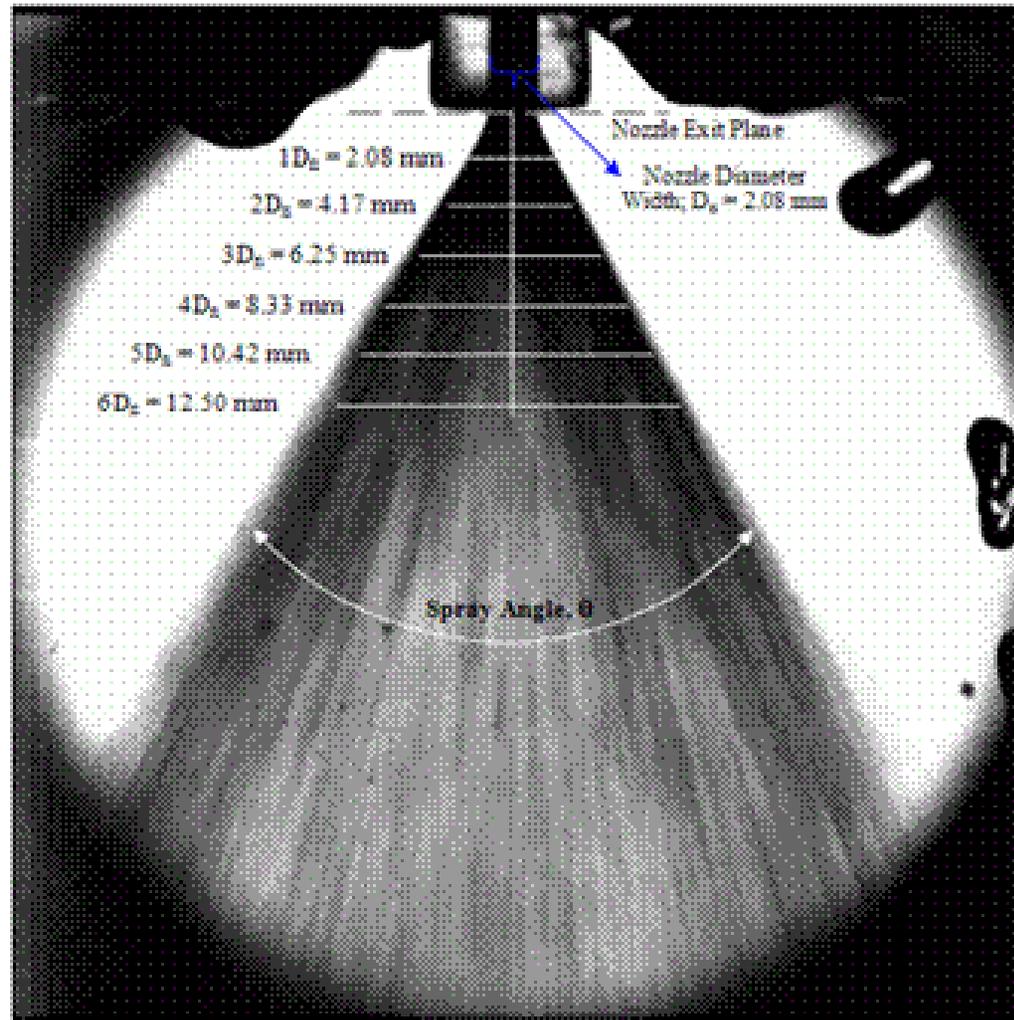


$$C_d = \frac{\dot{m}_{actual}}{\dot{m}_{ideal}} = \frac{\dot{m}_l}{\rho_l V_\Sigma \frac{\pi}{4} D_n^2} = \frac{\dot{m}_l}{\sqrt{2\rho_l \Delta P} \frac{\pi}{4} D_n^2}$$



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# Spray Angle Measurement





# Spray Angle Videography



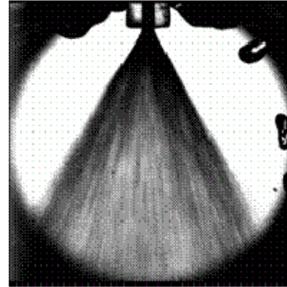
- Show movies of spray angle at full flow rate and chamber pressure of:
  - 0.10 MPa
  - 2.31 MPa
  - 4.83 MPa



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# Results: Spray Angle

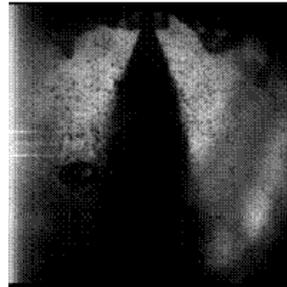
0.10 MPa: Pre-processed



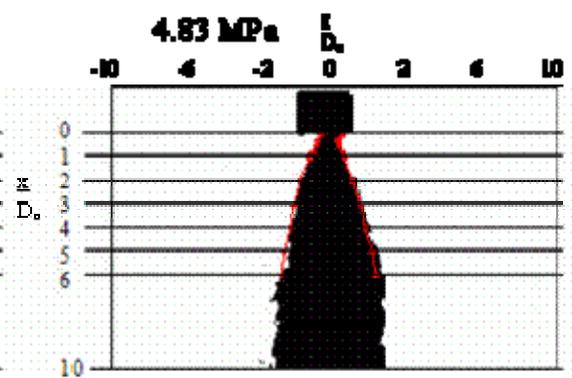
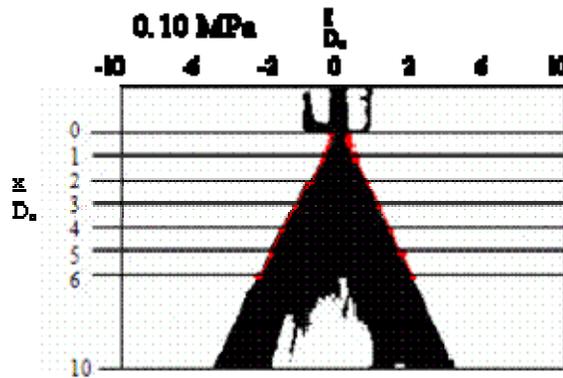
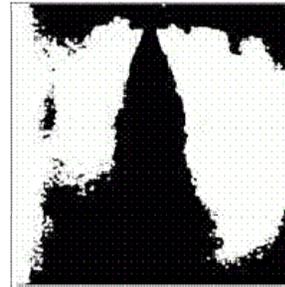
0.10 MPa: Post-processed



4.83 MPa: Pre-processed



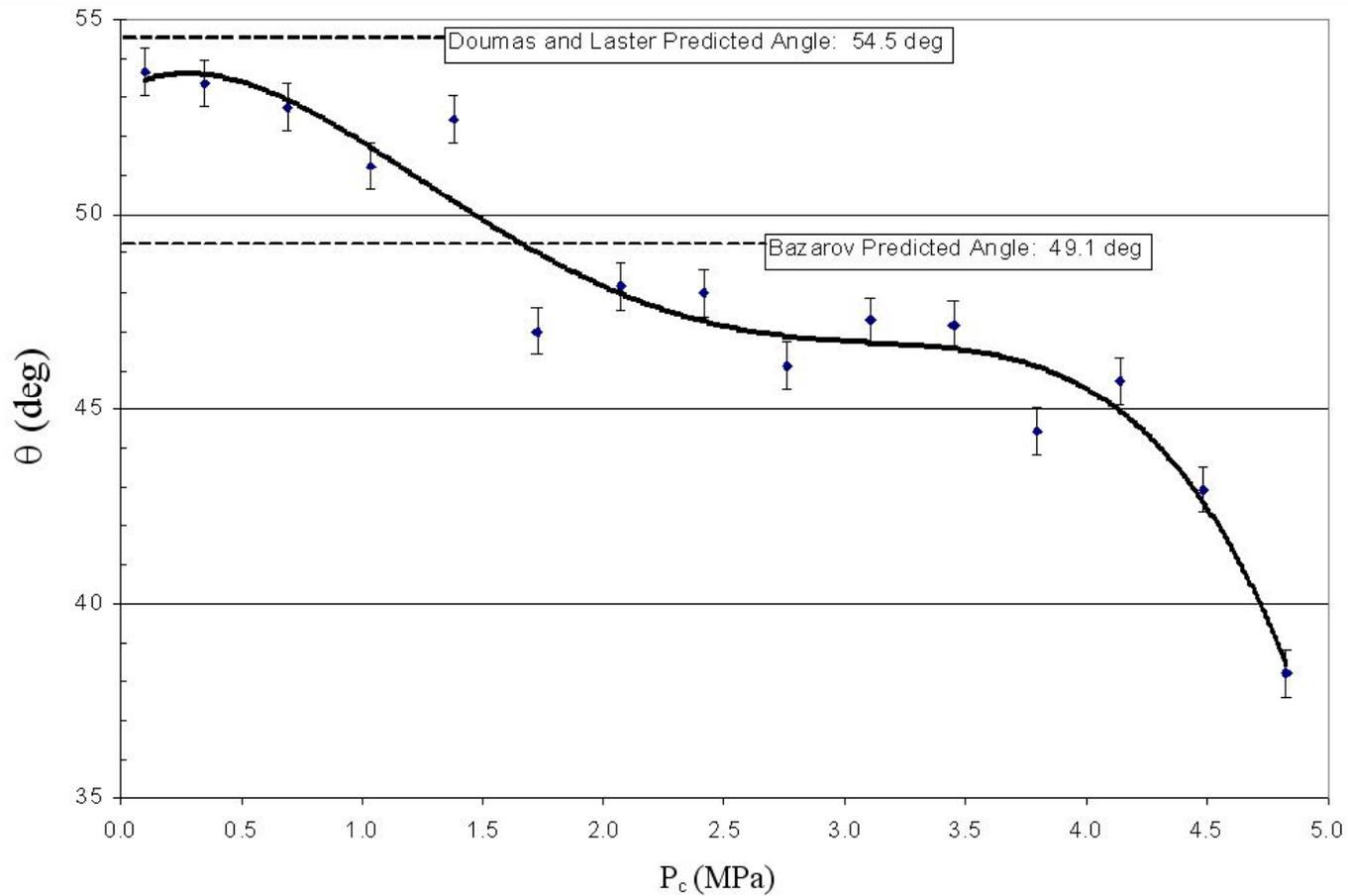
4.83 MPa: Post-processed





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# Downstream Spray Angle



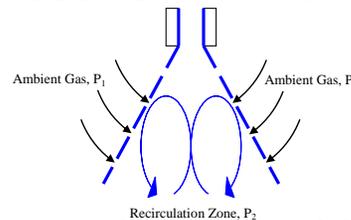
- Increasing chamber pressure causes more gas entrainment into the spray cone volume; angle decreases at a decreasing rate.



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# Conclusions

- Film Thickness
  - No numerical/analytical works exist that elaborate on hydraulic jump presence in liquid swirl injector
  - Previous work exist on vortex breakdown in swirling flows at ambient conditions
  - Sarpkaya: Adverse pressure gradient on vortex will cause pressure recovery and induce hydraulic jump
    - Generally, increasing downstream pressure will induce and move jump upstream
    - Increasing mass flow rate will cause similar effects
- Discharge Coefficient
  - Increasing chamber backpressure raises discharge coefficient for particular mass flow rate operating range.
  - Indicative of increasing viscous losses within swirl injector.
    - Increased gas/liquid interface shear
    - Increased axial flow retardation/recirculation within liquid annulus
- Spray Angle
  - Increasing ambient pressure will lower design spray angles



- Is correlated to the increasing internal film thickness of the nozzle, but not necessarily directly related.



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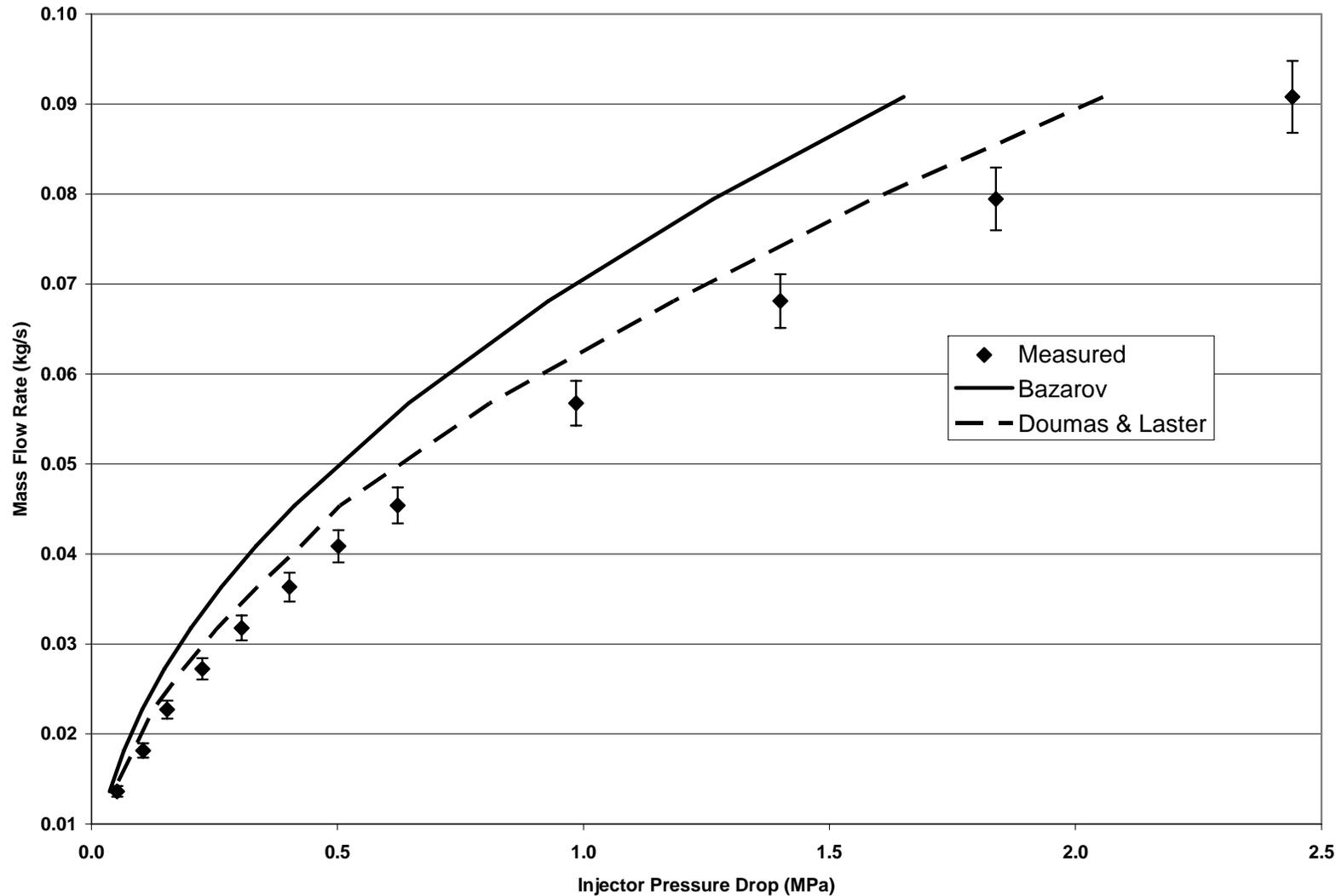
- QUESTIONS?



# Facility & Hardware: Swirl Element Atmospheric Operation

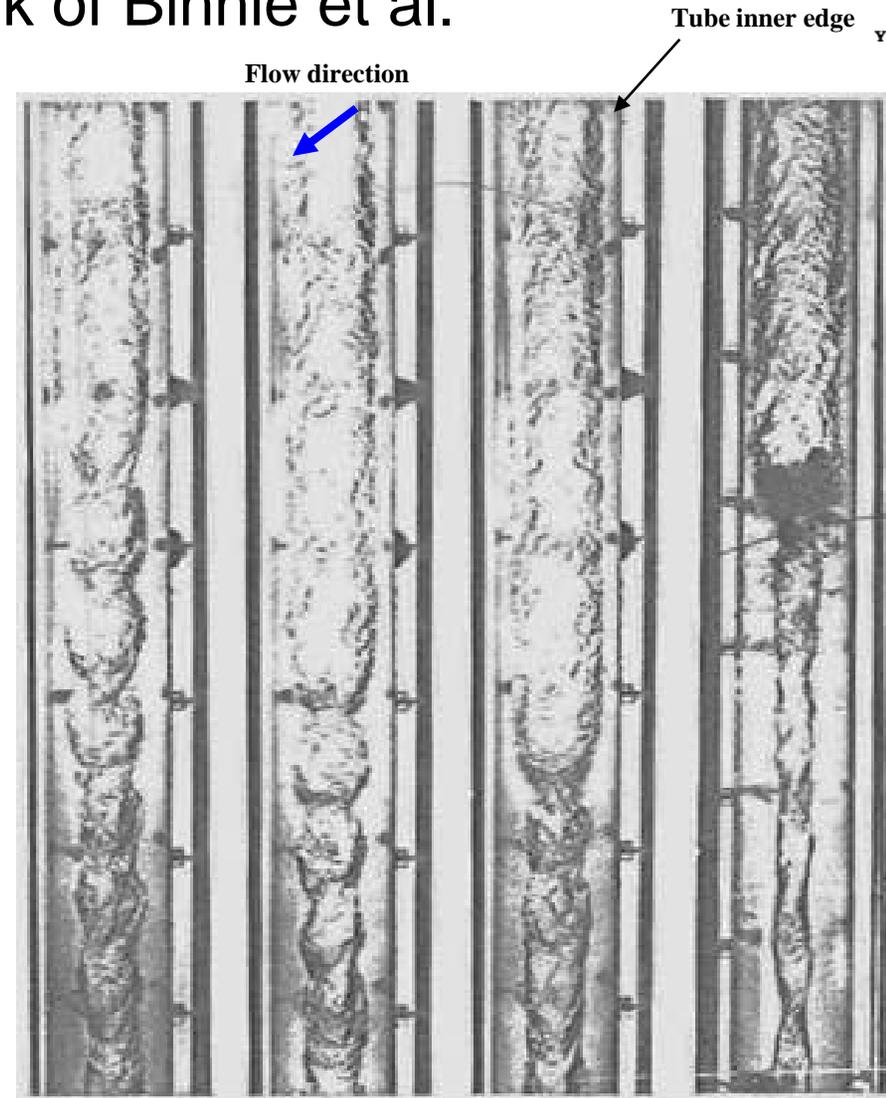
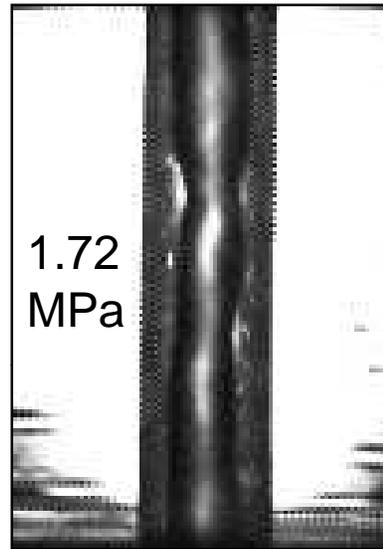


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## Inner Film Thickness Comparison to Previous Work of Binnie et al.



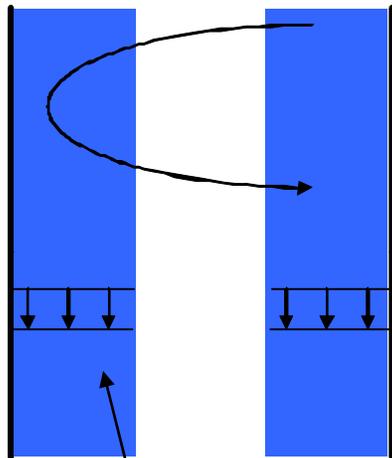
- Binnie stated that the jump in the swirling flow was a vortex breakdown phenomenon.
- Binnie stated that as the swirling flow's Froude number was increased, the intensity of the flow jump increased.



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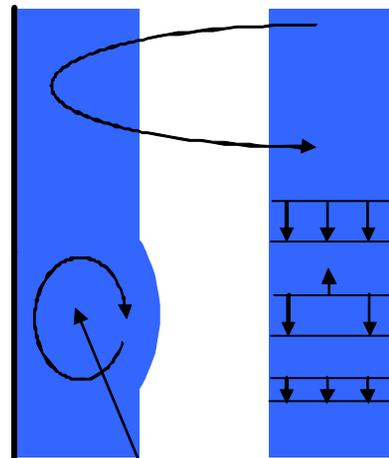
# Inner Film Thickness Vortex Breakdown

Flow at 0.091 kg/s and 0.10 MPa



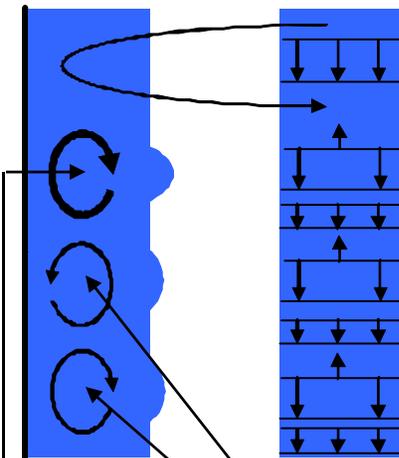
Mean axial velocity

Flow at 0.091 kg/s and ~1 – 1.4 MPa



Unsteady Vortex Breakdown

Flow at 0.091 kg/s and >1.5 MPa



Parent and Child Vortex Breakdowns

- Chamber pressure increase -> gas density in gas core increase -> increased shear
- Axial flow retardation and flow recirculation => Vortex Breakdown
- Vortex breakdown will move upstream into vortex chamber with increased momentum losses.



# Inner Film Thickness Quantification

High resolution digital stills were used to capture film thickness profiles at 13 locations along the acrylic nozzle length.

