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 GH2/LOX.
  – Historical GH2/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 H2O/GN2
  - Ambient chamber pressure set up to 1400 psia by additional GN2 feed lines
  - H2O mass flow rates up to 1 lbm/s
  - Real-time controllable backpressure, flow rates, and gas temperature
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
Swirl Element
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
## Swirl Element Design Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Bazarov Prediction</th>
<th>Doumas &amp; Laster Prediction</th>
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</thead>
<tbody>
<tr>
<td>Mass Flow Rate (kg/s)</td>
<td>0.09</td>
<td>0.09</td>
</tr>
<tr>
<td>Free Cone Spray Angle (deg)</td>
<td>49</td>
<td>52</td>
</tr>
<tr>
<td>Pressure Drop at Design Flow (MPa)</td>
<td>1.72</td>
<td>2.09</td>
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<tr>
<td>Discharge Coefficient</td>
<td>0.463</td>
<td>0.414</td>
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<tr>
<td>Film Thickness (mm)</td>
<td>0.43</td>
<td>0.40</td>
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<tr>
<td>Orifice Diameter (mm)</td>
<td>1.58</td>
<td>1.58</td>
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<tr>
<td>Orifice to Centerline Radius (mm)</td>
<td>1.55</td>
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<tr>
<td>Vortex Chamber Diameter (mm)</td>
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<tr>
<td>Orifice Length (mm)</td>
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<tr>
<td>Vortex Chamber length (mm)</td>
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<tr>
<td>Nozzle Diameter (mm)</td>
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<tr>
<td>Nozzle Length (mm)</td>
<td>16.05</td>
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</table>
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
Inner Film Thickness Profiles

12.65 mm

0.10 MPa

0.69 MPa

1.03 MPa

1.38 MPa

1.72 MPa

2.07 MPa

2.76 MPa

4.83 MPa

2.08 mm

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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

\[ C_d = \frac{\dot{m}_{actual}}{\dot{m}_{ideal}} = \frac{\dot{m}_l}{\rho_l V \sum \frac{\pi}{4} D_n^2} = \frac{\dot{m}_l}{\sqrt{2 \rho_l \Delta P} \frac{\pi}{4} D_n^2} \]
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
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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Increasing chamber pressure causes more gas entrainment into the spray cone volume; angle decreases at a decreasing rate.
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.
• QUESTIONS?
Facility & Hardware: Swirl Element Atmospheric Operation

![Graph showing Mass Flow Rate vs. Injector Pressure Drop with measured data and model predictions.](image)
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.
Inner Film Thickness Vortex Breakdown

Flow at 0.091 kg/s and 0.10 MPa

Flow at 0.091 kg/s and ~1 – 1.4 MPa

Flow at 0.091 kg/s and >1.5 MPa

• 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.

Mean axial velocity

Unsteady Vortex Breakdown

Parent and Child Vortex Breakdowns

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Inner Film Thickness Quantification

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