Cryogenic Experimentation on the Magnetohydrodynamics of Liquid Oxygen

Jeffrey C. Boulware
PhD Candidate
Mechanical & Aerospace Engineering
Utah State University

Advisors
Dr. Heng Ban
Associate Professor
Dr. Scott Jensen
Adjunct Professor
Dr. Steve Wassom
Adjunct Professor
Overview

• Magnetic Fluids
• Experimental Principle
• Test Setup
• Theory
• Numerical Model
• Results
• Conclusions
Magnetic Fluids

• Most research performed on ferrofluids
  – Colloidal suspensions of ferromagnetic nanoparticles

• Oxygen is a paramagnetic fluid
  – Attracted to a magnetic field, but does not create its own

• Susceptibility is inversely proportional to temperature
  – Curie’s Law

• Youngquist of KSC performed only known MHD tests on LOX

Verifying the experimental method with a ferrofluid

Boiling LOX suspended in a magnetic yoke

Courtesy of the University of Illinois at Urbana-Champaign
Experimental Principle

\[ P_1 V_1 = P_2 V_2 \]
Experiment Setup

- Oxygen Valve
- Helium Valve
- Condenser
- Test Section
- Quartz Tube
- Pressure Sensors
Theory – Force Balance

\[ \dot{m} \ddot{x} = F_P(x) + F_M(x) + F_S(\dot{x}) \]

\[ F_P = \pi a^2 \Delta p \]

\[ F_M = \frac{\pi a^2 \chi}{2 \mu_0 (1 + \chi)} \left( B_{x,US}^2 - B_{x,DS}^2 \right) \]

\[ F_S = 2\pi a L \tau_w \]

\[ \mu_0 = \text{permeability of free space} \]

\[ \chi = \text{volumetric magnetic susceptibility} \]

\[ B = \text{magnetic flux density} \]

\[ \tau_w = \text{wall shear stress} \]
Numerical Model

\[
B_{x,i} = \frac{\mu_0 I_i}{2} \sum_{m=-\frac{1}{2}(M-1)}^{\frac{1}{2}(M-1)} \sum_{n=0}^{M_i-1} \left( a_{sol} + nb\Delta r \right)^2 \left( a_{sol} + nb\Delta r \right)^2 + (x_i - mb\Delta x)^2 \right]^{3/2}
\]

\[
F_{M,i} = \frac{\pi a^2}{2\mu_0} \frac{\chi}{(1 + \chi)^2} (B_{x,US,i}^2 - B_{x,DS,i}^2)
\]

\[
F_{S,i} = 2\pi a L \tau_{w,i}
\]

\[
F_{P,i} = \pi a^2 (P_{DS,i} - P_{US,i})
\]

\[
F_{T,i} = F_{P,i} + F_{M,i} - \text{sgn}(\dot{x}_{i-1})F_{S,i}
\]

\[
\dot{x}_i = \frac{F_{T,i} + F_{T,i-1}}{2\rho a^2 L} \Delta t + \dot{x}_{i-1}
\]
Results – Single Pulse

![Graph showing pressure vs. time with 'ON' and 'OFF' labels. The graph displays data and predicted curves.](image-url)
Results – Single Pulse

1.9 cm length slug pulsed at 22 A

- Experimental Data
- Hydrostatic Breakdown
- Numerical Simulation

Max ΔP, kPa

Slug Center Position, cm
Results – Single Pulse

![Graph showing pressure changes with center position and length]
Results – Multiple Pulses

Measured Downstream Pressure, kPa

Estimated Displacement, cm

Time, s
Results – Hydrostatic Breakdown

\[
\Delta p_{\text{max}} = \frac{1}{2 \mu_0} \frac{\chi}{(1 + \chi)^2} (B_{x,US}^2 - B_{x,DS}^2)
\]
Conclusions

• LOX can be controllably displaced using magnetic fields in a closed system.
  – Enhances the potential for viability in a satellite system

• The single and multiple pulse dynamics of a LOX slug can be successfully simulated numerically.
  – Operating frequencies can be optimized during design phase

• The hydrostatic breakdown for LOX is mathematically predictable as verified by the data.
  – System capability range can be determined during design phase
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