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Experiment and Simulation on the Dynamics of a Slug of Liquid Oxygen Displaced by a Pulsed Magnetic Field

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EXPERIMENT AND SIMULATION ON THE DYNAMICS OF A SLUG OF
LIQUID OXYGEN DISPLACED BY A PULSED MAGNETIC FIELD

by

Jeffrey C. Boulware

A dissertation submitted in partial fulfillment
of the requirements for the degree
of
DOCTOR OF PHILOSOPHY
in
Mechanical Engineering

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2010
A magnetic fluid system could potentially replace mechanically moving parts in a satellite as a means of increasing system reliability and mission lifetime, but rather than a standard ferrofluid with magnetic particles, liquid oxygen (LOX) may be a more adequate working fluid. As a pure paramagnetic cryogen, LOX is already heavily used in space, but still requires basic research before being integrated into system development. The objectives of the research conducted were to verify LOX as a magnetic working fluid through experiment and establish a theoretical model to describe its behavior. This dissertation presents the theoretical, experimental, and numerical results of a slug of LOX being pulsed by a 1.1 T solenoid in a quartz tube with an inner diameter of 1.9 mm. The slug oscillated about the solenoid at 6-8 Hz, producing a pressure change of up to 1.2 kPa. System efficiency based on the Mason number was also studied for various geometric setups, and, using a one-dimensional, finite-differenced model in Matlab
2008a, the numerical analyses confirmed the theoretical model. The research provides groundwork for future applied studies with complex designs.
To my parents for their unending love and support and to my wife and our future family
who made it worth all the sacrifice
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CHAPTER 1
INTRODUCTION

1.1 Introduction

1.1.1 Problem Statement and Motivation

Actuator systems with magnetically responsive fluids have a unique advantage over those relying on a mechanical driver to instigate and propagate flow in that the magnetohydrodynamic force could potentially eliminate moving parts, increase subsystem lifetime, and enhance system robustness. Space systems, in particular, could benefit from a lack of mechanically moving parts as it would increase mission length and decrease dynamic loads during launch, mission-interfering vibrations, and overall risk of failure. But, while magnetic fluid technology has been used on Earth for decades, application to the cryogenic realm has not been significantly studied.

Conventional magnetic fluids are composed of a carrier fluid and a colloidal suspension of magnetic particles and are referred to as “ferrofluids.” Because of the thermal properties of the carrier fluid, typically water, oil, or a hydrocarbon, ferrofluids freeze in the cold temperatures of space. Liquid oxygen, or “LOX”, on the other hand, is a pure paramagnetic fluid and already used for life support, thermal management, and propulsion. While LOX seems to be a potential solution for cryogenic magnetic fluid technology, insufficient research exists on its quantitative experimental behavior; thus, the objective of the current study was to establish the viability of LOX as a working fluid through experiments and a theoretical model.
1.1.2 Research Goals and Objectives

As mentioned, the broad goal of the research was to support the notion that LOX could be used as a working fluid in a magnetic fluid system due to its significant paramagnetic susceptibility. This goal could be achieved by performing controlled, quantitative experiments, correlating them to a theoretical model, and determining predictable trends from the results. The theoretical model should limit empirical input (other than initial conditions) and should be able to make predictions regardless of system geometry. Most importantly, the final data should be useful to future, applied research.

The overall goals for the research were listed as follows:

1. Obtain a fundamental understanding of cryogenic magnetohydrodynamics.
   – Cryogenics and magnetohydrodynamics are individually well understood but have not been heavily researched in combination.

2. Determine the feasibility of a magnetic fluid system with no moving parts.
   – A thorough analysis of the industrial impact and optimal methods for integration is required for advanced subsystem development.

3. Develop a theoretical model to describe the phenomenon.
   – To strengthen the fundamental understanding, a mathematical base is required for all experiments and analyses.

Furthermore, specific objectives were created which supported and initiated the overall goals. These specific objectives were as follows:

1. Displace a LOX slug using magnetic fields.
   – Experimentally accomplishing this would quantify the potential of a LOX-based magnetic fluid system.
2. Detect the displacement through pressure.
   
   – Innovative measuring techniques will be required to study how LOX behaves in a magnetic field.

3. Simulate the dynamics numerically.
   
   – A verified numerical algorithm can quantify LOX performance outside the scope of laboratory testing.

4. Perform parametric studies to examine efficiency optimization methods.
   
   – Information on the sensitivity to uncertainties and geometric variance will help to estimate the potential capability of an optimized system.

The objectives will prove the viability of LOX as a working fluid and lead the way to advanced, applied research. To accomplish these objectives, a theoretical model was developed and an experimental apparatus was designed. The model and experiment were compared using a numerical simulation written in Matlab and have formed the foundation of the overall goals.

1.1.3 Experimental Principle and Data Analysis

1.1.3.1 Experimental Principle

In a tube with a solenoid wrapped around it, magnetic pressure on a slug is maximized when one edge is in the center of the solenoid and the other is in a negligible field. While this is achievable with a long column, a small slug would be nearly as effective and was the basis of the experimental principle. Fig. 1.1 shows that the magnetic flux density of a 0.6 cm (0.25 in) solenoid drops to 5% of its maximum value of 1.1 T at a distance 1.75 cm from the center of the solenoid. This benchmark differs
depending on solenoid geometry, applied current, and wire spacing, but the example shows that a slug could achieve nearly the same magnetic pressure as a long column, but for a much smaller mass and length. Eliminating mass and length reduces inertia and shear, which would otherwise retard slug motion.

In addition to using a small slug instead of a long column of LOX, the experiment was performed with the tube oriented horizontally to mitigate the dominance of gravity.
and was small enough so that the capillary forces allow slug formation without inhibiting motion. Because LOX is extremely volatile, helium was used as the surrounding gas since it does not react with oxygen and could be treated as an ideal gas at the test conditions. Also, since the test section was part of a closed volume, the slug displacement was able to be measured through pressure changes on either side of the slug as long as it did not breakdown as shown in Fig. 1.2. The experimental principle assumed the gas compression and expansion were isothermal and that the LOX slug did not boil.

The slug dynamics were sensitive to the following parameters:

- slug length
- initial position
- solenoid geometry
- applied current
- system volume
- tube radius
- initial system pressure

Experimentally, it was not feasible to vary the tube radius since it would affect the capillarity of the slug. Even marginal changes could significantly affect the dominance that surface tension would play; thus tube radius remained constant throughout the experiments. Likewise, the volatility of LOX precluded high pressure testing; thus the initial system pressure remained as close to atmospheric as possible throughout the experiments. Because the closed volume was placed in a liquid nitrogen bath to prevent LOX boil off, the test conditions and fluid properties were calculated at 77 K and 101 kPa (1 atm).
1.1.3.2 Data Analysis

Because the slug dynamics in the experiment were measured through pressure changes in the closed volumes, the theoretical model was compared using this data instead of displacement. The displacement still needed to be calculated in the theoretical model because the position of the slug must be known to determine the magnetic body force, but the pressure represents a more direct comparison due to the experimental measurement technique. Furthermore, the pressure change achieved will also allow for a more direct comparison to other fluid actuators.

The magnetic body force is a function of the position of the edges of the slug with respect to the center of the solenoid. As described earlier, a small slug may be nearly as effective as a long column due to reduced inertia and shear; however a limit to this trend exists. This dissertation will present a study on the maximum pressure change attainable with varying slug lengths. For each slug length, the experiments encompassed a full range of initial positions for expansion and compression within the limits of hydrodynamic breakdown. The applied voltage remained constant for the tests, but another series of experiments studied its influence as well. With one edge centered in the solenoid, the maximum pressure change was measured for a variety of applied voltages for certain slug lengths.

To determine the effect of experimental uncertainties, the theoretical model was applied to a numerical simulation to study the oscillations of the slug for a particular run. Trends found regarding changes in the frequency, amplitude, and mean of the oscillations were used to precisely calculate unknown parameters in the physical experiment. Using
the root mean square deviation of the absolute error between the experiment and the simulation, an accurate one-dimensional, finite-difference simulation was created.

With a confirmed theoretical model, the influence of geometry was studied to find trends regarding overall system size as well as optimal slug lengths for particular solenoids. With different wire gauges and overall sizes, two solenoids were designed to have approximately the same magnetic field while using the same power source. When correlated with the theoretical model, experiments on these two solenoids allowed studies on minimizing the damping force for the same pressure change.

These studies were performed to satisfy the test objectives and support the overall goals. In performing the experiments and developing the theoretical model, some basic assumptions were required.

1.1.4 Structure of Dissertation

This dissertation is prepared in a multi-paper format, following the requirements of the Graduate School of Utah State University. The structure of this dissertation is shown in Fig. 1.3. Every individual chapter from Chapter 2 to Chapter 4 is composed of a
journal article (Table 1.1). With a background knowledge related to magnetic fluids and liquid oxygen reviewed in Chapter 1, a study on the maximum pressure change attainable for varying slug lengths and applied currents is described in Chapter 2. Chapter 3 presents the numerical simulation and calculation of experimental uncertainties. A study on the influence of geometry and optimization methods is presented in Chapter 4. Major conclusions from all of the studies and future work required for the next steps of technology development are presented in Chapter 5.
1.2 Literature Review

1.2.1 Systems with No Moving Parts

Satellite design is a continually evolving process which adapts to enable wider ranges of missions and capabilities, but requires innovation and diversity of basic operating mechanisms to sustain development demand. Of the over 1500 satellites from 0.1–100 kg that have launched since Sputnik [1], Hecht reports that 24.8% of the failures that occurred were design related [2]. Mechanical failures are among the most notorious due to their low fault tolerance and are apparent in all classes of satellites, as reviewed by Harland [3]. Early tape recorder failures from spinning parts were experienced in small and large spacecraft such as the Ariel 3, Shinsei, Prospero, Spot 1, Compton Gamma Ray Observatory, and Galileo missions. Some failures, such as antenna or boom deployment, are recoverable, but still bear a considerable cost to find a solution, such as in the Voyager II, Anik E2, UoSat 1, and JERS 1 missions. Modern satellites undergo rigorous testing and use highly reliable parts, but an alternate design solution may be to eliminate the moving parts altogether.

Replacing moving parts requires using non-mechanical forces to generate motion or fluid compression. Bhatia provides an excellent review in the area of heat transfer [4], where, even when fully functioning, mechanically moving parts can hamper satellite operations. He showed that, while the technologies perform well in their roles, each has certain limitations on their applicability. Sorption coolers use chemical or physical adsorption reliably, but dependence on a cryostat limits their lifetime. Heat pipes use capillarity to regulate temperature but cannot generate high pressures or heat fluxes. Dilution refrigerators and thermosiphons are gravity-driven mechanisms and, thus, have
difficulty finding application in space. Pulse tubes have performed very well transferring heat with acoustic forces and could potentially be superseded by more advanced thermoacoustic engines [5], but are restricted by geometry due to their method of operation. Vuilleumier cycles are designed to replace mechanical compressors with thermal ones, but have low efficiency. Adiabatic demagnetization refrigerators are responsible for generating the lowest artificial temperatures ever by using the magnetocaloric effect but are still in development for space use. In summary, innovative designs have attempted to use chemical, capillary, gravitational, acoustic, thermal, and magnetic forces to replace mechanically moving Stirling cycle compressors. A magnetically driven mechanism can be particularly useful and robust since the field can be adjusted by an electrically controlled solenoid. The solenoid could then be coupled with a magnetic fluid to create a system with no moving parts similar to that used terrestrially for decades.

1.2.2 Magnetic Fluids

A magnetic fluid is a liquid which macroscopically responds to a magnetic field through atomic or molecular polar alignment. In solids, if the poles are aligned, the material is said to be “ferromagnetic” and generates its own magnetic field. Liquids, however, cannot maintain the alignment without a field and are either “paramagnetic”, in which the poles align with the applied field, or “diamagnetic”, in which the poles align opposite the applied field. The bulk effect of each is that paramagnetics are attracted to the field (towards an increasing gradient), and that diamagnetics are repelled from it (away from an increasing gradient) [6].
In the 1960s, NASA developed “ferrofluids” which are a colloidal suspension of ferromagnetic particles in a carrier fluid. A special surfactant on the particles prevents their alignment without a field; thus, ferrofluids actually exhibit superparamagnetism since they have an extremely high susceptibility, but only with an applied field. Ferrofluids have found many industrial applications such as high-end audio speakers, digital data storage, and resonance imaging. As a working fluid, ferrofluids have been proposed for pumps [7-14], valves [15], actuators [16], heat pipes [17-18], and even optical tuners [19]. However, the practical range of these ferrofluids is limited by the thermal characteristics of the carrier fluid, typically water, oil, or a hydrocarbon. The presence of nanoparticles and surfactants in ferrofluids complicates analyses, mainly due to agglomeration and nonhomogeneity. In the cryogenic realm, LOX possesses a natural paramagnetic susceptibility and does not require particles for practical application.

1.2.3 Liquid Oxygen

In all phases, the unpaired electrons in an O₂ molecule lead to a bulk paramagnetic effect. However, the thermal energy with the molecules may dominate the magnetic alignment with an applied field; hence warm oxygen does not have an appreciable susceptibility. As temperature decreases and thermal energy is reduced, the molecules are more able to align and susceptibility increases. This phenomenon is known as Curie’s Law, where, essentially, paramagnetic susceptibility increases as temperature decreases. Furthermore, once oxygen condenses (90 K, 101 kPa), the volumetric susceptibility, $\chi$, significantly increases with the density of the fluid. The relationship
between volumetric susceptibility, mass susceptibility, $\chi_{\text{mass}}$, and molar susceptibility, $\chi_{\text{molar}}$, is defined through density, $\rho$, and molecular weight, $MW$, as

$$\chi = \frac{1}{\rho} \chi_{\text{mass}} = \frac{1}{\rho} \frac{\chi_{\text{molar}}}{MW}.$$  \hspace{1cm} (1-1)

Throughout the remainder of the dissertation, “susceptibility” will refer to volumetric susceptibility. Although it is approximately 30 times weaker than a low-end ferrofluid, LOX has the highest known paramagnetic susceptibility of pure fluids. The lack of magnetic particles eliminates risks such as corrosion and shock and since LOX is already commonly used for life support, thermal management, and propulsion systems, the integration process is simplified.

As a pure fluid, LOX has the highest known paramagnetic susceptibility, but unfortunately has been overlooked in magnetic fluid research because of its boiling point at 90 K at atmospheric conditions. The basic properties of LOX have been measured under a variety of temperature and pressure ranges [20-24], but unfortunately, few experiments have studied the influence of a magnetic field. Uyeda performed experiments on the magneto-volume effect of LOX [25], which is shown to be negligible for the current study. Takeda [26] measured the surface tension under high magnetic fields and Catherall [27] and Hilton [28] investigated the magneto-Archimedes levitation to determine its use in mineral separation, but did not consider it as a working fluid in an actuator. Catherall also studied its surface instabilities [29] under an inhomogenous field but none of these experiments generated a bulk movement of the liquid. Yerkes [30] measured the wicking heights of liquid oxygen heat pipes when augmented by a magnetic field and showed an increase of up to 4 times the capillary pressure.
Youngquist performed experiments which quantitatively measured the magnetohydrodynamic characteristics of LOX [31], but it was mainly a benchmark study. While using a solenoid to pulse a magnetic field on one end of a column of LOX in an open-ended U-tube, he measured the displacement of the other end and correlated the results to a numerical model, as shown in Fig. 1.4. He applied an electric current of 30 A to the solenoid which generated a magnetic field with a maximum flux density of 0.9 T. With the field applied, the height of the column oscillated about a new mean, reaching a maximum displacement of 4-5 cm. Note that pulses of 100 A and 6 T were attempted, but had erratic results, often ripping off the top of the column. This study was a valuable first step, but required an evolution in its methodology to achieve progress.

1.2.4 Magnetic Fluid Pumps

Because the fundamental theory of magnetohydrodynamics has been developed for several decades, magnetic fluids have been used in industrial applications such as magnetic resonance imaging, digital data storage, and high-end stereo speakers. As a
working fluid in an actuator system, however, the uses are more limited due to the complex control systems required for pumping. Park and Seo [7-11] of Pusan National University have developed a magnetic fluid linear pump for the purpose of infusion pumps and artificial hearts in the medical industry. Using magnetic yokes to propagate droplets of a magnetic fluid, the device uses surface shear to pump water as shown in Fig. 1.5.

Park and Seo report pumping heights equivalent to 2 kPa (0.29 psi) for a maximum flux density of 0.036 T (360 G). While this seems like an extremely small field compared to Youngquist’s experiment, it is important to note the Park and Seo are using a ferrofluid and not LOX. LOX has the highest known paramagnetic susceptibility of pure fluids, but is dwarfed by artificial ferrofluids. An inexpensive ferrofluid can be up to 30 times stronger than LOX. The research performed by Park and Seo is useful as a study on traveling waves and their effects on the surface dynamics of a magnetic fluid droplet, but difficult to apply to LOX due to the lack of detail in the papers. Nonetheless, the work serves as a good benchmark for comparison.
Hatch [12] of the University of Washington developed a ferrofluidic rotary micropump to enhance lab-on-a-chip MEMS technology. The concept (shown in Fig. 1.6) achieved 1.2 kPa of pressure head using a rotating and stationary permanent magnet with a surface flux density of 0.35 T (3500 G). Like Park and Seo, the device pumps a separate, immiscible fluid, but by normal pressure, not surface shear. The study reports operation at 4 and 8 rpm for 3 days at a time. It was found that the steady-state pressure gradient decreased over time when the plugs were rotated clockwise and counterclockwise. Pumping speeds greater than 8 rpm generated too much pressure and disrupted the coupling between the permanent magnet and the translating ferrofluidic plug. Furthermore, the rotating permanent is a mechanically moving component and, therefore, negates the goal of creating a no-moving-parts system for fluid actuation.

Moghadam [13] also developed a microscale magnetic fluid pump but successfully managed to eliminate the moving parts. Similar to Park and Seo, he used a series of solenoids spaced along a tube to drive a magnetic fluid linearly. Rather than wrapping the tube though, the solenoids were offset and orthogonally aligned so that their

---

**Fig. 1.6. A rotating permanent magnet to propagate a ferrofluid plug, taken**
core could be filled with an iron rod and increase the magnetic flux density. The setup produced 0.64 kPa of pressure head for flow rates of 1.1 cm³/min at 0.45 T. The study compared different working fluids and particles, but relies on the viscous drag of the particles to create fluid motion.

Krauss [14] of the University of Bayreuth has used a two coil system to pump a ferrofluid circularly. The 90° phase difference of the two coils with orthogonal axes produced a net field able to rotate the fluid through the magnetic stress on the fluid surface as shown in Fig. 1.7.

The mean diameter of the duct was 100 mm and the system produced a maximum fluid velocity of 70 mm/sec and a magnetic field of 800A/m. Properties of the ferrofluid used were not presented; thus, the magnetic flux density is unknown.

In an applied sense, Goldstein [15] and Kamiyama [16] attempted to create bio-compatible devices for surgical implants. Ming [17] and Jeyadevan [18] augmented heat pipe performance by placing permanent magnets near the warm end. Liao [19] tuned an optical fiber filter by using two solenoids to control the position of the slug over long period gratings; thereby changing its refractive index. Although these works do not

Fig. 1.7. Two coil system for pumping a ferrofluid by magnetic surface stress,
generate a pressure head, they provide examples of an innovative use of magnetic fluid actuators.

Zahn and Greer [32] of the Massachusetts Institute of Technology took a theoretical approach to traveling waves, but without a free surface. They found that the magnetic fluid can actually be pumped backwards if the wave moves too fast. Without the free surface, the field interacts with the nanoparticles inside the ferrofluid and motion is generated through the particle spin. They studied the dynamics of a spatially steady field, but varying sinusoidally in time. Their work was followed up by Mao and Koser [33] of Yale University who were able to vary the field in space as well. Their findings showed that a maximum flow velocity was achieved when the product of the applied magnetic field frequency, the wave number, and the height of the channel approach unity. In other words, pumping becomes more efficient as the magnetic field frequency approaches the reciprocal of the relaxation time constant of the magnetic particles in the fluid. Mao and Koser compared their experimental data with numerical results for a 2D solution using FEMLAB and a 1D solution using Matlab. They found that all 3 agree well until the magnetic field frequency reaches about 30 kHz, when the Matlab solution begins to diverge.

The aforementioned research illustrates the importance of fluctuating magnetic fields for pumping. Without a gradient of the magnetic field, no net force is generated, just as with a pressure gradient. However, as shown by Youngquist and Liao, stationary solenoids are still able to create a magnetic field gradient since their strength lessens with distance. Furthermore, by pulsing the stationary solenoid, a time-varying gradient is induced and can also be used for position control of the magnetic fluid.
1.2.5 Magnetoviscosity

Viscosity is adherent with fluid motion and can be calculated through its stress and strain rates. The normal and tangential surface force on a differential element due to thermodynamic pressure can be found through a divergence of the stress tensor. Likewise, magnetic force can be found through the divergence of Maxwell stress tensor, but its associated viscosity is much more complicated.

Molecular or microscale magnetic particles in a paramagnetic fluid align with the applied field, and can induce additional shear as a function of the strength of the field. When aligned, the magnetic torque helps the particles resist rotation, thereby disrupting fluid flow. The magnetoviscous effect is heavily studied for ferrofluids, but questions remain for the case of a pure, paramagnetic fluid like LOX. For the purpose of the current research, LOX is considered as a ferrofluid with angstrom-scale particles, a fill fraction, \( \phi \), of 100%, and a carrier fluid with the same viscosity as non-magnetized LOX. From equations given by Shliomis [34], the full fill fraction approximation leads to a vortex viscosity of 1.5 times the magnetized value, the small diameter and viscosity lead to a nearly infinitesimal Brownian relaxation time, \( \tau \), and their ratio ultimately leads to a very small increase in the effective viscosity from particle alignment,

\[
\beta = \frac{3}{2} \eta \phi, \tag{1-2} 
\]

\[
\tau = \frac{3V\eta}{kT}, \tag{1-3} 
\]

\[
\frac{\Delta \eta}{\beta} = \frac{\mu_0 MH \tau / 4 \beta}{1 + \mu_0 MH \tau / 4 \beta}, \tag{1-4} 
\]
where $\beta$ is the vortex viscosity and $V$ is the particle volume. However, these equations were written for dilute solution and may not be applicable for high concentrations. Furthermore, experiments by McTague [35] have shown that interparticle interactions as well as particle alignment affect the overall viscosity even in dilute solutions. It is also possible that the atomic interactions between particles under a magnetic field generate an increase in the viscosity. The equations above assume particles up to 10,000 times larger than a molecule of oxygen; thus different forces may be at play. Without an adequate theory, the magnetoviscous effect of LOX cannot be declared insignificant or significant until a physical experiment can measure it.

Lastly, use of a high frequency AC field in the magnetic field may actually induce a “negative viscosity” as shown by Bacri [36]. As mentioned, a static or low frequency field will retard flow through particle alignment with the field. In the case of high frequencies, increased fluid motion was observed indicating a reduction in the viscosity. This effect may be desirable or undesirable depending on the intended application.

1.2.6 Magnetic Fluid Pipe Flow

Aside from the influencing the rotational viscosity and particle interactions, the field can have a macroscopic effect on the flow of a magnetic fluid through a pipe. White [37] provides the basic equations for Hagen-Poiseuille pipe flow for various Reynolds numbers. Krekhov [38] found that ferrofluids in pipe flow under the influence of a magnetic field cease to perform as Newtonian fluids due to magnetoviscous interactions. Even without ferromagnetic particles, observations can be made in the bulk flow of magnetic fluid. Cunha [39] studied the laminar flow through a pipe with a nonuniform axial magnetic field with a linear gradient. Of course, when the field gradient was
opposite the flow direction, the fluid was impeded; however, Cunha put attention on the
drag reduction as the field gradient facilitated fluid flow. He characterized the flow by a
magnetic pressure coefficient, $C_{pm}$, representing the ratio of the magnetic to
hydrodynamic pressures in the flow. Cunha correlated his results to a non-magnetic
friction factor relationship of $f = 8/\text{Re}$ and found that as the magnetic effects arise, $f$
reduces. The reduction is more pronounced for higher Reynolds numbers, but the study is
limited to an asymptotic value near $\text{Re} = 50$. Nonetheless, Cunha has shown that as an
axial field in the direction of fluid flow increases, drag on the walls decreases.

Fig. 1.8. Streamline patterns for magnetic fluid flow in a tube with (a) $\text{Re}_m = 10^3$
and $R = 0$ (no viscosity variance with field); (b) $\text{Re}_m = 10^3$ and $R = 1$; (c) $\text{Re}_m =
10^5$ and $R = 1$; and (d) $\text{Re}_m = 1.225 \times 10^6$ and $R = 3.5$, taken from Chen.
However, an axial field with a linear gradient is not simple to reproduce in a laboratory experiment. Instead, Chen [40] applied a ring magnet and focused on the streamlines for magnetic fluid flow in a tube as the field and magnetoviscous response varied. Fig. 1.8 shows the difference in the patterns as the magnetic Reynolds number, $R_{em}$, and a viscosity parameter, $R$, proportional to the magnetoviscous response vary.

The field was applied by a ring magnet at $z = 0$, but of undisclosed length or gradient. Study of the axial velocity profiles at various locations shows that an adverse gradient occurs even without a magnetoviscous influence. This indicates that even if the viscosity of LOX does not increase with a magnetic field, fluid damping still increases due to flow circulation.

Schlichting [41] gives the classical solution of oscillating flow through a pipe, but the presence of a magnetic field and the finite slug length complicate the analysis for the current study. For the case of an infinite slug without a magnetic field, the shear could be doubled during oscillations; it is expected that the augmentation would be greater with the magnetic field and finite slug.

1.2.7 Hydrodynamic Breakdown

The free surface of a liquid slug does not pose the same stability as a solid. The basic equations of motion indicate that a limit exists on the pressure differential on either side of the slug and is proportional to the strength of the applied magnetic field. The equations were verified through static experiments performed by Perry and Jones [42]. By suspending a ferrofluid slug between poles of an electromagnet, measurements could be made while increasing the pressure on one side of the slug. Fig. 1.9 shows the experimental setup and eventual failure mode.
In the experiment, forces due to capillarity and magnetism held the slug in place while force due to pressure attempted to displace it. Bashtovoi [43] showed that capillary effects are reduced under the influence of a magnetic field and, thus, are not included in the theoretical equations. Nonetheless, the experiment correlated well to prediction because it focused on a hydrostatic breakdown of the liquid slug. For the current study in which the slug will be in motion, the breakdown will instead be hydrodynamic and may have influencing factors due to a combination of the uneven force distribution along the slug, internal flow dynamics, gravity, and low surface tension of LOX. The phenomena related to a hydrodynamic breakdown may not be simply explainable, but under consistent experimental operations, the point of breakdown should also be consistent.

Fig. 1.9. Detail of a ferrofluid slug or plug showing failure mechanism, taken from Perry and Jones.
1.2.8 Conclusions of Literature Review

From the literature review described in this chapter, certain conclusions can be drawn which form the scope of the current study:

- A niche exists for space systems which can replace mechanically moving parts to increase reliability and lifetime.
- Current technologies which form the basis for systems with no moving parts perform well under specific conditions but must sacrifice lifetime, capability, applicability, efficiency, or a combination thereof for their method of operation.
- Magnetic fluid technology could theoretically be used to develop a system with no moving parts that satisfies all of the above conditions.
- Ferrofluids have found many practical applications in environments where the carrier fluid remains stable and does not boil or freeze.
- Liquid oxygen could potentially be used to expand magnetic fluid technology to the cryogenic realm due to its high natural paramagnetic susceptibility.
- Before advanced research can begin, basic studies and experiments are required to fully understand the depth of the technology.
- The fluid and thermal properties of liquid oxygen without a magnetic field present are well understood.
- Liquid oxygen has not been sufficiently studied as a working fluid for magnetohydrodynamic purposes.
- Ferrofluid pumps have been designed and built, thereby confirming theoretical equations of motion and setting a benchmark for comparison.
• Magnetoviscous interactions in LOX occur differently than in ferrofluids, but must be considered during testing.

• Studies on magnetic pipe flow show that flow damping may occur even if magnetoviscous effects are negligible.

• A hydrodynamic breakdown will limit the performance of a liquid slug.

• The point of hydrodynamic breakdown should be consistent with respect to the applied magnetic field and operating conditions.

• Basic experiments on liquid oxygen will be useful in obtaining an early assessment of the capability of a LOX-based magnetic fluid system.

• Basic experiments on liquid oxygen will be useful in determining the unknown effects due to magnetoviscosity, hydrodynamic breakdown, and other unforeseen parameters.

• Basic experiments on liquid oxygen will be useful in setting high level design guidelines for advanced research.

1.3 References


CHAPTER 2

EXPERIMENTAL STUDIES OF THE PRESSURES GENERATED BY
A LIQUID OXYGEN SLUG IN A MAGNETIC FIELD

This chapter is a paper published as a journal article in the Journal of Magnetism and Magnetic Materials (Volume 322, Issue 13, pp. 1752-1757, July 2010). All permissions to using this paper as a part of this dissertation are contained in the Appendix.

2.1 Abstract

The strong paramagnetic susceptibility of liquid oxygen (LOX) has established it as a good candidate for a cryogenic magnetic fluid system. While its properties have been known for several decades, a fundamental understanding of the behavior of LOX in a magnetically controlled fluid system is needed for the development of a suitable space application that can operate reliably and efficiently. This study conducted quantitative experiments on the dynamics of a LOX slug in a tube when subjected to electrically-induced magnetic fields within a solenoid. The experiments used a quartz tube with an inner diameter of 1.9 mm and LOX slugs of 0.6, 1.3, 1.9, 2.5, and 3.2 cm length at various initial positions relative to the solenoid. The pressures generated by the motion of the LOX slug under the magnetic force were recorded to characterize the pressure differential generated and the breakdown of the slug. The highest attainable pressure differential was found to be 1.45 kPa, which correlated well to theoretical predictions once the analysis accounted for the resistance heating of the solenoid. The noted differences between experimental results and theory could also be attributed to impeded
slug motion from shear and mass forces. Within the workable pressure range, however, an optimal slug length was found which appropriately balances the pressure, shear, and magnetic forces in the system. This paper presents the experimental data on the dynamics and the maximum pressure differential generated by a LOX slug in a magnetic field and discusses the viability of LOX in a magnetic fluid management system intended for space applications.

2.2 Introduction

Historically, the majority of research on magnetic fluids has focused on ferrofluids, a colloidal suspension of ferromagnetic nanoparticles in some type of carrier fluid. The practical application of ferrofluids has been proven and has found many industrial uses in areas such as audio speakers, digital data storage, and resonance imaging. Many theoretical ideas about ferrofluids as a working fluid have become textbook material as shown by Rosensweig [1] and Odenbach [2]. In the medical and computer industries, the works of Seo and Park [3], Krauss and Liu [4], Liao and Chen [5], and Hatch and Kamholz [6] have turned concept into reality. Each of these investigators has successfully created an actuator that used magnetic fields only to propagate a liquid slug made up of artificial ferrofluids. But while these artificial ferrofluids have customizable qualities, their applicability in space is severely limited due to harsh environmental constraints, such as cryogenic temperatures and outgassing.

Liquid oxygen (LOX), on the other hand, represents a pure paramagnetic fluid. Unlike ferromagnetic fluids that rely on magnetic particles, a pure fluid eliminates inherent risks associated with a colloidal fluid, such as corrosion and shock. As a
paramagnetic substance, oxygen follows Curie’s Law, explaining why LOX, at cryogenic temperatures, has an appreciable magnetic susceptibility. The use of LOX as a magnetic fluid for transport applications via direct interaction with an electromagnetic field in space systems is ideal because LOX is already commonly used for life support, thermal management, and propulsion in space applications. A LOX-based magnetic fluid system could potentially eliminate mechanically moving parts in selected space applications thereby increasing the reliability and robustness of satellite subsystems.

However, current knowledge of LOX behavior in a fluid system controlled by a magnetic field is very limited. Results from experiments by Catherall [7-8] on the magneto-Archimedes levitation and corrugation instabilities of LOX showed that it would be very useful for mineral separation, particularly on the lunar surface, but did not explore the feasibility of LOX as a working fluid in a magnetically-driven system. Youngquist [9] performed the only quantitative experiments found on the magnetohydrodynamics of LOX. With an open-ended U-tube, he measured the displacement of one end of a column of LOX, while the other was pulsed by a solenoid. The study successfully proved the viability of displacing LOX with a magnetic field, but further research was required to establish a fundamental understanding and modeling capability before any technology development could occur. The current study focuses on the dynamics and attainable pressure differential of a LOX slug in a piping system. The experimental study used a horizontal test section with a small slug of LOX, rather than a U-tube with a long column. The horizontal test section eliminates gravitational influence on the one-dimensional dynamics, and, by using a slug, the entire volume of LOX is affected by the magnetism.
In addition, the range of applications for any magnetic fluid is limited by hydrostatic or hydrodynamic breakdown. If the magnetic force that drives the working fluid is overcome by pressure, a surface instability occurs and destroys the slug. Although LOX has the highest known susceptibility of pure fluids, it can be 30 times weaker than an inexpensive ferrofluid. This study intended to determine the viability of LOX in a magnetic fluid system through experimental tests of the maximum attainable pressures for various conditions.

2.3 Theory

Rosensweig [1] provided a very thorough treatment of the theory behind magnetic fluid dynamics. Zahn [10] and Mao [11] presented numerical analyses focusing on ferrofluid pumping using a time-varying magnetic field. The governing equations of motion of LOX are the Navier-Stokes equations with an additional term for the magnetic force, the Kelvin force. The Kelvin force density, $f_m$, can be found through the divergence of the Maxwell stress tensor as a function of the permeability of free space $\mu_0$, the magnetization vector $M$, and magnetic field $H$ as

$$f_m = \mu_0 (M \cdot \nabla) H.$$  \hspace{1cm} (2-1)

In the linear portion of the Langevin function, volumetric magnetic susceptibility $\chi$ is the ratio of the magnetization vector to the applied field vector, $\chi = \frac{M}{H}$.

By substituting for $M$, using the vector identity, $H \cdot \nabla H = V(H \cdot H)/2 - H \times (\nabla \times H)$, and noting that Ampere’s Law cancels out the curl of the applied field, Eq. (2-1) can be reduced to

$$f_m = \mu_0 \chi \nabla^2 H^2 / 2.$$  \hspace{1cm} (2-2)
With a constant temperature, the relative permeability, $\mu$, also remains constant. The relative permeability is the ratio between the magnetic flux density, $B$, and applied magnetic fields, $\mu = B / H$, which can also expressed in terms of volumetric susceptibility, $\mu = \mu_0 (1 + \chi)$.

Given these relations, the Kelvin force density is

$$ f_m = \frac{1}{2\mu_0} \frac{\chi}{(1 + \chi)^2} \nabla B^2. \quad (2-3) $$

The force in the axial direction is

$$ f_{m,x} = \frac{1}{2\mu_0} \frac{\chi}{(1 + \chi)^2} \frac{d}{dx} B_x^2; \quad (2-4) $$

where the subscript $x$ denotes the axial direction.

The differential term considers the ends of the slug, and when Eq. (2-4) is integrated over the entire volume with a one-dimensional approximation, the force due to magnetism in the axial direction $F_M$ is

$$ F_M = \frac{\pi a^2}{2\mu_0} \frac{\chi}{(1 + \chi)^2} (B_{x,US}^2 - B_{x,DS}^2); \quad (2-5) $$

where $a$ is the tube radius and the subscripts $US$ and $DS$ denote the upstream and downstream directions.

For one-dimensional motion of the slug, shear along the walls acts as the primary damping force. Shear is directly related to viscosity, which fluctuates with a magnetic field. As the field is increased, the fluid flow is damped, as investigated by Chen [12]. Although further research is required to study the magnetoviscous effects of LOX, it can be declared that the shear has a significant impact on the flow dynamics.
Thus, with the forces due to pressure, magnetism, and shear, the equation of motion for the LOX slug becomes

\[
m\ddot{x} = \pi R^2 \Delta p + \frac{\pi R^2}{2 \mu_0} \left( \frac{\chi}{1 + \chi^2} \right)^2 (B_{x,US}^2 - B_{x,DS}^2) + 2\pi R L \tau_w,
\]

(2-6)

where \( m \) is the mass of the slug, \( \ddot{x} \) is the acceleration, \( \Delta p \) is the pressure differential across the slug, \( L \) is the length of the slug, and \( \tau_w \) is the shear stress on the walls. This one-dimensional force balance assumes that the finite-length slug is an incompressible solid and does not account for surface tension, instabilities, or breakdown of the slug. Bashtovoi [13] points out that capillary effects are reduced under the influence of a magnetic field and are thus considered negligible. Nonetheless, experiments by Perry [14] confirmed the theoretical predictions of ferrohydrodynamic breakdown as a balance of the magnetic and pressure forces. Beginning with the magnetic Bernoulli equation, the maximum pressure a slug can withstand can be predicted through the fluid’s magnetic susceptibility and magnetic flux density at the slug’s edges as

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

(2-7)

Perry was able to use the above equation to predict when a hydrostatic breakdown would occur. If the force from the pressure differential across the slug exceeds the magnetic force, a failure channel opens, allowing gas to pass through the slug. The correlation of experiment to theory in Perry’s study implies that surface tension did not play a major role in the hydrostatic breakdown of his experiments, while the slug length was an important factor. Although the current experiment actually tests the hydrodynamic
breakdown, Eq. (2-7) still describes the maximum pressure differential the slug can withstand and is a valid starting point for estimating the theoretical limits of capability.

2.4 Experiment

An apparatus was designed to displace a slug of LOX via electrically-pulsed solenoids as shown schematically in Fig. 2.1. With helium as the surrounding gas in a closed volume, an isothermal ideal gas compression assumption was used as long as the slug did not break down. Fig. 2.1 shows that as the slug moved to the right (considered hereafter as “upstream”), the downstream volume ($V_{DS}$) increased and upstream volume ($V_{US}$) decreased, causing a reciprocal reaction for the downstream and upstream pressures ($P_{DS}$ and $P_{US}$). The pressure fluctuations could be used to measure displacement, while also being used to characterize the performance of LOX through its response to specific test parameters.

The test section was composed of a quartz tube with an inner diameter of 1.9 mm and a solenoid capable of producing up to 1.1 T with a Hewlett-Packard 6268B 900 W DC power supply. As the solenoid was powered, the resistance heating reduced the

![Fig. 2.1. Schematic of the LOX slug displacement in a closed system.](image-url)
available current over time, thus limiting runs to 0.25 s each. The test section and total system plumbing can be seen in Fig. 2.2. The test section and condenser were completely submerged in liquid nitrogen to mitigate thermal acoustic oscillations. Therefore, the temperature condition for the entire experiment can be considered as the saturation temperature of liquid nitrogen under the atmospheric condition, or ~77 K as measured in the experiment. Helium acted as the surrounding gas for the LOX slug due to its low boiling point and because it is unreactive to oxygen. The total system volume was 337 cm³, although only about 1.8 cm³ was downstream of the test section, allowing for high-pressure changes when the slug was displaced. Kulite CT-375 pressure sensors upstream and downstream of the LOX slug in the test section recorded data at 5 kHz with a 0.17 kPa resolution. The operating pressure was maintained between 100–135 kPa to maintain safe operating levels. The LOX slug formed a concave meniscus and the edges were measureable within 0.8 mm resolution via notches on the quartz tube.

![Fig. 2.2. Photograph and CAD drawing of experimental apparatus.](image-url)
Prior to each test, the length of the slug and its initial position relative to the solenoid were recorded. Tests were carried out at various positions for 0.6, 1.3, 1.9, 2.5, and 3.2 cm slugs and for various currents for the 1.3, 1.9, and 2.5 cm slugs.

2.5 Results and Discussion

The magnetic field gradient is determined by the shape of the solenoid and amount of current; thus it must be determined in order to interpret the experimental results. Using the Biot–Savart Law, the magnetic flux density along the axis of the solenoid can be calculated as shown in Fig. 2.3 for an applied current of 23 A. The initial position of the center of the slug was recorded relative to the center of the solenoid and then power was switched on for 0.25 s. Fig. 2.4 shows a typical run profile and the current drop while the solenoid was powered. The peak differential pressure generated was recorded and plotted versus the initial position of the slug. Note that the current at the time the pressure peaked was less than 23 A.

![Magnetic flux density along axis of solenoid.](image)
Figs. 2.5 – 2.6 show the maximum pressure differential generated as the initial positions of the centers of the 0.6, 1.3, 1.9, 2.5, and 3.2 cm slugs were varied about the solenoid. The horizontal axis represents the relative difference between the center of the slug and the center of the solenoid, and the vertical axis represents the maximum pressure differential generated in the downstream section. So, if the center of the slug was to the left of the solenoid, the magnetic force moved the slug to the right causing an expansion in the downstream section (left side of the slug). This would therein cause a negative pressure differential as recorded by the downstream pressure sensor. In Figs. 2.5 – 2.6, the error bars represent the 0.8 mm measurement uncertainty of the edge of the slug.

Each plot indicated the same trend as the slug position varied. If the relative initial position of the slug was zero, it was already centered on the solenoid and did not move when the power was pulsed. As the initial position of the slug moved away from zero, the
maximum pressure generated increased. This is similar to increasing the stroke of a piston. The slope of the curve in Figs. 2.5 – 2.6 reaches a peak when one of the edges of the slug is near the edge of the solenoid, the area where the magnetic field gradient is
highest. The slug broke down when pressure greater than the limits of the magnetic force was generated.

The breakdown was apparent through the pressure data as well as visually in the experiment, since the slug broke up into several smaller slugs. For a flux density of 1.1 T and the volumetric susceptibility of LOX at 77 K, 0.0042, the breakdown pressure would have been 1.95 kPa, based on Eq. (2-7), for a slug with one edge centered and one in the near zero region of the field. However, as shown in Fig. 2.4, the current dropped due to resistance heating by the time the pressure peaked. The current at the time of the peak was approximately 19.5 A, correlating to a breakdown pressure of 1.45 kPa; thus, the experimental data matched well with the calculation using Eq. (2-7), regardless of the fact that Eq. (2-7) only predicts the maximum magnetic force of a static slug and does not include the fluid properties, such as surface tension, cohesion, contact angle, and viscosity.

While Perry’s experiments [14] implied that surface tension is not a factor in the case of a hydrostatic breakdown, the hydrodynamic case is clearly more complicated. It is believed that the breakdown occurs due to a combination of the uneven force distribution along the slug, pressure differential about the slug, gravity, and low surface tension of LOX. The velocity of the slug and internal flow dynamics may influence the breakdown in tests which drive the slug more rapidly, but, for the current study, the maximum Reynolds number was less than 1500. Further study is required to fully understand the mechanism of the breakdown, but, nonetheless, the static theory can be used to estimate the breakdown pressure, even in the dynamic process of this experiment. Figs. 2.5 – 2.6 also show that the slug breaks down at a lower pressure in expansion than in
compression. This is consistent with the understanding of force distributions at each end of the slug and may also be related to differences between the advancing and receding contact angles in the magnetic field. Further experiments must be conducted to study these instabilities.

Regarding the effect of the slug length, it can be seen that the point at which the breakdown occurred increased with respect to relative distance to the solenoid; however, the pressure at which it occurs does not vary significantly except for the 0.6 cm slug. This is again consistent with Eq. (2-7) because the edges of the 0.6 cm slug do not reach the near zero region of the field and remain in the high-gradient region, whereas the field gradient is very low for the edges of the longer slugs. But, as seen in Eq. (2-6), a longer slug is associated with additional shear and extra mass which reduces the efficiency of the pulses. Thus, an optimal length that balances the magnetic, pressure, and shear forces would be just long enough to reach the near-zero region of the magnetic field, but not so long that it retards slug motion. The data appear to show that this optimal length exists near 1.3 cm.

Each of the runs presented in Figs. 2.5 – 2.6 was performed with an initial current of approximately 23 A. However, resistance heating of the solenoid coils reduced the current over time and the field was not as strong by the time the pressure peaked. Fig. 2.7 shows the maximum pressure differential generated versus current at the time the pressure peaked for the 1.3, 1.9, and 2.5 cm slugs for various current levels. The variation between the lengths seems to have a negligible effect on the pressure differential for the current range explored; however, at higher currents, the differences may become more apparent. As more amperage is supplied to the solenoid, the shape of the curve in Fig. 2.3
changes and the optimum slug length increases. Since very large amounts of current may be required for a small difference, a more efficient method of changing the shape of the curve would be to change the solenoid geometry.

Eq. (2-7) also indicates that the trend in Fig. 2.7 should be quadratic; instead, it appears linear. This is, again, likely due to the limited heat capacity of the solenoid, the transient nature of the data taken, and the resistance heating. At high current levels, the solenoid may not stay cool long enough to generate high pressures, even during the 0.25 s pulse.

2.6 Conclusions

The experiments performed have given valuable insight as to the viability of LOX as a magnetic working fluid. Primarily, the slug is able to generate a pressure differential controlled by a solenoid and can be optimized for specific system parameters, as long as
it does not approach the breakdown point. The pressure differential generated by a slug is very sensitive to the slug’s initial position, but is predictable in expansion and compression. The optimal slug length is long enough to reach an appreciable difference in the magnetic field, but does not unnecessarily add mass and shear. The highest attainable pressure differential generated was 1.45 kPa with a 1.3 cm slug with one edge centered in the solenoid. This differential is consistent with theory once the reduced current from resistance heating is factored into the calculations. Within the workable pressure range, the slug and solenoid system act adequately as a fluid driver and could potentially be paired with other solenoids, as in other traveling wave, ferrofluid pump designs. The maximum attainable pressure differential is proportional to the applied current, but, unless a significant amount of power is available, the low susceptibility of LOX limits its applicability to low pressure systems. For space systems where power loads are very limited, high currents may not be available and alternate measures or methods to utilize the magnetic susceptibility of LOX may be required.

2.7 References


This chapter is a paper published as a journal article in Cryogenics (doi:10.1016/j.cryogenics.2010.03.004). All permissions to using this paper as a part of this dissertation are contained in the Appendix.

3.1 Abstract

This study presents the theoretical basis for the dynamics of a slug of liquid oxygen in a quartz tube when displaced by a pulsed magnetic field. The theoretical model calculated slug movement by balancing the forces due to magnetism, pressure, and damping and was verified with experimental data for a slug 1.3 cm long and 1.9 mm in diameter. During the experiments, the hidden slug length and damping factor were unknown, but quantifiable through the numerical solution. The hidden slug length accounted for the mass of LOX which cannot be seen during the experiment and was calculated as 10–14.5 cm. The damping factor was an empirical augmentation to represent increased damping from various phenomena and was calculated as 5.76–6.3. The experiments generated damped pressure waves of 6-8 Hz with maximum amplitudes of 0.8–1.3 kPa. Outside these ranges, the model indicated that the oscillation frequency decreased logarithmically with the hidden slug length, and the maximum amplitude decreased logarithmically with the damping factor. Measurement uncertainties of the visible length and slug initial position (0.8 mm) were also evaluated for their effects on the frequency and amplitude of the oscillations. The visible slug length did not seem to
significantly affect the pressure waves, but the initial position strongly altered the amplitudes and mean of the oscillations. The predictive model matched the experiment well and could be used to design advanced flow control systems for cryogenic applications.

3.2 Introduction

Magnetically responsive fluids have found application in various industrial areas, such as audio speakers, digital data storage, and resonance imaging, but their effectiveness is limited in low-temperature applications. The most researched type of magnetic fluids, ferrofluids, are colloidal suspensions of ferromagnetic nanoparticles in a carrier fluid typically made up of water, kerosene, or some type of oil. Rosensweig [1] and Odenbach [2] provide thorough basic research on ferrofluids, and Park and Seo [3–5], Krauss and Liu [6], Liao and Chen [7], and Hatch and Kamholz [8] have each built and tested prototypes for ferrofluid actuators. These prototypes, however, are limited by the freezing point of the carrier fluid.

Curie’s Law dictates that paramagnetic susceptibility increases as temperature decreases. For low-temperature applications, liquid oxygen (LOX) represents a pure paramagnetic fluid and is worthy of consideration as the working fluid. The lack of particles in the flow mitigates risks such as corrosion and electric shock, thereby increasing the lifetime of the actuator. Furthermore, the use of LOX in a magnetic fluid system in space is desirable, because it is already commonly used there in life support, thermal management, and propulsion systems. The basic research and theories supplied by Rosensweig [1] and Odenbach [2] are applicable to LOX, but quantitative
comparisons to experiments are limited. An experiment by Youngquist and Immer [9] measured the displacement of one edge of a column of LOX in an open-ended U-tube, while the other end was pulsed with a solenoid. A numerical method was created to simulate the results but did not factor in experimental uncertainty and was, therefore, considered non-optimized.

Experiments have also been performed by the authors on a slug of LOX inside a horizontal tube, and the maximum pressure changes achievable under various conditions were reported [10]. While much data is gained from these experiments, a numerical solution would provide design and performance evaluations without extensive and complicated laboratory work. A theoretical model has been developed to simulate the oscillations of the aforementioned slug when pulsed by a magnetic field, thereby giving introspect to the maximum velocities and pressures attainable before a hydrostatic breakdown occurs [11].

A simplified theoretical model was developed with a numerical solution method and verified by experimental data. A LOX slug of 1.3 cm length and 1.9 mm diameter was displaced by a pulsed magnetic field to generate pressure oscillations with frequencies of about 6–8 Hz and maximum amplitudes of about 0.8–1.3 kPa. The model calculated the magnetic and pressure forces and approximated the damping force through the collective influence of phenomena that could not be measured in experiments. The effects due to hidden slug length, damping factor, and measurement uncertainty were studied to estimate the adequacy of the model. The residual resulting from the variance of these three factors was used as a quantitative measure to match the experimental data and was minimized during an optimization routine. Their effect on the frequency and
amplitude of the oscillations was also determined to estimate the effectiveness of the model as a design tool.

3.3 Experiment Description

3.3.1 Test Concept

The test concept can be seen schematically in Fig. 3.1 with the slug in the initial position for an expansion test. When the solenoid power was switched on, the slug was pulled to the center of the solenoid, causing an expansion in the downstream side (the left side of Fig. 3.1) and a compression in the upstream side (the right side of Fig. 3.1). Note that not all of the upstream section is shown in Fig. 3.1. With helium as the surrounding gas in the closed volume, an isothermal ideal gas compression assumption could be used as long as the slug did not break down. As the slug moved upstream, the downstream volume \( V_{DS} \) increased and upstream volume \( V_{US} \) decreased, causing an inverse reaction for the downstream and upstream pressures \( P_{DS} \) and \( P_{US} \). The pressure fluctuations could be used to measure displacement, and also to characterize the performance of LOX through its response to specific test parameters.

Oxygen was introduced to the system as a gas at room temperature. Once submerged in liquid nitrogen, the gas condensed into LOX droplets and fell from the

![Fig. 3.1. Schematic of the LOX slug displacement in a closed system.](image-url)
condenser into the horizontal section of the plumbing. At this point, a magnetic wand was used to drag portions of the LOX into the transparent quartz tube to form a 1.3 cm slug; however, additional LOX remained in the steel sections. The mass of LOX that could not be seen was characterized as the hidden slug length and was seen to have a direct effect on the frequency of the oscillations. Because the temperature, pressure, and radius of the steel section were the same as the of quartz tube, the hidden slug length could be precisely calculated.

3.3.2 Apparatus and Procedures

The test section was composed of a quartz tube with an inner diameter of 1.9 mm

Fig. 3.2. Photograph and CAD drawing of experimental apparatus.
and a solenoid capable of producing up to 1.1 T with a Hewlett–Packard 6268B 900 W DC power supply. As the solenoid was powered, the resistance heating reduced the available current over time, thus limiting runs to 0.25 s each. The test section and total system plumbing is seen with a support structure outside of the liquid nitrogen bath in Fig. 3.2. Note that Fig. 3.2 shows that two solenoids were installed on the quartz tube as a matter of system redundancy in case one of them overheated and melted its insulation, making it no longer useful.

The test section and condenser were completely submerged in liquid nitrogen to mitigate thermal acoustic oscillations; therefore, the temperature of the entire experiment can be taken as the saturation condition of liquid nitrogen at atmospheric pressure, or ~77 K as measured in the experiment. Helium acted as the surrounding gas for the LOX slug due to its low boiling point and because it is unreactive to oxygen.

Kulite CT-375 pressure sensors located upstream and downstream of the slug in the test section recorded data at 5 kHz with infinitesimal resolution and a combined uncertainty of 0.17 kPa from the effects of nonlinearity, hysteresis, 16-bit analog-to-digital conversion errors, and repeatability. Because the changes in the upstream and downstream pressures were the desired output, the absolute pressure and the measurement uncertainty were not influencing factors. The noise in the raw data was reduced by using a Chebyshev Type II lowpass filter, which was set to 0 dB at 45 Hz and –40 dB at 50 Hz. To amplify the pressure oscillations, a small volume of the downstream section was required. With a downstream volume of 1.8 cm³ and an upstream volume of 337 cm³, the downstream pressure fluctuations were approximately 180 times greater than the upstream fluctuations for the experiment’s run; thus, the data from the
downstream pressure sensor were used for comparison to the numerical solution. The large upstream volume enabled safe pressure levels when filling as a gas at ambient temperatures. The operating pressure was maintained between 100 and 135 kPa to maintain safe operating levels. The LOX slug formed a concave meniscus, and the edges were measureable within 0.8 mm resolution via notches on the quartz tube. Compression tests were conducted at 40 V and 30 V, and an expansion test was conducted at 40 V. All tests used a 1.3 cm slug with one end at the center of the solenoid.

3.4 Theory

Complex analytical methods were developed by Zahn and Greer [12] and Mao and Koser [13] for sinusoidal time-varying magnetic fields, but for steady, single-pulse dynamics, the numerical application of the theoretical basis can be greatly simplified. The governing equations of motion of LOX are the Navier–Stokes equations with an additional term for the magnetic force, the Kelvin force. The Kelvin force density, $f_m$, can be found through the divergence of the Maxwell stress tensor as a function of the permeability of free space $\mu_0$, the magnetization vector $M$, and magnetic field $H$ as

$$f_m = \mu_0 (M \cdot \nabla)H .$$

In the linear portion of the Langevin function, volumetric magnetic susceptibility $\chi$ is the ratio of the magnetization vector to the applied field vector, $\chi = M / H$. By substituting for $M$, using the vector identity, $H \cdot \nabla H = \nabla (H \cdot H)/2 - H \times (\nabla \times H)$, and noting that Ampere’s Law cancels out the curl of the applied field, Eq. (3-1) can be reduced to

$$f_m = \mu_0 \chi \nabla H^2 / 2 .$$
With a constant temperature, the relative permeability, $\mu$, also remains constant. The relative permeability is the ratio between the magnetic flux density, $B$, and applied magnetic fields, $\mu = B / H$, which can also expressed in terms of volumetric susceptibility, $\mu = \mu_0(1 + \chi)$.

Given these relations, the Kelvin force density is

$$f_m = \frac{1}{2\mu_0} \frac{\chi}{(1 + \chi)^2} \nabla B^2. \quad (3-3)$$

The force in the axial direction is

$$f_{m,x} = \frac{1}{2\mu_0} \frac{\chi}{(1 + \chi)^2} \frac{d}{dx} B_x^2; \quad (3-4)$$

where the subscript $x$ denotes the axial direction.

The differential term considers the ends of the slug, and when Eq. (3-4) is integrated over the entire volume with a one-dimensional approximation, the force due to magnetism in the axial direction, $F_M$, is

$$F_M = \frac{\pi a^2}{2\mu_0} \frac{\chi}{(1 + \chi)^2} (B_{x,US}^2 - B_{x,DS}^2); \quad (3-5)$$

where $a$ is the tube radius and the subscripts $US$ and $DS$ denote the upstream and downstream directions. The magnetic flux density generated by the solenoid is found by summing the contribution of each loop. The magnetic flux density from an individual loop of wire is

$$B_{x,loop} = \frac{I(t)}{4} \mu \mu_0 r_{loop}^2 \left(r_{loop}^2 + dx^2\right)^{3/2}. \quad (3-6)$$
where $r$ is the radius of a single loop of coil, $I(t)$ is the applied current over time, the subscript \textit{loop} denotes a single loop of the coil, and $dx$ is the axial distance from that loop.

For the one-dimensional motion of the slug, shear along the walls acts as the primary damping force. The shear is directly related to viscosity, which, for a magnetic fluid, is a function of the strength of the field. Furthermore, Chen and Hong [14] showed that fluid damping increases with magnetoviscous effects not only because of increased shear, but also because of increased internal flow rotations induced by proximity of the magnetic fluid to a ring magnet. Although further research is required to fully understand the magnetoviscous effects of LOX, its impact on the flow dynamics are still worthy of consideration in the current study. Outside of magnetic effects, the internal flow dynamics are also influenced by the slug’s oscillatory flow in the tube and its complicated internal flow rotations from the slug’s finite length. Both these factors resist the formation of a boundary layer along the tube wall and attribute to the retardation of slug movement. To accommodate all these unknown phenomena, a damping factor, $\zeta$, was used. The damping factor is an augmentation of the viscosity of non-magnetized LOX at test conditions and is used in an approximation of the damping force for fully developed laminar pipe flow. The classic relation for laminar wall shear stress in Hagen–Poiseuille flow as given by White [15] and the force due to damping, $F_D$, can be found as

\begin{equation}
\tau_w = 4\dot{x}\zeta \eta / a; \quad (3-7)
\end{equation}

\begin{equation}
F_D = 2\pi a L \tau_w; \quad (3-8)
\end{equation}

where $\tau_w$ is the wall shear stress, $\eta$ is the non–magnetized dynamic viscosity of LOX, $L$ is the length of the slug, and $\dot{x}$ is the velocity of the slug in the axial direction.
The pressure force, $F_p$, results from the differential pressure on either side of the slug as

$$F_p = \pi a^2 \Delta p.$$  \hspace{1cm} (3-9)

where $\Delta p$ denotes the pressure differential across the slug. The change in pressure results from the closed volumes on either side of the slug being compressed and expanded.

Thus, with the forces due to pressure, magnetism, and damping, the equation of motion for the LOX slug becomes

$$m\ddot{x} = \pi a^2 \Delta p + \frac{\pi a^2}{2\mu_0 (1 + \chi)} \left( B_{x,LS}^2 - B_{x,DS}^2 \right) + 2\pi aL\tau_w;$$  \hspace{1cm} (3-10)

where $m$ is the mass of the slug and $\ddot{x}$ is the acceleration. This one-dimensional force balance assumes that the finite-length slug is an incompressible solid and does not account for surface tension, instabilities, or breakdown of the slug. Bashtovoi and Kuzhir [16] points out that capillary effects are reduced under the influence of a magnetic field and are thus considered negligible.

The one-dimensional approximation also treats the slug as an incompressible fluid; thus the mass conservation equation becomes

$$\frac{\partial \tilde{x}}{\partial x} = 0;$$  \hspace{1cm} (3-11)

however, the equation is ingrained in the rigid body approximation and does not need to be calculated separately.

3.5 Numerical Simulation

The governing equation of motion for the one-dimensional dynamics of the liquid slug (3-10), was solved numerically with initial and boundary conditions from
experiments. The numerical simulation was written in Matlab v7.6.0 (R2008a) on a 2.4 GHz Pentium 4 processor with 2 GB of RAM. The single-pulse dynamics were typically solved in less than 2 s, allowing for a thorough optimization of system variables through a regression analysis. The constants used in the numerical model can be seen in Table 3.1.

Fluid properties for LOX were taken from the CRC Handbook of Chemistry and Physics [17], and studies by Hilton and Van Sciver [18] indicated that the pressure fluctuations would not significantly affect those values. Geometric and solenoid parameters were based on measurements made of the experimental apparatus.

As shown by Eq. (3-6), the magnetic flux density was proportional to the applied current, which was dependent on the temperature of the solenoid over time. Eqs. (3-12)-(3-15) calculated the solenoid temperature and current over time.

\[ R_i = R_0 \left( I - \alpha (293 - T_{i-1}) \right) \]  
\[ I_i = \frac{V}{R_i} \]  
\[ P_i = I_i^2 R_i \]  
\[ T_i = T_{i-1} + \frac{P_i}{m_{sol} c_p \Delta t} \]

where \( R \) is the resistance of the solenoid, \( T \) is the temperature of the solenoid, \( P \) is the electrical power, the subscript \( i \) denotes the time step, and the subscript \( 0 \) represents the initial value.

Next, the position of the slug had to be determined according to the velocity and net force from the previous time step. Because extra LOX existed in the steel sections of the plumbing, additional mass had to be considered in the dynamics.
where $F_T$ is the total force from the previous time step with an initial value of zero.

The hidden slug length represented the unknown portion of LOX that was not visible through the quartz tube, but still influenced the oscillations. The hidden slug length was found empirically through an optimization routine. Since the volume of helium between the visible and hidden slugs was small compared to the upstream and downstream volumes, it was considered rigid; thus, the hidden slug moved with the visible slug, adding only mass and shear.

The initial velocity and net force on the slug were considered negligible since the slug was at rest. The center of the solenoid was considered as the origin, and positive displacement was in the upstream direction. With the applied current and position of the slug known, the magnetic flux density and force due to magnetism was found by Eqs. (3-17)-(3-19).

$$\sum_{i}^{(M_{i-1})} \sum_{n=0}^{M_{i-1}} \left[ \frac{(a_{sol} + 2nb\Delta r)^2}{\left[(a_{sol} + 2nb\Delta r)^2 + (x_i - 2mb\Delta x)^2\right]^{3/2}} \right]; \tag{3-17}$$

$$\sum_{i}^{(M_{i-1})} \sum_{n=0}^{M_{i-1}} \left[ \frac{(a_{sol} + 2nb\Delta r)^2}{\left[(a_{sol} + 2nb\Delta r)^2 + (x_i - 2mb\Delta x)^2\right]^{3/2}} \right]; \tag{3-18}$$

$$\frac{\pi a^2}{2\mu_0 (1 + \chi)^2}(B_{s,US,i}^2 - B_{s,DS,i}^2); \tag{3-19}$$

In calculating the magnetic flux density in Eqs. (3-17)-(3-18), the permeability of free space was used instead of the relative permeability of LOX. For these equations, the susceptibility of LOX has a negligible effect even at the liquid–gas interface and can,
therefore, be ignored since it does not influence the motion of the slug. The hidden slug never interacted with the magnetic field and, therefore, was not considered in the magnetic force equations. The force due to pressure, assuming isothermal conditions and using the ideal gas law, was found as

\[
V_{DS,i} = V_{DS,i-1} + (x_i - x_{i-1}) \pi a^2
\]

\[
V_{US,i} = V_{US,i-1} - (x_i - x_{i-1}) \pi a^2
\]

\[
P_{DS,i} = P_{DS,i-1} \frac{V_{DS,i-1}}{V_{DS,i}}
\]

\[
P_{US,i} = P_{US,i-1} \frac{V_{US,i-1}}{V_{US,i}}
\]

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

Finally, the force due to damping was approximated with the damping factor, hidden and visible slug lengths, and the steady state approximation from Eq. (3-7).

\[
Re_i = \frac{2 \rho \dot{x}_{i-1} a}{\zeta \eta}
\]

\[
\tau_{w,i} = \frac{16 \rho \dot{x}_{i-1}^2}{Re_i \frac{Re_i}{2}}
\]

\[
F_{D,i} = 2 \pi a (L + L_{\text{hidden}}) \tau_{w,i}
\]

where \(Re\) is the Reynolds number. None of the oscillations recorded in the experiment exceeded a Reynolds number of 1500; thus the simulation never approached the transition regime. The approximation was for steady-state laminar pipe flow with a smooth wall, but, in the experiment, the flow was actually a finite-length, magnetically responsive, and oscillating slug. Further research is required to determine a complete
analytical solution for the problem without the need for empiricism. The non–magnetized value for the viscosity of LOX is shown in Table 3.1 and was treated as the baseline for comparison.

Together, the pressure, magnetic, and damping forces formed the net force on the slug as

\[ F_{T,i} = F_{p,j} + F_{M,j} - \text{sgn}(\dot{x}_{i-1})F_{D,i}; \]  

(3-28)

where damping was always opposite the direction of velocity. To instigate the next time step, the velocity was found as

\[ \dot{x}_i = \left( \frac{F_{T,i} + F_{T,i-1}}{2 \rho \pi a^2 (L + L_{\text{hidden}})} \right) \Delta t + \dot{x}_{i-1}. \]  

(3-29)

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Value</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \rho )</td>
<td>1204 kg/m(^3)</td>
<td>Density of LOX at 77 K, 1 atm</td>
</tr>
<tr>
<td>( \eta )</td>
<td>277.7 ( \mu )Pa s</td>
<td>Non-magnetized viscosity of LOX at 77 K, 1 atm</td>
</tr>
<tr>
<td>( \chi )</td>
<td>0.0041</td>
<td>Volumetric susceptibility of LOX at 77 K</td>
</tr>
<tr>
<td>( a )</td>
<td>0.95 mm</td>
<td>Inner radius of the quartz tube</td>
</tr>
<tr>
<td>( V_{DS,0} )</td>
<td>1.8 cm(^3)</td>
<td>Initial downstream volume</td>
</tr>
<tr>
<td>( V_{US,0} )</td>
<td>334 cm(^3)</td>
<td>Initial upstream volume</td>
</tr>
<tr>
<td>( R_0 )</td>
<td>7.27 ( \Omega )</td>
<td>Resistance of the solenoid at 293 K</td>
</tr>
<tr>
<td>( \alpha )</td>
<td>0.0039/C</td>
<td>Coefficient of temperature resistance of copper</td>
</tr>
<tr>
<td>( b )</td>
<td>0.255 mm</td>
<td>Wire diameter</td>
</tr>
<tr>
<td>( a_{\text{sol}} )</td>
<td>6.1 mm</td>
<td>Inner radius of the solenoid</td>
</tr>
<tr>
<td>( d_r )</td>
<td>1.19</td>
<td>Wire spacing in the radial direction</td>
</tr>
<tr>
<td>( d_z )</td>
<td>1.3</td>
<td>Wire spacing in the axial direction</td>
</tr>
<tr>
<td>( M_r )</td>
<td>25</td>
<td>Number of turns in the radial direction</td>
</tr>
<tr>
<td>( M_z )</td>
<td>20</td>
<td>Number of turns in the axial direction</td>
</tr>
<tr>
<td>( V )</td>
<td>40 V/30 V</td>
<td>Applied voltage</td>
</tr>
<tr>
<td>( m_{\text{sol}} )</td>
<td>12.4 g</td>
<td>Mass of solenoid</td>
</tr>
<tr>
<td>( c_p )</td>
<td>0.565 J/g K</td>
<td>Specific heat capacity of solenoid</td>
</tr>
<tr>
<td>( \Delta t )</td>
<td>0.0002 s</td>
<td>Time step</td>
</tr>
</tbody>
</table>
To evaluate the fit of each run, the simulated downstream pressure over time was compared to the experimental data from the downstream pressure sensor. The absolute residual, $\delta$, was calculated at each time step as

$$\delta_i = P_{exp,i} - P_{sim,i};$$

where the subscripts $exp$ and $sim$ denote the experiment and simulation data. The simulation as a whole was characterized by the root mean square deviation (RMSD) of the residuals during the pulse period.

$$\delta_{RMS} = \sqrt{\frac{1}{N} \sum_{i=0}^{N} \delta_i^2};$$

where $N$ is the number of data points during the pulse.

3.6 Results and Discussion

The magnetic field gradient is determined by the shape of the solenoid and amount of current; thus, it must be determined in order to interpret the experimental results. Using the Biot–Savart Law, the magnetic flux density along the axis of the

![Fig. 3.3. Magnetic flux density along axis of solenoid.](image)
solenoid was calculated as shown in Fig. 3.3 for an applied current of 23 A, the maximum current achieved for a constant applied voltage of 40 V. For the 30 V test, the maximum current achieved was 17.2 A. The calculations used to create Fig. 3.3 were verified experimentally with an AlphaLab DC Magnetometer.

The data to be used for comparison were taken from the downstream pressure sensor. If the center of the slug was to the right of the solenoid (upstream), the magnetic force moved the slug to the left, causing a compression of the downstream section. This would cause a positive pressure differential therein and a resulting compression wave as recorded by the downstream pressure sensor. To maximize the pressure differentials recorded, the initial position was always set so that one edge of the slug was in the center of the solenoid, the strongest point of the magnetic field. Because a 1.3 cm slug was used for each test, the other edge would be at $\pm 1.3$ cm depending whether an expansion or compression test was being performed. Fig. 3.3 shows that a large difference existed in the magnetic flux density at each edge of the slug (at this position) which Eq. (3-5) shows will cause an appreciable magnetic force.

![Graph](image.png)

**Fig. 3.4.** Run profile for the 40 V compression test. $\delta_{RMS} = 30.6$ Pa, $z_{CP,0} = 7.1$ mm, $\zeta = 6.08$, $L_{hidden} = 14.5$ cm.
Figs. 3.4 – 3.6 show the experimental and simulated pressure profiles for the 40 V compression, 40 V expansion, and 30 V compression tests.

The maximum pressure changes in the downstream section shown in Figs. 3.4 – 3.6 were 1.30 kPa, –0.95 kPa, and 0.82 kPa, respectively. The negative pressure differential is indicative of the expansion run and is less in magnitude than for the compression run with the same current. The 30 V compression test also produced a
smaller pressure differential than the 40 V test. These results were consistent with findings from the aforementioned study [10].

Measured parameters, such as slug length and initial internal pressure, were input to the simulation, but since the hidden slug length and damping factor were unknown, an optimization routine found their values numerically. As seen from the captions in Figs. 3.4 – 3.6, the damping needed to be augmented about 5.76–6.3 times as much as the non-magnetized value. As mentioned, the damping factor was used to represent the additional shear from the finite length and oscillating slug as well as the hidden slug; thus, the increased damping does not necessarily imply strong magnetoviscous effects of LOX. Further investigation is required to fully understand all of the phenomena.

The initial position of the center of the slug relative to the center of the solenoid, \( z_{CP,0} \), for Figs. 3.4 – 3.6 correlates to one edge of the slug centered in the solenoid. In Fig. 3.4, the numerical solution found that \( z_{CP,0} \) needed to consider the 0.8 cm uncertainty of the slug edge measurement.

![Fig. 3.7. Contour plot of the RMSD of the residual versus hidden slug length and viscosity for the 40 V compression test.](image-url)
As seen through the run profiles and residuals, the simulation modeled the experimental data well. Since the residuals were a quantitative measure of the fit to data, the optimization routine minimized the RMSD to determine the values of the hidden slug length and damping factor. However, even after the filter was applied, high frequency noise was still seen in the data; thus a limit to the RMSD of the residual existed.

Within the given experimental data, the hidden slug length and damping factor could be calculated as long as all other parameters were known to be within their bounds of uncertainty. Because the simulation executed very quickly for a single case, a complete map of the RMSD of the residual could be created as shown in Fig. 3.7. This contour plot shows the RMSD of the residual for the 40 V compression test as the hidden slug length and damping factor varied. The area with the lowest residual was seen as a depression in the map, and the minimum value was taken as the solution.

Using the data from Fig. 3.7, the hidden slug length and damping factor which the optimization routine predicted would generate the smallest residual was input to the numerical solution to predict the most accurate run profile as shown in Fig. 3.4. The

![Fig. 3.8. The effect of hidden slug length on the frequency of the 40 V compression test where the solid line represents the solution in Fig. 3.4 of L_{hidden} = 14.5 cm. The dashed line represents L_{hidden} = 7.25 cm, and the dotted line represents L_{hidden} = 29.0 cm. The experimental data are not shown.](image-url)
viscous damper system was affected by the hidden slug length and damping in different ways and was visible through the run profiles. Increasing the hidden slug length decreased the frequency of the oscillations as shown in Fig. 3.8.

Increasing mass slowed down the oscillations and, therefore, decreased the system frequency. Note that this would not occur if the visible slug length were increased because of its proximity to the magnetic field. And, while the length had the largest influence on the frequency of the run profile, the damping factor seemed to dictate the amplitude of the peaks, as shown in Fig. 3.9.

As damping decreased, the slug was able to move faster, mainly due to reduced shear on the walls. This gave the slug greater momentum without increasing the mass and allowed it to be propelled further. Thus, by optimizing the residual through the hidden slug length and damping factor, the simulation determined the dominant frequency and amplitude of the decaying system.
According to Figs. 3.4 – 3.6, the damping factor seemed to vary by about 5% for the given conditions. This suggests that the model must account for that uncertainty when used as a predictive tool for future experiments. For the conditions in the current tests, however, Fig. 3.9 shows that the 5% inaccuracy did not have a significant impact on the pressure waveform.

The frequency dependence on hidden slug length can be seen in Fig. 3.10 for the 40 V compression test. The frequency was calculated by subtracting out the mean of the oscillations from the run profile and then using a fast Fourier transform. The line in Fig. 10 represents the most dominant frequency in the spectrum and is shown to decrease with the hidden slug length. When a logarithmic curve fit was applied, the $R^2$ value (the square of the Pearson product moment correlation coefficient) was 0.9714. The goodness of the fit implies that an analytical solution exists that could describe the relationship.

The jaggedness of the curve in Fig. 3.10 results from an insufficient number of wavelengths during the pulse. Without enough data, the fast Fourier transform could not precisely determine the frequency for every situation. It is expected that the correlation to a logarithmic fit would be even higher if more wavelengths were obtained.

Fig. 3.11 shows that the amplitude also had logarithmic dependence on the damping factor. The $R^2$ value for curve fit of the data in Fig. 3.11 was 0.9995. The values shown account for a damping factor of 5–12, since none of the simulations used damping factors below this range and, above this range, the oscillations ceased to exist as the run profile was over-damped.

The trends seen in Fig. 3.10 and Fig. 3.11 could be used not only to optimize a particular run profile, but also to design another with a desired operating frequency or
amplitude. In this case, the model becomes a tool which can be used to design advanced systems. But, physically applying the results of the prediction requires the experimental

Fig. 3.10. Frequency versus hidden slug length of the 40 V compression test with a logarithmic curve fit to $R^2 = 0.9714$.

Fig. 3.11. Amplitude versus damping factor of the 40 V compression test with a logarithmic curve fit to $R^2 = 0.9995$. 
uncertainties to be adequately refined. For the current experiment, markings on the quartz tube allowed for a measurement uncertainty of ±0.8 mm of the initial position and visible length of the slug. Fig. 3.12 shows the 40 V compression run with two simulations representing the upper and lower bounds of the initial position uncertainty in order to gauge the waveforms’ sensitivity to experimental uncertainties.

Clearly, the initial position of the slug had a strong effect on the amplitude of oscillations. The amplitude increased with distance from the solenoid, because the slug had an increased travel distance. This allowed more helium to be compressed, and, therefore, the amplitude of the oscillations increased. But, increasing the distance to travel also affected the equilibrium position of the slug, since a greater pressure force was generated. Although the equilibrium position shifted in the same direction as the change in the initial position, it did not shift as much. Thus, as the initial position increased, it was further from its equilibrium point and increased the amplitude and mean of the oscillations. Because the mean of the oscillations increased as well as the amplitude, the
influence of the initial position could be distinguished from the influence of the damping factor, which did not seem to affect the mean considerably.

Increasing the initial position had a negligible effect on the frequency, but nonetheless, Fig. 3.12 shows that the uncertainty of the initial position must be improved to obtain reliable, predictable results in the experiment. The model can be used to calculate the initial position for given experimental data, as was shown in Fig. 3.4, but the experimental uncertainties must be refined if the model is to be used as a predictive tool.

Fig. 3.13 shows the 40 V compression run with two simulations, representing the upper and lower bounds of the visible slug length uncertainty.

For each of the run profiles, one edge of the slug was held in the center of the solenoid, while the other end outside the solenoid was allowed to fluctuate to represent the changing length. As seen from Fig. 3.3, the strength and gradient of the magnetic flux density at the outside edge resulted in minimal changes of the $B_{x,US}$ term in Eq. (3-5). If the inside edge were to fluctuate, the changes would be similar to Fig. 3.12, where the
amplitude varied widely. The insensitivity to visible slug length implies that its uncertainty does not need to be as refined as the initial position uncertainty, thereby easing experimental design.

3.7 Conclusions

A theoretical model and numerical solution of the dynamics of a slug of LOX in a magnetic field have been developed and verified with experimental data. The pulsed magnetic field generated oscillating pressure waves with frequencies of about 6–8 Hz and amplitudes of about 0.8–1.3 kPa. These waves were used to verify that a simplified theoretical model could be used to simulate the dynamics of the slug.

The study found that the model could simulate compression and expansion waves for various field strengths by minimizing the RMSD of the residual. The optimization routine operated by calculating the appropriate hidden slug length and damping factor, which were unknown during the experiment. For the runs performed, the hidden slug length was found to be 10–14.5 cm and the damping factor was found to be 5.76–6.3. The damping factor was an empirical parameter used to account for magnetoviscous effects and internal flow dynamics.

The frequency and amplitude of the oscillations were also studied for their influences from hidden slug length, damping factor, and the uncertainties of the initial position and visible slug length. The model found that the frequency had a logarithmic relationship to the hidden slug length, and the amplitude had a logarithmic relationship to the damping factor. The initial position had a strong effect on the amplitude; however, unlike the damping factor, it also changed the mean of oscillations. Thus, the waveforms
were very sensitive to the measurement uncertainty of 0.8 mm for the initial position, but not to the visible slug length, because the other edge was far enough from the solenoid.

The theoretical model and numerical solution developed adequately modeled the dynamics of the slug for the given experiment and could also measure the unknown hidden slug length and damping factor. As a predictive tool, the model is useful as long as the experimental uncertainty is small. Future research should reduce the measurement and phenomenological uncertainties so that the theoretical model can be further verified and used as a design tool for advanced flow control systems using LOX as the working fluid in a cryogenic magnetic fluid system.

3.8 References


CHAPTER 4
INFLUENCE OF GEOMETRY ON LIQUID OXYGEN MAGNETOHYDRODYNAMICS

This chapter is a paper published as a journal article Experimental Thermal and Fluid Science (article in press). All permissions to using this paper as a part of this dissertation are contained in the Appendix.

4.1 Abstract

Magnetic fluid actuators have performed well in industrial applications, but have a limited temperature range due to the freezing point of the carrier fluid. Liquid oxygen (LOX) presents a pure, paramagnetic fluid suitable for use in a cryogenic magnetic fluid system; therefore, it is a potential solution to increasing the thermal range of magnetic fluid technology without the need for magnetic particles. The current study presents experimental work regarding the influence of geometry on the dynamics of a LOX slug in a 1.9 mm quartz tube when pulsed by a solenoid in a closed volume. A numerical analysis calculated the optimal solenoid geometry and balanced the magnetic, damping, and pressure forces to determine optimal slug lengths. Three configurations comprised the experiment: (1) a 24-gauge wire solenoid with an optimized 2.7 cm length slug, (2) a 30-gauge wire solenoid with an optimized 1.3 cm length slug, and (3) a 30-gauge wire solenoid with a nonoptimized 2.5 cm length slug. Typically, the hydrodynamic breakdown limit is calculated and used to determine the system range; however the experiment showed that the hydrodynamic breakdown limit was never reached by the slug. This implied that, instead, the system range should factor in a probabilistic risk of
failure calculated as a function of the induced pressure change from its oscillations. The experimental data were also used to establish a non-dimensional relationship between the maximum displacement and initial magnetic pressure on the slug. The average initial velocity of the slug was found to be proportional to the initial magnetic pressure, Mason number, and slug length. The results of this study can be used in the design and optimization of a LOX fluid system for space or low-temperature applications.

4.2 Introduction

The introduction of a magnetically responsive fluid to a mechanical system eliminates moving parts and increases system reliability. Since the development of ferrofluids by NASA in the 1960s, the use of a colloidal suspension of ferromagnetic particles in a carrier fluid has led to new designs for pumps [1-6], valves [7], actuators [8], heat pipes [9, 10], and even optical tuners [11]. However, the practical range of these ferrofluids is limited by the thermal characteristics of the carrier fluid, typically water, oil, or a hydrocarbon. The presence of nanoparticles and surfactants in ferrofluids complicates analyses, mainly due to agglomeration and nonhomogeneity. In the cryogenic realm, liquid oxygen (LOX) possesses a natural paramagnetic susceptibility and does not require particles for practical application.

4.2.1 Ferrofluid Applications

Because the fundamental theory of magnetohydrodynamics has been developed for several decades, magnetic fluids have been used in industrial applications such as magnetic resonance imaging, digital data storage, and high-end stereo speakers. As a
working fluid in an actuator system, however, the uses are more limited due to the complex control systems required for pumping.

Park and Seo [1-3] developed a magnetic fluid linear pump for the purpose of infusion pumps and artificial hearts in the medical industry. Using magnetic yokes to propagate droplets of a magnetic fluid, the device uses surface shear to pump water. Park and Seo report pumping heights equivalent to 2 kPa (0.29 psi) for a maximum flux density of 0.036 T (360 G). This is a much smaller field compared to what is required for LOX-based experiments, it is important to note the Park and Seo are using a ferrofluid. LOX has the highest known paramagnetic susceptibility of pure fluids, but is dwarfed by artificial ferrofluids, which can be up to 30 times stronger. The research performed by Park and Seo is useful as a study on traveling waves and their effects on the surface dynamics of a magnetic fluid droplet and serves as a good benchmark for comparison.

Hatch [4] developed a ferrofluidic rotary micropump to enhance lab-on-a-chip MEMS technology. The concept achieved 1.2 kPa of pressure head using a rotating and stationary permanent magnet with a surface flux density of 0.35 T (3500 G). Like Park and Seo, the device pumps a separate, immiscible fluid, but by normal pressure, not surface shear. The study reports operation at 4 and 8 rpm for 3 days at a time and found that the steady-state pressure gradient decreased over time when the plugs were rotated in both clockwise and counterclockwise modes. Pumping speeds greater than 8 rpm generated too much pressure and disrupted the coupling between the permanent magnet and the translating ferrofluidic plug. Furthermore, the rotating permanent magnet is a mechanically moving component and, therefore, negates the goal of creating a no-moving-parts system for fluid actuation.
Moghadam [5] also developed a microscale magnetic fluid pump but successfully managed to eliminate the moving parts. Similar to Park and Seo, he used a series of solenoids spaced along a tube to drive a magnetic fluid linearly. Rather than wrapping the tube though, the solenoids were offset and orthogonally aligned so that their core could be filled with an iron rod and increase the magnetic flux density. The setup produced 0.64 kPa of pressure head for flow rates of 1.1 cm³/min at 0.45 T. The study compared different working fluids and particles, but relies on the viscous drag of the particles to create fluid motion.

Krauss [6] used a two coil system to pump a ferrofluid circularly. The 90° phase difference of the two coils with orthogonal axes produced a net field able to rotate the fluid through the magnetic stress on the fluid surface. The mean diameter of the duct was 100 mm and the system produced a maximum fluid velocity of 70 mm/sec and a magnetic field of 800A/m.

In an applied sense, Goldstein [7] and Kamiyama [8] attempted to create biocompatible devices for surgical implants. Ming [9] and Jeyadevan [10] augmented heat pipe performance by placing permanent magnets near the warm end. Liao [11] tuned an optical fiber filter by using two solenoids to control the position of the slug over long period gratings; thereby changing its refractive index. Although these works do not generate a pressure head, they provide examples of an innovative use of magnetic fluid actuators.

Zahn and Greer [12] took a theoretical approach to traveling waves, but without a free surface. They found that the magnetic fluid can actually be pumped backwards if the wave moves too fast. Without the free surface, the field interacts with the particles inside
the ferrofluid and motion is generated through their spin. They studied the dynamics of a spatially steady field, but varying sinusoidally in time. Their work was followed up by Mao and Koser [13] who were able to vary the field in space as well. Their findings showed that a maximum flow velocity was achieved when the product of the applied magnetic field frequency, the wave number, and the height of the channel approach unity. In other words, pumping becomes more efficient as the magnetic field frequency approaches the reciprocal of the relaxation time constant of the magnetic particles in the fluid. Mao and Koser compared their experimental data with numerical results for a 2D solution using FEMLAB and a 1D solution using Matlab. They found that all 3 agree well until the magnetic field frequency reaches about 30 kHz, when the Matlab solution begins to diverge.

The aforementioned research illustrates the importance of fluctuating magnetic fields for pumping. Without a gradient of the magnetic field, no net force is generated, just as with a pressure gradient. However, as shown, stationary solenoids are still able to create a magnetic field gradient since the strength lessens with distance. Furthermore, by pulsing the stationary solenoid, a time-varying gradient is induced and can also be used for position control of the magnetic fluid.

4.2.2 Liquid Oxygen

As a pure fluid, LOX has the highest known paramagnetic susceptibility, but unfortunately has been overlooked in magnetic fluid research because of its boiling point at 90 K at atmospheric conditions. While not much demand currently exists for low-temperature magnetic fluid systems on Earth, space applications can greatly benefit since LOX is already commonly used in life support, thermal management, and propulsion.
systems. The basic properties of LOX have been measured under a variety of temperature and pressure ranges [14-16], but unfortunately, few experiments have studied the influence of a magnetic field.

Uyeda performed experiments on the magneto-volume effect of LOX [17], which is shown to be negligible for the current study. Takeda [18] measured the surface tension under high magnetic fields and Catherall [19] and Hilton [20] investigated the magneto-Archimedes levitation to determine its use in mineral separation, but did not consider it as a working fluid in an actuator. Catherall also studied its surface instabilities [21] under an inhomogenous field but none of these experiments generated a bulk movement of the liquid. Yerkes [22] measured the wicking heights of liquid oxygen heat pipes when augmented by a magnetic field and showed an increase of up to 4 times the capillary pressure.

Youngquist performed experiments which quantitatively measured the magnetohydrodynamic characteristics of LOX [23], but it was mainly a benchmark study. While using a solenoid to pulse a magnetic field on one end of a column of LOX in an open-ended U-tube, he measured the displacement of the other end and correlated the results to a numerical model. He applied an electric current of 30 A to the solenoid which generated a magnetic field with a maximum flux density of 0.9 T. With the field applied, the height of the column oscillated about a new mean, reaching a maximum displacement of 4-5 cm. Note that pulses of 100 A and 6 T were attempted, but had erratic results, often ripping off the top of the column. This study was a valuable first step, but required an evolution in its methodology to achieve progress.
The authors verified the advantages of a slug of LOX rather than a column through experiments on the maximum induced pressure change in a closed volume with various slug lengths, initial positions, and applied currents [24]. A short slug could experience the same amount of magnetic force for much less damping and inertia than a long column. The experiments were verified with a theoretical model which, when implemented in a numerical simulation, demonstrated the effects of experimental uncertainty and measurement errors [25]. The experiment and theoretical model provided valuable data on the viability of LOX as a magnetic working fluid, but did not address the importance of the influence of geometry on its dynamics. Non-dimensional relationships and geometric trends can greatly aid the design and development of magnetic fluid systems operating under the same mechanisms.

4.3 Experiment

The experimental system can be seen schematically in Fig. 4.1, and the apparatus is shown in Fig. 4.2 outside and inside the unfilled liquid nitrogen tub. Different configurations required different downstream volumes; Fig. 4.1 shows the smaller downstream section while Fig. 4.2 shows the larger downstream section. Fig. 4.1 also shows the LOX slug in blue with its upstream edge centered in the solenoid. When the solenoid was pulsed, the magnetic field pulled the slug to the center of the solenoid, causing an expansion in the downstream side and a compression in the upstream side. With helium as the surrounding gas in the closed volume, an isothermal ideal gas assumption could be used as long as the slug did not break down. Sensors on the upstream and downstream sides measure the internal pressure changes over time, which
can be correlated to slug displacement, since the upstream and downstream volumes are known.

Before the liquid slug could be precisely positioned in the quartz tube, gaseous oxygen had to be introduced to the system at room temperature. Once the system was closed and submerged in liquid nitrogen, the gas condensed into LOX droplets and fell from the heat exchanger into the horizontal section of the plumbing. From there, a magnetic wand was used to drag portions of the LOX into the transparent quartz tube. While the process allowed for precise measurement of the slug length within 0.8 mm, an unknown amount of LOX remained in the steel sections. The mass of LOX that could not be seen was dubbed the hidden slug length but could be precisely calculated through the frequency of the pressure oscillations [25].
The quartz tube had an inner diameter of 1.9 mm, and the solenoids were powered by a Hewlett-Packard 6268B 900 W DC power supply. The power supply had an upper limit of 30 V or 30 A; therefore, an optimization process for the solenoid sizing could be developed. To maximize the capability of the power supply, a resistance of 1 Ω was desired when the solenoid was in the 77 K liquid nitrogen tub; thus with a known coefficient of temperature resistance (CTR) of 0.0039 for copper, the corresponding resistance when at room temperature was approximately 6.34 Ω. With a wire of known gauge, the total wire length could be found, and then an iterative scheme using Matlab and Excel was used to determine the length and outer diameter of the solenoid that produced the highest magnetic field for a constant 30 V source. The process flowchart can be seen in Fig. 4.3.

Fig. 4.2. Photographs of test apparatus (a) outside and (b) inside the empty liquid nitrogen tub.
Kulite CT-375 analog pressure sensors located upstream and downstream of the slug in the test section were sampled at 5 kHz using a Measurement Computing PCIM-DAS1602/16 A/D card driven by Matlab with a combined uncertainty of 0.17 kPa from the effects of nonlinearity, hysteresis, 16-bit analog-to-digital conversion errors, and repeatability. Because the changes in the upstream and downstream pressures were the desired output, the absolute pressure and the measurement uncertainty were not

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**Fig. 4.3. Solenoid optimization process flowchart.**
influencing factors. The noise in the raw data was reduced by using a Chebyshev Type II lowpass filter, which was set to 0 decibels at 45 Hz and -40 decibels at 50 Hz. Two different configurations used downstream volumes of 1.8 cm³ and 5.9 cm³ (as reflected in Fig. 4.1 and Fig. 4.2), but the upstream volume remained constant at 337 cm³. Because the downstream volume was significantly less than the upstream volume in both cases, the data from the downstream pressure sensor was used for comparison. The operating pressure was maintained between 100-135 kPa for safety, and the runtime was limited to 0.25 seconds to reduce resistance heating in the solenoids. The LOX slug formed a concave meniscus with edges measurable within 0.8 mm resolution via notches on the quartz tube.

Three configurations were tested to determine the geometric influence on LOX magnetohydrodynamics as follows:

- Configuration 1: 24-gauge wire solenoid with an optimized slug length
- Configuration 2: 30-gauge wire solenoid with an optimized slug length
- Configuration 3: 30-gauge wire solenoid with a non-optimized slug length

The optimal slug length for a particular solenoid was determined as the length that generated the highest pressure change while accounting for forces due to magnetism, pressure, and damping. A theoretical model was created to find this length.

4.4 Theory and Numerical Simulation

Before a high order algorithm could be developed to calculate the three-dimensional internal and surface dynamics, a preliminary model was developed to capture the main physics of the bulk motion of the slug. This model was developed using
a one-dimensional approximation and verified using the experimental data. Assuming the slug was incompressible and remained intact throughout the run, the approximation was valid based on the experiments of the bulk motion. Rosensweig [26] provides a thorough analysis of the governing equations of magnetic fluid dynamics. The fluid motion can be described by the Navier-Stokes equations with an additional term for the magnetic force, also known as the Kelvin force. The Kelvin force density, $f_m$, can be found through the divergence of the Maxwell stress tensor as a function of the permeability of free space $\mu_o$, the magnetization vector $\mathbf{M}$, and magnetic field $\mathbf{H}$ as

$$f_m = \mu_o (\mathbf{M} \cdot \nabla)\mathbf{H}.$$  \hfill (4-1)

In the linear portion of the Langevin function, volumetric magnetic susceptibility, $\chi$, is the ratio of the magnetization vector to the applied field vector, $\chi = \mathbf{M} / \mathbf{H}$. By substituting for $\mathbf{M}$, using the vector identity, $\mathbf{H} \cdot \nabla \mathbf{H} = \nabla (\mathbf{H} \cdot \mathbf{H})/2 - \mathbf{H} \times (\nabla \times \mathbf{H})$, and noting that Ampere’s Law cancels out the curl of the applied field, Eq. (4-1) can be reduced to

$$f_m = \mu_o \chi \nabla H^2 / 2.$$ \hfill (4-2)

With a constant temperature, the relative permeability, $\mu$, also remains constant. The relative permeability is the ratio between the magnetic flux density, $\mathbf{B}$, and applied magnetic fields, $\mu = \mathbf{B} / \mathbf{H}$, which can also expressed in terms of volumetric susceptibility, $\mu = \mu_o (1+\chi)$.

Given these relations, the Kelvin force density is

$$f_m = \frac{1}{2\mu_o} \left( \frac{\chi}{(1+\chi)^2} \right) \nabla B^2,$$ \hfill (4-3)

and the force in the axial direction is
\[ f_{m,x} = \frac{I}{2\mu_0} \left( \frac{\chi}{1 + \chi} \right)^2 \frac{d}{dx} B_x^2; \]  

where the subscript \( x \) denotes the axial direction.

The differential term considers the ends of the slug, and when Eq. (4-4) is integrated over the entire volume with a one-dimensional approximation, the force due to magnetism in the axial direction, \( F_M \), is

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

where \( a \) is the tube radius and the subscripts US and DS denote the upstream and downstream directions. The magnetic flux density generated by the solenoid is found by summing the contribution of each loop. The magnetic flux density from an individual loop of wire is

\[ B_{x,\text{loop}} = \frac{1}{2} I(t) \mu_0 r_{\text{loop}}^2 \left( r_{\text{loop}}^2 + dx^2 \right)^{-3/2}, \]  

where \( r \) is the radius of a single loop of coil, \( I(t) \) is the applied current over time, the subscript \( \text{loop} \) denotes a single loop of the coil, and \( dx \) is the axial distance from that loop.

The oscillatory motion, finite slug length, and unknown magnetoviscous effects complicate the damping force on the one-dimensional analysis. These effects were treated as having a combined effect on the wall shear stress through a damping factor, \( \zeta \). Using data from one experimental run, the damping factor could be calculated through the decaying amplitude of the oscillations and then applied to every run performed within the same time frame as long as no changes to the experiment were made [25]. The use of the damping factor allows the development of the current theoretical model before a
comprehensive multi-dimensional model accounting for all the contributing factors can be developed. Using the damping factor and the classic relation for laminar wall shear stress in Hagen-Poiseuille flow as given by White [27], the force due to damping, $F_D$, was calculated as

$$ F_D = 8\pi (L + L_{\text{hidden}}) \dot{s} \zeta \eta ; $$

(4-7)

where $\eta$ is the nonmagnetized dynamic viscosity of LOX, $L$ is the visible length of the slug, $L_{\text{hidden}}$ is the hidden length of the slug in the steel sections, and $\dot{s}$ is the velocity of the slug in the axial direction.

The pressure force, $F_P$, results from the differential pressure on either side of the slug as

$$ F_p = \pi a^2 \Delta p . $$

(4-8)

where $\Delta p$ denotes the pressure differential across the slug. The change in pressure results from the compression and expansion of the closed volumes on either side of the slug.

Thus, with the forces due to pressure, magnetism, and damping, the equation of motion for the LOX slug becomes the nonlinear ordinary differential equation,

$$ m \ddot{s} = \pi a^2 \Delta p + \frac{\pi a^2}{2\mu} \frac{\chi}{(1 + \chi)^2} (B_{z,LS}^2 - B_{z,DS}^2) + 8\pi (L + L_{\text{hidden}}) \dot{s} \zeta \eta ; $$

(4-9)

where $m$ is the mass of the visible and hidden slugs and $\ddot{s}$ is the acceleration. This one-dimensional force balance assumes that the finite-length slug was an incompressible solid and does not account for surface tension, instabilities, or breakdown of the slug. Experiments by Perry and Jones confirm the theoretical prediction of a hydrostatic breakdown [28]; however the current case may be different due to the dynamic motion of the slug. Bashtovoi [29] points out that capillary effects are reduced under the influence
of a magnetic field and are thus considered negligible during the pulse; however, they must be significant enough to hold the slug in place when nonmagnetized. Gravity was also ignored because the tube was oriented horizontally.

The governing equation of motion for the one-dimensional dynamics of the liquid slug, Eq. (4-9), was discretized and solved numerically with initial conditions and test parameters from the experiments. For a particular run, the initial system pressure, solenoid temperature, and slug position relative to the solenoid were used in the algorithm, as well as the visible and hidden slug lengths, solenoid properties, applied voltage, and damping factor. Along with the dynamics, the solenoid temperature was calculated over time to determine the reduction of the magnetic field as resistance heating limited the amount of current that could be drawn. The numerical simulation was written in Matlab v7.6.0 (R2008a) on a 2.4GHz Pentium 4 processor with 2GB of RAM. The temporal discretization of the Lagrangian model achieved grid independence with a time step of 0.01 s, but, to obtain an adequate correlation to the pressure sensor sampling frequencies, the time step was decreased to 0.0002 s. Nonetheless, the dynamics were typically solved in less than 2 seconds, allowing for a thorough optimization of system variables through a regression analysis. The numerical accuracy of the model was adequate, particularly in regards to the experimental measurement uncertainty of 0.8 mm. The model was used to determine the exact initial position of the slug and the regression analysis varied slug length and initial position to find the maximum pressure change in the downstream section for specific geometric inputs and the optimized solenoids. The slug length which generated the greatest pressure change was dubbed the optimal slug length for a particular solenoid.
Thermal analyses on the gas compression and solenoid heating showed that the temperatures of the helium and LOX slug will remain within 0.2 K of their initial value of 77 K. Fluid properties for LOX were taken from the CRC Handbook of Chemistry and Physics [15], and studies by Hilton [16] indicated that pressure fluctuations of 2 kPa would affect those values by less than 0.001%.

The relationship between the initial magnetic pressure on the slug and its maximum displacement had to be non-dimensionalized to compare the different geometries tested. The maximum displacement was non-dimensionalized using the cross-sectional area of the tube and the downstream volume as

\[ s^* = \frac{s_{\text{max}} \pi a^2}{Vol_{DS}}; \quad (4-10) \]

where \( s_{\text{max}} \) is the maximum displacement of the slug and \( Vol_{DS} \) is the downstream volume. The initial magnetic pressure on the slug, \( p_{m,i} \), is defined as

\[ p_{m,i} = \mu_0 \int_{DS}^{US} M_i dH = \frac{1}{2\mu_0} \frac{\chi}{(1 + \chi)^2} \left( B_{US,i}^2 - B_{DS,i}^2 \right); \quad (4-11) \]

where the subscript \( i \) represents the initial value at the beginning of the pulse. By comparing Eq. (4-11) to Eq. (4-5), it can be seen that the initial magnetic pressure is the force due to magnetism in the axial direction at the beginning of the pulse divided by the cross sectional area of the tube. Because the initial magnetic pressure is a function of the magnetic flux density at each of the edges, it can be found as a function of the initial slug position. To non-dimensionalize the initial magnetic pressure, a term containing the magnetic flux density and the permeability of free space was required. This term could be represented through the Alfvén velocity, \( u_a \), as,
\[ u_a = \frac{B_{\text{max}}}{\sqrt{\mu_0 \rho}}. \]  

(4-12)

where \( B_{\text{max}} \) is the maximum magnetic flux density and \( \rho \) is the density of LOX.

The Alfvén velocity is the speed of a hydromagnetic wave along the field lines through the LOX and can be converted into a pressure term similar to the dynamic pressure of a fluid. This term is sometimes called the Alfvén pressure, \( 0.5 \rho u_a^2 \). The ratio of the initial magnetic pressure on the slug to the Alfvén pressure gives a non-dimensional initial magnetic pressure as,

\[ p_m^* = \frac{p_{m,i}}{0.5 \rho u_a^2}; \]  

(4-13)

Using Eq.'s (4-11) and (4-12), the non-dimensional initial magnetic pressure can be expanded to demonstrate its relevance to the normalized magnetic flux density and volumetric susceptibility of LOX as,

\[ p_m^* = \frac{\chi}{(1 + \chi)^2} \frac{B_{US,i}^2 - B_{DS,i}^2}{B_{\text{max}}^2} \]  

(4-14)

It is also useful to define an average initial velocity, \( u_i \), with the maximum displacement and the length of time required to reach that maximum displacement, \( dt \), which occurs during the first oscillation. The average initial velocity is thus,

\[ u_i = \frac{s_{\text{max}}}{dt}. \]  

(4-15)

Then, the Mason number represents the ratio of damping to magnetic forces and is defined for the current study as

\[ Ma = \frac{F_D}{F_M} = \frac{8\pi(L + L_{\text{hidden}})\zeta \eta u_i}{\pi a^2 p_{m,i}} \]  

(4-16)
4.5 Results

Using the process outlined in the flowchart in Fig. 4.3, two optimized solenoids were constructed of different wire gauges. Their specifications are listed in Table 4.1.

Although designed for 1 $\Omega$ of resistance at 77 K, the actual fabrication of Solenoid B led to a cold resistance of about 1.3 $\Omega$; hence, only 23.4 A of current could be drawn from the power supply. This led to a lower magnetic flux density than the larger, lower-gauge solenoid, but still maintained a higher flux density gradient. Fig. 4.4 shows the magnetic flux density and flux density gradient along the axis of the solenoids. The magnetic flux density and gradient are unique for a particular solenoid based on its physical geometry and applied power, and must be known for numerical simulation of the experiments.

To determine the optimal slug size for each solenoid, Eq. (4-9) was iterated over several slug lengths and initial positions. The resulting maximum pressure differences can be seen through the surface maps shown in Fig. 4.5 and Fig. 4.6.

The crests of the surface plots in Fig. 4.5 and Fig. 4.6 represent compression in the downstream section, and the troughs represent expansion. The center point of the slug

<table>
<thead>
<tr>
<th>Table 4.1. Optimized solenoid specifications.</th>
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<tbody>
<tr>
<td><strong>Solenoid A</strong></td>
</tr>
<tr>
<td>Wire Gauge:</td>
</tr>
<tr>
<td>Radial Turns:</td>
</tr>
<tr>
<td>Axial Turns:</td>
</tr>
<tr>
<td>Length:</td>
</tr>
<tr>
<td>Inner Diameter:</td>
</tr>
<tr>
<td>Outer Diameter:</td>
</tr>
<tr>
<td>Mass:</td>
</tr>
<tr>
<td>$B_{\text{max}}$:</td>
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<td>$dB/dz_{\text{max}}$:</td>
</tr>
</tbody>
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was considered relative to the solenoid center; hence the maximum pressure change was symmetric about a center point of 0. The dashed lines in Fig. 4.5b and Fig. 4.6b trace the peaks along the initial positions and show that a certain slug length existed which balanced the magnetic, pressure, and shear forces so that the maximum pressure change is optimized. For Solenoid A, the optimal slug size was 2.7 cm, and for Solenoid B, the optimal slug size was 1.3 cm.

With known solenoid geometries and slug sizes, the magnetic field at both ends of the slug could be calculated as a function of position to determine the overall magnetic pressure on the slug. Three configurations were tested to determine geometric effects on the dynamics of the LOX slug. The tested geometries were as follows:

- Configuration 1: Solenoid A with an optimized slug length of 2.7 cm
- Configuration 2: Solenoid B with an optimized slug length of 1.3 cm
- Configuration 3: Solenoid B with a nonoptimized slug length of 2.5 cm

Fig. 4.7 shows the magnetic pressure for each configuration as the center of the slug relative to the center of the solenoid varies.
The magnetic pressure represents the differential force on the slug as a result of the magnetic field as shown in Eq. (4-11). Because Configurations 2 and 3 both used Solenoid B, the magnitude of the peaks of the magnetic pressure was the same for both (~1.5 kPa); however, because Configuration 3 used a longer slug, the peak correlates to a larger center displacement than Configuration 2 (~1.25 cm versus ~0.65 cm). The peaks of positive and negative pressure correlated to one end of the slug in the center of the solenoid; hence the peaks were further apart for Configurations 1 and 3, which had longer slugs than Configuration 2. The peaks for Configurations 1 and 3 were at approximately
the same distance from the center of the solenoid because their slug lengths were nearly the same. If more or less current was drawn, the peaks would grow or shrink in magnitude, but their positions relative to the solenoid center were controlled by slug size and would not change along the horizontal axis. Solenoid A generated a higher magnetic pressure than Solenoid B because it could generate a higher magnetic flux density despite a lower gradient. Positive pressure indicated that the slug was being pushed upstream, whereas negative pressure indicated that the slug was being pushed downstream.

The dynamics of the slug were measured experimentally and calculated numerically using Eq. (4-9). Figs. 4.8 – 4.10 show the maximum pressure change generated in the downstream section as the initial positions of the centers of the slugs relative to the solenoids were varied. The experimental data obtained was compared with the theoretical model, and points of hydrodynamic breakdown are shown.
Since Configuration 1 had a larger downstream volume, the pressure change caused by slug displacement did not correlate with Configurations 2 and 3. The volumes were changed because the slug became more likely to experience a hydrodynamic breakdown as the displacement-induced pressure approached the maximum magnetic...
pressure. As seen from Fig. 4.7, the maximum magnetic pressures, and hence hydrodynamic breakdown strength, were 2.11 kPa for Configuration 1 and 1.54 kPa for Configurations 2 and 3. The experimental data in Figs. 4.8 – 4.10 indicated that the slug broke down around 1.5 kPa for all three. With a liquid slug, the hydrodynamic breakdown point cannot be treated as a defined barrier, but instead, must be considered with a probabilistic risk of occurrence. For example, if the slug began nearly centered on the solenoid, it had a low probability of breakdown; whereas if the initial position was outside the solenoid, that probability increased because of a greater acceleration and deceleration of the slug. Some runs near the limit of breakdown seemed to have remained in tact, but it is possible that a partial breakdown occurred since the maximum pressure change should have been higher.

The solid line in Figs. 4.8 – 4.10 represents the theoretical model from Matlab. Using empirical data from a few points for the hidden slug length and damping factor, the
line was created by simulating the run over time for various initial positions and extracting the maximum pressure change in the downstream section. The solid-body, one-dimensional approximation of the LOX slug allowed the analysis to continue without regard to hydrodynamic breakdown. The Matlab model showed that as the initial position of the slug deviated from the center of the solenoid, the maximum pressure change in the downstream section increased until a certain cutoff point. At that point, the magnetic force could not overcome the mass and shear of the slug to generate movement, since it was too far away from the solenoid.

The maximum pressure change was symmetric in expansion and compression. The peaks in Figs. 4.8 – 4.10 correlate to the magnetic pressure reaching near zero in Fig. 4.7. For Configuration 1, the magnetic pressure dropped to zero when the center position of the slug was approximately 3.25 cm from the center of the solenoid, which correlated to the cutoff of the maximum pressure change curve in Fig. 4.8. For Configuration 2, the peak correlates to negligible magnetic pressure at ~1 cm and for Configuration 3, the correlation occurred at ~1.75 cm.

The error bars in Figs. 4.8 – 4.10 represent the 0.8 mm measurement uncertainty during the experiment. For Configurations 2 and 3 using Solenoid B, the numerical simulation remained within the uncertainty bounds; however the larger size of Solenoid A caused it to deviate from the predicted value in Configuration 1. The lack of correlation implied that as the physical scale of the experiment increased, the uncertainties could not be extrapolated. A previous study [25] showed that the amplitude of the oscillations were more significantly affected by the damping factor than the hidden slug length, which likely remained fairly constant during the set of runs. As the initial position of the slug
deviated from the center of the solenoid, the maximum velocity of the slug increased as well. The increase in velocity generated more turbulent internal flow dynamics; thereby increasing the damping factor. For the smaller solenoid, the velocity change was small enough that the damping factor could be extrapolated to each run, but clearly, that was not the case for the larger solenoid.

Since the downstream volume dictated the magnitude of the pressure change and the slug length and solenoid characteristics dictated the magnetic pressure curve, the first-level specifications of a magnetic fluid actuator could be designed without the need for complicated magnetohydrodynamic equations as long as the hydrodynamic breakdown is not exceeded. For example, if an actuator needed to generate a pressure change of 1.5 kPa with a 6 cm stroke length, the geometry could be designed similar to Configuration 1 only using basic equations for ideal gas compression and magnetic field mapping.

A non-dimensional comparison of the configurations will prove useful in predicting alternate designs. By non-dimensionalizing the maximum displacement and initial magnetic pressure, as shown in Eq. (4-10) and Eq. (4-13), a common trend between the configurations was found. Fig. 4.11 shows the experimental data for each of the configurations in their non-dimensional form.

Fig. 4.11 shows that regardless of system geometry, the maximum non-dimensional displacement can be predicted through the non-dimensional initial magnetic pressure. The average slope of a linear curve fit to the three data sets was 2.38. This fit could be used as a guideline during the preliminary design stage of a magnetic fluid actuator employing a liquid oxygen slug. For other paramagnetic fluids, it is expected the trend would be similar; however, the average slope would be different depending on the
fluid’s susceptibility. Furthermore, it is not expected that this trend would hold true for designs where capillarity and gravity effects dominate the dynamics. The capillarity should be strong enough to allow for the formation of a nonmagnetized liquid slug, but weak enough to become negligible during the oscillations. Micci performed a molecular dynamics calculation to determine a surface tension of 0.0151 N/m for a LOX-helium interface [30]. This study implies that, for the current study, the capillary forces were approximately 50 times weaker than the pressure, damping, and magnetic forces.

By extracting the time to reach the maximum displacement from the experimental data, an average initial velocity could be found. Figs. 4.12 – 4.14 compare the initial magnetic pressure to the average initial velocity of the slug.

As expected, the average initial velocity increased as the initial magnetic pressure increased. The dashed lines in Figs. 4.12 – 4.14 represent a linear fit with a correlation

![Non-dimensional maximum displacement versus non-dimensional initial magnetic pressure.](image)
described by the square of the Pearson product moment correlation coefficient, $R^2$. Ideally, the y-intercept of the linear fit equation would be zero since no velocity would be obtained without magnetic pressure; instead, the nonzero intercept coefficient can be
attributed to experimental uncertainty as it is only 2%-3% of the slope coefficient. The slope coefficient represents the ratio of the initial velocity to the initial magnetic pressure, which is a component of calculating the Mason number in Eq. (4-16). Each data point was used to calculate the Mason number for each run, and the high correlation to a linear fit indicated that the Mason number was consistent for each test configuration regardless of initial position. Table 4.2 shows the average Mason number for each configuration and the standard deviation of all the runs performed on that configuration assuming each configuration had an average damping factor of 6 and hidden slug length of 13 cm. In each, the standard deviation was approximately one-fourth the overall value of the Mason number.

The Mason number represents the ratio of damping to magnetic forces; thus a correlation could be attributed between each configuration since, typically, longer slug lengths increased the damping force and greater magnetic fields increased the magnetic
force. With the same magnetic fields for Configurations #2 and #3, the difference in the slug length caused a greater Mason number for Configuration #3. However, Configuration #1 had a stronger magnetic field than Configuration #3 and nearly the same slug length, so it should have had a lower Mason number. But because Configuration #1 was able to achieve a higher velocity than Configuration #3, its damping force and, therefore, Mason number were proportionally higher.

In a highly efficient system, the Mason number would be minimized to maximize the potential from the magnetic force. The Mason numbers of Configurations #2 and #3 show the benefits of an optimized solenoid/slug combination by reducing the damping to magnetic force ratio by nearly 3 times. Furthermore, a comparison of Configurations #1 and #2 showed that reducing the overall size of the geometry can have considerable effects on the average Mason number as well. By choosing a smaller wire gauge and following the described optimization process, the Mason number was reduced 5 times. This implies that a magnetic fluid system operating under the same methods would be more efficient as the overall size decreases; however, unless measurement uncertainties can be reduced, the size limit is constrained by the ability to accurately manage the optimal slug length in the physical realm.

<table>
<thead>
<tr>
<th>Configurations</th>
<th># of Runs</th>
<th>Average Mason number</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>41</td>
<td>0.247</td>
<td>6.62 * 10^-2</td>
</tr>
<tr>
<td>2</td>
<td>26</td>
<td>0.091</td>
<td>2.03 * 10^-2</td>
</tr>
<tr>
<td>3</td>
<td>37</td>
<td>0.143</td>
<td>3.54 * 10^-2</td>
</tr>
</tbody>
</table>
4.6 Conclusions

The results from the experiments and analyses lead to certain conclusions about the effects of solenoid geometry, slug length, and position geometry on the LOX magnetohydrodynamics phenomenon. Although LOX was the only fluid used in the study, the conclusions can be applied to a slug of any paramagnetic fluid in a closed volume that is being pulsed by a solenoid in a tube. If gravity is negligible and if the capillary forces are strong enough to form a liquid slug in the tube (but weak enough to be considered negligible compared to the magnetic, pressure, and damping forces), the following conclusions can be drawn:

- An optimal slug length can be found for a particular geometry based on a balance of magnetic, damping, and pressure forces.
- A liquid slug will not reach its theoretical hydrodynamic breakdown limit because of the retardation of slug movement as it approaches that limit. Instead, a better method of determining system limits is to use a probabilistic risk of failure as a function of the initial position of the slug.
- Within the bounds of breakdown, calculations of the initial magnetic pressure and ideal gas compression can be used to determine the first-level design parameters of an actual system without the need for complicated MHD equations.
- The non-dimensional forms of the maximum displacement and initial magnetic pressure exhibit a relationship that is similar in various geometric configurations.
- A linear relationship exists between the average initial velocity and the initial magnetic pressure and is proportional to the Mason number and slug length.
4.7 References


CHAPTER 5
CONCLUSIONS AND SIGNIFICANCE

The case for a LOX-based magnetic fluid system to replace mechanically moving parts in a satellite system has been argued. In terms of the research goals and test objectives listed in Chapter 1, conclusions can be drawn from the studies performed. These conclusions are classified as pertaining to the maximum pressure change attainable, hydrodynamic breakdown, numerical simulation, and optimization of the system tested. These conclusions lead to potential paths for future research regarding the fundamental understanding of cryogenic magnetohydrodynamics and the significance to potential applications.

5.1 Conclusions

Regarding the objectives listed in Chapter 1, the experiment alone satisfied the first two objectives by confirming the potential of a LOX-based magnetic fluid system through innovative measuring techniques. The experiment and numerical simulation also verified the theoretical model, thus satisfying the third objective. The fourth objective was satisfied through the parametric studies which examined the maximum pressure change attainable, effect of uncertainty, and geometric variance. Accomplishing the objectives aids the overall goals by establishing concrete conclusions from the research.

5.1.1 Maximum Pressure Change Attainable

It was proven that the magnetic susceptibility of LOX can be used to create a non-negligible pressure change in a closed volume by inducing oscillations of a liquid slug
with a magnetic field. The displacement of the slug can be measured through pressure changes using an isothermal, ideal gas assumption of helium. The maximum pressure change attainable was symmetric in expansion and compression and was seen to be a function of the initial position of the slug, visible and hidden lengths of the slug, and magnetic flux density. For a visible slug length of 1.3 cm, a hidden slug length of 10-14.5 cm, and a damping factor of 5.76-6.3, the oscillation frequencies were 6-8 Hz with amplitudes of 0.8-1.3 kPa.

The maximum pressure change attainable is predictable and repeatable if the experiment’s measurement uncertainty is small compared to the gradient of the magnetic flux density. Table 5.1 shows the resulting effect of the variance of the main sources of uncertainty.

While most of the effects are recognizable, the uncertainty of the initial position of the slug should be minimized to help distinguish its influence from the damping factor. The effects of the hidden slug length on frequency and the damping factor on amplitude were both shown to be logarithmic as detailed in Chapter 3.

5.1.2 Hydrodynamic Breakdown

A hydrodynamic breakdown of the slug will occur if the pressure differential on either side of it is too high. The breakdown never occurred at its theoretical limit and was

<table>
<thead>
<tr>
<th>Table 5.1. Uncertainty effects on slug oscillation.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Visible slug length</strong></td>
</tr>
<tr>
<td><strong>Hidden slug length</strong></td>
</tr>
<tr>
<td><strong>Damping factor</strong></td>
</tr>
<tr>
<td><strong>Initial position</strong></td>
</tr>
</tbody>
</table>
shown to be more complicated than a hydrostatic breakdown. While the hydrostatic breakdown is a function heavily dominated by the magnetic flux density, the hydrodynamic breakdown is also expected to be heavily influenced by the bulk Reynolds number, velocity of the slug, fluid properties of LOX when magnetized (namely density, viscosity, and surface tension), tube radius, gradient of the magnetic flux density, and gravity. Due to its complex nature, the hydrodynamic breakdown should be predicted using probabilistic methods to calculate its risk of failure.

5.1.3 Numerical Simulation

The one-dimensional bulk fluid motion of the LOX slug can be predicted using a theoretical model implemented through a finite-difference, Lagrangian numerical simulation within the bounds of uncertainty. The simulation can be applied to a variety of test conditions with the same operating principles and can be used to precisely calculate the effects of phenomenological and measurement uncertainties in the experiment. Because the simulation runs very quickly, several iterations can minimize the root-mean-square deviation of the absolute error between the experiment and simulation. Aside from just a measurement tool, the simulation can also serve as a predictive tool for setups operating under the same assumptions and methodologies. Given a specific solenoid geometry, the optimal slug length which generates the greatest pressure change can be predicted regardless of power input. Finally, the simulation showed that an empirical damping factor can be used to cumulatively account for all of the unknown phenomena which attribute to damping of the flow.
5.1.4 System Optimization

An actual application of cryogenic magnetohydrodynamics requires efficient performance, particularly for use in space. From the studies performed, it was shown that a method can be developed to maximize the magnetic flux density from a solenoid for a particular power supply and that an optimal slug length exists for a specific solenoid geometry which maximizes the pressure change in the closed volume with minimal damping and inertia.

The oscillations of the slug also gave insight to efficiency in terms of the Mason number. The Mason number is the ratio of damping to magnetic forces and a lower value is indicative of reduced damping and losses in the system. The Mason number can be decreased by using the optimal slug length for a particular solenoid geometry and by minimizing the overall scale of the apparatus until capillarity effects begin to dominate. These effects were seen by noting the ratio of the initial magnetic pressure to the average initial velocity for each run. The ratio was consistent during a series of tests with the same configuration and is a factor in calculating the modified Mason number. Furthermore, non-dimensionalizing the initial magnetic pressure and maximum displacement produced a consistent relationship regardless of geometry.

5.2 Future Work

The prime motivator for conducting the current research was to develop a system with no moving parts by taking advantage of the magnetohydrodynamic properties of LOX. This has been accomplished in the experiments performed, but the direction of future work depends on the next level of motivation. Regardless of whether the research
will be academically or industrially inspired, the next phase will still require a combination of experimental, theoretical, and numerical work. Basic experiments like the ones performed are useful for confirming methods of operation (such as creating a non-negligible pressure change through magnetic forces), confirming theoretical predictions (such frequency and amplitude of oscillations), and measuring physical phenomena (such as the point of hydrodynamic breakdown). The theoretical and numerical work should be performed conjunctly and may require more advanced software for implementation. A finite-difference, one-dimensional simulation can be accurately modeled in Matlab; however a three dimensional simulation with coupled magnetohydrodynamic interactions will require a more advanced commercial solver such as Comsol Multiphysics. As a technology advances, so must its tools for study; thus, the next phase of research on cryogenic magnetohydrodynamics will require more sophisticated experiments and algorithms regardless of its motivation. In terms of the aforementioned conclusions, potential paths for further research can be defined regarding the fundamental understanding of cryogenic magnetohydrodynamics and the significance to potential applications.

5.2.1 Fundamental Understanding

Working with cryogens is physically dangerous, particularly with LOX as it is extremely volatile; for this reason, very few experiments have been performed on LOX with respect to stable, ambient fluids. Adding in a magnetic field and a controllable slug immersed in a liquid nitrogen tub greatly increases the complexity even before a precise measurement technique can be developed. The experimental complexity coupled with the lack of demand for knowledge on cryogenic magnetohydrodynamics has warded
researchers for many decades, but the rising need for advanced systems in space has prompted academic interest in the fundamental principles regarding the current study. While many of the conclusions listed above are specific to the current experiment, they lead to basic, fundamental questions regarding fluid mechanics and magnetism. With the intended final application of a LOX-based magnetic fluid system in space, the following potential research paths can be taken as fundamental studies which aid the overall goals listed in Chapter 1:

- Numerical studies on the internal flow dynamics of an oscillatory, finite-length, slug experiencing a body force.
- Experimental measurements of the fluid properties of LOX when influenced by varying magnetic fields.
- Variance of the point of hydrodynamic breakdown with system pressure.
- Hydrodynamic breakdown under a high magnetic field and high Reynolds number.
- Failure mode of hydrodynamic breakdown and its dependence on the magnetic field gradient.
- Statistical study on the point of hydrodynamic breakdown to determine its probabilistic risk of failure based on system parameters.
- System performance in low power modes and low radii.
- Convective cooling of a solenoid immersed in liquid nitrogen.

5.2.2 Significance to Potential Applications

While a proof of concept cannot be developed based solely on the conclusions of this research, the information obtained does provide significant lessons about the
application of cryogenic magnetohydrodynamics. Namely, the conclusions listed in the System Optimization section are valuable to space systems which must minimize power, mass, and volume while maximizing output in terms of pressure head, flow rate, or heat transfer. It is likely that funding for the next phase of technology development will be based on applicability to an industrial or commercial product; while some of this applicability requires further basic research, design guidelines for increasing efficiency can be developed immediately due to the work performed during this study. These guidelines are only able to be developed because of the confirmed theoretical predictions and established viability of LOX as a working fluid.

In the experiment, the system parameters were considered more efficient when the overall geometry was minimized and the slug and solenoid geometries were optimized to create the greatest amount of pressure change. The work generated by the slug can be calculated as boundary work during the gas compression. With 1.4 kPa of pressure change, the boundary work of the slug was 0.0025 J for the configuration with 1.8 cm$^3$ of downstream volume and 0.0082 J when the setup had 5.9 cm$^3$ of downstream volume. Electrical power input to the solenoid at 900 W is applied for 0.03 seconds until the maximum pressure change is reached and leads to 27 J of input energy. By comparing the ratio of the boundary work output to the electrical energy input, these values imply an overall system efficiency of 0.009% and 0.030%. Using the numerical simulation, the efficiency without damping can be predicted, but only reaches 0.013% and 0.036%, indicating that the viscous losses reduce the boundary work output by approximately 15-30%. The most influential hindrance to efficiency is the high power required to generate the magnetic field. Of the 900 W supplied to the solenoid, a majority of the power is lost
in the heating of the solenoid (other losses may be due to field generation in the materials, but are small by comparison). With the numerical simulation, the temperatures of the solenoids, and therefore, power consumed by Ohmic heating of the solenoids, was known over time. Because of convective cooling, the data only showed 895 W of heating for Solenoid A and 750 W of heating for Solenoid B, but, in actuality, all of the input electrical energy was used to heat the solenoids and the generation of the magnetic field was an induced effect that consumed nothing. By further optimizing the solenoids (for example, by using superconducting wires), they would remain much cooler and could drastically increase the compression efficiency of the system. Assuming that only 1 W of electrical power was required to generated the 1.1 T flux density, that the boundary work generated by gas compression was the same, and that damping was negligible, the system would then operate at 11.9% and 32.4% overall efficiency.

The studies found that the overall system efficiency is hampered by viscous losses, but much more significantly affected by the amount of power required to generate the magnetic field. With respect to industrial applications, the capability of cryogenic magnetohydrodynamic technology will also be limited by the point of hydrodynamic breakdown. Future studies should focus on reducing the Mason number, reducing the amount of power required to generate a magnetic field, and developing a deeper understanding of hydrodynamic breakdown.
APPENDIX
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Student Meritorious Paper Award – 2009 Cryogenic Engineering Conference (2009)
1st Place – 12th Annual Intermountain Graduate Symposium, Engineering Lecture (2009)
1st Place – 12th Annual Intermountain Graduate Symposium, Engineering Poster (2009)
Finalist – USU Man of the Year (2008)
Distinguished Service Award – Associated Students of USU (2008)
Golden Key International Honour Society, (2007-present)
Tomorrow PhD Fellowship – Space Dynamics Laboratory (2006)
2nd Place – AIAA Student Conference-Graduate Division (2006)
Flyer – NASA Reduced Gravity Student Flight Opportunities Program (2004)
University of Washington Dean’s List, (2002-2004)
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American Institute of Aeronautics and Astronautics (AIAA), 2004-present
American Society of Mechanical Engineers (ASME), 2006-present
Cryogenic Society of America (CSA), 2006-present

PAPERS AND PRESENTATIONS


*Observations on Braided Thin Wire Nucleate Boiling in Microgravity*, submitted for publication


*Cryogenic Experimentation on the Magnetohydrodynamics of Liquid Oxygen*, 12th Annual Intermountain Graduate Research Symposium, Engineering Lecture Session (2009)

*Cryogenic Experimentation on the Magnetohydrodynamics of Liquid Oxygen*, 12th Annual Intermountain Graduate Research Symposium, Engineering Poster Session (2009)


*Preliminary Studies for Utilizing Cryogenic Magnetohydrodynamics in Multi-functional Electro/Mechanical Systems*, AFOSR Young Investigators Program (2007)


The Effects of Varying Acceleration Functions on Rayleigh-Taylor Flow in a Microgravity Environment, AIAA Student Conference-Graduate Division (2006)


EMPLOYMENT

Utah State University – Space Dynamics Laboratory, Logan, UT
Fellow, August 2006 – present
Conducted basic research on the magnetohydrodynamics of a liquid oxygen slug; designed, built, and operated a cryogenic experiment while maintaining safety; developed and implemented a theoretical model to describe the 1D slug dynamics using Matlab; reported results to USU faculty, SDL staff, and AFOSR personnel; published in scientific journals and contributed to a collected book on cryogenics

Andrews Space, Inc., Seattle, WA
Intern, Consultant, November 2004 – December 2006
Studied thermal protection systems and developed innovative concepts for reentry ballutes; successfully proposed and managed a Phase I NASA SBIR program; performed heat transfer and CFD studies of reentry dynamics; worked on various projects to support lunar architecture aspect of NASA’s Project Constellation

USRA – Visiting Researchers Exchange & Outreach, Huntsville, AL
Intern, June 2004 – September 2004
Worked at NASA’s Marshall Space Flight Center within the Engineering Directorate; setup experiment to study the “water hammer” phenomenon aboard the Space Shuttle; aided in fluid system design for water filtration system aboard the International Space Station

UW Aeronautical Laboratory – Kirsten Wind Tunnel, Seattle, WA
Crew, January 2003 – June 2004
Operated and maintained an industry level wind tunnel with crew of undergraduate students; reduced, analyzed, and reported wind tunnel data on various test models;
submitted professional reports to industry customers with aerodynamic performance data

**UW Department of Aeronautics and Astronautics, Everett, WA**

*Teaching Assistant*, October 2004 – December 2004

Aided Prof. Kuen Lin in teaching a special offering of AA432: Composite Materials for Aerospace Structures to Boeing employees preparing for shift to 787 work; led weekly tutorial sessions for entry level to senior management personnel; graded homework and tests throughout the quarter

**Toyota Motor Company – Aviation Business Development Office, Torrance, CA**


Created a composite materials database to aid the design and development of a new aircraft; aided flight testing of prototype built at Mojave Airport; presented results of internship to bilingual office

**ADDITIONAL EXPERIENCE**

**AIAA – Utah Section, Logan, UT**

*Young Professionals Officer*, June 2010 – present

Acted as representative for early career aerospace professionals to the Utah Section of AIAA.

**USU Get-Away Special Team, Logan, UT**

*Team Member / Advisor*, September 2006 – present

Advised group of multidisciplinary undergraduate students on technical aspects of microgravity research; founded the USU chapter of the Students for the Exploration and Development of Space (SEDS); supported with proposal, design, and analysis of a water boiling experiment flown in microgravity via NASA’s Reduced Gravity Student Flight Opportunities Program

**Graduate Student Senate, Logan, UT**

*Engineering Graduate Senator*, April 2007 – April 2008

Volunteered as liaison between engineering graduate students and university administration; served on various committees for research symposiums, stipend enhancement awards, etc.; established technical writing workshop and peer review group for engineering graduate students

**Lunar Ventures, Golden, CO**

*Team Lead*, October 2007 – March 2008

Participated in a nationwide competition intended to help integrate the space and terrestrial economies; developed idea for lunar concrete to eliminate lunar dust and mitigate construction costs on Earth; advanced to final round with 5 other teams for $25,000 prize
SEDs-UW Microgravity Project, Kennedy Space Center, FL
Team Lead, Flyer, October 2005 – August 2006
Led the UW chapter of SEDS in a parabolic flight project with the Zero Gravity Corporation; acted as technical lead for the follow-up experiment on generalized Rayleigh-Taylor flow; organized high school outreach program which allowed two students and their teacher to also fly in microgravity

Association of Space Explorers – XIX Planetary Congress, Salt Lake City, UT
Volunteer, October 2005 – October 2005
Interacted with over 60 astronauts and cosmonauts from 11 countries; volunteered with equipment setup, event coordination, and public relations activities

NASA Reduced Gravity Student Flight Opportunities Program, Houston, TX
Flyer, December 2003 – April 2004
Successfully proposed an experiment aboard NASA’s KC-135A “Vomit Comet”; designed, built, and flew a fluid mechanics experiment to study Rayleigh-Taylor flow in microgravity; analyzed results and submitted interim and final reports to NASA

UAB Dept. of Biomedical Engineering Hemodynamics Laboratory, Birmingham, AL
Lab Assistant, July 2001 – September 2001
Assisted graduate researcher with experimental analysis of a coronary stint; worked with PDIV system to acquire and analyze blood flow data; helped to build, maintain, and operate a simulated full-scale human cardiovascular system