

# Cryogenic Experimentation on the Magnetohydrodynamics of Liquid Oxygen

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## ABSTRACT

The increasing demands of the small satellite industry are forcing the development of subsystems with increased reliability and robustness while maintaining harsh mass and volume constraints. Basic research has begun on the cryogenic magnetohydrodynamic properties of liquid oxygen to determine its feasibility as a working fluid in a magnetic system void of mechanically moving parts. A 1D finite-differenced numerical algorithm verified experimental data on the dynamics of a liquid oxygen slug propagated by pulsed magnetic fields. Up to 1.4 T was induced by electrically-sequenced solenoids wound with 30 gauge copper wire. The test section consisted of two solenoids and a 0.075 inch quartz tube and was completely submerged in liquid nitrogen. Because of this, visual confirmation of the slug size was difficult, and the algorithm was also used to determine its length. Using data obtained from upstream and downstream pressure sensors, the lengths were predicted as 3.75 inches for an oscillating slug test and as 2.2 inches for a propagating slug test. The maximum pressure differential obtained was 0.24 psi, which is comparable to ferrofluid-based experiments. The experiment resulted in the most detailed information to date on the paramagnetic susceptibility of liquid oxygen. It is anticipated that this basic research will eventually lead to the development of small satellite subsystems with significantly longer lifetimes.

## NOMENCLATURE

$a$	=	radius of the LOX slug
$A$	=	cross-sectional area of the LOX slug
$B_0$	=	magnetic flux density at the trailing edge of the LOX slug
$B_k$	=	magnetic flux density at the leading edge of the LOX slug
$B_z$	=	centerline axial magnetic flux density of the solenoid
$dP$	=	change in pressure of the downstream section
$dx$	=	displacement of the LOX slug
$f_m$	=	Kelvin force density
$F_m$	=	force due to magnetism
$F_p$	=	force due to pressure

$F_s$	=	force due to shear
$F_t$	=	total net force on the LOX slug
$H_0$	=	strength of the applied magnetic field
$\vec{H}$	=	magnetic field vector
$i$	=	electrical current
$L$	=	length of slug
$\vec{M}$	=	magnetization vector of the LOX slug
$\Delta p$	=	pressure differential induced by the LOX slug
$\Delta p_{max}$	=	hydrostatic breakdown pressure of the LOX slug
$P_1$	=	initial downstream pressure before slug displacement
$P_{GOX}$	=	partial pressure of gaseous oxygen
$r$	=	radial coordinate of the solenoid
$R_{O2}$	=	gas constant of oxygen
$Re$	=	Reynolds number
$T_{amb}$	=	ambient temperature
$v$	=	velocity of the slug
$V_1$	=	initial downstream volume before slug displacement
$V_{int}$	=	internal volume of the plumbing
$z$	=	axial distance to center of solenoid
$\chi$	=	magnetic susceptibility of LOX
$\eta$	=	dynamic viscosity
$\mu_0$	=	permeability of free space
$\rho$	=	density of a fluid
$\rho_{LOX}$	=	density of LOX
$\tau_w$	=	wall shear stress

## INTRODUCTION

The strong paramagnetic susceptibility of liquid oxygen (LOX) has established it as an ideal candidate for a cryogenic magnetic fluid system void of mechanically moving parts. Before a complete system can be designed, laboratory experiments must verify theoretical predictions on the magnetohydrodynamic behavior. These experiments have begun by studying the dynamics of a LOX slug and correlating it to a numerical simulation.

As a paramagnetic material, LOX is attracted to a magnetic field. Paramagnetic susceptibility is the ratio of the strength of magnetization to the strength of the

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applied field and is governed by Curie's Law. Curie's Law states that the susceptibility of paramagnetic materials increases as temperature decreases, explaining why the magnetic effects of oxygen are not seen until well into the cryogenic realm. The fundamental principle of all magnetism lies in the polarity and electron spin within the molecular structure of materials.

Experimentation with LOX is hazardous and must be treated carefully. Oxygen supports combustion and, with enough supply, can make anything flammable. Oxygen intoxication leads to blindness and death and can begin with only a 1% increase above normal. Such stringent safety constraints for laboratory procedures have limited scientific research, but can be overcome with proper preparation and foresight. The experimental study presented is unique because it allowed for repeatable, reliable data on the magnetohydrodynamics of LOX without significant risk to the experimenters.

### **SCIENTIFIC NEED**

Artificial ferrofluids have found commercial application in many areas including the medical, computer, and heat transfer industries. Unfortunately, ferrofluid use is limited due to their structural makeup. Ferrofluids are colloidal suspensions of magnetic nanoparticles embedded in a viscous carrier fluid. The nanoparticles are typically made of rare-earth materials or other iron-containing compounds and could potentially cause physical erosion on a non-supervised plumbing system. Furthermore, interactions between the nanoparticles complicate analyses and contribute to ferrofluids' limited use. To mitigate the interactions, a surfactant is coated on the nanoparticles causing steric repulsion; however, this introduces a potential threat to chemical corrosion.

As a pure substance, LOX is essentially a magnetic fluid with paramagnetic particles down to the molecular limit. The challenges of working with oxygen have been known for decades and do not require advanced materials development. For space applications, LOX is already used in propulsion, thermal management, and life support systems. In addition, LOX's paramagnetic susceptibility is higher than any other pure substance thus making it ideal for a space-based magnetic fluid system.

Using LOX to replace mechanically moving parts where applicable would reduce a subsystem's risk of failure and increase its adaptability to change. As moving parts rub and grind on each other, considerable friction and damage can occur. A magnetic fluid system would prevent the need to repair or replace these limited-lifetime parts, and eliminate the need for expensive space-rated lubrication. Furthermore, a

magnetic fluid system would have increased robustness since its operating principle is governed by a simple command algorithm. Without the physical limitation of moving parts, the system has much more flexibility and an increased range of operation.

The advantages listed above are particularly beneficial to satellite applications where human interaction is not possible. Easy integration, enhanced reliability, and increased robustness have the potential to drastically increase a satellite's lifetime and expand mission timelines. Small satellites in particular would be effected because the system could potentially become much more compact than available technology. Conversely, small satellites become useful to the technology because they are the perfect platform for flight readiness certification for an advanced system. Unfortunately, system development cannot occur until cryogenic magnetohydrodynamics and their potential applications are fully understood through basic research.

### ***Similar Work***

Magnetohydrodynamic theory has been studied for decades, but applying the field to the cryogenic realm is much more difficult. Nonetheless, lessons can be learned from other experimenters seeking to design magnetic fluid systems with artificial ferrofluids.

Seo and Park<sup>1-5</sup> have developed a magnetic fluid linear pump that uses the surface tension of a magnetic fluid to propel an immiscible pumping liquid with magnetic yokes. Their small, lightweight magnetic fluid pump is capable of producing 0.3 psi of pressure and, although intended for medical applications such as infusion pumps or artificial hearts, is treated as the baseline for comparison. Other magnetic fluid pumps created by Krauss<sup>6</sup>, Hatch<sup>7</sup>, and Liao<sup>8</sup> were studied during preliminary trade studies, but could not produce as much pressure as Seo and Park's pump. It is noteworthy to mention that all these pumps use artificial ferrofluids with very high susceptibility, whereas the current study focuses on LOX. LOX has the strongest paramagnetic susceptibility of pure fluids, but is still about 30 times weaker than an inexpensive ferrofluid.

Youngquist<sup>9</sup>, et. al., of the Kennedy Space Center performed the only found scientific experimentation on the magnetohydrodynamics of LOX. By purging a U-tube with oxygen and immersing it in an open bath of liquid nitrogen, Youngquist was able to pulse a solenoid at one end and study the dynamics at the other. Youngquist ceased studies before any significant understanding could be achieved, but created a numerical model to simulate the experiment. This model was used as a starting point for development of a more advanced simulation.

After researching the most recent technology developments in magnetic fluid systems, a series of goal and objectives were outlined for the current study.

### Goals and Objectives

As mentioned, the field of magnetohydrodynamics becomes more complex when applied to the cryogenic realm due to Curie's Law. While several theoretical models account for the changing physics, no experimentation has been found studying the field of cryogenic magnetohydrodynamics to a high level, thus forming the basis of this study.

The overall goals listed reflect the long term scope of the project and are necessary for the development of complete subsystems. The overall goals are as follows:

**1) Obtain a fundamental understanding of cryogenic magnetohydrodynamics.**

– Cryogenics and magnetohydrodynamics are individually well-understood, but complicate analyses when combined.

**2) Determine the feasibility of a magnetic fluid system with no moving parts.**

– A thorough analysis on 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 experimentation and analyses.

If these goals are achieved, a significant advancement will have been established. With the information gained, the basic research will have been completed, and subsystems could be designed for any application.

For the short term, specific objectives can be attained which support and initiate the overall goals. These specific objectives are 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) Create detailed performance charts.**

– Characterizing LOX performance for certain scenarios will enable future researchers to develop advanced subsystems.

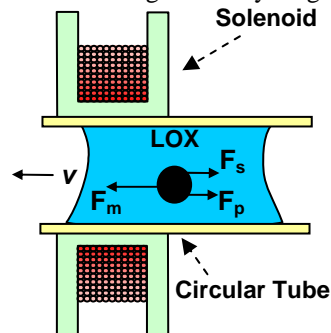
**4) Simulate numerically.**

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

The objectives will prove the viability of LOX as a working fluid and lead the way for advanced, applied research. To accomplish these objectives, an experimental apparatus was designed and a numerical simulation was created.

### ANALYTICAL METHOD

Magnetohydrodynamic theory has existed in some form or another since the famous discovery of electromagnetic induction by Faraday. Most modern researchers follow methodology developed by Rosensweig<sup>10</sup> for high-level analysis, and so the governing equations he presents were used to describe the motion of a slug of LOX under a magnetic field. The experimental procedure studies a slug undergoing the forces in the following free body diagram.



**Figure 1. Free Body Diagram of LOX Slug Dynamics.**

In Figure 1, the magnetic force,  $F_m$ , is greater than the combined shear force,  $F_s$ , and pressure force,  $F_p$ , and results in a net velocity to the left. As the slug's momentum moves it past the solenoid, the magnetic force changes direction and the slug is pushed in the other direction. The shear force dampens the slug's velocity and an eventual steady-state will balance only the magnetic and pressure forces. If the pressures on either side are in equilibrium, the slug will center itself on the solenoid since magnetism acts as a body force. To develop the numerical simulation, a mathematical analysis of the forces is required.

### Theory

The total force on the LOX slug is made up of pressure, shear, and magnetic forces as shown below.

$$F_t = F_p + F_s + F_m \quad (1)$$

The force due to pressure accounts for differences in the surface pressure on either side of the solenoid. It can be expressed as shown in Equation 2,

$$F_p = A\Delta p \quad (2)$$

The force due to wall shear can be expressed as shown in Equation 3.

$$F_s = 2\pi\tau_w AL \quad (3)$$

In the laminar region, the steady state wall shear stress can be identified as simply  $8*\rho_{LOX}*u^2/Re$ . But upon transition to turbulent flow ( $Re \sim 2100$ ), the Blasius correlation for turbulent flow in a circular duct must be used. White<sup>11</sup> presents the Blasius correlation for turbulent wall shear stress as shown in Equation 4.

$$\tau_w = 0.0396\rho^{3/4}v^{7/4}\eta^{1/4}a^{-1/4} \quad (4)$$

By orienting the tube horizontally, the force due to magnetism is the only body force present. Rosensweig<sup>10</sup> presents the Kelvin force density as

$$f_m = \mu_0(\overline{M} \cdot \nabla)H_0 \quad (5)$$

For soft magnetic materials, Ampere's Law ( $\nabla \times \overline{H} = 0$ ) can be used to translate Equation 5 into the more useful form shown below.

$$f_m = \frac{\mu_0\chi}{2}\nabla(\overline{H} \cdot \overline{H}) \quad (6)$$

The axial component of Equation 6 can be integrated and reduced using the definition of the induced magnetic flux density as shown in Equation 7.

$$F_m = A\frac{\chi}{(1+\chi)^2}\frac{1}{2\mu_0}(B_k^2 - B_0^2) \quad (7)$$

The subscript  $k$  denotes the leading edge of the solenoid and the subscript  $0$  denotes the trailing edge. A solenoid optimization study analyzed the axial and radial fields at all points in the solenoid; however, for the numerical simulation, only the axial field along the center was considered. The axial magnetic field along the center of a loop of a current-carrying wire can be expressed at any point as a function of the loop's radius and axial distance as shown below.

$$B_z = \frac{i\mu_0r^2}{2(r^2 + z^2)^{3/2}} \quad (8)$$

Finally, Perry and Jones<sup>12</sup> experimentally confirmed theoretical calculations for the hydrostatic breakdown of a magnetic fluid. The hydrostatic breakdown is essentially the maximum pressure differential a slug can withstand and is described by Equation 9.

$$\Delta p_{\max} = \frac{1}{2\mu_0}\frac{\chi}{(1+\chi)^2}(B_k^2 - B_0^2) \quad (9)$$

As seen by comparing Equations 7 and 9, the hydrostatic breakdown occurs when the magnetic and pressure forces are balanced.

Internally, the fluid dynamics within the LOX slug can be described by a dampening oscillating magnetic body force with fixed walls. White<sup>11</sup> presented a solution to Stokes's 2<sup>nd</sup> Problem of an oscillating plate and remarks on the internal velocity profile if instead the plate were held fixed and the fluid mean velocity oscillated. He noted that a near-wall velocity overshoot dubbed Richardson's annular effect decreased the wall shear but did not present an analytical description. White does present an analysis for the pipe flow due to an oscillating pressure gradient and states that the measure of viscous effects in oscillating flows is determined by the kinetic Reynolds number. Unfortunately, Richardson's annular effect and the kinetic Reynolds number are both functions of viscosity. Previous experiments on ferrofluid pipe flow by Cunha<sup>13</sup>, Felderhof<sup>14</sup>, Kamiyama<sup>15</sup>, Krekhov<sup>16</sup>, Schumacher<sup>17</sup>, and Shimada<sup>18</sup> have found magnetically-induced changes in viscosity ranging from 20% to 10 times as great. The viscosity changes are effected by field strength and magnetic fluid structure, but until it is experimentally confirmed with some precision for LOX, the internal flow cannot be completely described. Despite this, the overall dynamics are still well-described with steady-state assumptions for wall shear stress indicated previously.

Once completed, the aforementioned performance charts will report the experimentally-found breakdown pressure for a variety of configurations for LOX and correlation to theory.

### Numerical Simulation

The numerical simulation is a 1D finite-differenced multiphysics algorithm written in MATLAB<sup>®</sup>. The above equations were discretized and sequenced over time with an assumed slug length, initial position, and initial velocity to determine the overall absolute slug dynamics. Aside from the displacement of the slug itself, upstream and downstream pressure changes were also calculated, assuming known closed volumes on either side of the slug. Equation 10 shows the calculation for the downstream pressure change based on displacement. In the experimentation, the pressure change was measured and correlated to this calculation. Note that as  $dx$  increases,  $dP$  decreases; thus indicating expansion in the downstream side and compression in the upstream side.

$$dP = \frac{P_1 V_1}{V_1 + \pi a^2 dx} \quad (10)$$

The numerical simulation assumes LOX is incompressible; future, more rigorous testing may need to account for the bulk modulus and resonant frequencies. The simulation also assumes negligible leak rates, negligible gravity, and constant material properties. The block diagram in Figure 2 illustrates the program flow and parameters passed during operation.

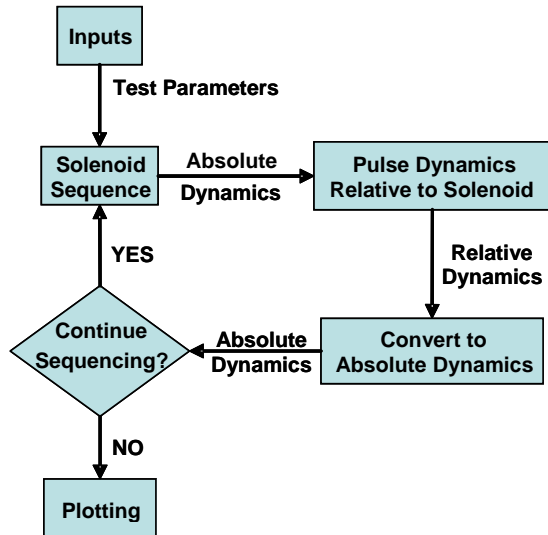


Figure 2. Numerical Simulation Block Diagram.

The slug dynamics were calculated relative to each solenoid, and then collaborated to determine the absolute changes in displacement and velocity. Equation 8 was integrated for every turn of wire in the solenoid and used to determine the magnetic field at the leading and trailing edges of the solenoid. Furthermore, current was seen as a function of time due to electrical transient and solenoid heating. As a constant voltage was applied, the solenoid heated up and wire resistance increased. The increased resistance decreased the amount of current that can flow. Preliminary testing was used to find the solenoids' specific heat capacity, thereby allowing the prediction of solenoid heating and current drop as a function of applied voltage over time.

Youngquist's numerical model employed empirical damping coefficients, whereas real physics could be used to determine the wall shear and dampening effects on the slug. Unfortunately, as mentioned previously, the viscosity of a magnetic fluid changes when a field is applied and such studies have not been performed with LOX. It is believed that the test apparatus designed will eventually be able to measure these changes; however, the non-magnetized viscosity for LOX ( $\eta = 252 \mu\text{Pa}\cdot\text{sec}$ ) was used to initiate the simulation and increased when necessary to match experimental data. Theoretical predictions by Bacri<sup>19</sup>, Cheng<sup>20</sup>, Kroger<sup>21</sup>, McTague<sup>22</sup>, and Odenbach<sup>23</sup> were used to guide the simulation, but cannot be considered complete until experimental verification occurs with LOX.

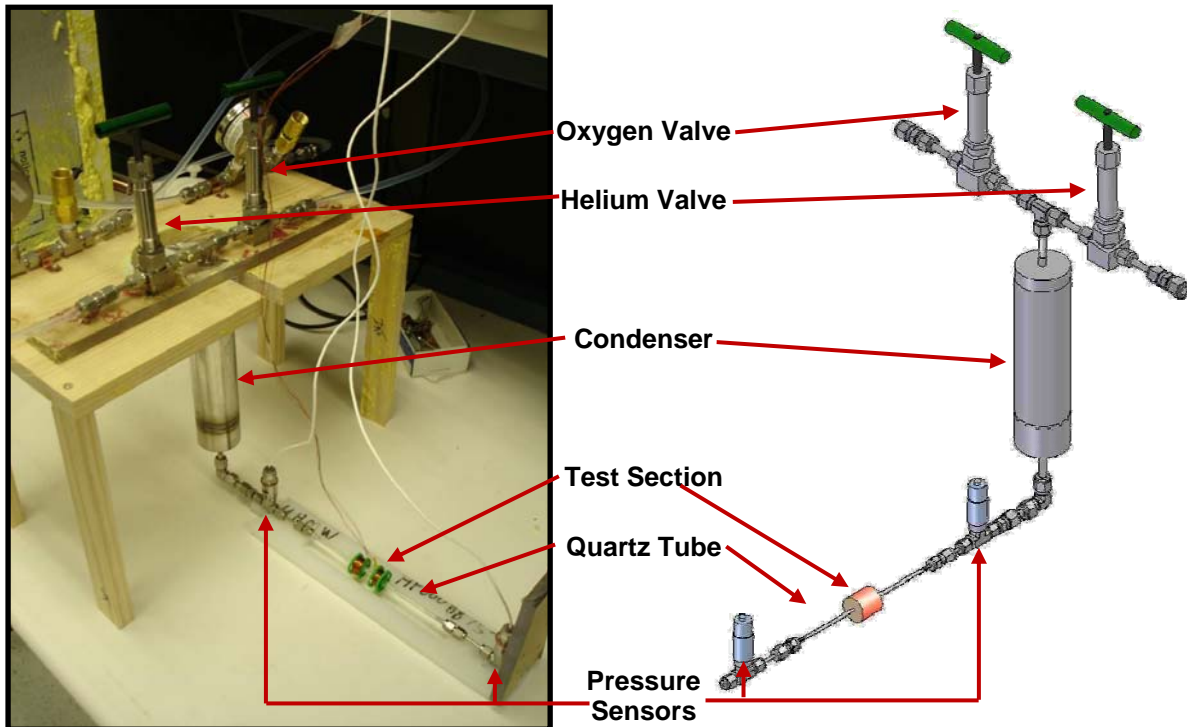


Figure 3. Cryogenic Experimentation Test Apparatus.

Preliminary testing with a ferrofluid was conducted to verify various aspects of the numerical simulation; however, the cryogenic test apparatus was required for complete verification.

**EXPERIMENT DESCRIPTION**

**Apparatus Design**

The test apparatus was designed with control, safety, and interchangeability as top priorities. In order to ensure oxygen would remain liquefied, all testing occurred in a liquid nitrogen (LN2) bath with the inlet valves submerged to mitigate thermal acoustic oscillations. Helium acted as the surrounding gas for the LOX slug due to its inertness and low boiling point. After inlet valves were closed, the total system volume was approximately 20.7 in<sup>3</sup>, although only about 0.2 in<sup>3</sup> exists downstream of the test section. The small, closed volume downstream of the test section allowed for high pressure fluctuations when the slug was displaced.

The solenoids and test section were created by wrapping a 30-gauge copper wire on several plastic bobbins and then sliding them over a 0.075” ID quartz tube. When the solenoid was immersed in liquid nitrogen, its resistance dropped and a magnetic field density of 1.4T was obtained with about 22 amps of electrical current. With this setup, the hydrostatic breakdown occurs at around 0.45 psid, if it can be obtained.

The quartz tube interfaces with stainless steel plumbing through Teflon heat shrink tubing that allows for easy interchangeability of the test section. The maximum pressure in the system does not exceed 25 psia and all fittings, including the heat shrink, provide a helium-

tight seal with leak rates less than 0.004 psi/min. Pressure sensors upstream and downstream of the test section record at 5 kHz and are precise within 0.01 psi at condition. A photograph and CAD drawing of the plumbing setup can be seen in Figure 3.

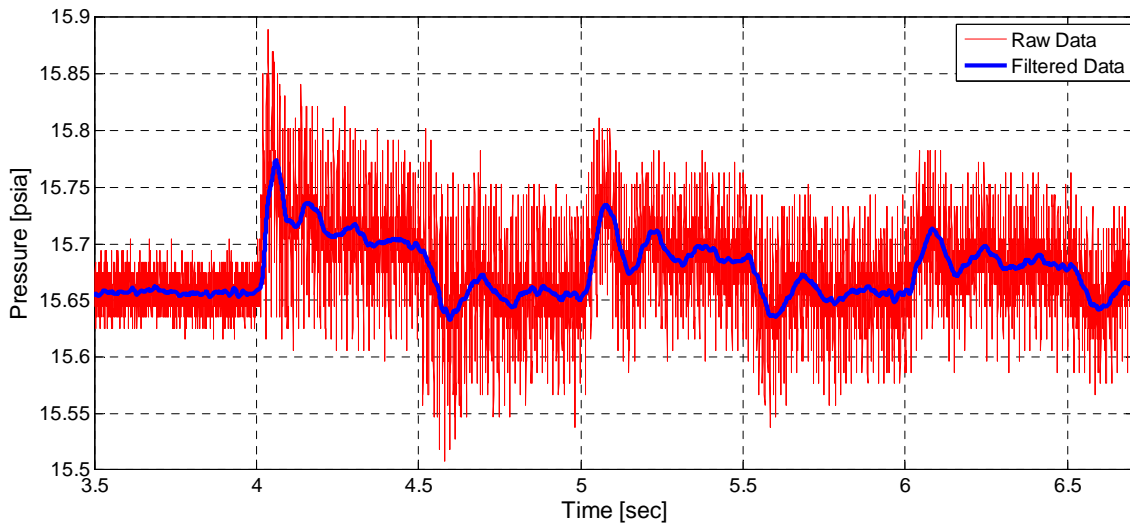
**Operations**

Because the testing took place at high altitude, the ambient pressure was only 12.6 psia. Therefore, the operating regime was 13-20 psia to prevent a cold vacuum. While warm, the system was purged with helium and then reduced to near atmospheric pressure. Next, gaseous oxygen was introduced so that its partial pressure was consistent with the desired length of LOX slug. Using mass conservation, the predicted slug length was,

$$L = \frac{P_{GOX} V_{int}}{R_{O2} T_{amb}} \frac{4}{\rho_{LOX} \pi a^2} \quad (11)$$

The system was then immersed into LN2 and the oxygen was allowed to condense. Additional helium was added during cooling to maintain the desired operating pressure. The condenser seen in Figure 3 dually acts as a heat exchanger and safety mechanism in the case of sudden expansion of the liquid oxygen. Once condensed, the slug was positioned in the test section with a magnetic wand and was visually observed as the LN2 boiling diminished. Unfortunately, at this point, the exact slug size could not be measured, but future testing will attempt new approaches to improving visibility.

The solenoids were pulsed with a 900W power supply and sequenced using real-time test software based on



**Figure 4. Experimental Data on a 3.75” Oscillating LOX Slug.**

MATLAB/Simulink/xPC Target<sup>®</sup>. The current response time was less than 3 msec. Thus, the pulse sequencing algorithm was highly controllable without significant delay or uncertainty. Testing at low pulsing frequencies has started.

### RESULTS AND SIGNIFICANCE

Data collection began in March 2009 and has already produced the highest quality data on the magnetohydrodynamics of liquid oxygen. Figure 4 shows the raw and filtered data for downstream pressure when the solenoids were switched at 2 Hz. The numerical simulation was used to estimate the slug length as 3.75 inches.

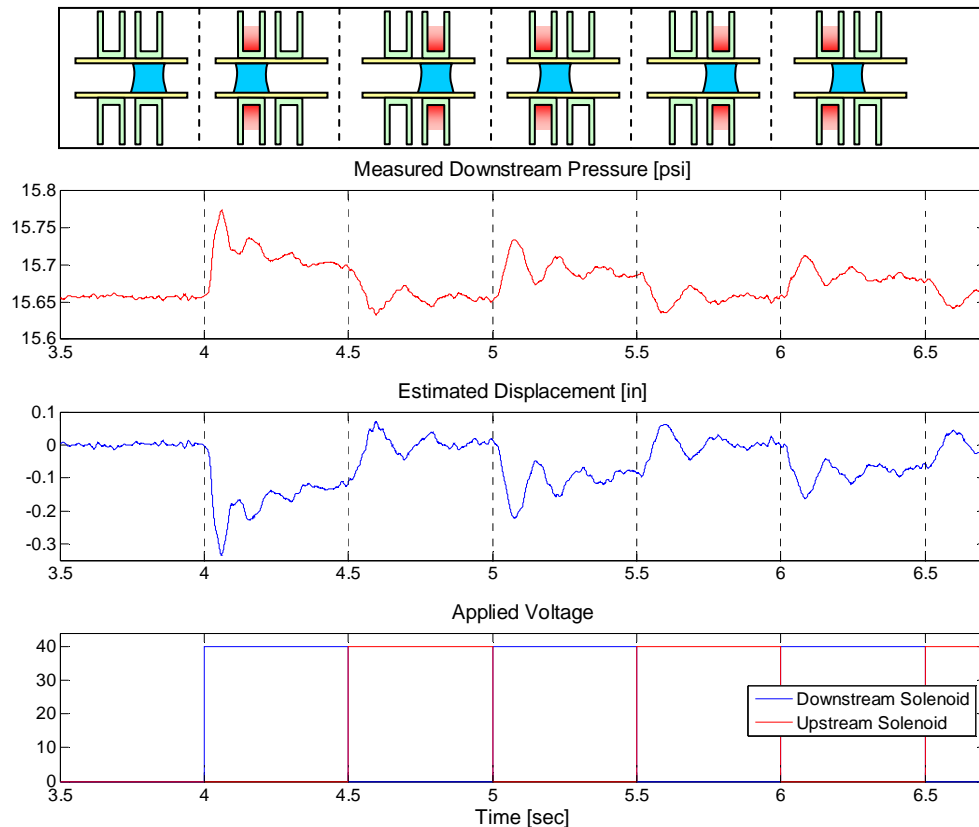
The noise in the raw data was reduced by using a Chebyshev Type II lowpass filter that was set at 45 Hz and reduces to -40 db at 50 Hz.

To illustrate the dynamics, Figure 5 shows the filtered downstream pressure, estimated displacement, and applied voltage over time with indicators for slug position.

At 4 seconds, the downstream solenoid was switched on and the slug was pulled into the magnetic field. The

dampening oscillations were due to the counteracting forces shown in Equation 1. When the power switched to the upstream solenoid, the slug returned to its original position, still with the dampening oscillations. The process was repeated and the slug was transferred back and forth between the solenoids as shown in the illustration. With a known downstream volume and because helium can be analyzed as an ideal gas, the displacement of the slug could be estimated within 0.03 inches. The vertical dashed lines illustrate when the 40V was switched from solenoid to solenoid every half second.

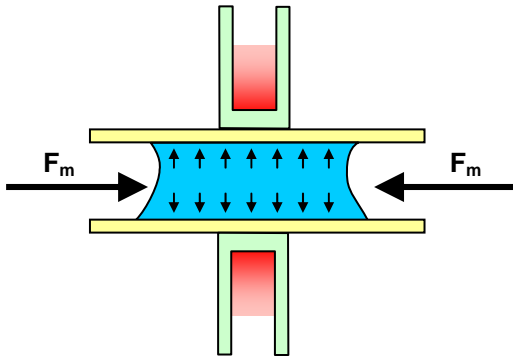
During the periods of time when the downstream solenoid was powered, the mean pressure decreased due to increased wire resistance as the solenoid heated up. The increasing resistance reduced current and, therefore, the applied magnetic field. If the solenoid were left powered on, the current and magnetic field would continue to drop and the LOX slug would continue regressing to its original position because it could not overcome the pressure differential with the decreasing magnetic force. The effect was not as pronounced when the upstream solenoid was powered because the upstream and downstream pressures were near equilibrium. The solenoid heating was accounted for in



**Figure 5. Induced Pressure, Estimated Displacement, and Applied Voltage for a 3.75'' Oscillating LOX Slug (illustration not to scale).**

the numerical model.

In order to accurately model the wall shear dampening effects, the viscosity of LOX had to be increased beyond its known level, thereby indicating strong magnetoviscous effects. During peak velocity, the Reynolds number reaches as high as 9200, indicating that the slug transitions from laminar to turbulent flow with nearly every oscillation. This further complicated the viscosity and wall shear analysis. The effects of a magnetic fluid's field-induced viscosity have been studied since 1969, but as aforementioned, are still not completely understood. In order to match the simulations to the data, the viscosity of LOX had to be increased to about 5 times greater than its non-magnetized value. This is consistent with the aforementioned studies on magnetoviscous effects, but may not be the only reason for increased damping. In this case, the high wall shear may also have resulted from slug inducing radial pressure on the wall as a result of the unknown internal flow field as shown in Figure 6.



**Figure 6. Magnetically Induced Radial Pressure.**

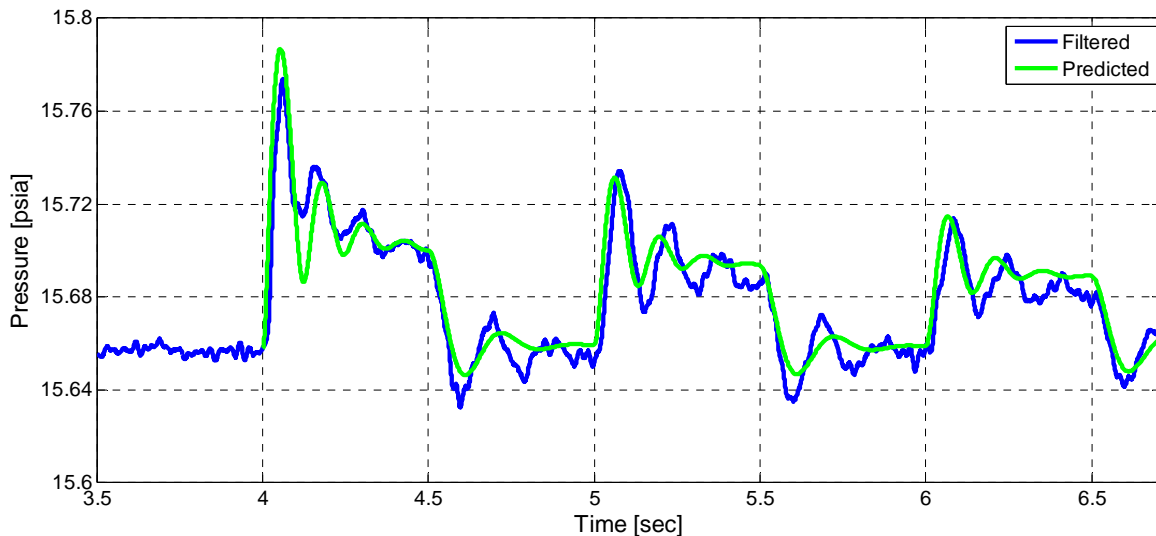
As the magnetic field drew in the incompressible LOX from both sides, an outward radial pressure was induced. The extra force on the wall increased the wall shear and accounts as an additional dampening force.

With the increased wall shear, the dynamics for the first pulse was modeled and the slug length was estimated to be approximately 3.75 inches, as mentioned earlier. Considering the length to diameter ratio of the slug was  $> 40$ , there was a high probability that a gaseous helium bubble was effecting the dynamics. The bubble would contribute to the force at which the slug returns to its original position and may be effecting the simulation. Further testing will attempt to create shorter slugs to eliminate this possible source of error.

Figure 7 shows the filtered downstream pressure and correlation to the numerical model.

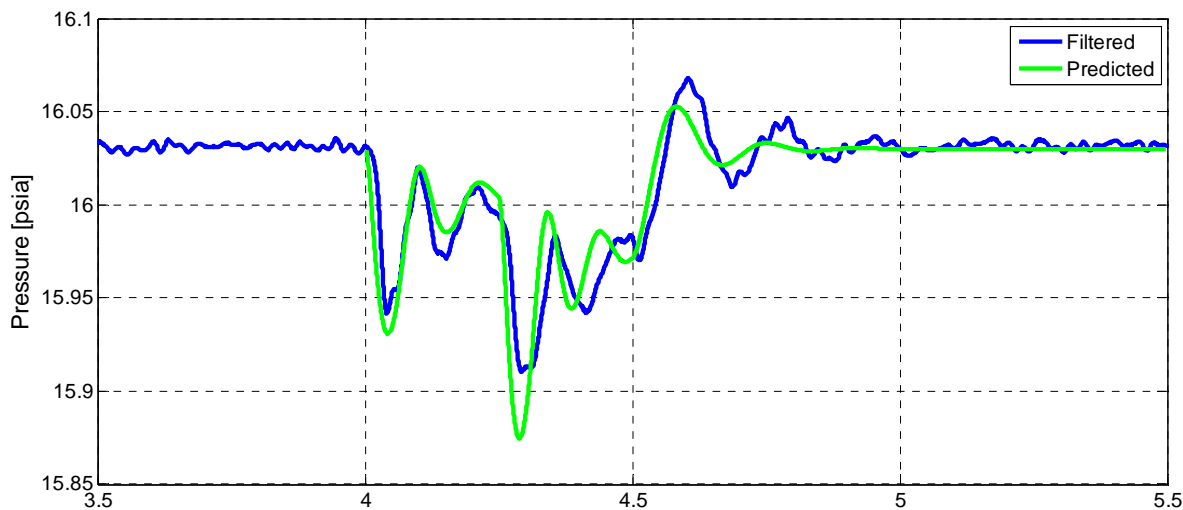
The results from another test are shown in Figure 8 showing a 2.6 inch slug being pulled upstream by the solenoids in series and then released. This test demonstrated the capability of operating at a slightly higher pulsing frequency (4 Hz) than in Figure 7 (2 Hz) but was stopped after one cycle to study the post-pulsing behavior.

The test shown in Figure 8 also demonstrated the capability to propagate a slug continually in one direction against pressure. This type of sequencing will be used to test the hydrostatic breakdown pressure and characterize the limits of the viability of LOX. The maximum slug velocity in Figure 8 also indicates that the operating frequency can be increased up to about 30 Hz. Ideally a unidirectional system would only propagate the slug to its maximum velocity and then



**Figure 7. Numerical Correlation to Experimental Data of a 3.75'' Oscillating LOX Slug.**





**Figure 8. Numerical Correlation to Experimental Data of a 2.2'' Linearly Driven LOX Slug.**

release when the momentum peaks. This would increase efficiency in maximum induced pressure differential and power required for operation. The next series of experimentation will test this concept as well.

All experimentation shown was performed with a two solenoid test setup. These initial tests have been successful in characterizing the slug dynamics, but have not yet been able to achieve the hydrostatic breakdown pressure. The maximum induced pressure differential was about 0.24 psi, which is about half the breakdown pressure, but very close to the 0.3 psi attained by Park and Seo. Future tests will use more solenoids to propagate the slug further and induce higher pressures.

### **CONCLUSION**

In conclusion, the magnetohydrodynamics of LOX have been well studied and important steps have been made in its basic research. The apparatus designed has produced data which can be used to verify a numerical simulation. The numerical simulation performs well for a single pulse, but seems to falter as the solenoids are sequenced. This is most likely due to the changing viscosity due to a magnetic field. Nonetheless, the steady-state assumptions described the dynamics reasonably well, but in order to achieve greater precision, the magnetoviscous effects of LOX must be known.

The internal flow dynamics of a LOX slug being pulsed by magnetic fields is a complicated subject which originally was thought unnecessary to explain the overall bulk motion of the fluid, but the higher than expected damping of the fluid indicates otherwise. At this point, it is unknown whether the viscosity changes

in LOX accounted for the increased damping, or if other fluid phenomena were occurring. A 3D multiphysics CFD analysis is required to fully study the internal fluid flow.

As a scientific instrument, the test apparatus has done well in providing precise data in a variety of test scenarios. Future testing will address the viscosity, uniformity, and compressibility of LOX under a magnetic field to refine the numerical simulation. Once adequately correlated, the numerical simulation and test apparatus will produce data on the performance of LOX and help to design complex subsystems based on magnetic fluids. These subsystems would be ideal for small satellites due their enhanced reliability and robustness. In the meantime, small satellites would be ideal for advanced testing of a magnetic fluid system as a cheap method for flight readiness verification.

In all, the experiments performed confirm the viability of LOX as a working fluid in a magnetic fluid system. The tests have achieved pressure differentials at the same level as those by previous experimenters using artificial ferrofluids, and design improvements seek to increase the differential even further. Once the hydrostatic breakdown limit has been experimentally determined, systematic performance charts can be created which will enable the design of advanced systems and lead the way to further applied research. It is envisioned that these advanced systems will enable longer lifetimes for small satellites subsystems and increase the range of operations for which they can perform. This basic research has taken the first steps to proving that such a system is possible and future experiments will determine its limits.

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