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Influence of geometry on liquid oxygen magnetohydrodynamics

Jeffrey C. Boulware [a,*], Heng Ban [a], Scott Jensen [b], Steve Wassom [b]

[a] Department of Mechanical and Aerospace Engineering, Utah State University, 4130 Old Main Hill, Logan, UT 84322-4130, USA
[b] Space Dynamics Laboratory, Utah State University Research Foundation, 1695 North Research Park Way, North Logan, UT 84341, USA

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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 nondimensional 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.

1. 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.

1.1. 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.

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* Corresponding author. Address: 1695 North Research Park Way, North Logan, UT 84341, USA. Tel.: +1 206 818 4432; fax: +1 435 797 4495.

E-mail addresses: j.c.boulware@aggiemail.usu.edu (J.C. Boulware), hban@engineering.usu.edu (H. Ban), sjensen@sdl.usu.edu (S. Jensen), swassom@sdl.usu.edu (S. Wassom).

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Nomenclature

Symbols

a	tube inner radius [m]
$\mathbf{B}$	magnetic flux density [T]
$\mathbf{B}_{max}$	maximum magnetic flux density during a run [T]
dt	time to reach the maximum displacement of the slug [s]
dx	axial distance from a loop of coil in the solenoid [m]
F_D	damping force [N]
f_m	Kelvin force density [N/m^3]
F_M	magnetic force in the axial direction [N]
F_P	pressure force [N]
$\mathbf{H}$	magnetic field vector [A/m]
I	applied current [A]
L	visible slug length [m]
L_{hidden}	hidden slug length [m]
m	combined mass of the visible and hidden slugs [kg]
$\mathbf{M}$	magnetization vector [A/m]
Ma	Mason number, ratio of damping to magnetic forces [–]
p_m	magnetic pressure [kPa]
p_m^*	nondimensional initial magnetic pressure [–]
r	radius of a single loop of coil in the solenoid [m]
$\dot{s}$	velocity of the slug in the axial direction [m/s]
$\ddot{s}$	acceleration of the slug [m/s^2]
s^*	nondimensional maximum displacement of the slug [–]
s_{max}	maximum displacement of the slug [m]
u_a	Alfven velocity [m/s]
u_i	average initial velocity of the slug [m/s]
Vol_{DS}	volume in the downstream section of the plumbing [m^3]
χ	volumetric magnetic susceptibility [–]
Δp	pressure differential across the slug [kPa]
η	nonmagnetized dynamic viscosity of LOX [Pa s]
μ	relative permeability [H/m]
μ_0	permeability of free space [H/m]
ρ	density of LOX at 77 K, 101 kPa [kg/m^3]
τ_w	wall shear stress [kPa]
ζ	damping factor [–]

Subscripts

DS	downstream
i	initial
$loop$	individual loop
US	upstream
x	axial direction

Hatch et al. [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 et al. [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 cm^3/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 et al. [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/s and a magnetic field of 800 A/m.

In an applied sense, Goldstein [7] and Kamiyama [8] attempted to create bio-compatible devices for surgical implants. Ming et al. [9] and Jeyadevan et al. [10] augmented heat pipe performance by placing permanent magnets near the warm end. Liao et al. [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.

1.2. 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.