Magnetohydrodynamic Propulsion Drive for Marine Transportation

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2.0 INTRODUCTION

- Conventional marine propellers have remained the standard propulsion mechanism for surface ships and underwater vehicles for over 200 years. However, propellors face several issues including noise, cavitation, and the need for extensive mechanical maintenance.

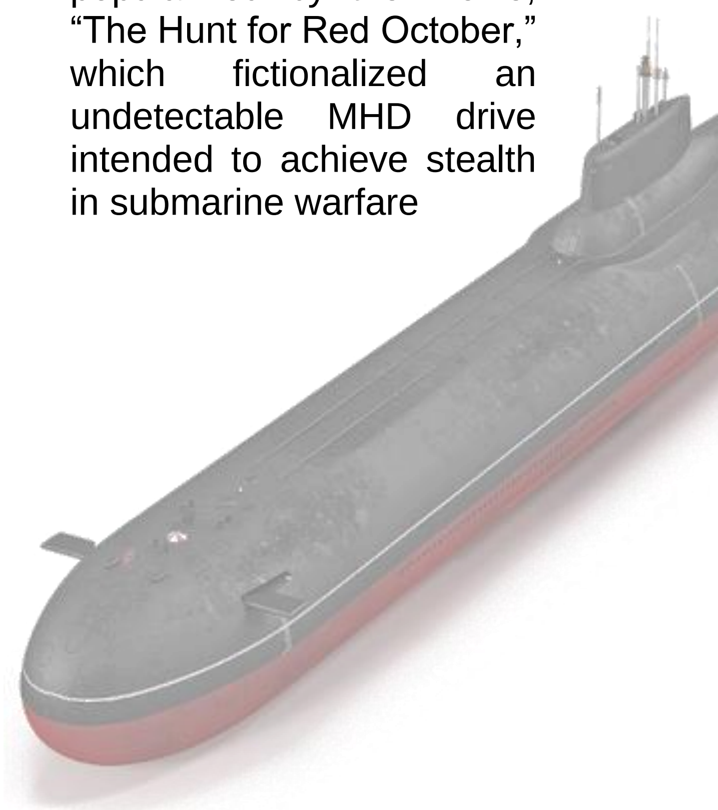
- This study will develop a magnetohydrodynamic (MHD) drive as a more reliable and silent alternative to traditional propellors. MHD drives directly accelerate seawater without any moving components such as propellors through the concept of the Lorentz force, which describes the forces on charged particles subjected to an electromagnetic field [1-10].

- **Benefits**: MHD drives hold the promise to be a more reliable and silent alternative to traditional propellors due to the elimination of any mechanical movement or fluid vibration, and the related wear and tear on motors, gearboxes, transmission shafts, and propellers.

- **Project Goal**: This study will assess the design elements that maximize the flow rate for MHD drives, including magnetic field strength, current density, and channel geometries.

- **Design Criteria**
  - Target minimum seawater flow rate of 30 cm^3/s operating for a minimum period of 30min at a maximum power load of 500 watts

MHD drives were popularized by the movie, “The Hunt for Red October,” which fictionalized an undetectable MHD drive intended to achieve stealth in submarine warfare



3.0 METHODS

3.1 Theoretical Foundations

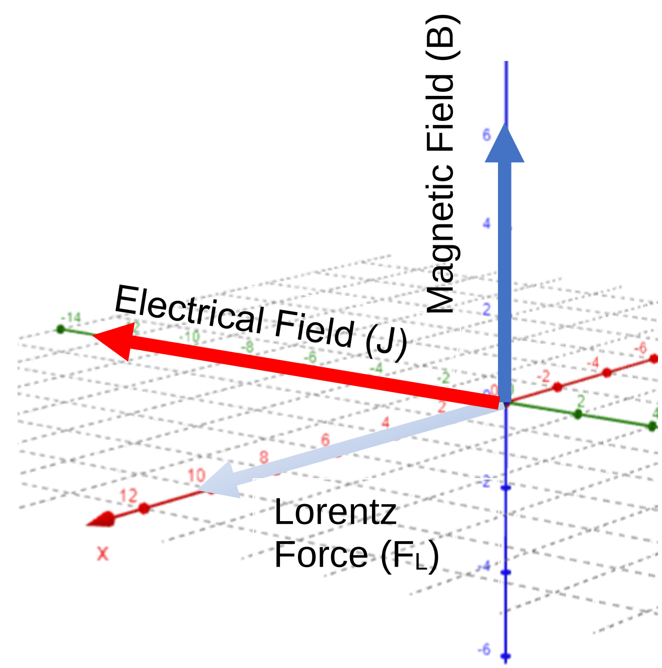
- When a conductive fluid is placed under the influence of a magnetic and electric field, the Lorentz force propels the fluid in a direction perpendicular to both the magnetic and electric fields
- Equations governing MHD are based on solving
  - Navier-Stokes equations for fluid mechanics
  - Maxwell's equations for electromagnetism
- While the derivation of the MHD equations is beyond the scope of this study, two equations describe the Lorentz force (F_L) which directly generates seawater flow at a flow rate (u)

$$F_L = JB \qquad (1)$$

$$u \sim \sqrt{\frac{1}{\rho} JBG} \qquad (2)$$

- Flow rate is proportional to
  - Magnetic field strength (*B*)
  - Current density of electric field (*J*)
  - Electrode gap (*G*)

Left-Hand Rule

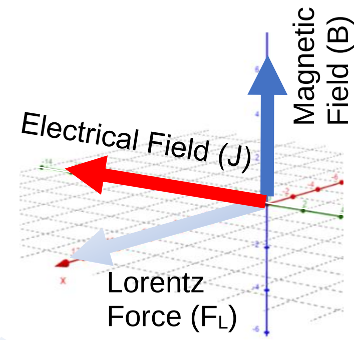


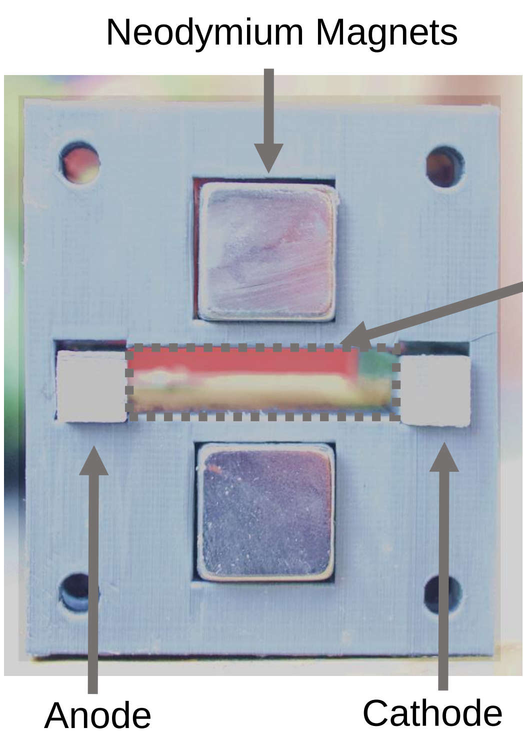
Variable		Unit	Description
F_L	Lorentz force	(Newton x sec)/(Coulomb x meter)	Force applied to fluid
J	Current density	Amps/cm^2	Electrical current per electrode area
B	Magnetic field	Gauss	Static magnetic field
u	Fluid flow rate	m^3/s	Volume of water displaced
ρ	Fluid density	kg/m^3	Water salinity
G	Electrode gap	cm	Distance between electrodes

3.0 METHODS

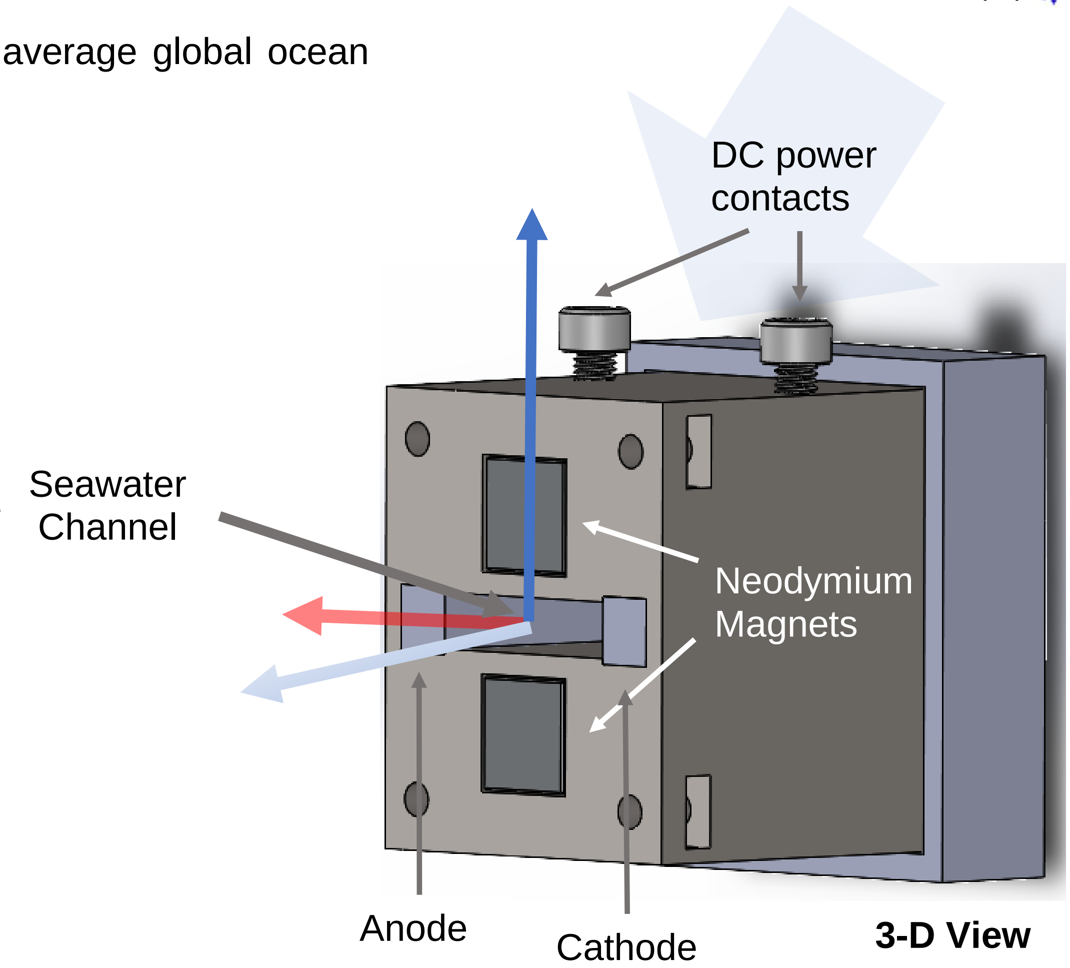
3.2 MHD Pump Design

- MHD drive housing designed in SolidWorks and 3D printed
- Electric field generated by aluminum electrodes connected to a 300W DC power generator (0-30V & 1-10A)
- Magnetic field generated by N52 neodymium permanent magnets
- Seawater solution prepared based on average global ocean salinity (35 ppt NaCl)





2-D Cross-Section



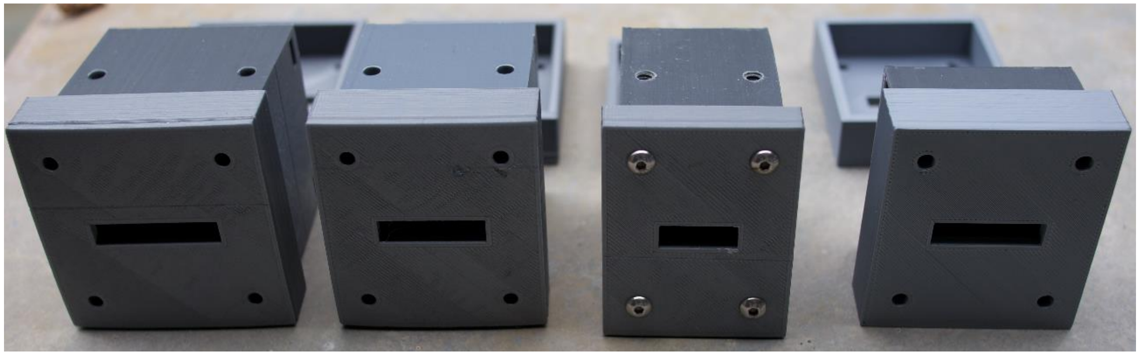
3-D View

3.0 METHODS

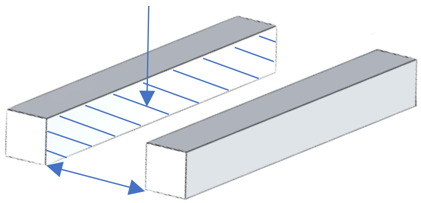
3.3 Testing Process

- Four different drive housings were designed to test the impact of various channel geometries on flow rate
- The two primary variables tested were electrode gap and electrode area

Rear view



Front view



Channel Geometry

Electrode Gap (in)	1.2	0.7	1.0	1.2
Electrode Area (in^2)	0.25	0.5	0.5	0.5

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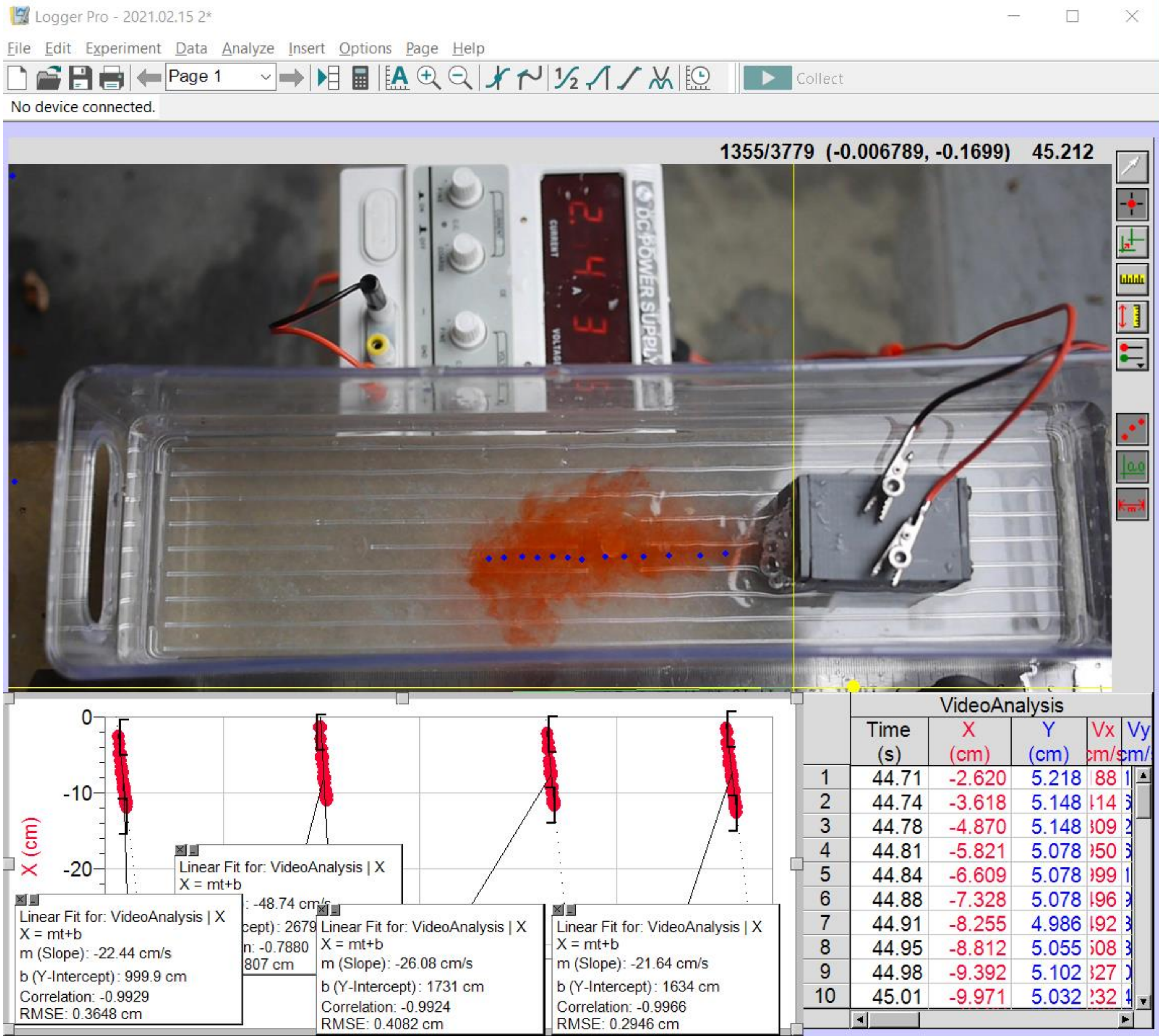
[Video Link: MHD in Operation (bit.ly/MHDdemo)](bit.ly/MHDdemo)

3.4 Testing Process

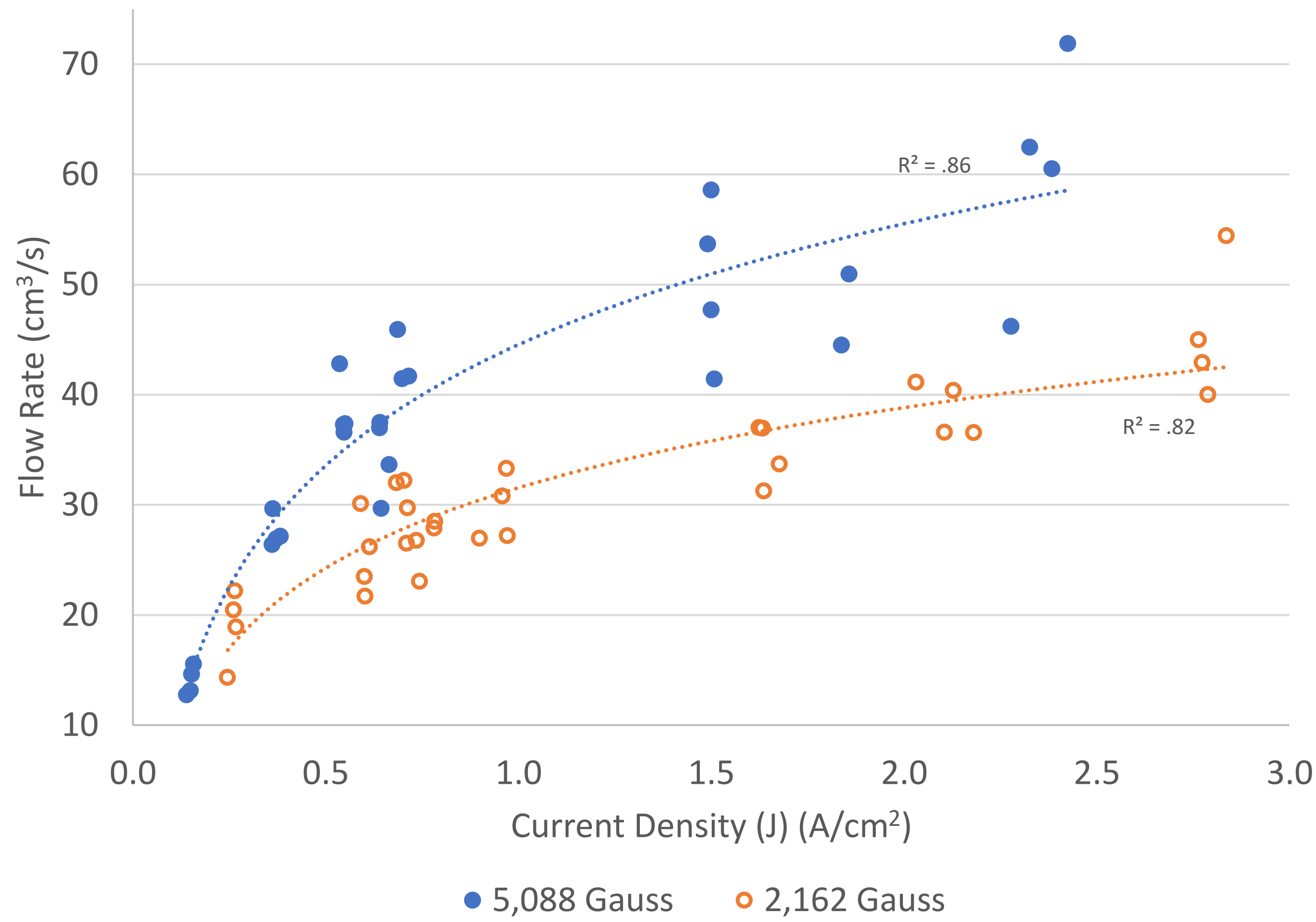
- Ran 80 test panels to assess different variables including
  - Magnetic field strength
  - Current density
  - Channel geometry
- Magnetic field strengths were measured at the center of the channel cross-section using a digital DC gauss meter
- For each test panel, 4 different dye tracers were used to collect 4 separate flow rate measurements
- Total sample size of 320 flow rate measurements
- All test panels were video recorded at 30 fps and velocimetry was based on video analysis of dye tracers using Logger Pro™ data-collection and analysis software



4.0 EXPERIMENTAL RESULTS: FLOW RATE vs ELECTROMAGNETICS

4.1 Observation

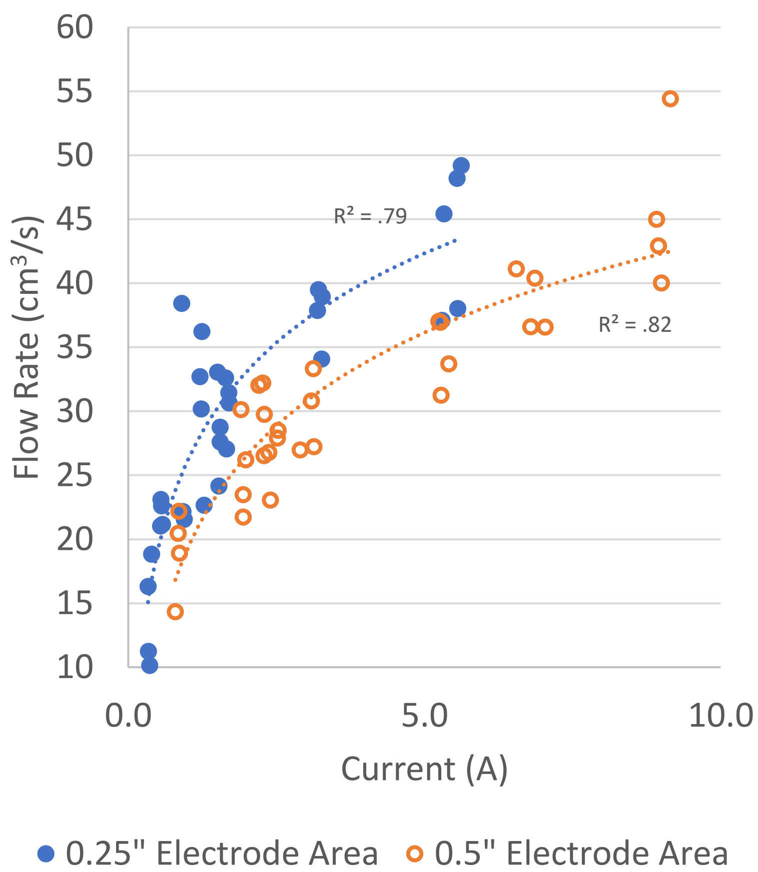
- Flow rate is proportional to both
    - Current density
    - Magnetic field strength
- Higher current densities and magnetic field strengths result in higher flow rates
- However, the relationship appears to be nonlinear. Above a certain threshold, increases in current density led to diminishing returns on flow rate



Note: All data points were based on channel geometries of 1.2” electrode gap and 2” channel length

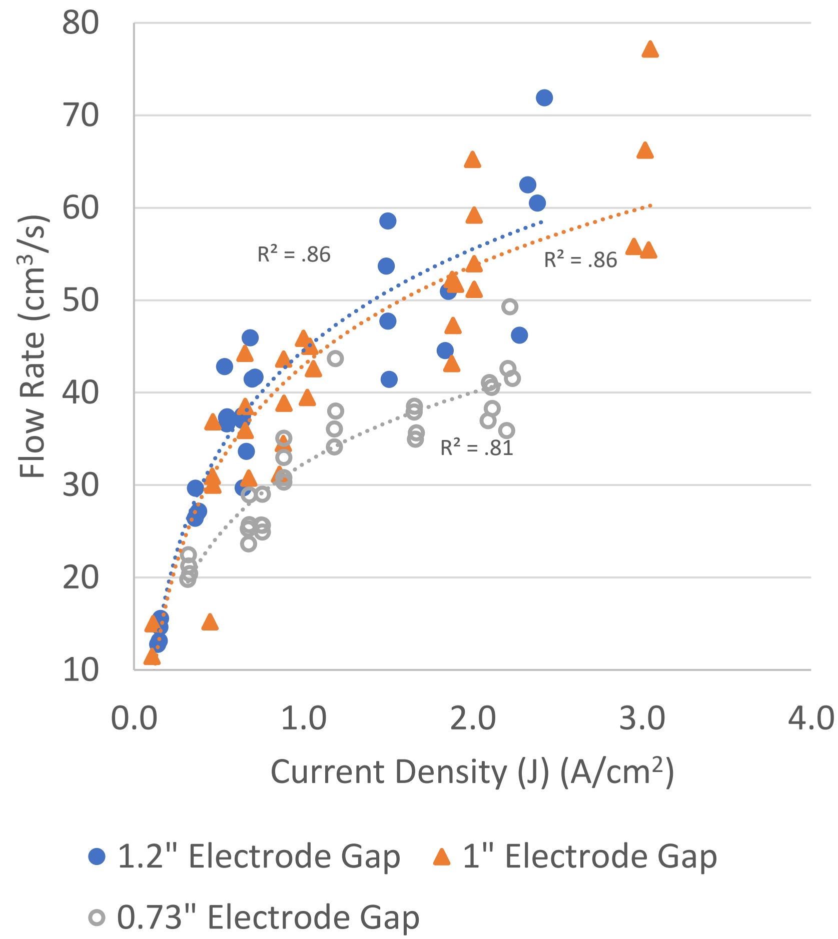
4.0 EXPERIMENTAL RESULTS: FLOW RATE vs CHANNEL GEOMETRY

Flow Rate vs Electrode Area



- Smaller electrode areas result in higher current densities and faster flow rates

Flow Rate vs Electrode Gap



- Larger electrode gaps result in higher flow rates

Note: All data points were based on 5,088 Gauss magnetic field configuration

4.0 EXPERIMENTAL RESULTS: RUNNING TIME

4.3 Observation

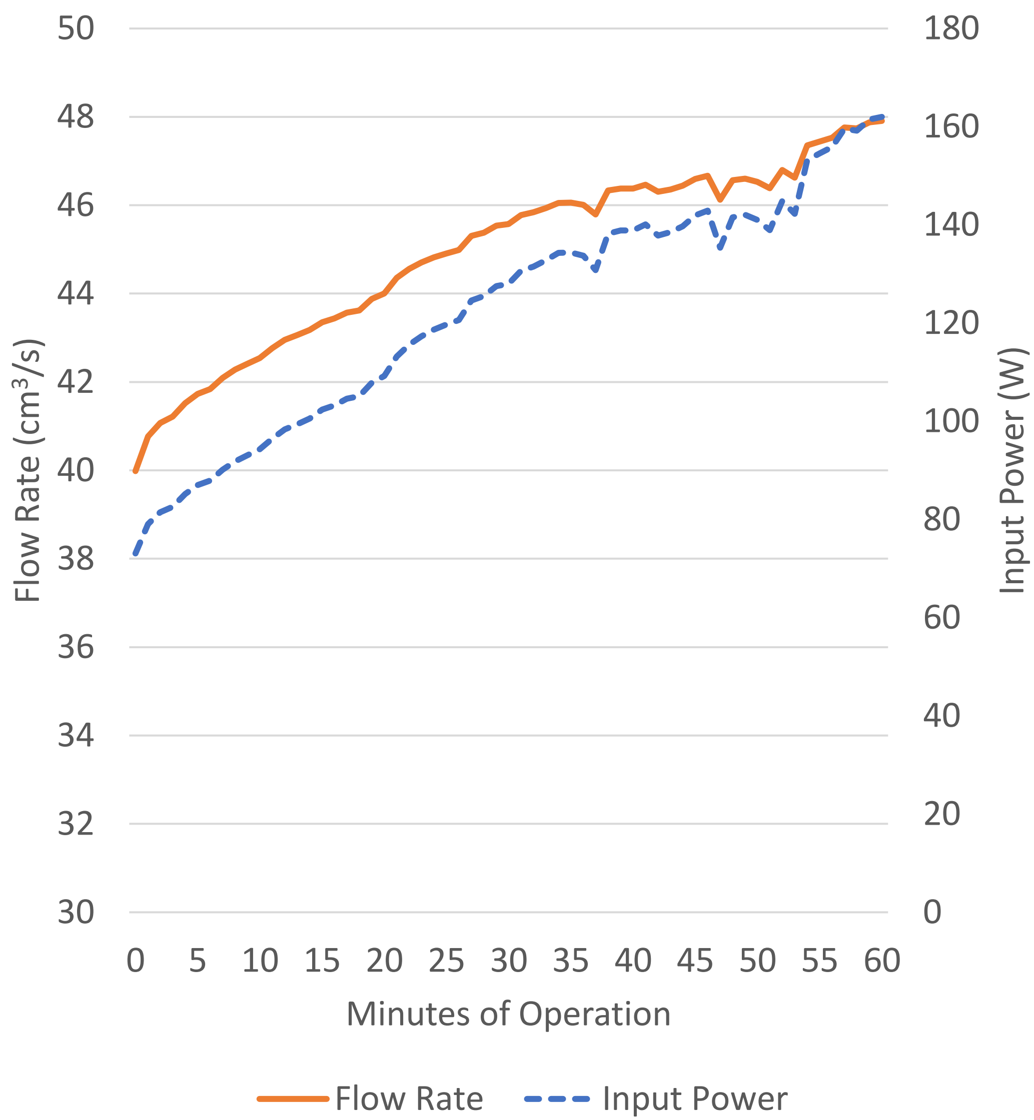
The MHD drive was run for 60min and the following graph plots the flow rate and input power

Both flow rate and input power gradually increased over time. We believe this is due to the chemical electrolysis that occurred at the cathode

As Cl^- ions transferred electrons to the cathode, they became chlorine atoms, which then reacted with the aluminum cathode to form $AlCl_3$ precipitate

Because the experiments were conducted in a closed system with recirculating fluid, this aluminum precipitate likely increased the electrical conductivity of the seawater, thereby increasing current density and flow rate

In an open ocean environment, this precipitate would not accumulate, and we would expect the flow rate to remain constant over time



Note: All data points were based on channel geometries of 1” electrode gap and 2” channel length

5.0 DISCUSSION

Electrochemical Electrolysis

- During the course of the experiments, a significant amount of electrolysis was observed in the MHD drive. This was manifested in the form of gas bubbles that formed in the channel, slight erosion of the cathode, and precipitate in the seawater solution

Cathode Chemistry

- As Cl^- ions transferred electrons to the cathode, they became chlorine atoms, which then reacted with the aluminum cathode to form $AlCl_3$ precipitate. These reactions led to corrosion of the cathode
- The chlorine atoms also reacted with the surrounding water to form hydrochloric acid and oxygen (Eq 3)

$$4Cl + 2HOH = 3HCL + O_2 \tag{3}$$

Anode Chemistry

- After the Na^+ ion received an electron, it became a sodium atom and reacted with the surrounding water to form sodium hydroxide and hydrogen (Eq 4)

$$2Na + 2HOH = 2NaOH + H_2 \tag{4}$$

$$NaOH + HCl = NaCl + H_2O \tag{5}$$

- The released O_2 and H_2 results in the bubbles detected in the experiments
- The sodium hydroxide then reacted with the hydrochloric acid to form salt and water (Eq 5), and the cycle repeats

6.0 CONCLUSIONS

6.1 Conclusions

This study successfully demonstrated an MHD-based propulsion drive for seawater transport

- Relative to the original design criteria (minimum seawater flow rate of 30 cm^3/s operating for a minimum period of 30min), this study achieved flow rates in excess of 50 cm^3/s under a 5,088 Gauss magnetic field, 2 A/cm^2 current density, and 1" electrode gap

- This study demonstrated that flow rates scale along with the following variables, in order of impact from highest to lowest
  - Magnetic field strength (B)
  - Current density (J)
  - Electrode gap (G)

  However, this scaling appears to be nonlinear. Above a certain threshold, incremental increases in either current density or electrode gaps lead to diminishing returns on flow rate

- Consistent with the theoretical model, flow rates also scaled inversely to electrode areas, i.e., larger electrode areas resulted in slower flow rates

- In addition, this study successfully demonstrated the ability to operate an MHD drive for 1 hour while maintaining a maximum power load under 160W. This exceeded the original design targets of 30min at a maximum power load of 500 watts

Future Work

Several areas were identified for future design refinements, including

- **Closed recirculating channel design**. To improve the accuracy of flow rate measurements, future designs could replace the open tray bed with a closed, recirculating channel that includes an embedded in-line flow turbine meter

- **Carbon electrodes**. To minimize the effects of electrolysis on the experimental results, future designs could replace the aluminum electrodes with carbon or graphite electrodes that are electrochemically inert

- **Parallel geometries**. To maximize flow rate given limitations on channel geometries and commercially available permanent magnets, future designs could further increase flow rate by creating

6.0 CONCLUSIONS

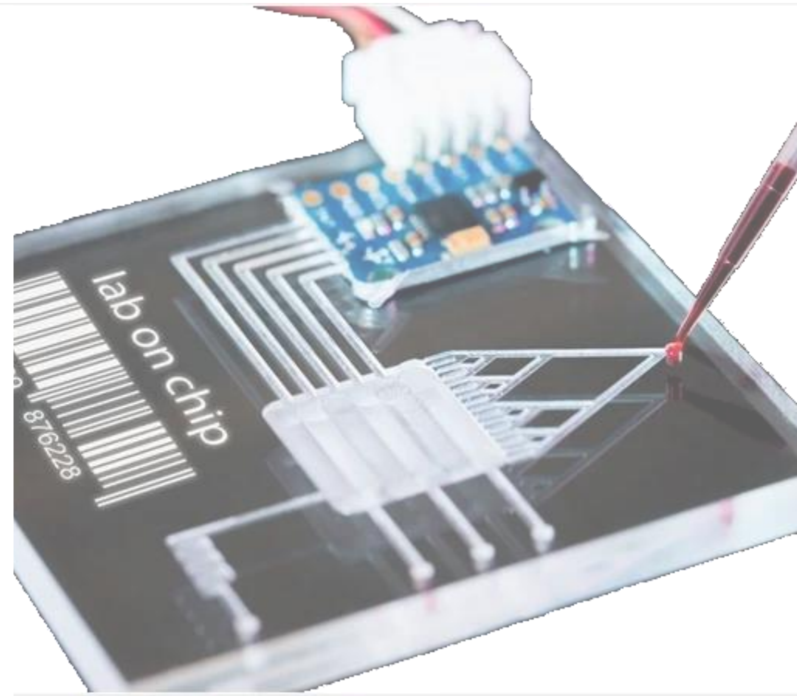
6.2 Non-Marine Applications

In addition to marine transportation, MHD drives can be used in a variety of other applications, including

Biomedical microfluid pumps
- MHD micro-pumps can be used to transport micro fluids for lab-on-chip applications (11). In these environments, traditional mechanical pumps are unable to meet the size and mechanical requirements required for micro-fluidic channels

Molten salt pumps for nuclear reactor coolants
- Molten salts are used in nuclear reactors for heat transfer. Given the extreme conditions, the useable lifetime for traditional pumps is relatively short
- MHD pumps without any moving mechanical parts can provide a significantly more reliable solution for an application that requires high degrees of reliability

Spacecraft propulsion
- Long-range spacecraft propulsion is currently limited by the amount of on-board fuel
- MHD propulsion using ionized gases (plasma) to generate thrust (also called Lorentz Force Accelerators) can be used to solve these challenges



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