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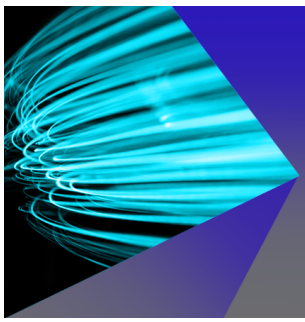
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ABSTRACT

This study designs a closed-loop magnetic circuit using permeable materials to increase the uniformity and intensity of the magnetic field based on an internal conductive square Magnetohydrodynamics (MHD) thruster that consists of a pair of NdFeB magnets. To reduce the magnetic leakage from the thruster, magnetic shields made of various permeable metals are used to encase the MHD thruster. The experimental results show that a stainless steel shell lighter than a black iron shield and moderately increases the magnetic field strength is more suitable for applications in seawater. For a single shield, the field intensity inside the thruster increases linearly with the thickness of the shell. The field strength increases further when a second shell is used. However, the field intensity decreases when the distance between the two shells is increased. An MHD thruster that is 100 mm long, 5mm wide, and 50mm high is hung on a sliding track with negligible friction and is fully submerged in the saline water for the verification of its performance. Increasing the thickness of the stainless steel shell from 2mm to 4mm results in the increase of the propulsive force from 0.064 N to 0.265 N, and the speed of the thruster from 0.075m/s to 0.098 m/s, respectively. The experimental results are used to propose a modified design for a magnetic circuit that increases the uniformity and strength of the magnetic field in the central region of a square MHD thruster that consists of permanent magnets.

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I. INTRODUCTION

The Magnetohydrodynamic (MHD) principle concerns the mobilization of fluids inside a channel without the need for any external moving parts. The magnetohydrodynamic concept was first used to propel a vehicle in salt water in the 1960's.[1] The main challenge at that time was creating a sufficiently strong magnetic field to give powerful propulsion because the superconducting magnets had yet to be developed, thus limiting magnetic fields to what conventional permanent magnets could create. The powerful Lorentz force that is generated by the orthogonal magnetic field and electric current means that MHD could be applied in seawater for high-speed ship without any cavitation,[2] for high-speed submarines,[3] or for noiseless propulsion of naval submarines.[4,5] However, numerous practical tests have shown that MHD thrusters are significantly less efficient than the conventional propulsion devices, mainly due to the weakness of the magnetic fields that can be created by permanent magnets.

Various studies have determined the efficiency of the MHD thrusters.[5–10] Doss[6] showed that the thruster efficiency increases with the strength of the magnetic field, and decreases with the flow velocity. The other report also shows that higher efficiency can be maintained over a wide range of cruising speeds at higher magnetic fields.[11] Some studies seek to increase efficiency by increasing the conductivity of seawater.[12] Some studies focus on the electrochemical aspect of the thrusters to achieve better performance for this technology.[13] Most studies show that an MHD thruster with a higher magnetic field intensity has the potential to achieve higher propulsion efficiency.

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Several MHD thruster configurations that are being considered for seawater propulsion. Inductive and conductive systems can be used either within a duct (internal configuration), or in the surrounding fluid (external configuration), so there are four different types of MHD thrusters.[14] The so-called internal conductive configuration with dipole magnets can be regarded as the simplest MHD model. However, the field strength at the center of the duct of the thruster decays significantly because magnetic leakage results in a non-uniform and weak magnetic field. This study designs a permeable shell as a closed-loop magnetic circuit to enhance the uniformity and intensity of the magnetic field based on an internal conductive square thruster. The effect of the material and thickness of the shell is determined to define the optimal design that increases the strength of the magnetic field inside the duct of the square MHD thruster. The effectiveness of the shell in increasing propulsion of the thruster is experimentally and theoretically verified in this work.

II. EXPERIMENTAL SETUP AND METHOD

The MHD thruster for this study consists of an electric and magnetic circuit that generates electric and magnetic fields that are orthogonal to each other. The size of the available magnets is the key factor used to define the dimensions of a single thruster unit as shown in Figure 1, which shows the structure of the prototype design for an internal conductive square thruster that consists of two neodymium cuboid magnets and two pieces of aluminum electrodes. The sample MHD thruster is 100 mm long, 50mm wide, and 50mm high. The pair of the commercial of neodymium iron oron (NdFeB, N35) permanent magnets have strength on the surface of about 0.22 T and are placed at the bottom and top of the thruster. To prevent the propagation of an electric current in the metal casing, the electric circuit is isolated from the magnets using pieces of resin that are produced using a 3D printer. The electrodes are connected to a 6200mAh Lithium-Polymer (LiPo) battery, which supplies a maximum voltage of 22.2V. A metal shell is used to make the closed-loop magnetic circuit to increase the uniformity and intensity of the magnetic field inside the duct of the thruster. For a rectangular cross-section, the Lorentz force (F_L) obtained due to the interaction of the orthogonal magnetic field (B) and electric field density (J) is given by:[15]

$$F_L = J \times B \tag{1}$$

where J and B are the current density and magnetic flux density, respectively. When an electric current passes through an electrically neutral conducting seawater in the presence of a magnetic field B, a vector body force F_L is applied to accelerate seawater in the MHD duct. The induced electric current density J is a vector with a magnitude and direction defined by Ohm's Law:

$$J = s(-\nabla\varphi + v \times B) \tag{2}$$

where s, φ, v are the electric conductivity, the electric potential, and the velocity, respectively. These equations show that the electrical and magnetic fields must be perpendicular in a large fluid volume to maintain a maximum Lorentz force. Thus, the thruster for this study is an internal conductive type, as shown in figure 1, which creates orthogonal electric and magnetic fields. The thrust that is created by Lorentz force and the speed of the thruster depend on the external magnetic field and the electric current, so the strength and distribution of the magnetic field are the important factors to dictate the design of the thruster module.

Figure 2 shows the experimental setup for the measurement of the essential parameters for the MHD thruster. All the experiments were conducted in a 100 cm long, 40 cm wide, and 30 cm high water tank. Industrial salt was added to the water tank to increase the salinity to 35.5 ppt, which nearly equals the average concentration of the seawater, for which the conductivity is 4.5 S/m. The MHD thruster was hung on a nearly frictionless sliding track. A camera was installed on the top to record the movement process of the MHD thruster and the velocity was accurately determined using the photogates. A force gage was used to measure the propulsive force of the MHD thruster.

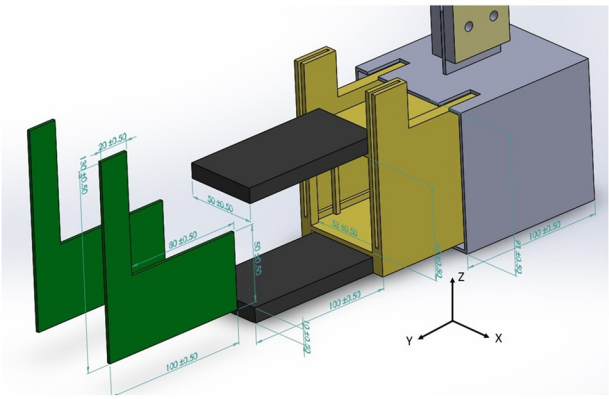


FIG. 1. Geometry of a single MHD thruster unit that is 100 mm long, 50mm wide, and 50mm high. The black area is the pair of N35 magnets, the green part is the electrodes, the yellow part is the plastic that is used to isolate the electric circuit and the gray part is the metal housing that holds all parts and attaches to the sliding track using a strut. (units: millimeters).

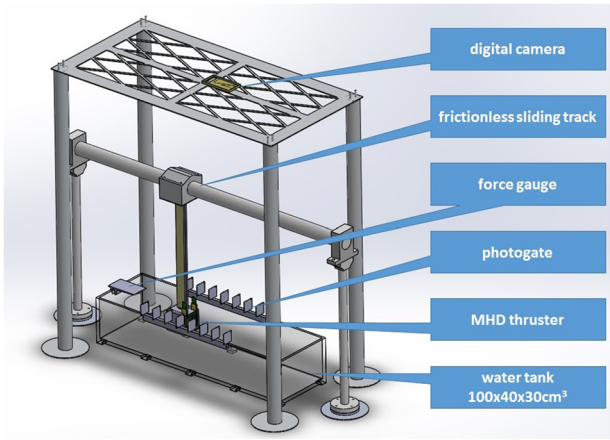


FIG. 2. Schematic diagram of the experimental setup to measure the velocity and thrust of the MHD thruster unit.

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III. THE EFFECT OF A PERMEABLE SHELL ON THE DISTRIBUTION OF FIELD STRENGTH INSIDE THE MHD THRUSTER

To practically determine the effect of the different metal shells on the enhancement for the field intensity in the dust of the MHD thruster, three types of material were used for the shell. Figure. 3 shows the measured field strength along the y-axis at the center of the thruster, in which the flux density is lower than the values near the surfaces of the magnet (0.22T). The peak in figure 3 shows that the central point of the thruster (x=0, y=0, and z=0) has the strongest magnetic field. The distribution of the magnetic field along the y-axis at the center generally declines and is non-uniform toward both ends of the channel (y=±50). The thruster without a metal shell has the lowest field strength of B_z= 0.116T at the center, which shows a significant decrease in the magnetic intensity at the center of the thruster due to the effect of magnetic leakage flux. If a metal shield with a thickness of 2mm is used, the respective maximum magnetic intensity B_z increases to 0.118T, 0.142T, and 0.155T for the aluminum, stainless steel, and black iron shells. These results show that permeable metal decreases the magnetic leakage flux between the two parallel permanent magnets and effectively increases the overall field strength inside the channel of the MHD thruster.

To investigate the key factors that affect the permeability of the metal, the surface morphology of the permeable metals was characterized using transmission electron microscopy (TEM, FEI TecnaiG2 F20) and the composition of the metals was measured using an energy-dispersive spectrometer (EDS) that is incorporated in the TEM. The results in Table I show that the Fe content in black iron is much higher than the others, so it is important to determine the effectiveness of its permeability. However, the higher density and higher concentration of Fe increases weight and the risk of corrosion when it is used in saltwater. The stainless steel has 82.6 wt% Fe (iron) gives the second-highest maximum B_z of 0.142T, as shown in figure 3. The 15.9 wt% Cr (Chromium) and 1.2 wt% O (Oxygen) in the stainless steel can reduce the risk of corrosion and is more suitable for application in the seawater, whereas the aluminum shell with 0.5 wt% Fe has an almost negligible effect on the enhancement of the field strength. As a result, the lighter stainless steel shell, which gives a moderate increase in the magnetic intensity of the thruster is used for the magnetic shield of the MHD thruster for this study.

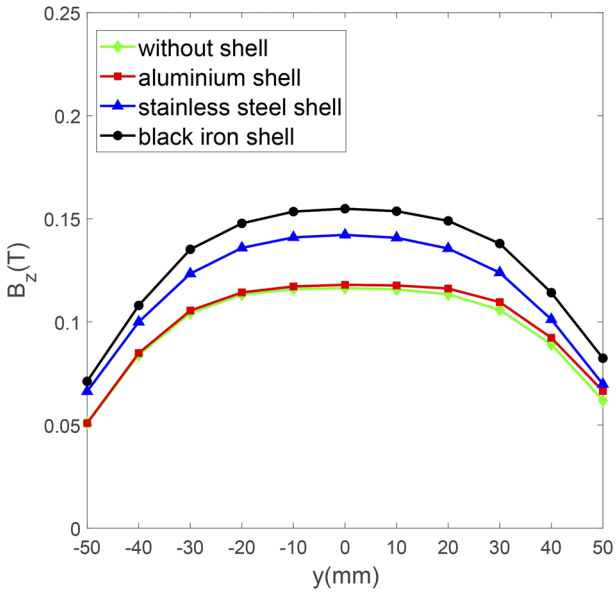


FIG. 3. The measured field strength along the y-axis at central cross-section (x=0 and z=0) of the thruster for shells that are made of various materials with a thickness of 2mm, comparing to the result for a thruster without a permeable shell. The black-iron shell demonstrates the most significant increase in the field strength, followed by the stainless steel shell. The aluminum shell gives almost no increase in field intensity for the MHD thruster.

TABLE I. The chemical composition of each permeable metal, as measured using the EDS equipped in the TEM.

	Element- wt%				
	Fe	Cr	O	Si	Al
black iron	100	0	0	0	0
stainless steel	82.6	15.9	1.2	0.4	0
aluminum	0.5	0	4.5	0	95

IV. THE EFFECT OF THE THICKNESS AND THE NUMBER OF THE METAL SHELLS

For the optimal configuration of the closed-loop magnetic circuit for the MHD thruster, the effect of the thickness and the number of the shells is determined experimentally. Figure 4(a) shows the field along the y-axis at the center of the thruster that uses various numbers of stainless steel shells of various thicknesses. For a single shield, the respective maximum magnetic field intensity B_z is 0.142T, 0.152T, and 0.163T for a thickness of 2mm, 3mm, and 4mm. These results demonstrate that the enhancement of the field strength inside the MHD thruster is increased effectively by increasing the thickness of the magnetic shield. Figure 4(b) shows that the maximum magnetic field intensity along the y-axis at the central cross-section increases linearly as the thickness of the permeable shell is increased.

On the other hand, the increase in the number of shields also shows an influence on the enhancement of the field intensity. The dashed light blue curve in figure 4(a) shows that the maximum value of B_z increases slightly from 0.142 to 0.148T when a second 2-mm stainless steel shell is used. This means an additional permeable shell further increases the field intensity inside the MHD thruster. Besides, the maximum field intensity is further increased to B_z=0.158T when the distance between the two shells is reduced from 40mm to 20mm. These results show that increasing the thickness of the permeable shield has a greater effect than increasing the number of the shell. Thus, increasing the thickness of the permeable shell would be a better designing methodology for the improvement of the performance of a square MHD thruster.

V. IMPROVEMENT OF THE PERFORMANCE OF THE MHD THRUSTER

To practically verify the performance of the proposed design in terms of increasing the field intensity of an MHD thruster, dynamic experiments are conducted using the apparatus shown in figure 2.

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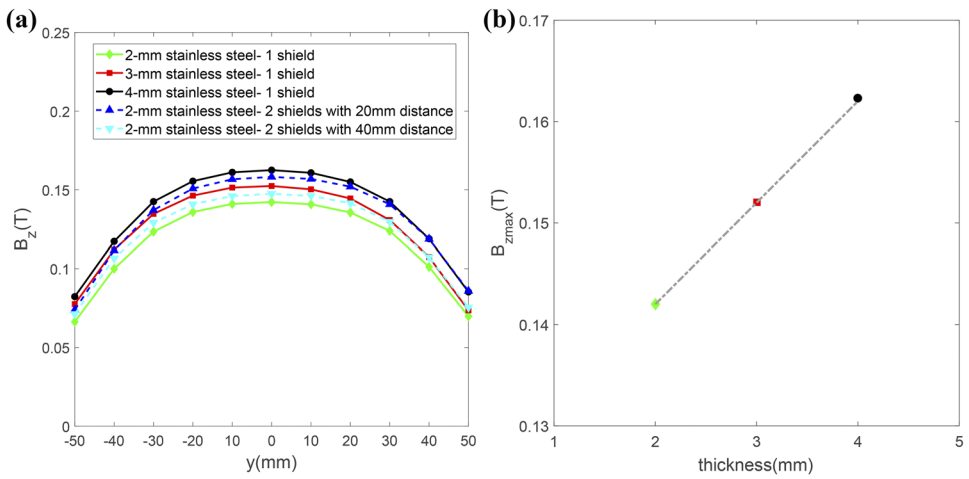


FIG. 4. (a) Comparison of the measured field strength along the y-axis at the central cross-section (x=0 and z=0) of the thruster for different numbers of stainless steels of different thicknesses. (b) Maximum magnetic field intensity along the y-axis at the central cross-section (B_{zmax}) as a function of the thickness of the permeable shell. The field intensity increases linearly as the thickness of the metal shell is increased.

The thruster unit shown in figure 5 is fully submerged in the saline water with a concentration of 35.5 ppt and is hung on a sliding track with negligible friction. The thruster is powered by a Lithium-Polymer (LiPo) battery with a maximum voltage of 22.2 V. The average maximum measured electric current is nearly 22 A based on the experimental conditions in this study. Increasing the thickness of the permeable shell increases the field intensity inside the thruster, however, the total weight of the thruster also increases when the shell becomes thicker. Therefore, the field-to-weight ratio is used to evaluate the overall effectiveness of the proposed design through systematic experiments.

Figure 6(a) shows the field-to-weight ratio for the thruster decreases as the thickness of the shell increases. The performance may decline if a heavier thruster is installed on an underwater vehicle because the hydrodynamic drag increases when the total weight increases. The results in figure 6(a) show that the measured average moving speed of the MHD thruster increases from 0.075m/s to 0.098 m/s when the thickness of the stainless steel shell is increased from 2mm to 4mm. These results demonstrate that an increase in weight due to a thicker shell does not significantly affect the performance of an MHD thruster that has an optimal field intensity enhancement. This argument can be further verified using figure 6(b), which shows the measured net thrust increases almost linearly with the thickness of the permeable shell. The results shown in figure 6(b) demonstrate that the equilibrium net thrust of the MHD thruster increase from 0.064 N to 0.265 N when the thickness of the permeable shell is increased from 2 mm to 4 mm. In addition, the thrust to weight ratio also increases from 0.004 to 0.013 when

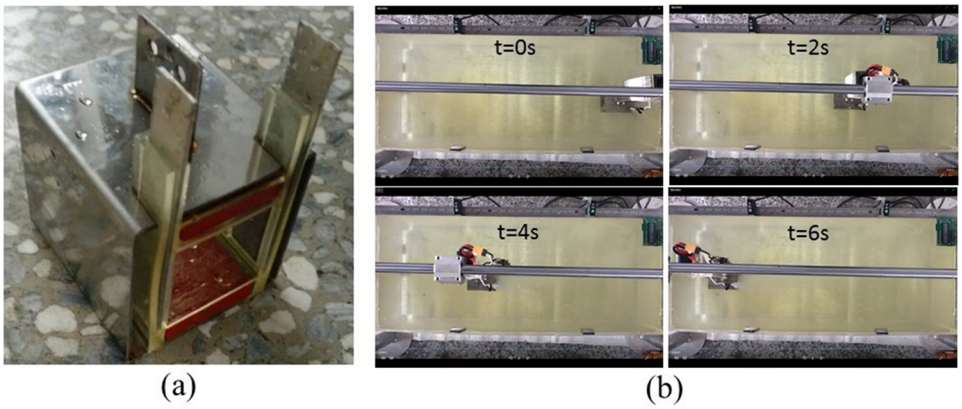


FIG. 5. (a) A sample manufactured MHD thruster that is 100 mm long, 50 mm wide, and 50 mm high, with a 2-mm thick stainless steel shell. (b) Sequential images of experimental tests of an MHD thruster with a 4-mm thick stainless steel shell that is hung on a sliding track. The measured velocity is nearly at 0.098 m/s, which is faster than that for a thruster installed with a 2-mm thick shell whose speed is around 0.075m/s in the identical experimental conditions.

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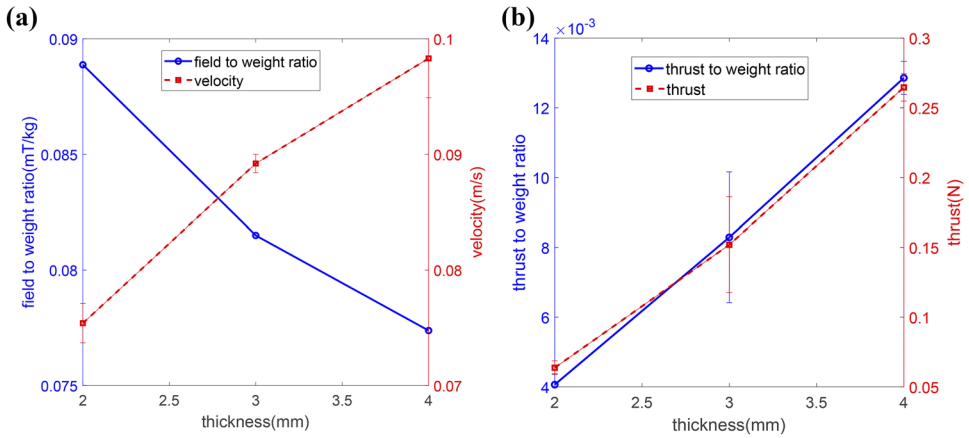


FIG. 6. (a) The maximum equilibrium velocity and the field to weight ratio and (b) the maximum equilibrium thrust and the thrust to weight ratio for an MHD thruster with shells of various thickness shown in figure 5. All the thrusters are powered by a Lithium-Polymer (LiPo) battery with an electric current of 22A.

the thickness of the shell is increased. These experimental results show that the net thrust is effectively increased if the field intensity inside the MHD thruster is increased using the closed-loop magnetic circuit. Eventually, increasing the thickness of the permeable shell improves the performance of a square MHD thruster that consists of dipole magnets.

VI. CONCLUSIONS

This study demonstrates a simple technique to increase the magnetic field intensity inside a square MHD thruster that consists of a pair of neodymium N35 cuboid magnets. The effect of three types of materials is investigated to determine the optimal material for a permeable shell that gives an increase in uniformity and magnetic field intensity at the central region of a square MHD thruster. A 2-mm black iron shell with an extremely high concentration of Fe significantly increases the maximum field strength from 0.116T to 0.155T. On the other hand, a lighter stainless steel shell gives a moderate increase in the maximum magnetic intensity to 0.142T and is more suitable for applications of the MHD thruster in seawater because there is less risk of corrosion.

Increasing the thickness and the number of shells both enhances the field intensity inside the thruster. The experimental results show that increasing the thickness of the permeable shield is a better design methodology than increasing the number of shells for the improvement of the performance of an MHD thruster. Increasing the thickness of the stainless steel shell from 2mm to 4mm results in a decrease in the field-to-weight ratio for the thruster and an increase in the measured speed from 0.075m/s to 0.098 m/s. The experimental results show that increasing the weight of the permeable shell does not have a significant influence on the performance of an MHD thruster that has an optimal field intensity enhancement. Finally, the thrust and the thrust to weight ratio increase when the thickness of the permeable shell is increased. This study proposes a simple technique for the enhancement of the magnetic field intensity between two dipole magnets, which can be applied to increase the propulsive force for a square MHD thruster that is used for an underwater vehicle.

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DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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