

Magnetohydrodynamic Propulsion for the Classroom

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The cinema industry can sometimes prove to be an ally when searching for material with which to motivate students to learn physics. Consider, for example, the electromagnetic force on a current in the presence of a magnetic field. This phenomenon is at the heart of magnetohydrodynamic (MHD) propulsion systems. A submarine employing this type of propulsion was immortalized in the movie *Hunt for Red October*.¹ While mentioning this to students certainly gets their attention, it often elicits comments that it is only fiction and not physically possible. Imagine their surprise when a working system is demonstrated! It is neither difficult nor expensive to construct a working system that can be demonstrated in the front of a classroom.² In addition, all aspects of the engineering hurdles that must be surmounted and myths concerning this “silent propulsion” system are borne out in a simple apparatus. This paper details how to construct an inexpensive MHD propulsion boat that can be demonstrated for students in the classroom.

Physics of Magnetohydrodynamic Propulsion

The physical principle behind an MHD propulsion system is not very complicated: An electrically charged particle moving through a magnetic field feels a force. The force is

$$\mathbf{F} = q\mathbf{v} \times \mathbf{B}, \quad (1)$$

where q and $\mathbf{v}$ are the particle charge and velocity, respectively, and $\mathbf{B}$ is the applied magnetic field. The

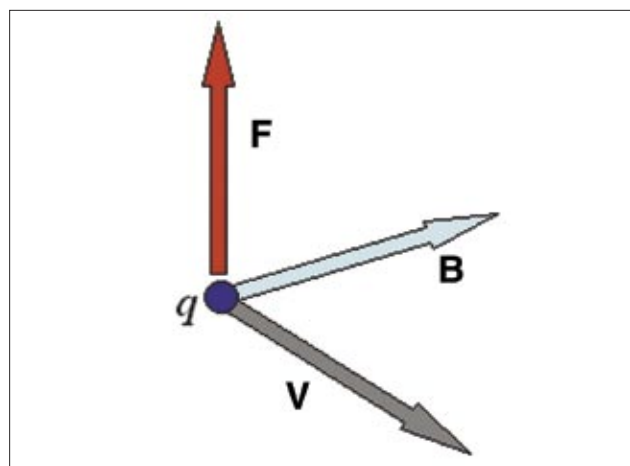


Fig. 1. Direction of force arising from charged particle moving in a magnetic field.

resulting force is perpendicular to both the velocity of the particle and the magnetic field. Its direction may be determined with the right-hand rule, as shown in Fig. 1 (for a positive charge).

In order to harness this force for propulsion, one simply passes a stream of charges through a magnetic field and the charges are accelerated. By Newton's third law, the propulsive force is exactly equal to the force imparted on the charges. Since more than one charge will be accelerated, the equation above may be recast by rewriting the term $q\mathbf{v}$ using

$$q\mathbf{v} = (qnAL)\mathbf{v},$$

where n is the number of charges per volume, A and L are the cross-sectional area and length, respectively,

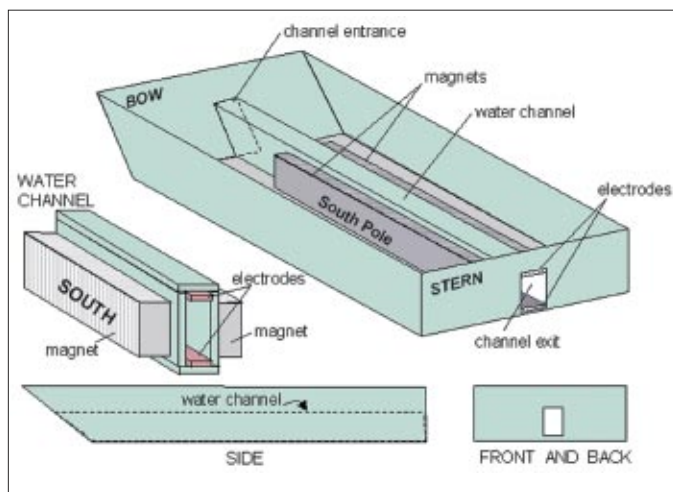


Fig. 2. Design of a simple MHD boat.

of the region where the charges will travel. The quantity $qnAv$ is then defined as the current I . This leads to the statement for the force imparted on a current in the presence of a magnetic field,

$$F = LI \times B. \quad (2)$$

In MHD propulsion systems, the current is usually passed through a medium, such as salt water, and electro-magnets are used to apply a magnetic field perpendicular to the current path. The sodium and chlorine ions in the water act as the charge carriers. They are accelerated by the magnetic force and transfer their momentum through collisions to the water molecules. The result is that the water itself is accelerated, although the water molecules are not directly affected by the magnetic force.

MHD Boat Design

The design of an MHD propulsion boat is illustrated in Fig. 2. It consists of a rudimentary boat with a channel down the center through which water passes and is accelerated for the propulsion. The top and bottom of the channel have electrodes. The boat must be sufficiently large in order to float its power source, in this case six 9-V batteries in series. Permanent magnets are situated along the channel to provide the external magnetic field.

It is important that the magnet poles are located on the sides of the magnet and not on the ends. This

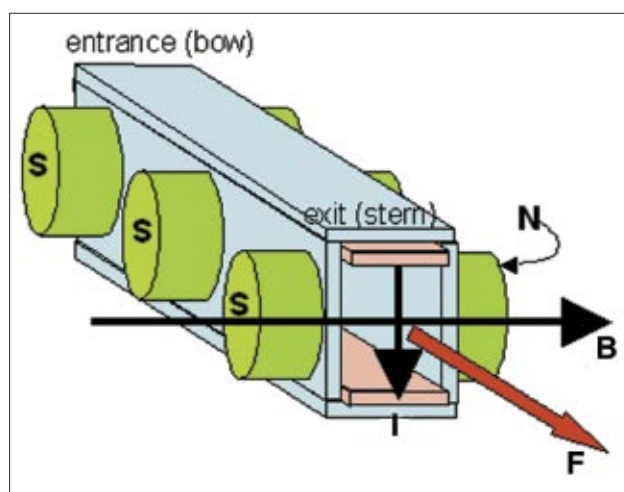


Fig. 3. Relationship of magnetic field, current, and force in the water channel.

creates a magnetic field perpendicular to the current direction and results in the water being pushed down the channel. This is illustrated in Fig. 3 and is emphasized by the use of cylindrical magnets, which are less efficient but easier to visualize. **Note:** If the current direction is instead chosen to flow upward, the pole orientation of the magnets will have to be reversed.

Optimization of the MHD Boat Design

The dimensions of all components can be chosen as desired. Generally, the size of the boat is simply chosen so it is large enough to float the battery stack. The water channel is as long as the boat, and the channel height is chosen to match the height of available magnets. The width of the channel, however (shown in Fig. 4), allows for some optimization. Since the magnetic field diminishes as the distance from the magnets (width of the channel) increases, it appears that in order to maximize the magnetic field strength, a thin channel should be chosen. This approach is valid if the current in Eq. (2) can be independently controlled. Since our boat will be powered with batteries, however, the voltage will be constant. The current, therefore, will depend on the electrical resistance of the channel. This in turn depends on the width of the channel.

In order to determine the dependence of the current on the channel dimensions, it is necessary to examine the transmission characteristics (i.e., resis-

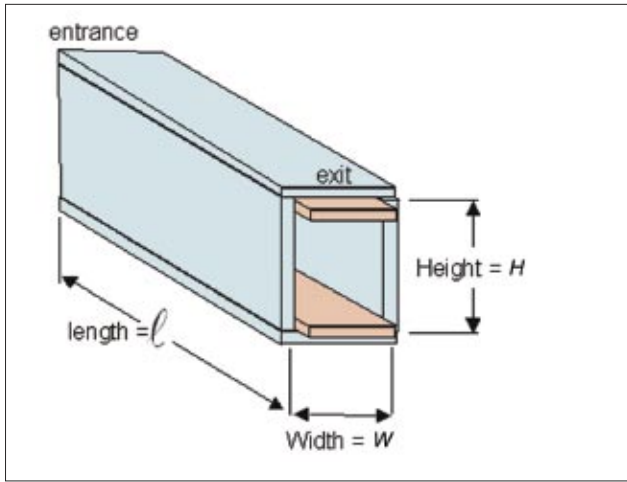


Fig. 4. Water channel orientation.

tances) of an electrical conductor. The current flowing from the top electrode to the bottom electrode can be expressed in terms of the current density:

$$I = \mathbf{J} \cdot \mathbf{A} = J(\ell W), \quad (3)$$

where $\mathbf{J}$ is the current density (A/m^2) and A is the cross-sectional area (ℓW). The current density can be written in terms of the electric field E and the conductivity σ , or resistivity ρ of the water:

$$\mathbf{J} = \mathbf{E}\sigma = \frac{\mathbf{E}}{\rho}. \quad (4)$$

The resistivity can be found in textbooks. Pure water has a resistivity ρ value of $2.6 \times 10^5 \, \Omega\text{m}$, while sea (salt) water has a resistivity of about $0.22 \, \Omega\text{m}$. It is immediately clear that very little current can be transmitted through pure water. The electric field E can be approximated by the potential difference across the electrodes divided by the distance between the electrodes:

$$E = \frac{\Delta V}{\Delta y} = \frac{V_{\text{battery}}}{H}. \quad (5)$$

Therefore, the current in the channel is given by

$$I = \frac{V_{\text{battery}} A}{H\rho} = \frac{V_{\text{battery}} \ell W}{H\rho}. \quad (6)$$

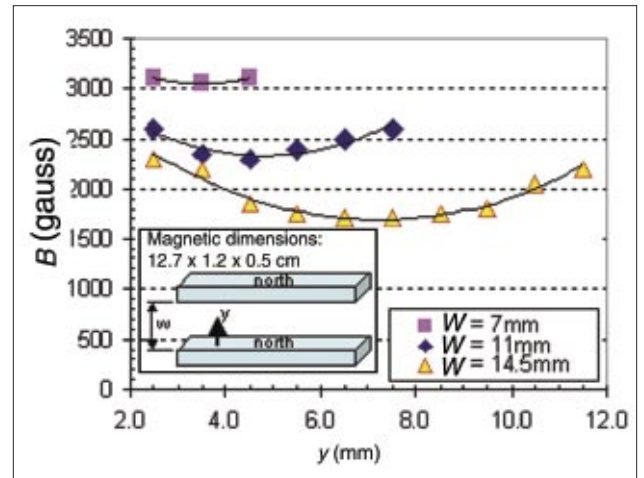


Fig. 5. Magnetic field strength between magnets.

Inserting this in Eq. (2), and assuming that the current and the magnetic field are perpendicular to each other, gives the force produced,

$$F = ILB = \left(\frac{V_{\text{battery}} \ell W}{H\rho} \right) H B \\ = \left(\frac{V_{\text{battery}} \ell W}{\rho} \right) B. \quad (7)$$

Note that the quantity L in Eq. (2) is the current path and is equivalent to the height (H) in this geometry because the current path is vertical. Therefore, to first order, the force produced does not depend on the channel height (H) but increases with longer channels (ℓ) and wider channels (W). This conclusion is only valid where the magnetic field is constant along entire the channel. Any part of the channel that is outside of the influence of the magnets will not add to the force.

In order to optimize the force, the exact behavior of the magnetic field strength (B) as a function of magnet separation (W) must be determined. A gaussmeter was used to take measurements of the magnetic field strength between two neodymium-iron-boron (Nd-Fe-B) magnets that were positioned side by side. The results, displayed in Fig. 5, show that the magnetic field decreases as the magnet separation increases. The results were curve-fitted and integrated to determine the average magnetic field as a function of the distance between the magnets. The result is shown in

Fig. 6. **Note:** The magnetic field is now given in teslas and the separation in meters in order to allow substitution for the magnetic field strength (B) directly into Eq. (7). The average magnetic field decreases almost inversely proportional to distance. Inserting the curve-fit for the results of Fig. 6 into Eq. (7) yields an empirical force function that is proportional to a cubic function of W :

$$F = \left(\frac{V_{\text{battery}} \ell}{\rho} \right) (248W^3 - 19.3W^2 + 0.45W). \quad (8)$$

The function F versus magnet separation W is graphed in Fig. 7. The results show that an optimum does indeed exist. As the magnet separation increases from zero, the force also increases. It must increase because the conducting area is increasing [Eq. (3)]. The average magnetic field is decreasing, but not as fast as the conducting area is increasing. The result is that maximum is reached between 16 and 18 mm, after which the force decreases due to the diminishing magnetic field. The MHD boat water channel width (W) in the present study was therefore chosen to be 17 mm. These results are specific to the magnets chosen, but a similar optimum should exist for any pair of magnets. Generally, the optimum separation width between the magnets should be about the width of the pole side of the magnet, 1.2 cm in the present case.

Building and Operating the MHD Boat

The design and dimensions of the boat in this study are shown in Fig. 8. The hull size was chosen in order to be able to float six 9-V batteries. The water channel height is equal to the magnet pole width plus the thickness of the electrodes. The water channel width was determined through the optimization detailed above. The electrodes have the same width as the channel and are made of brass scraps. Copper can also be used although it suffers vigorous erosion from the chlorine ions during operation. Heavy-gauge wire connects each electrode to a pole of the battery stack. The batteries are connected in series and laid in the hull. The wire must be sufficiently thick to be able to support 1- to 3-A currents. The hull is made of

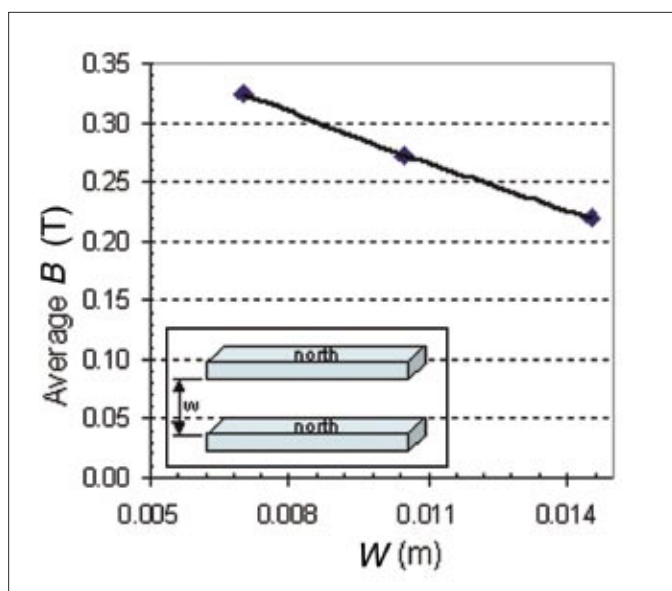


Fig. 6. Average magnetic field strength as a function of magnet separation. The curve represents the function $B_{\text{avg}} = AW^2 + BW + C$, where $A = 248 \text{ T/m}^2$, $B = -19.3 \text{ T/m}$, and $C = 0.45 \text{ T}$.

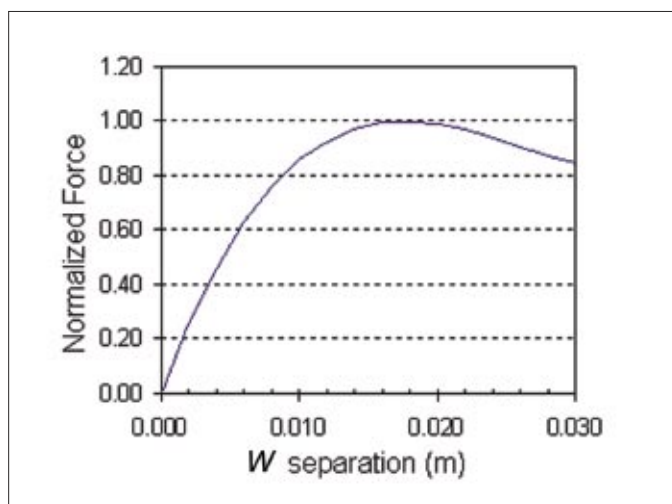


Fig. 7. Normalized force as a function of magnet separation (channel width).

styrene plastic bonded with CA (cyanoacrylate) glue. Both are available at any hobby store and can be purchased for a total of less than \$10. A pair of rare-earth (Nd-Fe-B) magnets was bought online through eBay for \$17.

The boat along with the magnet stack was run in a *small* tub of salt water. The salt concentration was made as high as possible in order to reduce the resistance and maximize the current. The tub was 20 x 30 cm long and contained only sufficient water

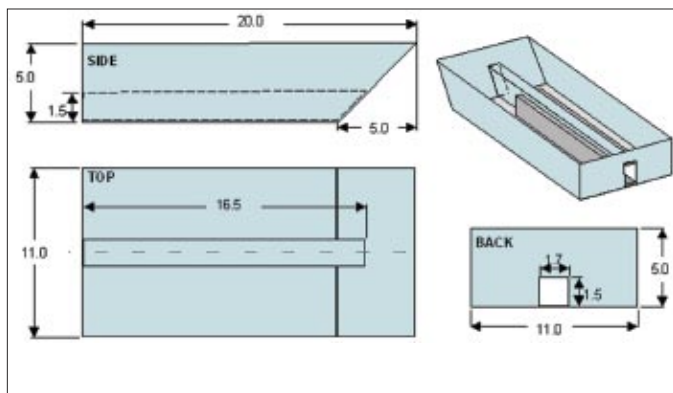


Fig. 8. Dimensions of final MHD boat design (cm).



Fig. 9. MHD boat operational setup.

to float the boat (about 3.5 l). This minimized the amount of salt needed. Two hundred or more grams of salt were added to the water. The proper orientation of the batteries/electrodes was verified by checking that the water was ejected from the stern of the boat. A picture is shown in Fig. 9. An ammeter was connected in series and 0.8 A were measured during operation. The boat attained a speed of 0.5 to 1.0 cm/s. When a laboratory power source was connected to the boat in place of the batteries, 7 A flowed through the system and the water velocity was measured as 10 to 15 cm/s. The boat did not move, however, due to being tethered by the wires. A second boat was constructed with identical dimensions but with a water channel width of 7 mm. Under the same operating conditions, its velocity was either very small or undetectable. This would tend to support the analysis, although this boat may also have had problems with hydrogen buildup (discussed below) on the electrodes, which could result in greatly diminished current flow.

Myths and Monsters

Students are generally impressed with the demonstration, especially when an external power source is connected and a vigorous water jet is produced. The question that is immediately voiced is the following: “When is the Navy going to make one of these?” In the process of building and operating this boat, all of the data needed to answer that question have been collected. Unfortunately, the data debunks several myths. The first myth is that this propulsion system is silent. As the students can clearly observe, the boat produces many bubbles and the associated noise. The bubbles are hydrogen and oxygen being liberated through electrolysis as the current passes through the water. This propulsion system is anything but silent. The second myth is that it is nondetectable. Setting sound considerations aside, the system produces a jet of chlorine ions and metal chlorides that pour out the back of the boat. While this is useful for flow visualization in the classroom, it is doubtful that a stealthy submarine would want to leave such a trail pointing back at itself.

The metal chloride stream also points to one of the greatest engineering difficulties (monsters) with this technology. The chlorine ions are very reactive and furiously corrode most metals. The prototype MHD boat for this study lost 1 cm of 12-gauge wire in just 15 minutes of operation. Thus, an operational ship would have to find a material that would not be consumed by the chlorine ions or else resign itself to replacing its electrodes on a regular basis. The amount of salt needed is also of concern. Since pure water does not conduct electricity to an appreciable degree, this propulsion system would not work in freshwater lakes or near coastal rivers. The final monster that must be examined is the current and magnetic field requirements. A Trident-class submarine has a mass of 18750 tons (17.0×10^6 kg) and a power of 90,000 hp (67 MW) available from its propulsion system.³ If this drives it at about 20 knots (10.3 m/s), a quick calculation ($P = FV$) shows that it must be exerting a thrust force of about 1.5×10^6 lb (6.5×10^6 N).

Now, let's attempt to drive a submarine of this size with a magnetohydrodynamic propulsion system. Assume the water channel through the submarine is about 3 m in diameter. This will be our electric cur-

rent path length. A typical power plant produces a current on the order of thousands of amps. Let us assume that we can generate 5000 A with our 67-MW nuclear reactor. In order to create the 6×10^6 N force necessary to drive the submarine at 20 knots, a 435-T magnetic field is needed [Eq. (2)]. The best field-portable, superconducting electromagnet used on a full-scale Japanese experimental MHD ship only developed about 4 T.^{4,5} Therefore, the magnet technology is not yet available. Conversely, if we limit ourselves to 4.0 T and the same geometry, in order to drive our Trident-class submarine, a current of 540,000 A is needed. This is clearly an unreasonable requirement, at least in the near future. Incidentally, this makes for an excellent eye-opening example in class.

Summary

The magnetohydrodynamic propulsion system used by Hollywood is an excellent motivator for students to learn some interesting physics relating to magnetic force on electric currents. A simple demonstrator can be inexpensively built and shown in the classroom. The process of optimizing the geometry can also be used to reinforce and/or teach physical principles relating to electric current transmission. In this study several such MHD demonstrators were built, tested, and optimized. The final design was self powered with 9-V batteries and moved at about 0.5 to 1.0 cm/s.

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