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Simple Magnetohydrodynamics (MHD) System Optimization for Fluid Flow Applications

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Abstract: *Magnetohydrodynamics (MHD*) studies the relationship between electromagnetism and fluid mechanics, a concept with various practical applications, including marine propulsion systems and electromagnetic pumps. This study aims to optimize a simple MHD system to improve the performance of fluid rate measurement based on electromagnetic principles. Optimization is carried out through the analysis of the influence of variations in several system characteristics, namely the given electrical voltage, the distance between electrodes, the length of the electrode, and the salinity of the saltwater. The method employed is experimental, utilizing a simple MHD system design that enables the quantitative observation of changes in the speed of saltwater resulting from the interaction between magnetic and electric fields. The speed of saltwater is measured using a visual approach with the *Tracker* analysis application. The results showed that increasing the voltage and salinity of the saltwater, as well as decreasing the electrode length or the distance between electrodes, all contribute to increasing the speed of saltwater flow. In other words, each parameter makes a significant contribution to fluid dynamics, thereby allowing for the optimal configuration of the MHD system. The findings in this study are expected to serve as the basis for the development of simple MHD-based fluid rate measurement instruments that are efficient and applicable, enabling a concrete illustration of electromagnetic theory and fluid dynamics.

Keywords: Fluid flow; Lorentz force; Magnetohydrodynamic.

Introduction

Recent advances in the interdisciplinary field of magneto-fluid dynamics have attracted the interest of the scientific and engineering community (Akinola et al., 2024). The term *Magneto Hydro Dynamic* (MHD) was first introduced by Alfvén (1942), who studied the relationship between electromagnetism and fluid mechanics, especially regarding the influence of magnetic fields on the dynamics of conductive solutions (Bera, 2020; Davidson, 2017). A saltwater solution can act as a conductive solution because it can conduct electricity (Awchar et al., 2018; Chan et al., 2020).

Magnetohydrodynamics has attracted considerable research interest due to its potential application in physics, medicine, and engineering (Kabeel et al., 2015). MHD is a concept that is very relevant to various practical applications, one of which is in marine propulsion systems, electromagnetic pumps, flow control using plasma drives with dielectric barrier discharges, and various devices involved in the interaction of fluids and electromagnetic fields (Abbaszadeh et al., 2022; Timofeev et al., 2019). The MHD concept provides fascinating insights into the fundamental understanding of physics related to the concepts of electricity, magnetism, and conducting fluids (Xisto et al., 2015). Many investigations have been

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established with the main emphasis on the influence of MHD over heat transmission characteristics and motion of the fluid (Lone et al., 2023).

MHD consists of a series of parallel electrode plates, a power source with a direct electrical voltage, and a permanent magnet in a sodium chloride (NaCl) solution. The system in MHD uses electric and magnetic fields to create a thrust force due to the movement of charged particles from salts, namely Na+ and Cl-, dissolved in water. These particles move under the influence of a static electric field toward the plates with opposite polarity (Aktaibi et al., 2019). By creating an electric field between the electrode plates, the dissolved ion particles, namely Na+ and Cl-, will move to the opposing electrode, which is then deflected by the magnetic field so that the particles move along the electrode.

Under the influence of a constant external electric field E, the particles move with velocity v and then interact spontaneously with the external magnetic field B that is applied perpendicular to the circuit (Li et al., 2021). The combination of the magnetic field, electric field, and the relative direction of motion of the particles results in a Lorentz force, whose direction is determined by the vector cross-product between the current and the magnetic field. The Lorentz force acting on particles bound to water will push the water out of the system (Al-Habahbeh et al., 2016; Liu et al., 2006).

The Lorentz force acting on particles has the equation (Griffiths, 2017).

$$\vec{F} = Q(\vec{E} + \vec{v} \times \vec{B}) \quad (1)$$

$$\vec{E} = \frac{V}{d} \quad (2)$$

Equation 1 gives information where F is the magnitude of the Lorentz force produced, Q is the magnitude of the charge, E is the magnitude of the electric field, v is the speed of the particles moving from the positive to the negative plates, and B is the magnitude of the magnetic field. In equation 2, the magnitude of the electric field will depend on the magnitude of the given potential difference V and d, which is the distance between the electrode plates.

$$F = m\frac{dv}{dt} \quad (3)$$

$$v_f = \int \frac{F}{m} dt + v_i \quad (4)$$

Equations (3) and (4) show the relationship of the equation to obtain v_f Which represents the flow rate of saltwater that can be measured during a simple experimental process. Through equation (4), the speed of saltwater v_f Will be influenced by the magnitude of the Lorentz force (F). The change of variables E and B in equation (1) can affect the value of the force F obtained, thus corresponding to the magnitude of the saltwater velocity v_f.

This study aims to optimize a simple MHD system to improve the performance of fluid rate measurement based on electromagnetic principles by adjusting variables such as potential difference (voltage), distance between electrode plates, electrode plate length, and saltwater salinity. Those variables indicate the formation of an electric field as a system that affects fluid dynamics in the MHD circuit. The relationship between variables became the basic knowledge to review the application of MHD in simple experiments.

Previous research conducted by Fithriyah & Khotimah (2016) using a prototype of an MHD propulsion ship with a propulsion engine produced a relatively low speed of 0.12 cm/s. This design features a thick and heavy ship system, requiring significant energy to move quickly, which makes it challenging to make observations. Based on the prototype design of the study, the researcher is interested in conducting experiments related to the MHD system using a stationary design to observe water speed, such as using pump systems. This research was conducted by utilizing a simple MHD system that can provide information on the speed of water resulting from the influence of the Lorentz force. Understanding these interactions is essential for practical applications and can serve as a foundation for physics learning in the classroom. Using readily available materials and simple tools, this MHD series presents physics learning resources that can effectively illustrate electromagnetic theory and fluid dynamics in the future.

These simple experiments might be useful for physics learning resources for the concept of magnetic fields, because the concept is categorized as one of the concepts that are still considered difficult by early-level students, due to only being taught without practice (Jufri et al., 2024). This present study did not develop the experiments as learning resources and thus will not provide any information on the effectiveness for the students. However, in the future, learning resources can provide more concrete experiences, motivate, and enhance students' retention and understanding during the learning process (Hunaidah et al., 2024)

Method

The research method employed an experiment using several tools and materials, including electrode plates, power supplies, water, salt, magnets, tubs, and video recording devices. The electrode plate is made of iron with a variation in length of 6 cm, 8 cm, 10 cm, 12 cm, and 14 cm, with a thickness of 0.05 cm and a width of 3 cm. DC power supply with 3V, 6V, 9V, and 12V voltage variations. Saltwater solutions with varying salt masses of 35 g, 40 g, 45 g, 50 g, and 55 g, all in the same 1000 mL water volume. Ferrite magnets measuring 15×5×2.5 cm^3 and video recording devices. The experimental circuit is arranged by attaching a magnet to the bottom of a plastic container, where a pair of iron electrodes of the same size are attached to the top of the container. The magnet is positioned in the center, ensuring that the B field and E field are perpendicular to each other. In the next step, the saltwater is poured into the container, and then the electrodes are connected to the DC power supply. The experimental setup is shown in Figure 1.

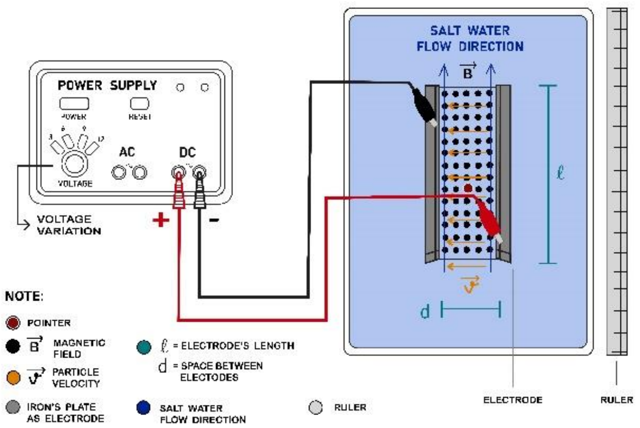

Figure 1. Experimental setup

The movement of the saltwater due to the electric and magnetic fields was recorded using a video recording device positioned at an optimal angle for visual analysis. The camera was positioned on top of the container at a 90° angle to the system surface to record the movement. The pointer is put on the end of the electrode plate and allowed to flow to the other end of the plate. Data collection was carried out by measuring the speed of saltwater through the movement of a pointer that moved with the water and then recorded.

The movement of the pointer in the experiment lasted for a short time, making it difficult to measure the speed directly. To overcome this, the Tracker Video Analysis application (Version 6.1.6) is used to quantitatively analyze changes in the position of particles in the saltwater, which allows motion analysis on a frame-by-frame basis. This application uses high-resolution video with a high frame rate (high FPS) to produce more accurate motion data, namely in the form of pointer motion speed. With features such as scale calibration and automatic graphing, the app provides strong support for quantitative analysis in physics experiments.

Some of the control variables applied in this experiment include the temperature of the saltwater, which is maintained at room temperature, as well as the volume of the saltwater, which is ensured to remain 1000 mL at each experiment repetition. Additionally, the experiments were conducted in an environment with consistent lighting to minimize visual interference in the video recordings. Several variations are carried out, namely variations in electrode length (L), distance between electrodes (d), voltage (V), and saltwater salinity.

Result and Discussion

The Magnetohydrodynamic (MHD) principle concerns the mobilization of fluids inside a channel without the need for any external moving parts (Li et al., 2021). The system on MHD utilizes the force generated by the interaction of the electric field and the magnetic field, according to the Lorentz force mechanism. To create a uniform electric field, parallel plate electrodes are usually used. The electric field between the two electrodes is the same except for the edges of the electrode due to the increased field (Dalvi-Isfahan et al., 2016). For particles to move quickly, the particles must be in an area with a relatively significant potential difference so that the electric field that arises between the electrodes is also relatively large (Fithriyah & Khotimah, 2016). The potential differential can be applied by applying a voltage from the outside (power supply). This potential difference is necessary to move the charge from one point to another (Usman et al., 2017). This corresponds to equation (1), which shows that the force is proportional to both the electric and magnetic fields. The flow rate of the saltwater was initially zero (v_i = 0) when given a potential difference combined with the presence of a magnetic field that would cause the Lorentz force. This force causes a change in the rate of saltwater flow to be v_f based on equation (4). The magnitude v_f depends on the variables that affect the electric field. These variables include different potential sources, electrode length, distance between electrodes, and the salinity of saltwater.

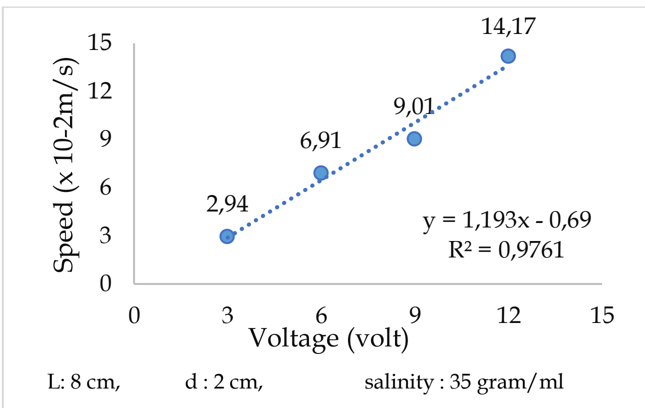

Figure 2. Voltage variety to speed

Figure 2 illustrates the effect of potential (Voltage) variation on the saltwater flow rate. The experimental data showed a linear increase in speed with increasing potential differences. This is consistent with the Lorentz force equation (1). As the voltage increases, the electric field E between the electrodes becomes stronger, which increases the magnitude of the Lorentz force acting on charged ions in the solution. This force induces motion perpendicular to both E and the magnetic field B, causing the ions to drift and generating fluid flow in the saltwater. The linearity relationship indicates that within the range of 3 to 12 Volts, an increase in the electric field results in a proportional increase in the flow speed.

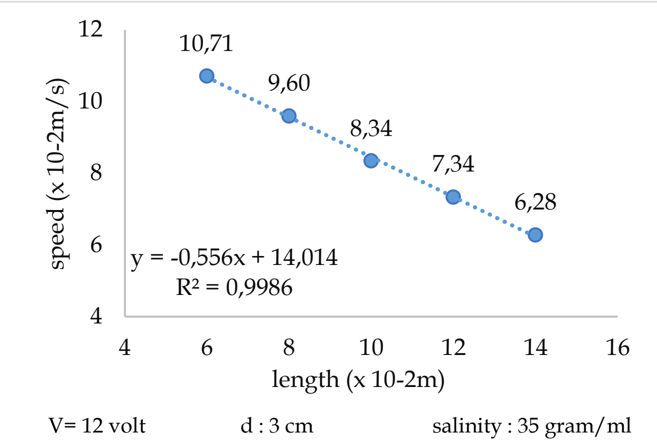

Figure 3. Electrode's length to speed

Figure 3 shows the results of experiments on variations in electrode length. The electrodes used are 6 cm to 14 cm in size with an interval of 2 cm. The distance between the electrodes used is 3 cm, which is the minimum distance to prevent the observation pointer from being distracted by the excess bubbles generated during the electrolysis process, allowing it to move toward the edge of the electrode. Based on the analysis of the tracker application, the data shows that the speed of the saltwater flow decreases with the increase in electrode length. An increase in the length of the electrode will result in a decrease in the speed of the saltwater flow because the electrical and magnetic forces are weaker when distributed along the electrode using a fixed source potential difference of 12 volts. An increase in the length of the electrode causes the distribution of electric current to occur over a wider area, resulting in a decrease in current density per unit length of the electrode. This decrease in current density results in a reduction of the resulting Lorentz force, weakening the thrust on the fluid and decreasing the flow speed. This finding is based on numerical research conducted by Karimi-Sibaki et al. (2024), which demonstrates that the distribution of current density influences the flow speed between electrodes.

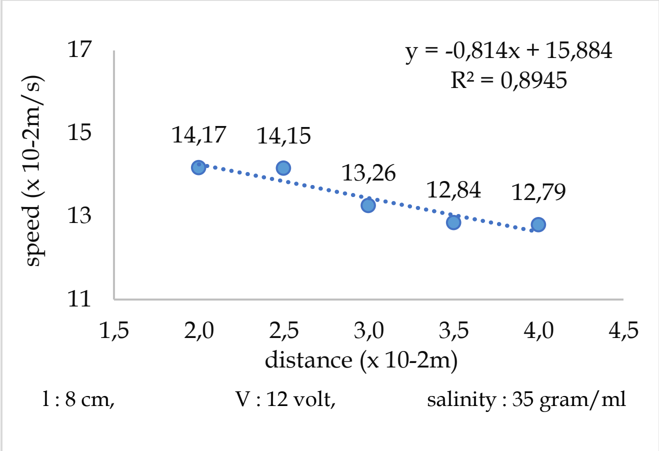

Figure 4. Electrode's distance to speed

The effect of the distance between the electrodes on the saltwater flow rate is shown in Figure 4. The greater distance between the electrodes results in a decrease in the speed of the saltwater flow. However, the regression value of 0.89 suggests that the relationship between the two variables is not sufficiently linear. The distance between the electrodes affects the magnitude of the electric field applied (Budi et al., 2020). The electric field is calculated by dividing the potential difference by the distance between the electrodes, based on equation (2). If the distance between the electrodes is enlarged with a fixed voltage source, then the magnitude of the electric field will decrease. As the applied electric field decreases, the Lorentz force also decreases, which, in turn, drives the movement of the pointer in the saltwater flow. In addition, the greater the distance between the electrodes, the more heterogeneous the electric field and current in the fluid become, making the movement of saltwater flow less efficient. This results in an obstacle that reduces the speed of saltwater flow.

MHD is highly dependent on the salinity of saltwater. The level of solution concentration affects the number of dissolved particles, namely Na^+ and Cl^-. Based on the data in Figure 5, the speed of saltwater flow increases with increasing salinity. The salinity level in the solution determines the electrical conductivity, which then affects the interaction between the saltwater and the magnetic field. Conductivity is a measure of the ability of a fluid to conduct an electrical current (Mathur, 2015). In other words, the increased conductivity of the fluid contributes to an increase in the flow rate of the fluid in response to the influence of the magnetic field (Peng et al., 2008). The greater the number of dissolved particles interacting with the magnetic field, the greater the force produced; in this case, the speed of the saltwater flow is depicted in the graph because of the force. An increase in the concentration of the saltwater leads to an increase in the production of hydrogen gas due to electrolysis (De Luca, 2011; Torabian et al., 2022).

However, an increase in saltwater concentration has a critical saturation point that affects the flow speed. In conducting this study, the researcher used variations in salt concentration, with the salt mass ranging from 20 to 40 grams in increments of 4 grams. This variation was chosen because when a salt mass of less than 20 grams is used, there is no fluid flow. When a salt mass exceeding 40 grams is used, the results reach the saturation point, rendering the linearity condition unattainable.

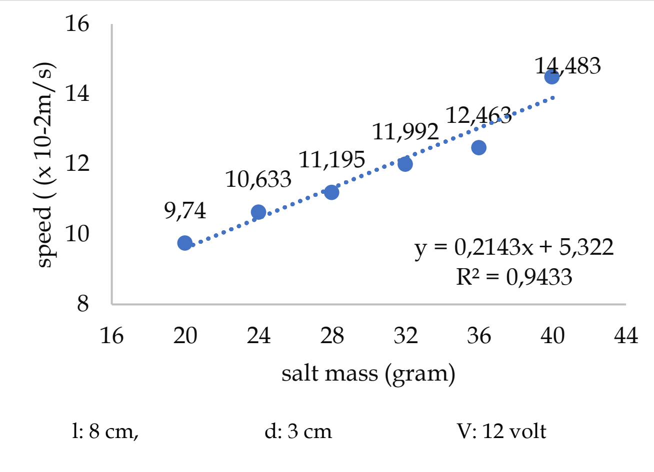

Figure 5. Salinity variety to speed

An electrochemical process will occur if two electrodes are stored in an electrolyte (such as saltwater) and passed through a direct electric current (Setianingrum et al., 2016). The electrochemical processes on the plates affect foam production. The magnetic field can release bubbles from the surface of the electrode due to the flow of MHD (Chen et al., 2022). The presence of bubbles indicates that MHD is less efficient, as the energy used for water movement is partly diverted to foam production. The follow-up effect is that the electrodes will quickly rust due to the electrolysis effect, therefore increasing the resistance (Overduin et al., 2017). Another research study determines the behavior of hydrogen bubbles in a magnetohydrodynamic (MHD) channel that is equipped with platinum electrodes and analyzes the effects of varying inter-electrode distances and different electrical current intensities on bubble flow patterns within the channel. The results show that narrower electrode spacing promotes laminar flow, while wider spacing induces turbulence.

The results of the simple linear regression analysis are presented through the regression equations.

$$Y = ax + b \tag{5}$$

a is a number representing a regression coefficient to show the magnitude of the change in the dependent variable due to a one-unit change in the independent variable. Linear regression analysis of the resulting data reveals that the saltwater flow speed in the MHD system is linearly affected by voltage, electrode length, distance between electrodes, and saltwater salinity. The relationship between variables is illustrated by the determination coefficient (R^2), which indicates the degree of linear correlation between each variable. Based on the linearity equation shown in Figures 2, 3, 4, and 5, it is evident that the regression coefficients for voltage (a = 1.193) and salinity of saltwater (a = 0.2143) have a positive influence, indicating that increases in both tend to increase the flow speed. Conversely, the length of the electrode (a = -0.556) and the distance between the electrodes (a = -0.814) have a negative influence; thus, the longer the electrode and the greater the distance between the electrodes, the slower the flow of saltwater.

Conclusion

Magnetohydrodynamics (MHD) in this study is explained through the effects of electric and magnetic fields on fluid dynamics in saltwater. This research aims to enhance the performance of fluid flow measurement in a simple magnetohydrodynamic (MHD) system by optimizing key variables, including the applied voltage, the distance between electrode plates, electrode length, and the salinity of saltwater. The research shows that a simple MHD system can be optimized by setting these variables. The experimental results show that increasing the voltage and salinity, as well as reducing the electrode length and the distance between electrode plates, consistently increases the flow speed of saltwater. Thus, each variable contributes significantly to the system's performance, enabling the design of an optimal MHD configuration. These findings can serve as a basis for the development of MHD-based fluid rate measurement devices that are simple, applicable, and support real-world understanding of electromagnetic concepts and fluid dynamics. The limitation in this experiment is the lack of equipment facilities such as a DC power supply with high voltage and a large strong magnet, which causes the observation results to be less than optimal for advanced research. However, this simple MHD experimental circuit can be used in the learning process to provide students with an understanding of the Lorentz force. Further research can be conducted by developing learning media that utilize simple MHD to test its effectiveness in improving student understanding.

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Author Contributions
Conceptualization, H. R. P, B. A. R, N. K, S. N. K.; methodology, H. R. P, and B. A. R.; Software, H. R. P, and N. K.; validation, H. R. P, B. A. R, N. K.; formal analysis, H. R. P, and N. K.; investigation, H. R. P, B. A. R, N. K.; resources, S. N. K, B. A. R, N. K.; data curation, B. A. R.; writing-original draft preparation, H. R. P.; writing-review and editing, B. A. R, and N. K.; visualization, N. K.; supervision, S. N. K.; project administrator, S. N. K. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest
The authors declare no conflict of interest.

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