MODELING AND CONSTRUCTION OF A MAGNETOHYDRODYNAMIC TUNNEL

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Abstract. *Magnetohydrodynamics or simply (MHD) is a field of science that studies the movement of conductive fluids subjected to electromagnetic forces. Such a phenomenon brings together concepts of fluid dynamics and electromagnetism. Over the years, MHD has been encountered in a wide area of technological applications, from electromagnetic propulsion to biological devices. However, few students know exactly how an MHD device works, whether in theory or practice. The present work didactically shows the construction (materials and equipment) and operation of an MHD device (in which case a small salty water tunnel without any mechanical parts), where you learn for example how to use basic measurement equipment like the manometer and the multimeter. It is also possible to calculate de fluid velocity, current and pressure. The objective is to demonstrate the capabilities of MHD (its technologies and applications) and to show the various disciplines present in this area. The concepts, theory, and the water tunnel involved serve as a powerful teaching tool for any graduate and undergraduate student regardless of their area of research.*

Keywords*: magnetohydrodynamics, electromagnetic forces, salty water*

1. INTRODUCTION

MHD studies the interaction between the movement of conductive fluids (electrolyte) and their interaction with electric and magnetic fields, combining the basic equations of the fundamental fluid dynamics (Navier-Stokes) with the equations of electromagnetism (Maxwell).

Such a principle has been highlighted in several knowledge subjects; including nuclear engineering to pump liquid sodium, naval and aerospace engineering to pump propelled gases with electromagnetic devices, and metal melting environments and biological research.

Many studies in this area are still being developed. For example, Andreev *et al*. (2006) in his work demonstrated experimentally, a very detailed rectangular channel study of velocity profiles present in an MHD phenomenon and underlines the importance of aluminum production. Ramos and Winovich (1990) applied finite element method to simulate an MHD channel flows as a function of the Reynolds number and wall conductivity. Lemoff and Lee (2000) applied a computational method to describe a micro fluidic pump using alternated current and MHD propulsion to propel an electrolyte solution. However the MHD phenomenon was discovered by Ritchie (1832), who described the basic operation principle of such devices.

This paper will discuss the construction and methods of use of an electromagnetic pump device filled with salty water. In an electromagnetic pump, a direct current is applied across a flat rectangular channel filled with electrically conducting fluid (salty water) which is submitted to a non uniform orthogonal magnetic field. The interaction between the magnetic field and the current produces an electromagnetic force called Lorentz´s force, which acts as a pump, moving the fluid forward.

2. THEORETICAL ANALYSIS

The MHD channel's physical model is based mainly on the Lorentz electromagnetic force which drives the fluid trough the channel.

The formulation of the MHD steady state model has been derived from the Maxwell´s equations (electromagnetic domain) coupled with Navier-Stokes equations for a non Newtonian incompressible flow. Therefore the model is governed by the electromagnetism and fluid dynamics equations.

$$\nabla \times \left(\frac{\nabla \times \mathbf{A}}{\mu} \right) \tag{1}$$

$$\mathbf{J} = \sigma \left[-\nabla \phi + \mathbf{u} \times \left(\nabla \times \mathbf{A} \right) \right] \tag{2}$$

$$\nabla \cdot \mathbf{J} = 0 \tag{3}$$

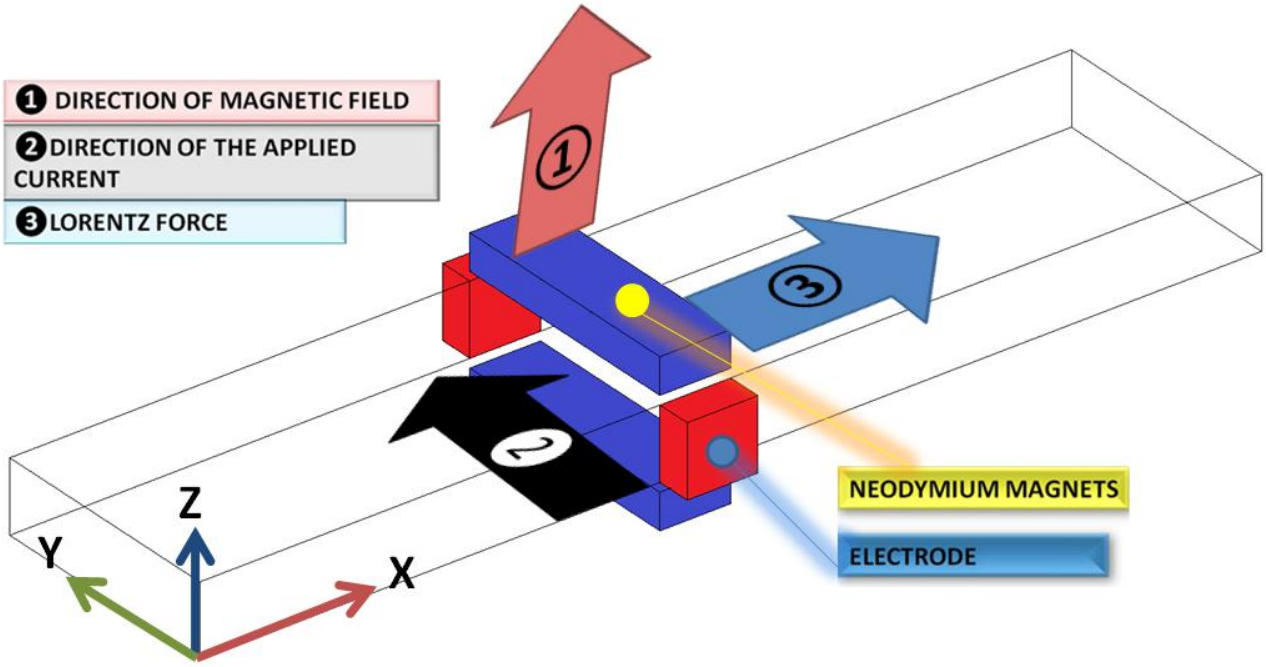

Figure 1. Rectangular MHD tunnel configuration

Eq. (1) represents the Maxwell-Ampère´s Law, Eq. (2) represents Ohm´s law and Eq. (3) the conservation of the electrical current, where $\mathbf{J}$ is the total current density, $\mathbf{A}$ is the magnetic vector potential, μ is the permeability, σ is the electrical conductivity of salty water and ϕ is the electrical vector potential.

$$\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla)\mathbf{u} = -\frac{1}{\rho}\nabla P + \eta \nabla^2 \mathbf{u} + \frac{1}{\rho}(\mathbf{J} \times \mathbf{B}) \tag{4}$$

$$\nabla \cdot \mathbf{u} = 0 \tag{5}$$

Where $\mathbf{u}$ is the fluid´s velocity, ∇P is the gradient pressure, η is the kinematic viscosity of salty water and ρ is its density. The electrical scalar potential ϕ can be determined by solving the Poisson equation:

$$\nabla^2 \phi = \nabla \cdot \left[\mathbf{u} \times (\nabla \times \mathbf{A})\right] \tag{6}$$

Here the space dependent variables are $\mathbf{A}(x, y, z)$, $\mathbf{J}(x, y, z)$ and $\phi = (x, y, z)$. Equation (2) can be also formulated in terms of:

$$\mathbf{E} = -\nabla \phi \tag{7}$$

$$\mathbf{B} = (\nabla \times \mathbf{A}) \tag{8}$$

Leading to:

$$\mathbf{J} = \sigma(\mathbf{E} + \mathbf{u} \times \mathbf{B}) \tag{9}$$

The coupling between the electromagnetic model and the fluid model is achieved by introducing the Lorentz force $\mathbf{F}$, given by $\mathbf{J} \times \mathbf{B}$. The total Lorentz pumping force in Newton, acting directly on the volume of the liquid, can be defined by integrating all elemental forces $d\mathbf{F}$.

2. EXPERIMENTAL PROCEDURE

The problem consists of a closed circuit made of acrylic with settings and arrangements showed in Fig. (2). The reason for using the acrylic was due to availability and flexibility, allowing more simple and accurate cuts, resulting in 16 pieces that were glued and vetoed by chloroform and silicone, Fig. (3). The circuit has an oval geometry allowing fluid recirculation without external losses.

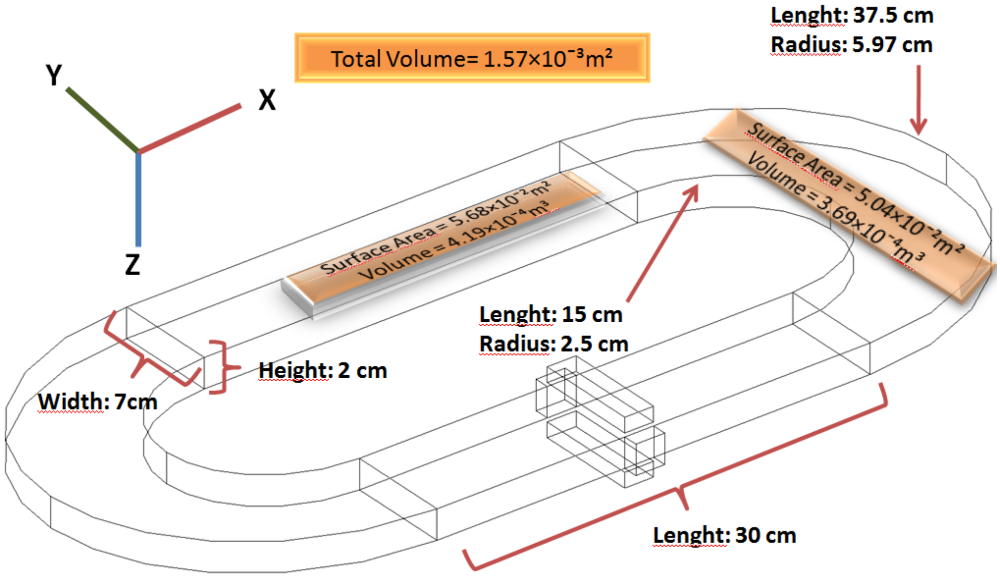

Figure 2. The MHD tunnel dimensions

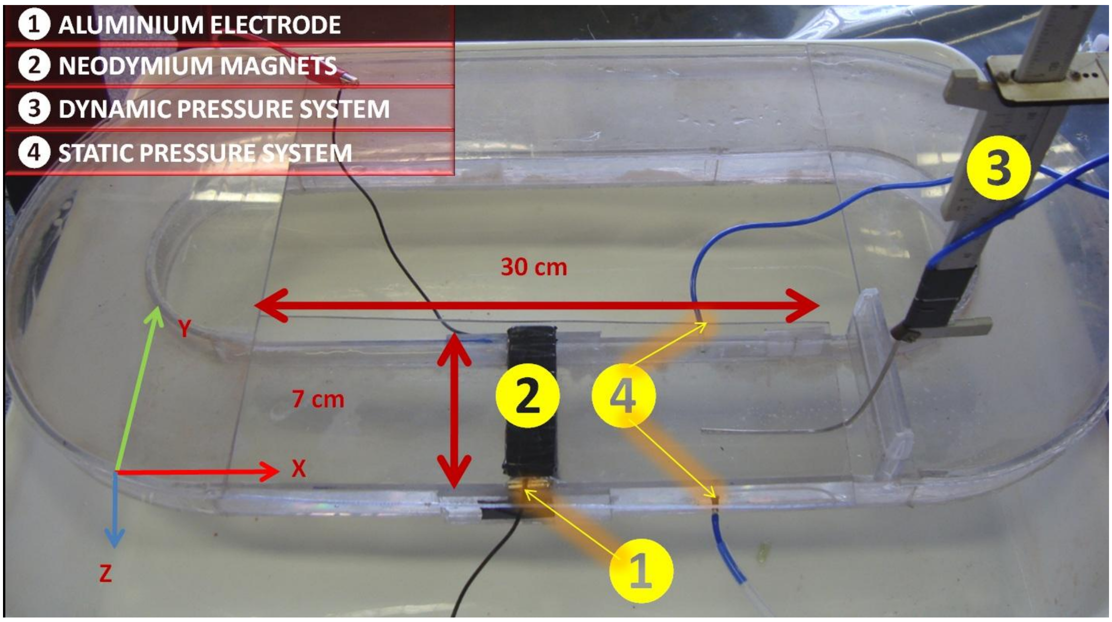

Figure 3. The MHD tunnel configuration and the electromagnetic region

The circuit was filled with salty water (approximately 120 grams of salt to 1.5 liters of water) to simulate an electrolyte solution. Two neodymium *NdFeB* magnets were used (with grade N35, remanence 1.21 T and magnetic flux density 0.3 T) with dimensions 70 mm x 20 mm x 10 mm and aluminum plates with dimensions 20 mm x 20 mm x 3mm were used to reproduce the electrodes. For the full operation of experiment a power supply that provided a direct current of 0 A – 5 A and 0 V – 30 V was needed. The power supply was connected to the electrodes.

The experiment was done at 0.92×10^{5} Pa and 297 K (23.85 ºC). The electromagnetic domain schematic follows as shown in Fig. (1) and the system characteristics is found in Tab. 1.

Figure 4. DP - Calc manometer used to measure static and total pressure

Figure 5. MPC – 3006D Power supply

Table 1. MHD circuit features

Electromagnetic Domain Length (m)	Circuit Height (m)	Circuit Width (m)	Circuit Volume (m^3)	Magnets Volume (m^3)	Electrodes Volume (m^3)
3.0×10^{-1}	2.0×10^{-2}	7.0×10^{-2}	1.5×10^{-3}	1.4×10^{-5}	1.2×10^{-6}

Table 2. MHD fluid features

Solution	Electric Resistance (Ω)	Electric Conductivity (S/m)	Density (kg/m^3)	Dynamic Viscosity ($N\cdot s/m^2$)
$H_2O+NaCl$	15.000	4	1020	1.4×10^{-5}

The total pressure system (Pitot) could move freely through the channel. In this experiment the Pitot was configured to measure local velocities, next to the electromagnetic domain, since this phenomenon is presented only in the magnets and electrodes areas. The set points that the Pitot could move are plotted in Fig. (6).

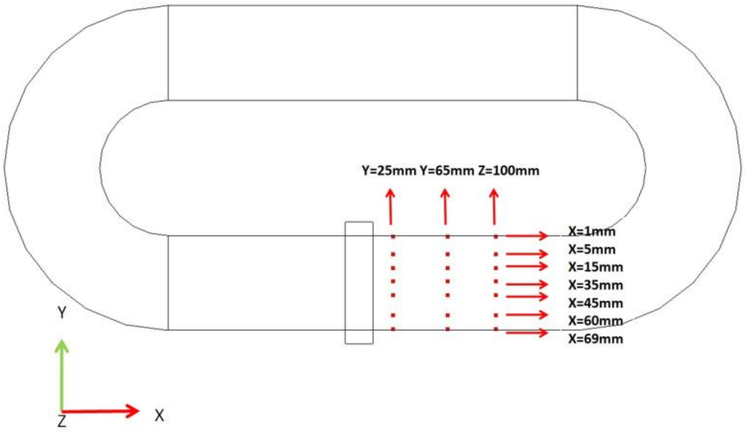

Figure 6. Points defined for the pitot

The main experimental objective is measuring pressures at the cross section with a differential manometer Fig. (4), capturing the channel´s static and total pressures and then trace a velocity profile as a function of applied voltage in the y-axis region. The reason for this choice of profile is due to the presence of the MHD force in this area. For educational purposes the author chose some pre determined points where the Pitot would be inserted and the voltages would be alternated between 12 V, 20 V and 30 V, recalling that the system has no moving mechanics parts. As the manometer had a resolution of 0.1 Pa the direct measurement of velocity was impossible since we have worked with very low values. Soon, it was necessary to calculate the velocity using an analytical solution $V_{loc}=\sqrt{\frac{2(P_d-P_s)}{\rho}}$ where P_d is the dynamic pressure and P_s is the static pressure, according to Fox *et al* (2004). Other data such as applied current and final system´s temperature were also entered. Soon after the analysis of comparative data graphs were plotted.

3. RESULTS

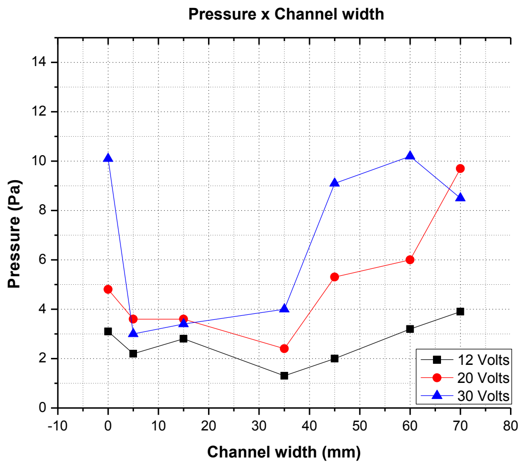

Figure 7. Mean pressure versus *y* position as a function of voltage and x = 25 mm

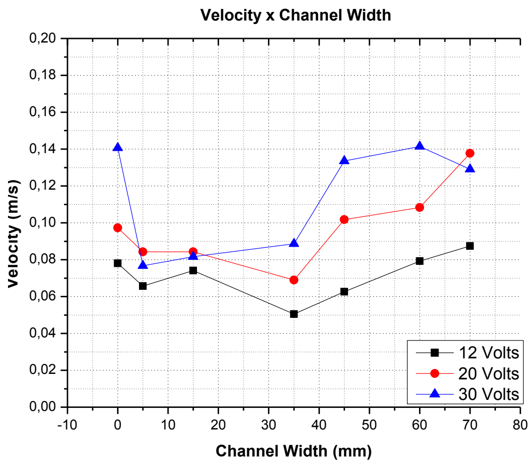

Figure 8. Mean velocity versus *y* position as a function of voltage and x = 25 mm

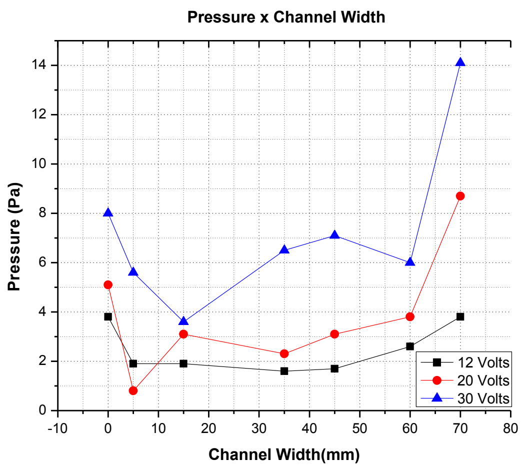

Figure 9. Mean pressure versus *y* position as a function of voltage and x = 65 mm

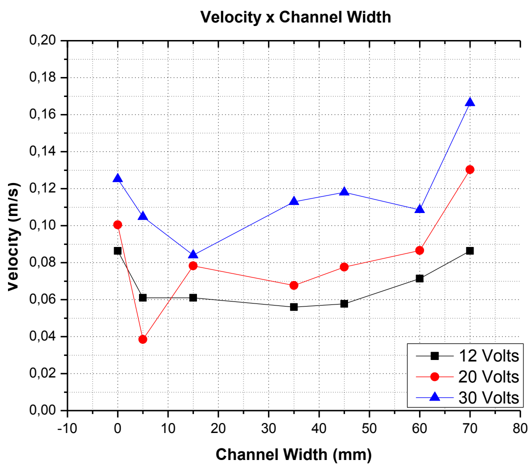

Figure 10. Mean velocity versus *y* position as a function of voltage and x = 25 mm

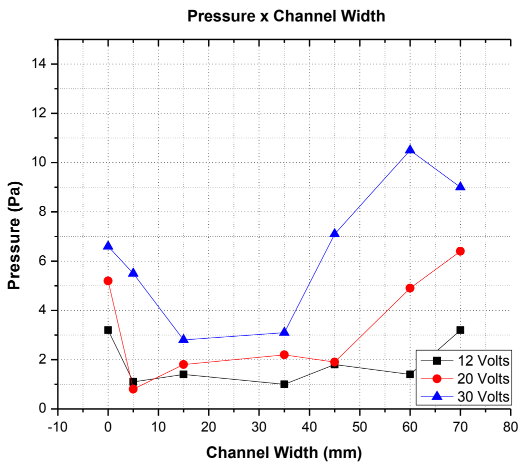

Figure 11. Mean pressure versus *y* position as a function of voltage and x = 100 mm

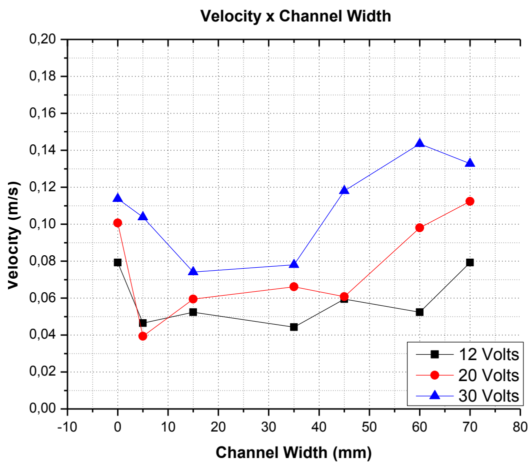

Figure 12. Mean velocity versus *y* position as a function of voltage and x = 25 mm

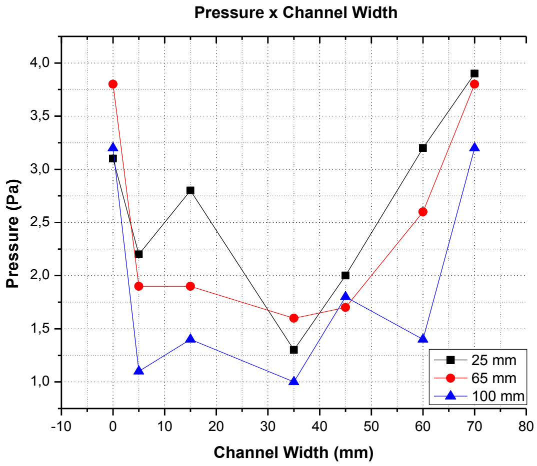

Figure 13. Mean pressure versus *y* position at 12 Volts in function of all Pitot positions

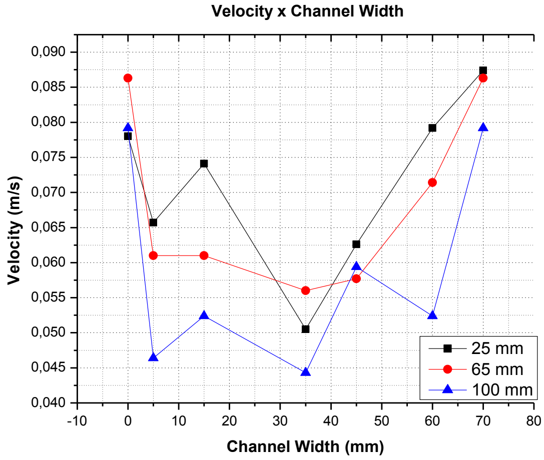

Figure 14. Mean velocity versus *y* position at 12 Volts in function of all Pitot positions

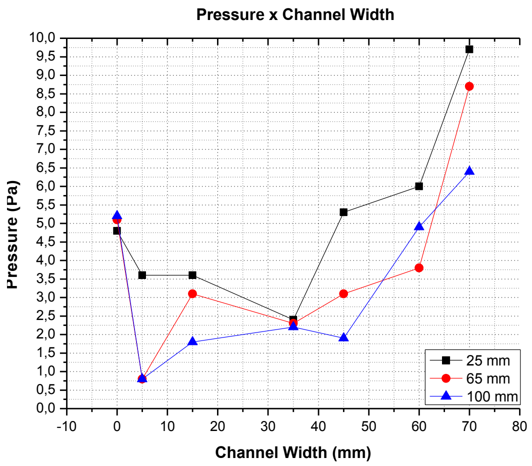

Figure 15. Mean pressure versus *y* position at 20 Volts in function of all Pitot positions

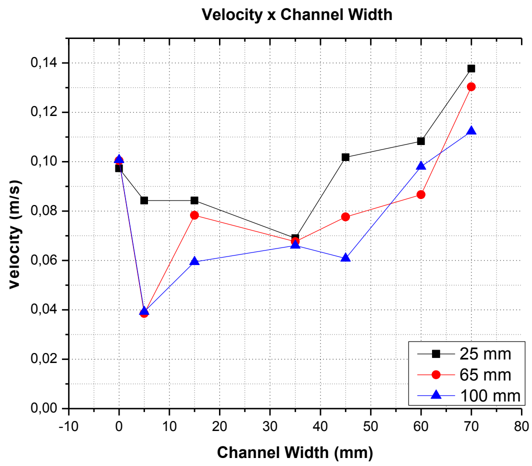

Figure 16. Mean velocity versus *y* position at 20 Volts in function of all Pitot positions

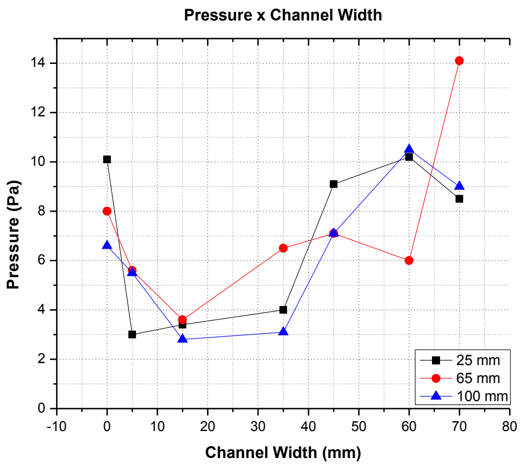

Figure 17. Mean pressure versus *y* position at 30 Volts in function of all Pitot positions

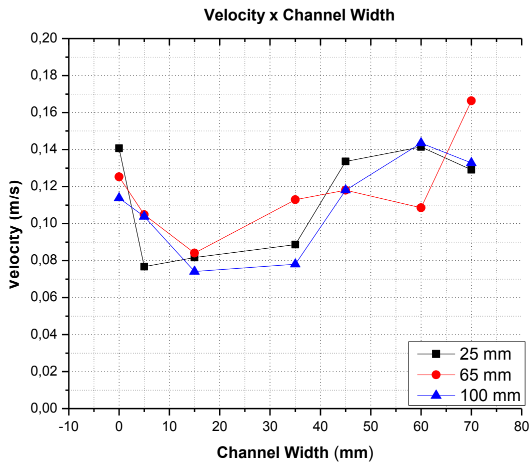

Figure 18. Mean velocity versus *y* position at 30 Volts in function of all Pitot positions

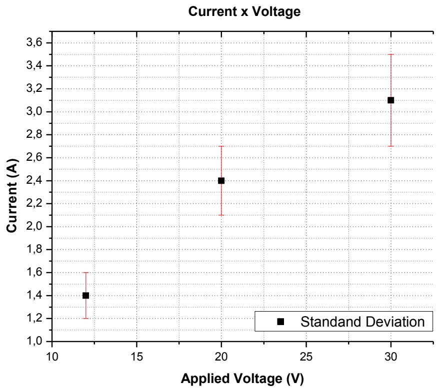

Figure 19. Current versus Applied Voltage

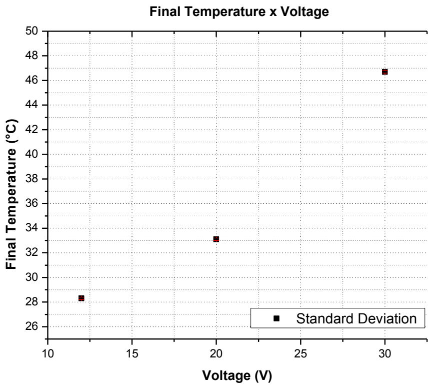

Figure 20. Final Temperature versus Voltage

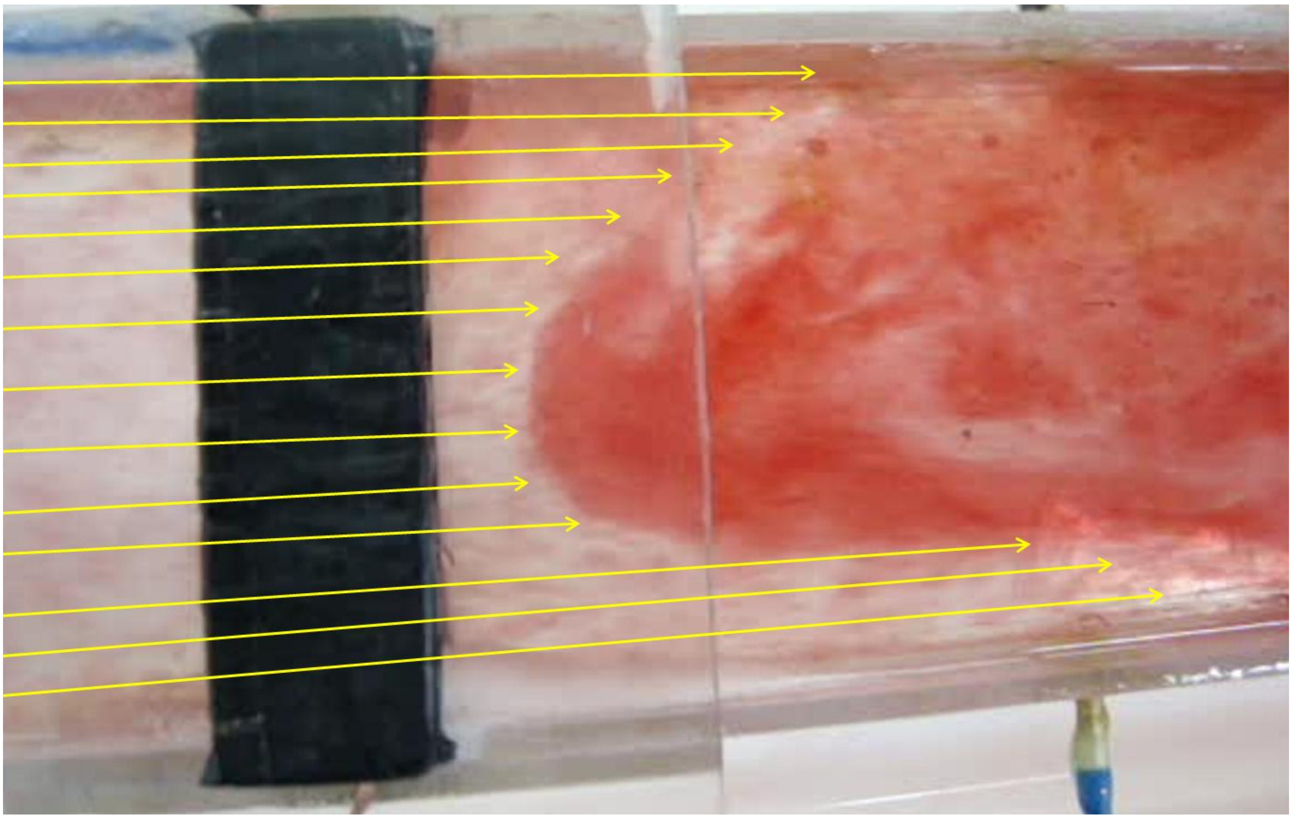

Figure 21. The MHD velocity profile

3. CONCLUSION

This simple experiment demonstrated the capacity and functionality of an MHD device. The low fluid velocity, however, did not prevent its movement through the circuit and it was possible to calculate the local velocity of the fluid and plot an interesting profile. A brief look at the graphs shows an unusual velocity profile; the effect of Lorentz forces is it at maximum at the middle of the channel. The fluid decelerates and its velocity is almost zero in some points while it accelerates near the channel walls. This velocity profile can be found in several MHD devices.

The velocity and pressure profile also increases by varying the voltage. This is directly reflected in the equations of electromagnetism and fluid dynamics, where the Lorentz force resulting from the electric and magnetic fields cause a change in the fluid pressure gradient moving it.

Despite appearing similar to a conventional water pump, the MHD pump has no moving mechanical parts while exhibiting a precise flow control, reduced energy consumption and less dross formation. We can adjust the flow rate and velocity by adjusting the electric and magnetic field values only.

According to Daoud and Kandev (2008), different electromagnetic pumps are widely used in many liquid metal environments such as extrusion billet casting, metal refinery for transporting molten metals, alloys production etc.

Finally another important aspect in the experiment was the multidisciplinary approach, involving fundamental equations of classical electromagnetism and fluid dynamics, providing a solid foundation of physical concepts. In the early years of college or university the student learns how to use the basic measurement tools, like a manometer or multimeter. Another advantage is the low operational cost and high availability of materials for the construction of the circuit. Because of its simplicity, small size and low cost, the circuit becomes a powerful tool for teaching and student learning.

4. REFERENCES

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