THE EFFECTS OF UNIFORM TRANSVERSE MAGNETIC FIELD ON LOCAL FLOW AND VELOCITY PROFILE

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ABSTRACT

A numerical model studied the effects of uniform transverse magnetic field for two fluids (pure water and water with electric conductivity), two different non-magnetizable duct and two flow velocities (steady flow for laminar and incompressible) was examined and The results showed an increase in the magnetic field caused a decrease in the local flow and effected on velocity profile. The result also showed that the water with electrical conductivity more affected than pure water.


1. INTRODUCTION

Fluid flow and the effects of the magnetic field is one of the important scientific applications which is known as the Magnetohy-dromodynamics (MHD). Its concept is that magnetic fields can stimulate currents in a conductive liquid which creates a force that will be affective in flow and also can lead to change in the magnetic field itself. The grow interest in this field as a result of its association with the science of physics and chemistry, as well as its relationship with many industrial, agricultural, medical and their applications.

A basic understanding of the MHD phenomenon is essential where many researchers were highlighted in this field due to its wide potentials:

- Parasuraman et al., 2010 studied Hydromagnetic flow of electrically conducting viscous incompressible fluid through a circular pipe. The results were expressed
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graphically to bring out the effects of various parameters entered in the governing equation.

- Xie, 2010 studied flows liquid metal in strong magnetic fields by using analytical tool to investigate the effect of applied magnetic and electric fields on the flow phenomena of an electrically conducting fluid.
- Gedik et al., 2011 studied the effects of uniform transverse magnetic field on the two phases (solid/liquid) steady flow for laminar, incompressible and electrically conducting fluid in the cylindrical non-magnetizable pipes was examined theoretically.

Since the effect of the magnetic on flow patterns may be quite important, it is worthwhile to study the effect of them on separated flows. The goal in this section is to investigate the effects of the applied magnetic on the flow by developing numerical and analytical different models.

2. BASIC EQUATIONS OF HYDROMECHANICS

The basic equations in hydromechanics are transport equations (1) of mass, momentum, energy, etc. It is possible to handle all of these equations in a unified formula. To prepare that formula the generic transported quantities were used

- Extensive quantity m.
- Intensive quantity \( \phi \) (Intensity of the quantity m).
- Flux \( j \) of the quantity m.
- Sources/sinks \( s \) of the quantity m.

\[
m = \int \phi d\Omega
\]

Through integration of equation (1); obtaining the differential form in equation (2).

\[
\frac{\partial \phi}{\partial t} + \nabla \cdot j = s
\]

3 FLUID FLOW EQUATIONS

The equations relevant in hydromechanics follow from equation (2) through appropriate choice of the quantities \( m, \phi, s \) and \( j \). So for the transport of fluid mass (continuity equation) taking \( m = M \) (mass), \( \phi = \rho \) (density), \( j = \rho u \) (mass flux) we obtained the continuity equation (3).

\[
\frac{\partial \rho}{\partial t} + (u \cdot \nabla) \rho + \rho \nabla \cdot u = 0
\]

The momentum equation was obtained by using equation (4-3) and taking \( m = MVu \) (momentum in the volume \( V \), \( \phi = \rho Vu \) (momentum density), \( j = \rho u Vu \) (momentum flux) and \( s \) = force density (volume and surface forces) .The result was equation (4-4).

\[
\rho \frac{\partial u}{\partial t} - \nabla \cdot (\mu (\nabla u + (\nabla u)^T) + \rho u \nabla u + \nabla p = F
\]

This equation being also known as Navier Stoke’s equations which describe the behavior of fluids in terms of continuous functions of space and time. They state that changes of momentum in the fluid are based on the product of the change in pressure and internal viscous dissipation forces acting internally. In this case the F term is a volume force (\( F_x, F_y \)) that is constituted by a magnetic force.

The basis of two fundamental effects (fluid flow and magnetic field) can be understood: the induction of electric current due to the movement of conducting
material in a magnetic field, and the effect of Lorentz force, is the combination of electric and magnetic force on a point charge due to electromagnetic fields, is the result of electric current and magnetic field interaction while the Lorentz equation (5) used fluid with an externally applied magnetic field either an electromagnet or permanent magnet.

\[ F_{\text{MHD}} = J \times B \]  

Where: \( F_{\text{MHD}} \) (N/m\(^3\)) designated the MHD force is the vector force acting on the charge-carrying ions, \( J \) (C/sec cm\(^2\)) is the vector flux of ions and \( B \) (T) is the externally applied magnetic field vector.

4. MAGNETOSTATIC EQUATIONS

The magnetic part of this case is static so Maxwell-Ampere’s law for the magnetic field applied in equation (6) and Gauss’ law for the magnetic flux density \( B \) (Vs/m2) states the equation (7):

\[ \nabla \times H = J \]  

\( H \) (A/m) and the current density \( J \) (A/m2)

\[ \nabla \cdot B = 0 \]  

The constitutive equations describing the relation between \( B \) and \( H \) in the different parts of the modeling domain read:

\[ B = \begin{cases} 
    \mu_0\mu_r(H + B_{\text{rem}}) & \text{permanent magnet} \\
    \mu_0(H + M_{\text{eff}}H) & \text{fluid stream} \\
    \mu_0H & \text{pipe wall and air}
\end{cases} \]

Where: \( \mu_0 \) is the magnetic permeability of vacuum (Vs/(A·m)); \( \mu_r \) is the relative magnetic permeability of the permanent magnet (dimensionless); \( B_{\text{rem}} \) is the remanent magnetic flux (A/m); and \( M_{\text{eff}} \) is the magnetization vector in the water stream (A/m), which is a function of the magnetic field, \( H \).

The calculations for a static magnetic field made by depending on Poisson’s equation (8) in the region of permanent magnets, and on Laplace's equation (9) in the region of the all other parts of magnetic device:

\[ \nabla \times \left( \frac{1}{\mu} \nabla \right) A = \frac{1}{\mu_0} \nabla B_r \]  

\[ \nabla \times \left( \frac{1}{\mu} \nabla \right) A = 0 \]  

Where: \( A \) is magnetic vector potential, \( B_r \) is remaining magnetic flux density of permanent magnets, \( \mu_0 \) is the absolute permeability of material and \( \mu \) is the permeability of vacuum (4π·10\(^{-7}\) Vs/Am).

Because the magnetic field is conservative; the magnetic vector potential is defined by:

The velocity field \( u \) and the magnetic field \( B^0 \) are coupled. The movement of this conducting fluid in the magnetic field ensued electric currents (also called eddy currents) \( J^* \) in the fluid which are governed by the Ohm’s law equation (10):

\[ \overline{J} = \sigma \left( \overline{E} + \nabla \times \overline{B} \right) \]

\[ \overline{B} = \nabla \times \overline{A} \]

\[ \nabla \cdot \overline{A} = 0 \]
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Where: \( V = (0,0,u) \) is the velocity distribution, \( \rho \) the water density, \( \mu_o \) magnetic permeability, \( \vec{B} = (0,B_y,0) \) the magnetic field, \( E \) the electric field, \( J \) the current density, \( k \) is the permeability parameter of porous medium, \( \mu \) is the dynamic viscosity of the water, \( \mu_i \) is the elastico-viscosity coefficient of the water and \( \sigma \) is the electric conductivity of the water.

Under the above assumptions the equation of motion is

\[
\rho \frac{\partial u}{\partial t} = A_y + A_1 \cos(\omega_y t) + \left( \mu + \mu_1 \frac{\partial}{\partial t} \right) \left( \frac{\partial^2 u}{\partial r^2} + \frac{1}{r} \frac{\partial u}{\partial r} \right) + \rho \left( a_y \cos(\omega_y t) \right) - \frac{1}{k} \left( \mu + \mu_1 \frac{\partial}{\partial t} \right) u - \sigma B_y^2 u
\]

5. NUMERICAL MODEL

A finite element model using COMSOL Multiphysics 4.4a was used to understand the interactions between magnetic fluids and an applied magnetic field. The Navier-Stokes relations were used to solve the velocity profile of the magnetic fluid. Maxwell’s equations, along with Gauss’ and Ampere’s Laws were used to determine the magnetic field from the permanent magnet. The model described below is a derivation of a previously established model by COMSOL Multiphysics to describe the interactions between a magnetic fluid and a permanent magnet to be used for drug targeting studies. The finite element model setup, boundary conditions, the simulations performed and the observed results are discussed in this chapter.

5.1. The Implementing Model

The interactions between magnetic fluids and an applied magnetic field model coupled the Mesh element, incompressible Navier-Stokes and Magneto statics mode. Through this implementation, forces placed on water channel are taken into account. The flow examined numerically for laminar, incompressible and electrically conducting fluid in the non-magnetizable duct, the flow exposed to uniform transverse magnetic field. The first liquid was water with high electrical conductivity (5 ds/m) and the second was chosen as pure water which has very poor electrical conductivity. The system of the derived governing equations, which were based on the Navier-Stokes equations including Maxwell equations, were solved numerically by partial differential equations on the COMSOL Multi-Physics for both phases. The obtained results from the numerical analysis are presented and discussed in terms of local axial velocities of particle and fluid phases against flow time and the duct damnation. The problem is for laminar flows at low Reynolds numbers and steady state conditions. Magnetic field which was applied perpendicular to the flow was changed (0 to 1) Tesla. Non-magnetic duct which had 1 cm and 0.75 cm in diameter were used as a duct of flow regime material. The geometry, physics modes, and mesh being discussed before the presentation of the final results.

5.2. The Geometry

The geometry used in the 2D finite element model is shown in Figure (1). The blue boundaries encompassed the magnetic fluid. The red boundaries refered to the permanent magnet. Sufficient space for dissipation of the magnetic flux lines was given by creating a large domain with air surrounding the magnets and the fluid. It
was assumed that the magnetic field between the two parallel magnets be more uniform, thus having a great effect with the alignment of the magnetic moments of the magnetic fluid.

![Figure 1 Finite Element Model Geometry](image)

**5.3. Constant Flow**

The input flow rate considered steady, laminar and fully development, the fluid velocities in a horizontal duct were (0.2 and 0.1) m/sec. Also, the magnetic field produced by the permanent magnet configuration varied, by changing the strength of the magnets used from (0 to 10000) Gauss.

**4.5.4 Boundary Conditions**

Proper boundary conditions were declared to find solutions to the model. Descriptions of the boundary conditions are explained below.

**4.5.4.1 Magnetostatics**

- Magnetic Insulation: \( A = 0 \); Magnetic potential is equal to zero in the normal direction. Boundary condition selected for all boundaries surrounding the domain containing air.
- Continuity: \( n \times (H_1 - H_2) = 0 \); Signifies continuity of the tangential component of the magnetic field. Boundary condition selected for all boundaries surrounding the magnets and the fluid, with an exception of the fluid inlet and outlet.
4.5.4.2 *Laminar Flow*

- No Slip: $u = 0$; refers to the non-slip condition between the fluid and rigid walls. Boundary condition selected for the top and bottom boundary of the fluid.
- Inlet: $u = C$; Velocity at the inlet is equal to a constant $C$.
- Outlet: $P = 0$; pressure at outlet is equal to zero, signifies an open boundary. Boundary condition selected for the outlet of the fluid.

5.5. *Mesh*

For the multi-physics Model, the mesh element sizes and concentration are important for the channel, inlet, and permanent magnet where the solution of the magnetic field has its greatest impact. To accomplish this, a maximum element size of $5.5 \times 10^{-3}$ m was defined for the channel and inlet in the Free Mesh Parameters. The resulting mesh can be seen in Figure (2).

![Figure 2 The Mesh for the Mixture Model.](image)

5.6. *Checking The Magnetic Flux*

Before presenting the numerical results, the magnetic flux and stream line of magnetic field must compared according to the literature, where magnetic field being applied perpendicular to the flow to get high effects. Figure (3) shows the contours of magnetic flux density at time zero, the effective magnetic intensities inside the duct section between magnetic blocks ranged (0.8 to 0.9) Tesla, (1 Tesla =10000 Gauss). The stream lines of magnetic fields in Figure (4) shows that the fields perpendicular to the flow direction also Figure (5) shows the contour of volume forces inside the duct.
**Figure 3** Contour of Magnetic Flux Density at Time=0

**Figure 4** Magnetization Streamline
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5.8. Numerical Result
The COMSOL Multiphysics Software solved equations for flow and magnetization numerically under the initial and boundary conditions depending on finite element method. The effect of magnetic fields on the two axial local velocities, (0.13 and 0.2) m/sec, for fluid with different concentrations, and magnetic intensity were reported. Magnetic field induction which may be applied to the flow, pressure, fluid concentration can be changeable depending on the program used. Axial velocity profiles is shown in Figures (6), (7), (8) and (9) with field intensities (0, 4000, 1000) Gauss for two ducts (1 and 0.75) cm. The increase in the magnetic field intensity caused a decrease in axial velocity along the height of the duct and the results showed clear changes between the examined fluids where the fluid (CW) with EC (5 dS/m) more affected than the pure water (PW) (poor electric conductivity). Figures (10) and (11) show that the increase in the magnetic field caused a decrease in the local flow velocity. It was clear from Figures (10) and (11) that the flow velocity of 0.13 m/sec has high influence than the 0.2 m/sec velocity.

The numerical results were consistent with experimental results where the treatment decreased as flow velocity increased. Also, they were consistent with Malekzadeh1 et al., 2010 who found magnetic field changed the profile of axial velocity from the parabolic to a relatively flat. In this study, the profile shape did not change but resulted from the changes in field intensity, stream line of magnetic field and the velocity of flow. Those changes in practical and theoretical tests proved the existence of changes in the characteristics and specifications of the water; the reason may due to the influence of a magnetic field which acted momentarily in the section of treatment and created a vibration in water molecules.
Figure 6 Local flow velocities (V=0.2 m/sec, Duct height =0.01 m).

Figure 7 Local flow velocities (V=0.2 m/sec, Duct height =0.0075 m).
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Figure 8 Local flow velocities (V=0.13 m/sec, Duct height =0.01 m)

Figure 9 Local flow velocities (V=0.13m/sec, Duct height =0.0075 m).
6. CONCLUSIONS
Numerical results show increase in magnetic field led to an increase in water treatment and that appeared clearly when magnetic intensity increased and resulting in a decrease in the axial velocity along the height of the duct and a decrease in the local flow velocity. The result also showed that the water with electrical conductivity more affected than pure water.

Figure 10 Local velocity (0.2 m/sec) changed at the increase in field values.

Figure 11 Local velocity (0.13 m/sec) changed at the increase in field values.
REFERENCES


