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CFD Simulation of Magnetohydrodynamic Flow of a Liquid- Metal Galinstan Fluid in Circular Pipes

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Abstract: In this paper, the steady, laminar, incompressible viscous flow of an electrically conducting liquid-metal fluid is investigated numerically in a circular non-conducting pipe. The considered work fluid is Galinstan (GaInSn, i.e. Gallium-Indium-Tin). Such a liquid metal is subjected to a constant pressure gradient along the axial direction and a uniform transverse magnetic field in the spanwise direction. Numerical simulations are performed by means of the Fluent commercial software (used to solve the governing three dimensional fluid dynamics and electromagnetic field partial differential equations iteratively). The magnetic field induction, B, takes values between 0 and 1.5 T with a 0.5 T step size. The fluid velocity is found to decrease with an increase in the intensity of the applied magnetic field. The results, plotted as a function of system parameters, are critically discussed with respect to potential industrial applications.

Keywords: MHD Flow, Liquid-metal, Galinstan, CFD, magnetic field.

1 Introduction

Magnetohydrodynamics (MHD) treats the phenomena that arise in fluid dynamics from the interaction of an electrically conducting fluid with the electromagnetic field [Frank (2001); Gedik (2012); Gedik et al. (2012a)]. Generally, MHD describes the fluid flow of an electrically conducting media in presence of an electromagnetic field. Hartmann (1937) investigated for the first time the MHD flow of a viscous, incompressible, electrically conducting fluid between two parallel plates in the presence of a transverse magnetic field. The study of an electrically conducting liquid metal fluid flow under a transversely applied magnetic field has become the basis of many scientific and engineering applications and in many devices such as MHD pumps, MHD power generation etc. It has also been a topic of great interest in metallurgical industries and in the development of a fusion reactor blanket [Ab-

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dou et al. (2005); Nia and Li (2012)]. Liquid metal is used as a primary coolant in a nuclear fusion reactor and a working fluid in the MHD power generation [Sheng (1990)]. The deformation of a liquid metal drop in a high-frequency electromagnetic field was studied by [Kocourek et al. (2002); Karcher et al. (2003)]. Magnetic field effect on the electrically conducting fluid motions was studied several researchers up to now [Singh and Lal (1984); Gardner and Gardner (1995); Takhar et al. (1991); Chamkha (2000); Hossain et al. (2001); Attia et al. (2001)] and its solution was done numerically and analytically by developing different models. Attia and Ahmed (2005) investigated numerically the unsteady flow of a dusty viscous incompressible electrically conducting Bingham fluid through a circular pipe at constant pressure gradient. Kurt and Recebli (2008) have studied analytically steady two-phase fluid flows under the effects of magnetic and electrical fields in circular pipes. The same problem mentioned [Kurt and Recebli (2008)] has solved numerically using MATLAB for both steady and unsteady flow in our previous two works [Gedik et al. (2011); (2012a)].

The control of liquid metal free surfaces by electromagnetic forces is used in many metallurgical processes; [Mohring et al. (2005)] have studied experimentally on the stability of a free liquid metal surface influenced by an alternating magnetic field. The pumping of liquid metal may use an electromagnetic device, which induces eddy currents in the metal. These induced currents and their associated magnetic field generate the Lorentz force whose effect can be actually the pumping of the liquid metal [Takorabet (1998); Kadid et al. (2004)]. In our other two previous work i) steady two-dimensionally flow between two-fixed parallel plates under the external magnetic field ii) steady, three dimensionally NaK liquid-metal magnetohydrodynamic flow in non-conducting circular pipes have studied [see Gedik et al. (2012b); (2012c)] numerically.

In present work electrically conducting liquid-metal flow in circular non-conducting pipe is studied numerically under the influence of a uniform transverse magnetic field. Eutectic Galinstan GaInSn alloy, which can be used safely due to the steady chemistry performance and environmental protection, is used as a working fluid in the simulation. A short description of this study was presented [Gedik et al. 2012d] and extended version of the work detailed in here.

2 Problem Descriptions

We consider the flow of a steady, laminar, viscous, conducting liquid-metal in circular pipe under the influence of a uniform transverse magnetic field with constant pressure gradient as can be seen schematically in Fig.1. The pipe is located at the r=± 5 mm and extend from z=0 to 500 mm. The fluid flow in a pipe under the influence of constant pressure gradient (dp/dz) is in the axial direction. The geometry of the pipe has been divided into the eight subsections to see magnetic field effect on the flow clearly. It is assumed that the flow is the fully developed after the f_3 region. The magnetic field is applied to the f_4 and f_5 region of the pipe as can be seen from the Figure 1.

A uniform external magnetic field is applied perpendicular to the flow direction. The magnetic Reynolds numbers is small; this means the induced magnetic field can be negligible compared to the applied magnetic field. The fundamental equations governing the steady motion of an incompressible electrically conducting liquid-metal fluid in circular pipes can be expressed as follows;

Conservation of mass:

$$\nabla \cdot \mathbf{V} = 0 \tag{1}$$

Conservation of momentum:

$$\rho \left(\frac{\partial \mathbf{V}}{\partial \mathrm{t}} + (\mathbf{V} \cdot \nabla)\mathbf{V} \right) = -\nabla \mathbf{P} + \eta \Delta \mathbf{V} + [\mathbf{J} \times \mathbf{B}] \tag{2}$$

Maxwell First Law:

$$\nabla \times \mathbf{B} = \mu_e \mathbf{J} \quad \nabla \cdot \mathbf{B} = 0 \tag{3}$$

Ohm's Law:

$$\mathbf{J} = \sigma [\mathbf{E} + \mathbf{V} \times \mathbf{B}] \tag{4}$$

where; ρ is the density of fluid, **V** the velocity vector, **P** the pressure, η is the viscosity, **J** the current density, **B** the total magnetic field which can be expressed **B**=B_0+b, here B_0 and b the applied externally and induced magnetic field respectively, **E** is the electrical field, μ_e is the magnetic permeability and σ the electrical conductivity. The induced magnetic field is neglected in this present study due to the small magnetic Reynolds number approximation.

The solution of the governing equations describing the flow in circular pipe is solved numerically under the initial and boundary conditions by using Fluent MHD module based on solving the magnetic induction equation technique. The Semi-Implicit Method for Pressure-Linked Equations (SIMPLE) described by [Ferziger and Peric (1996)] is used to couple the momentum and continuity equations. The spatial discretization is based Green-Gauss cell and second order upwind is selected for momentum equation in the solutions. The wall boundary conditions are implemented as an insulating and stationary wall and no slip conditions through user profile functions. The discrete system of linearized equations is solved by an iterative procedure.

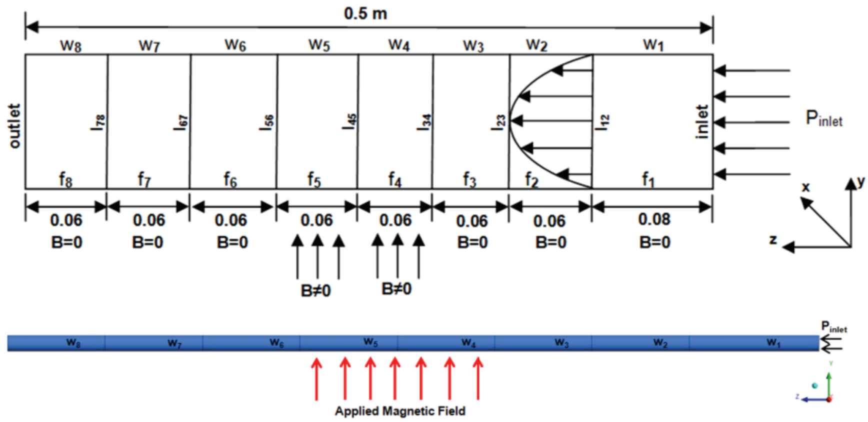

Figure 1: Geometry of the problem

Constant physical properties of liquid-metal such as density ρ=6363 kg/m^3, viscosity η=0.0024 kg/ms, electrical conductivity σ=3.46x10^6 1/Ωm and magnetic permeability 1.257x10^{-6} H/m were defined. The magnetic induction equation is derived from Ohm's law and Maxwell equations described above in Equation 3-4. The equation provides the coupling between the flow field momentum equation (2) and the magnetic field.

3 Results and Discussions

In this paper, the effect of magnetic field on the liquid-metal steady, laminar flow has been examined numerically. Obtained results from the numerical solution, local velocity profiles and pressure distributions have been plotted depending on magnetic field, coordinates and the physical parameters of the fluid. Fig.2 provides the mean velocity distributions that occurred throughout the flow at the centre of pipe. In this figure the velocity value was found as 0.106 m/s for hydrodynamic (HD) flow model (when B=0 T) whereas in MHD flow model (when B>0 T) velocity values decreasing depend upon the applied magnetic field. These decreases were larger in the area where magnetic field was applied, whereas they were smaller in areas where magnetic field was not applied. In area, where magnetic field was applied, the decrease in velocity values became 82.9%, 92.5% and 95.3% at B=0.5 T, B=1 T and B=1.5 T, respectively.

Fig.3. shows the velocity distributions along the R at x-direction of the pipe. In this figure, results have been obtained for two different flow models such as previous figure these are: the situation with no magnetic field (B=0 T) is for HD flow and

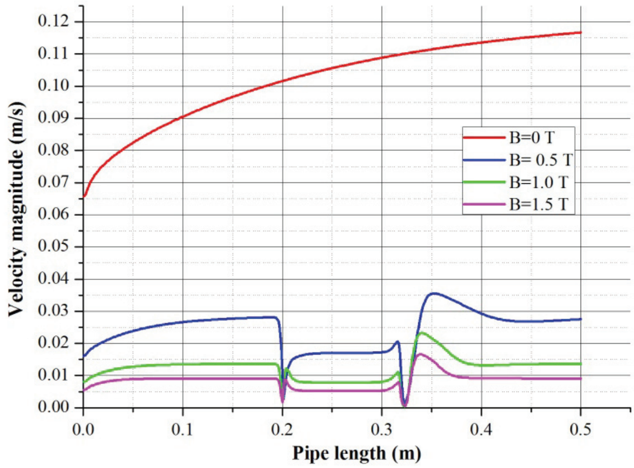

Figure 2: Velocity distributions along the flow in z-direction.

for MHD flow in the existence of magnetic field.

Maximum velocity value reached on line45 (l_{45} in Fig.1) for HD flow model at the centre of pipe (R=0) has been obtained as 0.106 m/s. In MHD flow model, depending on increasing magnetic field, the decrease in velocity can be clearly seen from the figure. In this figure, maximum velocity values calculated at l_{45} for MHD flow is 0.017, 0.0078 and 0.0049 m/s for B=0.5, 1 and 1.5 T respectively.

In Fig.4., distribution of the total pressure is given for different magnetic field values. The pressure which is 50 Pa at the initial was decreased throughout the pipe. While pressure drop for HD flow was linear, in MHD flow model sudden pressure changes occurred in the area where magnetic field was applied (between 0.2 and 0.32 m throughout z). As can be seen from the figure, the decreases in pressure changed depending on the increase in magnetic field. In MHD flow situation the pressure distributions decreasing suddenly at side walls of applied magnetic field zone and it is found smallest increase at midpoint of applied magnetic field zone as being reverse at velocity plots. The largest decrease in pressure has been occurred at B=1.5 T situation for MHD flow.

Furthermore, a plane has been added along axial direction on the applied magnetic field zone so that streamlines for HD and MHD flow situations are can be clearly seen from the Fig.5. The pattern of instantaneous streamlines is plotted in steady flow for different B in this Figure. While parallel straight 3D arrow lines obtaining for HD flow, vortex and swirling flows lines observed in MHD flow situation. Also, in this figure enlarged views of the streamlines for HD and applied magnetic field

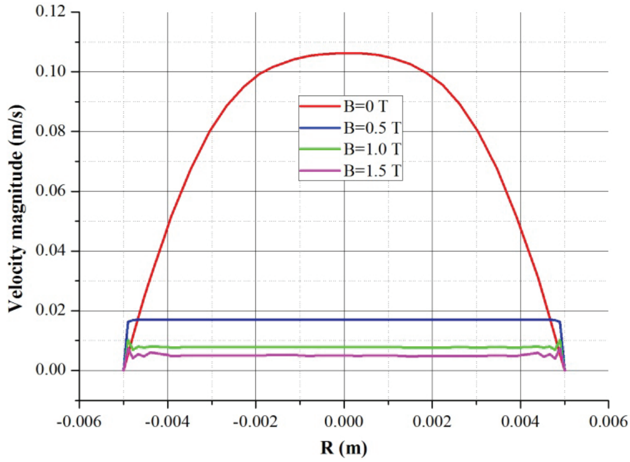

Figure 3: Velocity distributions along the R at x-direction.

region in MHD flow situation is also given to see magnetic field effect clearly on the fluid flow.

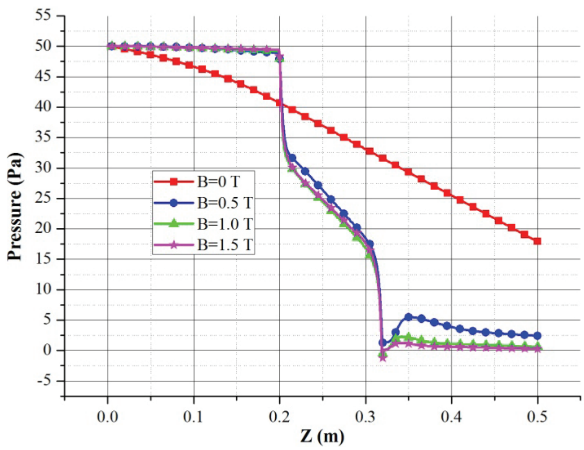

Figure 4: Pressure distributions along the R at x-direction.

The velocity contour graphs with the mesh view of liquid-metal fluid in pipe are given in Figure 6. The circular contour views are created on the l_{45} of the pipe geometry. It can be clearly seen from the Figure the velocity is decreased when the B increases for B>0. In the absence of magnetic field, namely B=0 T the velocity value is computed as 0.116 m/s. Likewise it was computed that as 0.017, 0.0078

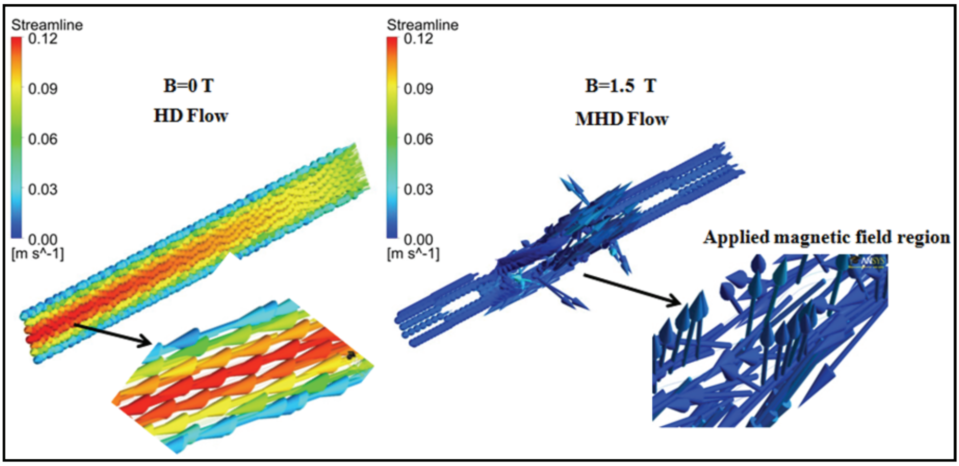

Figure 5: Streamlines for HD and MHD flow situations.

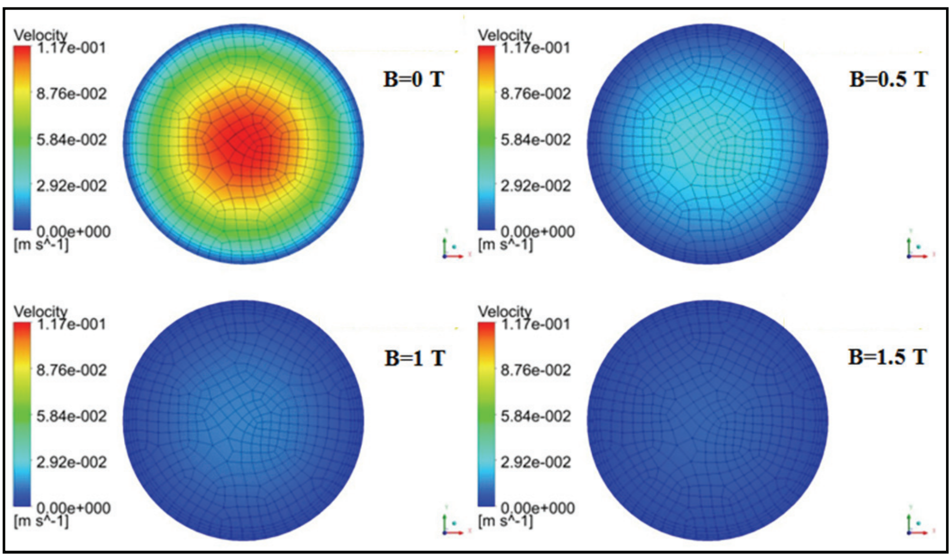

Figure 6: Contours views of velocities for different magnetic field values.

and 0.0049 m/s for B=0.5, 1 and 1.5 T respectively.

4 Conclusions

In this study, the flow of liquid-metal Galinstan (GaInSn) fluid in circular pipe under the influence of external magnetic field has been examined numerically using CFD code. The transverse external magnetic field was applied perpendicular to the fluid flow. The flow was steady, laminar, viscous and incompressible. Analyses for MHD flow model were conducted solving Magnetic Induction Equation method on Fluent MHD module. In this study, analysis were done and compared for two different flow models of liquid-metal, as HD and MHD. From the results of these analyses, graphs have been obtained for HD and MHD flow models and presented in the figures. As a result, it has been observed that the magnetic field applied to liquid-metal flow decreases its flow velocities depending on the increase of magnetic field. Such decreases occurred as 82.9%, 92.5% and 95.3% for B=0.5, 1 and 1.5 T values, respectively. To know velocity change and pressure drop is so important so that it can give us ability to control of the liquid-metal flow needed flow controls applications such as metallurgical process, nuclear reactor cooling applications and also producing of MHD pump, MHD power generation. Also, it should be pointed out that the computations performed in this work can display a useful starting point to study more complex problems, such as unsteady MHD flows and considered induced magnetic field effect studies can be next work.

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Nomenclature

B	Total Magnetic field, (T)
B_0	Applied external magnetic field, (T)
b	Induced magnetic field induction vector, (T)
E	Applied external electrical field intensity vector, (V/m)
J	Electrical current density vector, (A/m2)
V	Velocity vector, (m/s)
P	Pressure gradient, (Pa)
R	Pipe diameter, (m)
r	radius, (m)
x,y,z	Coordinate
η	Dynamic viscosity, (kg/ms)

ρ Density, (kg/m3)
σ Electrical conductivity, (1/Ωm)
μe Magnetic permeability, (H/m)
f fluid
l line
w wall

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