LIQUID METAL FLOW AND HEAT TRANSFER IN RECTANGULAR DUCT UNDER THE INFLUENCE OF AXIAL MAGNETIC FIELDS

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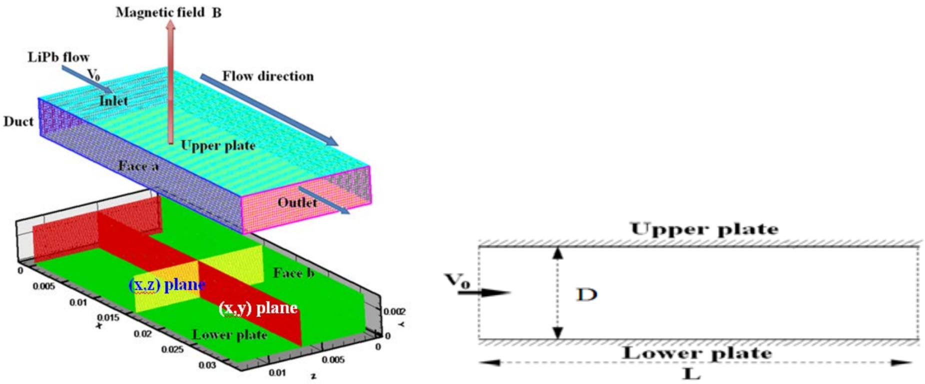
Abstract: The present work deals with the numerical analysis of the liquid metal 83Pb–17Li MHD flow which moves in a parallelepiped duct. Numerical method based on the finite volume is employed in simulations. The effect of different values of the magnetic field on the eutectic 83Pb–17Li alloy flow, heat and momentum transfer is studied for small and moderate values of the magnetic field strength. The estimates of the MHD flow, pressure and temperature have been analyzed for all duct surfaces and planes. We need to have more knowledge and interesting information in order to determine and control the MHD pressure drop encountered in the blanket fusion operating system. The distribution of pressure is very important in all duct walls and planes. It changes radically when axial magnetic field is applied. In the direction parallel to the magnetic field, the pressure gradient decreases near the walls and perpendicularly to the magnetic field, the pressure gradient increases.

1. Introduction

The controlled thermonuclear fusion is one of the main technological challenges to produce of the energy that will be very requested and needed for the near future. Liquid metal alloy such as lead lithium 83Pb-17Li is used as breeder material and coolant in advanced nuclear systems. It is being used to operate the blankets in fusion reactors at high temperature due to their higher thermal efficiency. Therefore, the lead lithium eutectic is considered to be very promising for the design of fusion blankets. Magnetohydrodynamic (MHD) metal liquid flows have been already studied by J. Hartmann [1]. Magnetic fields have several applications in liquid metal flows and can relaminarize the turbulent regimes in these flows. Different problems in liquid metal systems lie in the corrosion of their stainless steels EUROFER, instabilities flow, MHD pressure drop, Tritium permeation, MHD insulators, buoyancy effects and Heat transfer. Extensively, the properties of duct flows in the magnetic field present one of the basic problem in Magnetohydrodynamic because the study of MHD flows under real blanket conditions is still limited due to the complexity of the blanket geometry and the structural materials that consist mainly of martensitic and austenitic steel. Different studies proved that Magnetic field applied to a flowing liquid metal produces a force which alters the velocity field [2-5]. Numerical analyses have been conducted in previous papers [6,7] for a fully developed flow and unsteady vortical flows in a rectangular duct of cross section with a transverse magnetic field. Analytical researches of MHD flow in the magnetic field have been carried out [2,8]. Phenomena of MHD thermofluid of liquid-metal that are present in different concept blankets have been showed by N. Morley [9] and S.Smolentsev [10, 11]. The MHD pressure gradient for the fully developed flow in a rectangular duct is given by [12, 13]. Direct numerical simulations of transverse and spanwise magnetic field effects on turbulent flow were analyzed [14-15]. In this paper we present preliminary results on magnetohydrodynamic effect in a rectangular duct under vertical magnetic field at low Prandtl number. Numerical simulations in rectangular duct have been carried out. The main goal of this work is to determine the magnetic field effect on the eutectic alloy Pb–17Li flow in laminar regime.

2. Formulation of flow problem

The present work analyzes the influence of the magnetic field on the hydrodynamic liquid metal flow in a rectangular duct. We consider the steady flow of an incompressible liquid metal in a rectangular duct with insulating walls and with an externally applied magnetic field perpendicular to flow direction. The schematic of the physical and computational domain is shown in figure 1. The dimensions of the duct are L= 31.5mm (length), E=12mm (Width) and D=3mm (Height).



(a) (b)

Figure 1: Physical domain of computational duct: (a) Three-dimension mesh model used for numerical simulations and (b) Sketch of the cross-sectional area of the channel

The working fluid is 17Li-83Pb alloy with constant density ρ, kinetimatic viscosity ν and electric conductivity σ. Flow moves in the x-direction with mean velocity V_0= 5 cm/s at the inlet. Fixed temperatures are imposed on the walls of the melt duct and the inlet interface; viscous dissipation and Joule heating are negligibly small. The magnetic Reynolds number is so small that the flow field does not affect the magnetic field.17Li-83Pb eutectic was chosen as a good liquid because of its lowest melting temperature and its adequate stability. The physical properties of lead lithium used in our simulations are calculated at melting temperature. The magnetic permeability η is the same everywhere and equal to the vacuum magnetic permeability ($\eta=\eta_0$).

In general, the equation set of MHD for liquid-metal flows consists of Navier–Stokes and Maxwell equations, which are coupled with the equations for heat and mass transport. For an incompressible MHD flow in a duct they consist of equations for conservation of mass, conservation of momentum in three directions and the equation governing the electric potential. The magnetic field induces an electric current, which is calculated from the electric potential field. This MHD system can be expressed as follow:

$$\rho\left[\frac{\partial V}{\partial t} + (V.\nabla)\mathrm{V}\right] = -\nabla\mathrm{P} + \rho\nu\nabla^2\mathrm{V} + \mathrm{J}\times\mathrm{B} \qquad (1)$$

$$\nabla.\mathrm{V} = 0 \quad , \quad \nabla.\mathrm{J} = 0 \qquad (2)$$

$$\mathrm{J}/\sigma = -\nabla\varphi + \mathrm{V}\times\mathrm{B} \qquad (3)$$

$$\nabla.(\nabla\varphi) = \nabla.(\mathrm{V}\times\mathrm{B}) \qquad (4)$$

$$\frac{\partial T}{\partial t} + V.\nabla T = \nabla\left(\frac{k}{\rho C_p}\nabla^2 T\right) \qquad (5)$$

Where V, p, J, B,φ and t are velocity, pressure, current density, applied magnetic field, electrical potential and time, respectively. The term f on the right-hand side of the momentum equation denotes the gravitational force. In order to characterize inertial effects in MHD flows, such as the onset of MHD instabilities, transition regime, and the MHD effects, there are three important dimensionless parameters in MHD flows. Hartmann number $\mathrm{Ha} = \mathrm{BD}\sqrt{\sigma/\rho\nu}$ represents the ratio of electromagnetic to viscous forces, the hydrodynamic Reynolds number $\mathrm{Re} = \mathrm{V_0 D}/\nu$ gives a measure of the ratio of inertial forces to viscous forces and the interaction parameter number is given by $\mathrm{N} = \mathrm{Ha}^2/\mathrm{Re}$. The duct aspect ratio $\Gamma = \mathrm{E}/\mathrm{D} = 4$. Prandtl number $\mathrm{Pr} = \nu/\alpha$ characterizes the importance of thermal diffusivity compared to molecular diffusivity where α is the thermal diffusivity.

In this work, the cases of MHD flow in insulating rectangular duct at Re=1363, 0≤Ha≤90 corresponding to the range of interaction parameter number 0≤N≤5 are studied. The boundary conditions for the present computation are given as follows:

(1) Velocity inlet, which corresponds to the inlet surface of LiPb eutectic, V_0=5cm/s.

(2) Outflow, which is corresponding to the outlet surface of LiPb fluid.

(3) Wall condition with fixed temperature, faces a and b at $T_a=T_b$=508K, lower and upper plate (T_c=623K, T_h =823K).

(4) All wall conditions are insulting σ_w=0, where the thickness of wall is neglected.

The problem is solved using the finite volume package Fluent with three-dimensional double precision, the first order upwind discretization for convection, the SIMPLE algorithm for pressure-velocity coupling and the STANDARD scheme for pressure interpolation. For the magnetic field equations the first order upwind is used. The convergence is handled by monitoring residuals of continuity, momentum and energy equations. Reynolds numbers is fixed to Re = 1363 (based upon total duct height D). The three-dimension mesh model of the rectangular duct is done by Gambit software. The computational domain is discretized with 1990656 cells, 6046272 Faces and 2065525 Nodes.

The most substantial parameters to predict MHD flows are pressure, velocity and temperature under the magnetic field effect .To simplify the analysis of eutectic flow behavior, the computations were performed for laminar flow in the duct. The magnetic field is applied in the vertical direction (oy), it is changed in the range of B =0, 0.5Tesla and 1Tesla ,which corresponds to Hartmann number values of Ha=0, 40 and 90, Reynolds number characterized by a velocity V_0=5cm/s is Re=1363. The magnetic interaction parameter N which mesures the ratio of electromagnetic forces to inertial forces, is deduced from the Hartmann and Reynolds numbers, it is equal to N=0, 1.2 and 5.

In order to study the effect of magnetic field in different areas of the considered geometry, we present our results in all externe duct surfaces, namely, upper and lower plate, inlet and outlet surfaces and faces a and b. In addition, we show the obtained results in three middle planes parallel to each side, (x,y) plane, (x,z) plane and (y,z) plane. Figure 2 displays the temperature distribution in different sections in the cases with and without magnetic field. In the studied system the upper plate is hot at T_h=823K whereas the lower one is relatively cold T_c=623K then heat is transferred from the upper to the lower plate and the whole fluid primarly by conduction. This heat transfer is obviousely shown in isotherms distribution. It can be seen that the temperature has a parabolic profile near the inlet surface in (x,y) plane, then it becomes asymmetric when one moves away from the inlet. High thermal gradients are present near the outlet surface and between the upper and the lower plate from the duct mid-length until the output. Although there are no important modifications when magnetic field intensity increases, thermal gradient decreases near the outlet surface and the parabolic profile disappears before as for the case without magnetic field. In (y,z) plane, isothermes are concentrated near the upper plate, however in the outlet surface the temperature gradient is better distributed from the upper to the lower plate. The temperature profile is not significantly affected by the imposed vertical magnetic fields for B=1T. Figure. 3 depicts the evolution of isotherms in (x,z) plane for the vertical magnetic fields strength B=0T and B=1T.

The distribution of temperature is important in this plane, it increases gradually along (x, z) plane from the inlet to the outlet surface. This temperature profile is due to the inhomogeneous heat transfer in the melt.

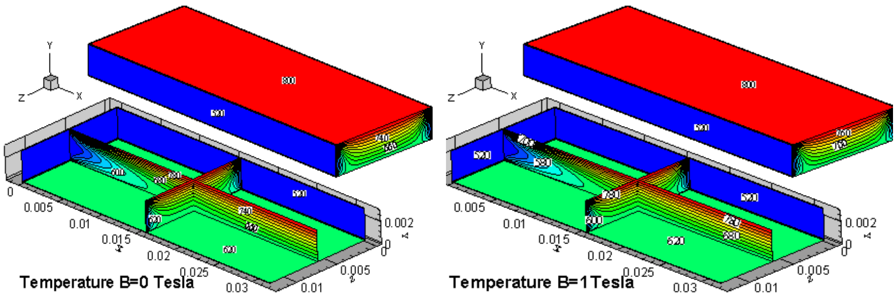


Figure 2: Temperature distribution in different planes without and with magnetic field B=1Tesla

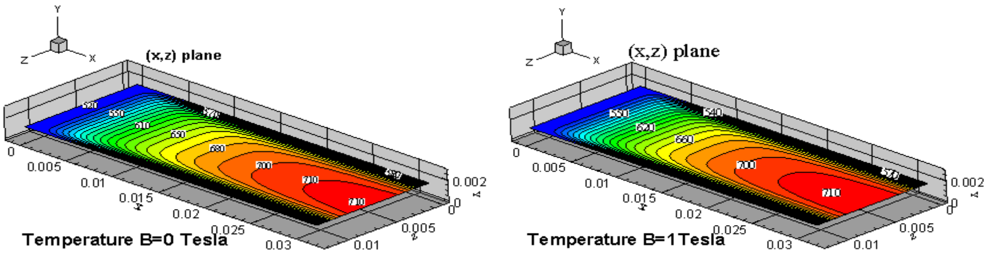


Figure 3: Temperature distribution in (x,z) plane without and with a vertical magnetic field B=0 and B=1Tesla

Now let us analyze the pressure field in this MHD problem (fig 4). Without magnetic field, the pressure is almost constant in the core of the flow and isobars are concentrated near the upper and lower walls, a strong pressure gradient therefore exists. The overall analysis shows that the pressure field is high at the inlet and decreases gradually as we approach the outlet when magnetic field is applied. When magnetic field of intensity B = 0.5T is imposed, isobars become flattened in a parallel direction to the magnetic field in (x,y) plane.

Vertical pressure gradients (dp/dy) decreases strongly in the fluid and near the upper and the lower plates. In the case without the magnetic field, the pressure gradient along the X axis is too weak , under magnetic field effect this gradient becomes considerably important for B = 1Tesla, this gradient increasing is evidently shown in figure 5.

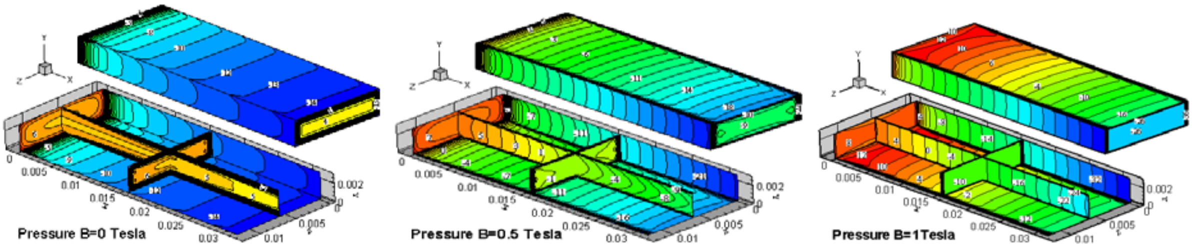


Figure 4: Presure distribution in the cases without and with magnetic field (B=0.5Tesla and B=1Tesla)

The magnetic field has reduced the pressure in the entire channel except at the entrance. In the direction parallel to the magnetic field, the pressure gradient decreases near the walls and perpendicularly to the magnetic field, the pressure gradient increases. As the magnetic field increases, the isobars become flat and straight across the channel in almost 40% of the duct for B = 0.5 T and in 100% of the channel for B = 1T. In (x, z) plane we note the same modifications as for the (x, y) plane, namely, pressure drop, decreasing vertical pressure gradient and increasing pressure along the X axis. In faces a and b, the pressure gradient is increased along the X axis. The effect of magnetic field on pressure profiles are reported in fig 6 which the local pressure values decreases with increase the magnetic field intensity.

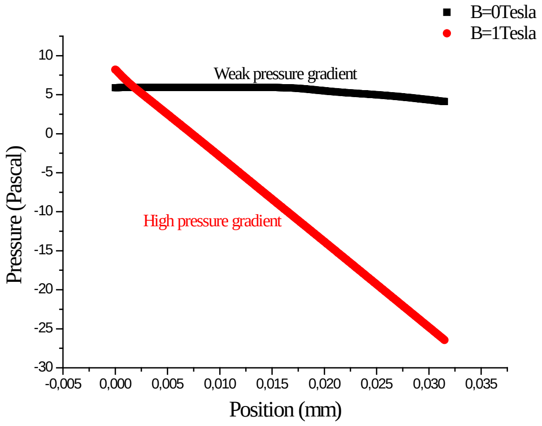


Figure 5: Evolution of pressure versus x-position at y= 1.5mm in (x,y) plane without and with magnetic field (B=1Tesla)

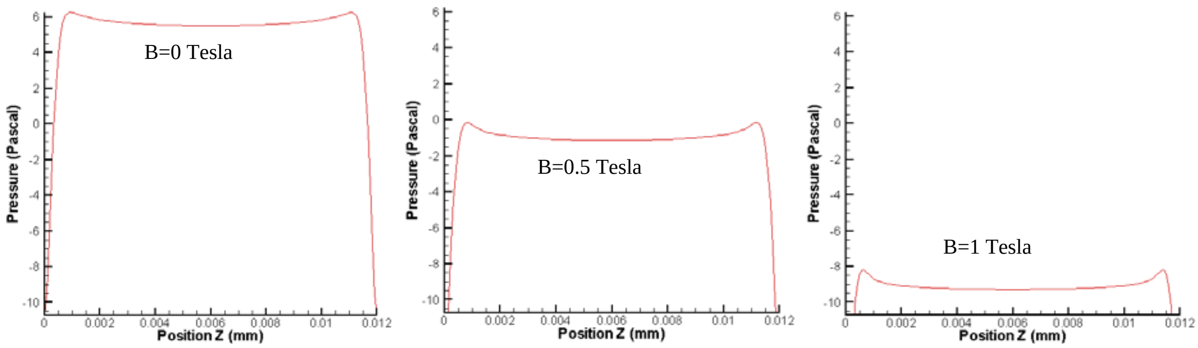
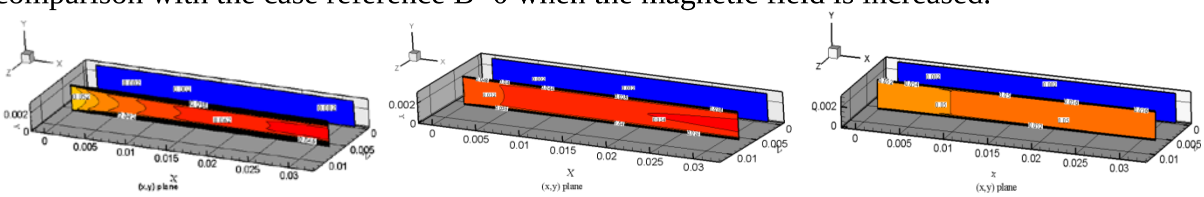


Figure 6: Pressure profiles without and with magnetic field

Figure 7 indicates velocity distribution in different sections with and without magnetic field. Parabolic velocity distribution is observed in (x,y) plane. In the case without magnetic field, the flow in the channel is induced by forced convection caused by the inlet velocity. The mean flow is maximum in the core of flow and minimal near the walls. A hydrodynamic boundary layer is clearly visual on the upper and lower plates and it is more concentrated in the upper plate. When a vertical magnetic field is imposed, the velocity profile in the channel crucially changes, or the velocity profiles become increasingly flat it favours the development "M-shaped" profile, see figure 7 for B=1T, as well as significantly changes the nature of metal flow. This M-shaped profile velocity observed even with insulating walls at plans which are parallel to B has been observed before by R.Moreau et al [2] and I. Bucenieks [3]. The velocity profiles under the effect of vertical magnetic field values as B = 0 Tesla, B = 0.5 Tesla and B = 1 Tesla were plotted (fig 8) and determined at 0.01575 m in the (y, z) plan of the duct heigh. The obtained results show that the velocity profiles decrease relatively in comparison with the case reference B=0 when the magnetic field is increased.



B=0Tesla B=0.5Tesla B=1Tesla

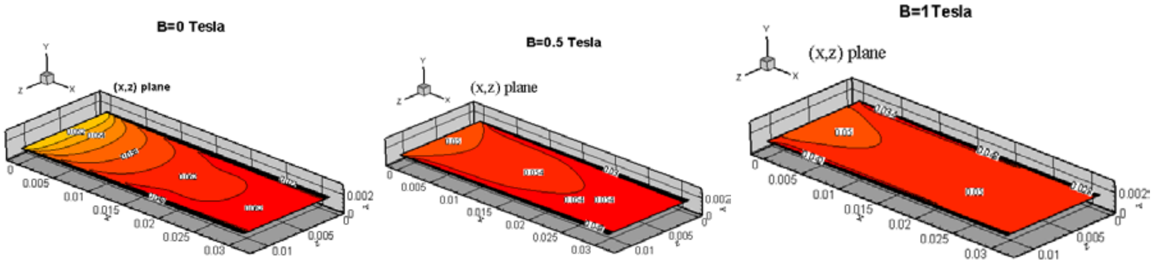


Figure 7: Velocity magnitude distribution in (x,y) plane without and with a magnetic field (B=0.5Tesla and B=1Tesla)

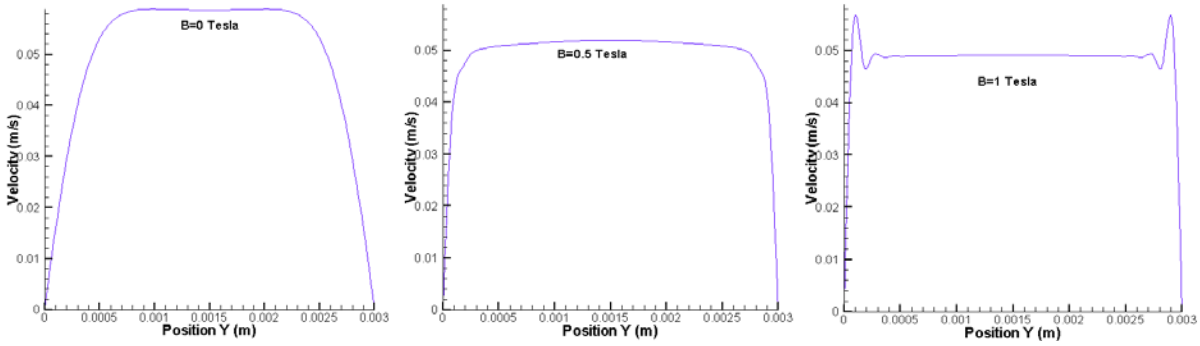


Figure 8: Velocity profiles for various values of magnetic field and with a magnetic field (B=0.5Tesla and B=1Tesla)

4. Conclusion

In the present work, numerical simulations in rectangular duct have been carried out under vertical magnetic field in order to provide a theoretical basis for practical applications, such as liquid-metal blankets of a fusion reactor. The magnetic interaction parameter is varied in the range of 0 to 5. Interesting effects of vertical magnetic field on mean flow and pressure have been observed. Pressure drop is induced with horizontal pressure gradients increasing. The presence of the vertical magnetic field changes decisively the velocity profile in the channel while it favors the formation of the so-called M-shaped velocity profile. Due to lower Prendth number value of LiPb, temperature profile for different planes is not affected by the various magnetic field strengths B=0.5T and B=1T.

4. References

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