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Numerical Study of an AC Electromagnetic Pump of Liquid Metal Flow

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Abstract: This work presents the results of a 2D numerical magneto-hydrodynamic (MHD) simulation of an electromagnetic AC pump for liquid metal. The flow characteristics of the MHD pump are analyzed by coupling electromagnetic with Navier-Stokes equations, and the thermic phenomena are analyzed by coupling Maxwell's equations with energy equations. In this study, numerical simulation based on the finite element method was carried out using the computer package COMSOL Multiphysics 3.5. The application and the limits of the electromagnetic, hydrodynamic, and thermic models are discussed herein.

Keywords: *AC magnetic pump, MHD flow, finite volume method, finite element method.*

I. Introduction

MHD is the theory of the interaction of electrically conducting fluids and electromagnetic fields. Application arises in astronomy and geophysics as well as in connection with numerous engineering problems, such as liquid metal cooling of nuclear reactors, electromagnetic casting of metals, MHD power generation and propulsion [1- 4].

Two different concepts of electromagnetic pumps for molten metals have been developed over the last forty years: a) a linear induction electromagnetic (AC) pump and b) a direct current (DC) electromagnetic pump. The most frequently used is the linear induction EM pump. The main advantage of this AC concept is that no direct contact with the molten metal is necessary. However, the linear induction AC pump can transfer molten metal just horizontally without any metal head. The direct current (DC) electromagnetic principle has been used mainly to develop electromagnetic micro-pumps for biomedical and chemical applications for precise control of small volumes of fluids in micro-channels [Jaime H. L. Parada and B.J. William (2007), Pei-Jen Wang, Chia-Yuan Chang, and Ming-Lang Chang (2004), and Jang J. and S. S. Lee (2000)]. Our recent investigation [N.P. Kandev V. Kagan and A. Daoud (2010), A. Daoud and N.P. Kandev (2008)] showed that the DC electromagnetic pump can be used successfully in many liquid metal environments such as extrusion billet casting, metal refinery for transporting molten metals at different heads, alloys production, etc. Electromagnetic DC pumps for aluminum with a capacity up to 30 T/h were developed in 2008 and commercialized in the USA for different industrial applications [5].

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The concept of electromagnetic pumping of liquid metals was developed in the nineteen seventies first for zinc and aluminum and later for other molten metals. Electromagnetic pumps have many advantages over mechanical pumps including precise metal flow control without any moving parts, reduced energy consumption and less dross formation. A well-known example of the industrial applications of the EMP principle is the electromagnetic brake used in the continuous casting of large steel stabs to suppress the liquid metal motion within the mold. Another example of possible industrial application is as a velocity-meter for molten metal by measuring the Lorentz braking force [6], [7].

In the previous works [8] and [9] we have studied the 2D electromagnetic phenomena in a MHD pump by the finite volume method in harmonic mode using the MATLAB multiphasic. Different characteristics of the MHD pump (vector potential, magnetic induction, currents density and the electromagnetic force) were obtained.

II. Mathematical Models And Equations

The geometry of the MHD model considered in this work is shown schematically in Figure 1.

The liquid metal flows along a channel with a cylindrical geometry of annular cross section. A ferromagnetic core is placed on the inner and the outer side of the channel, [9 - 11]

The principle of the MHD pump (Fig.1) is similar to that of the asynchronous motor; the supply of the inductor creates a magnetic field B sliding with the velocity of synchronism, where electric currents are induced in the liquid metal by means of a magnetic field, producing an electromagnetic force F with the instantaneous field ensuring the flows of the fluid [12].

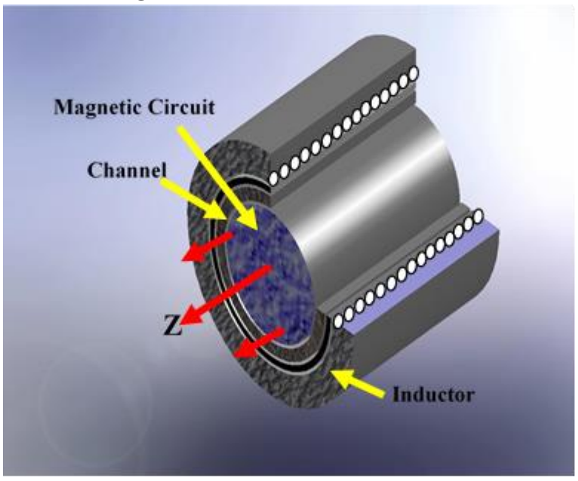

Fig.1 Schematic view of the MHD pump

Simplified schema of the MHD model, channel length L = 0.4 m, height H = 0.02 m and width of the inductor Wm = 0.2 m. Magnet length Lm = 0.4 m, width of the air-gap W_{air}=0.004.

In this study, where the model must represent an actual pump for mercury, working at different operating conditions, liquid mercury at 356.7° C is used as an electrically conductive fluid with density $\rho = 13.6\times10^3$ kg/m^3, electric conductivity $\sigma = 1.06\times10^6$ S/m, relative permeability μr=1.55 and kinematic viscosity $\nu = 0.11\times10^{-6}$ m^2 /s.

The usual theoretical formulation of the magneto hydrodynamic model for electrically conducting and Newtonian incompressible fluid has been derived from Ohm's law for moving media, coupled with the Navier-Stokes equations for laminar flow with Lorentz force given by the cross product $\vec{F} = \vec{J} \times \vec{B}$. The equations used for the 2D MHD model can be summarized as follows:

1. Electromagnetic Part of The Problem

$$\overrightarrow{rot}\left(\frac{1}{\mu}\overrightarrow{rot}\vec{A}\right) = \vec{J}ex - \sigma\left(\frac{\partial \vec{A}}{\partial t} - \vec{\vartheta}\wedge\overrightarrow{rot}\vec{A}\right) \quad (1)$$

$$\vec{B} = \overrightarrow{rot}\vec{A}, \quad (2)$$

Here Maxwell-Ampère's law in equation (1) includes Ohm's law. The constants in equations (1) are the electrical conductivity σ and the permeability μ.

2. Fluid dynamics for laminar flow

$$\frac{\partial V}{\partial t} + \left(\vec{V}.\vec{\nabla}\right)\vec{V} = -\frac{1}{\rho}\,\overrightarrow{grad}P + \upsilon\Delta\vec{V} + \frac{\vec{F}}{\rho} \quad (3)$$

$$div\vec{V} = 0 \quad (4)$$

The fluid dynamics part of the problem is determined by equation (3) representing the conservation of momentum of the fluid in motion, where **P** denotes the pressure, **ρ** is the density and then is the kinematic viscosity of the fluid, where the conservation of mass is given in equation (4)

The formulation of this model in COMSOL has been derived from the Maxwell-Ampere equation, also using Ohm's law, coupled with the Navier-Stokes equations for laminar flow with Lorentz force $\vec{F} = \vec{J}\wedge(\nabla\wedge\vec{A})$ by introducing the magnetic vector potential $\overrightarrow{A}$ where given in equation (2).

3. Thermic Part of The Problem

$$\rho C_P\left(\frac{\partial T}{\partial t}\right) = div\left(K\overrightarrow{grad}T\right) + P_S$$

$$P_S = \frac{1}{2\sigma}A.A^* \quad (6)$$

The thermic parte is presented in equation (5) where **ρ** denotes the mass density, $\mathbf{C_P}$ is the heat capacity at constant pressure, **T** is the temperature**, K** is the isotropic thermal conductivity, where the heat source term is given in equation (6).

III. Numerical Simulation

In our simulations we have used the computer package COMSOL-Multiphysics which is based on the finite element method. The main advantage of using COMSOL is that it is not necessary to write all internal source codes since the basic expressions are already built-in. Moreover, with COMSOL it is possible to use coupling of different physical modules to carry out MHD simulations.

The coupling between the electromagnetic model and the fluid model is achieved by introducing the Lorentz force as a body force in the conservation of momentum and the use of the fluid velocity, calculated by the fluid model, in Ohm's law. The MHD effect depends on the electrical conductivity, the density and the viscosity of the liquid metal.

III.1 Electromagnetics Results

The electromagnetic phenomena result of the MHD pump in harmonic mode such as: vector potential, magnetic induction and the electromagnetic force are carried out using the MATLAB multiphasic.

The figures (2, 3 and 4) represent respectively the geometrical model of the MHD pump in the plane (r, z), the equipotential lines and the vector potential of the MHD pump.

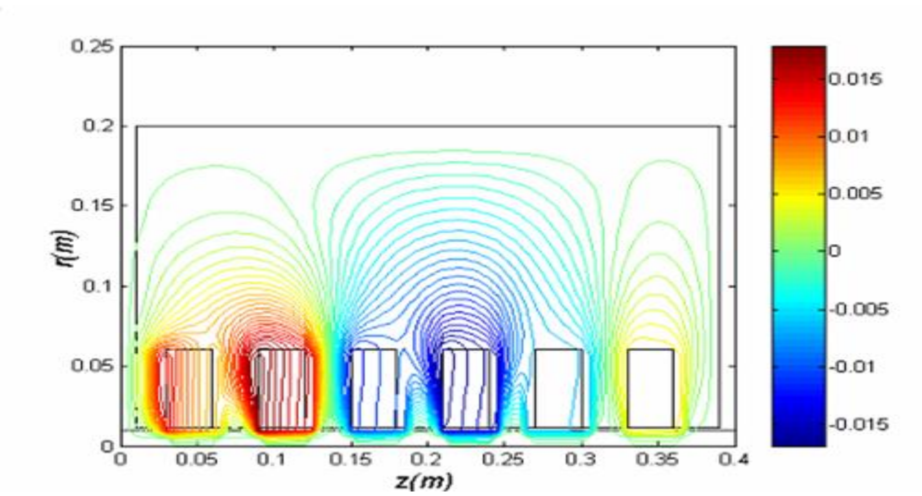

Fig.2. Geometrical Model in the plane (r, z)

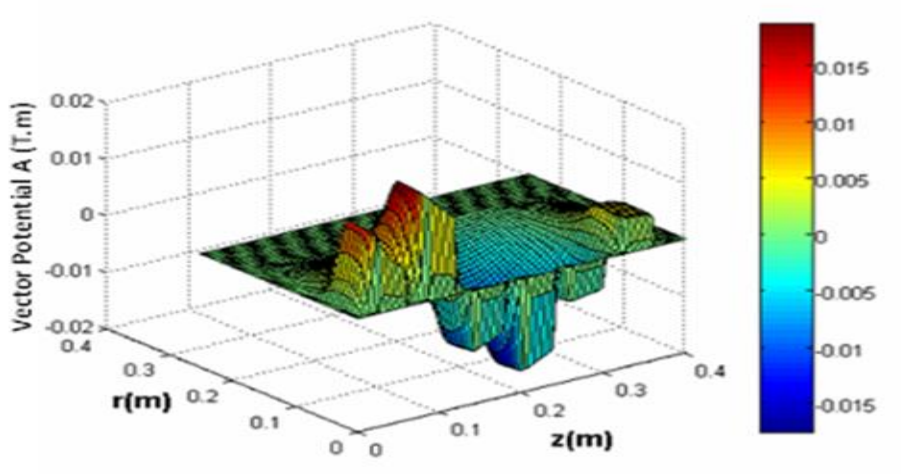

Fig.3. Equipotential lines in the MHD pump

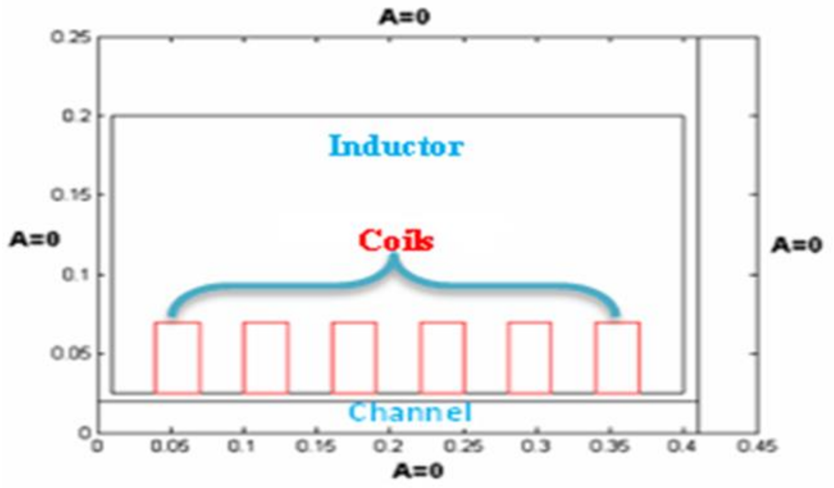

Fig.4. Vector potential of an annular induction pump

By the Faraday's law, the electromagnetic force is depended on the electrical current and the magnetic flux density. As the electric current density and the magnetic field are both proportioned, the Electromagnetic force will also be proportioned.

The figures (5) and (6), present respectively, the magnetic induction and the electromagnetic force in the MHD pump.

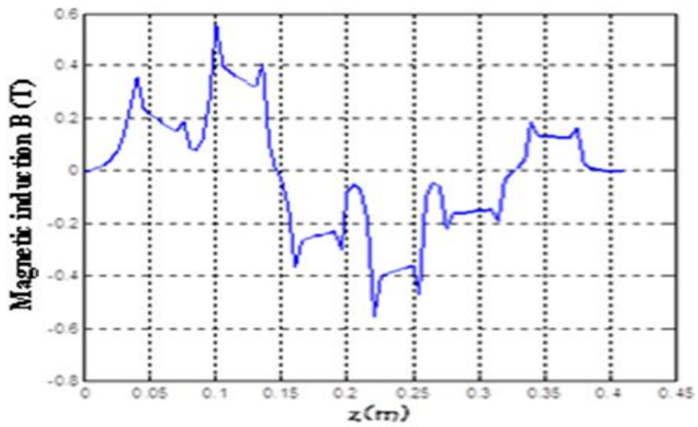

Fig.5 Magnetic induction in the MHD pump

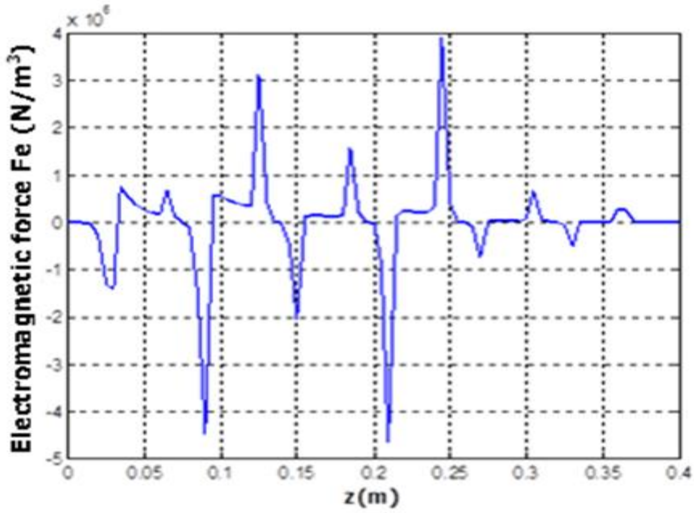

Fig.6 Electromagnetic force in the channel of the MHD pump

We note that the vector B reaches its limit value at the inductor and decreases as one moves away from the field, is more sinusoidal as one moves away from the inductor– air gap boundary.

III.2 Hydrodynamics Results

The hydrodynamic phenomena results in the channel of the MHD pump such as: velocity and pressure are carried out using the software COMSOL multiphasic.

To find the flow velocity distribution in the channel of the MHD pump when fluid flows in the channel, a 2-D fluid numerical analysis is carried out.

The vorticity distribution in the channel is shown in figure 7.

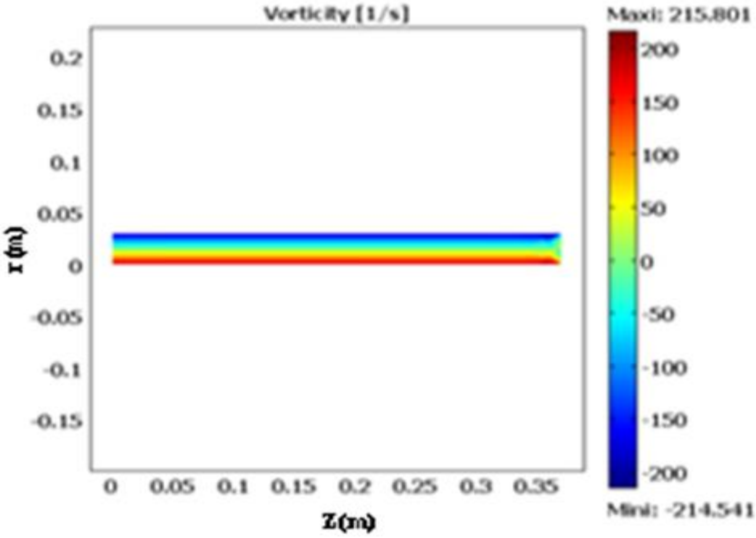

Fig.7. Distribution of the velocity in the channel

Figure 8 is representing the variation of the velocity in the channel of the MHD pump. We note that the velocity of the fluid passes through a transitional period and then stabilizes as all the electrical machines. The velocity increases as we advance in the channel.

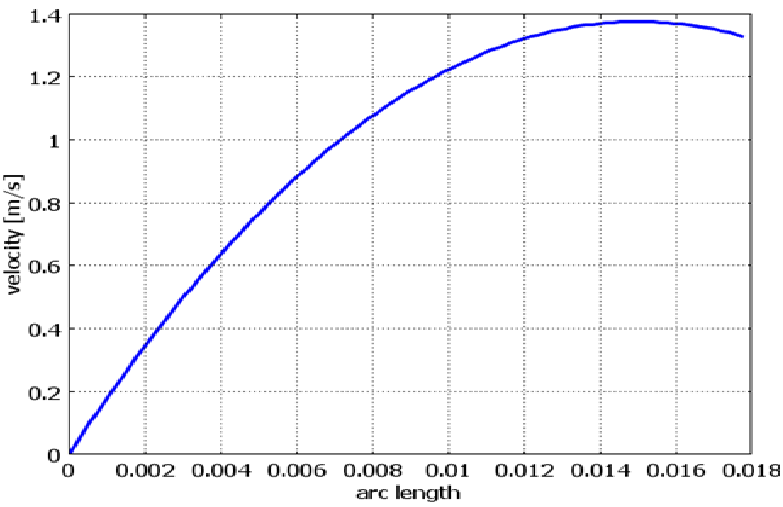

Fig.8. Velocity in the channel of the MHD pump

Figure 9 show the variation of the pressure along the channel.

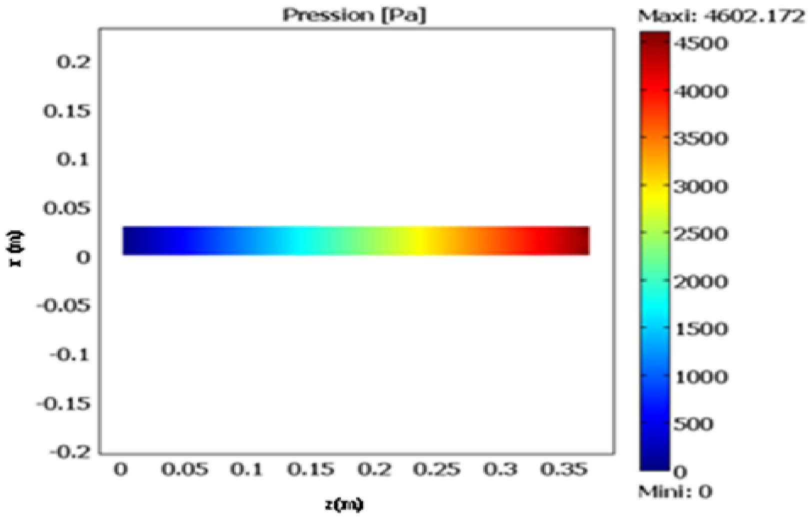

Fig.9. Distribution of the pressure in the channel

III.3 THERMIC RESULTS

The thermic phenomena result, such as temperature, is carried out using the software COMSOL multiphasic.

The variation of the temperature along axis z from its inlet to outlet is shown in figure 10, the temperature of fluid located within the channel and moving along axis z.

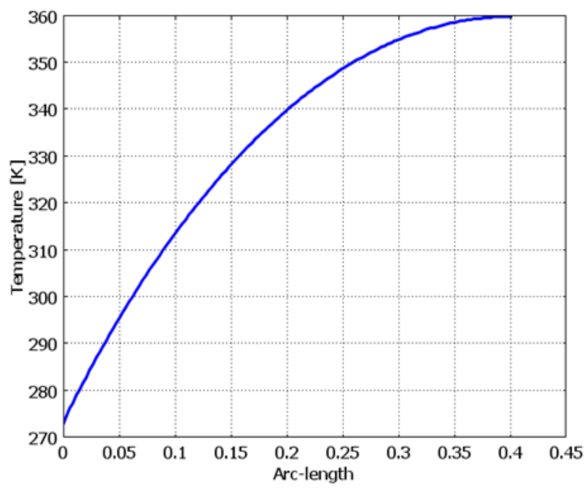

Fig.10 Temperature distribution in along axis Z of the channel

VI. CONCLUSIONS

This model utilizes not only Ohm's law but also the Maxwell-Ampere equation, thus representing more precisely a real EM pump, especially for turbulent pumping conditions involving high driving AC currents and high flow velocity. Actually, for the turbulent pumping case, our fully 2D simulation revealed the appearance of two couples of small current loops located on both sides of the magnetic poles ensuing from the complex spatial interaction of electromagnetic and hydrodynamic phenomena. There is a need for an electromagnetic pump that works without any moving parts and produces large thrust.

The maximum temperature occurs at the medium of the channel as it proceeds liquid metal along the z-axis of the MHD pump.

The obtained results of the velocity pressure and the temperature are in perfect agreement with those presented in [9] and [10].

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