Analysis and Design of Electromagnetic Pump

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Abstract: Liquid metal loops are used for heat removal and for the study of certain magneto-fluidic phenomenon like MHD (Magneto-Hydro Dynamic) effects. These loops operate at high temperatures and carry fluids that are invariably toxic in nature. To ensure the purity of fluid in a closed loop application, non-intrusive electromagnetic pumps are used. We have designed and analyzed a prototype electromagnetic pump to be used in mercury loop for carrying out various studies. This Electromagnetic pump is designed using permanent magnets which are mounted on the periphery of the rotor, driven by a DC motor. The liquid metal flows in a semi-circular duct surrounding the rotor. The paper brings out the qualitative and quantitative analyses of the pump as function of magnetization of the permanent magnets, the speed of rotation of the pump and magnet pitch. This electromagnetic pump has been developed and is running successfully in our lab at BARC.

Keywords: Electromagnetic pump, liquid metals, permanent magnets, MHD

1. Introduction

Electromagnetic pump is used for driving liquid metals in various industrial and research set ups. Liquid metals are invariable toxic and are mostly operated at high temperatures. Loops used for the study of corrosion and MHD studies need to maintain liquid metal purity within tight limits. Electromagnetic pumps provide non-intrusive method for driving liquid metals in loops. Mechanical seals are not required in these pumps; hence their chances of failures due to high temperatures and wear/tear get eliminated. Electromagnetic pumps for liquid sodium loops are designed using electromagnets and flow is maintained in pipes. Electromagnetic pumps can also be designed using MHD phenomenon. Both these EMP are similar to conventional linear pumps.

The EMP presented in this paper is similar to conventional centrifugal pump. Its key components are rare earth permanent magnets, rotor, DC motor, semi-circular duct and CRNGO backing iron. Permanent magnets bars are fitted on the periphery of rotor and magnetized alternately along the radially in and radially out directions. High strength NdFeB magnets are used as they have large remnant flux density. A DC motor is used to rotate the rotor at various speeds. Rectangular channels provide passage for liquid metal flow. CRNGO laminated magnetic steel has been used to provide low reluctance path return path for the flux. This paper provides theoretical, analytical and practical aspects of electromagnetic pump. One such pump had been successfully designed and is operating at our lab at BARC.

2. Theory

A rotating magnetic field is generated in the air-gap using alternately magnetized permanent magnets oriented in the radial direction. The magnetic field cuts the conducting metal filled inside the channels. This induces eddy currents in the conducting metal, which thereby experience a Lorentz force, whose direction is defined by the Fleming's left hand rule. When analyzed in cylindrical coordinate system, magnetic flux has a radial component in the air-gap. Lorentz forces are generated due to the interaction between radial magnetic field and the perpendicular induced currents due to changing radial magnetic field. The vector multiplication of perpendicular induced currents and radial magnetic field produces unidirectional Lorentz force in the azimuthal (tangential) direction. The magnitude of Lorentz force is equal to magnitude of eddy currents multiplied by the magnitude of magnetic flux density.

3. Governing Equations

Maximum pressure developed by the pump is given by equation 1. [1]

$$P_{max} = 0.5\sigma V_M B^2 s l_{mp} k \qquad (1)$$

Where σ is electrical conductivity of liquid metal, V_M is velocity of alternating magnetic field in radians per second given by equation (2), *B*[T] is average of magnetic fled density along the width of liquid metal layer, *s* is slip defining relative velocity of magnetic field in respect to the velocity of liquid metal in duct of the pump given by equation (3), l_{mp} is the length of active part of pump's channel and *k* is a coefficient taking into account the influence of negative transversal end effects lowering maximal pressure developed by pump. An optimum design of the pump should maximize *k*.

$$V_M = 2\pi\omega N \qquad (2)$$

Where ω is rotation speed of the motor-pump assembly in revolutions per second and *N* is number of magnets mounted on the rotor.

$$s = 1 - \frac{V}{V_M} \qquad (3)$$

V is velocity of fluid in the channel.

The pressure developed by the pump is directly proportional to rotational velocity of the pump and the square of magnetic flux density. Another parameter which influences the maximum pressure developed is the magnet pitch. In the present context magnet pitch refers to the angular distance between magnets. The dependence of maximum pressure developed, on magnetic pitch is not straight forward. The pressure also depends on magnet size and dimensions of the rotor. For optimum performance of the pump, magnet pitch should be judiciously decided. This paper also discusses the qualitative effect of magnet pitch on Lorentz force generation.

4. Use of COMSOL Multiphysics

The FEM model of electromagnetic pump is solved as a quasi-static magnetic problem using perpendicular induction current vector potential included in AC/DC module of COMSOL. The problem was modeled as a time varying 2-dimensional problem. Analysis is carried out on a cross section through the axial centre of the rotor of the pump. The motion between the rotor and the stator is accounted by proper boundary conditions. The PDE solved is given in (4).

$$\sigma\frac{\delta A}{\delta t} + \nabla\times\left(\frac{1}{\mu}\nabla\times A\right) = 0 \qquad (4)$$

The rotation is modeled using a deformed mesh application mode (ALE); the center part (rotor) rotates with an angular velocity with respect to the fixed coordinates of the stator. The rotor and the stator are drawn as two separate geometry objects and concept of assembly [2] is used. Advantages of using assembly are discussed in [2].

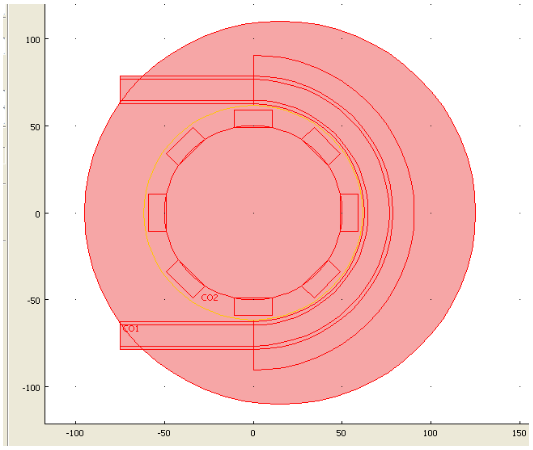

Figure 1: Model of Electromagnetic pump in COMSOL.

The model of the pump is shown in figure 1. Eight permanent magnets are fixed on periphery of the rotor. The magnets are magnetized alternately in radially inward and radially outward directions. The direction of magnetization is shown in *figure 10* in *section 7* of this paper. The stator consists of a semi-circular duct, carrying the molten metal and a C-shaped backing iron of CRNGO steel. The yellow line in the model signifies the pair formation. Pair formation is required for solving relative motion problems in COMSOL. The model is solved at an angular velocity of 600 rpm. The conductivity of the liquid metal is taken as 1.3e6 [S/m]. The remnant magnetic flux density of the permanent magnet is 1.3 [T].

5. Post processing results and analysis

Figure 2 shows the normalized magnetic flux density profile and magnetic potential profiles. Figure 3 shows the profile of normalized Lorentz force generated in N/m^3, arrows shows the direction of the force and arrows magnitude is proportional to Lorentz force's strength. Perpendicular Induced currents density profile is shown in figure 4. The induced currents are in axial z-direction (perpendicular to cross-section of rotor). Lorentz force generation is dependent on magnetic flux density profile and perpendicular induced currents. For generation of Lorentz force in azimuthal direction (along the channel), magnetic flux density and induced currents shall be perpendicular to each other. The time varying radial magnetic flux density in the air-gap induces eddy currents in the z direction. The two fields interact to produce the necessary Lorentz force. Figure 5 shows the variation of radial magnetic flux density, perpendicular induced currents and tangential Lorentz force at t=50 msec along the arc passing through the radial centre of the channel carrying the liquid metal. The variation of perpendicular induced currents and radial magnetic flux density is such that unidirectional azimuthal Lorentz forces are generated.

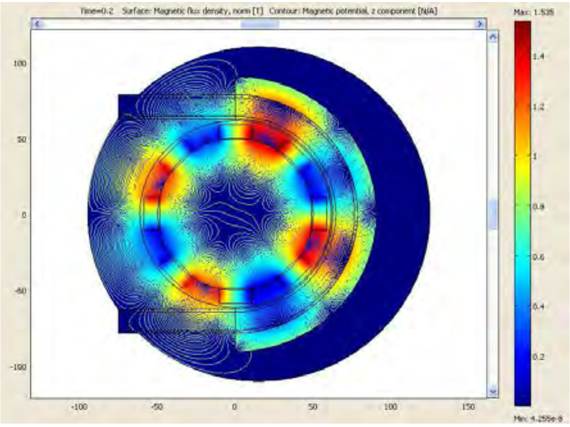

Figure 2: Post processing results: Magnetic field density (surface plot) and magnetic potential (contour).

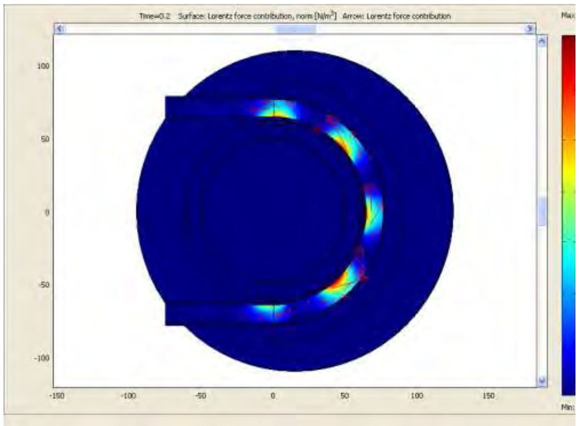

Figure 3: Post processing results: Normalized Lorentz force distribution[N/m^3].

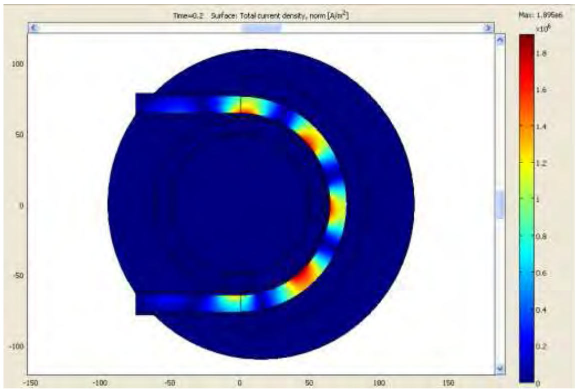

Figure 4: Post processing results: Induced perpendicular current density [A/m^2](z-direction).

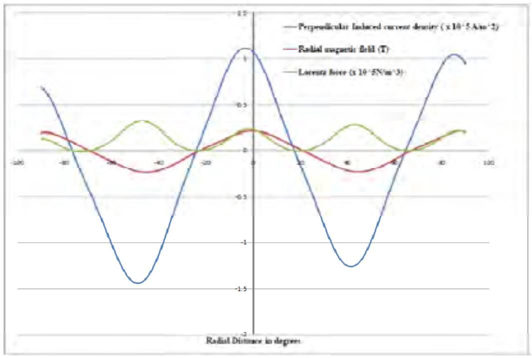

Figure 5 : Variation of tangential Lorentz force (green) [10^5N/m^3], radial magnetic flux density (red)[T] and perpendicular induction current (blue) [10^5A/m^2] along the midway of liquid carrying duct.

6. Effect of angular velocity, magnet strength and magnet pitch

The analysis of the electromagnetic pump was carried out for two angular speeds of 600 rpm and 300 rpm. The normalized surface integrated Lorentz force from 0 to 200 milliseconds was evaluated and is shown in figure 6.As evident from this figure; the Lorentz force is directly proportional to angular velocity. The strength of permanent magnets is an important parameter for maximizing the Lorentz force in EM pump. The Lorentz force is proportional to the square of air-gap magnetic field. Analysis was carried out for two sets of permanent magnets with remnant magnetic flux densities of 1.3[T] and 0.65[T]. The Lorentz force in the latter case is reduced by a factor of four when compared to former. The results are shown in figure 7.

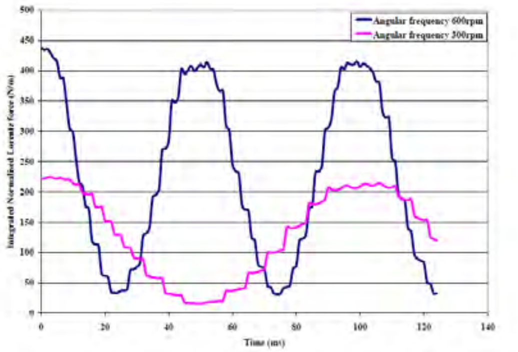

Figure 6: Effect of angular velocity on Lorentz force at 600 rpm(blue) and 300 rpm(pink).

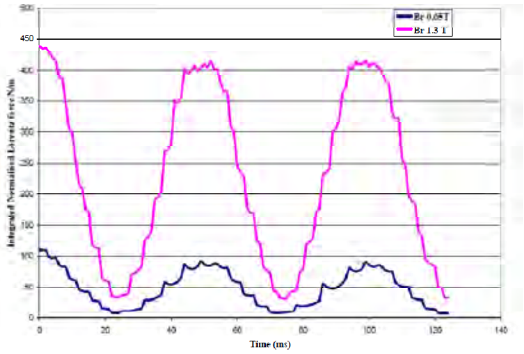

Figure 7: Effect of permanent magnet strength on Lorentz force generated in EM pump. At remnant magnetic field 1.3[T] (pink) and 0.65[T] (blue).

Analysis of EM pump was carried out for three different magnet pitches of 90°, 45° and 22.5°. The results are not straightforward and needs explanation. The results are shown in figure 8.

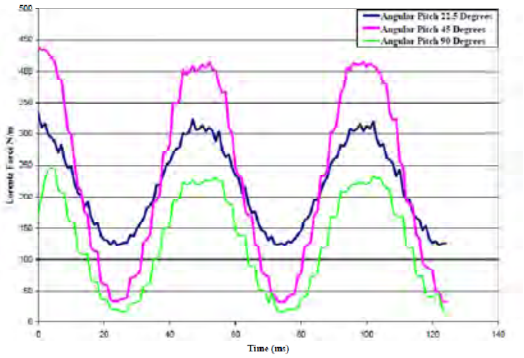

Figure 8: Effect of magnet pitch on Lorentz force generation at magnet pitch 22.5 °(blue), 45°(pink) and 90°(green).

These results can be explained as follows. Two factors are influenced by changing the magnet pitch, first is the velocity of travelling magnetic flux density which is proportional to angular velocity of the rotor and number of permanent magnets. Second is the rate of change of magnetic flux density. When magnet pitch is reduced from 45 degrees to 22.5 degrees, the magnets almost touched each other and the rate of change of magnetic flux density is reduced comparatively. The increase in travelling magnetic flux density is not able to compensate the decrease in magnetic flux density change rate. On other hand increase in magnet pitch has reduced the travelling magnetic flux density velocity and rate change of magnetic flux density is not able to compensate it. The magnet pitch thus shall be optimized in order to use fruitfully the effect of travelling magnetic flux density and change rate of magnetic flux density.

7. Design

A prototype EM pump is designed and fabricated to establish the principle. The pump is undergoing lab trials and its performance is being evaluated. Schematic drawing of EM pump fabricated is shown in figure 9. Pump can be divided into three sections, firstly stator, rotor and liquid metal. The rotor of the EM pump is rotated with a DC motor as shown in figure 9. This prototype EM pump is designed for mercury as it is the only liquid metal at room temperature. However it should be handled carefully as it is toxic in nature.

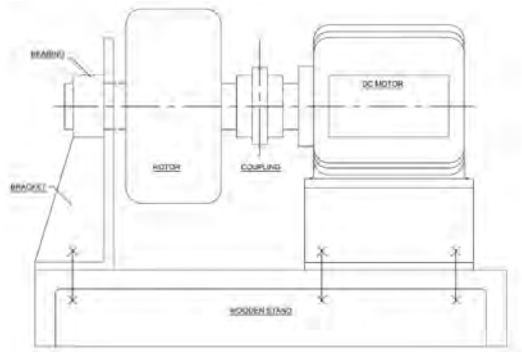

Figure 9: Schematics of EM pump

7.1 Stator

The non-moving part of the EM pump consists of the semi-circular duct carrying the liquid metal, magnetic backing iron and other supporting arrangements for support. Soft iron confines the magnetic field and also provides support to the duct. The duct carrying the liquid metal is made of fiber plastic.

7.2 Rotor arrangement

The rotor arrangement along with semi-circular duct and back iron is shown in figure 10. The physical arrangement of magnets, their magnetization direction, direction of flow and soft iron backing is shown this figure. The circular arrangement next to semi-circular duct is the rotor portion of the EM pump.

Neodymium iron boron magnets are used as permanent magnets. These magnets are strong magnets and are made up of rare earth elements. Strength of these magnets is superior to Alnico, ferrites and other rare earth magnets .Magnetic Properties of the Neodymium iron boron magnets are tabulated in table 1.

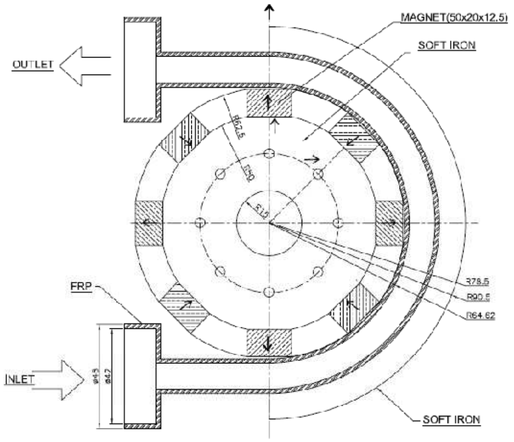

Figure 10: Rotor, liquid metal carrying duct and soft iron backing of EM pump

Table-1: Properties of permanent magnets used in EM pump

Parameter	Value
Remnant magnetic field	1.3 T
Recoil permeability	1.04
Curie temperature	320°C
Operating temperature	150°C
Coercive field	1285 kA/m
BH_{MAX}	45 MGOe

Figure 11 shows Electromagnetic pump fabricated on this principle. Bar magnets are arranged along the periphery. As seen in the figure the rotor is coupled to a DC motor. Lower duct is the suction and upper duct is the discharge.

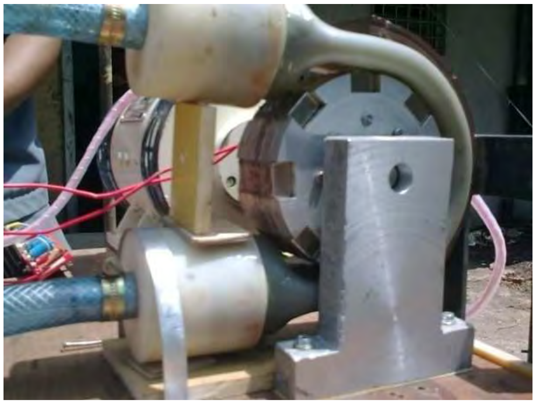

Figure 11: Electromagnetic pump fabricated and successfully running at BARC.

7. Conclusions

An electromagnetic pump based on the above-mentioned theory has been developed.The pump design needs to be optimized for optimum efficiency .The rotor’s angular velocityand magnetization strength of the magnets have direct bearing on the Lorentz force developed , whereas magnet pitch optimization need further qualitative and quantitative analysis and optimization.

8. References

1. M. Butzek, I. Bucenieks, Proposed Mercury Pump for ESS, *16th Meeting of the International Collaboration on Advanced Neutron Sources*, May 12-15, 2003.
2. COMSOL Multiphysics AC/DC Module user’s guide.

9. Acknowledgements

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