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Design and Fabrication of Pilot Scale Linear EMS

Dr. Nirmal Kumar Kund

Associate Professor, Department of Production Engineering, Veer Surendra Sai University of Technology, Burla, India

ABSTRACT

The important thrust of the present research work is the development of a linear electromagnetic stirrer capable of developing adequate force field to break the dendritic structure that normally ensues during solidification. This technique employs travelling magnetic fields to produce strong convection deep inside the molten metal pool close to the solidification front. Usually, low-frequency magnetic fields are used to improve the penetration depth of induced forces in the molten metal pool. This is in contrast to high frequencies employed in induction heating where the force field inside the melt pool is insignificant. In comparison with induction heating, the stirring of liquid metal is a more complex phenomenon involving the interaction of fluid flow and electro-magnetic fields generated in the molten metal. As a preliminary step towards understanding electromagnetic stirring, the present research work focuses on the basic electrical design, constructional features and characterization of a linear electromagnetic stirrer for liquid metals.

Keywords: Design, Development, Pilot Scale, Linear EMS.

I. INTRODUCTION

The movable and electrically conducting solid or liquid in a magnetic field experiences an electromotive force, which drives a current whose magnitude depends on the resistance of the conducting medium. Alternatively, current may also be induced in a pool of molten metal by imposing a time dependant or a spatially varying magnetic field. Either of these phenomena can result in two consequences as mentioned aside: (a) Induced magnetic field linked with these currents in the melt pool opposes the original magnetic field (b) Electromagnetic force linked with this induced current and the field opposes the original motion. This force is commonly termed as Lorentz force which is calculated from the mathematical equation represented by $\mathbf{F} = \mathbf{J} \times \mathbf{B}$. Where, $\mathbf{J}$ is the current density (A/m^2) and $\mathbf{B}$ represents the magnetic flux density (Wb/m^2).

Above all, if the conducting media is in liquid state then the above forces give rise to stirring of the liquid. Ideally, it can be seen that the fluid velocity field and the Lorentz force field are coupled. This effect of back emf, is often ignored for the applications involving electromagnetic stirring. However, in the present research, it is found that the electromagnetic force in the solid can be significantly different from that in the liquid because of fluid motion. The pertinent interpretations are described consequently in forthcoming sections.

The most primitive application of magneto hydrodynamics (MHD) in metallurgy is in stirring of liquid metals during casting. Depending on the kind of primary excitation field used, electromagnetic stirrer (EMS) may be categorized as linear, rotary or helicoidal electromagnetic stirrer. A linear electromagnetic stirrer utilizes a travelling magnetic field, as in the case of a linear electric motor. In addition, a rotary electromagnetic stirrer deploys a rotating field to produce swirling action in the melt pool. However, a helicoidal electromagnetic stirrer practices a twisted magnetic field which is a combination of rotary and linear electromagnetic fields.

II. PRINCIPLE OF ELECTROMAGNETIC INDUCTION

A circular solenoid of length L and radius R excited with a current density of $\mathbf{J_p}$ (A/m) has been taken into account, as demonstrated in figure 1.

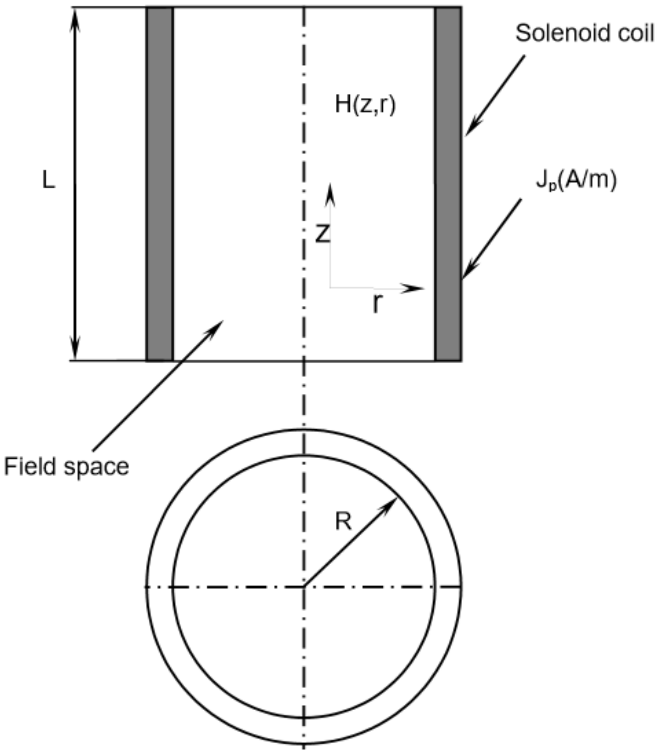


Figure 1. Magnetic field due to a solenoid excited by a current density of $\mathbf{J_p}$ (A/m)

The total current flow in the solenoid is given by $\mathbf{J_p}$L. The current in the conductor sets up a magnetic field **H** (A/m) in the core of the solenoid. The magnetic field causes a magnetic flux in the core of the solenoid whose density **B** is represented by equation as $\mathbf{B} = \mu_e\mathbf{H} = \mu_o\mu_r\mathbf{H}$. Where, μ_r is the relative permeability of the material and μ_o is the permeability of the free space (1.2×10^{-6} H/m).

When a conducting medium is kept in the field space, an electromotive force (emf) **V** will be induced in the conductor. This emf, in turn, will induce an opposing secondary current in the conducting medium placed along the axis of the solenoid having a current density **J** (A/m^2). **J** is given as $\mathbf{J} = \sigma\ \mathbf{E}$. Where σ is the electrical conductivity of the conductor, and E is the electric field intensity in the conductor (Volt/m). The Lorentz force experienced by the conducting medium is given by the equation $\mathbf{F} = \mathbf{J} \times \mathbf{B}$, as already described in previous section.

From the forgoing discussions it is quite obvious that so as to generate an external force, either the conductor is in motion or the current in the primary solenoid is to be transient, or both. Hence, to set up a stationary conductor in motion, time dependent currents are imperative. If a single solenoid excited with alternating current is used, the force produced will, at best, create a local ripple. Hence, in order to produce bulk motion, the current in the solenoid should be varying as a function of time and space.

Ultimately, the electromagnetic stirrer should produce a force field as already discussed. However, in reality, such a field cannot be achieved as it is physically not possible to have spatially varying current within a single solenoid. At best, such an ideal field can be produced using a series of spatially distributed coils excited by phase-displaced currents. In order to visualize such a field, it is first necessary to understand the field due to single coil carrying current.

As already discussed previously in this section, a net mechanical force is produced only if a series of such coils are arranged in space and excited by phase displaced currents. The net result will be generation of travelling/rotating magnetic field which will produce force/torque in the conducting medium placed in the core of the solenoid. The direction of force/torque depends on the phase sequence of the currents exciting the coil. One such coil arrangement consisting of six coils A, A$^|$, B, B$^|$, C, C$^|$ (used in the present linear EMS) is described in the subsequent section.

III. DEVELOPMENT OF A LINEAR EMS

Figure 2 (a) illustrates the arrangement of a linear electromagnetic stirrer. The coils AA$^|$, BB$^|$, CC$^|$ are arranged in a linear fashion to form the stator windings. These coils are displaced in space by L/6 (m) where L is the total length of the stirrer. The coils A$^|$, B$^|$, C$^|$ carry the same currents as coils A, B and C, respectively, but in opposite directions. The phasor representation of the currents at a particular instance is shown in figure 2 (b). The above coil arrangement, when excited by a three phase alternating current, generates sinusoidally distributed magneto motive force (mmf) in space as well as time. The resulting mmf establishes a magnetic field $\mathbf{H}(r,z,t)$ travelling along the axis of the stirrer. The variation of the axial field induces voltage $\mathbf{E}(\phi)$ in the molten metal in the tangential direction. As a result of the induced voltage, a tangential eddy current field **J**(ϕ), is created. The interaction of the tangential eddy currents **J**(ϕ) and induced magnetic field, **B**(r,z), in the metal generate axial and radial forces $F_z(r, z, t)$ and $F_r(r, z, t)$, respectively, in the metal. The molten metal undergoes convection under the influence of these forces.

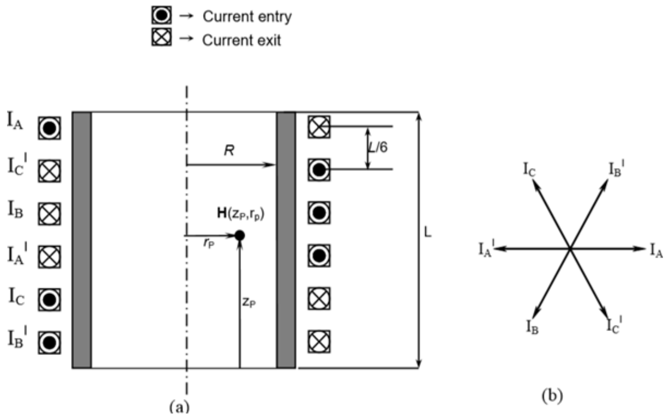


Figure 2. (a) Coil arrangement in a two pole LEMS (b) Phasor notation of currents

The details about the developed pilot scale linear EMS from the preliminaries for a stirrer are described in table 1.

Table 1. Details of the pilot scale linear EMS

Number of coils	6
Number of turns in the coils (N)	10
Primary current (I)	200 A
Excitation Frequency (f)	50 Hz
Length of the Stirrer (L)	0.160 m
Coil radius (R)	0.042 m
Coil width (W)	0.009 m

IV. FORCE FIELD ANALYSIS IN METAL

Though, in the situation of non-metal, it is considered as a non-conducting medium in the annular field space. However, when an electrical conductor such as molten metal is introduced in the field space, the induced currents in the metal oppose the primary excitation current (fig. 3). This alters the magnetic field intensity **H** in the field space. The field analysis is done with the succeeding assumptions: (a) the stirrer is infinitely long in the z direction (i.e L>>R). In such cases, the travelling field is completely axial, (b) the current density **J** in the molten metal is not a function of melt velocity, (c) the end effects and flux leakage due to the presence of air gap between the primary coils and the metal core are ignored, and (d) the entire magnetic flux generated by the primary coils is concentrated in the core of the linear EMS where the metal is kept.

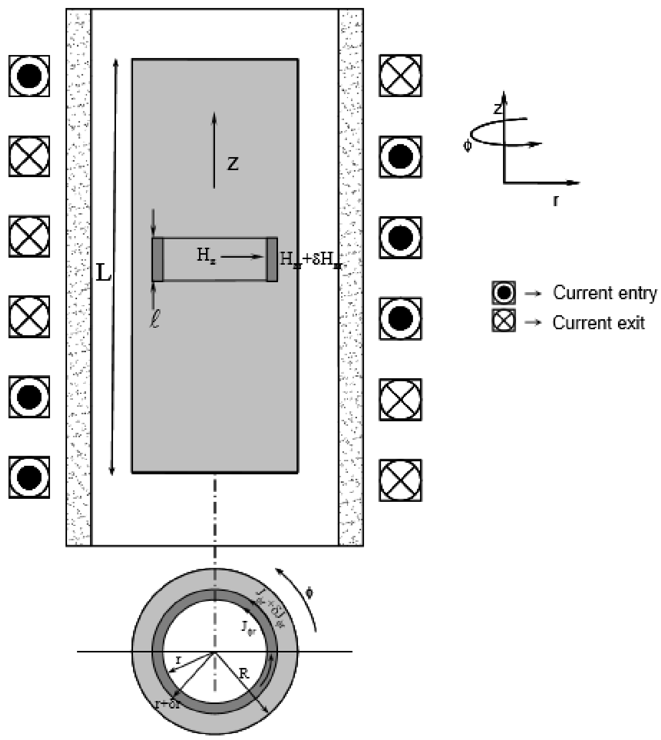


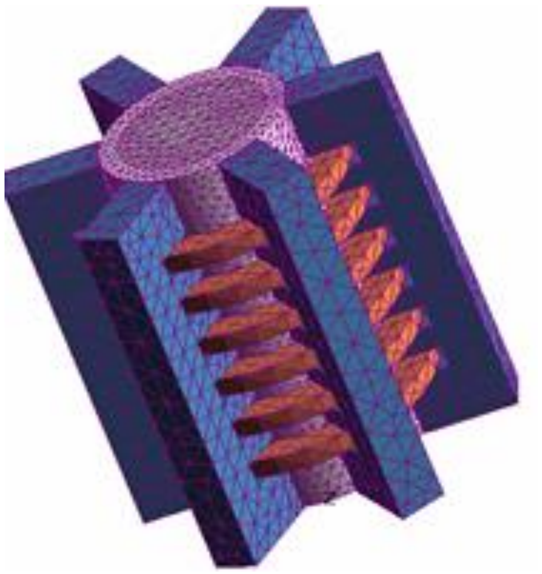
Figure 3. Field formulation for **J** (A/m^2) in metal

In addition, the succeeding observations are also noticed: (i) the radial and axial force densities are proportional to the radius and square of the radius, respectively, (ii) the radial force averaged in space and time, is zero, and (iii) the axial force, when averaged in space or time, is in the direction of phase sequence.

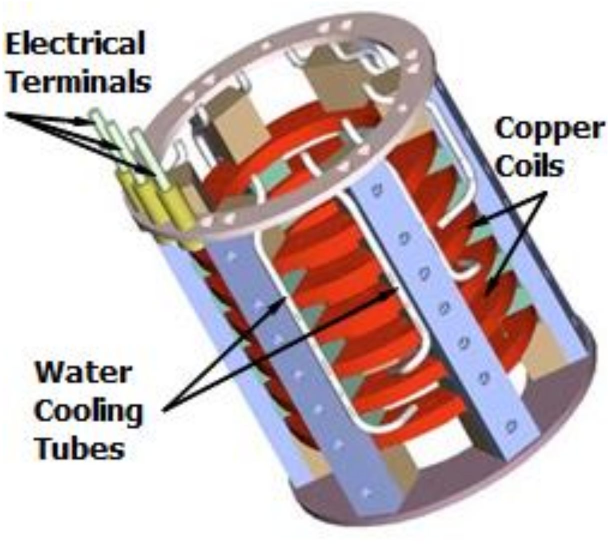
In a linear EMS, it is the axial force (F_z) which is responsible for bulk motion in the liquid. As the net average radial force is zero, it does not directly be part of the cause in the fluid motion. The radial force, at most, would generate a pressure field around the melt.

V. PILOT SCALE LINEAR EMS FOR LOW MELTING POINT ALOOYS

By way of an initial stage, the previous analytical exemplary gives us an idea of the forces generated and its spatial distribution for a given excitation current. The induced eddy current is based on the distribution of axial magnetic field intensity (H_z). The influence of the radial magnetic field intensity (H_r) is ignored. However, it is recognized that the radial magnetic field is solely responsible for creation of the axial force field, F_z, in the metal. In practical applications, this radial magnetic field is enhanced by introducing a magnetic return path (MRP) surrounding the primary coils. In such cases, an analytical solution is not possible. Since the problem now is geometry specific, a numerical solution is sought. Accordingly, an FEM model using MagNet software is developed, as shown in figure 4 (a). Based on the detailed numerical analysis, the present electrical design for a two pole pilot scale LEMS is physically constructed, as shown in figure 4 (b) and 4 (c). In this design, the magnetic return paths are provided as shown in the FEM model (fig. 4 (a)). However, the design challenges of the MRP will be described in future for aluminium alloys in the context of the full scale linear EMS.



(a)



(b)

(c)

Figure 4. Pilot scale linear EMS for low melting point alloys (a) FEM model (b) CAD model (c) physical construction

VI. TEST SETUP OF PILOT SCALE LINEAR EMS

The pilot scale LEMS is built to validate the mathematical formulation and to set up a case for numerical modelling. The pilot scale model also serves to bring out any mechanical/electrical system design issues which cannot be easily predicted theoretically at the design stage. The specifications and design parameters of the pilot scale linear EMS are listed in table 1. The stirrer coils are designed for handling excitation current up to 200A. As there is high amount of heat generation in the coils (Joule heating), a water cooling arrangement for the coils is provided, as shown in the CAD model in figure 4 (b). The fabricated pilot scale linear EMS arrangement is demonstrated in figure 5. In addition, the electromagnetic force on the aluminium cylinders is measured by either suspending the solid cylinders or mould containing the alloy from a weighing balance placed on a test table as shown in figure 5.

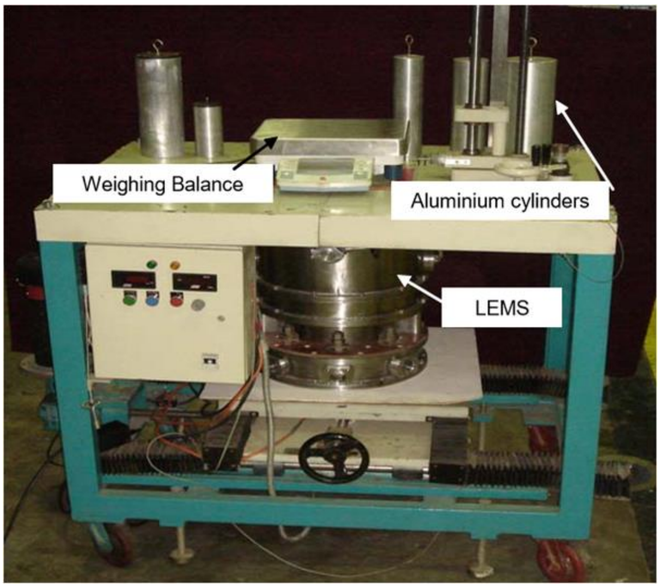


Figure 5. Test table set up for force measurement

A series of step-down transformers are used to reduce the line voltages. This arrangement enables precise control of input supply current and frequency to the linear EMS. The software in the inverter offers flexibility in the form of phase reversal to reverse the direction of axial forces without interrupting the cycle.

VII. CONCLUSION

The fundamental principle of electromagnetic stirring is well illuminated. A comprehensive description of the potential electro-magnetic field orientation is demonstrated and the resulting convective flow patterns of molten alloys for the present stirrer geometry is illustrated as well. A simplified analysis of a linear axisymmetric stirrer for molten alloy solidification process and the associated thermal and electrical design issues are described. A pilot scale model for low melting point alloys is fabricated to set up the cases for thorough experiments. The experimental linear EMS arrangement also considers the influences of process variables. The necessary safety precautions are also followed in the experimental designs, trials and practices. In addition, the complete force measurement experimental facilities are developed for the pilot scale linear EMS. However, a full scale linear EMS model is also planned for future to extend the present design and development for handling molten aluminium alloys.

VIII. REFERENCES

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