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Design and Fabrication of Full Scale Linear EMS

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ABSTRACT

The fundamental issues and challenges related the pilot scale EMS are presented elaborately. Additionally, the basic analysis of a full scale linear EMS and the relevant thermal and electrical design issues and challenges are strongly demonstrated. Ultimately, a full scale linear EMS prototype for handling low melting point alloys like molten aluminium is designed and fabricated, in accordance with the key aspects involved, for performing comprehensive trials and tests. The key motivation of the current research exercise is to develop a full scale linear EMS very well equipped to produce suitable force field for breaking the dendritic microstructure which is generally formed throughout solidification. This technology deploys travelling magnetic fields to yield very strong convection deep inside the molten metal pool near to the solidification front.

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

I. INTRODUCTION-KEY ISSUES AND CHALLENGES WITH PILOT SCALE LINEAR EMS

The pilot scale linear EMS is not suitable for large scale production of semisolid slurry in manufacturing industries because of the experience with the pilot scale linear EMS has raised several related issues and challenges, which are also considered while designing and developing the full scale linear EMS. Some of the issues and challenges are as mentioned aside: (a) Excitation current in the coils-The excitation current is fixed by the required force density in the melt. But high excitation current in the coils also result in increased I^2R (R- coil resistance) loss which demands more cooling of coils (b) Force density-The magnitude of the force density depends primarily on the excitation current. Force density ultimately affects the liquid velocity in the melt which should be adequate to shear off the dendrites located at the solid-liquid phase change interface (c) Optimum stirring frequency-Pilot scale linear EMS employs low frequency to achieve better field penetration in melts. But at lower frequencies, magnitudes of the induced currents in the metal are also lower, resulting in low force densities (d) End effects-End effects are dominant with pilot scale linear EMS because the rotor does not close on itself i.e. they have finite length. End effects cause non-uniform flux distribution along the length of the pilot scale linear EMS.

Thermal and electrical design issues and challenges demonstrated in the subsequent sections are based on dimensions and heat load data for the full scale linear EMS useful for molten aluminium alloy. Table 1 summarizes the detailed specifications of the full scale linear EMS for molten aluminium alloy.

Table 1. Particulars of the full scale linear EMS for molten aluminium alloy

No. of coils	6
No. of turns in the coils (N)	10
No. of poles (p)	2
Width of the coil (w)	0.015 m
Pole pitch (λ)	0.172 m
Mould radius (r)	0.05 m
Coil radius (R)	0.085 m
Length of the Stirrer (L)	0.450 m
Primary current (I)	500 RMS
Excitation Frequency (*f*)	5-200

II. ELECTRICAL DESIGN ASPECTS FOR FULL SCALE LINEAR EMS-DESIGN OF MAGNETIC RETURN PATHS (MRP)

Hence, the next step is to extend the model design and develop a full scale prototype linear EMS for handling molten aluminium alloy. The basic and extended electrical design and development of a full scale prototype linear EMS (for handling molten aluminium alloy) corresponding to MRP primarily involves (a) MRP height (b) Number of poles and (c) Circumferential pitch between MRP's, as described underneath. The current applied to the coils produces a magnetic field around them. To get maximum force field in the metal, the entire magnetic field produced should be concentrated in and around the mould containing the molten metal. Hence, for this purpose, in a linear stirrer, slotted iron cores are kept at the coil periphery. This slotted iron core provides low reluctance and diverts the magnetic field at the coil periphery towards the centre, where the mould is placed. Besides minimizing the magnetic flux leakage, the slots provide mechanical support to the coil and hold it in place. The slotted iron core or magnetic return paths function in a like way as a pole shoe in an induction machine. The structure of a magnetic return path and its location in a linear EMS is presented in figure 1.

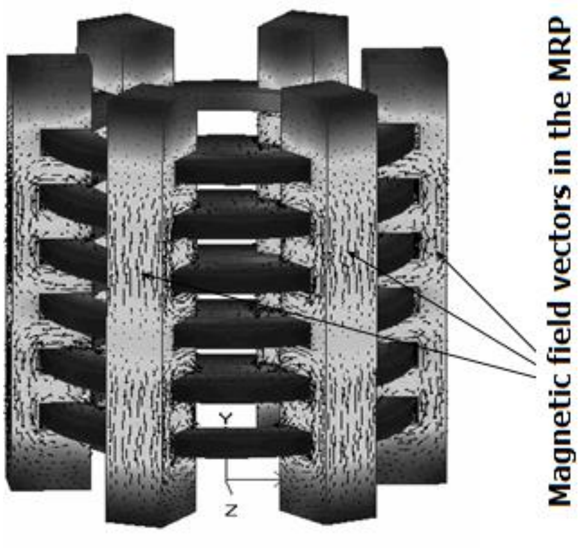


Figure 1. Magnetic field due to a solenoid excited by a current density of $\mathbf{J_p}$ (A/m).

Lion's share of the axial force field generated is due to the presence of MRPs. The design of a MRP is critical to the performance of the linear EMS. The shape, width, thickness of the slots, the number of slots, pole pitch of the iron core and mounting positions of the MRP are important factors in the design of the linear EMS. The comprehensive design comprises magnetic field analysis of the MRP. Nevertheless, some fundamental design course of action are enumerated underneath.

A. MRP Height

Here is also a compromise for the ideal MRP height as well. A very short length results in magnetic saturation, whereas a very long slot makes the MRP large and heavy. A suitable height of 284 mm is selected by the current magnetic field analysis, depending on the pole pitch and the number of poles in the stirrer. Figure 2 demonstrates the magnetic flux density distribution in a usual MRP of a full scale linear EMS for aluminium. The flux density distribution is found for a primary coil current of 500A. The saturation magnetic flux density for electrical steel is approximately 2 T.

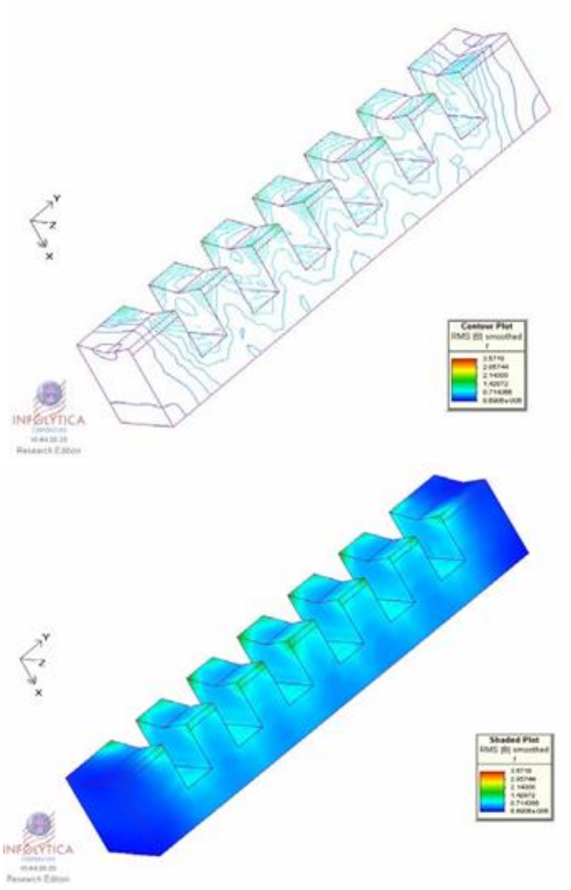
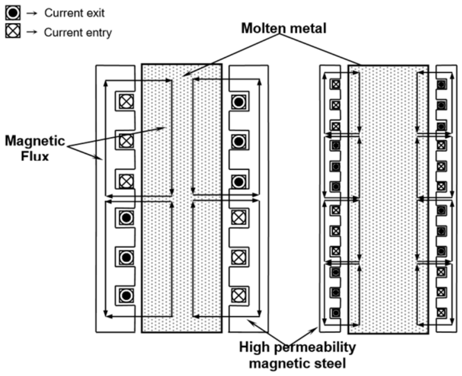


Figure 2. Magnetic flux density distribution in MRP for an excitation current of 500A as simulated using MagNet software.

B. Number of Poles in Linear EMS

With the increase in the number of poles, the penetration of the magnetic field occurs only in the peripheral region of the metal, causing lower electromagnetic forces in the molten metal. The pole pitch and the number of poles should be chosen depending on the mould diameter and the radial distance between the mould and the metal. If the mould is far away from the coil, the number of poles should be maintained to a minimum. The influence of number of poles on the depth of penetration is schematically presented in figure 3. The current full scale linear EMS is a two pole device.



(a) (b)

Figure 3. Magnetic flux penetration in linear EMS (a) 2-pole and (b) 4-pole.

C. Circumferential Pitch of MRPs

After reaching at the ideal slot width, thickness and height, the only parameter that leftovers to be calculated is the circumferential pitch between the MRP. Experimentally, it is observed that the surface of the MRP facing the mould should nearly cover 30% of the total circumferential area of the liquid metal core. This is observed to be essential for good field penetration. Likewise, a sound number of MRP is found to be six. Any more increase in the number or MRP's does not increase the magnetic field intensity meaningfully; instead it obstructs the inter coil connection and creates the assembly deadly.

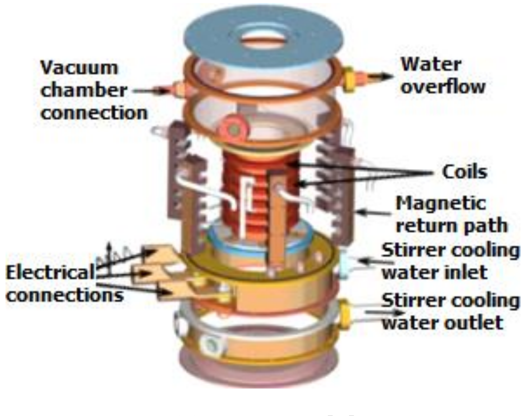
III. ELECTRICAL DESIGN ASPECTS FOR LINEAR FULL SCALE EMS-DESIGN OF EMS COILS

The prime complication in the design of the linear EMS is the coil design. Contrast TO the rotary EMS, where the coils are wound longitudinally along r or z directions, the coils in a linear EMS are wound tangentially (i.e. along φ direction,) alike to that of an induction furnace. The mere dissimilarity is that in an induction furnace there is normally only one turn, however in a linear EMS there are more turns. In the current situation, there are 10 turns. Usually, hollow copper tubes are utilized for the production of coils. Water is circulated through the hollow sections to overcome Joule heat (I^2R losses, R- coil resistance) produced in the coils. The use of water cooled conductors for the linear EMS increases the size and total radius of the coil winding. The increase in the coil winding radius declines the magnetic flux density in the molten metal core for the same primary excitation current applied to a solid conductor having comparable cross sectional area. In the current design, the coils are wound by means of vacuum impregnated Kaptone insulated copper strips. According to the manufacturer's specification the insulation failure occurs at about 200°C of temperature.

One more design necessity is that the number of turns has to be minimum, so as to lessen the potential drop across the primary coils. Since water is utilized to cool the coils, low primary excitation voltages are essential from the perspective of operational protection of the equipment. Less turns also result in low coil resistance, thereby dropping Joule heating losses.

In a linear EMS, since axial force is proportional to the square of the coil radius, the coils have to be kept very close to the mould to have more advantage of the travelling magnetic field. Bearing in mind the above matters in the current design of the linear EMS, the coil radius is chosen to be 85 mm and the number of turns is limited to 10 turns. The conductor cross-sectional area is idealized to have a maximum current density of 25 A/mm^2 in the conductor for an excitation current of 500A.

The stated ideal dimensions for the full scale linear EMS are attained after thorough numerical simulation and field analysis expending MagNet software. The ultimate structure of the full scale stirrer is demonstrated in figure 4.



(a) CAD model

(b) Physical structure

Figure 4. Particulars of the full scale linear EMS: (a) CAD model and (b) physical structure.

IV. THERMAL DESIGN OF FULL SCALE LINEAR EMS

As discussed in the preceding sections, the coils produce large amount of heat (of the order of25 kW) which has to be dissipated. Such heat loads cannot be combated by air cooling practices. Therefore, from the perspective of functioning protection of the equipment, a distilled and de-ionized water cooling arrangement is introduced in the current design.

The existing surface area of the coil for cooling is around 0.50 m^2. This causes heat flux of nearly 50 kW/m^2. Even though the Kaptone insulation can securely bear temperatures up to 170°C (as per manufacturer's specification), a maximum working edge of 80°C is set for the design of the cooling arrangement. Supposing that the average temperature of water is kept at 25°C, it can be valued that heat transfer coefficients of the order of 1200 W/m^2-K are essential. Consequently, jet impingement cooling is selected to realize these working settings.

The design flow rate of cooling water is estimated such that the temperature rise of water is not above 10°C as it flows through the linear EMS. This will cause a design flow rate of 70 lpm. This flow is uniformly circulated through 72 jets at 12 jets per coil. These jets are evenly dispersed around the outer circumference of the coil, as shown in figure 5. Therefore, every jet will release about 1.0 lpm. To avoid surface erosion of the Kaptone insulation, the jet velocity is limited to 1.5 m/sec. Subsequently, a 4 mm jet diameter is selected. This provides a jet Reynolds number (Re) of 6000. The impingement distance is fixed at 4d (where d is the nozzle diameter) to attain maximum heat transfer. Furthermore, the jets are inclined at 16° to the normal surface, so as to benefit from circumferentially asymmetric/boundary layer distribution about the point of impact of the jets. This system is observed to provide the essential heat transfer coefficient of 1200 W/m^2.

Water outlet in the linear EMS is kept at the bottom. The downward draining of water evades interaction with the coil. This warrants high heat transfer rates caused by breaking of free jet upon impingement on the coil surface.

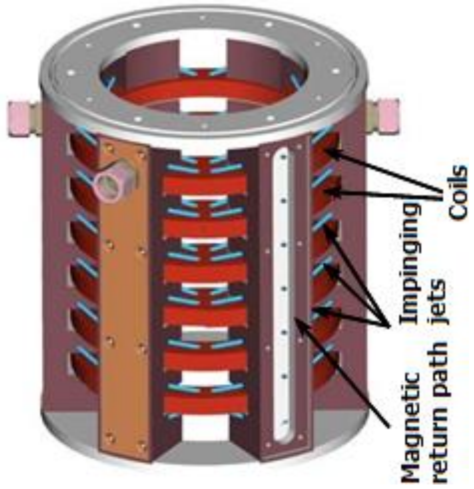


Figure 5. Schematic of jet impingement method used for linear EMS coil cooling.

V. HEAT REJECTION ARRANGEMENT FOR COOLING WATER

The cooling water for the coils is taken from a storage tank of 1000 litres capacity. If no external cooling practice is done, the water temperature will increase at a rate of 0.01°C/sec. For usual run duration of 6 hours, a significant increase in the temperature of water will ensure. Therefore, an external cooling arrangement is developed for dissipating the heat from the flowing water. The cooling arrangement involves of two components: (a) Heat delivery arrangement to the ambient in a water-to-air heat exchanger and (b) Refrigeration arrangement with a 300 liters chilled water storage capacity which is mixed with water from the main storage. Around 2kW of heat is dissipated in the former. A refrigeration system of capacity 10.5 kW and providing cold water at 5°C facilitates maintaining cooling water inlet temperature within the allowable limit. Besides the refrigeration arrangement, the cooling arrangement also has a distiller for descaling and de-ioniser for preventing dissociation of water. The representative illustration of the whole arrangement is presented in figure 6. The physical arrangement is also depicted in figure 7.

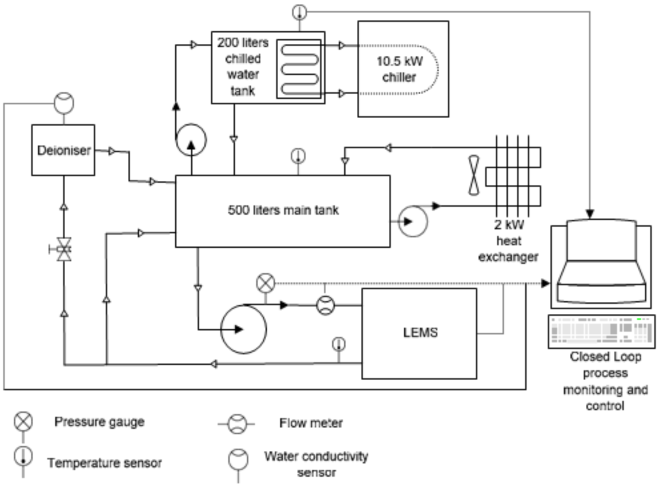


Figure 6. Schematic of linear EMS coil cooling arrangement.

The extreme cooling load of 25 kW ensues only for a restricted period (for nearby an hour) after the molten metal is poured. But, linear EMS arrangement has to be stabilised before pouring of the metal, during pre-heating period of the mould. Throughout this period the linear EMS is functioned at a higher frequency so as to produce induction heating. Therefore, the cooling load on the heat rejection arrangement during this period is likely to be much lower than the extreme load. Subsequently, the refrigeration component of the heat rejection arrangement is occasionally switched on during the initial pre heating period of the linear EMS operation. Also, a 25 kW of peak load is in accordance with a designed maximum current capacity of 500A. This scale of current may not be used throughout the standard runs. Therefore, the complete design of the cooling arrangement can be understood to be conservative. The parameters that require to be examined are: coil surface temperatures at several positions, cooling water inlet and outlet temperatures, pressure and its flow rate, water level in the supply tank of the cooling water, and electrical conductivity. These parameters are uninterruptedly monitored in a closed loop from end to end with a out-and-out programmable logic control (PLC).

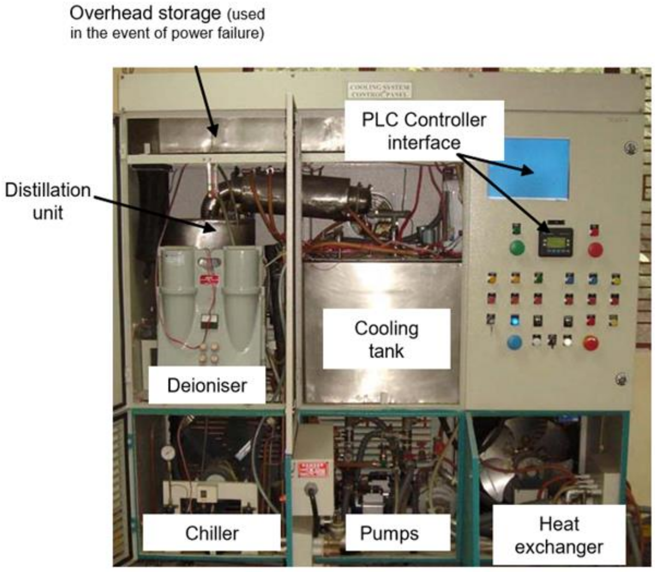


Figure 7. Photograph of linear EMS coil cooling arrangement.

VI. CONCLUSION

The key issues and challenges involved with the pilot scale EMS are very well described. In addition, the particulars about the full scale linear EMS relating to the molten aluminium alloy is also summarized. The electrical design aspects for full scale linear EMS relating to the design of magnetic return paths (MRP) in terms of MRP height, number of poles and circumferential pitch between MRPs, are thoroughly discussed. Furthermore, the electrical design aspects of EMS coils for full scale linear EMS are also explained. Besides, the thermal design synthesis of full scale linear EMS is also reported as well by considering the heat rejection system for cooling water. In other words, a comprehensive and detail about the full scale linear EMS is superbly demonstrated and the resulting convective flow patterns of water through various jets are also illustrated. As a whole, the simplified analysis of a full scale linear EMS and the related thermal and electrical design issues and challenges are marvellously illuminated. Finally, a full scale linear EMS prototype (for handling low melting point alloys like molten aluminium) is fabricated for conducting exhaustive experiments. The detailed design and fabrication of the experimental setup is in accordance with the key aspects involved.

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