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To cite this version:
Ma Yong-Lin, Chen Yan-Jiang, Jiang Tao, Xing Shu-Qing. Design of a small Annular Linear Induction Electromagnetic Pump - Simulation and Experiment. 8th International Conference on Electromagnetic Processing of Materials, Oct 2015, Cannes, France. hal-01333547

HAL Id: hal-01333547
https://hal.archives-ouvertes.fr/hal-01333547
Submitted on 17 Jun 2016

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Design of a small Annular Linear Induction Electromagnetic Pump - Simulation and Experiment

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Abstract:
An annular linear induction electromagnetic pump (ALIP) is used for pumping liquid tin alloy with a flow rate and developed pressure of 17l/min and 0.5bar respectively. The electromagnetic force, flux density and inducted current density are calculated using a by finite element method (FEM) the various design variables. The performance of ALIP is tested with liquid tin for various melting point temperatures. Results show that pressure increases as electromagnetic forces. Comparing experimental and measured values, the relative error of simulation results was lower 15%.

Keywords: annular linear induction, electromagnetic pump, electromagnetic force, developed pressure, simulation.

Introduction
To pump molten metal annular linear induction electromagnetic pump (ALIP) has been widely investigated to transmit coolant, toxic heavy metals such as mercury, lead and so on. Early electromagnetic pumps (EMP) were applied to circulate sodium for nuclear reactor[1]. Since the invention of the Cosworth Process able to put EMP into use for molten aluminum alloy in low pressures casting, the exploration and development of EMP was never stopped [2]. The planar DC EMP was applied to low pressure and casting of aluminum alloys. Advantages of EMP, are the simple construction, no mechanical motion which minimize oxidation of liquid metal and corrosion of the mechanical components and no maintenance that steadily carries out for a long period of time. Those reasons conduct ALIP to be the only option for a nuclear liquid metal reactor (LMR), rather than planar induction electromagnetic pump because of electrodes easy corrosion [3,4].

Simulation with 3D transient magnetic field, changing geometrical variables and load current is used for ALIP. In this paper, a small annular linear induction electromagnetic pump with nominal flow rate and static pressure of 17 l/min and 0.5bar respectively has been build with the help of ANSYS for for optimizing the design[5,6].

Design analysis
ALIP could be divided into two parts, pump body serving as primary part of linear induction motor and the duct with inner core as the path of transmitting molten metal. The geometrical variables of ALIP, tooth width of outer core, pole pitch affecting the length of magnetic yoke iron core were considered according to $L = \frac{2pT}{\pi}$; groove width and depth which affect coil number of turns were analyzed in the numerical simulation. The load variables such as current, voltage and frequency that change magnetic field intensity directly were determined by simulation. The developed pressure and flow rate were derived with electromagnetic force getting from finite element results [6,7]. The symbols definition in this paper is listed in Table 1.

Those design variables which affect developed pressure and mechanical efficiency are optimized using ANSYS software. The three- phase AC loading was employed and the edge method to settle 3D magnetic field of transient state
was adopted during the analysis of ALIP. The differential form of Maxwell’s equations, have been employed[7,8]. According to the requirement of geometrical variables, model dimensions of various parts are shown in Fig. 2.

Table 1: Definition of the symbols

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
<th>Name</th>
<th>Description</th>
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<tbody>
<tr>
<td>( T )</td>
<td>Period of input current</td>
<td>( L )</td>
<td>length of magnetic yoke iron core</td>
</tr>
<tr>
<td>( A1,X1 )</td>
<td>One phase of the ac current (same as ( B1,Y1 ) and ( C1,Z1 ))</td>
<td>( FMAG )</td>
<td>resultant electromagnetic force</td>
</tr>
<tr>
<td>( \Delta H )</td>
<td>liquid height difference</td>
<td>( FMAG^* )</td>
<td>Component force at * direction, (*=x,y) or ( z)</td>
</tr>
<tr>
<td>( P )</td>
<td>Number of magnetic poles</td>
<td>( VI )</td>
<td>Input voltage multiplied input current</td>
</tr>
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Fig. 2: 3D simulation model of ALIP for the supply of liquid tin
(a) Mesh model of mine components tetrahedron; (b) Boundary conditions.

In the model, the main object are meshed by hexahedral elements to improve calculation accuracy and speed compared with tetrahedron elements in Fig. 2(a). The parallel boundary condition of magnetic flux density is added to the outer surface of the air region around the small EM pump and the values of the magnetic flux density is assumed zero, as shown in Fig. 2(b). Current density in the inducting coil is time depending shown in Fig. 3, where the time is at 0.01125s (Current intensity : 17A , frequency : 50Hz).

Fig. 3: Frame captured from vector diagram showing the path of the current density.
Note: Diagram of coil is shown in three parts for convenient observation.
The transient analysis based on edge FEM (finite element modeling) is applied to reveal variation and spatial distribution of the magnetic flux, the induced currents and electromagnetic forces in the liquid tin. The simulation analysis is divided sixteen steps in a cycle. Each step could reveal the Z-axis of electromagnetic force (FMAGZ) by transient analysis. Here, the spatial distribution of magnetic flux density changes in liquid tin in the duct is calculated when inducting currents and frequency equal to 20A and 50Hz respectively\textsuperscript{[9]}. 

There are four frames corresponding to the vector distribution of the magnetic flux density at time $T/4$, $T/2$, $3T/4$ and $T$ in a calculation cycle. Fig.4(a) shows the magnetic flux density through the liquid tin which is generated by the outer core. The direction is changing every interval of $T/2$ and is always perpendicular to the z-axis. At any time, two opposite directions of magnetic flux density alternating distribution are existing along the axial. The spatial distributions of electromagnetic force with four different times are shown in Fig.4(b). Moreover, occupied most of the electromagnetic resultant force (FMAG), FMAGZ, along with +Z direction, forced the liquid tin to move. So it is the effective component. FMAGX and FMAGY, the electromagnetic component forces along with +X and +Y respectively are not contributing to the driving force. The spatial distributions of FMAG components were reproduced each $T/2$, i.e., the periodic transformation of FMAG was half that of AC power loaded to the coil.

![Fig.4: Spatial distribution of magnetic flux density and Lorentz force in liquid tin in the duct (20A, 50Hz)](image)

(a) The magnetic flux density ; (b) The Lorentz force

**Results of experimental analysis and comparison**

Fig.5 shows the ALIP fabricated combined with the design factors discussing above and the tin experimental facility for testing the designed ALIP. The experiment is conducted when the tin fluid temperature is 350°C. The measurement of the developed pressure was obtained by the raising liquid weight\textsuperscript{[9,10]}.

![Fig.5: Tin experimental facility for testing the designed ALIP](image)

When the frequency, the pump gap and the pipe diameter are 50 Hz, 5 mm and 50 mm respectively, the FMAGZ
and $\Delta H$ evolve as showed in Fig.6.

![Graph showing the contrast of numerical simulation and experimental results](image)

Fig.6: The contrast of numerical simulation and experimental results

From Fig.6, the FMAGZ and the raised liquid height ($\Delta H$) increased with the input voltage multiplied current (VI) in approximate linear relationship. The relative error between the experimental and numerical simulation values is equal to 11% in average. The difference is decreasing when the input VI voltage is increasing.

**Conclusion**

An annular linear induction electromagnetic pump has been fabricated based on the FEM calculations. The spatial distribution and evolution of magnetic flux, the induced current and electromagnetic force in liquid tin were investigated by a transient time analysis. The magnetic flux is mainly perpendicular to the duct and changed direction to opposite direction every interval of half cycle. The electromagnetic force is in the liquid flowing direction all time. In the operation temperature of 350°C, the desired performance of the ALIP was available and experimental was consistent with the simulation data.

**Acknowledgment**

Financial support from the Innovation Foundation (Grant No.2009NC011) and the Foster Foundation (Grant No.PY-201004) are gratefully acknowledged. I am also deeply indebted to all the other researchers and teachers in Inner Mongolia University of Science and Technology for their direct and indirect help to me.

**References**