Influence of Double-Frequency Lorentz Force Component in modelling Electromagnetic Stirring of Molten Metals

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***Abstract*—Electromagnetic stirring (EMS) is nowadays widely applied in continuous casting of metals, in order to increase the quality of the solidified cast. Therefore, an accurate investigation of the stirring effect represents a matter of great interest. Numerical simulations normally calculate only the average Lorentz force distribution inside the molten metal, which plays the major role in the final velocity field generation. Double-frequency component of the force is then neglected, and the real Lorentz force is approximated. In this paper, the stirring effect under the influence of the real Lorentz force distribution is investigated: both average and double-frequency components are calculated, and the resulting flow field inside the melt is analysed. Numerical simulations are experimentally validated with the use of GaInSn melt and UDV probe.**

Keywords—electromagnetic stirring, Lorentz force, GaInSn melt, coupled simulation

I. Introduction

Electromagnetic stirring (EMS) plays nowadays a fundamental role in the continuous casting of metals, since it allows to strongly increase the mechanical properties of the final cast. Increasing interest on the stirring process over the last decades made electromagnetic stirring an attractive matter of study, due to its widely spread applications in the industry of continuous casting. Travelling magnetic field (TMF) represents in some cases an attractive solution to achieve intense stirring within the molten metal [1]: multiphase power supply induces a distribution of the Lorentz forces whose peak shifts over the time according to the phase sequence itself; a unique toroidal vortex is therefore generated inside the melt. The dimension of the vortex corresponds to the global length of the inductor. Direct measurements on the stirring effects, though, still remains a strong limit in the investigation of the process; therefore, numerical simulations represent powerful tools to achieve a global overview of the process, both from the electromagnetic point of view, and the hydrodynamic one. Furthermore, they allow to easily investigate any variation in the stirring setup: geometry of the setup and its electrical parameters (e.g. working frequency and magnitude of the current supplied to the inductor) play a fundamental role in the mixing of metal, in terms of velocity magnitude and flow field distribution. In order to investigate the electromagnetic stirring effect, coupled electromagnetic (EM) and hydrodynamic (HD) simulations are realized: Lorentz force distribution, generated by the inductor within the melt, is the input for a subsequent calculation of the melt velocity field. Normally, only the average component of the Lorentz force is calculated, since it has the main influence on the distribution of the flow field. Double-frequency component of the force is commonly neglected, since it plays a minor role in the stirring effect at the main frequency: mechanical inertia of the melt is too high to follow the variation of the Lorentz force double-frequency component. The aim of this paper consists in investigating the effect of the double-frequency Lorentz force on the stirring process, for a range of frequencies lower than the main one ($f < 50$ Hz). Two numerical simulations of the stirring effect are carried out on the same setup: the former simulates the electromagnetic stirring effect under the influence of the averaged Lorentz force only; the latter calculates the real distribution of the Lorentz force (sum of the average and double-frequency components) to simulate the stirring effect. Flow field within the molten metal is qualitatively and quantitatively compared in the two cases. Numerical simulations are finally validated through experimental activities: instantaneous velocity of the flow is measured along the crucible axis. The investigated setup consists on a laboratory-scale, cylindrical vessel, containing Galinstan and velocity of the flow is practically measured thanks to a UDV probe, fixed on the same axis direction.

II. Experimental Setup and Simulation Strategy

A. Experimental setup

The experimental setup consists of a cylindrical vessel containing GaInSn, an eutectic alloy, already molten at the ambient temperature. Thanks to its properties (Tab. 1), GaInSn melt has been widely applied in the experimental investigation of electromagnetic stirring [2]: its low-melting point allows direct measurement of the flow field generated inside of it. The vessel, made of plexiglass, is 240 mm long and has a radius of 31 mm. The vessel is surrounded by a cylindrical, 6-turns copper inductor, with a radius of 61 mm. Three-phase power is supplied to the inductor and each phase consists therefore of two turns: phase sequence starts from the bottom, with phase A, and goes to the top, with a final phase C. Current supplied to each phase of the inductor has the same magnitude of $I_{rms} = 200$ A, and it is shifted by 120 electrical

Ga 68%, In 20 %, Sn 12 %		
Parameter	***Notation***	***Value***
Density, kg/m^3	ρ	6440
Dynamic viscosity, Pa·s	μ	0.0024
Thermal conductivity, W/(m·K)	λ	16.5
Melting temperature, °C	T	- 19
Electric conductivity, S/m	σ	3.46·10^6

Tab. 1 Properites of GaInSn melt at ambient temperature (20 °C)

degrees between subsequent phases. Working frequency represent the only electrical parameter of the investigation: frequency values of f = [2, 5, 10, 15, 25, 50] Hz are selected to investigate the stirring effect within the molten metal. In the experimental activity, velocity of the flow is measured along the axis of the melt volume with the help of a Ultrasound Doppler Velocity meter (UDV). This probe allows to achieve velocity distribution along the crucible axis with a sampling time of 300 ms, to be compared with the instantaneous velocity calculated in the related numerical simulation.

B. Simulation Strategy

The numerical FEM model is based on coupled EM and HD simulation: electromagnetic results are carried out with ANSYS Mechanical APDL, while the hydrodynamic simulation is performed with ANSYS Fluent. A 2D-axisymmetric model is realized, and two different approaches are chosen to carry the simulations out: the former EM solution is harmonic and calculates only the average Lorentz force distribution within the melt; double-frequency component of the force is therefore neglected. The latter performs a time-dependent EM solution, and real force distribution is calculated with a step of 12 electrical degrees. Both EM simulations are subsequently coupled with a time-dependent HD simulation. In this last case, k-ε model is applied, since the flow is supposed to be fully turbulent. Free surface of melt is fixed, since magnitude of the force density is low enough to produce no significant variation in the surface shape. Flow field distribution over time is plotted in the two cases, and velocity magnitude along the axis is calculated. Maximum velocity of the flow is finally analysed within the entire melt volume. Total HD simulation time is 25 s, since it represents a correct compromise between computational cost of the simulation and steady-state FD regime of the flow.

C. Lorentz force calculation in the two simulation cases

Lorentz force that emerges from inside the melt upon the application of an alternated magnetic field is expressed as

$$\vec{f}em = \vec{J} \times \vec{B}, \qquad (1)$$

where $\vec{J}\ (\frac{A}{m^2})$ is the current density, and $\vec{B}\ (T)$ the magnetic induction field.

This force can be split in two components: an average component, constant over time, and a time-dependent force, oscillating with a frequency equal to the double of the main Velocity field within the molten metal, generated by the TMF: on the left, velocity isovalues within the melt in m/s;

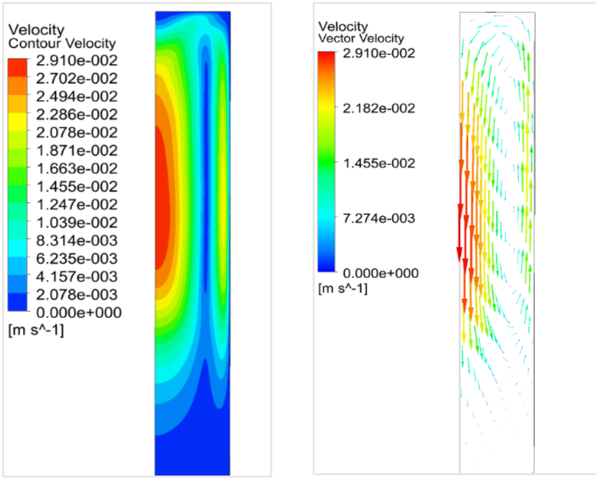

Fig. 1. Velocity field distribution within the molten metal, at the working frequency of f = 15 Hz. On the left, velocity isovalues in m/s; on the right, vector velocity field in m/s. Travelling Magnetic Field generates a unique toroidal vortex inside the melt.

on the right, the related vector field in m/s. Working frequency is f = 15 Hz.

In the hypothesis of harmonic regime, current density and magnetic induction field can be written in the following way:

$$\vec{\boldsymbol{J}}(t) = \sqrt{2} \cdot J \cdot \sin\left(\omega t + \gamma\right), \qquad (2)$$

$$\vec{\boldsymbol{B}}(t) = \sqrt{2} \cdot B \cdot \sin\left(\omega t + \beta\right), \qquad (3)$$

with J, B – RMS values of the current density and magnetic induction field, γ, β – initial phase of the current density and the magnetic induction field respectively.

In this way, average component of the force can be explicated as

$$\vec{f}em, avg = 0.5 \cdot J \cdot B \cdot \cos\left(\gamma - \beta\right), \qquad (4)$$

while double-frequency oscillating component

$$\vec{f}em, 2\omega = 0.5 \cdot J \cdot B \cdot \cos\left(2\omega t + \gamma + \beta\right). \qquad (5)$$

III. PRELIMINARY RESULTS

Preliminary analysis in the two simulation cases evidences the same qualitative distribution of the velocity field: a unique, toroidal vortex is generated in both cases (see Fig. 1), for all of the frequency values in the considered frequency range. Maximum velocity of the flow, though, is expected to be higher when double frequency component of the force is implemented; difference between the two simulations is expected to be more evident for lower frequency values.

REFERENCES

[1] D. Musaeva, E. Baake, A. Köppen and P. Vontobel, “Application of Neutron Radiography for In-Situ Visualization of Gallium Solidification in Travelling Magnetic Field” Magnetohydrodynamics, vol. 53 (2017), No. 3, pp. 583–593.

[2] D. Musaeva, V. Ilyin, V. Geža, E. Baake, “Experimental investigation of low-frequency pulsed Lorentz force influence on the motion of Galinstan melt” St. Petersburg Polytechnical University Journal: Physics and Mathematics, 000 (2016), pp. 1–8