Liquid metal flow generating by unsymmetric traveling magnetic field

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***Abstract*—The object of present work is a investigation of inductor currents parameters influence on a liquid metal flow. The investigation was carried out using the finite element method. Verification was performed using experimental data.**

The aim of this work is to obtain the flow dependence on the asymmetry coefficient of the three-phase currents, which will predict the flows of liquid metal in the cell at a significant asymmetry of the windings or current source.

***Index Terms*—Finite element analysis, Electromagnetic forces, Magnetohydrodynamics, Gallium alloys.**

I. INTRODUCTION

Electromagnetic stirring is widely applied technique in modern industry, successfully used in casting of ferrous and non-ferrous alloys [1], because it can help to enhance heat and mass transfer in liquid metals. That phenomenon promotes grain refinement, avoiding segregation and consequently increases mechanical properties of casting production.

The source of the magnetic field for this type of application is a travelling magnetic field inductor. However, this type of electromagnetic device is often cause asymmetry of supply currents as shown in work [2]. This asymmetry can result in nonuniform Lorentz forces a more complex flow pattern. This phenomenon is insufficiently investigated, in this article it is suggested to study more closely and to consider at the influence of phase shift and current magnitude on the flow pattern. So we want to investigate hypothesis that asymmetrical inductor currents cause ununiform forces in the melt, resulting in more unstable flows that can improve heat transfer.

Thus, the goal of research is to investigate a wide range of asymmetry coefficients and determine the character of instability.

II. EXPERIMENTAL SETUP

The investigated installation is shown at Figure 1. The source of TMF is a linear induction machine consists of 6 coils that are supplied by a controllable 3-phase source Pacific Smart Source 360 ASX-UPC3. The magnetic flux is going through the magnetic core and penetrates into the GaSnZn alloy. The frequency of the supply current is 50 Hz. Induced current density occurs into metal under the influence of TMF. The product of this current and magnetic flux is the Lorentz forces. That forces impacts on a GaSnZn volume and lead to move a liquid part of metal. The description of setup in more detail is given in [3].

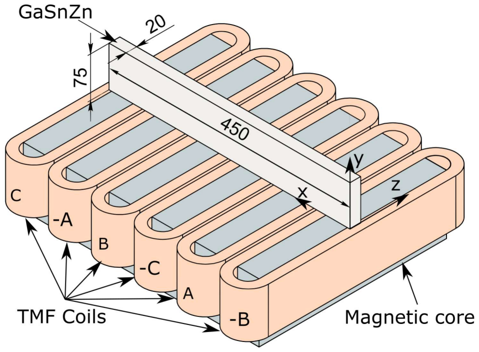

Fig. 1. Experimental setup.

III. METHODS

3D numerical calculations were carried out by the finite element method using the Comsol Multiphysics software.

Under the assumption of low magnetic Reynolds number ($Re_m = 0.065$), induction-free approximation was used, therefore, it is possible to divide the calculation into two parts, taking into account the rigid body approximation, electromagnetic and hydrodynamic, the forces from the first stage are transferred into second:

At the first stage for electromagnetic calculations we used the Maxwell equations, which were formulated in terms of the magnetic vector potential. The calculations of the magnetic field, induced current and Lorenz force distribution were made with the use of the Magnetic Fields interface.

Analysis of magnetic saturation showed that the magnetic core saturates at 25 A and more [4]. Therefore, the magnetic permeability was specified by a constant $\mu = 150$. The coil was a homogenized multi-turn coil, whose winding consisted of 170 turns of copper wire. To validate numerical results the magnetic flux density was measured by Hall effect sensor above the linear induction motor surface. The electromagnetic force acting on a liquid metal was calculated as $\mathbf{f}_{EM} = \mathbf{J} \times \mathbf{B}$, where $\mathbf{B}$ is the magnetic flux density and $\mathbf{J}$ is the induced current density.

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Supply currents are described using the method of symmetrical components, taking into account the following assumptions:

$$\begin{cases} \mathbf{I}_a = \mathbf{I}_{a1} + \mathbf{I}_{a2} + \mathbf{I}_{a0} \\ \mathbf{I}_b = \alpha^2 \mathbf{I}_{a1} + \alpha \mathbf{I}_{a2} + \mathbf{I}_{a0} \\ \mathbf{I}_c = \alpha \mathbf{I}_{a1} + \alpha^2 \mathbf{I}_{a2} + \mathbf{I}_{a0} \end{cases} \qquad (1)$$

$$\mathbf{I}_a = \mathbf{I}_{a0} + \mathbf{I}_{a1} + \mathbf{I}_{a2} = const, \frac{\mathbf{I}_{a2}}{\mathbf{I}_{a1}} = var, \frac{\mathbf{I}_{a0}}{\mathbf{I}_{a1}} = var \qquad (2)$$

where $\mathbf{I}_a$, $\mathbf{I}_b$, $\mathbf{I}_c$ is the phase currents respectively, $\mathbf{I}_{a0}$ is the zero sequence current, $\mathbf{I}_{a1}$ is the positive sequence current, $\mathbf{I}_{a2}$ is the negative sequence current and α is the phasor rotation operator equal $e^{\frac{2}{3}\pi i}$

At the second stage the calculation of hydrodynamics was carried out by Navier-Stokes equations, using k-ϵ turbulence model, walls are considered as no-slip condition, top surface was set as slip. The low melting point Ga based alloy was used as a working fluid, its temperature-dependent properties within the range of 323 to 823 K [5] are listed in the Table I.

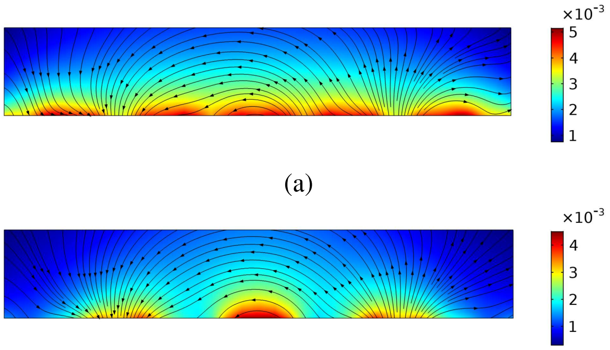
TABLE I
PHYSICAL PROPERTIES LIQUID GASNZN

Property	Value	Unit
Conductivity	3560000-4130·T+2.82·T^2	S·m^{-1}
Density	6332-0.610·T	kg/m^3
Surface tension	0.71648-0.074·10^{-3}·T	N^{-1}
Dynamic viscosity	0.000376·exp(3824.3/(8.314·T))	Pa·s

IV. RESULTS

Figures 2-3 show the results obtained for the symmetric case (a) and for the case $I_{a2}/I_{a1} = 0.5$ (b). As can be seen, asymmetric distribution of currents in a windings lead to distortion of the magnetic field, which causes flow fluctuations. Further consideration of the conditions of instability occurrence can help to control the flows.

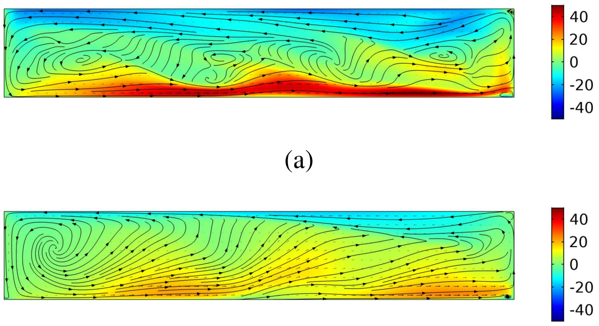
As a result the dependence of current asymmetry parameter on intensity of flow and pattern is obtained.



(a)

(b)

Fig. 2. Distribution of magnetic flux density (T) at symmetrical power supply (a) and $I_{a2}/I_{a1} = 0.5$ (b)



(a)

(b)

Fig. 3. Instantaneous velocity (mm/s) at symmetrical power supply (a) and $I_{a2}/I_{a1} = 0.5$ (b)

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