ELECTRO VORTEX FLOWS IN HEMISPHERE VOLUME WITH DIFFERENT BOTTOM ELECTRODE POSITIONS

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Abstract: This paper devoted to the theoretical and experimental investigation of isothermal electrovortex flows of liquid metal in hemisphere volume with top and bottom electrodes. It is shown that changing bottom electrode position significantly change velocity and structure of electrovortex flows through the liquid metal volume. This results can be used in numerous industrial applications, especially in metallurgical applications such as DC arc furnace with bottom electrode.

1. Introduction

The theoretical and experimental investigation of electro vortex flows (EVF) in hemisphere volume with different geometrical parameters has both theoretical and applied value, especially for numerous metallurgical application such as DC arc furnaces with bottom electrode, electro-welding, etc [1-3]. This work devoted to the numerical and experimental modelling of EVF in hemisphere volume with two electrodes: top and bottom. The bottom electrode in this work set up in different positions.

2. Presentation of the problem

The generalize installation with hemispherical volume of liquid metal presented in Fig. 1. The main parts of the installation are insulator, liquid metal, top and bottom electrodes, air above the installation.

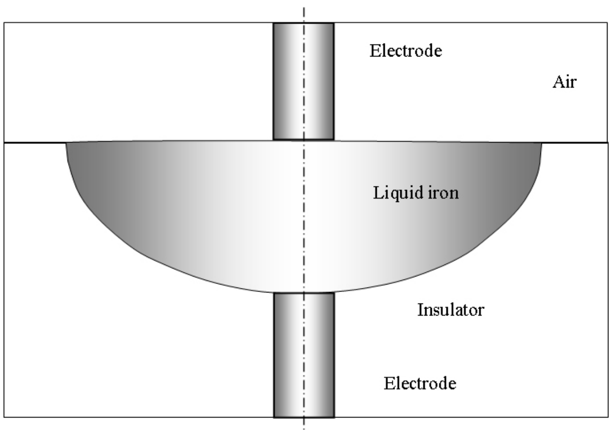

Figure 1: The arrangement of hemisphere installation with two electrodes.

To build a mathematical model of the processes in this installation let us take the following assumptions: the medium is considered non-magnetic; the medium is a good conductor and its permittivity can be neglected; convective current, caused by the medium movements compared to the current of conductance, can be neglected; physical characteristics of the medium (conductance, viscosity and heat-conduction indexes, etc.) are assumed to be homogeneous and isotropic and do not depend on temperature and pressure; medium heating caused by viscosity (viscous dissipation of energy) can be ignored.

The processes are rather slow and can be described in quasi-steady or just steady formulation. For steady processes the system of equations of magnetic hydrodynamics, describing the molten metal flows in this installation is as follows:

momentum equation

$$(\vec{u}\nabla)\vec{u} = -\frac{1}{\rho}\nabla p + \nu\Delta\vec{u} + \vec{g} + \frac{1}{\rho}\vec{j}\times\vec{B} \quad (1)$$

equation of continuity

$$\nabla\cdot\vec{u} = 0 \quad (2)$$

Maxwell's equations

$$\nabla\cdot\vec{B} = 0;\nabla\times\vec{H} = \vec{j}; \quad (3)$$

$$\nabla\times\vec{E} = 0;\nabla\cdot\vec{D} = \rho_e; \quad (4)$$

Ohm's law for fluid in motion

$$\vec{j} = \sigma(\vec{E} + \vec{u}\times\vec{B}); \quad (5)$$

charge conservation law

$$\nabla\cdot\vec{j} = 0; \quad (6)$$

where: $\vec{u}$ - liquid velocity, ρ - density, p - pressure, $\vec{g}$ - gravitation, ν - coefficient of kinematics viscosity, $\vec{j}$ - current density, $\vec{B}$ - magnetic induction intensity vector $\vec{B} = \mu\mu_0\vec{H}$, $\vec{H}$ - magnetic field vector, σ - specific conductance, ε_0 и μ_0 - electrical and magnetic constant, $\vec{E}$ - electrical field intensity, $\vec{D}$ - electric induction, $\vec{D} = \varepsilon\varepsilon_0\vec{E}$, ρ_e - volume density of electric charge. The following forces are considered in the equation (1): $-\rho^{-1}\nabla p$ - pressure force, $\nu\Delta\vec{u}$ - force of viscous drag, $\rho^{-1}\vec{j}\times\vec{B}$ - Lorentz electromagnetic force.

The problem was solved with the following boundary conditions:

– for electric field

$$\vec{E}_1\times\vec{n} = \vec{E}_2\times\vec{n},\ \vec{D}_1\times\vec{n} = \vec{D}_2\times\vec{n}; \quad (7)$$

– for magnetic field

$$\vec{B}_1\times\vec{n} = \vec{B}_2\times\vec{n},\ \vec{H}_1\times\vec{\tau} = \vec{H}_2\times\vec{\tau}; \quad (8)$$

– for current density on boundary with insulated and normal cross-section of electrode

$$\vec{j}\times\vec{n} = 0,\ j = j_0. \quad (9)$$

where: $\vec{n}$ - normal vector, $\vec{\tau}$ - tangential vector, j_0 - initial current density.

– for hydrodynamic parameters no-slip boundary condition was used for hydrodynamic processes at boundaries with solid walls and slip boundary condition on free surface. Mathematically it means that velocity and turbulent components for no-slip boundary condition were all set to zero

$$u = 0, v = 0, w = 0, k = 0, \varepsilon = 0.$$

For the simulation of flow in wall region the universal logarithmic law was applied

$$\frac{\rho u_p k_{const}^{1/2} C_\mu^{1/4}}{\tau_w} = \frac{1}{k_{const}}\ln(Ey^+),$$

where $y^+ = \frac{y_p k_{const}^{1/2} C_\mu^{1/4}}{\upsilon}$, $E_{const} = 9.79$ - empirical constant, $k_{const} = 0.42$ - Von Karman's constant, τ_w - shear stress on the wall, y_p – resultant velocity of the fluid near the wall, y^+ - dimensionless normal distance from the resultant velocity, y_p - distance of the first node point p from the wall. For slip boundary condition normal component of velocity will be set to zero $u_n = 0$.

For all types of analysis on the axis of symmetry of the calculation domain the following condition were used:

$$\frac{\partial u}{\partial y} = 0, \frac{\partial w}{\partial y} = 0, \frac{\partial k}{\partial y} = 0, \frac{\partial \varepsilon}{\partial y} = 0.$$

The problem in question has no analytical solution and, therefore, it was solved numerically. As a result of the numerical solving methods analysis the ANSYS system were chosen. The problem belongs to the class of multiphysics and the strategy of solution consists of the following stages:

1st stage – solving electromagnetic fields;

2nd stage – solving EVF.

This consecutive order of solving this problem is due to the specialty of solving multiphysics problems in ANSYS. The result of electromagnetic field modelling is the value of electromagnetic force and other electromagnetic parameters, obtained for every nodal point in terms of liquid metal volume. To determine velocity of liquid metal produced by electromagnetic effect the distribution of electromagnetic force as the initial condition can be used at the next 2nd stage. At this stage it is necessary to check how motion of metal changes all electromagnetic parameters. Taking into account all these factors and repeating this algorithm to achieve the precision of the results, we obtain the velocity distribution with the closest correspondence to the experimental data.

The turbulent EVF was simulated with taken into account $k - \varepsilon$ turbulence model, that tested for the same vortex flow in laboratory installation. The obtained results in $k - \varepsilon$ turbulence model for this installation correlate with the experimental data within 15% limits [1-2]. That is why the further calculations are carry out with taking into account $k - \varepsilon$ turbulence model. The comparisons of the experimental and numerical results are given in Fig. 2.

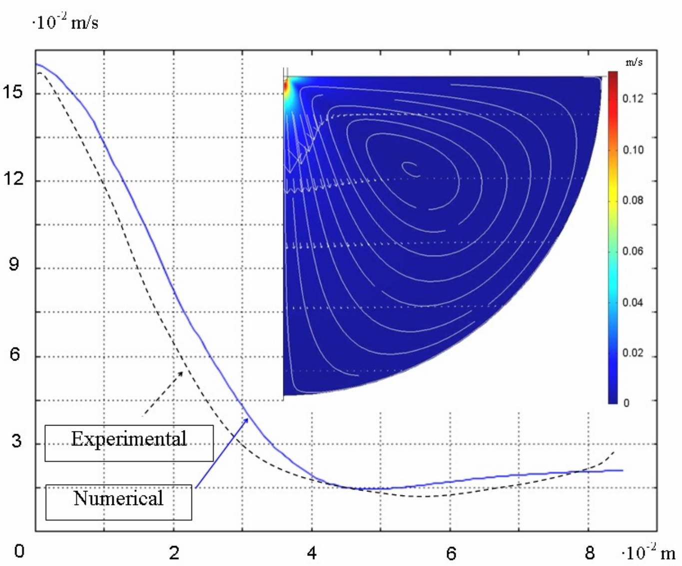

Figure 2: Numerical and experimental results for the laboratory unit.

Some results of simulation the processes proceeding in liquid metal are given below. Fig. 3 demonstrates the fields of the rotor Lorentz force near the bottom electrode (anode), where 1 – insulator, 2 – liquid metal, 3 – bottom electrode. The value of Lorentz force ranged and comprised about 30% of volumetric gravity force. The results of the calculations prove the fact that the Lorentz force in such furnaces is essential for the appearance of EVF.

At the next stage, according to the solution strategy, the hydrodynamic processes in liquid metal were simulated taking into account the electromagnetic parameters in axial symmetry formulation. In Fig. 4 the hydrodynamic fields of velocity vector, contour and streamlines are given. The figure demonstrates that the higher intensity of vortex flows appears in liquid metal volume. The vortex arises near the bottom electrode, as Fig. 4 shows. The vortex flow of liquid metal on axis of symmetry is directed upwards. When the flow achieves the upper boundary of liquid metal, it comes along the boundary and comes down. The maximum value of the vortex flow velocity was located on the axis of symmetry and reaches 0.3 m/s. The vortex flow velocity value in close proximity to the bottom electrode comprises about 0.1 m/s. According to the figure, at the top electrode area the inverse vortex flow appears. This vortex is produced by the uneven distribution of current density near the top electrode.

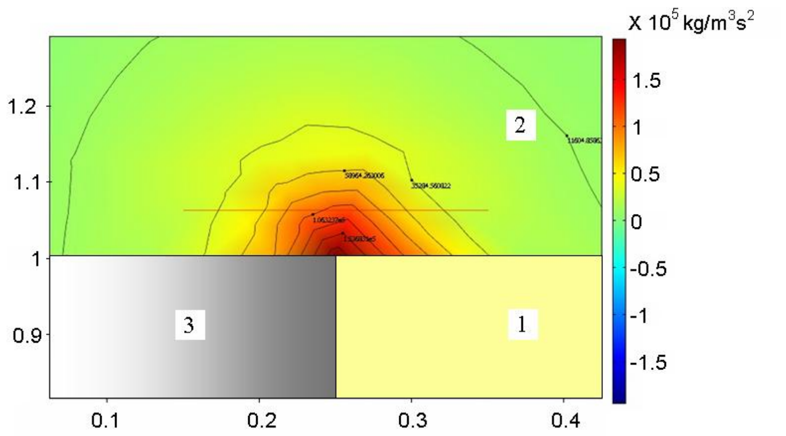

Figure 3: Rotor Lorentz force near the bottom electrode (1 – insulator, 2 – liquid metal, 3 – bottom electrode).

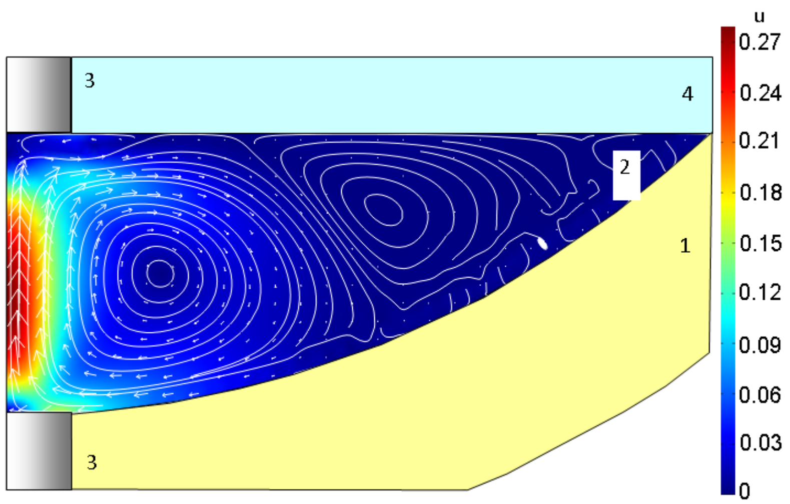

Figure 4: The vector, contour field and streamlines of vortex flow velocity (1 – insulator, 2 – liquid metal, 3 – electrodes, 4 – air).

It is shown that lifting the bottom electrode above the surface by the electrode radius value leads to the decrease of shear stress on the fettle area by 30%, while bottom electrode lower than the insulator surface by the electrode radius value and expanding it by the same value reduce the stress – by 10%.

The verification of the obtained results has shown a good correlation with the general theoretical data concerning EVF, the results obtained by other authors, as well as a good correlation with the experimental data for laboratory installations. All of that has proved the reliability of the methods and approaches, as well as the accuracy of the obtained results.

3. Conclusion

The physical and mathematical model of processes proceeding in hemisphere volume with different bottom electrode positions has been build. To describe the processes in the hemisphere volume the model of the magnetohydrodynamics is adopted. The strategy of solving the stated conjugate problem in commercial software packages is worked out. Numerical modelling of proceeding processes in liquid metal for hemisphere volume with different bottom electrode positions is carried out. It is established that the volumetric Lorentz force makes up governing contribution to the vortex flow appearance. It is shown that bottom electrode positions changes lead to essential changes of structure and intensive of the EVF velocity. The results of the calculations in ANSYS are compared with the experimental data, calculations in COMSOL, general theoretical conceptions. Similarity of the calculations done by different methods and experimental data proves the reliability of the methods and significance of the results.

4. References

[1] Ivochkin Yu., Oksman A., Kazak O., Teplyakov I., Zhilin V.: Numerical and experimental investigation of the electrovortex flow in hemispherical container under action of external magnetic field, Proc. the 8th International PAMIR Conference on fundamental and applied MHD. Borgo, Corsica, France September 5-9 (2011) 85-88.

[2] Kazak O., Semko O.: Numerical modelling of electrically vortical flows, Proc. the 8th International PAMIR Conference on fundamental and applied MHD. Borgo, Corsica, France September 5-9 (2011) 605-609.

[3] Kazak O. Modelling of vortex flows in DC electric arc furnace with different bottom electrode positions Metallurgical and Materials Transactions B, Volume 44B Number 3 (2013) 1243-1250.