Investigation of vortex flows and electrical discharges forming under the action of external magnetic field in the system with liquid metal

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Abstract. Different kinds of vortices forming under the action of electromagnetic force are considered in the paper. The causes that lead to vortices generation and some attendant phenomena like appearance of electrical discharges are also discussed here.

1. Introduction
Electrovortex flows are the part of many technological processes. For example they take place in the working areas of such industrial facilities as: electro-arc furnaces and reactors in metallurgy and waste recycling, electro-slag remelting and welding apparatus.

Basically the described systems look like the following one: working area is a container filled with electro-conducting material, electric current passes through the melt from a rod electrode towards a volume one, there are systems with an electric arc between the rod electrode and the melt and without the electric arc, the electric current interacts with its own magnetic field and as a result under the action of electromotive body force the electrovortex flow (EVF) is generated in the system (figure 1). The base theory of the classical EVF is presented in \cite{1}. The influence of contact surface deformation on electrovortex flow structure was considered in \cite{2}. It was also found that azimuthal rotation of the melt at the presence of external magnetic field can lead to appearance of additional secondary vortex near the bottom area of the container, which could affect mass and heat exchange processes in the volume. The purpose of the work covered in the current paper is to study formation of the vortices of the liquid metal under the action of the external magnetic field in a hemispherical geometry.

2. Task setup
We investigate the system experimentally and numerically. Experimental setup consists of the following elements (figure 2). The copper hemispherical container of 94 mm radius filled with indium–gallium–tin eutectic alloy serves as a volume electrode. The copper or steel rod electrode with hemispherical tip of 2.5 or 9.4 mm radius is immersed into the alloy. The main physical properties of the In–Ga–Sn are following: melting temperature is 10.5 °C, density is 6482 kg/m\textsuperscript{3},
kinematic viscosity is $4.3 \times 10^{-7}$ m$^2$s$^{-1}$, electroconductivity is $3.3 \times 10^{-6}$ S. Direct electric current passes through the metal. The dc source constructed on the basis of a three-phase rectifier is used to power the system. An electromagnetic coil is set up coaxially to the hemispherical container to create the external magnetic field. Velocity measurements are carried out with the fiber-optic probe developed in our laboratory [3]. The very sensitive element of the probe is a glass construction of several micrometers in size. The probe measures two components of the velocity in the working volume.

Numerical investigations are based on magnetohydrodynamical model in electrodynamical approach, where induction electric current, connected with the movement of electroconducting medium in magnetic field, is neglected. That is true for systems with small magnetic Reynolds numbers, which take place for the task conditions under consideration. As a result it is possible to calculate current density distribution and the own magnetic field inside a hemisphere using analytical expressions. Three-dimensional solenoid is numerically calculated with Biot–Savar law for the determination of the distribution of the external magnetic field in the system. The procedure of the calculation is defined by the results of the preliminary investigations showing that the magnetic field distribution inside the coil influences the time moment of the formation of the secondary vortex. The solenoid geometry in the calculation corresponds to experimental one: radius is 0.15 m, height is 0.14 m, number of turns is 14, upper end face of the coil is situated 0.01 m above the surface of the melted metal. First the current density distribution, own and external magnetic fields and force density are calculated, after that the equation of motion is solved and the force density is a source term on the right-hand side of the equation.
Figure 3. Flow structure in the volume at $I = 100$ A, $B = 7.5 \times 10^{-5}$ T, the central electrode radius is 9.4 mm, time of observation is 30 and 112 s.

Figure 4. Velocity on the axis of the volume at $I = 100$ A, $B = 7.5 \times 10^{-5}$ T, the central electrode radius is 9.4 mm.

Control volume method and SIMPLE approximation scheme of second order accuracy are used to solve three-dimensional non-stationary laminar Navier–Stokes equation. The region of the calculations is the domain bounded by two hemispheres of the same parameters as the test section. The domain consists of 30,300 tetrahedral cells. Border conditions are following: all surfaces, including the free surface of the liquid metal, are solid walls, that is corresponds to reality as the eutectic alloy is covered with thin oxide film during experiments. The ranges of the investigations are from 100 to 1000 A for the electric current value $I$ and from $10^{-5}$ (magnetic field of the Earth) to $5 \times 10^{-4}$ T for the external magnetic field induction value $B$.

3. Results and discussion

After switching on of the electric current due to the current interaction with its own magnetic field under the action of the electromotive body force the intense electrovortex flow forms in the volume and the velocity increases on the axis of the working area getting the values of several centimeters per second for the cases under consideration. The electrovortex flow looks like a toroidal one. At the same time due to the current interaction with the external magnetic field the azimuthal rotation develops in the system. The azimuthal rotation in its turn leads to the
Figure 5. (a) Velocity on the axis of the volume: 1—numerical simulation; 2—experiment; $I = 400$ A, $B = 2 \times 10^{-4}$ T, the central electrode radius is 2.5 mm. (b) Fiber-optic probe: 1—sensor; 2—pointer; 3—light guides; 4—tube; 5—photodiode; 6—photoreceiver.

Figure 6. Regimes of the vortex flows in the system.

The formation of the secondary vortex at the bottom part of the container and the velocity decreases on the axis of the working area. The secondary vortex directs counter to the electrovortex one. As a result a complex flow exists in the volume. It consists of two axially symmetric vortices rotating in opposite directions at the presence of the azimuthal swirling: the secondary vortex of low intensity occupying the bottom part of the volume and the electrovortex flow concentrating mainly at the surface (figure 3). The described structure is confirmed by the velocities distributions in the system. The axis velocity reflects the formation of the secondary vortex (figure 4) and numerical data correspond to experimental ones (figure 5).

Structure, time and place of the formation of the electrovortex flow and the secondary vortex are strongly depends on the electric current and external magnetic field values. It is possible to have several regimes of the flows in the system in dependence on the external magnetic field: the flow with one toroidal vortex at the absence of the external magnetic field, the toroidal vortex with the azimuthal rotation at the relatively low external magnetic field, the electrovortex flow...
with the weak secondary vortex, the weak electrovortex flow with the intensive secondary vortex (figure 6). Moreover, another realization is possible—the oscillatory mode of the structures existence where the intensities of the electrovortex flow and the secondary vortex are alternate.

The curve on figure 7 divides the regions with one and two vortex structures in dependence on the current and external magnetic field values.

The higher the external magnetic field value the earlier the time moment of the appearance of the secondary vortex (figure 8). It is also depends on the electric current value—the lower the electric current, ceteris paribus, the earlier the time moment. The time moment of the generation of the secondary vortex is determined by the time moment of its occurrence regardless of the location in the system. However, the depth of the secondary vortex formation depends on the values of the external magnetic field and electric current which define the thickness of the azimuthally rotating melt layer. The lower the field and the higher the current the deeper the location where the secondary vortex appears.

If electric current is high enough then the following phenomenon is observed. At switching on of a power supply under the action of the electromotive body force, that is the result of the interaction of the electric current with its own magnetic field, the free surface of the melt starts to deform. While deforming the surface takes the complex shape that is concave with
Figure 9. Formation of the constriction under the rod electrode.

a constriction under the rod electrode (figure 9). The shape is defined by the distribution of the electric current density around the hemispherical tip and is due to pinch-effect. The liquid metal constriction contracts, overheats, explodes and as a result the electrical discharge ignites [4, 5].

It is possible to explain the formation of different types of the vortex flows by the following. The electromotive body force acts on a conducting medium in the magnetic field and it is determined by the electric current density. The vortex component of the electromotive body force is characterized by its rotor for quasi-stationary conditions. The rotor of the electromotive body force is defined by the non-uniformity of the magnetic field along the vector of the electric current for our case. The electromotive body force is non-potential one and it can not be stabilized by pressure gradient that is the cause of the vortex flows generation [6]. In our case the mechanism of the vortices formation is similar to the generation of vortex structures at the electric arc movement in the external magnetic field [7, 8].

4. Conclusion
The results of numerical and experimental investigations were discussed in the paper. It was found that the azimuthal rotation of the melt in the external magnetic field leads to the generation of the secondary vortex. It was found that structure, time and place of its formation are strongly depends on the electric current and external magnetic field values. The higher the external magnetic field and the lower the electric current values the earlier the time moment of the appearance of the secondary vortex. Different regimes of the vortex flows forming in the hemispherical volume were obtained. The curve dividing the regions with one and two vortex structures was constructed. From the point of view of practical applications it is possible to conclude the following. The external magnetic fields always exist during technological processes (Earth magnetic field, magnetic fields of surrounding current carrying circuits). As it was shown they decrease the intensity of the vortex flows in the working area, deteriorate mixing in the volume and hence reduce the efficiency of energy deposition. At the same time with the specially designed magnetic systems it seams feasible to control the hydrodynamics, to enhance the intensity of the vortex flows and convective transport processes. All that can help to get the optimal regimes increasing the power efficiency of industrial facilities.

Acknowledgments
The reported study was funded by the Russian Science Foundation, grant No. 14-50-00124.

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