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PHYSICS

Effect of the Earth's Magnetic Field on the Electric-Vortex-Flow Structure

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Abstract—The results of numerical and experimental study of the effect of the Earth's magnetic field on the electric-vortex flow of liquid metal in a hemispherical container are presented. It is found that the combination of toroidal flow and azimuthal force caused by the interaction of an electric current flowing through the liquid metal with a relatively weak external magnetic field leads to an intense twist of the fluid. This effect can be observed, for example, in electrometallurgical aggregates.

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INTRODUCTION

When a nonuniform electric current of density **J** flows through the liquid-metal bulk (a similar process is characteristic for electrometallurgical technologies), a bulk force **F** = **J** × **B** arises as a result of the interaction of this current with the intrinsic magnetic field **B**, which puts the fluid in motion and leads to the formation of the so-called electric-vortex flow (EVF). In the industry, intense EVFs, which are observed, for example, in an electric arc or electroslag remelting of metals [1], can contribute to the enhancement of heat–mass exchange processes and improve the quality of products. It is assumed that, under natural conditions, EVFs could be the cause of the formation of hydrodynamic structures similar to tornadoes.

Among different lines of investigating the EVF properties, there is a separate problem of studying the causes of the spontaneous azimuthal twist of the axisymmetric EVF formed during the spreading of an electric current from a point source to the bulk of an electrically conductive fluid. This phenomenon, which is similar to the effect of the formation of a spiral funnel (vortex) on the surface of a bath during the flow of water, was described in [2], which presents the results of experiments in a hemispherical container filled with mercury. The results of observations of the state of the surface showed that mercury without apparent causes begins to rotate in the horizontal plane at a current $I = 10$ A; i.e., there is a spontaneous azimuthal twist of the fluid. No reliable explanation of the causes for generating such a rotation in an axisymmetric system is given in [2].

At the end of the last century, the scientific literature described certain possible causes of this phenomenon, which caused a lively discussion among specialists in liquid-metal MHD flows. An original hypothesis devoted to the explanation of the twist mechanism is presented in [3], where it was shown on the basis of analytical and numerical estimates that, for a certain EVF type with axial symmetry, even under conditions of small values of the Reynolds magnetic number, the MHD-dynamo effect is possible. A number of other authors (see references in [2]) associate the occurrence of this twist with the action of body forces caused by the Earth's rotation or external electromagnetic fields. It should be noted that the experiments in which the twist was observed were carried out under conditions of the practical absence of the effect of magnetic fields generated by a current flowing along a current guide on the EVF. However, the problems related to the force interaction of the electric current flown through the liquid-metal bath with the Earth's magnetic field (MF) or the twist under the action of the Coriolis force have no adequate elucidation in the scientific literature.

EXPERIMENTAL INSTALLATION AND MEASUREMENT METHOD

The experimental investigations were performed on the installation schematically shown in Fig. 1. The working part was a hemispherical vessel made of copper with a diameter of 188 mm, the frame of which served simultaneously as a large electrode. The eutectic indium–gallium–tin alloy with a weight content of

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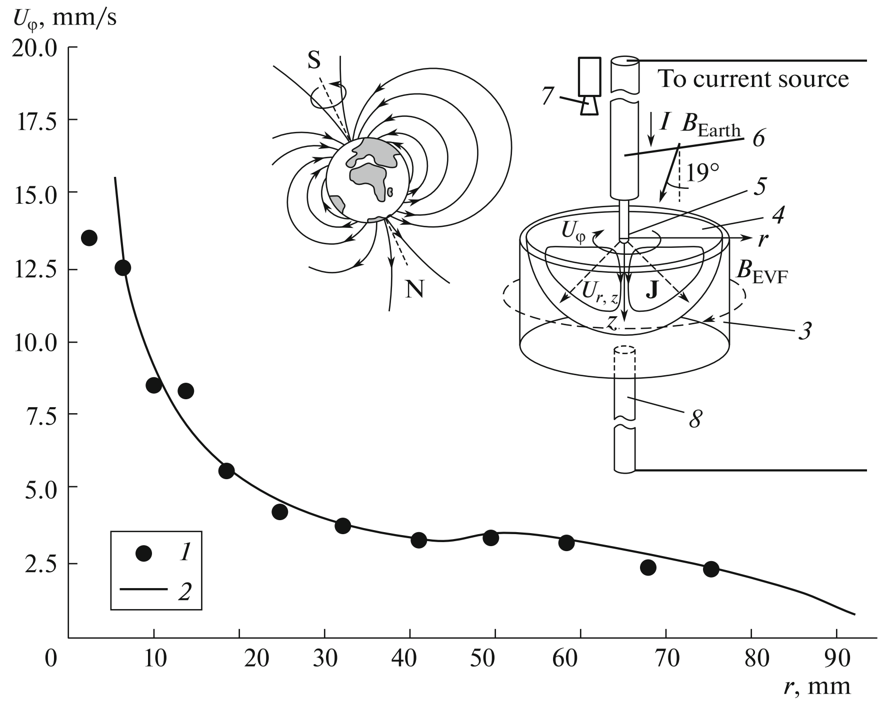

Fig. 1. Dependence of the velocity of a liquid-metal twist at the surface on the radius and the scheme of the installation. $I = 40$ A, $d_{el} = 0.55$ mm. *1*, calculation; *2*, experiment; *3*, container (large electrode); *4*, eutectic alloy In–Ga–Sn; *5*, small electrode; *6*, *8*, current leads; and *7*, camera.

67% for Ga, 20.55% for In, and 12.5% for Sn was used as the working fluid filling the container volume. The physical properties of the alloy are given in [4].

The small electrode was a copper cylinder with the hemispherical end located in the center of the container and immersed in the melt to a depth of the hemisphere radius of 0.27 mm. The power supply of the stand was provided by a dc source developed on the basis of a three-phase rectifier.

For determining velocities on the alloy surface, we used the method of flow visualization with the help of hydrogen bubbles. For this purpose, the liquid-metal surface was filled with a 3% solution of sulfuric acid, which chemically reacted with the melt and was accompanied by the release of hydrogen bubbles. The velocities at the surface of the melt were estimated from the change in the position of individual bubbles in various video shots. For photo and video shooting, we used a Canon 550D camera with a shooting speed of 25 frames per second.

The horizontal portions of the current distributors were removed to a distance sufficient for minimizing the effect of their MF on the results of the investigations. At the same time, the measured MF level (including that of the Earth's MF and of noise) near the working portion did not exceed 60 μT.

METHOD OF NUMERICAL CALCULATION

We solved the unsteady two-dimensional axisymmetric ($\frac{\partial(\cdot)}{\partial\varphi} = 0$, $U_\varphi \neq 0$) set of equations of motion and continuity in cylindrical coordinates

$$\rho\left(\frac{\partial \mathbf{U}}{\partial t} + (\mathbf{U}\nabla)\cdot\mathbf{U}\right) = -\nabla p + \rho\nu\Delta\mathbf{U} + \mathbf{F}_{el}, \qquad (1)$$

where $\mathbf{U}$ and U_φ are the instantaneous velocity vector and its azimuthal component, p is the pressure, ν and ρ are the kinematic viscosity and the fluid density, and $\mathbf{F}_{el}$ is the Ampere force. The direction of the coordinate axes is shown in Fig. 1. The two-dimensional calculation region consisting of 5000 quadrangular elements was a quarter of the ring circumscribed by the inner and outer radii, which corresponded to the sizes of the large and small electrodes, as well as by the free surface of the melt and the axis of symmetry.

The calculation was carried out in the electrodynamic approximation; i.e., the effect of the magnetic-field action on the velocity field was implemented by adding the force $\mathbf{F}_{el} = \mathbf{J} \times (\mathbf{B}_{EVF} + \mathbf{B}_{Earth})$ (here $\mathbf{B}_{EVF}$ and $\mathbf{B}_{Earth}$ are the inductions of the Earth's magnetic fields and the spreading electric current with the density $\mathbf{J}$) to Eq. (1) and disregarding the effect of the motion of the medium on the current.

As shown in [5], such an approximation is valid for the values of the parameter of the electric-vortex flow (an analog of the Reynolds number for the EVF) $S =$

$\frac{\mu_0 I^2}{\rho \nu^2} < 10^{12}$. Here, μ_0 is the magnetic constant and I is the total magnitude of the spreading working current. This value of S in terms of actual values corresponds to operating currents up to several tens of kiloamperes.

For an axisymmetric cylindrical configuration, the expressions for the current density and magnetic field in cylindrical coordinates can be found analytically. The expressions for the current density are obvious:

$$J_r = \frac{Ir}{2\pi\sqrt{(r^2 + z^2)^3}},$$

$$J_z = \frac{Iz}{2\pi\sqrt{(r^2 + z^2)^3}},$$

and the expression for the magnetic field can be found from the solution of the Maxwell equation: curl$\mathbf{B} = \mu_0 \mathbf{J}$. Then,

$$B_{\mathrm{EVF}\varphi} = \frac{\mu_0 I(\sqrt{r^2 + z^2} - z)}{2\pi r\sqrt{r^2 + z^2}};$$

the magnetic field of an axisymmetric system has only one component in the cylindrical coordinate system.

According to the Institute of Terrestrial Magnetism and Ionosphere of the Russian Academy of Sciences, the Earth's magnetic field in the Moscow region (Troitsk station) has an average value of B_{Earth} = 52.175 μT and an inclination of 19°. Thus, the z-component of the field that generates the azimuthal force can be written as $B_{\mathrm{Earth}\,z} = B_{\mathrm{Earth}}\cos\alpha$.

As the calculation scheme for solving equations, we used the control-volume method on an unstructured grid. The sticking condition on all solid surfaces and the zero tangential stresses on the open liquid-metal surface were set.

We estimate the forces acting in the liquid-metal bulk (see Table 1) under the conditions of the laboratory installation and for a typical dc arc furnace. The Coriolis force can be estimated as $F_{\mathrm{C}} = 2\rho\omega U$, the force F_{EVF} generated as a result of the interaction of the current with the intrinsic field as $F_{\mathrm{EVF}} = \mu_0 I^2/(4\pi^2 R^3)$, and the force arising as a result of the interaction of the current with the Earth's magnetic field as $F_{\mathrm{Earth}} = IB_{\mathrm{Earth}}/(2\pi R^2)$. Here, U is the characteristic velocity, $\omega = 2\pi\sin\alpha/T$ is the Earth's rotation frequency, α = 55° is the latitude of Moscow, $T = 86\,400\ \mathrm{s}^{-1}$, and R is the characteristic radius of the small electrode. The typical value of the axial velocity is ~0.1 m/s for the laboratory installation and ~1 m/s for the industrial installation.

It can be seen from Table 1 that the Coriolis force is 3–5 orders of magnitude weaker than the remaining forces; therefore, it was disregarded in the calculations.

Table 1. Forces acting in the liquid-metal bulk, N/m^3

Conditions	F_{EVF}	F_{Earth}	F_{C}
I = 40 A, In–Ga–Sn	2.5×10^6	4×10^3	8×10^{-2}
I = 10 000 A, steel	1.6×10^6	4×10^2	8×10^{-1}

RESULTS

The experiments carried out showed that, after the current was switched on, the stable azimuthal rotation of the melt, which was clearly visible to observers, arose spontaneously near the small electrode within about five minutes and was accompanied by deformation of its surface [6]. In Fig. 1, we present the experimental and calculation data on the dependence of the velocity of the liquid-metal twist, which is caused by the Earth's MF, on the distance to the small electrode. It is seen from the graph that the azimuthal velocity on the melt surface exceeds 1 cm/s, and the experimental and calculation values of U_φ are in good agreement with each other.

The following three important circumstances should be noted. First, such relatively large values of the rotational speed are caused precisely by a combination of the azimuthal twist of the melt with its motion in the vertical plane, which looks like a toroidal vortex, which converges on the surface of the small electrode and is directed downward from it to the depths of the bath. The calculation of the velocity field without components of the electromagnetic force generating such a toroidal vortex leads to significantly lower (by an order of magnitude) values of the azimuthal velocity. Second, as shown in [7], the appearance of the twist can lead to a cardinal hydrodynamic reconstruction of the flow caused by the transition depending on the regime process either to the multivortex EVF structure or to the almost complete suppression of this toroidal electric-vortex flow by the secondary vortices, which are caused by the azimuthal rotation of the melt. Third, the presented analysis of publications shows that this is probably the first direct experiment proving the effect of the Earth's magnetic field on the EVF.

We consider in more detail the question of the possible effect of the Earth's magnetic field on the EVF during welding and in industrial installations such as arc furnaces. Table 2 shows the typical values of certain determining parameters characteristic for the electric welding of metals and their remelting in dc furnaces. The value of the diameter of the current-lead region (the arc spot) according to [8] can be estimated as $\sim 8\sqrt{I}$ (here, the diameter is in millimeters, and the current is in kiloamperes).

The calculation of these parameters with taking into account the action of the Earth's magnetic field showed that an intense azimuthal flow arises in the subelectrode region of the arc furnace with the veloc-

Table 2. Values of certain determining parameters

Parameter	Arc furnace	Welding
Current I, A	10000	200
Size, m	2.5	0.005–0.01
Density of liquid steel, kg/m^3	7000	
Kinematic viscosity, m^2/s	5×10^{-7}	

ity achieving ~0.3 m/s, which can significantly affect the heat–mass transfer processes [9]. During electric welding, the occurrence of azimuthal flow with a velocity on the order of 0.1 m/s is also possible. It should be noted that, in the studies devoted to calculations of arc furnaces [8, 10], this effect is being ignored at the present time.

CONCLUSIONS

The results of the calculations and experiments showed that the electric-vortex flow is extremely sensitive to the actions of the axial magnetic field, while the effect of the spontaneous EVF twisting in the axisymmetric hemispherical container is most likely caused by the interaction of the Earth's magnetic field with the spreading electric current. It can also be assumed that this effect can significantly affect the nature of the MHD and heat–mass transfer processes associated with electric arc welding and the electric remelting of various metals.

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