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Study of the Generation Mechanism of Large-Scale Vortex Motion in Electrically Conductive Media

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Abstract—The purpose of this study is to identify the mechanisms of formation of vortex structures in electrically conductive media under the effect of a magnetic field. An experimental set-up is created, and the selection of electrolytes as model fluids is justified. Procedures are developed for visualization of the processes of vortex formation and for measurement of the flow velocity field. In the experiments, we managed to obtain well reproducible and visualized patterns of a spiral vortex flow resulting in a large-scale swirl. A physical model for the generation of a large-scale vortex motion in electrically conductive fluids is proposed.

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INTRODUCTION

Study of the problems of vortex dynamics, the topological features of vortex structures, and the conditions of their origin, development, and sustainability is of particular interest to various areas of physics (for example, thermal physics, geophysics, or astrophysics), meteorology, and engineering applications. The issues of the formation and development of atmospheric vortices and the laboratory simulation and visualization of tornado-like vortex structures have been studied in a large number of works; among them, the publication by Russian authors should be mentioned [1–4]. In these papers, the focus is on study of the dynamics of the processes of vortex formation in electrically neutral air above an underlying surface heated from below. However, investigations related to the identification of the formation mechanisms of vortex structures in electrically conductive media under the effect of a magnetic field are of great interest. Such studies may be important for the nuclear power industry, namely, for liquid-metal cooled fast-neutron reactors.

Special studies performed with the use of a BN-600 reactor, the results of which are given in [5], showed that in bringing the reactor to operating power, the phenomena of self-excitation of the magnetic field caused by thermoelectric currents were recorded. It is found that the mechanism of self-generation of the magnetic field can lead both to significantly nonstationary pulsation modes of a thermohydraulic circuit and to complete blocking of the coolant flow with the emission of the full power of the circulation pumps released as the Joule loss in the region of self-excitation [5, 6]. This mechanism occurs when the critical values of the defining criteria are exceeded: the magnetic Reynolds number, $\mathrm{Re}_{\mathrm{cr}} \approx 20$, which characterizes the ratio of volume inertial forces and electromagnetic forces, and the Lundqvist criterion, $\mathrm{Lu}_{\mathrm{cr}} \approx 2$, defining the relationship between the energy density of the magnetic field of thermoelectric currents and the kinetic energy density of vortices [6]. Studies of the generation of a magnetic field in the vicinity of the main circulation pumps (MCP) have confirmed the hypothesis that the magnetic field is "frozen-in", that is, the convective transport of the magnetic field has a defining role in the complex vortex flow.

The objective of this study is to investigate the interference of the three factors in the conductive fluid: the static magnetic field, the electric field, and the flow swirl. The presence of two of the three conditions mentioned leads to the appearance of the third. The program of study includes the creation of an experimental set-up, the selection of an electrolyte as a model fluid, and the development of procedures for the measurement and visualization of vortex formation.

EXPERIMENTAL PROCEDURE

Experimental Set-Up

To study the mechanism of generation of a vortex motion in electrolytic media under a constant magnetic field, we created an experimental set-up with a variable geometry of the work area, depending on the configuration of the applied magnetic field. The scheme of the set-up with a spherical magnet is shown in Fig. 1. The main elements of the set-up are magnet *1* creating a constant magnetic field, vessel *4* filled with electrolyte *3*, in which two immersed electrodes are connected to power source *5*, and equipment for photo and video recording *7*. One of the electrodes is a permanent neodymium magnet 0.04 m in diameter

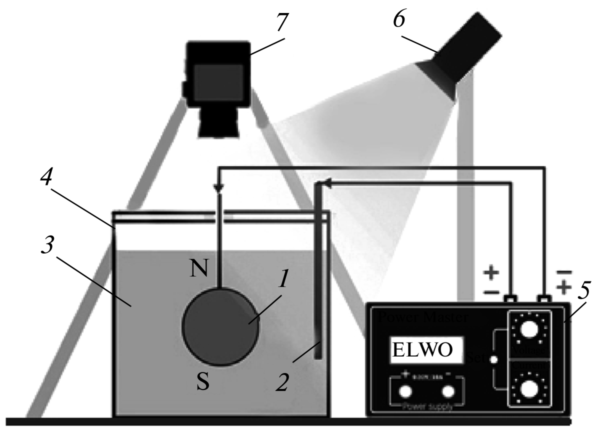


Fig. 1. Scheme of the experimental set-up: (*1*) permanent neodymium magnet, (*2*) movable copper electrode, (*3*) solution of a conductive liquid, (*4*) glass vessel, (*5*) power source with an ammeter and voltmeter, (*6*) light source, and (*7*) recording equipment.

with nickel coating *1*, having a spherical shape. The induction of the magnetic field created by the magnetized sphere, according to its certificate, was 1.3 T.

Movable cylindrical rod *2* made of copper was used as the second electrode. For better visualization of the effects, we selected a glass vessel with an internal diameter of 0.12 m. The applied voltage was adjusted, and the current flowing in the electrolyte solution was measured with the help of power source *5*. The ranges of applied voltage and measured current were 2.2–30.0 V and 0.4–1.0 A, respectively. The effects of vortex formation were recorded using photo or video camera *7* with optional lighting *6*.

Selection of the Electrolyte

One of the key moments in the setting of experiments to study the generation mechanism of vortex motion was the development of a methodology for visualizing the vortex formation. The selection of salt solutions and electrode materials contributing to the conditions for the best visualization of the effects of vortex formation played a major part: they should not cause abundant gas release, significant clouding of the solution by insoluble reaction products, corrosion of the electrode materials, or other effects.

Several salts were considered as options for the preparation of the electrolyte solution: sodium chloride NaCl, copper sulfate $CuSO_4$, ferrous sulfate $FeSO_4$, and glacial acetic acid CH_3COOH. Copper, graphite of nuclear grade, and various iron alloys were studied as electrode materials.

The organized fluid motion observed for all solutions upon an electric current is accompanied by a variety of chemical reactions having different effects on the vortex formation and visualization of flow patterns.

The electrolyte is a second-class conductor; that is, ions are charge carriers in it. In the absence of an external electric field, dissociation and recombination of ions in the electrolyte are competing with each other, maintaining the electrical neutrality of the medium. Upon creating a voltage difference between the electrodes, a directed movement of charged particles occurs. The ions of the solute in water undergo the process of hydration (surrounding by water dipoles); water molecules thus are involved in the movement together with the ions.

During experiments with sodium chloride solutions, copious gas formation was observed at any polarity of the power source, which has an adverse effect on the visualization and hampered study of the resulting effects. The use of copper sulfate $CuSO_4$ ensured stronger currents and relatively high rates of fluid rotation. However, in long-term observations, the presence of the reducing metal made visualization difficult because of abundant formation of flakes in the solution and further clouding. The use of a ferrous sulfate (heptahydrate $FeSO_4 \cdot 7H_2O$) solution led to similar, even more pronounced effects. Acetic acid turned out to be the best electrolyte from the viewpoint of visualization of vortex phenomena.

Solutions of copper sulfate and glacial acetic acid were selected for the experiments. The study of the mechanisms of vortex formation with the use of these electrolytes offers a certain analogy with the processes taking place in liquid metals: acetic acid has a large difference in the weight of oppositely charged ions (the weight of a negatively charged acetate ion CH_3COO^- is 59 times the weight of a positively charged hydrogen ion H^+). In the case of copper sulfate (pentahydrate $CuSO_4 \cdot 5H_2O$), the directional movement of positive copper ions along with associated water molecules $[Cu \cdot 5H_2O]^{2+}$ determines the direction of flow swirling, corresponding to the effects of vortex formation in the motion of liquid-metal coolants under a magnetic field.

Procedure for Measuring the Flow Velocity

By passing an electric current through the electrolyte solution under a static magnetic field, both mechanical effects (swirl) and chemical phenomena (electrolysis and dissolution and reduction of metals) were observed at various positions of the electrodes. The recombination of ions generated in chemical reactions led to the release of gas bubbles at the electrodes, which visualized the resulting effects of vortex formation being engaged in the fluid flow.

The distribution of the fluid velocity was calculated from the measured tracks of individual gas bubbles in the processing of photo and video frames. The size of the gas bubbles was 10^{-5} to 10^{-3} m. In particular, in a series of experiments to determine the velocity distribution of the electrolyte flow in a large-scale vortex motion, a Pentax D200 reflex digital camera with a Sigma 17–70 mm macrolens was used for visualizing the swirl effects; the camera was fixed so that the focal plane of the lens was parallel to the electrolyte surface in the bath (Fig. 1).

In order to obtain quantitative data for determining the radial distribution of the circumferential velocity, namely, the parameters of the track left by gas bubbles in the liquid, the images of the swirling flow were produced with an exposure time on the order of 0.05–0.5 s. Such an exposure was selected, on the one hand, because of the need to obtain the longest track measured in order to minimize the error and, on the other hand, to avoid the possibility of merging the individual tracks because of an excessively high exposure time of the camera. The images were taken at different polarities of the power source and different voltages between the electrodes at a fixed value of the current flowing through the circuit. The resulting images were processed in a graphics-editing program, which measured the lengths of the tracks of indicators and the distance to the center of rotation (Fig. 2a).

Figure 2b presents the circumferential velocity distribution of the fluid flow around the movable electrode arranged at an angle of 54° relative to the equator of the spherical magnet (Fig. 1), which was obtained by processing the experimental data for a solution of acetic acid. As was shown earlier [7], there is a threshold integral swirl parameter, starting from which a self-similar regime of the swirling flow is established. In this regime, the profile of the circumferential velocity can be divided into two regions: region *1* of quasi-solid rotation (or a "forced" vortex) in the center of vortex motion and region *2* of quasi-potential flow (or a "free" vortex, that is, a flow with constant circulation) on the periphery of the vortex (Fig. 2b). The profile of circumferential velocity, demonstrated in Fig. 2b, is consistent with a self-similar form of the profile of the tangential velocity of the swirling flow [7].

The processing of the visualized flow patterns makes it possible to estimate the intensity of the vortex motion, since the angular velocity of rotation ω can be determined from the slope of the curve in the central region of the vortex (Fig. 2b, region *1*) by the equation $\omega = u_\phi(r)/r$. In particular, in the case of vortex motion shown in Fig. 2, the rotational angular velocity of the electrolyte was ω = 2.73 1/s at an applied voltage of 20 V and the measured current value of 0.08 A.

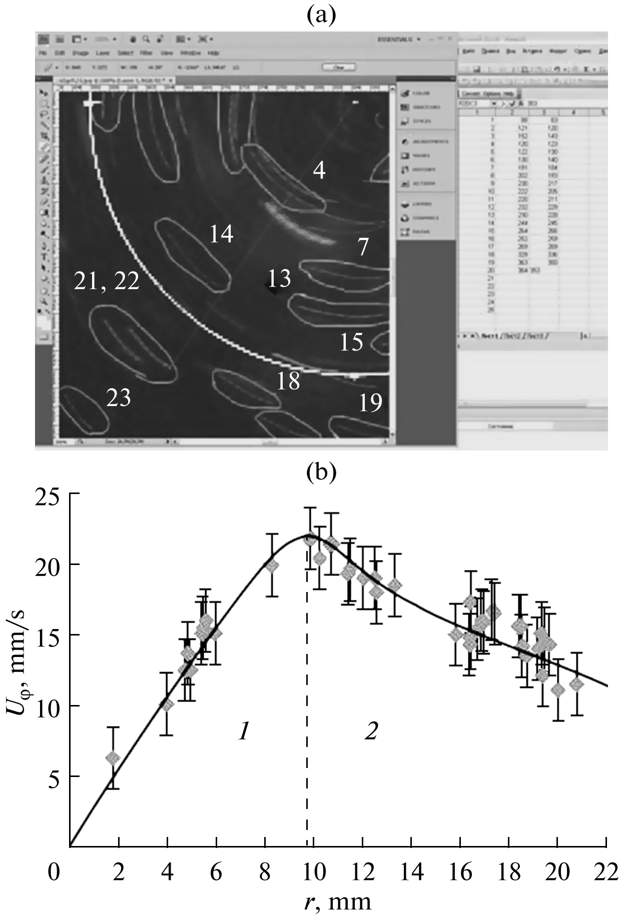


Fig. 2. Determination of the velocity distribution in an electrically conductive fluid: (a) a fragment of the image in the calculation of the track lengths and the distance from the center of rotation and (b) the distribution of the circumferential velocity of the electrolyte flow around the rod electrode in the field of electromagnetic forces.

RESULTS AND DISCUSSION

In the experiments, we used an 8% solution of copper sulfate and a 40% solution of acetic acid. The concentration of copper ions Cu^{2+} generated in the dissociation of $CuSO_4$ in an aqueous solution was 1.9×10^{23} 1/L, and the concentration of acetate ions CH_3COO^- was 1.6×10^{23} 1/L.

The experiments were conducted at different angles of inclination of movable electrode *2* (Fig. 1) with respect to the equatorial plane of the spherical magnet. A stable formation of tornado-like vortex structures with the rotation axis perpendicular to the surface of the spherical magnet was observed when electrode *2* is located in the range of angles from 30° to 80°.

A diagram of the rotation of the liquid and the magnet and the forces acting on Cu^{2+} ions in the solution of copper sulfate at an angle of movable electrode *2* of 90° is presented in Fig. 3. In this case, the effect of the electromagnetic field produced in the electrolytic solution under the voltage supplied from the power source led to a swirl of the entire mass of liquid and/or the spherical magnet. With rigid fixation of the magnet, only the electrolyte rotated. The formation of tornado-like vortex structures in this case is excluded.

The mechanism of the phenomenon observed is connected with the action of the Lorentz force. When creating a voltage difference between the electrodes,

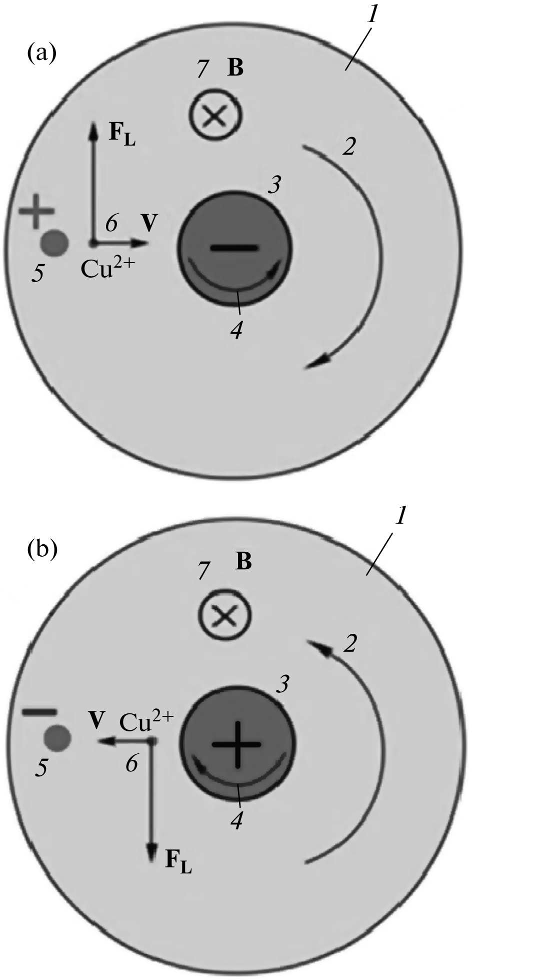


Fig. 3. Direction of rotation of the components of the system for the scheme of the experiment corresponding to Fig. 1, at different polarities of the applied voltage at a (a) negative and (b) positive charge on the spherical magnet; **B**, magnetic induction; $\mathbf{F_L}$, the Lorentz force; **V**, velocity of the ions upon the Coulomb force.

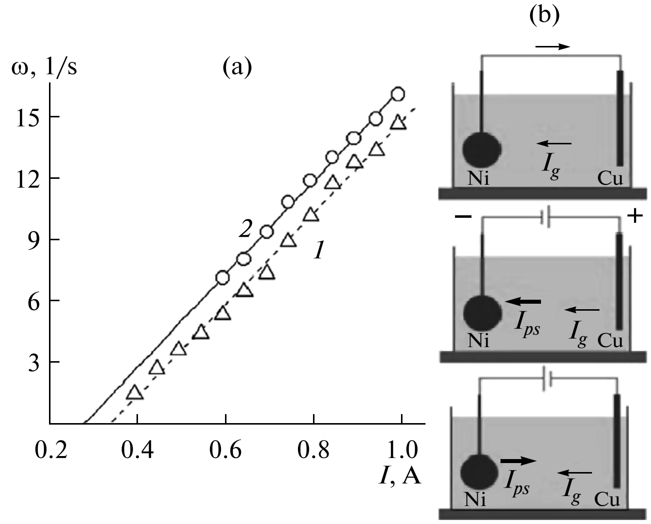


Fig. 4. Rotation frequency of the spherical magnet depending on the current through the circuit and the polarity of the voltage at the power source: (a) experimental data (at a (*1*) positive and (*2*) negative charge at the spherical magnet) and (b) the direction of galvanic current I_g and currents created by the power source in the electrolyte I_{ps} in the case of various polarities.

positively charged copper ions *6* are attracted to the negatively charged sphere under the action of the Coulomb force (Fig. 3a). The vessel with electrolyte *1* is penetrated by magnetic field *7* generated by sphere *3*. The appearance of an electric current in the solution is due to the movement of "heavy" positively charged complex acetate ions of copper $[Cu \cdot 5H_2O]^{2+}$, and in the metal sphere (a first-class conductor), because of the movement of electrons. Ions in the electrolyte and electrons in the metal are affected by the Lorentz force, directed oppositely, which drives the solution or the sphere. With the polarity of the applied voltage changed, the direction of swirl *2* is reversed (Fig. 3b).

When measuring the rotation frequency of the sphere as a function of the current strength and polarity of the power source, the following effect was observed: a change in the polarity of the applied voltage led to a change in the rotation frequency of the magnetic sphere at the same values of voltage and current fixed by the power source. The results of two experiments conducted at different times were identical, which proves the repeatability of the observed effect. The dependence of the rotation frequency of the spherical magnet on the current of the power source at different polarities of the voltage is shown in Fig. 4a.

It follows from the experimental curves presented in Fig. 4a that the plotted curves are equidistant, that is, arranged parallel to each other. In the case of a positive charge at the magnetized sphere, the frequency of its rotation is lower than that for the negative charge.

The explanation of this effect follows from electrochemistry. If two dissimilar metals characterized by different values of the electrode potentials are immersed in an electrolyte solution, constant current I_g appears between them, created by the chemical reactions between the electrode materials and the electrolyte (Fig. 4b). This current is called galvanic, and the electromotive force (EMF) causing the current is equal to the difference between the potentials of composing electrodes $E = E_1 - E_2$, where E_1 is the potential of the oxidant electrode and E_2 is the potential of the reducing electrode. In this case, the copper electrode acts as an oxidant and the nickel coating of the spherical magnet is a reductant. The values of the calculated electrode potentials of the copper and nickel electrodes, based on the concentrations of copper and nickel ions in the electrolyte solution, were $E_1 = 0.32$ V and $E_2 = -0.33$ V, and the EMF of the galvanic current was $E = 0.65$ V.

The component of the Lorentz force, caused by the presence of a galvanic current of constant direction (Fig. 4b), will generate the rotational moment directed in the same direction irrespective of the polarity of the applied voltage. Therefore, if the directions of galvanic current I_g and current from the power source I_{ps} do not coincide, the rotational moment caused by the resulting Lorentz force acting on the unfixed spherical magnet decreases and the intensity of its rotation in the electrolyte decreases.

The statistical analysis of the experimental data shows that by changing the polarity on the power source, the difference in voltage at the same current strength averaged 0.6 V, which is close to the theoretical value for the voltage difference estimated for pure metals (Cu and Ni). The error in this case can be associated with the more complex composition of the materials of electrodes and the changing concentration of Cu and Ni in the solution.

In a series of experiments with changing the position of the movable electrode, tornado-like vortices of varying intensity were observed. The arrangement of electrodes is shown schematically in Fig. 5a.

The measurements were carried out for the movable electrode angles of 0°, 45°, and 60° relative to the equator of the magnetized sphere at the location of the uninsulated part of rod electrode *2* at a distance of 1 cm from the surface of the sphere.

The flow did not swirl around the rod when the movable electrode is set to 0° relative to the equator of the spherical magnet, which is explained by the coplanarity of the vectors of the magnetic field induction and the velocity of the electrolyte ions under the action of the Coulomb force near the surface of the uninsulated part of the movable electrode.

With an increase in the inclination of the movable electrode from the equatorial plane to 30° and above (up to 80°), a well-visualized stable swirling flow occurred around the longitudinal axis of the rod (Figs. 6a, 7a).

The resulting profiles of the circumferential velocity of swirling flow generated in the region of the uninsulated part of the movable copper electrode with an inclination angle of 45° are compared in Fig. 5b for different values of current in the closed circuit loop. The processing of the experimental data according to the above procedure shows that in all cases the radial distribution of the circumferential velocity demonstrates similarity with the self-similar swirling flow [7]; that is, two regions of rotation—quasi-solid and quasi-potential—can be distinguished in each of the profiles. The results presented show that with increasing current strength, angular velocity ω in the central part of the vortex in the region of quasi-solid rotation increases, indicating that the intensity of the large-scale vortex motion also increases with growing electric field strength.

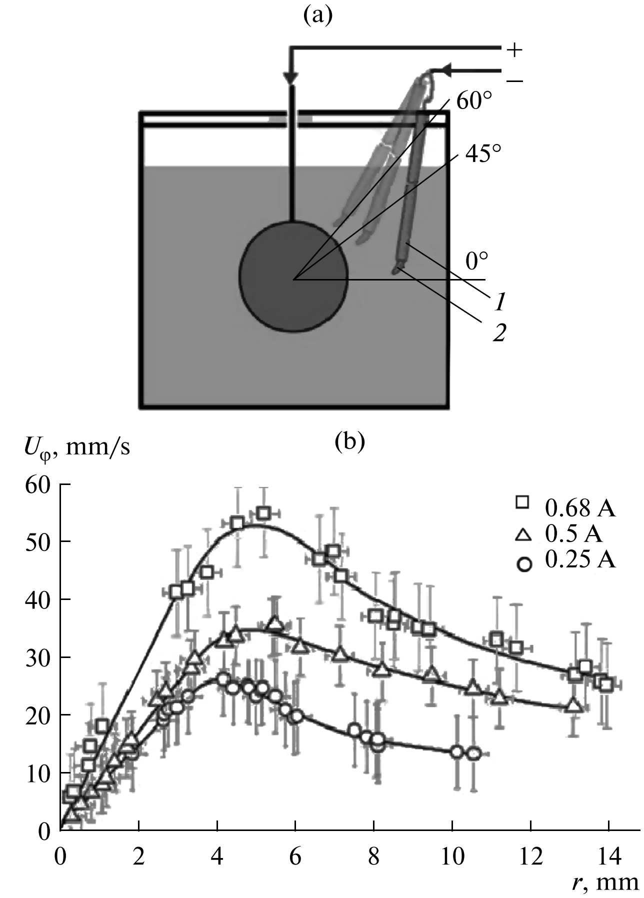


Fig. 5. Experimental measurements with varying the position of the movable electrode and the current flowing through the electrolyte: (a) arrangement of the movable electrode ((*1*) insulated part and (*2*) uninsulated part of the copper wire) and (b) the results of measurement of the profile of the circumferential velocity of the swirling flow at the location of the rod electrode at 45° for different values of the current in the circuit.

The visualized patterns of vortex motion and the processed images of tracks left by gas bubbles in the swirling flow are shown in Figs. 6 and 7 for the same value of current flowing through the electrolyte solution (I = 0.5 A) at various positions of the movable electrode.

The results of experiments on the assessment of the intensity of vortex motion, corresponding to the above cases of generating vortices (Figs. 6, 7), are generalized in the table. The values for angular velocity ω of the electrolyte flow were calculated for the region of quasi-solid rotation, depending on the current strength and the position of the electrode relative to the equatorial plane of the magnetized sphere (Fig. 5a).

Thus, the measurements of velocity fields of the generated vortex motion in solutions of copper sulfate (Figs. 5b, 6b, 7b) and acetic acid (Fig. 2b) showed that the rate of generation of tornado-like vortex motion is maximum at the position of the rod electrode corre-

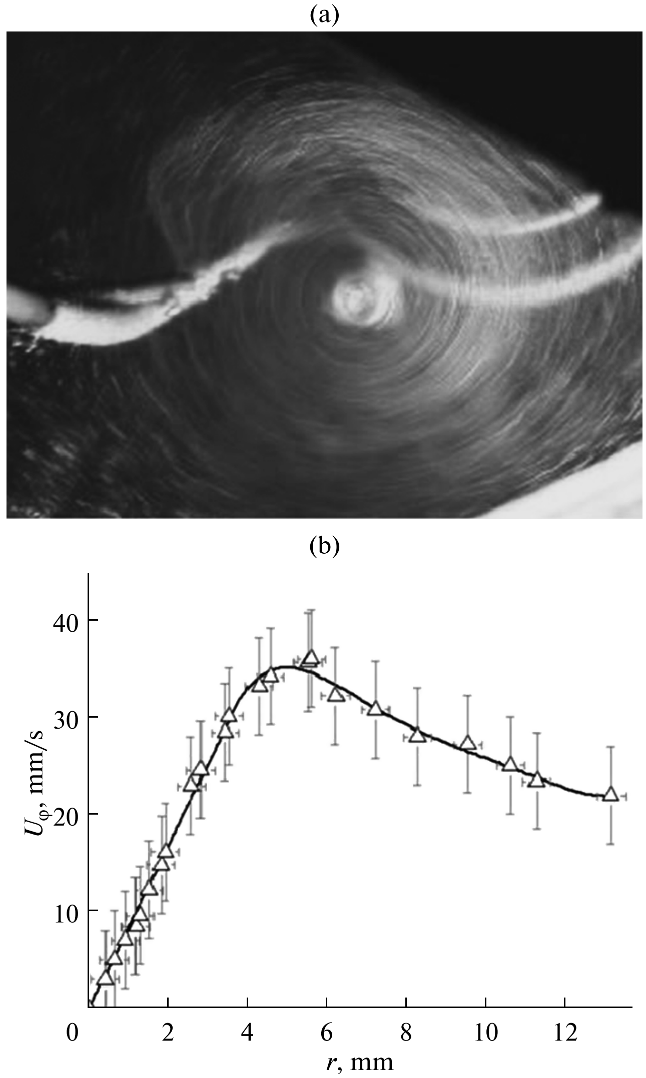


Fig. 6. Vortex motion generated in a solution of copper sulfate at the location of the rod electrode at 45°: (a) visualized flow pattern and (b) measured profile of the circumferential velocity of the swirling flow at a current in the circuit of $I = 0.5$ A.

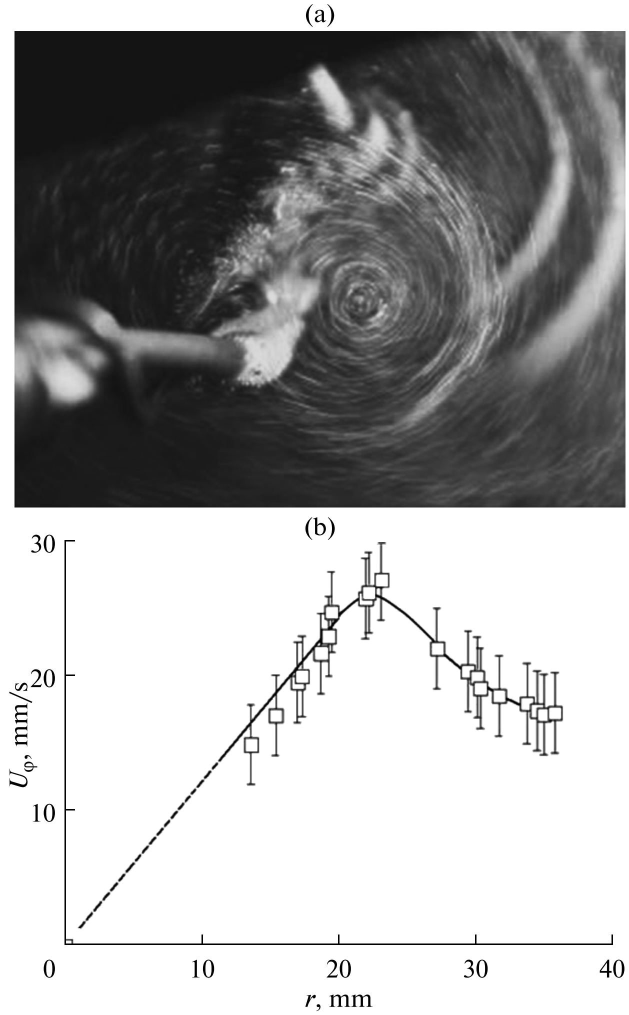


Fig. 7. Vortex motion generated in a solution of copper sulfate at the location of the rod electrode at 60°: (a) visualized flow pattern and (b) measured profile of the circumferential velocity of the swirling flow at a current in the circuit of $I = 0.5$ A.

sponding to a 45° inclination to the equatorial plane of the magnetic sphere, and increases with increasing electric field strength. Drawing an analogy of the results to natural phenomena, it should be noted that the majority of the most intense tornadoes occur in the latitudes of 30°–40°.

PHYSICAL MODEL OF THE FLOW

In the absence of a voltage difference between the electrodes in an electrolyte solution that is in a state of thermodynamic equilibrium and contains an equal number of ions of opposite signs, it is possible to suggest the presence of electric dipoles in the solution, randomly oriented in space. At the same time, the total dipole moment cannot be determined in the medium. The magnitude of the dipole moments of the test electrolyte solutions was calculated by the Debye method [8]. The dipole moment of an acetic acid solution is 33.73 D, and the average distance between ions in dipoles is estimated at 3.5×10^{-8} m.

By passing an electric current through the electrolyte solution, which is under a constant magnetic field, the dipoles acquire an orientation in the direction of the electric field and the ions of opposite signs begin ordered motion under the effect of electromagnetic forces, creating the total magnetic moment in the liquid.

Based on these studies, a physical model of the observed effect of vortex formation was proposed. The schematic diagram of vortex formation is presented in Fig. 8 for the example of an acetic acid solution. Figure 8a illustrates the directions of forces acting on the acetate ions (CH_3COO^-) and the trajectory of the liquid at the considered mutual orientation of the force lines of the magnetic and electric fields. The corresponding visualized pattern of the flow obtained in the experiment is given in Fig. 8b.

It follows from the laws of electrodynamics that, for the motion of a charged particle in a uniform magnetic field with velocity **v**, making angle **α** with the direction of the magnetic induction **B**, a helix curve with radius r and step h becomes the trajectory of the particle. Radius r of the helix curve for a particle of mass m and charge q is determined by equating the centrifugal force and the Lorentz force $\frac{mv_\perp^2}{r} = |q| v_\perp B$, where $v_\perp = v\sin\alpha$:

$$r = \frac{mv\sin\alpha}{|q| B}, \quad (1)$$

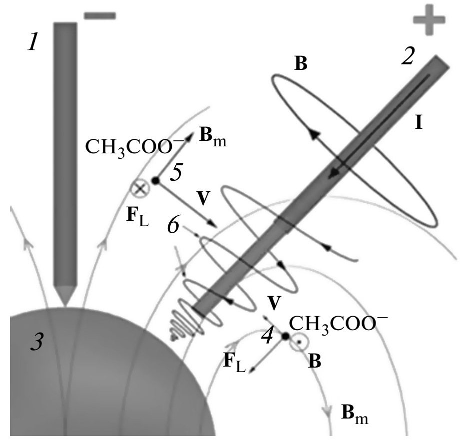
and helix step h is

$$h = \frac{2\pi mv\cos\alpha}{|q| B}. \quad (2)$$

If the velocity of a charged particle makes angle **α** with the direction of vector **B** of an inhomogeneous magnetic field, the induction of which increases in the direction of motion of the particle, radius r and step h of the helix curve decrease with increasing **B**.

The physical process of the formation of a tornado-like vortex in an electrically conductive medium can be described by the following scenario. In the presence of a current passed through the electrolyte, additional magnetic field **B** is induced around the rod electrode, and a directed movement of ions occurs near the uninsulated part of the rod electrode under the effect of the Coulomb force. The action of the Lorentz force in this region leads to a mutually opposing spiral motion of oppositely charged ions. As for the electrolyte solution, the weight of a negatively charged acetate ion is much greater than the weight of the positively charged ion of hydrogen and the total effect of the Lorentz forces applied to the opposite charges is close to the effect of the Lorentz force on the negative ion and only slightly reduces this effect. This is the basic mechanism of creating of a macroscopic rotation of the fluid flow by the action of the mechanical moment associated with the presence of the total magnetic dipole moment. The process of vortex formation, schematically shown in Fig. 8a, with a spiral rotation of massive negative acetate ions in inhomogeneous magnetic field $\mathbf{B}_m$ occurring with increasing magnetic flux density near the surface of the spherical magnet is clearly reproduced in the experiment. Figure 8b shows that the trajectories of movement, visualized by gas bubbles, correspond to the helical nature of flow *1–2* with decreasing (*1*) radius r and (*2*) step h of the helix in the motion toward the increasing magnetic induction at the approach to the surface of the spherical magnet.

(a)



(b)

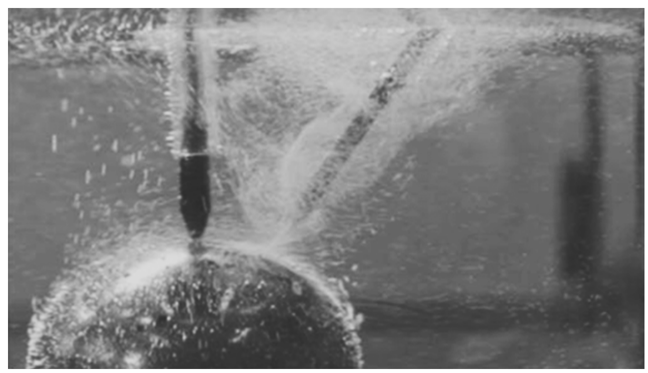


Fig. 8. Vortex formation in a solution of acetic acid in the orientation of the positive movable electrode at 54° to the horizontal plane; (a) pattern of vortex formation: (*1*) magnet holder, (*2*) movable electrode, (*3*) permanent magnet, (*4*, *5*) Lorentz force $\mathbf{F}_L$ acting on the ions of the electrolyte, and (*6*) vortex motion trajectory; $\mathbf{B}_m$, magnetic induction field produced by a magnetic sphere; **B**, induction of the magnetic field generated by a current-carrying conductor; **V**, velocity vector of acetate ions under the Coulomb forces; (b) visualization of vortex formation.

It should also be noted that, under the Lorentz force associated with the radial motion of charged particles, the vertical (with respect to the surface of the sphere) axis of a tornado-like vortex is shifted in latitude in the azimuthal direction. This shift corresponds

Angular velocities ω of the electrolyte in the central region of the vortex

Position of electrode	Current strength I, A	ω, 1/s
45°	0.25	7.2
	0.5	8.4
	0.68	13.6
60°	0.5	8.14
	0.75	10.44

to the swirl of the flow for the cases considered by the example of Fig. 3.

CONCLUSIONS

The experimental set-up was created to study the generation mechanism of vortex motion in electrolytic environments under a constant magnetic field. The selection of electrolytes as model fluids simulating the behavior of liquid-metal coolants is justified. The procedure of measurements is developed ensuring the most proper visualization of the process of vortex formation in an electrically conductive medium.

A series of experiments were conducted on the generation of large-scale vortex motion in an electrically conductive medium under a constant magnetic field with changing the voltage difference between the electrodes and their various orientations with respect to the force lines of the constant magnetic field. Photo and video records illustrating the development of the processes of vortex formation are obtained.

A phenomenon associated with the effect of a galvanic current on the value of the rotational moment affecting the elements of the hydromechanical system in the changing polarity of the electric voltage is observed.

A physical model of the vortex flow generated in a conductive medium under a constant inhomogeneous magnetic field at various mutual orientations of the force lines of the electric and magnetic fields is proposed.

These studies belong to basic thermophysical research and are of interest in various areas of physics and engineering applications.

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