HYDRODYNAMIC EFFECTS IN WATER MEDIA IN ELECTRIC AND MAGNETIC FIELDS

E. Z. Gak

UDC 536.2:538.4:583.692

The appearance of different convection and wave phenomena in media with high ($\sigma \geq 10^5$ $\Omega^{-1}\cdot m^{-1}$) and low ($\sigma \leq 10^{-6}$ $\Omega^{-1}\cdot m^{-1}$) conductivities in the presence of electric and magnetic fields and in the absence of forced convection has been quite well studied. The nature of such phenomena in water media ($10^{-4} \leq \sigma \leq 10^3$ $\Omega^{-1}\cdot m^{-1}$) has been studied in less detail. The phenomenological treatment of water media as liquids that differ only by their relatively low conductivity is inadequate in solving a number of theoretical, experimental, and especially applied problems, for which it is necessary to take into account the special rheological, electrical, and thermal properties of water and its solutions in the bulk and near interphase boundaries.

Convection and Waves ($E \perp B$). The creation of vortex flows and surface and internal waves with a given structure permits studying the different types of mass transfer and methods for enhancing them, which is one of the important problems in physical hydrodynamics [1] both for Newtonian liquids and for complex rheological systems [2, 3].

In contrast to fused metals, water media are optically transparent and permit operating at low temperatures and carrying out experimental investigations for a wide range of different magnetohydrodynamic problems [4-9].

The dynamics of the motion of a viscous, weakly conducting, incompressible fluid, which includes aqueous electrolytic solutions, are described by the Navier—Stokes equations

$$\rho\left[\frac{\partial \mathbf{V}}{\partial t} + (\mathbf{V}\nabla)\,\mathbf{V}\right] = -\nabla p + \rho\mathbf{g} + \eta\Delta\mathbf{V} + \mathbf{f} \tag{1a}$$

and the equation of continuity

$$\operatorname{div}\mathbf{V} = 0. \tag{1b}$$

The relatively low values of σ and V permit, according to the criterional estimates made in [5-6], neglecting the induced currents and magnetics fields. Equations (1) can be solved exactly only in certain particular cases, which makes it difficult to interpret and compare the theoretical and experimental results. An exact solution for the velocity of a steady state flow V in a ring-shaped axisymmetrical channel situated in a homogeneous axial magnetic field was obtained in [7]:

$$V = \frac{IB}{4\pi h\eta}\left[\left(\ln R_0 + \frac{r_0^2 \ln \frac{R_0}{r_0}}{R_0^2 - r_0^2}\right) r - \frac{r_0^2 R_0^2 \ln \frac{R_0}{r_0}}{R_0^2 - r_0^2}\,\frac{1}{r} - r\ln r\right]. \tag{2}$$

Taking into account the fact that I is the total current in the system, for the average value $\bar{V}$ over the cross section of the channel $r = 0.5\,(R_0 - r_0)$, we have

$$\bar{V} = \frac{IBr_0}{16\pi h\eta}\,\frac{K^4 - 2K^2\ln^2 K + 1}{(K-1)^2(K+1)}. \tag{3}$$

For $\operatorname{rot} f_{MHD} = 0$ and the capabilities of the channel, the operation of such a system is realized in the conduction pump mode [10].

Using a conductivity input current and constant magnetic fields, it is possible to control the structure of the boundary layer. The theoretical and experimental papers [6, 8, 11, 12] are of great interest, as well as results obtained in [13, 14].

Aerophysical Scientific-Research Institute VASKhNIL. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 43, No. 1, pp. 140-153, July, 1982. Original article submitted February 9, 1981.

0022-0841/82/4301-0815$07.50

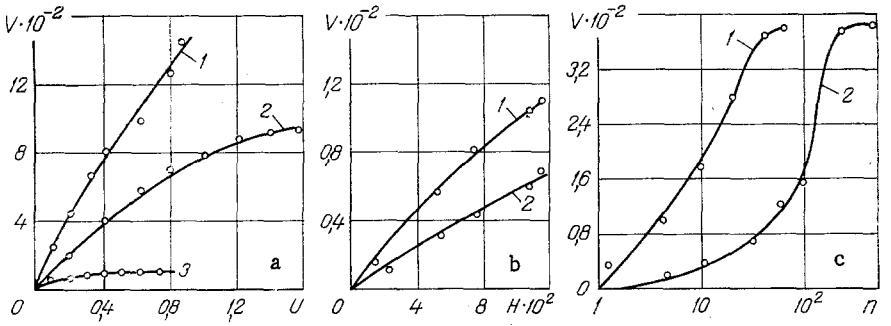

Fig. 1. Experimental dependences of the flow velocity V on the surface of a water electrolyte $CuSO_4$ at the center of an axisymmetrical ring-shaped channel with $r = 0.5$ ($R_0 - r_0$) (dimensions of the channel: $R_0 = 0.03$ m, $r_0 = 0.005$ m; height of liquid $h = 0.012$ m; $j \perp B$; $\nabla B = 0$; copper electrodes): a) $V = f(U)$, $B = 0.36$ T, 1) $c_0 = 1$ N, 2) 0.2 N, 3) 0.02 N; b) $V = f(H)$, $H = H_0 \sin \omega t$, $I = I_0 \sin \omega t$, $c_0 = 1$ N, $I = 0.6$ A, $\varphi = 0$, 1) $f_0 = 50$ Hz, 2) 2 kHz; c) $V = f(n)$, $B = 0.3$ T, $c_0 = 1$ N, 1) $\tau = 15$ msec, 2) 1.5. V, m/sec; U, V; H, A/m; n, counts/sec.

For rot $f_{MHD} \neq 0$, where

$$\operatorname{rot} \mathbf{f}_{MHD} = \operatorname{rot} [\mathbf{j} \times \mathbf{B}] = (\mathbf{B}\nabla)\,\mathbf{j} - (\mathbf{j}\nabla)\,\mathbf{B} \neq 0, \tag{4}$$

a vortex motion of the electrolyte arises when one of the conditions $\nabla j \neq 0$ or $\nabla \mathbf{B} \neq 0$ is satisfied.

Quantitative measurements of the flow in a water medium as a function of different physical and chemical factors were performed in [7, 15-18]. In particular, experiments in ring-shaped and rectangular channels showed that according to (3), V increases with I and B (Fig. 1). The characteristic $\sigma = f(E)$, outside regions where Wien's law is valid [19], is linear for electrolytes. However, under certain conditions, the magnitude of j is bounded in aqueous electrolytes by the limiting value of the current density j_{lim}, determined by the electrolyte concentration, geometric dimensions of the system, coefficients of diffusion, and charges of cations and anions (D_1, D_2, z_1, z_2), which also limit velocities in electrolytes [7]. Thus, for a flat electrolytic channel with an interelectrode separation d

$$j_{\lim} = \frac{1}{d} D_1 F z_1 (z_1 + z_2)\, c_0, \tag{5}$$

as is evident from Fig. 1a, the dependence $V = f(U)$ is nonlinear and V is determined by c_0. The dependence $V = f_{MHD}(t)$ was investigated. For $\varphi = 0$, $j = j_0 \sin\omega t$, $B = B_0 \sin\omega t$, and taking into account (3), for a ring-shaped channel,

$$\overline{V} = \frac{I_0 B_0 r_0}{32\pi h \eta} f(K)\,(1 - \cos 2\omega t). \tag{6}$$

It follows from [18, 20] that for $H = (0.5\text{-}1)\cdot 10^3$ A/m and $j = (1\text{-}2)\cdot 10^2$ A/m^2, a pulsating fluid flow arises with frequency 2ω, and V increases with I and B and decreases with increasing f_0 (Fig. 1b). Similar results occur also for pulsed f_{MHD} with different duty factor and pulse duration τ [21, 22] (Fig. 1c).

When periodically varying f_{MHD} are created in the bulk of the fluid, for $f_{MHD} \perp g$ or $f_{MHD} \parallel g$, capillary-gravitational waves form on the surface of the fluid. The frequency and amplitude of the waves that appear are determined by the parameter f_{MHD} and the parameters of the hydrodynamic system [4, 9, 23-25]. Experimental data for the case $j = j_0 \sin \omega t$, B = const, and $f_{MHD} \perp g$ are presented in Figs. 2-4. The use of an LG-75 laser permitted increasing the accuracy and contrast of the pictures of the wave surface that were recorded.

When a pulsed exciting mass force is used in the input section of an open channel (Fig. 5) or when an exciting force is created in the center of the channel, nonlinear traveling shock or soliton type waves were obtained [26, 27]. In order to record wave phenomena on the surface of the liquid, the resistance of the electrolyte between two electrodes with different areas was measured. Figs. 6a and b present some traveling surface wave structures

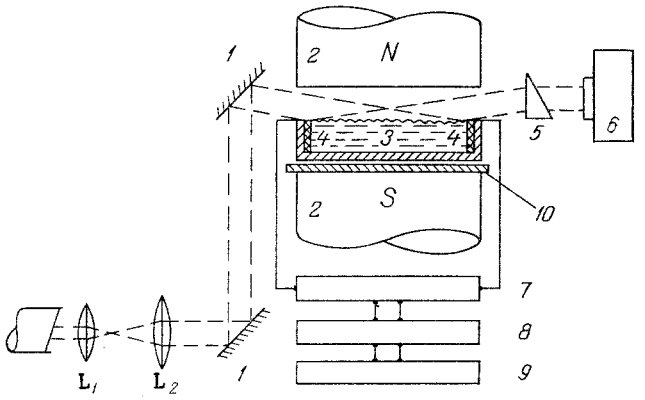

Fig. 2. Scheme for generation and optical detection of hydrodynamic oscillations in a closed rectangular channel: L_1 and L_2 are the collimator lenses; 1) mirrors; 2) pole of a magnet; 3) channel with electrolyte 1 N $CuSO_4$; 4) electrodes; 5) deflecting prism; 6) "Zenit" camera; 7) matched transformer; 8) low-frequency TU-100 amplifier; 9) ZG-33 sound frequency generator; 10) nonmagnetic spacer.

observed at different distances from the region of excitation, arising with the decay of nonlinear waves.

Based on the methods proposed for generating wave processes, methods have been developed for simulating nonlinear hydrodynamic phenomena in various kinds of dispersive media [28] and for measuring the coefficient of surface tension of the liquid [29].

The microscopic mechanism for exciting convection in aqueous electrolytes under the action of magnetic fields, based on the basic assumptions of Frenkel's kinetic theory of liquids [30, 31], was proposed in [32]. It was shown that the macroscopic phenomena that appear are based on the change in the momentum of an ion as it moves under the action of the Lorentz force

$$\mathbf{f}_L = \frac{z_{iq}e}{c}[\mathbf{V}_{iql,T} \times \mathbf{H}], \tag{7}$$

$V_{iql,T} \sim \sqrt{kT/m_{iq}} \sim 10^3$–$10^4$ m/sec. The change in the momentum of an ion in the field H, according to [28], with $\nabla B = 0$ is determined by the expression

$$\Delta \mathbf{p}_{iql} = \frac{z_{iq} \cdot e}{c}[\mathbf{V}_{iql,T} \times \mathbf{H}] \cdot t_0. \tag{8}$$

However, in spite of the high values of the momenta of separate ions, the momentum of the entire mass of liquid can change only in the presence of an additional energy factor, creating a nonequilibrium distribution of ions. It should be noted that the energy, introduced as a result of this factor, can be much lower than the thermal energy per unit volume of liquid. Starting from considerations of the velocity of the center of mass of the system

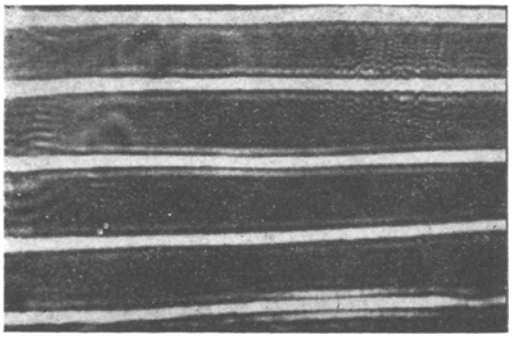

Fig. 3. Photograph of standing waves on the surface of a 1 N water solution $CuSO_4$, excited by a magnetohydrodynamic method, I = 0.4 A, f_0 = 20 Hz, H = 0.4 T, rectangular channel 0.12 × 0.08 × 0.015 m; $\nabla H = 0$.

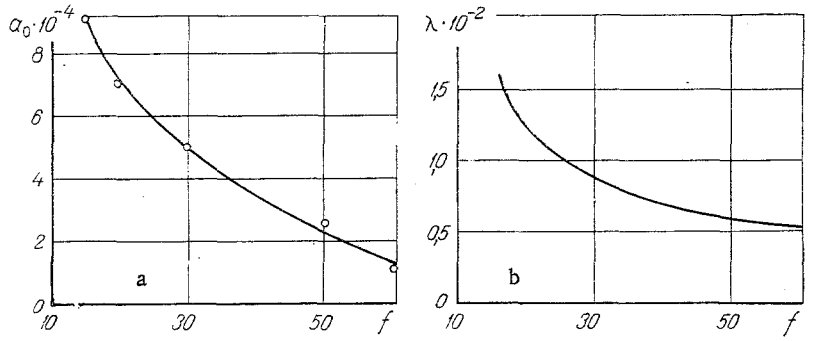

Fig. 4. Experimentally obtained amplitudes a_0 (a) and lengths of surface waves λ (b) as a function of the frequency of the exciting current. c_0 = 1 N $CuSO_4$; B = 0.4 T; $\nabla B = 0$; I = 0.6 A. a_0, λ, m; f, Hz.

of material points, V_S, an expression is obtained for the macroscopic velocity of a unit volume under the conditions $\nabla B = 0$ and $\nabla E = 0$ for a stationary flow

$$V_S = \frac{\sum_{i=1}^{i}\sum_{q=1}^{q}\sum_{l=1}^{j}\Delta p_{iql} + \sum_{i=1}^{i}\sum_{l=1}^{j}\Delta p_{H_2O}}{\sum_{i=1}^{i}\sum_{q=1}^{q} m_{iq} + \sum_{i=1}^{i} m_{H_2O}}. \quad (9)$$

Carrying out the summation,

$$V_S = \frac{N_0}{\rho}\sum_{q=1}^{q} c_{0,q}\bar{p}_q, \quad (10)$$

where

$$\bar{p}_q = z_q e V_E H. \quad (11)$$

From quantitative calculations, $V_S \gg V_E$.

Such an approach explains the experimentally observed magnitudes of the flow velocities of liquids of the order of 0.01-1 m/sec in crossed electric and magnetic fields [7, 16-18]. The effects examined above are determined by the collective unidirectional motion of cations and anions in a direction perpendicular to E and H and by the transmission of the total momentum to the entire mass of liquid over the time of action of the forces $t \gg t_0$. We note that everything that has been said above is valid only for low-molecular ions, whose dimensions are comparable to that of water molecules and whose thermal velocities are quite high.

Thus, the physical mechanism for the appearance of a macroscopic flow of water is as follows: The entire mass of neutral water molecules is "pulled" simultaneously by a large number of low molecular cations and anions and, in addition, the source of energy is the energy in the electric field, while the magnetic field plays the role of a control system. Apparently, this is the mechanism on which the different electromagnetic actions on aqueous electrolytes, both in the bulk and near interfaces, are based.

Physics of Microhydrodynamic Phenomena. The investigation of the motion of water and its solutions in layers with characteristic thickness $\delta \leq (0.1\text{-}100) \times 10^{-6}$ m can be classified, according to Batchelor [33], among microhydrodynamic phenomena. However, due to the necessity of studying simultaneously hydrodynamic and surface phenomena, and the structure of the liquid in boundary layers, this new area of hydrodynamics, keeping in mind [1, 34], should rightfully be called physical microhydrodynamics. The problems considered in this review concern this area or, more precisely, one of its divisions, namely, electromagnetic microhydrodynamics.

In order to examine the properties of the physicochemical processes in regions δ, apparently, it will be useful to draw upon ideas concerning the three-layer model of the structure of moving water in thin layer near interfaces, proposed by Drost-Hansen [35, 36]. In these regions [37], the microscopic nature of the electric and magnetic interactions and the fact that E, ∇E, B, and ∇B stem from surface phenomena or the actions of external fields, can

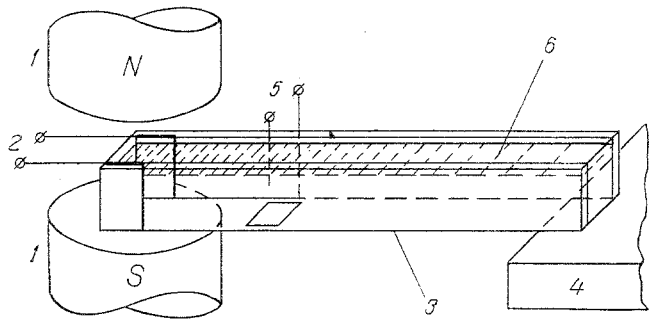

Fig. 5. Scheme for recording and exciting traveling capillary gravitational waves: 1) pole of the magnetic system; 2) electrodes for exciting waves; 3) organic glass channel; 4) insulating support; 5) electrode system for recording changes in the resistance of the liquid; 6) electrolyte.

exceed by 1 to 2 orders of magnitude their value in the bulk should be taken into account. In addition, on such small scales, the irregularity of the interface begins to be important. It becomes necessary to take into account the viscoplastic properties of the liquid in the boundary phases and the limiting shear stress in them $\tau_0 \sim 10\text{-}15$ N/m^2, changing η [34, 38].

The analysis and practical utilization of electrohydrodynamic phenomena in aqueous solutions is customarily limited to electroosmotic processes, whose theory is developed for the case $E_t \neq 0$ (E_t is the intensity of the electric field parallel to the interface), stationary conditions, and laminar flow regimes [35, 39, 40]. As is well known, the magnitude of the velocity in a rigid single capillary for $r_0 \gg \delta_{db}$

$$V_t = \frac{\xi\varepsilon}{4\pi\eta} E_t. \tag{12}$$

When the ionic atmospheres overlap, for $r_0 \ll \delta_{db}$, the velocity decreases and is determined, according to [36], for a gap with width h_0 [36] by

$$V = \frac{\xi\varepsilon}{4\pi\eta} E_t \left(1 - \frac{\text{th}\,\frac{h_0}{2\delta_{db}}}{h_0/2\delta_{db}}\right). \tag{13}$$

In an electric field oriented perpendicular to the interphase boundary, for $E_n \neq 0$, and $\nabla E_n \neq 0$, motion of the liquid can arise. For example, at an air-water boundary, motion will arise from the change in the surface tension of the liquid, differences in the dielectric permittivity, displacement of the liquid into the region of large ∇E, and induction effects, whose magnitude is determined by σ [4, 41-45]. Thus, G. I. Taylor [46] observed jets of water pulled out of drops and their deformation in inhomogeneous electric fields. Under analogous conditions, we observed a stationary flow of liquid out of a capillary, whose velocity varied from 0 to 1 m/sec with E varying from 0 to 50 kV/m; for $E = 0$, we did not observe a flow.

Let us examine the microhydrodynamic nature of the fluid flow that arises in the region δ_{db} with $E_t \neq 0$ using the results obtained in [32]. Using the general form of the expression for the macroscopic velocity V_s (9), it may be assumed that in this case V_s is also determined by the total cooperative effect of the action of the momenta of low-molecular ions on the entire liquid mass. For $E_t \neq 0$ $f_{EHD,t} = z_{iq} e E_t$. For a separate ion

$$\Delta p_{iql,T} = z_{iq} e E_t \cdot t_0. \tag{14}$$

The total effect $\overline{\Delta p}_q \neq 0$, determining $V_s \neq 0$, stems from the fact that in the region δ_{db} the cation and anion concentrations are different. The special characteristic of microhydrodynamic phenomena in layers δ [33] consists of the fact that electric fields, caused by the electric charge on the phase separation surface and the total volume charge of ions in the region δ, begin to play an important role. Under these conditions, $\sum_{i=1}^{i} \sum_{l=1}^{j} \Delta p_{H_2O} \neq 0$, which, apparently, has a retarding effect on the flow that arises. The well-known increase in the structural

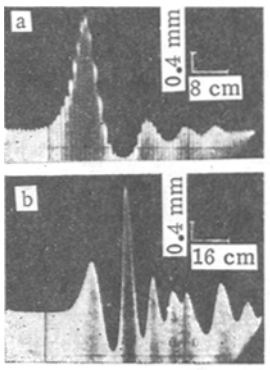

Fig. 6

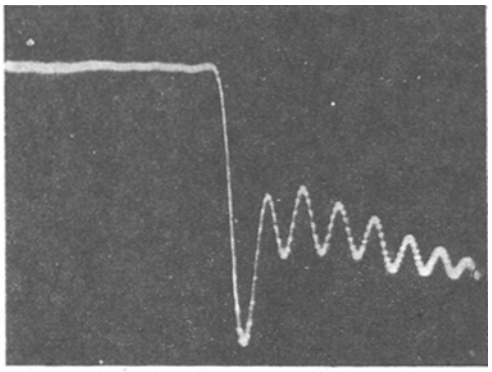

Fig. 7

Fig. 6. Oscillograms of the evolution of the wave profile as it propagates along the channel, excited by an exponential electric pulse with amplitude 10 A and duration $\tau = 20$ msec, $B = 0.36$ T, $h = 0.015$ m at $x = 0.05$ m (a) and $x = 0.25$ m (b).

Fig. 7. Oscillograms of the function $I = f(t)$ when the alternating electric voltage is switched on. Ring-shaped channel, $R_o = 0.03$ m, $r_o = 0.005$ m, $h = 0.012$ m, $E_{per} = 12 \cdot 10^3$ V/m, $f_o = 50$ Hz, $c_o = 0.01$ N $CuSO_4$, region of diffusion kinetics; at $t = 0$, $U = 1.5$ V and $I = 0.0018$ A.

order of water under the action of the electric field of a substrate, due to the dipole moment of water molecules [35, 36, 38], leads to the appearance of motion outside the stationary layer with $E_t \neq 0$. For $p_{EHD} \geq \tau_{o,lim}$, the flow entrains additional, previously stationary, volumes of fluid, carrying a volume charge with density $\rho_{vc} \neq 0$ [36], which must increase the "flow current." With $E_t(t)$, flow is possible both in stationary and in nonstationary regimes. The velocity curve in the presence of electroosmosis is unique [39, 40]: the flow velocity is maximum along the periphery and minimum at the center and, in addition, after a time $t \sim 0.1$–0.6 sec, after an electric field is created, the velocities equalize.

Let us now examine the characteristics of fluid flows under the conditions $B \neq 0$, $j \neq 0$, and $\nabla B = 0$ near electrode–electrolyte interphase boundaries. In this case, $\Delta p_{iql,T}$ is determined from (8). However, in expression (9) for V_s, in contrast to the case of the bulk fluid, as for $E_t \neq 0$, $\sum_{i=1}^{i} \sum_{l=1}^{l} \Delta p_{H_2O} \neq 0$. Tangential forces $f_{MHD,t}$ are created directly on the surface of the electrode, where $j \neq 0$ and $B \neq 0$ near the solvation and boundary layers of the liquid. This leads to considerable differences in the structure of the boundary layers with $f_{MHD,t}$ and with forced convection ($f_{MHD,t} = 0$) [16, 17]. For $p_{MHD} \geq \tau_{o,lim}$, the structure of the liquid in the solvation layer breaks down and the velocity curves with electroosmosis and magnetohydrodynamic effects are similar.

A microscopic approach, analagous to that used in [32], was applied to the analysis of the nature of the convection phenomena in surface layers δ with $\nabla B \neq 0$ in aqueous solutions, containing paramagnetic ions or particles [47].

Convection and Heterogeneous Transformations. Up to the present time, the possibility of an effect of magnetic fields on the flow of those reactions, in the course of which the spins of electrons and nuclei change and electrons are emitted into the solution from a phase separation surface, has been demonstrated experimentally [48–52].

We shall examine the influence of hydrodynamic effects with $f_{MHD} \neq 0$ on the course of a typical heterogeneous transformation: the electrode process. The appearance of convection with $j \neq 0$ and $B \neq 0$ decreases the size of the diffusion layer δ_{dif}, increasing the rate of input of reagents [9, 16, 17, 53–58]. As shown in [15–17], the increase in j_{lim} is determined by c_o, B, ∇B, E, and ∇E. When j and B attain values for which $p_{MHD} \geq \tau_{o,lim}$, in the near electrode regions, V becomes so large that the transfer of ions to the electrode from the flow slows down and j decreases, i.e., the rate of the reaction decreases. This

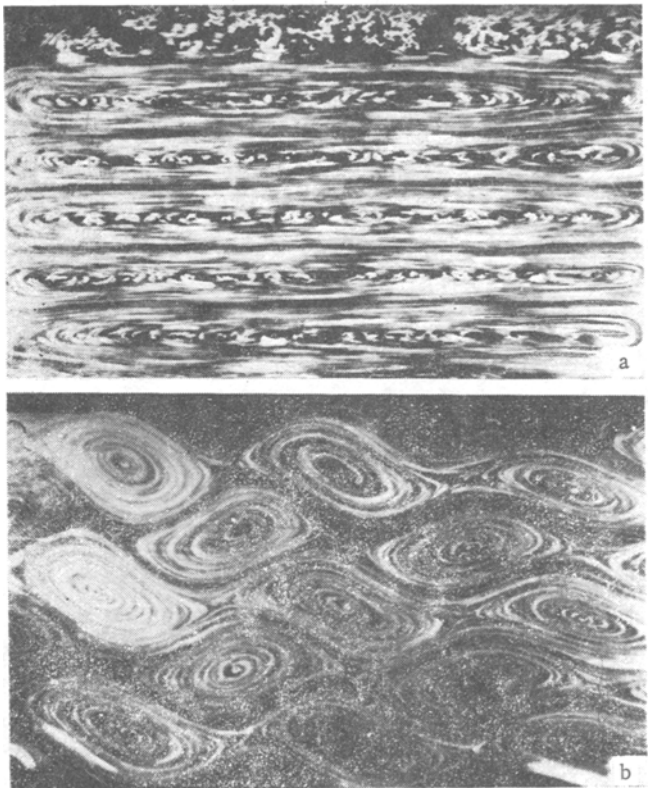

Fig. 8. Formation of secondary flows from a plane-parallel flow under the action of a periodic force, excited by the MHD method ($h = 0.003$ m, 1 N $CuSO_4$): a) $j = 2 \cdot 10^2$ A/m^2, subcritical regime; b) $j = 6 \cdot 10^2$ A/m^2, supercritical regime.

phenomenon can be treated as an increase in the effective resistance of the electrolyte in the channel, while in the case of an increase in j, in the region of mixed and diffusion kinetics, it can be treated as a decrease in the resistance. These results confirm the experimental data in [59-61]. The problems of controlling the magnetoresistance properties of capillary electrochemical cells are examined in [62, 63].

In the presence of an electrode reaction occuring in the region of the diffusion kinetics, near the electrode on which the reaction occurs, a "macroscopic" volume charge forms [64, 65]. This charge, or more precisely charged layer, is characterized by a thickness $\delta_{mvc} \gg \delta_{db}$ and volume density $\rho_{mvc} \ll \rho_{vc.db}$, automatically playing the role of an electric barrier. Apparently, the appearance of this charged layer is one reason for the appearance of limiting current densities in electrochemical cells.

As is well known, it is impossible to avoid diffusion limitations even with intense mixing. Direct application of an alternating electric field $E_{per} = E_0 \sin \omega t$ on the region δ_{mvc} leads to its resorption (Fig. 7) due to the creation of a volume mass force $f_{EHD}(t) = \rho_{mvc} E_0 \sin \omega t$. The increase in j_{lim} constituted 400-500% and increased with increasing E_{per} and decreasing c_0, beginning only at the threshold value $E_{per}(t) \geq (5\text{-}10)E$. According to our experimental estimates, for aqueous electrolytes, the minimum value of $E_{per}(t)$, at which an increase in j was observed constituted 2-10 kV/m.

The effects examined above could find application both in experimental physics and electrochemistry and in enhancing different heterogeneous processes, involving the transfer of one or several types of ions through the phase separation boundary with $\nabla c_0 \neq 0$.

Apparently, the formation of a volume charge with considerable extent near charged interfaces, permeable to ions of a single sign, at the boundary with an ionized system containing charged carriers with different coefficients of diffusion in the neutral medium, has a universal character and is encountered in different natural phenomena. For this reason, the

results presented above could be useful in plasma physics [66], geophysics [67], biophysics [68], and in other areas of science and technology.

We note also other phenomena that affect the rate of heterogeneous transformations. The formation of reaction products near electrodes with densities different from that of water (solution), namely, gases and ions of heavy metals, leads to the creation of convection flows, carrying away the reaction products from the electrodes. For small electrodes, these are stream flows of "ripples" [41]. The velocity of the ripples and their dimensions are determined by the geometry of the electrodes and of the channel, the magnitude of j, c_0, the mass of the ions, and the concentration of the free gas formed. They can be viewed as sources of stationary macroscopic charges, if ions of a single sign predominate in them. The change in the trajectories of a single type of charged jet in capillary cells with $B \neq 0$ and the effect of these phenomena on the course of the electrode process were examined in [63].

The velocity and kinetics of settling of paramagnetic ions or particles in water media will change considerably only with ∇H of the order of 10^9-10^{11} A/m^2. Such values of ∇H are observed for boundary effects of magnetic fields [69-71] at distances of the order of $\delta \ll a$ and $\delta \ll l_0$, where a is the linear dimension of the end piece and l_0 is the distance between the poles. The quantity δ, where H and ∇H are considerable, could constitute a quantity of the order of $(1\text{-}5)\cdot 10^{-3}$ m for $l_0 \sim (3\text{-}10)\cdot 10^{-2}$ m as well. For such cases, a change in the structure of the settling of iron bacteria [72] and erythrocytes [8] was observed. An example of the influence of ∇H on the kinetics of heterogeneous reactions in capillary-porous media is given in [73].

Engineering-Physical Problems. The physical phenomena examined above have numerous applications, already mentioned in part. In this section we shall consider only the case $f_{MHD} \neq 0$. Apparently, these areas are of greatest interest. This is related both to the requirements of physical hydrodynamics, namely, the necessity of developing a nonlinear theory of hydrodynamic stability [74], and to the fact that a thin fluid layer represents a classical model in applications of this theory to meteorology, geophysics [75], and heat and mass transfer and their applications in chemical technology.

The magnetohydrodynamic method of exciting convection permits attaining under laboratory conditions and in technological practice large values of the Reynolds number $Re = \rho Vr/\eta$ of the order of $Re_{cr} = 2400$ and greater up to 10^4-10^5 as a result of the small density of the fluid and lower surface tension compared to liquid metals. Such values of Re can be obtained with easily attainable values of j and B and with the usual geometric channel dimensions, which permits operating under isothermal conditions.

In addition, vortex convection and nonlinear surface waves, by changing the area of the free surface, enhance mass transfer in the space between the phases. Convection in the near-electrode regions increases the limiting permissible currents, decreases the energy expenditures, opens up paths for increasing the quality of the electrode deposits [52-58, 76], and improves the dissipating capability of the electrolytes [77] and heat transfer [78-80]. At the same time, the necessity for applying homogeneous magnetic fields in closed magnetic systems, due to their high cost and large dimensions, have precluded widespread use of this method in simulation and in technological processes. The use of open magnetic systems with unrestricted size has permitted attaining in thin layers of the fluid and in the near-electrode regions values of B and ∇B that are sufficient to develop intense convection. Thus, e.g., this method can be used in electrometallurgy, electrochemical refining, and regeneration of spent solutions [58, 57] and is most useful when forced convection cannot be used or is ineffective.

In addition, based on the use of the phenomena examined, automatic small-scale apparatuses of the chemotron type [8, 62, 63] and new methods of electroanalysis can be developed [81].

The method of modeling different nonlinear hydrodynamic phenomena in thin fluid layers examined above [82] was further developed in a series of theoretical and experimental papers of interest for geophysical hydrodynamics [75, 83-89]. In particular, the MHD method has permitted observing for the first time experimentally a plane-parallel flow caused by the action of a sinusoidal force (Kolmogorov flow) in the subcritical and supercritical regimes (Figs. 8a and b) [85-88]. The same method was used to investigate the interaction of vortical structures. The appearance of an autooscillatory regime, consisting of pairwise reconnection of vortices with a period of 30 to 10 sec, was observed in a closed volume with the interaction of four vortices excited by the MHD method [89].

The generality of the transport equations permits modeling problems of convective diffusion and gasdynamics and permits examining wave phenomena in different media [28, 8].

In our experiments, together with water solutions of low molecular electrolytes, we used water soluble polymers, polyelectrolytes, and proteins, i.e., liquids that have significant viscoplastic properties. From our point of view, such investigations could be useful for solving various problems in rheophysics, especially for studying phenomena occuring in film flows [3].

NOTATION

Here t is the time; ρ, σ, ε, μ, η, α, density, electrical conductivity, dielectric and magnetic permittivities, and the coefficient of molecular viscosity and surface tension of the liquid; $\tau_{0,lim}$, limiting shear stress of the liquid; c_0, $c_{0,1}$, $c_{0,2}$, concentrations of the electrolyte, cations, and anions in the bulk; z_1, z_2, D_1, D_2, valences and coefficients of diffusion of cations and anions in the liquid; F, N_0, Faraday and Avogadro numbers; k, Boltzmann's constant; δ, δ_{db}, δ_{dif}, δ_{mvc}, thicknesses of the near-wall, double, and diffusion layers and of the layer of macroscopic volume charge; u, mobility of ions in water under the action of an electric field; V_E, velocity of ions in water, caused by $E \neq 0$; $V_{iq\ell,T}$, thermal velocity of an ion; i, number of the ion of a single kind in unit volume; q, type of ion; ℓ, transference number of an ion ($1 \leq \ell \leq j$); V_S, macroscopic velocity of a unit volume of liquid; m_{iq}, m_{H_2O}, mass of the iq-th ion and of a water molecule; t_0, time of translational transfer of an ion from one equilibrium position to a neighboring position; T, absolute temperature; e, electron charge; c, velocity of light; $\Delta p_{iq\ell,T}$, Δp_{H_2O}, changes in the momenta of ions in the magnetic field and water molecules; p_q, mean value of the momentum of a type q ion per unit time; R_0, r_0, radii of the walls of an axisymmetrical ring-shaped channel; h, height of the fluid in the channel; $K = R_0/r_0 > 1$, number that characterizes the ratio of the diameters of the axisymmetrical channel; d, interelectrode distance; V, velocity of the fluid; g, acceleration of gravity; f, f_{MHD}, f_{EHD}, p, pMHD, pEHD, volume densities of the mass forces and pressures: total, magnetohydrodynamic, and electrohydrodynamic; $f_{0,MHD}$, $f_{0,EHD}$, amplitudes of the alternating force of magneto- and electrohydrodynamic origin; Re, Re_{cr}, usual and critical Reynolds numbers; E, H, intensities of the constant electric and magnetic fields; B, magnetic field induction; H_0, E_0, B_0, amplitudes of the alternating magnetic and electric field intensities and of the magnetic field induction; E_t, E_n, tangential and normal components of the electric field intensity vector; E_{per}, alternating electric field; j, j_{lim}, usual and limiting current densities in a galvanic bath, electrochemical cell; f_0, frequency; ω, circular frequency; $\omega = 2\pi f_0$, τ, n, duration and duty factor the electric and magnetic pulses; φ, phase difference angle; U, potential difference; U*, potential difference in the electrochemical cell for which a change in the limiting current does not occur ($U < U^*$ $\Delta I_{cr} > 0$ for $U > U^*$ $\Delta I_{lim} < 0$); ΔI, quantity that characterizes the change in current in the electrochemical cell due to magnetohydrodynamic forces; ρ_{vc}, ρ_{mvc}, volume charge densities of the diffusion part of the double layer and the macroscopic volume charge in the electrolyte; a_0, λ, amplitude and length of the surface waves in the electrolyte excited by the MhD method; I, I_{lim}, $I_{(H\neq 0)}$, $I_{(H=0)}$, magnitudes of the currents in the channel: total and limiting in the presence and absence of a magnetic field; I_0, amplitude of the alternating current.

LITERATURE CITED

1. S. S. Kutateladze, "Three problems in the theory of heat transfer and physical hydrodynamics," Inzh.-Fiz. Zh., 38, No. 6, 1115-1136 (1980).
2. Z. P. Shul'man, Convective Mass Transfer of Rheologically Complex Fluids [in Russian], Énergiya, Moscow (1975).
3. Z. P. Shul'man and V. I. Baikov, Rheodynamics and Heat and Mass Transfer in Pellicular Flows [in Russian], Nauka i Tekhnika, Minsk (1979).
4. V. A. Briskman and G. F. Shaidurov, "Parametric excitation of fluid instabilities in magnetic and electric fields," Abstracts of Reports at the VIth Riga Conf. on MHD, Riga (1969), Vol. 1, pp. 60-63.
5. I. L. Povkh and B. V. Chekin, MHD Separation [in Russian], Naukova Dumka, Kiev (1978).
6. I. M. Kirko, Liquid Metal in an Electromagnetic Field [in Russian], Énergiya, Moscow (1964).
7. E. Z. Gak, "Problem of magnetohydrodynamic effect in strong electrolytes," Elektrokhimiya, 3, No. 1, 89-93 (1967).
8. É. Ya. Blum, Yu. I. Mikhailov, and R. Ya. Ozols, Heat and Mass Transfer in a Magnetic Field [in Russian], Zinatne, Riga (1980).

9. V. A. Briskman and V. G. Nevolin, "Parametric excitation of surface MHD waves in crossed electric and magnetic fields," Abstracts of Reports at the Xth Riga Conf. on MHD, Riga (1981), Vol. 1, pp. 77-78.
10. A. P. Vasil'ev and I. M. Kirko, "Problem of optimizing marine MHD engines," Zh. Prikl. Mekh. Tekh. Fiz., No. 3, 86-94 (1981).
11. A. G. Fedin, "Application of optical methods for studying MHD processes," Magn. Gidrodin., No. 3, 15-24 (1973).
12. R. K. Dukure and O. A. Lielausis, "Experimental study of the effect of electromagnetic forces on flow of electrolytes around bodies," in: Problems in MHD and Dynamics of Plasma, Izd. Akad. Nauk Latv. SSSR (1962), Vol. 2, pp. 647-651.
13. E. Grauss and P. Cachon, "Action electromagnetiques sur les liquides on mouvement inotamment dans la couche limite d'ostales immerges," C. R. S., 238, No. 26, 2488-2495 (1954).
14. I. L. Kuznetsov, "Experimental study of the effect of an electromagnetic field on flow past a cylinder," Zh. Tekh. Fiz., 30, No. 9, 1041-1046.
15. E. Z. Gak, É. E. Rokhinson, and N. F. Bondarenko, "Characteristics of the variation of the kinetics of electrode processes in electrolytes in constant magnetic fields," Elektrokhimiya, 11, No. 4, 528-534 (1975).
16. E. Z. Gak, É. E. Rokhinson, and N. F. Bondarenko, "Influence of MHD effects on the current—voltage characteristics of flow-through electrochemical cells," Elektrokhimiya, 11, No. 4, 528-534 (1975).
17. E. Z. Gak, É. E. Rokhinson, and N. F. Bondarenko, "Influence of magnetohydrodynamic phenomena in electrolytes on kinetics of heterogeneous processes," Elektron. Obrab. Mater., No. 4, 62-66 (1977).
18. E. Z. Gak and G. P. Komarov, "Stationary flow in electrolytes in low frequency magnetic fields," Zh. Tekh. Fiz., 41, No. 9, 1996-1998 (1971).
19. N. A. Izmailov, Electrochemistry of Solutions [in Russian], Khimiya, Moscow (1966).
20. F. A. Heinmets and A. Hershman, "Considerations on effects produced by superimposed electric and magnetic fields in biological systems and electrolytes," Phys. Medicine Biol., 5, No. 3, 271-288 (1961).
21. A. V. Kibyakov, G. P. Komarov, and E. Z. Gak, "Role of hydrodynamic factors in synaptic transmission," Fiziologischeskii Zh. SSSR, 57, No. 11, 1641-1646 (1971).
22. Yu. V. Berlin, G. M. Buvin, V. I. Bel'kevich, and E. Z. Gak, "Certain characteristics of the action of pulsed magnetic fields on biological objects," in: Reaction of Biological Systems to Magnetic fields [in Russian], Nauka, Moscow (1977), pp. 39-48.
23. M. Z. Gak and E. Z. Gak, "Nonstationary magnetohydrodynamic effects in electrolytes in bounded volumes," Zh. Tekh. Fiz., 42, No. 9, 1992-1994 (1972).
24. T. Z. Fahidy, "Wave phenomena in magnetoelectrolytic systems," Electrochimica Acta, 21, 21-24 (1976).
25. J. M. Crowley, "Effect of electromagnetic force on the stability of liquid films," Ind. Eng. Chem. Fund., 6, No. 2, 243-246 (1967).
26. N. F. Bondarenko and M. Z. Gak, "Application of magnetohydrodynamic effects for investigating nonlinear properties of capillary gravitational waves," Elektron. Obrab. Mater., No. 1, 60-63 (1977).
27. E. Z. Gak, M. Z. Gak, and G. P. Komarov, Inventor's Certificate No. 410821, "Method of direct generation of mechanical oscillations in the volume of an electrolyte," Byull. Izobret., No. 2 (1974).
28. E. Z. Gak, M. Z. Gak, G. P. Komarov, and N. F. Bondarenko, Inventor's Certificate 568058, "Apparatus for modeling nonlinear wave processes in dispersive media," Byull. Izobret., No. 29 (1977).
29. E. Z. Gak, M. Z. Gak, and G. P. Komarov, Inventor's Certificate No. 409116, "Method for determining the coefficient of surface tension of a liquid," Byull. Izobret., No. 48 (1973).
30. Ya. I. Frenkel', "Kinetic theory of liquids," in: Collected Works [in Russian], Vol. 3, Izd. Akad. Nauk SSSR, Moscow (1959).
31. Ya. I. Frenkel', "Theory of the liquid state," in: At the Dawn of the New Physics [in Russian], Nauka Moscow (1970), pp. 215-238.
32. E. Z. Gak and G. R. Rik, "Effect of a constant magnetic field on the kinetic motion of ions in aqueous solutions of strong electrolytes," Dokl. Akad. Nauk SSSR, 175, No. 4, 856-858 (1967).
33. D. K. Batchelor, "Progress in microhydrodynamics," Proceedings of the XIVth International Congress in: Theoretical and Applied Mechanics, Mir, Moscow (1979), pp. 136-187.

34. L. I. Sedov, "Promising directions and problems in the mechanics of continuous media," Prikl. Mat. Mekh., 40, No. 6, 963-969 (1976).
35. W. Drost-Hansen, "On the structure of water near solid surfaces and the possible existence of long-range order," Ind. Eng. Chem., 61, No. 10, 5-59 (1969).
36. N. F. Bondarenko, Physics of the Motion of Underground Water [in Russian] Gidrometeoizdat, Leningrad (1973).
37. J. A. Stratton, Electromagnetic Theory, McGraw-Hill (1941).
38. B. V. Deryagin, "Solvate layers as special boundary phases based on direct methods of investigation," Proceedings of the All-Union Conf. on Colloidal Chemistry [in Russian], Izd. Akad. Nauk SSSR, Moscow (1952).
39. O. N. Grigorov, Electrokinetic Phenomena [in Russian], Leningrad State Univ. (1978).
40. K. P. Tikhomolova and L. A. Shishkanova, "Characteristics of electrokinetic flow through capillary porous bodies with microinhomogeneities on the surface," Inzh.-Fiz. Zh., 39, No. 1, 70-76 (1980).
41. R. V. Pol', Science of Electricity [Russian translation], Fizmatgiz, Moscow (1962).
42. F. L. Sayakhov, V. P. Dyblenko, and I. A. Tufanov, "Investigation of the influence of high-frequency electric field on the surface tension of liquids," Elektron. Obrab. Mater., No. 6, 34-35 (1979).
43. N. K. Adam, Physics and Chemistry of Surfaces [Russian translation], Gostekhizdat, Moscow (1947).
44. A. V. Adamson, Physical Chemistry of Surfaces [Russian translation], Mir, Moscow (1979).
45. T. K. Buraev, I. P. Vereshchagin, and M. M. Pashin, "Investigation of the process of atomization of liquids in an electrostatic field," in: Strong Electric Fields in Technological Processes [in Russian], Énergiya, Moscow (1979), No. 3, pp. 87-105.
46. G. I. Taylor, Electrically driven jets," Proc. R. Soc. London, 313, No. 1515, 453-475 (1969).
47. E. Z. Gak, "Magnetokinetic effects in strong electrolytes in inhomogeneous magnetic fields," Zh. Tekh. Fiz., 41, No. 8, 1758-1759 (1971).
48. F. Roca, "Magnetisme et vitess des reactions chimiques," Ann. Chim., 2, No. 5, 255-261 (1967).
49. A. L. Buchachenko, R. V. Sagdeev, and K. M. Salikhov, Magnetic and Spin Effects in Chemical Reactions [in Russian], Nauka, Siberian Branch, Academy of Sciences of the USSR, Novosibirsk (1978).
50. A. L. Buchachenko, "Magnetic interactions in chemical reactions," in: Physical Chemistry, Contemporary Problems [in Russian], Khimiya, Moscow (1980), pp. 7-48.
51. Yu. N. Molin, "Magnetic effects in chemical radical reactions," Vestn. Akad. Nauk SSSR, No. 8, 13-20 (1981).
52. E. Z. Gak, "Magnetokinetic phenomena in aqueous solutions of electrolytes (Review)," Elektrokhimiya, 12, No. 5 (1976), Dep. VINITI, No. 3511-75.
53. E. Z. Gak, "Effect of a constant magnetic field on the current—voltage characteristics of electrochemical cells," Elektrokhimiya, 3, No. 2, 263-266 (1967).
54. É. Ya. Blum, S. I. Lisovskaya, and P. V. Kulis, "Effect of a magnetic field on the intensity of mass transfer in systems with electrochemical reactions," Izv. Akad. Nauk SSSR, Fiz. Tekh., No. 6, 54-62 (1967).
55. S. I. Lisovskaya, É. Ya. Blum, P. B. Kulis, and A. G. Fedin, "Mass transfer of a circular cylinder in a transverse magnetic field," Izv. Akad Nauk Latv. SSR, Fiz. Tekh., No. 3, 69-73 (1970).
56. O. A. Surzhko, V. A. Korolenko, and V. A. Lyutsdarskii, "Kinetics of some contact reactions in a magnetic field," Proceedings NPI, Research in Applied Electrochemistry [in Russian], Novocherkassk (1970), No. 217, pp. 75-78.
57. N. F. Bondarenko, E. Z. Gak, and N. K. Gindiya, "Application of magnetophores in order to intensify electrochemical processes," Elektron. Obrab. Mater., No. 3, 66-69 (1979).
58. S. Mohanta and T. Fahidy, "Hydrodynamic and mass transport phenomena in a multiple-electrode magnetoelectric cell," J. Appl. Electrochem., 8, No. 1, 5-10 (1978).
59. C. G. Fink and M. A. Coler, "Electrolytic processes in the magnetic field," Trans. Electrochem. Soc., 72, No. 115, 247-280 (1938).
60. L. A. Blyumenfel'd, G. N. Zatsepina, E. Ya. Pozin, and S. V. Tul'skii, "Investigation of the effect of a magnetic field on the spatial distribution of electrical conductivity of water and aqueous solutions of electrolytes established during electrolysis," Zh. Fiz. Khim., 46, No. 8, 2073-2077 (1972).
61. B. Pal, "Variation of electrolytic resistance of $CuSO_4$ solution with magnetic field," Indian J. Appl. Phys., 17, 702-707 (1979).

62. A. P. Shorygin, G. L. Daniélyan, and R. Z. Alimova, "Action of a magnetic field on the characteristics of a capillary mercury-electrolytic cell," Elektrokhimiya, 11, No. 10, 1478-1481 (1975).
63. A. P. Shorygin, É. V. Kazaryan, and R. Z. Alimova, "Action of a magnetic field on jet flows in an electrochemical cell with a microelectrode in the channel," Elektrokhimiya, 15, No. 5, 678-680 (1979).
64. E. Z. Gak, É. E. Rokhinson, and N. F. Bondarenko, "Possibility of electrodynamic effects in electrolytes," Zh. Tekh. Fiz., 44, No. 5, 1076-1079 (1974).
65. E. Z. Gak, É. E. Rokhinson, and N. F. Bondarenko, "Role of volume charges in the kinetics of electrode processes," Elektron. Obrab. Mater., No. 6, 23-28 (1973).
66. B. B. Kadomtsev, Collective Phenomena in Plasma [in Russian], Nauka, Moscow (1976).
67. N. V. Krasnogorskaya, Electricity of the Lower Layers of the Atmosphere and Methods for Measuring It [in Russian], Gidrometeoizdat, Moscow (1978).
68. E. Z. Gak, G. P. Komarov, and M. Z. Gak, "Magnetohydrodynamic and electrohydrodynamic effects in the action of magnetic fields on biological objects," in: Reaction of Biological Systems to Magnetic Fields [in Russian], Nauka, Leningrad (1977), pp. 26-38.
69. E. Z. Gak, "Influence of edge effects of magnetic fields on the motion of paramagnetic particles in fluids," Zh. Tekh. Fiz., 40, No. 8, 1764-1767 (1970).
70. E. Z. Gak, Inventor's Certificate No. 290244, "Method for visual determination of the intensity of inhomogeneous magnetic field intensities," Byull. Izobret., No. 2 (1971).
71. E. Z. Gak and T. G. Zhgenti, Inventor's Certificate No. 324680, "Method for magnetic working of small objects with highly inhomogeneous magnetic fields," Byull. Izobret., No. 2 (1972).
72. E. Z. Gak, "Problem of the effect of external and local magnetic fields on biological objects," Tr. Len. o-va estesvoispytatelei, 76, No. 1, 57-69 (1971).
73. V. M. Kobizskii, O. G. Kadnikov, and G. I. Vitovtova, "Magnetic effects in mass transfer processes," Zh. Tekh. Fiz., 50, No. 2, 398-400 (1980).
74. M. A. Gold'shtik and V. N. Shtern, Hydrodynamic Stability and Turbulence [in Russian], Nauka, Sib. Otd. Akad. Nauk SSSR, Novosibirsk (1977).
75. E. B. Gledzer, F. V. Dolzhanskii, and A. M. Obukhov, Hydrodynamic Systems and Their Application [in Russian], Nauka, Moscow (1981).
76. A. N. Klyatkovskii, V. M. Bobrov, M. I. Apaev, and S. V. Lipkin, "Effect of electromagnetic mixing of commercial electrolyte on the process of electrorefining of copper," in: Metallurgy and Enrichment [in Russian], Alma-Ata (1976), No. 11, pp. 61-68.
77. E. G. Konovalov, N. I. Zhinovich, and V. V. Smekaolova, "Scattering capability of zinc electrolyte with the action of a magnetic field," Izv. Akad Nauk BSSR, Ser. Khim., No. 6, 27-29 (1971).
78. A. V. Leont'ev and A. G. Smirnov, "Mixing of an electrolyte by a transverse magnetic field with electrolytic processes," in: Problems of Magnetic Hydrodynamics, [in Russian], Izd. Akad. Nauk Latv. SSR (1963), pp. 357-361.
79. N. I. Pekhteleva and A. G. Smirnov, "Hydrodynamics of an electrolyte with electrochemical processes in a rectangular bath with flat electrodes in a constant magnetic fields," Magn. Gidrodin., No. 2, 89-92 (1965).
80. Ling Yang, "Effect of rapid cathode rotation in magnetic fields on crystal orientation in electrodeposited metals," J. Electrochem. Soc., 101, No. 9, 456-460 (1954).
81. A. V. Zheleztsov and L. A. Baltina, "Magnetopolarography. Oscillopolarographic investigation of the behavior of ions at the mercury electrode in an external magnetic field," Zh. Anal., Khim., 27, No. 3, 440-445 (1972).
82. E. Z. Gak and G. R. Rik, "Application of magnetohydrodynamic effects in electrolytes for modeling certain transport processes," Zh. Tekh. Fiz., 38, No. 5, 931-934 (1968).
83. M. Z. Gak and N. F. Bondarenko, "Applications of magnetohydrodynamic effects in electrolytes for modeling nonlinear wave processes," Zh. Tekh. Fiz., 46, No. 3, 634-637 (1976).
84. N. F. Bondarenko and M. Z. Gak, "Application of magnetohydrodynamic effects for modeling vortex hydrodynamic processes," Izv. Akad. Nauk SSSR, FAO, 14, No. 2, 207-211 (1978).
85. N. F. Bondarenko, M. Z. Gak, and F. V. Dolzhanskii, "Laboratory and theoretical models of two-dimensional periodic flow," Izv. Akad. Nauk SSSR, FAO, 15, No. 10, 1017-1026 (1979).
86. V. A. Dovzhenko, Yu. V. Novikov, and A. M. Obukhov, "Modeling the generation of vortices in axisymmetrical azimuthal field by a magnetohydrodynamic method," Izv. Akad. Nauk SSSR, FAO, 15, No. 11, 1199-1202 (1979).

87. A. M. Obukhov, G. S. Golitsyn, and F. V. Dolzhanskii, "Problems of geophysical hydrodynamics," in: Some Problems in the Modern Physics of the Atmosphere [in Russian], Nauka, Moscow (1981), pp. 94-118.
88. V. A. Dovzhenko, A. M. Obukhov, and V. M. Ponomarev, "Generation of vortices in axisymmetrical shear flow," Izv. Akad. Nauk SSSR Mekh. Zhidk. Gaza, No. 4, 27-36 (1981).
89. M. Z. Gak, "Laboratory investigation of autooscillations in a system of four vortices," Izv. Akad. Nauk SSSR, FAO, 17, No. 2, 209-213 (1981).