12. V. G. Selivanov, K. I. Soplenkov, and S. D. Frolov, in: Problems of Power Station Gas Thermodynamics [in Russian], No. 2, Kharkov Aviation Institute (1975), p. 19.
13. G. A. Gorbenko, V. G. Selivanov, K. I. Soplenkov, and S. D. Frolov, in: Problems of Power-Station Gas Thermodynamics [in Russian], No. 2, Kharkov (1975), p. 88.

CHANGE IN THE NATURE OF HYDRODYNAMIC CAVITATION IN NONUNIFORM MAGNETIC FIELDS

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It is known that in nonuniform magnetic fields the precavitation properties of aqueous media change, leading to an increase in the irreversible physicochemical changes.

The effect of magnetic fields on the physicochemical processes in aqueous media when there is hydrodynamic cavitation has not been investigated to any great extent. This problem is nevertheless of considerable practical interest for solving the problem of monitoring hydrodynamic cavitation. The results obtained in this paper show the leading part played by hydrodynamic factors in the mechanisms by which magnetic fields act on the properties of technical waters, and may be useful in constructing technological equipment and in choosing its mode of operation.

1. Vortex Formation and Dehydration in the Precavitational Mode. Consider the flowing hydrodynamic system shown in Fig. 1. The length of region II is l, the diameter of the tubes in regions I and III is D, and the diameter of the tube in region II is d, d < D; p_I, p_{II}, p_{III} and V_I, V_{II}, V_{III} are the pressures and velocities in regions I, II, and III, respectively. The flow in region II is turbulent due to hydrodynamic factors and Re = $dV_{II}/\rho/\eta \geq Re_{cr}$.

A flowing system like this one in practice contains dissolved and free gases and microparticles. In 1 cm^3 of natural water there are several hundreds of gas bubbles of diameter from 4 μm to 30 μm and up to $5 \cdot 10^5$ foreign particles of dimensions down to several microns [1]. Technical water contains different ions of electrolytes and has an electrical conductivity σ.

Suppose that in region II there is a nonuniform magnetic field represented by the induction **B** and an induction gradient grad **B**. We will also assume that $B = B_{max}$ on the walls of the magnetic conductor, which is usually a component part of the hydroconductor. Satisfaction of the conditions grad**B** ≠ 0, B ≠ 0 ensures that in region II in the volume of the liquid there will be induced nonuniform electric fields $\mathbf{E} = [\mathbf{V}_{II} \times \mathbf{B}]$ and grad**E** ≠ 0 leading to the occurrence in the volume of the liquid of induced currents of density $\mathbf{j}_i = \sigma[\mathbf{V}_{II} \times \mathbf{B}]$.

When considering flowing liquid media of low conductivity, the spatial distribution of the rotational forces which occur in the liquid under practical conditions [2] becomes of considerable importance. Hence, we will consider the phenomena that arise in aqueous media only when the conditions $\mathbf{j}_i \neq 0$, grad B ≠ 0 are satisfied, which automatically leads to the condition

$$\mathrm{rot}\,\mathbf{f}_{MHD} = (\mathbf{B}\,\mathrm{grad})\,\mathbf{j}_i - (\mathbf{j}_i\,\mathrm{grad})\,\mathbf{B} \neq 0, \tag{1}$$

where

$$\mathbf{f}_{MHD} = [\mathbf{j}_i \times \mathbf{B}]. \tag{2}$$

Note that the effect of large-scale vortex formations in aqueous media when they flow through nonuniform magnetic fields is well known in the literature as an obstacle to the operation of magnetohydrodynamic (MHD) flowmeters [2].

Condition (1) ensures vorticity of the flow in space and time. Under turbulent conditions the values of the MHD forces in the boundary layers are determined not by the value of σ, but by σ_b, $\sigma \ll \sigma_b$ [3].

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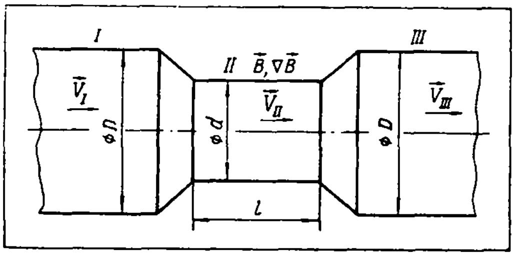

Fig. 1. **Schematic representation of a flowing hydrodynamic system.**

By convection the magnetic induction in the boundary layer is a maximum (B_{max}), and since under turbulent conditions in the boundary layers the values of the velocities become of the same order as the volume velocity, the volume forces in the boundary layers are much greater than in the volume of the liquid and are equal to

$$f_{MHD} = \sigma_b V_{II} B_{max}^2. \tag{3}$$

In actual aqueous systems electrohydrodynamic (EHD) phenomena due to currents in the flow when they interact with the magnetic field become of considerable importance [4]. The space-charge density ρ_{sc} differs from zero in the region of the diffuse parts of the double layers close to the interphase boundaries of length δ_{sc} and since the current density of the flow $j_T = \rho_{sc} V_{II}$, under turbulent conditions

$$f_{MHD,\,b} = V_{II} B_{max} \rho_{sc}. \tag{4}$$

Hence, in the boundary layers under turbulent conditions the MHD forces per unit volumes

$$f_{MHD,\,b} = V_{II} B_{max} (\rho_{sc} + \sigma_b B_{max}). \tag{5}$$

It follows from (5) that it is possible for an additional MHD pressure to occur directly on the walls of the tube and on the surface of microparticles and gas bubbles due to the action of forces, in the majority of cases normal to the surface of the interphase boundaries. These pressures will vary along the length of the tube due to fluctuations in the flow velocity and the nonuniform distribution of the magnetic field in volume II. As the flow velocity increases an even deeper disturbance of the boundary structures will occur until the hydrated layers disintegrate, which occurs when $P_{MHD} \geq \tau_0$ [5]. Taking (5) into account, this condition can be written

$$V_{II} B_{max} l (\rho_{sc} + \sigma_b B_{max}) \geqslant \tau_0. \tag{6}$$

When condition (6) is satisfied a breakup of the hydrated layers can occur as well as short-term impairment of the wetting of the surface, and a reduction in the surface tension of the liquid due to complete or partial compensation of the surface tension forces. The values of the limiting velocity ($V_{II,lim}$) for which the structure of the boundary layers becomes disturbed is found from (6) to be

$$V_{II,\,lim} = \frac{\tau_0}{B_{max} l (\rho_{sc} + \sigma_b B_{max})}. \tag{7}$$

The value of τ_0 varies in the range 10-15 N/m^2 [6]. It follows from (7) that small limiting velocities are reached only for values of the induction greater than 1.0 T, which is usually limited by technical considerations. On the other hand, the formation and breakdown of vortices, dehydration processes, and, under cavitation conditions, an increase in cavitation bubbles, require a finite time of not less than 0.1-0.05 sec, which sets an upper limit to the flow velocity. These phenomena may lead to an extremal form of the dependence of the rate of different physicochemical processes in aqueous media on the induction and flow rate. In addition, since τ_0, σ, σ_b may depend on the properties of the liquid, the surfaces of separation, and the gas content, in a number of cases these relations may have a polyextremal form.

Note that when nonstationary magnetic fields are present, similar phenomena will be observed at lower values of B and V_{II} due to the occurrence of additional MHD and EHD forces in the liquid. Since the value of τ_0 is relatively constant we can regard the product on the left-hand side of inequality (6) as constant for this type of magnetic system. The optimum values of V_{II} and B will vary depending on the concentration of the electrolyte containing free and dissolved gases and the presence of impurities in the form of microparticles.

2. Quantitative Estimates and Model Experiments. We will estimate the value of the MHD pressure developed in volume II of the tube by the forces which arise. Taking (3) into account, we can write

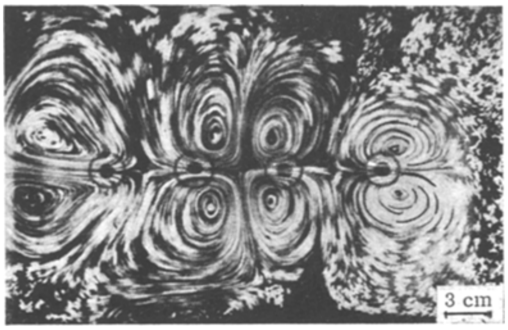

Fig. 2. Photograph of the MHD flows in a layer of electrolyte 0.005 m thick in nonuniform magnetic fields when the electric current is fed in by conduction. The exposure time is 2 sec.

$$p_{\mathrm{MHD}} = \sigma V_{II} B^2 l. \tag{8}$$

For $\sigma = 10\ \Omega^{-1}\cdot m^{-1}$, $V_{II} = 10$ m/sec, B = 0.1 T, and l = 1 m we obtain from (8) the value $p_{MHD} = 1\ N/m^2$; the time of flow through tube II is 0.1 sec. In the boundary layer where p_{MHD} is given by (5), it is possible for p_{MHD} to increase by 1-2 orders of magnitude to values $p_{MHD} \approx 10\text{-}15\ N/m^2$. This is due to the effect of dehydration of the boundary layers at flow velocities on the order of 1-5 m/sec. At the same time, under laminar flow conditions when the velocities in the boundary layers are small, vortex formation due to p_{MHD} is small and all the effects mentioned above are negligible or, in general, not present.

For an experimental investigation of the vortex structures which arise, their interaction, and the loss in stability of the flow, we studied MHD phenomena in a plane horizontal thin layer of liquid without a hydrodynamic pressure. Note that in this experiment the volume MHD forces corresponded in order of magnitude to the values obtained from expression (8). The experimental arrangement enabled us to observe and record two-dimensional vortex structures and the instants at which turbulence occurred. We used different types of permanent magnet systems of considerable length having large field values only close to the surface as the sources of nonuniform magnetic field. The thickness of the liquid layer was on the order of 0.005-0.01 m and was chosen so that the values of the induction B and grad B were considerable ($B \geq 10^{-2}$ T and grad B ≥ 0.1-1 T/cm). In the experiment the current was fed by conduction from an external dc source parallel to the surface of the liquid, grad j = 0. The current density was varied in the range $10^2\text{-}10^3\ A/m^2$. To prevent vibration the electrodes were made in the form of massive copper plates rigidly fastened to the walls of the cuvette. The flow was visualized using particles of lycopodium and was photographed using the Zenit apparatus with an exposure of 2 sec. In a closed rectangular cell filled with an aqueous solution of 1N $CuSO_4$, for small magnetic field nonuniformities, we observed vortex structures with a vortex scale on the order of the dimensions of the cell. In the case of polygradient magnetic fields, we observed a breakdown of the vortices, and the occurrence of flows of different scales determined by the dimensions of the individual terminals (Fig. 2). We used a set of barium ferrite rings (grade 2.8 VA) 30 mm in diameter magnetized in an axial direction (B_{max} = 0.05 T) as the sources of polygradient nonuniform magnetic field. The rings had alternating polarity of the magnetic poles. The dimensions of the poles were much less than the surface of the liquid. The velocities of the liquid in the vortex structures were 0.01-0.2 m/sec.

For certain values of the current density there was a loss in stability of the flow and a change from macroscale structures into fine-scale structures.

It follows from the model experiments and theoretical considerations that in regions close to the poles of the nonuniform magnetic field sources, zones of constant vorticity are formed. The vortex model of turbulence given in [7] applied to these regions. The vortex zone is separated from the surface where it is formed, and begins to move in the main flow. Then in view of the motion in this zone besides the velocity V_{II} of the main flow there will also be a component of the velocity perpendicular to V_{II}. This moving vortex zone gives rise to turbulent mixing in the liquid layer, the dimensions of which exceed tenfold the dimensions of the scale of the magnetic field nonuniformity on the tube surface.

Nonuniform magnetic fields: B, grad B

↓

Nonstationary open system – a region of hydrodynamic cavitation in a flowing liquid containing gas bubbles and microparticles:
$Re > Re_{cr}$, $\mathrm{rot}\, V \neq 0$, $j \neq 0$, $\mathrm{grad}\, j \neq 0$, $\rho_{sc} \neq 0$, $E \neq 0$, $\mathrm{grad}\, E \neq 0$

↓

MHD and EHD effects in aqueous media and on interphase boundaries:
$f_{MHD} = [\mathbf{j} \times \mathbf{B}]$, $\mathrm{rot}\, f_{MHD} \neq 0$, $f_{EHD} = \rho_{sc} E + \frac{\varepsilon_g - \varepsilon_l}{2}\, \mathrm{grad}\, E^2$

↓

MHD activation of physicochemical processes when there is cavitation
$c'_{gf} > c^{\circ}_{gd}$ $p'_{cr} > p^{\circ}_{cr}$, $V'_{cr} < V^{\circ}_{cr}$

↓

Irreversible physicochemical processes in aqueous media – increase in the concentration of free gas, atomic oxygen, the formation of peroxides, crystallization, and coagulation.

Fig. 3. A scheme showing the physicochemical mechanism by which nonuniform magnetic fields act on a flowing aqueous system when there is hydrodynamic cavitation present.

Hence, the occurrence of rotational MHD forces under all flow conditions in region II gives rise to intense breakdown of the macroscale vortex structures, a loss in stability, and turbulence of the flow at velocities less than the velocities when there is no magnetic field. In the boundary regions variable MHD pressures occur due to the presence of $\mathrm{grad}\, B \neq 0$ on the walls of the magnetic conductor, which leads to intense breakdown of the boundary layer, its breakdown from below with respect to the flow, and intense vortex formation.

Note that the particular feature of the action of the MHD forces on aqueous media is deep disturbance of the boundary layer. A similar disturbance is only possible when the liquid is heated in the region of this layer [8].

The generally accepted representations of the decay of turbulence in a magnetic field and laminarization of the flow only hold for systems with very large σ and when $\mathrm{rot}\, f_{MHD} = 0$. In our case this is not satisfied [2]. At the same time, the transition of the macroscale turbulence into fine-scale turbulence in nonuniform magnetic fields leads to a transfer of the turbulence spectrum into the higher-frequency region, which leads to considerable dissipation of the flow energy.

3. Hydrodynamic Cavitation. We will consider the case of cavitation separately. Suppose that in region II, $p_{II} = p_{cr}$, where p_{cr} is the pressure at which cavitation occurs in the liquid. For convenience in classifying the phenomena that occur in an aqueous medium when acted upon by nonuniform magnetic fields with induction B and $\mathrm{grad}\, B \neq 0$, we present the scheme shown below. The region II can be regarded as an open system which exchanges material and energy with regions I and III. It is represented by $Re > Re_{cr}$, by the vortex formations $\mathrm{rot}\, V_{II} \neq 0$, by the electric currents in the volume of the liquid and in the boundary layers with density $j \neq 0$ and $\mathrm{grad}\, j \neq 0$, where $j = j_i + j_b$, by the space charges in the region of the diffuse layers and the diffuse double layers close to the interphase boundaries of the gas bubbles and the microparticles $\rho_{sc} \neq 0$, and by the nonuniform electric fields $E \neq 0$ and $\mathrm{grad}\, E \neq 0$. As in the examples considered, in a flowing system under cavitation conditions MHD forces arise represented by the quantity $\mathrm{rot}\, f_{MHD} \neq 0$. The EHD effects also acquire considerable importance due to the presence of $\rho_{sc} \neq 0$, and due to the fact that in the two-phase system considered the dielectric constant of the liquid may vary abruptly over a large range. Thus, whereas in the region of a continuous aqueous medium $\varepsilon_l = 80$, in vapor–gas bubbles $\varepsilon_g = 1$, and in the region of the diffuse layers in the low-frequency and very-low frequency region due to macroscopic space charges of the diffuse layer $\varepsilon_d = 10^5$-10^6 [3]. In general,

$$f_{EHD} = \rho_{sc} E + \frac{\varepsilon_l - \varepsilon_g}{2}\, \mathrm{grad}\, E^2 \qquad (9)$$

and facilitates additional vortex formation, pulsation of the gas bubbles, and dehydration of the particles. In view of the complexity of a quantitative estimate of the value of the space charge which occurs in the liquid, and the nonstationary nature of the processes, in this paper we will only give a qualitative estimate of these quantities for hydrodynamic cavitation and nonuniform magnetic fields.

We will consider the processes which lead to a change in the hydrodynamic cavitation.

One of the most important quantities characterizing hydrodynamic cavitation is the critical pressure p_{cr}. Until recently, the quantity p_{sv} was taken as the value of p_{cr}. However, for actual technical water the critical pressure at which cavitation occurs depends on the gas content and can be approximated by the expression [1]

$$p_{cr} = \frac{p_a \sqrt{2\alpha} + p_{sv}}{1 + \sqrt{2\alpha}}, \tag{10}$$

where $\alpha = c_{gf}/c_{gd}$. In a fixed liquid or in a flow with relatively low velocities the concentration of free gas is negligible ($\alpha = 10^{-9}$–10^{-10}) and $p_{cr} = p_{sv}$. When intense convective motion of the liquid occurs and, in particular, when the flow has a vortex character the concentration of free gas even in the precavitation flow state and at relatively low velocities increases by several orders of magnitude to a value $\alpha = 10^{-2}$–10^{-3} [9]. Thus, for $\alpha = 10^{-2}$, $t° = 20°C$, and $p_a = 1$ atm, $p_{sv} = 0.02$ atm and p_{cr}, from (10), is 0.16 atm, which is an order of magnitude higher than p_{sv}.

This increase in the concentration of free gas is due to convection in the liquid, which intensifies the mass transfer of gas from the liquid into the microbubbles (turbulent diffusion), and the reduction in the pressure at the center of the vortex structure, which leads to the occurrence of gas "suction" at the center of the vortex. The more intense the process of vortex formation in the liquid, the greater the region with reduced pressure, and the higher the concentration of free gas and the greater the number of cavitation nuclei in the flow irrespective of the cause of the vortex formation.

Obviously, the dehydration effect when $p_{MHD} > \tau_0$ is an additional source of cavitation nuclei since the presence of unwetted surfaces intensifies cavitation effects [1, 12], and may be an additional source for the increase in p_{cr}.

Hence, the occurrence of MHD and EHD effects in the region of hydrodynamic cavitation leads to an increase in the concentration of free gas, ($c'_{gf} > c^0_{gf}$), to an increase in the critical pressure ($p'_{cr} > p^0_{cr}$), and to a reduction in the critical cavitation velocities ($V'_{cr} < V^0_{cr}$).

The action of nonuniform magnetic fields should also change the course of irreversible physicochemical phenomena, and, primarily, of heterogeneous processes in regions II and III. The occurrence of turbulent diffusion increases by many orders of magnitude the transport of gas from the volume of the liquid to the surface of the microbubbles. The effect of local dehydration of the ions and particles gives rise to an intensification of microcrystallization processes [5, 11]. In the cavitation zone intensive separation of free gas and vapor occurs, and vibrations occur in the liquid and in the constructional components over a wide frequency spectrum, electrical discharges develop when the electric field strength at the boundaries of the bubbles reaches 10^6–10^7 V/m on collapse, and microheating of the liquid occurs [1, 12-13]. In flowing media, due to the very high energy reactions, free radicals, atomic oxygen, peroxides, and nitrogenous compounds may be formed, coagulation may take place, and products of erosion breakdown may fall into the liquid. When there is hydrodynamic cavitation, the large dimensions of the bubbles and caverns formed (from a few to tens of millimeters) makes it difficult for them to transfer from the region of reduced pressure to the region of high pressures, where collapse of the bubbles occurs. When bubbles of small size on the order of 10-100 μm with a low air content collapse, intense chemical reaction occurs similar to a plasma discharge. The presence of nonuniform magnetic fields leads to an increase in the instability of the caverns and they decay and produce in region II small-scale vortices and bubbles. The intense vortex formation in the boundary layers facilitates the transfer of bubbles of gas into region II, and hence regions II and III therefore perform the function of a "chemical reactor." Since the pressure is reduced at the center of a vortex [13], the vortices, in effect, "conserve" the gas bubbles of small size. The irreversible changes which occur in the flow can be regarded as a "memory" of the liquid of the physical phenomena occurring in it. This has been shown experimentally in [11, 14] where an increase in the content of atomic oxygen and hydrogen peroxide was observed after solutions pass through magnetic fields. Obviously, in nonuniform magnetic fields the nature of the hydrodynamic cavitation changes and approximates to acoustic cavitation.

The main difference between the phenomena we have considered the is fact that all the effects which occur are due to the energy of the hydrodynamic flow, whereas in acoustic cavitation the energy is supplied from an external source via electroacoustic transducers.

The results obtained above enable one to conclude that the action of nonuniform magnetic fields on the processes which occur in hydrodynamic cavitation can provide a new effective method for the MHD activation of aqueous systems.

At the same time, an analysis of the experimental results on the action of magnetic fields on natural water [5, 10-11, 15, 16] has shown that the greatest irreversible physicochemical changes in the properties of aqueous systems occur when the following conditions are satisfied: the presence of turbulent flow ($Re > Re_{cr}$), the presence of hydrodynamic cavitation, and the presence of nonuniform magnetic fields in the boundary layers of the liquid with $\mathrm{grad}\, B \geq 0.1$-1 T/cm, in which case the highest values of the fields should be observed at the solid–liquid boundary ($B \geq 0.01$-1 T). The absence of turbulence and particularly of hydrodynamic cavitation may mean that these effects will not occur even for high values of the magnetic induction [17].

NOTATION

l	is the length of zone II;
D and d	are the diameters of tubes I, III, and II;
p_I, p_{II}, p_{III}	are the pressures in regions I, II, and III;
p_{cr}	is the critical pressure at which cavitation occurs;
p'_{cr} and p^0_{cr}	are the critical pressures in the magnetic field and when there is no magnetic field;
[V_I, V_{II}, V_{III}]	are the velocities of the liquid in regions I, II, and III;
$V_{II,lim}$	is the velocity of the liquid at which breakdown of the hydrated layer occurs for a certain value of the induction;
V'_{cr} and V^0_{cr}	are the critical velocities at which cavitation occurs in the magnetic field and when there is no magnetic field;
p_a	is the atmospheric pressure;
p_{sv}	is the saturation-vapor pressure at the given temperature;
ρ	is the density of the liquid;
η	is the kinematic viscosity;
Re	is the Reynolds number;
Re_{cr}	is the critical Reynolds number;
c_{gf} and c_{gd}	are the concentrations of free and dissolved gases in the magnetic field and when there is no magnetic field;
c'_{gf} and c'_{gd}, and c^0_{gf} and c^0_{gd},	are the concentrations of free and dissolved gases in the magnetic field and when there is no magnetic field;
ρ_{sc}	is the space-charge density;
σ	is the electrical conductivity in the volume of the liquid;
σ_b	is the electrical conductivity in the boundary layer;
ε_l, ε_g, ε_d	are the dielectric constants of the liquid in the volume, of the gas in the bubbles, and of the diffusion layer;
j, j_b, j_i, and j_T	are the current density of the general, boundary layer, induced and current flow;
f_{MHD} and f_{EHD}	are the volume forces of magnetohydrodynamic and electrodynamic nature (per unit volume);
p_{MHD}	is the pressure in the liquid due to the action of the magnetohydrodynamic forces;
τ_0	is the limiting shear stress in the liquid;
B	is the magnetic induction;
E	is the electric field strength in the volume of the liquid.

LITERATURE CITED

1. V. M. Orgo, Hydroturbines [in Russian], Leningrad State Univ. (1975).
2. J. A. Shercliffe, Textbook of Magnetohydrodynamics, Pergamon (1965).
3. S. S. Dukhin and V. N. Shilov, Dielectric Phenomena and the Double Layer in Disperse Systems and Polyelectrolytes, Halsted Press (1975).
4. N. F. Bondarenko, E. Z. Gak, and G. P. Komarov, Zh. Tekh. Fiz., 43, No. 1, 222; No. 3, 676 (1973).

5. E. Z. Gak, N. F. Bondarenko, and É. E. Rokhinson, Proceedings of the Third All-Union Seminar "Problems of the Theory and Practice of the Magnetic Processing of Water and Aqueous Systems," Novocherkassk (1975), p. 57.
6. N. F. Bondarenko, Physics of the Flow of Subterranean Water [in Russian], Gidrometeoizdat, Moscow (1973)
7. M. A. Lavrent'ev and B. V. Shabat, Problems of Hydrodynamics and Their Mathematical Models [in Russian], Nauka, Moscow (1973).
8. G. Z. Gershuni and E. M. Zhukovitskii, Convective Stability of an Incompressible Liquid [in Russian], Nauka, Moscow (1972).
9. L. R. Gavrilov, in: Physical Principles of Ultrasonic Technology [in Russian], Vol. 3, Nauka, Moscow (1970), p. 395.
10. V. A. Boichenko and L. G. Sapogin, Inzh.-Fiz. Zh., 33, No. 2 (1977).
11. V. I. Klassen, Gornyi Zh., No. 6 (1976).
12. Ya. I. Frenkel', Collected Works [in Russian], Vol. 3, Izd. Akad. Nauk SSSR, Moscow–Leningrad (1959).
13. R. T. Knapp, et al., Cavitation, McGraw-Hill (1970).
14. V. Patrovsky, Mol. Phys., 31, No. 4 (1976).
15. D. A. Grigor'ev, N. F. Bondarenko, É. E. Rokhinson, and E. Z. Gak, Gidrotekh. Melior., No. 10 (1976).
16. N. N. Kruglitskii, Physical-Chemical Mechanics of Disperse Structures in Magnetic Fields [in Russian], Naukova Dumka, Kiev (1976).
17. L. A. Baranov and Sh. Sh. Gubaidullin, Tr. KuzNIIUgleobogasheniya, No. 5, 208 (1970).

SLIGHTLY NONEQUILIBRIUM CONDENSATION OF A SATURATED VAPOR ON A LIQUID SURFACE

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UDC 536.423.4

A solution of the Barnett equations is obtained for the problem of slightly nonequilibrium vapor condensation on a liquid surface. It is shown that a Barnett sublayer with nonzero pressure gradient exists inside the nonequilibrium wall layer. The sublayer diminishes the interphase condensation resistance and induces supersaturation of the vapor.

In the present article we solve the problem of steady-state slightly nonequilibrium ("slow") condensation of a saturated vapor on a plane infinite liquid surface on the basis of the simplified Barnett equations [1]. The most complete statement of this problem is obtained within the framework of the kinetic theory of gases, where it is known to be reducible to the solution of the Boltzmann equation with the appropriate boundary condition on the surface of the condensed phase. However, under the condition of slight nonequilibrium of the condensation process the state of the vapor outside a certain Knudsen "wall layer" can be described in terms of hydrodynamical equations derived from the Boltzmann equation by the Chapman–Enskog method. The boundary conditions necessary for closing the hydrodynamical equations are deduced from the solution of the Boltzmann equation (or a modification thereof) in the Knudsen wall layer. The Navier–Stokes equations are usually used here.

In this setting, boundary conditions have been obtained for mass flux toward the surface (of the Hertz–Knudsen type) and for a temperature jump [3-7]. The temperature distribution in a nonequilibrium vapor layer has also been found [3] on the basis of the Navier–Stokes equations.

Below we formulate the slightly nonequilibrium condensation problem on the basis of the simplified Barnett distribution function obtained in [1] by a modified Chapman–Enskog method. From this function and the conditions of mass, energy, and normal momentum balance inside the vapor volume we use the standard procedure to obtain the Barnett equations, in which the one-dimensionality of the vapor flow is automatically taken into account. From the simplified Barnett function and these same balance conditions on the surface of the condensed phase we deduce boundary conditions by the classical method of Maxwell [9], closing the Barnett equations.

The stated problem is solved correct to first-order terms in the difference between the vapor pressures at infinity and on the liquid surface. We perform numerical calculations for the case of steam.

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