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ELECTROCONVECTON AND HEAT EXCHANGE IN DISPERSED GAS–LIQUID SYSTEMS

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The problem of momentum, energy, and electrical charge transport is formulated for gas–liquid dispersed systems; electroconvection, heat liberation, and interphase heat exchange are considered, and practical applications of such studies in diffuser systems are described.

Introduction. In a number of branches of industry, such as thermal energy production and chemical and food technology processes in which a gas interacts with a liquid are often used, and they are often carried out under bubbler conditions to intensify them. The main questions involved in study of such processes are the hydrodynamics of the gas–liquid layer, removal of the liquid phase, heat-mass transport and organization of various processes both in the bubble layer and the vapor–gas space.

The action of electric fields can significantly intensify heat exchange in gas–liquid media. To a certain extent such questions have been investigated in bubble boiling [1]. It follows from data available in the literature on the problem of heat exchange in bubble-

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layer processes that in the dependence of the bubbler plate heat liberation coefficient on gas velocity one can distinguish at least three regions, with the dependence being self-similar in two of these [2]. There are studies which indicate that under certain conditions an electric field can intensify interphase heat exchange.

The mechanism of electric-field action in bubbling processes is related to the effect of electroconvection on the hydromechanical state of the phases: the change in the phase thermodynamic properties in an electric field is negligibly small compared to electroconvective phenomena [3].

The absence of a unified viewpoint on this problem and the extreme lack of data, especially experimental, on the effect of an electric field stimulated our study of the question.

Momentum, Energy, and Electrical Charge Transport in Gas–Liquid Dispersed Systems. One method of describing the interrelated processes which occur in such systems is based on the concepts of the mechanics of a continuous medium, although in formulating problems consideration of electrical fields is either a special case [3-5] or absent [6].

We will consider the system formed upon escape of a gaseous phase into a liquid medium and divided by the free liquid surface into the bubble region Ω' and the vapor–gas volume Ω'', in which the liquid phase is dispersed and carried off. Before the process commences the region Ω' is filled with liquid, while Ω'' is filled by gas, and the regions are in a state of thermodynamic equilibrium which, in particular, assumes absence of macroscopic motion of the phases $(v_1')_0 = (v_1'')_0 = 0$ and uniform temperature distribution over volume $(T_1')_0 = (T_1'')_0 = T_0$.

At the beginning of the process (t = 0) a vapor–gas flow with parameters $(G_2')_0$, $(T_2')_0$, $(\rho_{2v}')_0$, and $(n_{2I}')_0$ bubbles through the liquid (region Ω') in the form of bubbles with a mean breakaway radius $(a')_0$. On the surface s bubbles are generated in the form of the dispersed system medium Ω'', while liquid is dispersed into droplets with characteristics $(2a'')_s$, $(\ _2'')_s$, and $(n'')_s$.

At the initial time (t = 0) in region Ω'' an ionized vapor–gas flow appears with parameters $(G_1'')_0$, $(T_1'')_0$, $(\rho_{1v}'')_0$, and $(n_{1I})_0$. From the region Ω'' a flow of liquid electroaerosol is extracted with phase transitions occurring on the phase boundaries.

We consider the assumptions of [5, 6] and neglect collisions between unipolarly charged droplets and bubbles.

We then require the time and space distribution of v_i, v_{ra}, a, n, α_i, j_{12}, j_{21}, T_i, T_σ, ρ_i, P_i, P_σ, E, φ, ρ_{eI}, and j_e in the regions Ω' and Ω''.

We calculate the distributions of these parameters for the region Ω' until the process reaches a steady state, where

$$\frac{\partial T_i}{\partial t} = 0, \quad \frac{\partial P_i}{\partial t} = 0, \quad \frac{\partial \rho_i}{\partial t} = 0, \tag{1}$$

and for the region Ω'', in addition, until thermodynamic equilibrium is reached between the phases

$$\alpha_2'' = \alpha_{2E} \quad \text{or} \quad \rho_v'' = \rho_{vE}. \tag{2}$$

Within the concepts of [3, 4, 6, 7] we represent the problem by the system of equations

$$\frac{\partial \rho_i}{\partial t} + \nabla(\rho_i v_i) = \pm n(j_{21} - j_{12}); \quad \frac{\partial n}{\partial t} + \nabla(n v_2) = \psi; \tag{3}$$

$$\frac{da}{dt} = v_{ra} + \frac{j_{12} - j_{21}}{4\pi a^2 \rho_{2a}^0}; \tag{4}$$

$$\frac{dv_{ra}}{dt} = \frac{1}{a(1 - 1.1\alpha_2^{1/3})}\left[\frac{\alpha_1(P_2 - P_1 - 2\sigma/a)}{\rho_1^0} - \frac{4\mu_1\alpha_1}{a\rho_1^0} - \right. \tag{5}$$

$$\left. - \frac{3(\alpha_1 - 1.47\alpha_2^{1/3} + 0.33\alpha_2}{2} v_{ra}^2 + \frac{(v_2 - v_1)^2}{4}\right];$$

$$\rho_i\left[\frac{\partial \mathbf{v}_i}{\partial t}+(\mathbf{v}_i\cdot\nabla)\,\mathbf{v}_i\right]=\alpha_i\left[-\nabla P^*+\nabla^k\tau^k_{*1}-n\,(j_{12}-j_{21})(\mathbf{v}_2-\right.$$
$$\left.-\mathbf{v}_1)\right]\pm\alpha_1 n\mathbf{F}^*+\rho_i\mathbf{g}+\mathbf{f}_{ei}; \tag{6}$$

$$\mathbf{E}=-\nabla\varphi; \tag{7}$$

$$\varepsilon_0\nabla(\varepsilon\mathbf{E})=\sum_{i=1}^{2}\rho_{ei}; \tag{8}$$

$$\mathbf{j}_e=\sigma_e\mathbf{E}+\sum_{i=1}^{2}\rho_{ei}\mathbf{v}_i+\varepsilon_0\frac{\partial(\varepsilon\mathbf{E})}{\partial t}; \tag{9}$$

$$\sum_{i=1}^{2}\frac{\partial\rho_{ei}}{\partial t}+\nabla\mathbf{j}_e=0; \tag{10}$$

$$\rho_1\frac{dk_{v1}}{dt}=-n\,(\alpha_1\mathbf{F}_m+\mathbf{F}_\mu)(\mathbf{v}_2-\mathbf{v}_1)-3\rho_1^0\alpha_2 v_{ra}(\mathbf{v}_2-\mathbf{v}_1)^2- \tag{11}$$
$$-\eta_f n\mathbf{F}_\mu(\mathbf{v}_2-\mathbf{v}_1)-\eta_k\frac{\mu_1}{a^2}k_{v1}-n\,(j_{12}-j_{21})\left[\frac{(\mathbf{v}_2-\mathbf{v}_1)^2}{2}-k_{v1}\right];$$

$$[\alpha_i\rho_i^0 c_{pi}+\alpha_i\beta_i P_i(\gamma_i T_i-1)]\left(\frac{\partial T_i}{\partial t}+\mathbf{v}_i\nabla T_i\right)+\frac{\alpha_i\gamma_i P_i T_i}{\rho_i^0}\times$$
$$\times\left(\frac{\partial\rho_i}{\partial t}+\mathbf{v}_i\nabla\rho_i\right)=-4\pi a^2 n\beta_{ti}(T_i-T_\sigma)\mp n\,(j_{12}-j_{21})\left[(c_{pi})_a T_\sigma-\right.$$
$$\left.-c_{pi}T_i-\frac{P_{ia}}{\rho_{ia}}+\frac{P_i}{\rho_i^0}\right]+Q_i^*; \tag{12}$$

$$\left[\frac{\partial\sigma}{\partial T_\sigma}-T_\sigma\frac{\partial\sigma}{\partial T_\sigma}\frac{\partial^2\sigma}{\partial\sigma\partial T_\sigma}-T_\sigma\frac{\partial^2\sigma}{\partial T_\sigma^2}-\frac{\partial T_\sigma}{\partial\sigma}\left(\frac{\partial\sigma}{\partial T_\sigma}\right)^2\right]\left(\frac{\partial T_\sigma}{\partial t}+\right.$$
$$\left.+\mathbf{v}_2\nabla T_\sigma\right)-\frac{2T_\sigma}{a}\frac{\partial\sigma}{\partial T_\sigma}\frac{da}{dt}=\sum_{i=1}^{2}\beta_{ti}(T_i-T_\sigma)+(j_{12}-j_{21})\times$$
$$\times\left(\frac{\mu_1 v_{ra}}{\pi a^3\rho_1^0}\pm\frac{r^*}{4\pi a^2}\right); \tag{13}$$

$$\frac{\partial\rho_{n1}}{\partial t}=D_{n1}\nabla^2\rho_{v1};\quad\frac{\partial\rho_{v2}}{\partial t}=D_{v1}\left(\frac{\partial^2\rho_{v2}}{\partial r^2}+\frac{2}{r}\frac{\partial\rho_{v2}}{\partial r}\right); \tag{14}$$

$$\rho_2^0 c_{p2}\frac{\partial T_2'}{\partial t}-\frac{\partial P_2'}{\partial t}=\lambda_2\left(\frac{\partial^2 T_2'}{\partial r^2}+\frac{2}{r}\frac{\partial T_2'}{\partial r}\right)-(c_{p2}-c_{p1})(j_{12}-j_{21})\frac{\partial T_2'}{\partial r};$$

$$\rho_2^0 c_{p2}\frac{\partial T_2''}{\partial t}=\lambda_2\left(\frac{\partial^2 T_2''}{\partial r^2}+\frac{2}{r}\frac{\partial T_2''}{\partial r}\right). \tag{15}$$

Equation (3) reflects conservation of mass for each phase and conservation of the volume concentration of bubbles and droplets in the dispersed phase, where $\rho_i=\alpha_i\rho_i{}^0$, $\alpha_1+\alpha_2=1$, and $\alpha_2=4\pi a^3 n/3$. Here and below, the upper sign (+ or −) is taken for the phase i = 1, and the lower for the phase i = 2, unless otherwise noted. Mass exchange intensity in the region Ω' is defined by the diffusion equation within the dispersed particle

$$j_{12}'=-j_{21}'=-\frac{\rho_2^0 D_{v2}}{1-\rho_{va}}\left(\frac{\partial\rho_{v2}}{\partial r}\right)_{r=a}+\rho_2^0\rho_{va}\frac{da}{dt}, \tag{16}$$

which can be solved jointly with the first expressions of Eqs. (14) and (15). In the region Ω'' the mass exchange intensity is determined by the criterial equation of mass liberation from the phase boundary into the carrier phase [7]:

$$j''_{12} = -j''_{21} = \frac{D_{v1}\rho_1^0(\rho_{va} - \rho_{v1})}{2a}\left\{2 + 0.625\left(\frac{\mu_1}{\rho_1^0 D_{v1}}\right)^{1/3}\left[(v_2 - v_1)\frac{2a\rho_1^0}{\mu_1}\right]^{1/2}\right\}, \tag{17}$$

which is solved jointly with the second equations of Eqs. (14) and (15).

Equation (4) describes radial motion of the phase boundary of a dispersed particle, pulsations of which are defined by the generalized Rayleigh–Lamb equation (5).

The hydrodynamic state of each phase is defined by Navier–Stokes equation (6), where

$$\tau_{*1}^{kl} = 2\mu_{ef1}\left(e^{kl} - \frac{1}{3}\delta^{kl}\nabla v_1\right) - \frac{1}{2}\rho_1^0\alpha_2\left[(v_2 - v_1)^k(v_2 - v_1)^l - \right. \\ \left. - \frac{1}{3}\delta^{kl}(v_2 - v_1)^2\right]; \tag{18}$$

$$e^{kl} = \frac{1}{2}\left(\frac{\partial v_1^k}{\partial x_*^l} + \frac{\partial v_1^l}{\partial x_1^k}\right); \tag{19}$$

$$P^* = \alpha_1 P_1 + \alpha_2(P_2 - 2\sigma/a) + \rho_1^0\alpha_2\left[v_{ru}^2 + \frac{(v_2 - v_1)^2}{6}\right]; \tag{20}$$

$$F^* = F_\mu + F_m + F_\omega + F_{\Delta P} + F_B; \tag{21}$$

$$f_{e1} = \rho_{e1}E - \frac{1}{2}\varepsilon_1 E^2\nabla\varepsilon + \frac{1}{2}\varepsilon_0\nabla\left[\rho_1^0 E^2\left(\frac{\partial\varepsilon_1}{\partial\rho_1^0}\right)_{T_1}\right]; \quad f_{e2} = \rho_{e2}E. \tag{22}$$

Equation (18) is a reduced viscous stress tensor, where the external deformation rate tensor is described by Eq. (19). Equations (20)-(22) describe generalized interphase pressure and force, as well as electrical force density within the phases. Equations for the forces written in Eq. (21) were given in [6]; their relative values can be estimated from the criterion

$$L = 2a\sqrt{\frac{\rho_1^0}{\mu_1 t_*}} = \sqrt{\mathrm{St}\,\mathrm{Re}}. \tag{23}$$

For $L \ll 1$ (Re $\ll 1$), $F_m \ll F_B \ll F_\mu$ and we may limit ourselves to the viscous friction force, while for $L \gg 1$ (Re $\ll 1$), $F_m \gg F_B \gg F_\mu$ and we consider only "combined mass" force.

The volume charge density ρ_{e1} appearing in Eq. (22) has a Boltzmann distribution, distorted by the presence of excess charge of one sign $n_I^{\pm}$ from ionized gas flows

$$\rho_{e1} = -2(\rho_{e1})_0\,\mathrm{sh}\left(\frac{q_I\varphi}{kT_1}\right) \pm (n_{1I}^{\pm})_0 q_I \exp\left(\mp\frac{q_I\varphi}{kT_1}\right), \tag{24}$$

where in the region Ω' $(n_{1I}^{\pm})_0 = (n_{1I}')_0$, and in the region Ω'', $(n_{1I}^{\pm})_0 = (n_{1I}'')_0$. Here $(n_{1I})_0$ defines charge diffusion from the dispersed phase volume into the carrier phase volume. If $n_I^{\pm} = 0$, the kinetics of dispersed phase particle charging are defined by the expression

$$\rho_{e2} = [q_\infty + (q_0 - q_\infty)\exp(-t/\tau)]\,n, \tag{25}$$

where $q_0 = 3(\varepsilon_1 - \varepsilon_2)\varepsilon_0\pi a^2 E/(\varepsilon_2 + 2\varepsilon_1)$ and $q_\infty = 3(\sigma_{e1} - \sigma_{e2})\varepsilon_0\pi a^2 E/(\sigma_{e2} + 2\sigma_{e1})$ are, respectively, the initial and limiting particle charges; $\tau = \varepsilon_0(\varepsilon_2 + 2\varepsilon_1)/(\sigma_{e2} + 2\sigma_{e1})$ is the characteristic time of the charging process. For low conductivities σ_{e1} and σ_{e2} and $n_I^{\pm} \neq 0$, the dispersed phase charging kinetics are defined by [6]

$$\rho_{e2} = 4\pi\varepsilon_0 E n a^2\left(1 + 2\frac{\varepsilon_2 - \varepsilon_1}{\varepsilon_2 + 2\varepsilon_1}\right)\frac{q_I(n_{1I}^{\pm})_0 b_I t}{4\varepsilon_0 + q_I(n_{1I}^{\pm})_0 b_I t}. \tag{26}$$

For rot E = 0, the relationship between electric field intensity and potential is determined by Eq. (7), while they themselves are found with Poisson equation (8).

The transport current density in Eq. (9) is composed of the mixture conductivity current $\sigma_e \mathbf{E}$, the convection current $\sum_{i=1}^{2} \rho_{ei} \mathbf{v}_i$, and the displacement current $\varepsilon_0 \frac{\partial \varepsilon \mathbf{E}}{\partial t}$. In the nonsteady case the equation of continuity of the total current has the form of Eq. (10).

The energy equations for the system include Eq. (11) for the kinetic energy k_{v1} of fine-scale motion produced by noncoincidence in phase velocities, while Eqs. (12) and (13) are written for each phase, including the σ-phase, where the additional term is

$$Q_1^* = \nabla(\lambda_1 \nabla T_1) + 2\mu_{ef\,1}\left(e^{kl} - \frac{1}{3}\delta^{kl}\nabla \mathbf{v}_1\right) e^{kl} + \eta_f n F_\mu (\mathbf{v}_1 - \mathbf{v}_2) + \\ + \eta_k \frac{\mu_1}{a^2} k_{v1} + \frac{12\alpha_1\alpha_2\mu_1 v_{ra}^2}{a^2}; \quad Q_2^* = 0. \tag{27}$$

The coefficients β_{ti} can be calculated from the criterial equation of dispersed particle heat liberation into the surrounding medium [7] and energy [Eq. (15)]:

$$\beta_{t1} = \frac{\lambda_1}{2a}\left\{2 + 0.46\left[\frac{2a\rho_1^0}{\mu_1}(\mathbf{v}_1 - \mathbf{v}_2)^{0.55} \cdot \left(\frac{\mu_1 c_{p1}}{\lambda_1}\right)^{0.33}\right]\right\}; \\ \beta_{t2} = \frac{\lambda_2}{T_2 - T_\sigma}\left(\frac{\partial T_2}{\partial r}\right)_{r=a}. \tag{28}$$

The sign before the term $r^*/4\pi a^2$ in Eq. (13) is positive for the region Ω'' and negative for Ω'. The intensity of mass and heat exchange is determined by Eqs. (14)-(17).

System (3)-(15) is completed by dependences of the physical properties of the phases on their state parameters. It should be noted that for greater precision it is necessary to consider the distribution of particles over size, although this complicates description of this class of phenomena even more.

The conditions required for uniqueness may vary depending on the concrete problem considered. For example, as initial conditions we specify thermodynamic and hydrostatic equilibrium of the media in the absence of a dispersed phase and electric field. The boundary conditions include those at the electrodes – the attachment condition, wall temperature, and electrical potential (in addition, on the lower electrode we specify specific flow rate, temperature, pressure, concentrations of the vapor–gas flow ions and bubbling liquid, and the diameter of the perforations through which the flow is supplied); on the free liquid surface we have conditions for the change in aggregate state of the phases, including the function ψ for the dispersed phase in the last expression of Eq. (3), discontinuities in phase velocity and volume content, as well as refraction conditions for the electric field intensity and thermodynamic parameters; on the phase boundaries we have boundary conditions of the fourth sort, attachment conditions, and values of excess charge surface density; on the remaining boundaries we have attachment conditions and boundary conditions of the first sort.

Electroconvection in Gas–Liquid Media. A significant role is played in the development of electroconvective phenomena by inhomogeneity of the medium with respect to the electrophysical parameters ε and τ [3]. When temperature variation in the medium is insignificant, one can speak of electromechanical convection (EMC) in gas–liquid systems, since the phases differ in their mechanical and, thus, electrophysical composition.

It should be stressed that electromechanical convection is the fundamental but not the only form of convection in such media. The processes of charge, heat, and mass transport occur in the presence of high gradient temperature and concentration fields which increase the inhomogeneity of the ε and τ distributions: the nonisothermal state of the medium causes electrothermal convection (ETC), while concentration gradients cause electroconcentration convection (ECC). Thus, a nonisothermal medium in an electric field is located in a complex dynamic state defined by the simultaneous action of EMC, ETC, and ECC. System reaction to stimulation by the field can be predicted by the criterion R [3], which is the ratio of the displacement current to the through-conduction current, and is proportional to τ/t_0. For $R \gg 1$, the system behaves like an ideal dielectric, while for $R \ll 1$ it acts as a weakly conductive medium. Even relatively good liquid dielectrics with parameter $\tau \gtrsim 1$ sec cannot be considered ideal after lengthy maintenance in a dc field ($t_0 \to \infty$), while

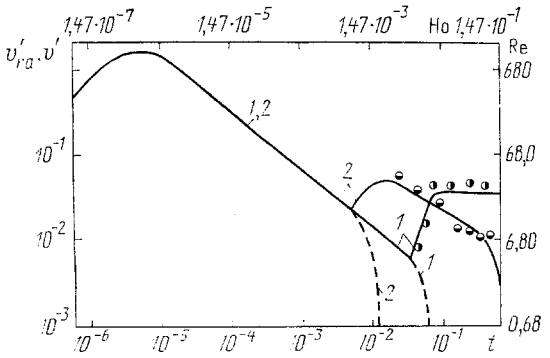

Fig. 1. Dynamics of growth and motion of an air bubble in transformer oil (v_{ra}', v_2', m/sec; t, sec); P_g = 0.13 MPa; E', kV/cm: 1) 0; 2) 30. Solid lines, calculation of bubble linear velocity; dashes, radial velocity calculation; points, experiment.

in hf field ($0 \ll t_0 \ll 1$ sec) gas–liquid media with relaxation times characteristic of conductors become ideal.

The process of bubble flow through a high-resistance liquid within a volume exposed to the electric field of a horizontal system of planoparallel electrodes is accompanied by various electrodynamic effects. In the absence of an electric field gas bubbles detached from the lower electrode settle on the upper one, forming a multilayer structure. At low gas velocities the settling bubbles are driven by rising ones to the edges of the electrodes and are removed from the interelectrode space. Their place is taken by rising bubbles and, thus, there is a constant renewal of the foam. With increase in gas velocity the thickness of the layer of deposited bubbles increases and foam renewal is extended, although the intensity of renewal over layers is stabilized.

In an electric field the bubble layer moves away from the upper electrode toward the lower one, a greater distance, the higher the field intensity. Simultaneously bubbles are scattered and intensely removed from the region under the action of electrical forces. The electric field also affects the hydrodynamic state of the continuous phase. With increase in field intensity electroconvection of the liquid increases, while the character of liquid flow at the lower electrode differs from that at the upper. Visual observations have shown that jets of gas escaping from capillaries in the lower electrode are the source of vortices which form about that electrode; with increase in gas velocity the intensity of electroconvection and turbulization of the layer adjoining the electrode increase. The layer of bubbles departing from the upper electrode limits the scale of liquid circulation in the interelectrode space and with increase in gas velocity at low field intensities the intensity of electroconvection at the upper electrode is less than at the lower.

Judging from the hydrodynamic pattern of bubble flow in an electric field, one would expect a strong dependence of heat liberation at each electrode on the field intensity and gas velocity. It has also been proposed that the main force acting on bubbles is caused by the electric field gradient, inhomogeneity in which reaches large values at the electrodes, as has been shown by probe measurements.

This hypothesis has been confirmed by study of the mathematical model of [8], describing evolution of a gas bubble under such circumstances. The mathematical description of the problem is based on the equations of motion, Rayleigh–Lamb equation (5), and Poisson equation (8). The phases of bubble growth, separation, detachment, and free ascent in the interelectrode space of a horizontal planoparallel capacitor were studied. Numerical calculations were compared to experimental data obtained by the trajectory method. Calculations showed that a bubble nucleus begins to grow slowly at first due to the influence of all the retarding factors, especially surface tension (Fig. 1). The duration of this period is very brief and is determined mainly by gas pressure ahead of the capillary. Soon the effects of surface tension and liquid velocity become negligibly small in comparison to the gas pressure and liquid inertia, and the bubble growth rate increases rapidly, reaching a maximum. With increase in gas pressure the maximum growth velocity increases significantly. For example, at 0.11 MPa, v_{ra}' = 0.17 m/sec, while at 0.16 MPa, v_{ra}' = 3.23 m/sec.

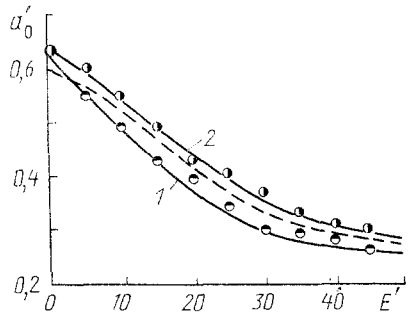

Fig. 2. Field intensity E' (kV/cm) vs bubble detachment radius a_0', mm. Gas-permeable electrode polarity: 1) positive; 2) negative; solid lines along points, experiment; dashes, calculation.

At the maximum the effect of inertial forces decreases, the growth rate falls off, and the process enters an asymptotic stage. The growth curves in this phase are qualitatively analogous to corresponding dependences for boiling. With increase in field intensity the bubble detachment diameter decreases (Fig. 2), this dependence being determined by the polarity of the lower electrode, due to the asymmetry of the field distribution. The effect of the field on bubble growth and detachment dynamics reduces to earlier completion of these stages as compared to the absence of a field. However, in the free bubble ascent stage the bubbles rise more rapidly in the absence of a field (curve 1, Fig. 1), but then are braked, not reaching the upper electrode in an electric field (curve 2). Thus, the results obtained indicate the validity of the propositions presented above regarding the nature of the electrical force.

We will consider electromechanical convection for the case where there acts upon the dispersed phase from the direction of the electric field a Coulomb force, which is typical for droplet removal upon bubbling through low-resistance liquids [9]. It is known that upon destruction of bubbles on the free surface of the bubble layer droplets are produced by dispersion of the bubble domes and secondary fountaining. In the absence of an electric field the main mass of droplets moves inertially against the force of gravity, and under the action of the latter returns into the liquid or is carried off by the same, contaminating it, so that measures are required to separate the droplets. In an electric field the droplets take on excess charge and become capable of being controlled, depending on the field configuration, intensity, and frequency. In a dc field fine droplets are carried off to the seed electrode along force lines; dispersed phase motion in ac fields is characterized by two regimes: impulsive and oscillatory. If the characteristic time of droplet motion is greater than the electric field oscillation period, but less than the droplet charge relaxation time, such drops perform an oscillatory motion in some intermediate region of the interelectrode space at the external field frequency. The opposite relationship of characteristic times leads to impulsive motion of the dispersed phase. If the characteristic times are comparable to each other, droplet motion is unstable and represents a spontaneous transition from the one regime to the other.

The basic parameters of the electroaerosol removed depend basically on the gas velocity and field intensity; their characteristic dependences are shown in Fig. 3.

With consideration of the equations of droplet motion, conservation of their volume concentration in the steady state, Eq. (3), and the Poisson equation (8), a mathematical model was developed for generation and electroconvective removal of droplets [10], describing dynamic removal regimes observed experimentally.

Summarizing, we note that analysis of the problem of Eqs. (3)-(15), the particular models of [8, 10], and experimental results permit determination of limits of dispersed phase concentration and electric field parameters at which the effect of collective processes begins to appear: scattering, coagulation, particle breakup, hydrodynamic inheritance effects, etc.; these should be considered at volume dispersed phase concentrations greater than 0.0001 in gas-dispersed and greater than 0.001 in liquid-dispersed media. There also exists a "threshold" for field effect on such collective phenomena.

Electroconvective Heat Exchange in Gas–Liquid Emulsions. In exerting a significant influence on the structural-hydrodynamic characteristics of the bubble layer, the electric field leads to intensification of heat liberation and interphase heat exchange. To study these questions use was made of the experimental arrangements described in [11].

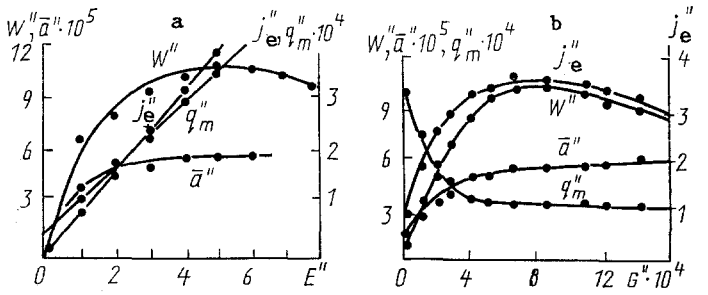

Fig. 3. Transport current density j_e'', μA/m², mass removal W'', g/(m²·sec), mean mass charge q_m'', C/kg, and mean droplet size $\bar{a}''$, m, vs field intensity E'', kV/cm (a), and gas velocity G'', m/sec (b), for bubbling through water: a) $G'' \approx 0.68 \cdot 10^{-3}$; b) $E'' = 5$.

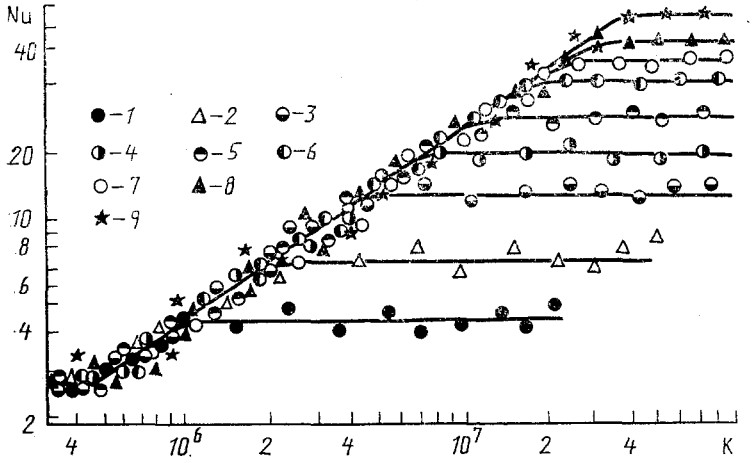

Fig. 4. Heat liberation of gas permeable electrode oriented opposite gravitation, under bubbling conditions with dc electric field: 1) $(Ar + 0.2Ar^e)Pr_* \cdot 10^6 = 0.19$; 2) 0.52; 3) 1.52; 4) 3.18; 5) 5.52; 6) 8.52; 7) 12.2; 8) 16.6; 9) 21.5.

The first series of experiments studied heat liberation from the electrodes of a horizontal planoparallel capacitor in a bubbling medium for a transformer oil–air system. In contrast to the upper one, the lower electrode was gas-permeable and served simultaneously as the bubble source. Using the method of [2], Fig. 4 generalizes the experimental data on heat liberation from the gas permeable electrode. With increase in gas velocity (quantity K) for all field intensities (quantity Ar^e) there are three regions in the dependence of the number Nu on the dynamic parameters. In the first region, the heat liberation intensity depends weakly on gas velocity, which can apparently be explained by the laminar character of the gas escape into the liquid. However, with increase in gas velocity to some critical value, dependent on field intensity, the intensity of heat liberation, as in boiling, increases by a rule $Nu \propto K^{2/3}$ (second region). Upon exceeding a critical gas velocity the heat liberation exits into a regime self-similar with respect to K, but Nu depends on field intensity (third region). In this region the dispersed phase and the electrical field lead to a stable turbulent flow regime of the phases in the electrode region and heat liberation reaches a stable maximum value. The effect of field intensity on heat liberation is most marked at gas velocities greater than 5 mm/sec; at E = 40 kV/cm and a gas velocity of 1 m/sec, heat liberation increases by ten times. Thus, the criterial equations of heat liberation of the gas-permeable electrode have the form:

$$Nu \simeq 2.75 \quad \text{at} \quad K < 5 \cdot 10^5; \quad Nu = 4.45 \cdot 10^{-4} K^{2/3} \quad \text{at} \quad 5 \cdot 10^5 \leqslant K < K_{cr1};$$

$$Nu = 0.01 (A Pr_\ell)^{1/2} \quad \text{at} \quad K_{cr1} \leqslant K < K_{cr2};$$

$$A = Ar + 0.2Ar^e; \quad Ar^e = \varepsilon_0 \varepsilon_1 E^2 l^2 (\rho_1^0 - \rho_2^0)/\rho_1^{02} \nu_1^2;$$

$$K_{cr1} = 106.53 (A Pr_\ell)^{3/4}; \quad K_{cr2} = 1976.42 (A Pr_\ell)^{3/4}. \qquad (29)$$

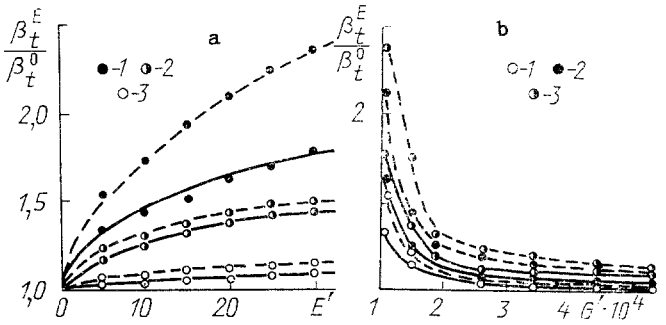

Fig. 5. Effect of field intensity E', kV/cm (a) and gas velocity G', m/sec (b) on intensity of interphase heat exchange for bubbling of air through transformer oil: a) G': 1) $1.0\cdot10^{-4}$; 2) $1.5\cdot10^{-4}$; 3) $5.3\cdot10^{-4}$; b) E': 1) 5; 2) 20; 3) 30. Solid lines, dc field; dashes, ac.

These expressions are valid within the limits $1.9\cdot10^5 \leq A\cdot Pr_\ell \leq 2.2\cdot10^7$.

A qualitatively different pattern can be seen for the dependence of heat liberation on field intensity at the upper electrode. In the absence of field the heat-liberation coefficient, as at the lower electrode, increases proportionally to gas velocity, which is related to the increased intensity of renewal of liquid transported by bubbles from the flow core to the heat-exchange surface. When some critical gas velocity is reached (about 1 cm/sec) the intensity of bubble renewal stabilizes and the heat-liberation coefficient is practically independent of gas velocity. In an electrical field the intensity of heat liberation is inversely proportional to gas velocity. With increase in field intensity the heat liberation coefficient increases due to scattering of bubbles from the interelectrode space and increase in electroconvection in the closed phase, which leads to turbulization of the boundary layer and flow of liquid from the flow core to the electrode region. However, with increase in gas velocity, the liquid circulation zone is restricted by bubbles from the electrode region and the heat-liberation coefficient falls. Only at sufficiently high field intensities (35-40 kV/cm) is the heat-liberation coefficient self-similar relative to gas velocity and controlled by the intensity of liquid electroconvection. The heat-liberation coefficient at the upper electrode and the field intensity are directly proportional to each other at all gas velocities. Thus, heat liberation in the given case can be generalized to an accuracy of ±15% by a dependence of the type

$$\mathrm{Nu} = a\mathrm{K}^n + b, \tag{30}$$

where $n = -24.214\cdot B^{-0.15}$ at $1.87\cdot10^5 \leq B < 6.86\cdot10^7$, $n = -1.634\cdot10^{-3}B^{0.45}$ at $6.86\cdot10^7 \leq B < 8.22\cdot10^7$, $b = 0.757B^{0.04}$ at $1.87\cdot10^5 \leq B < 1.86\cdot10^6$, $b = 4.736\cdot10^{-3}B^{0.55}$ at $1.86\cdot10^6 \leq B < 8.22\cdot10^7$, $a = (3.1\cdot10^{-3}B^{0.45} - b)/(3.92\cdot10^5)^n$ at $1.87\cdot10^5 \leq B < 8.22\cdot10^7$, $B = (Ar + Ar^e)/Pr_\ell$. The effect of temperature head and thermal flux density on the heat-liberation coefficient is one of linear proportionality over the entire range of field intensities and gas velocities studied.

Interphase heat exchange during bubbling of a high-resistance liquid was studied under the action of the electrical field of a multisection planoparallel capacitor oriented vertically [11]. Field intensity, temperature head and gas velocity were varied at both polarities of the applied potential in a dc field and a 50-Hz field for phase motion with and against the main flow. In the absence of a field the heat-exchange intensity increases with increase in gas velocity due to increase in the interphase surface and change in the gas flow regime. There is also some intensification of heat exchange with increase in temperature head due to decrease in the detachment diameter of bubbles and liquid viscosity. In an electrical field polarization and deformation of the bubbles occur, which with an inhomogeneous distribution and variable field induction leads to oscillations of the phase boundary, and at high intensity to breakup of the phases. Therefore, growth in field intensity leads to intensified heat exchange (Fig. 5a). It is also evident that in ac fields the intensification effect is greater than in a constant field. With increase in frequency of the applied voltage the intensity of heat exchange increases, reaching a maximum in resonant bubble oscillation regimes, where the field frequency is equal to the bubble natural

oscillation frequency [4]. However, with increase in gas velocity, the degree of heat-exchange intensity falls off (Fig. 5b), since the effect of the field becomes comparable to the turbulizing action of the gas phase. Similarly, increase in temperature head leads to intensification of heat exchange only in the region of laminar gas escape, while with increase in gas velocity this dependence becomes self-similar. The qualitative pattern of these results is identical for flow with and opposite the main flow; the only differences are quantitative.

Thus, intensity of heat exchange in bubbling processes proves to be strongly dependent on gas velocity and electrical field parameters, which makes possible flexible regulation and decrease in metallic bulk of the equipment used.

CONCLUSIONS

The high efficiency of electric field action on gas–liquid systems has stimulated ever-increasing interest of researchers and practicians in the problem of heat mass transport under electrical convection conditions; no less important are the advantages of the latter over natural and, often, other forms of forced convection, its applicability under conditions of weightlessness, the low energy and metal mass requirements of the technologies, and its ecological nature.

The promise of studies in this direction has resulted in wide application of results in practical problems. Thus, use of an electric field, aside from the traditional struggle with loss phenomena in chemical technology and vapor-based energy production, has permitted development of new technical approaches for effective generation of liquid electroaerosols, as well as processes for high-level purification of materials, volume boiling and condensation, temperature stabilization and heat-exchange regulation, separation of ions in aqueous electrolyte solutions, etc.

NOTATION

v, v_{ra}, and G, linear, radial, and reduced velocity, m/sec; T, temperature, K; ρ, density (kg/m^3) or relative mass concentration; n_I and n, volume density of ions and numerical particle concentration, m^{-3}; ρ_e, space charge density, C/m^3; a, particle radius, m; α, volume content of phase i; j_{12} and j_{21}, phase transition intensity, kg/(m^2·sec); P, pressure, Pa; E and φ, electric field intensity (V/m) and potential (V); j_e, transport current density, A/m^2; ψ, function which considers processes of breakup, agglomeration, efflux and influx of particles, (m^3·sec)$^{-1}$; t, time, sec; D, diffusion coefficient, m^2/sec; σ, liquid surface tension, N/m; μ, dynamic viscosity coefficient, Pa·sec; $\delta^{k\ell}$, Kronecker delta; x_*, generalized coordinate, m or rad; F_μ, F_m, F_ω, $F_{\Delta p}$, F_B, interphase viscous friction force, "combined mass" force, force produced by velocity gradient in carrier phase, excess pressure head force for accelerated motion of carrier force, and Basset force, N; γ and β, thermal coefficients of pressure and volume expansion, K^{-1}; λ and β_t, thermal conductivity [W/(m·K)] and heat liberation [W/(m^2·K)] coefficients; c_p, isobaric specific heat, J/(kg·K); η_f and η_k, energy dissipation coefficients for translational fine-scale motion in boundary layer and Stokes quasistationary flow over particle; r*, heat of phase transition, J/kg; r, spherical coordinate, m; g, acceleration of gravity, m/sec^2; St and Re, Struchal and Reynolds numbers; ε, relative dielectric permittivity; ε_0, electrical constant, F/m; q_I, excess charge, C; b_I, ion mobility, m^2/(V·sec); k, Boltzmann's constant, J/K; t_*, τ, and t_0, characteristic time for change in velocity of sphere motion, electrical relaxation time, and characteristic time for change in field induction, sec; Nu, Ar, K, Pr_ℓ, similarity criteria used in [2] for processing of data on heat liberation under bubbling conditions; Ar^e, analog of Archimedes number in electrical field. Indices: ' and ", parameters in regions Ω' and Ω''; k and ℓ, tensor components; i = 1, 2, σ, parameters of carrier, dispersed, and "sigma" [4] phases; s, 0, v, and a, parameters at free liquid surface, beginning of the process, vapor component, and particle surface; E, ef, equilibrium and effective values.

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BEHAVIOR OF LIQUID THERMODYNAMIC STABILITY UNDER SUPERHEATING AND SUPERCOOLING

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It is noted that evaluation by van der Waals equation of the asymptotic ($T \to 0$ K) spinodal tensile stress of liquids is close in order of magnitude to the ideal strength of solids and the limiting pressure on the extension of the fusion line of various substances.

1. Equilibrium coexistence of phases on a planar phase boundary is determined by equality of temperatures, pressures, and chemical potentials μ within the phases. For slow (quasistatic) processes phase transition produces no marked deviation of the system from equilibrium conditions. But for sufficiently rapid change in external parameters such deviations may become significant. This is especially true of the initial stage of phase transition. This stage includes the appearance of metastability of the original phase, nucleation, and growth of the new phase. A number of questions arising here were considered in a previous study [1]. The thermodynamic factor in the expression for nucleation rate is very sensitive to difference in the chemical potentials of the phases and the value of the interphase surface tension. With deeper penetration into the metastable state range, the height of the activation barrier for nucleus formation decreases rapidly. Development within the system of an intense flux J of fluctuation nuclei of the new phase is of almost a threshold character [1]. This may be treated as loss of stability of the medium with respect to heterophase local fluctuations. The onset of such instability is not necessarily accompanied by reduction in stability of the metastable system relative to homophase changes in density and entropy. The response of the isotropic system to small local perturbations in pressure and temperature is characterized by the isothermal compressibility $\beta_T = -(1/v)(\partial v/\partial P)_T$ and the isobaric specific heat $c_p = T(\partial s/\partial T)_p$. For stability the conditions of [2] must be satisfied: $\beta_T > 0$, $c_p > 0$ or $(\partial P/\partial v)_T < 0$ and $(\partial T/\partial s)_p > 0$.

The boundary of thermodynamic stability (spinodal) is defined by the equations

$$\left(\frac{\partial P}{\partial v}\right)_T = 0, \quad \left(\frac{\partial T}{\partial s}\right)_P = 0. \tag{1}$$

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