vapor content; x, mass vapor content; $K_v = c_{pv}(T_w - T_s)/r$, dimensionless temperature head; $K_v^* = K_v/(1 + 0.34K_v)^2$, modified dimensionless temperature head; $L = \sqrt{\sigma/g(\rho_\ell - \rho_v)}$, capillary constant; D, channel diameter; $D_h = D(\pi - \Theta_b + 0.5\sin 2\Theta_b)/(\pi - \Theta_b + \sin\Theta_b)$, hydraulic diameter; $\bar{D} = D/L$, relative diameter; F, cross-sectional area of the pipe; U, perimeter; $Pr = \mu c_p/\lambda$, Prandtl number; $Nu = qL/(T_w - T_s)\lambda_v$, Nusselt number; $Re = \rho u D_h/\mu$, Reynolds number; c_m, coefficient in the equation of state. Indices: ℓ, liquid; v, vapor; av, parameter determined at the average temperature $T_{av} = (T_w + T_s)/2$; w, at the heat-transfer wall; s, at the saturation line; e, parameter determined under equilibrium conditions.

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INFLUENCE OF ELECTRIC FIELDS ON THE KINETICS OF PHASE TRANSITIONS

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It is established that a nonuniform electric field with an average strength of 10^4-10^7 V/m has an insignificant effect on the evaporation of polar liquids, reducing its rate, while it does not affect the evaporation of nonpolar liquids.

The hypothesis that the state of the surface layer of a liquid, the degree of order of the molecules of this layer, has great influence on the kinetics of phase transitions was advanced in [1, 2]. The fact that high values of the evaporation coefficients, characterizing the kinetics of phase transitions, are obtained in evaporation from dynamic surfaces, e.g., in the discharge of liquids from orifices at a high velocity, testifies in favor of this hypothesis. The possibility of the influence of an electric field on the kinetics of phase transitions of polar substances, the molecules of which possess a constant electric moment in the direction of the axis of symmetry, due to a change in mutual orientation, disruption of surface dipoles, and the appearance of additional degrees of freedom, is discussed in [3].

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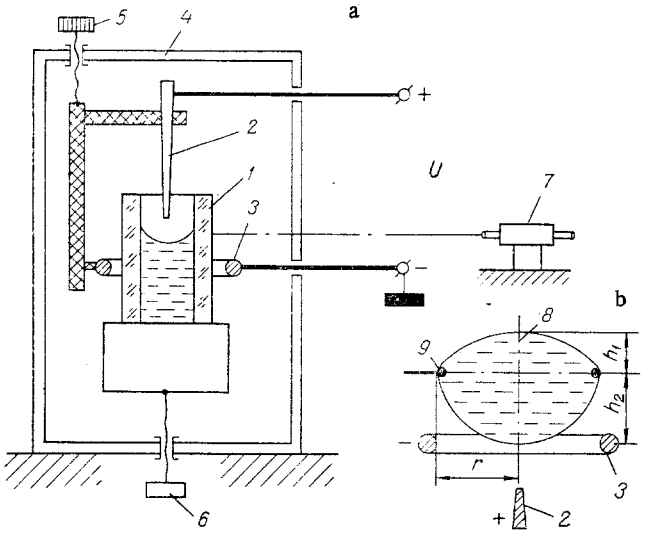

Fig. 1. Diagram of the experimental stand for investigating the evaporation of liquid from thin tubes (a) and the evaporation of drops (b): 1) glass tube containing the investigated liquid; 2, 3) electrodes; 4) camera; 5, 6) micrometer screws for measuring the position of the electrodes relative to the liquid meniscus; 7) optical system; 8) liquid drop; 9) holder of quartz filament. U, kV.

Strong electric fields are presently used in many technological processes and devices in order to intensify heat exchange [4-7]. The results of research that also confirms the influence of electric fields on the rate of moisture transfer in capillary-porous materials are presented in [8-14]. A main feature of this research is that the electric field is produced by a system of point–plane electrodes, while the investigated specimen (a capillary-porous solid impregnated with a liquid or an individual capillary containing the liquid) is placed in the space between the electrodes. The observed change in the rate of evaporation of the liquid is explained by the effect of the action of the electric field directly on the evaporating liquid, rather than the evaporation process itself, by the appearance of additional thermodynamic forces of mass transfer and polarization effects. Here three main factors are distinguished: the drawing of dipole molecules of the liquid into the region of greater nonuniformity of the electric field, the formation of an electroconvective flux of dipole molecules in the vapor phase, and the stretching out of the liquid film along the walls of the microcapillary. What the role of each of the possible mechanisms is and what influence the parameters of the electric field have on the variation of evaporation kinetics have remained undisclosed, however. And yet the study of these processes is important for an understanding of the kinetics of phase transitions and the development of methods of intensifying heat- and mass-exchange processes.

The influence of a nonuniform electric field on the rate of evaporation of polar and nonpolar liquids was investigated in the present work, with the conditions for the development of an electric discharge being eliminated in the experiments.

The liquid was evaporated from glass tubes with an inside diameter 2r = 1.6 and 2.5 mm (Fig. 1). The electric field was produced directly at the surface of the liquid meniscus using a system of point–ring electrodes. For this the point was located near the meniscus inside the tube, while the ring outside the tube was somewhat below the liquid level. Such an arrangement of the electrodes made it possible, upon the application of high voltage to them, to produce a strong nonuniform field and practically eliminated discharge conditions, at least to within 10^{-7} A. To monitor leakage currents, a resistor and a microammeter were connected into the electrical circuit in series in such a way that the total current passed through them, with allowance for its branching from the point to the ring and from the point to ground. In addition, an electric pulse on the resistor was recorded with a storage oscillograph. The electrode system was inside a chamber in which the temperature and humidity of the medium were kept constant. All the experiments were conducted at atmospheric pressure. The evaporation rate was monitored continuously with an optical system by constantly following

the lowering of the liquid meniscus in the tube. The movement Δh in a time $\Delta\tau$ was recorded to within 0.05 mm. The surface area of the meniscus can be identified with sufficient approximation with the surface area of a spherical segment for the chosen tube diameters. Then the evaporation rate is determined from the formula

$$j_m = \frac{\rho r^2}{\Delta x^2 + r^2} \frac{\Delta h}{\Delta \tau}, \tag{1}$$

where Δx is the depth of the spherical meniscus relative to its boundary at the tube walls.

Varying the voltage applied to the electrodes from 1 to 6 kV made it possible to vary the parameters of the electric field within wide limits and to investigate the kinetics of liquid evaporation in the absence and with the application of external electric fields of different intensities. A polar liquid (water) and a nonpolar one (carbon tetrachloride) were used as the investigated liquids. The necessary measures were taken to assure sterile experimental conditions in each case.

With the high degree of localization of the electric field near the liquid meniscus and the small tube diameter, it was practically impossible to experimentally determine the strength of the nonuniform electric field and the degree of its nonuniformity, so these quantities were estimated theoretically. The electric field produced in the apparatus was modeled by superposing the fields of a charged ring and a spherical charge located at the axis of the ring. The estimate showed that the electric field excited near the liquid meniscus is sufficiently strong; for the values of the quantities characteristic for the experimental installation (ring radius 2.5 mm, radius of the spherical charge equal to the radius of curvature of the pointed electrode at its end, 0.05 mm, distance from the center of the sphere to the ring plane 0-1.1 mm, potential at the surface of the pointed electrode, equal to the potential set by the high-voltage generator, $5 \cdot 10^3$ V, and a zero potential at the surface of the grounded ring), for example the field strength ranged from 10^8 near the point to 10^3 V/m near the ring, and the degree of nonuniformity, estimated from the intensity gradient, was very high, from 10^{12} to 10^8 V/m^2.

A quantitative estimate of the influence of a strong nonuniform electric field on liquid evaporation through the action of this field on the dipole moments of water molecules showed that, at the average electric field strengths characteristic for our installation, $E \approx 10^5$ V/m, the average energy of thermal motion of water molecules is much greater than their energy $p_0 E$ in the electric field [15]:

$$\frac{p_0 E}{kT} \approx 10^{-4} \ll 1. \tag{2}$$

Consequently, in this case only a very small fraction of the dipole molecules of water will be directed along the field. In accordance with the well-known theory of the polarizability of polar gaseous dielectrics, the average dipole moment of the molecule is

$$p = \frac{p_0^2 E}{3kT}. \tag{3}$$

Then the average force exerted on a dipole molecule of water by the electric field is $F = p\nabla E$. Hence, the average velocity of a water molecule in the direction from the mouth of the tube is

$$v \approx \sqrt{\frac{p \nabla E \Lambda}{2m}}. \tag{4}$$

For the rate of mass transfer we obtain [2]

$$j_e \approx \frac{1}{4} nmv = \frac{1}{4} \sqrt{\frac{p_0^2 E \nabla E \rho_v}{12\sqrt{2}\pi k d^2 T}}. \tag{5}$$

Here ρ_v is the density of saturated water vapor; d is the effective diameter of the water molecules. Substituting values of the parameters appearing in (5) that are typical for water, $T = 300$ °K, $p_0 = 6.07 \cdot 10^{-30}$ C·m, $d = 4.7 \cdot 10^{-10}$ m, $\rho_v = 0.7$ kg/m^3, $E = 10^5$ V/m, and $\nabla E = 10^8$ V/m^2, we find that the additional mass flux due to the action of the electric field on the dipole

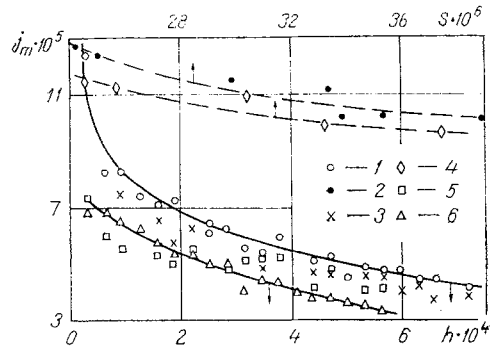

Fig. 2. Variation of the water evaporation rate as the liquid meniscus descends in the tube (solid lines) and as the surface area of the drop varies (dashed lines). Voltage applied to the electrodes: 1, 2) U = 0 kV; 3, 4) 3; 5) 4; 5) 5 kV.

molecules has a maximum value of $2 \cdot 10^{-5}$ kg/m²·sec, which is an order of magnitude less than the rate of water evaporation measured without applying an electric field and equal to $1.2 \cdot 10^{-4}$ kg/m²·sec, i.e., we can conclude that the influence of a strong nonuniform electric field on the evaporation kinetics is insignificant.

But, on the other hand, the evaporation rate is determined by the state of the liquid surface [1, 2]. For water, distinguished by a complicated structure due to hydrogen bonds, because of the strong polarity one observes surface orientation of the dipole moments of the molecules, which can lead to the appearance of a potential jump in the surface layer, alter the character of the rotation of the molecules, etc. [16]. Similar laws are observed for other polar liquids. In [1, 2] a theory is advanced from which it follows that constraint of the rotational degrees of freedom in a liquid to rotational oscillations due to the surface orientation of dipoles leads to a considerable decrease in the evaporation rate. Since the strongest external fields are extremely small in comparison with the internal field of a liquid, the action of such a field on a polar liquid must come down to a slight turning of the equilibrium orientation toward the external field. In the case that we are considering, the electric field is concentrated near the liquid meniscus and acts primarily on the dipole moments of molecules in the surface layer, orienting them in the direction of the resultant field, resulting in a decrease in the liquid evaporation rate.

Thus, the kinetics of the evaporation of a liquid that is in a nonuniform electric field is determined by the relation between several competing factors, some of which may intensify the evaporation process while other retard it.

The experimental dependence of the rate of water evaporation from a thin tube on the depth of the liquid meniscus under the action of a nonuniform electric field of varied strength is given in Fig. 2. In all the cases investigated, the evaporation rate depends on the depth of the liquid meniscus in the tube, so that the j_m were compared for the same h. As the voltage on the electrodes is varied from 0 to 4 kV, the evaporation rate decreases slightly (by an average of no more than 20%), while with a further increase in the field strength the evaporation rate starts to grow. At U = 6 kV (the field strength varies from 10^9 V/m near the point to 10^4 V/m near the ring) for a tube 2.5 mm in diameter, the influence of the electric field on the water evaporation rate was no longer detected. The evaporation rate of nonpolar carbon tetrachloride remained unchanged at all the investigated values of the electric field strength.

It should be noted that in the experiments with capillary tubes of $2r > 1$ mm we did not observe the effect of stretching out of the wetting film of considerable length behind the descending meniscus of a polar liquid evaporating from a microcapillary of 1-50 μm, established in [17] and resulting in a change in the evaporation rate.

To test the laws obtained, we also made a series of tests on the evaporation of liquid drops in a nonuniform electric field.

A drop of the investigated liquid was suspended on a holder of quartz filament ending in a ring 3.2 mm in diameter (see Fig. 1b). The variation in the weight of the drop was determined from the bending of the quartz filament. The amount of bending and the variation of the size of the drop were recorded by the optical system of the installation during the time while the drop retained the shape of a spherical segment. The weight sensitivity was 0.07 mg. The surface area of the drop was calculated from the formula

$$S = \pi (2r^2 + h_1^2 + h_2^2), \tag{6}$$

where h_1 and h_2 are the heights of the upper and lower spherical segments of the drop.

A voltage of 3 kV was applied to the electrodes, upon which the rate of water evaporation decreased by 8-10% in comparison with the evaporation rate without the action of the electric field (Fig. 2, curves 2 and 4), while that of carbon tetrachloride did not change, which agrees with the results of the investigation of liquid evaporation from the ends of tubes. The intensification of the process of evaporation of polar liquids in a nonuniform electric field of the same strength as in the present work, observed in [12, 13], can be explained, in our view, by the possible action of electric discharge, not subject to monitoring by the measuring instruments used in the work, and the appearance of which is quite realistic with the point–plane electrode system used in that work and the placement of the capillary containing the liquid in the interelectrode space.

Thus, the research that was done enables us to conclude that nonuniform electric fields with an average intensity of 10^4-10^7 V/m have slight influence on processes of evaporation of polar liquids, somewhat decreasing their evaporation rate. Evidently, the orienting action of the nonuniform electric field on the surface layer of liquid can be considered as the main cause of such an effect.

NOTATION

r, radius of the tube or drop, m; ρ, liquid density, kg/m^3; h, depth of liquid meniscus in the tube or height of a spherical segment of liquid; τ, time, sec; p_0, dipole moment of a molecule, C·m; E and ∇E, electric field strength and its gradient, V/m and V/m^2; T, temperature, K; k, Boltzmann constant; Λ, mean free path of a molecule, m; m, mass of a molecule, kg; j_m, evaporation rate, kg/m^2·sec; S, surface area of the drop, m^2.

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NUMERICAL AND EXPERIMENTAL STUDY OF A NONISOTHERMAL TURBULENT JET WITH A HEAVY IMPURITY

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Temperature and momentum distributions of the carrier phase are determined experimentally and compared to results of numerical calculations using the (k − ε) model.

A second-order turbulence model using transfer equations for pulsation quantities was proposed in [1, 2] for calculation of two-phase jets. Experimental material permitting verification of models describing isothermal flows was presented in [3-5]. In connection with the wide use of nonisothermal two-phase turbulent jets in various equipment, the development of models for such flows and their experimental verification are a problem of very practical interest.

We will present below the results of an experimental and numerical study of a nonisothermal turbulent gas-suspension jet. A two-parameter turbulence model using transfer equations for pulsation energy and its dissipation rate is employed.

Mathematical Model. The system of equations describing escape of a nonisothermal two-phase turbulent isobaric axisymmetric submerged jet with consideration of velocity and temperature nonequilibrium between the phases, as obtained in the boundary-layer theory approximation, has the following form for the average values of the quantities:

$$\frac{\partial}{\partial x}(\rho_g u_g)+\frac{1}{y}\frac{\partial}{\partial y}(y\rho_g v_g)=0, \tag{1}$$

$$\frac{\partial}{\partial x}(\rho_p u_p)+\frac{1}{y}\frac{\partial}{\partial y}(y(\rho_p v_p+\langle \rho_p' v_p'\rangle))=0, \tag{2}$$

$$\rho_g\left(u_g\frac{\partial u_g}{\partial x}+v_g\frac{\partial u_g}{\partial y}\right)=\frac{1}{y}\frac{\partial}{\partial y}\left(y\rho_g\nu_t\frac{\partial u_g}{\partial y}\right)-F_x, \tag{3}$$

$$\rho_p u_p\frac{\partial u_p}{\partial x}+(\rho_p v_p+\langle \rho_p' v_p'\rangle)\frac{\partial u_p}{\partial y}+\frac{1}{y}\frac{\partial}{\partial y}(y\rho_p\langle u_p' v_p'\rangle)=F_x, \tag{4}$$

$$\rho_p u_p\frac{\partial v_p}{\partial x}+(\rho_p v_p+\langle \rho_p' v_p'\rangle)\frac{\partial v_p}{\partial y}+\frac{1}{y}\frac{\partial}{\partial y}(y(\rho_p\langle v_p'^2\rangle+v_p\langle \rho_p' v_p'\rangle))=F_y, \tag{5}$$

$$\rho_p u_p\frac{\partial \omega_{p\varphi}}{\partial x}+(\rho_p v_p+\langle \rho_p' v_p'\rangle)\frac{\partial \omega_{p\varphi}}{\partial y}+\frac{1}{y}\frac{\partial}{\partial y}(y\rho_p\langle v_p'\omega_{p\varphi}'\rangle)=-\rho_p\beta_\omega\Omega, \tag{6}$$

$$\rho_g\left(u_g\frac{\partial h_g}{\partial x}+v_g\frac{\partial h_g}{\partial y}\right)=\frac{1}{y}\frac{\partial}{\partial y}\left(y\lambda_t\frac{\partial T_g}{\partial y}\right)+$$
$$+\rho_g\nu_t\left(\frac{\partial u_g}{\partial y}\right)^2-Q_{gp}+F_x(u_g-u_p)+F_y(v_g-v_p), \tag{7}$$

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