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DIAGNOSTICS OF ELECTRO-GAS-DYNAMIC FLOWS OF A LOW-CURRENT HIGH-VOLTAGE DISCHARGE

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The results of an experimental investigation of the dynamic and energy characteristics of electro-gas-dynamic flows are presented.

In [1], in a study of the action of a low-current, high-voltage discharge on the kinetics of evaporation of a liquid, it was established that the process is significantly intensified (by one to two orders of magnitude) and the intensification depends on the strength of the discharge current, the form of the electrodes, and the polarity of the electrodes and their arrangement relative to the surface of evaporation as well as on the physical properties of the liquid. This effect is explained by the action of electro-gas-dynamic (EGD) flows forming in the zone near the electrode on the surface layer of the liquid and the entrainment of vapor by it into the discharge processes.

The purpose of this work is to determine the possible mechanism for the action of EGD flows on the kinetics of phase transitions and to determine their dynamic and energy characteristics. The investigations were performed on the experimental apparatus described in [2].

The discharge current varied from 0.5 to 100 μA and the voltage varied from 3 to 10 kV. The liquid was evaporated from thin tubes and flat volumes as well as from drop surfaces. The gas-dynamic flows were visualized with the help of the schlieren method for determining the nonuniformities of transparent materials (the point-source method) [3]. The EGD flow created in the point-ring system of electrodes (the ring diameter equalled 2.5 mm and the distance between the point and the plane of the ring equalled 1.5 mm) was probed with a parallel light beam. The investigations showed that a directed gas-dynamic jet 15-30 mm long and 2-3 mm in diameter is generated in the discharge gap of the point-ring electrode system.

The flow velocity was measured by the well-known method of [4], realized in a Pitot–Prandtl tube and modified for the specific case of EGD flows. It was established that the velocity on the axis of the flow depends on the strength of the discharge current and the polarity of the electrodes. For positive polarity of the electrode-tip and currents in the range 5-100 μA the velocity varied from 5 to 9 m/sec, and for a negative potential on the tip with the same discharge currents it varied from 2.5 to 4 m/sec. At distances of 1-1.2 mm from the axis of the flow the velocity decreases by a factor of 2.8-3.

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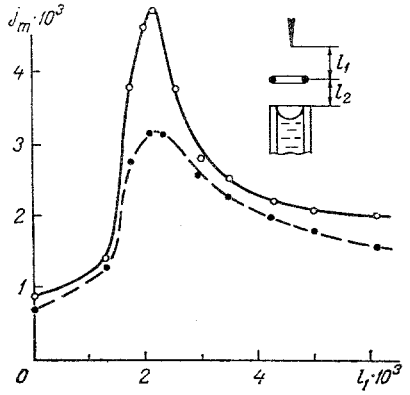

Fig. 1

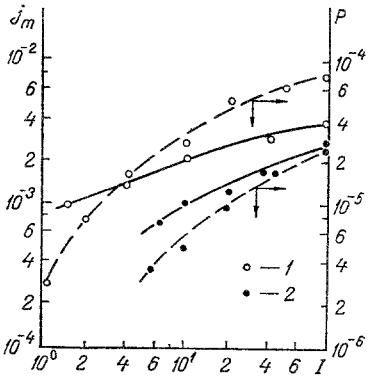

Fig. 2

Fig. 1. Rate of evaporation of water versus the distance between electrodes with the meniscus of the liquid lowered by 1.5 (solid line) and 2 (broken line) mm from the cutoff of the tube; the discharge current equals 50 μA, the tube is 1.6 mm in diameter, j_m, kg/(m²·sec); ℓ_1, m.

Fig. 2. The pressure of the EGD flow (broken curves) and rate of evaporation of water (solid lines) versus the current strength and the polarity of the electrodes: 1) positive tip; 2) negative tip. P, N; I, μA.

The parameters of EGD flows and therefore their effect on evaporation processes are determined by the size of the interelectrode gap ℓ_1 and the arrangement of the electrodes relative to the surface of the liquid. The rate of evaporation is maximum for $\ell_1 \approx 2$ mm (Fig. 1), and as the meniscus sinks into the tube the effect of the EGD flow decreases (compare curves 1 and 2). The analogous dependence of j_m on the distance ℓ_2 between the ring electrode and the cutoff of the tube with the liquid has a maximum for $\ell_2 \approx 1.8$ mm. For $\ell_2 = 0$ the rate of evaporation is 1.2 times lower than the maximum rate. For $\ell_2 > 1.8$ mm j_m decreases and for $\ell_2 = 15$ mm it is six times lower than its maximum value.

The results presented indicate that there exist optimal arrangements of the electrodes relative to one another and the surface of evaporation for which the efficiency of EGD flows is maximum.

The action of gas-dynamic flows generated in the discharge gap and air flows formed with the help of a narrow nozzle connected to a compressor on evaporation processes were compared. The equality of the velocities of the flows being compared was evaluated according to their mechanical action on a small area – a target 3 mm in diameter, fastened on an elastic element (a thin quartz filament). The elastic filament together with the optical system played the role of sensitive balances, enabling the evaluation of the magnitude of the pressure force P exerted by the flow on the surface of the target.

As one can see from Figs. 2 and 3, the effect of these flows on the character of the action on the evaporation process is significantly different. The smallest difference in the evaporation rate (approximately by a factor of two) is observed for a pressure force of 10^{-5} N, which corresponds to a discharge current of ∿3 μA for a positive tip and 20 μA for a negative tip (Fig. 2). To the right and left of this region the difference increases and j_m under the action of EGD flows is four to eight times greater than j_m from the surface of a liquid in a flow obtained without a discharge. The investigations performed show that the electro-gas-dynamic flow excited by a low-current high-voltage discharge differs from a gas-dynamic flow by its energy content.

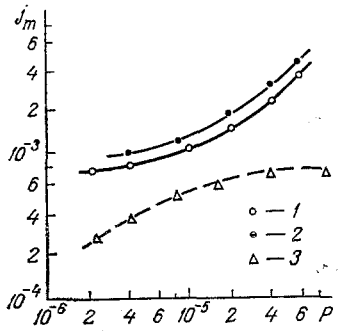

Fig. 3

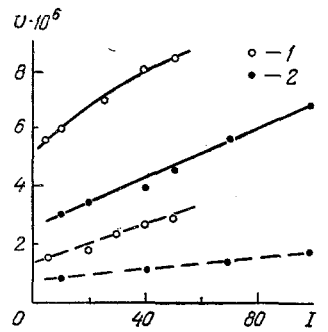

Fig. 4

Fig. 3. Comparison of the action of EGD flows formed with an electric discharge (curves 1 and 2) and the action of flows formed without a discharge (curve 3) on the kinetics of evaporation; the rate of evaporation in the absence of the flows equals $1.2 \cdot 10^{-4}$ kg/(m²·sec); 1) positive tip; 2) negative tip.

Fig. 4. Velocity of the melting front (solid lines) and evaporation front (broken lines) versus the current strength and polarity of the electrodes: 1) positive tip; 2) negative tip. v, m/sec.

Evaluation of the parameters of the electric field in the interelectrode space of the point-ring electrode system [2] shows that for characteristic voltages on the electrodes a strong electric field ($E \sim 10^5$-10^8 V/m), sufficient for formation of a nonequilibrium plasma by free electrons, forms near the point. Collisions between the electrons and gas molecules lead to excitation and storage of energy in separate internal degrees of freedom of the molecules. The overall energy balance of the discharge plasma depends on the cross sections of the corresponding elementary processes and the form of the electron energy distribution function. The determining macroscopic parameters, in this case, are the ratio of the electric field intensity to the gas density and the composition of the gas mixture [5]. The parameters of the collision processes for electrons in air are presented in [5, 6]. An estimate of the electric field in the cases we studied [2] showed that for the characteristic values U = 5 kV and an interelectrode gap of ℓ_1 = 1.5 mm the ratio E/n_0 varies from $18 \cdot 10^{-16}$ to $1.6 \cdot 10^{-16}$ V·cm², i.e., in different zones of the discharge gap ionization of molecules by electrons with energy exceeding 10 eV as well as electronic (5-14 eV) and vibrational (0.3-5 eV) excitation of molecules can occur. Relaxation of excited particles determines the transformation of the starting energy of the discharge into thermal energy and transport of the energy by the EGD flow toward the target (the surface of a liquid or solid); here it is important that the vibrational relaxation processes are significantly slower than other processes, i.e., vibrationally excited molecules can relax directly on the surface of the phase transition of the target [7].

The limiting liberation of energy on the surface intensifies the phase transformations of the target material (melting, evaporation); this was observed in a study of the action of a low-current high-voltage discharge on liquids [1] and solids — phenol, naphthalene, salol, and ice [8]. It was established that two regions form in the solid target material: a liquid region $0 \leq x_1 \leq x_m$ with a temperature field $T_1(x_1, t)$ and a solid region $x_m \leq x_2 \leq \infty$ with a temperature field $T_2(x_2, t)$. Both fronts move with velocities $v_1(t)$ and $v_2(t)$ relative to a stationary coordinate system. These velocities, as numerous experiments have shown, become constant but unequal ($v_2 > v_1$) within a definite time interval of the development of the process. For such a regular regime the thermophysical process determined by the action of an energy flux with density q from the discharge is described by the following system of partial differential equations [8]:

$$\frac{\partial T_1(x_1, t)}{\partial t} = a_1 \frac{\partial^2 T_1(x_1, t)}{\partial x_1^2} + v_1 \frac{\partial T_1(x_1, t)}{\partial x_1};$$

$$\frac{\partial T_2(x_2, t)}{\partial t} = a_2 \frac{\partial^2 T_2(x_2, t)}{\partial x_2^2} + v_2 \frac{\partial T_2(x_2, t)}{\partial x_2};$$

$$-a_1c_{1V}\frac{\partial T_1(0,\ t)}{\partial x_1}=q-v_1r_V;\quad -a_1c_{1V}\frac{\partial T_1(x_m,\ t)}{\partial x_1}=$$

$$=-a_2c_{2V}\frac{\partial T_2(x_m,\ t)}{\partial x_2}+(v_1+\dot{x}_m)L_V;\quad v_1+\dot{x}_m=v_2;$$

$$\dot{x}_m=\frac{dx_m}{dt};\quad \frac{\partial T_2(\infty,\ t)}{\partial x_2}=0;\quad T_1(x_m,\ t)=T_2(x_m,\ t)=T_m;$$

$$T_2(\infty,\ t)=T_0;\quad T_1(0,\ t)=T;\quad x_m(0)=0.$$

Integration of these equations gives the following expression for the energy flux density:

$$q=v_1r_V+v_2L_V+c_{1V}v_1(T-T_m)+c_{2V}v_2(T_m-T_0)+c_{1V}\int_0^{x_m}\frac{\partial T_1(x_1,\ t)}{\partial t}dx_1+c_{2V}\int_{x_m}^{\infty}\frac{\partial T_2(x_2,\ t)}{\partial t}dx_2. \quad (1)$$

The last two terms in (1) are determined by the rate of heating of the material not participating at a given moment in the phase transformations, and they can be neglected. An estimate of the terms $c_{1V}v_1(T - T_m)$ and $c_{2V}v_2$ $(T_m - T_0)$ shows that they do not exceed 10-15% of the total value of the first two dominant terms and they can be neglected. After these simplifications Eq. (1) assumes the form

$$q=v_1r_V+v_2L_V. \quad (2)$$

Equation (2) enables determining the energy flux density absorbed by the surface of the target exposed to EGD flows in the approximation valid only for the regular regime of development of the thermophysical process.

In the course of the experiments the time-dependence of the positions of the evaporation and melting fronts was determined. A region of regular development of the process, for which the values of the velocities of the evaporation and melting fronts were determined, was separated on the graphs. The results of these studies for ice are presented in Fig. 4. Water was poured into glass tubes, frozen, and placed in a thermostat with the medium at a negative temperature. The electrical discharge was excited above the open surface of the ice.

The following values of the energy flux density were obtained for the range of variation of the discharge current strength presented in the graph: 6-10 kW/m^2 for a positive point and 2.5-6.5 kW/m^2 for a negative point. For all discharge conditions studied the magnitude of the first term in the expression (2), determining the relative fraction of the energy flux released at the evaporation front, equals approximately 70% of the total energy absorbed by the surface of the target. Quantitative comparison of these results with the data presented in Fig. 3 shows that the intensification of the phase transformations by the EGD flows is determined primarily by thermophysical processes occurring at the boundary of the target. From 10 to 25% of the energy flowing into the surface zone near the target, depending on the strength of the discharge current and the polarity of the electrodes, is expended on removing vapor by the mechanical action of EGD flows on the surface of the liquid.

Thus the electro-gas-dynamic flows generated by a low-current high-voltage discharge have a significant energy content, determined by the elementary processes occurring in the nonequilibrium discharge plasma. The energy content, the spatial concentration, and the local character of the action of EGD flows on the target make such flows useful for applications in heat engineering in the solution of special applied problems in heat transfer, heat regulation, drying, and sublimation cleaning of surfaces.

A method for intensifying the evaporation of a liquid was developed based on the investigation performed [9].

NOTATION

I, discharge current; U, voltage applied to the electrodes; E, electric field intensity; ℓ_1 and ℓ_2, distance between the point electrode and the plane of the ring electrode and between the plane of the ring and the cutoff of the tube with the liquid, respectively; P, force of the flow pressure exerted on the target; n_0, number of molecules per unit volume; T, temperature; v, velocity of the phase transformation front; a, coefficient of thermal diffusivity; t, time; $x_m(t)$, coordinate of the melting front relative to the moving evaporation front; r_V and L_V, specific volume heats of evaporation and melting; c_V, specific volume heat capacity; and q, energy flux density.

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GENERATORS OF NONEQUILIBRIUM LOW-TEMPERATURE PLASMA

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Results are described of a study and of the characteristics of sources of a nonequilibrium gas-discharge plasma.

Plasma chemistry, metallurgy, deposition of coating and films on various details and separators, plasma sharpening and welding, plasma engines, lasers, the handling of surface materials, and MHD-generators are an incomplete list of the promising applications of low-temperature plasma. To enhance the effectiveness of these applications and create new plasma techniques it is necessary to have stability of operational plasma generators, having high efficiency and large resources. For conversion of gas, liquids, and solids into a low-temperature plasma one may use electric discharge energy, laser radiation, electron beams, and chemical fuels. In the present study we consider plasma generators with glow, high-frequency, and arc discharges. The discharges enumerated make it possible to obtain plasma flows in a wide range of variations of sizes, temperatures, and pressures.

The ion mobility in a plasma is substantially smaller than the electron mobility, and therefore the electric field transports its energy mostly by electrons. As a result the kinetic energy of the directed electron motion increases. During collisions the dominant part of this energy is transported by heavy particles (ions, atoms, molecules), consumed by ionization, dissipation of neutral particles, converted into kinetic energy of chaotic thermal electron motion, and the remaining part is transported by the surrounding plasma due to the thermal conductivity. In this connection the electron temperature in a gas discharge

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