NOTATION

n_e, electron concentration; ε, mean number of oscillatory quanta per nitrogen molecule; ε_0, equilibrium value of ε; E_o, oscillatory energy of nitrogen molecules per unit volume; N, number of molecules per unit volume; $N\psi$, number of nitrogen molecules per unit volume; T, gas temperature; T_o, nitrogen molecule oscillatory temperature; P, pressure; v, gas velocity; (τP), normalized oscillatory-translational relaxation time for nitrogen molecule oscillatory energy in air; t, time; x, coordinate along discharge chamber; x_0, distance between adjacent cathodes along discharge chamber; W, power density distribution along chamber; Wg, total power contained in gas; K_Σ, net rate of excitation of oscillatory levels of nitrogen molecule ground state oscillatory levels (per electron) defined by electron energy distribution and oscillatory temperature T_o; $h\nu$, energy of nitrogen molecule oscillatory quantum; v_0, v value at x = 0; P_0, P value at x = 0; T_0, T value at x = 0; γ, adiabatic index; k, Boltzmann's constant; η, fraction of electrical energy expended in gas heating; G, air flow rate; X_{H_2O}, partial pressure of water vapor.

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EXPERIMENTAL INVESTIGATION OF THE INTERACTION BETWEEN THE PLASMA OF AN ELECTRICALLY EXPLODED WIRE AND A PLANE OBSTACLE

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The results of an investigation of the physical processes that occur when pulses of dense low-temperature plasma, generated by electrical explosion of a wire, flow over a plane dielectric obstacle are presented.

The interaction of dense pulsed flows of low-temperature plasma with the surface of a solid is an important subject for scientific investigation. The impact drag and flow of a pulsed plasma beam around different obstacles have been investigated in [1-6], where the nature of the radiation was studied, and the temperature and density of the gas discharge and the erosion plasma in the layer perturbed by the obstacle were estimated. However, there appear to be no data available in the literature on the relationship between the properties of a collision-compressed plasma and the nature of its interaction with the surface of the obstacle. In this paper we study this relationship using the example of the collisional slowing down of a plasma from an electrically exploded wire. The electrical-explosion method was chosen to generate the plasma because it enables one to obtain dense, high-

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energy pulsed plasma flows having pronounced two-phase properties (finely dispersed liquid drops are present).

The coaxial-type plasma generator operated at an initial external pressure of 6.6×10^{-3} N/m^2 and an energy of the capacitive store of 2.5 kJ. We used copper foil 1 cm in diameter and 30 μm thick as the exploded wire. The discharge current had a rapidly decaying periodic form with a half-period of 50 μsec. Using the output nozzle of the generator the plasma flow was directed onto a plane dielectric obstacle (K-8 glass) 6 cm in diameter, situated perpendicular to the axis of the flow at a distance of 10 cm from the mouth of the nozzle.

For plasma diagnostics we simultaneously used holographic interferometry in real time, and emission spectroscopy in the visible region of the spectrum with a time resolution of 1 and 4 μsec, respectively. The time frame sweeps of the interferograms and the radiation spectra were recorded using high-speed photographic recorders, and, as in [6], were processed both independently and together. The independent processing of the interferograms enabled us to estimate the electron density, neglecting the contribution of heavy particles to the refractive index, or the atomic density neglecting the contribution of the electron component. Local values of n were found by numerical solution of the Abel integral equation. The technique for obtaining interferograms is described in [7]. The plasma temperature was found by Bartels's method from the intensity of the reabsorbed spectral lines of the copper atoms. Combined processing of the interferograms and the spectra enabled us to find the electron density, the atomic density, and the pressure of local equilibrium plasma from the measured values of $(n - 1)$ and T [7].

To study the properties of the surface of the obstacle we took oscillograms of the time behavior of the reflection coefficient of its central part (of area 6 mm^2). The reflection coefficient was defined as the ratio of the intensity of the specularly reflected beam of a He–Ne laser to the intensity of the beam incident normally on the surface. To eliminate the effect of absorption, scattering, and refraction in the plasma on the measurements of k, the laser emission was directed at the obstacle from the opposite side of the plasma flow. The obstacle itself was wedge-shaped, so that we were able to separate spatially the beams reflected from its two opposite surfaces. The effect of the plasma radiation itself on the value of the signal recorded by the photoreceiver was eliminated using interference and polarization filters placed in the path of the laser beam, and also by means of spatial filtering.

To determine the effect of the characteristics of the generated flow on the plasma parameters in the slowing region, plasma diagnostics were carried out both on the surface of the obstacle and at the output of the generator. As a result of combined processing of the data from spectroscopic and interferometric measurements, we established that at the generator output a dense nonstationary plasma flow is formed, whose parameters correlate in time with the periodicity of the energy supplied to the discharge. The maximum values of the temperature and electron density were reached at t = 15-20 μsec and were equal to 15×10^3°K and 7.5×10^{18} cm^{-3}, respectively. The degree of ionization at these instants of time was 0.6. The second maximum of these plasma parameters was reached at t = 80-90 μsec, corresponding to the maximum discharge current of the second half-period, and they equal 9×10^3°K, 8.5×10^{17} cm^{-3}, and 0.12. We took as the origin of the time readout the instant when the plasma appeared in the mouth of the generator nozzle. In the time interval 120-220 μsec, the plasma brightness is not sufficient for spectroscopic measurements of T with the required time resolution. Interferometric measurements show that at this stage of the discharge the plasma flow emerging from the generator is only slightly ionized ($\alpha < 0.1$), with an atomic density that decreases monotonically with time from 9×10^{18} to 10^{18} cm^{-3}.

The nonstationary nature of the parameters of the plasma flow were the reason for the time changes in the properties of the region in which it is slowed down by the obstacle. During the first 65 μsec the structure of the interaction region agrees qualitatively with the structure of this region when the plasma from an erosion accelerator flows over the plane of the obstacle [6]. The results of measurements of the spatial and time behavior of the parameters of plasma from an electrically exploded wire in the region where slowing occurs are shown in Figs. 1 and 2. For t ≈ 3 μsec, a slightly luminous highly ionized layer is formed on the surface of the obstacle with a density which increases with time (curve 1, Fig. 1), and this gradually extends reaching a thickness of 2 mm at a time t = 10 μsec. The main feature of the spatial distribution of the density of this layer is its increase towards the surface of the obstacle (curve 1, Fig. 2). This variation of the plasma properties for $3 \leq t \leq 10$ μsec was established from interferograms, neglecting the contribution of the atomic component to the refractive index. The nonequilibrium nature of the plasma and the weak intensity of the radiation did not enable us to estimate the temperature of the supersonic flow in the layer considered with sufficient time resolution. The appearance of this layer can be explained by the collision of high-energy plasma clusters, which flow at a velocity of ≈30 km/sec, with the obstacle. The value of the velocity was found by delaying the instant when the illumination on the obstacle was recorded with respect to the mouth of the generator nozzle. The practically constant value of the reflection coefficient of the obstacle surface at the stage when the plasma clusters are slowed down (curve 4, Fig. 1) indicates that no condensation of the flux occurs during this period. For a kinetic energy of directional motion of the heavy particles of the copper plasma of the order of 300 eV, observed in our experiment, there is very little sputtering of the surface layer of the obstacle [5], which has no effect on the value of k.

When $t \approx 13$ μsec, because of the reduction in the mean free path of the particles, due to the increase in the density of the incident flux and the flux reflected from the obstacle, a collisional shock wave is formed on its surface. Beginning from this instant, the kinetic energy of the directed motion of the plasma flux is completely converted into thermal energy. We recorded the onset of a shock wave in the medium of heavy particles from the sudden increase in the brightness of the continuous spectrum, due to recombination and braking radiation, and also from the formation of a characteristic kink in the interference fringes. The ion-atom shock wave then leave the surface of the obstacle with the velocity of ≈250 m/sec. When $t = 40$ μsec this withdrawal takes its maximum value of 3 mm, and after 65 μsec it is reduced to 2 mm. The intensity of the sudden change in the shock-wave front falls with time, and when $t > 65$ μsec the shock wave is not recorded. This is due to the fact that at the instant of time considered the first half-period of the discharge is completed, and the parameters of the flow over the obstacle decrease sharply.

Spectroscopic and interferometric measurements showed that after the shock wave is formed, the character of the spatial temperature and density distribution of the plasma in the slowing region is analogous to that established in [4], and corresponds to the case of the formation of an isoelectronic-thermal jump. In Fig. 2, curves 2, 3, and 4 represent the behavior of the density and temperature on the axis of the plasma flow along the braking line at the instant of time $t = 26$ μsec. The maximum value of the Mach number of the shock wave, i.e., the maximum value of ρ and T on the shock-wave front, corresponds to this instant of time. Estimates from the value of the jump in density give $M = 5$, for $t = 26$ μsec. In the time interval 13-65 μsec the shock wave of the plasma layer makes direct contact with the obstacle. The equilibrium of the plasma of this layer is confirmed by the low value of the relaxation time of the electron and ion temperature. An estimate of τ_{ei} from the experimentally measured T and N_e showed that behind the shock-wave front τ_{ei} is two orders of magnitude less than the characteristic time of motion of the plasma flow.

As can be seen from Fig. 2, a characteristic feature of the spatial behavior of the parameters of the shock-compressed layer is the drop in temperature, the sharp increase in density, and also the increase in the gradients of these parameters as one approaches the obstacle. It was not possible to make spectroscopic measurements of the temperature of the plasma of this braking geometry for $l < 0.05$ cm, while the interferograms at these small distances cannot be processed because of the possibility of introducing errors due to diffusion phenomena at the obstacle-flow boundary. The nature of the time variation of the properties of the shock-compressed layer on the axis of the flow at a point a distance $l = 0.05$ cm from the obstacle is represented by curves 1, 2, and 3 in Fig. 1. As can be seen, the temperature and degree of ionization of the shock-compressed plasma, in contact with the obstacle, fall, whereas the density has a maximum at $t = 26$ μsec.

The space and time distributions of the parameters of the shock-compressed plasma obtained enable the heat flow to the obstacle due to contact thermal conductivity to be estimated. The electron, atomic, and ionic thermal conductivity were determined using the relations given in [8]. The gradients of the enthalpy and its derivatives with respect to temperature were found by graphical differentiation, taking into account the contribution to the enthalpy of the ionization and excitation energies. Calculations showed that as one approaches the obstacle, the flow of heat due to contact thermal conductivity increases, and for $l = 0.05$-0.07 cm takes values of 0.7×10^3, 1.5×10^3, and 0.2×10^3 W/cm² at times of 18, 26, and 58 μsec, respectively. As can be seen, the behavior of the heat flux with time correlates with the change in the density on the obstacle surface.

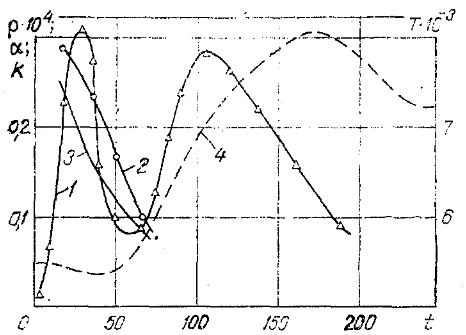

Fig. 1

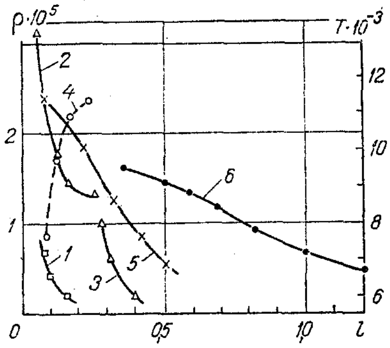

Fig. 2

Fig. 1. Time dependence of the reflection coefficient k of the surface of the obstacle and the axial value of the density ρ (g/cm^3), the temperature T (°K) and the degree of ionization α of the plasma flow in the surface layer: 1) ρ; 2) T; 3) α; 4) k; t, μsec.

Fig. 2. Axial distributions of the density ρ (g/cm^3) and the temperature T(°K) in the braking zone of the plasma flow: 1, 2, 3, 5, 6) ρ; 4) T, 1) t = 10; 2, 3, 4) t = 26; 5) t = 90°, 6) t = 162; l, cm; t, μsec.

The plasma temperature behind the shock-wave front obtained under our experimental conditions leads to intense radiation fluxes at the obstacle. Estimates using the Schwartschild—Shuster approximation [9] give values of from 1.4×10^4 to 0.4×10^3 W/cm^2 for the radiation flux in a time interval from 18 to 58 μsec, respectively, which considerably exceeds the flux due to contact thermal conductivity, particularly in the initial stages of the existence of the shock-compressed plasma layer. The total thermal flux Q correlates quite well in time with the plasma temperature.

The results of a measurement of the reflection coefficient of the obstacle surface (curve 4, Fig. 1) show that after the shock wave is formed its value becomes lower than the initial value, which is equal to the reflection coefficient at the glass—vacuum boundary, despite the increase in the density of the surface layer of the plasma. This indicates firstly that plasma-particle reflection and reevaporation of particles from the surface of the obstacle predominate over condensate formation. The absence of condensation when $t < 40$ μsec is also confirmed by the intense radial spread of the shock-compressed plasma along the substrate. Measurements using a high-speed camera showed that at this stage of the braking, the radial component of the velocity of the bright plasma nonuniformities reaches 2×10^5 cm/sec as it approaches the edges of the obstacle in a cross section situated at a distance of 0.1 cm from its surface. As the increase in the reflection coefficient shows, the condensate begins to form at a time $t \approx 40$ μsec. As estimates have shown, the heat flux on the surface of the obstacle at this instant of time is 5×10^3 W/cm^2, i.e., it is the limiting heat flux Q'. When $Q < Q'$ condensation of the plasma occurs under the experimental conditions.

The reduction in the reflection coefficient at $15 < t < 40$ μsec which we observed is most probably due to the occurrence of mechanical damage to the surface of the obstacle (mainly fine cracks) as a result of thermoelastic stresses. The appearance of this type of damage due to the radiation of a neodymium laser with a power density of $\approx 7 \times 10^5$ W/cm^2 was pointed out in [10, 11]. The lower value of the surface-strength threshold in our experiments ($\approx 10^4$ W/cm^2) is due to the presence in the light flux incident on the obstacle of intense short-wave radiation, for which the absorption coefficient of the glass increases sharply. In addition to this factor, the drop in the reflection coefficient of the surface of the obstacle may be due both to a change in the refractive index of the medium on it, resulting from the formation of the shock-compressed layer of plasma, and to a change in the refractive index of the glass resulting when it is heated. Quantitative estimates showed that the contribution of these processes to the drop in k is below the sensitivity of the oscillographic measurements.

The maximum value of the rate of increase in the reflection coefficient of the obstacle surface and, consequently, of the thickness of the condensate, was observed in the time interval of 65-100 μsec, corresponding to the second half-period of the discharge current. This stage of the braking of the product of the electrically exploded wire is characterized by subsonic flow of the plasma over the whole region of its interaction with the obstacle, and also lay close to a linear increase in the density of the surface layer with time (curve 1, Fig. 1), and along the axis (curve 5, Fig. 2). The brightness of the plasma radiation at $t > 65$ μsec is insufficient to measure the temperature, and for this reason the flux density was found by direct interferometric measurements of N_α. This is justified since the degree of ionization of the plasma at these instants of time is less than 0.1.

Using the relationship between the reflection coefficient of a thin film of copper and the thickness [12], which has a linear section at $0.05 < k < 0.35$, we obtain for the rate of condensation dh/dt a value of 9×10^{-3} cm/sec in the time interval 65-100 μsec. For this same time interval, from the experimentally measured parameters of the plasma on an axial line in the braking region we can approximately estimate the flow of mass towards the obstacle and the corresponding rate of condensation as

$$\left(\frac{dh}{dt}\right)' = \frac{1}{\rho_0}\, \rho(t)\, v(t),$$

where ρ(t) and v(t) are the density and directional velocity of the plasma in the initial part of the region where flux braking occurs. A calculation using an approximation of the ρ(t) and v(t) relations by linear functions showed that (dh/dt)' increases over the time interval considered, taking values from 0.05 to 0.1. The error of this estimate does not exceed 50%, and is mainly due to the large error in measuring the velocity using the slit photorecording method. The ratio dh/dt/(dh/dt)', which in our case took values from 0.18 to 0.09, is the condensation coefficient of the plasma flux. Hence, even when $65 < t < 100$ μsec, when the maximum rate of condensation is observed, the fraction of the material condensed on the obstacle is 9-18 % of the flowing material. The high velocity of radial spread of the flow in the surface layer also confirms the small value of the condensation coefficient at this stage of the braking. At t = 75 μsec it reached a value of 10^5 cm/sec at the edge of the obstacle.

A feature of the braking of the products of the electrically exploded wire when $t > 100$ μsec is not only the drop in ρ and v in the region of interaction with the obstacle, but also the appearance on its surface of a layer with a high content of the liquid-drop phase, whose thickness increases with time, reaching a maximum of 0.4 cm at 170 μsec. Within this layer the contrast of the interference fringes falls sharply until the interference pattern completely disappears. The reason for this is the scattering of the probing laser beam by the finely dispersed liquid drops, the increase in the concentration of which, most probably, is due to their reflection from the surface of the obstacle and their slowing down when they enter the more dense region of the flow. Curve 1 in Fig. 1 of the relationship ρ(t) when $t > 110$ μsec corresponds to a distance from the obstacle of 0.1-0.4 cm, at which the boundary of the layer of the liquid-drop phase is situated.

The drop in the reflection coefficient of the surface of the obstacle observed at $170 < t < 240$ μsec is due not to the reduction in the thickness of the condensate, but to the formation in it of defects in the form of punctures. The largest drops with dimensions of tens of microns, on being reflected from the surface of the obstacle, break down the condensate at the point of collision. The two-phase nature of the flow, generated during the last stages of the discharge, was confirmed by dynamic tracking, which consisted of precipitating the products of the electrically exploded wire on a rotating disc. For $t > 240$ μsec, the liquid-drop layer is not observed, and k remains constant. It should be noted that the effect of the temperature of the condensate on the change in its reflection coefficient is negligibly small [13].

NOTATION

n and α, refractive index and the degree of ionization of the plasma; T, N_e, and N_α, temperature, and the electron and atomic density of the plasma flow; v and ρ, velocity and density of the plasma flow; t, current time; l, distance from the surface of the obstacle; k, reflection coefficient of the obstacle surface; τ_{ei}, relaxation time of the electron and ion temperatures; ρ_0, density of copper in the solid state; M, Mach number; Q, heat flux on the surface of the obstacle; and h, thickness of the copper film.

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