INVESTIGATION OF PULSED DISCHARGES IN A DIELECTRIC CHANNEL WITH ABLATING WALLS

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The current-voltage characteristics of a pulsed discharge in a hollow cylindrical channel formed by dielectric walls are investigated. The erosion of the channel walls is measured, together with the mean velocity of the plasma flowing into a vacuum through an opening in one of the electrodes, and related to the channel geometry. Conclusions are drawn regarding the temperature of the plasma in the channel and the mechanism of heat transfer to the walls.

NOTATION

d—channel diameter
l—channel length
C—capacitance of capacitor bank
U—capacitor voltage;
M—consumption of dielectric per discharge
m—specific consumption
W—discharge energy
R_0—resistance of discharge gap at instant of maximum current
R—variable resistance of discharge channel
I_m—maximum discharge current
W_1—chemical bond rupture energy of dielectric of mass M
W_2—ionization energy of dielectric of mass M
W_3—kinetic energy of dielectric of mass M
W_4—electrode heating energy per discharge
W_5—thermal energy of dielectric of mass M
$\langle T \rangle$—mean temperature of channel plasma
S—energy of light flux on dielectric layer
h—depth of dielectric layer heated to temperature T
γ—density of dielectric
c—specific heat of dielectric
m_0—mass of dielectric layer heated to temperature T
T—temperature of heated layer
k_1, k_2—constants
u—residual stress.

Research on discharges in channels bounded by dielectric walls is being conducted in two directions: the creation of stable sources of light and plasma at relatively high temperatures to $2 \cdot 10^5$ °K [1], and the formation of high-velocity jets of dielectric decomposition products [2].

In these studies the channel shape depends on the nature of the problem. In [1] the channels were short (length $l = 1$–10 mm) and narrow (diameter $d = 1$–2 mm); in [2] both dimensions were an order greater.

Moreover, the study of the interaction of plasma with dielectrics is of independent interest and important in relation to the design of heat-resistant coatings [3].

Accordingly, we decided to investigate the variation of the plasma parameters in a dielectric channel as the duration and amplitude of the discharge current increase.

The dischargers (Fig. 1) had teflon channels with dimensions $d = 9$ mm, $l = 200$ mm and $d = 16$ mm, $l = 30$–165 mm. The discharge was struck between electrodes 1 and 2 in the hollow cylindrical channel formed by the dielectric walls 3. The plasma jet flowed out through the open end of the channel into a vacuum. The discharge was initiated by means of an auxiliary spark created by igniter 4. The experiments in the channel with d = 9 mm were conducted at C = = 150–2400 μF, voltages U up to 5 kV (IM-5-150 capacitors) and a pressure in the vacuum chamber of 10^{-1} mm Hg. At a lower pressure the energy of the auxiliary spark (3 J) was insufficient for reliable initiation of a discharge. In the experiments with a channel diameter d = 16 mm the pressure in the chamber was 10^{-5} mm Hg. In this case we used a bank of MGBV capacitors with C = 100–7200 μF at U = 1 kV. The discharge currents and the voltage across the discharge gap were recorded with an oscillograph, and the erosion of the channel walls was investigated. The mean velocity of the plasma jet flowing into the vacuum was calculated from the measured momentum of the jet and the consumption of dielectric per discharge. The profile of the jet registered by a high-speed photorecorder is shown in Fig. 2.

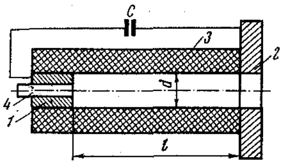

Fig. 1

As the discharge energy W increases, so does M, the consumption of teflon. In Fig. 3 m = M/W has been plotted as a function of W; curve 1 is for d = 9 mm and l = 200 mm, curves 2, 3, and 4 for d = 16 mm and l = 60, 115, and 165 mm, respectively. At W ≥ 500–1000 J the erosion of the walls is chiefly determined by the channel geometry: the dimensions d and l. At W < 500 J, m also depends on W. The anomalous increase in m at W = 4.2 kJ is caused by incomplete decomposition of the dielectric due to thermal overloading of the channel and the face of the electrode leading to melting. The table gives values of the residual voltage u, kV, the maximum discharge current I_m, kA, and $w = W_1/W \cdot 100\%$ for a dielectric of mass M at C = 150, 600, 1200, and 2400 μF for a series of values of the voltage U, kV.

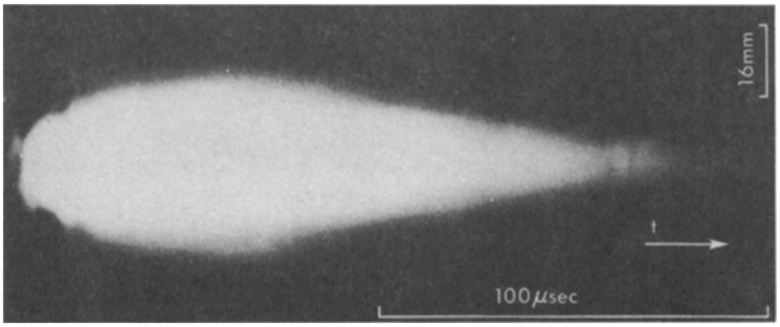

Fig. 2

In all the experiments the capacitor bank was incompletely discharged and the residual voltage u increased both with increase in capacitance and with increase in the initial voltage (table). In Fig. 4 the resistance of the discharge channel R_0 at the instant of the current maximum I_m is shown as a function of W. Curve 1 was constructed for C = = 150 μF, U = 5 kV, d = 9 mm, and l = 200 mm; curves 2, 3, and 4 were constructed for C = 100–7200 μF, U = 1 kV, d = 16 mm, and l = 165, 115, and 65 mm, respectively. An increase in capacitor voltage at fixed C leads to a linear fall of R_0; an increase in C at fixed voltage leads to a rise in R_0. This dependence of R_0 on C and U can be explained as follows. At small C = 150–600 μF the discharge is short (≈60 μsec) and depends only weakly on U. As U increases, the temperature and degree of ionization of the channel plasma increase; consequently, the resistance of the discharge gap falls. An increase in C from 100 to 7200 μF (U = const) causes a substantial increase in the duration of the discharge with a very flat discharge current front. In this quasi-stationary regime the discharge channel is intensely cooled by the gas from the ablating wall, the temperature and conductivity of the plasma fall, and hence the discharge current decreases as C increases. Moreover, in this regime the removal of heat is intensified as a result of the entrainment of energy by the escaping jet throughout the discharge. At small C the expansion process may be regarded as taking place after the majority of the energy has been released in the discharge channel. The time dependence of the channel resistance (curves 1, 2), calculated from the maximum current amplitude up to $I = 0.1 I_m$, and the current I (curves 1', 2') is shown in Fig. 5 for C = 150 μF. Curves 1 and 1' correspond to U = 4 kV, and curves 2 and 2' to U = 1 kV; R has a minimum at $I = (0.3–0.4)I_m$.

C	150					600			1200		2400
U	1	2	3	4	5	1	2	3	1	2	2
u	0·2	0.38	0.67	1	1.15	0.1	0.93	1	0.34	1.4	1.77
I_m	6.23	11.6	20.8	23.6	44.4	6.54	15.2	27.3	5	13.1	—
w	15.2	52.4	67.6	103	87	49	66	92.6	95.3	81	754

The mean temperature of the channel plasma was estimated for discharges in which the complete decomposition of the vaporized dielectric was most probable, i. e., in cases in which the energy expended on breaking the molecular bonds of the material eroded during a single discharge was not more 0.5 W. The following assumptions were made: 1) the plasma is in thermodynamic equilibrium; 2) the excitation energy of the atoms and ions leaving the channel is negligibly small.

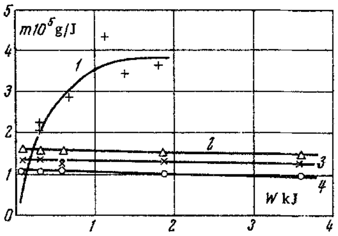

Fig. 3

The energy supplied to the discharge channel is distributed among the ionization energy W_2, the molecular bond rupture energy W_1, the kinetic energy of the jet W_3, the electrode heating energy W_4, and the thermal energy W_5 in accordance with the equation:

$$\int_0^\infty UI\,dt = W_1 + W_2 + W_3 + W_4 + W_5\ . \tag{1}$$

For an approximate solution of this equation we used the Saha formula. The mass of vaporized dielectric, the mean velocity of the jet and the electrode energy losses were determined experimentally. This method of estimating the temperature gave the following results:

$\langle T\rangle = (2.3-2.5)\cdot 10^4\,°\mathrm{K}$ for $W = 72$ J and $\langle T\rangle = (1.2-1.3)\cdot 10^4\,°\mathrm{K}$.
for $W = 290$ J .

In the initial period of the discharge the temperature may be somewhat higher than ⟨T⟩ owing to the nonstationarity of the process.

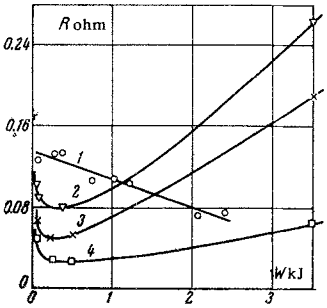

Fig. 4

Assuming the optical transparency of the discharge channel, we calculated the radiation energy from the emission curves of a teflon plasma [4], starting from ⟨T⟩ and the mean particle density. Good agreement was obtained between the radiation energy and the energy expended on breaking the chemical bonds W_1. Hence in this case the emission of the optically transparent plasma plays an important role in the mechanism of energy transfer from the discharge channel to the walls. An estimate of the temperature from Spitzer's conductivity formula on the assumption of a uniform current distribution over the channel cross section gives $\langle T\rangle = 10^4$ °K for channels with $d = 16$ mm. For narrow channels at small W it leads to exaggerated values: $\langle T\rangle \approx 7\cdot 10^4$ °K. It may be assumed that in a narrow channel inelastic atom-electron collisions affect the plasma conductivity.

Light radiation is absorbed by the long molecules of dielectrics of the teflon type in a surface layer of a certain thickness h. If the discharge energy is small, the temperature of this layer may increase by

$$\Delta T = \frac{S}{\pi h d l \gamma c}\,. \tag{2}$$

Here S is the energy of the light flux, γ is the density of the dielectric, and c is the specific heat. As the temperature rises, the mass yield increases rapidly in accordance with the Arrhenius formula for the evaporation of dielectrics [5],

$$\frac{dm_0}{dt} = m_0 k_1 \exp(-k_2 / T)\,. \tag{3}$$

Here, T is the temperature of the layer, m_0 is the mass of the heated layer, and k_1 and k_2 are constants. This explains why at small energies m is anomalously small.

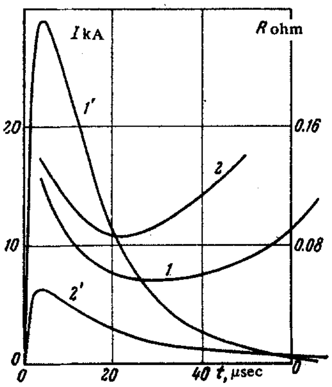

Fig. 5

In the experiments it was found that the amount of ablating material does not depend on the initial pressure in the channel on the pressure range 10^{-1}–10^{-5} mm Hg. This is because at these pressures the mean free path is much greater than the characteristic dimensions of the channel.

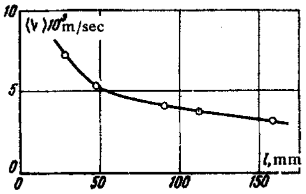

Fig. 6

In Fig. 6 the mean jet velocity has been plotted as a function of the length of the discharge channel. The velocity depends only slightly on the channel length at $l \geq 50$ mm, which indicates the purely gasdynamic nature of the forces at large channel lengths and the presence of an electrodynamic effect at small lengths. On the basis of the equations of nonstationary gas flow from tubes of constant cross section, it can be shown that the mean values of the velocity correspond to the calculated temperature values [6]. The mean velocity was calculated from the formula

$$\langle v \rangle = \zeta \sqrt{2E / M}\,. \tag{4}$$

Here, E is the energy expended on heating the ablation products, M is the mass of the evaporated material, and ζ is a coefficient depending on the composition of the gas. The maximum velocity of the flow front was determined with the high-speed photorecorder and, as a rule, exceeded the mean velocity by a factor of 4–5. A theoretical estimate, based on the formula [6]

$$v_{\max} = \frac{2}{k-1} c_0 \tag{5}$$

(here, k is the ratio of specific heats, and c_0 is the speed of sound in the undisturbed gas), gave satisfactory agreement with experiment.

Since the shape of the channel remained almost cylindrical over a long period, it may be assumed that the presence of hydrodynamic flow along the channel does not have a strong influence on the ablation process, but this question requires further investigation.

REFERENCES

1. N. I. Ogurtsova and I. V. Podmoshenskii, The Capillary Discharge as a Source of Plasma for Quantitative Investigations, Low-Temperature Plasma [in Russian], Mir, Moscow, 1967.
2. R. Goldstein and F. N. Mastrup, "Performance measurement of pulsed ablating thruster," AIAA J., vol. 4, no. 1, p. 99, 1966.
3. Yu. A. Buevich and M. I. Yakushin, "Some characteristics of the ablation of decomposing materials" PMTF [Journal of Applied Mechanics and Technical Physics], no. 1, 56, 1968.
4. V. A. Derevshchikov, "Line emission of a carbon and fluorine plasma on the temperature interval 10^4–10^{5}° K," Teplofizika vysokikh temperatur, no. 3, 540, 1968.
5. V. V. Korshak, Chemistry of High-Molecular Compounds [in Russian], Izd-vo AN SSSR, 1950.
6. K. P. Stanyukovich, Nonsteady Motion of a Continuum [in Russian], Gostekhizdat, Moscow, 1955.

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