Journal of Engineering Physics and Thermophysics, Vol. 73, No. 6, 2000

OPERATING EFFICIENCY OF AN ELECTRIC-DISCHARGE SOURCE OF EROSION PLASMA FROM A DIELECTRIC MATERIAL

V. B. Avramenko UDC 533.9.99

Consideration is given to the operating efficiency of an electric-discharge source of erosion plasma from a dielectric material with a minimum quantity of impurities of the electrode material in comparison with a pulsed erosion plasma accelerator of cylindrical geometry. A method is proposed for determining the rate of condensation of a substance from a plasma jet of complex composition using the basic parameters of the moving plasma in the case of employment of an electric-discharge erosion source in vacuum plasma technology.

Among promising methods of generating a plasma of complex composition is an electric discharge over the surface of a dielectric [1-3]. The development of more refined structures [4-6] based on surface or near-surface discharges permits the production of a plasma with a low content of impurities of the electrode material or a preset quantity of metallic impurities. Such plasma sources can be used to solve both scientific and applied problems, specifically, in plasma technology. In this connection, it is of interest to consider the efficiency of electric-discharge sources of erosion plasma from a dielectric material in comparison with similar systems, for example, erosion-type plasma accelerators.

The main point for plasma accelerators is the generation of high-velocity plasma flows [7, 8]. When such accelerators are used in technology, specifically, for implementing efficient plasma technological processes in a vacuum, the main point is the generation of high-velocity highly ionized plasma flows with high concentrations of particles and a low content of undesirable impurities. The electric-discharge sources of erosion plasma from a dielectric material with a small quantity of impurities of the electrode material [6] that are considered in the present work can also be used in vacuum technology. Therefore it is important to know both the basic parameters of the plasma jet formed and the possible quantity of impurities of the electrode material in the erosion plasma flow. Also, the question of the rate of condensation of a substance from a plasma flow on a substrate surface seems important.

The structure of a discharge device that depends for its operation on a pulsed discharge over the surface of a dielectric at a decreased pressure is described in [6]. Comprehensive study of sources of erosion plasma from a dielectric material permitted experimental determination of the basic parameters of the plasma jet. Organic glass and Teflon were used as the plasma-forming dielectric. Spectroscopic measurements of the basic parameters demonstrated that the plasma at the nozzle cut is fairly dense (the electron concentration reaches $1.2–1.4 \cdot 10^{24}$ m^{-3}) and low-temperature (up to $4 \cdot 10^4$ K). The jet considered is characterized by a relatively high velocity of plasmoids: measured from the broken structure of continuous photosweeps at the nozzle cut, it reaches 20 km/sec or more. The jet is characterized by fairly high purity of the erosion plasma with respect to the electrode material. A qualitative analysis of emission spectra revealed that mainly atoms and ions of the dielectric material are present in the plasma jet. Only with multiple repetition of the experiment on a highly sensitive aerophotofilm are the last lines of the copper atom recorded (327.4 and 324.7 nm CuI), whose intensity depends on the experimental conditions. In the case of spectroscopic study of the jet of a pulsed erosion plasma accelerator of cylindrical geometry with a combined dielectric insert (a discharge chamber) and copper electrodes, apart from the last lines sensitive lines of the copper atom are also recorded (521.8 nm CuI).

Institute of Molecular and Atomic Physics of the National Academy of Sciences of Belarus, Minsk, Belarus; email: lrpd@imaph.bas-net.by. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 73, No. 6, pp. 1229-1233, November–December, 2000. Original article submitted April 13, 2000.

The operating efficiency of the considered source of erosion plasma from a dielectric material and the erosion-type plasma accelerator can be compared using, as the principal characteristic, the quantity of evaporated mass of the dielectric that is the working substance, per unit of expended energy, and considering the electrode erosion. The higher the entrainment of the dielectric as the working substance and the lower the erosion of the electrode material, the more efficient is the source. Therefore it is necessary to know the consumption of the dielectric used for plasma formation and of the electrodes that supply the electric energy. Under the present experimental conditions, the dielectric and electrode erosion was measured by weighing individual parts of the electric-discharge device before and after the experiment. It should be noted here that, with copper electrodes used, their erosion was so low that its measurement was not feasible. Therefore quantitative data were determined using aluminum electrodes, whose erosion turned out to be sufficient for measurements. Here, one value was obtained from 10 discharges. The error was $5{\cdot}10^{-8}$ kg. In terms of one discharge, the erosion was equal to $2.5{\cdot}10^{-6}$ kg for the dielectric discharge chamber, $3{\cdot}10^{-7}$ kg for the dielectric head on the electrodes, and less than 10^{-8} kg for the electrode. Since the measurements were performed for an energy stored in the accumulator of 300 J and the energy input to the discharge was 225 J, the specific erosion of the dielectric on the whole relative to the energy input to the discharge was $1.38{\cdot}10^{-8}$ kg/J.

The dielectric erosion obtained permits its comparison with the dielectric erosion in similar electric-discharge systems. As was pointed out previously, a pulsed plasma accelerator with erosion of a dielectric wall [7, 8] is most similar in its characteristics (electrophysical and plasmadynamic) to the source of erosion plasma considered. In [9], working media for such pulsed accelerators with dielectric erosion were considered and an empirical equation that is based on experimental data and reflects the dependence of the mass consumption of the working medium on its mean atomic mass and the energy input to the discharge for this accelerator was given. The equation was obtained for the energy range of 50–350 J.

For a plasma consisting of the destruction products of organic glass $C_5H_8O_2$, the mass consumption per unit energy is $6.1{\cdot}10^{-9}$ kg/J. A comparison of this value with the experimental value for the source of erosion plasma indicates that the source considered is much more efficient than the pulsed plasma accelerator.

The use of sources of erosion plasma from a dielectric material can be most efficient in the vacuum technology, specifically, in the application of coatings and thin films and in the production of new materials. This use is ensured by parameters of the plasma jet that are characteristic of plasma technology and by their regulation: a fairly high outlet velocity of the plasma flow, high concentrations of charged particles and temperature, a small quantity of impurities of the electrode material, and the possibility of introducing and controlling the quantity of impurities of any substance. Since among the principal characteristics in technologies for production of coatings and thin films is the deposition rate, it is of interest to evaluate it proceeding from the basic parameters of the issuing plasma jet.

In a first approximation, the number of particles reaching the substrate surface in unit time is proportional to the particle concentration N, the projection of the particle velocity onto the direction $\vec{n}$, and the surface area dS , i.e., $\sim N v_n dS$.

However, the scattering of erosion products is characterized by the directivity diagram of the scattering of components with a solid angle ω. If the scattering occurs in the form of a cone, then, with allowance for the directivity diagram, the density of the particle flux P to the surface dS that is located at the distance L from the nozzle cut can be evaluated as

$$P \approx \frac{N v_n dS}{\omega L^2} .$$

This number of particles reach the substrate surface in unit time. After condensation, this number of particles deposit on the area dS, and the layer thickness corresponds to the thickness of the substance in the condensed state. Let the mass of a single particle be m; then, the mass of all particles condensed on the area dS is Pm. If the density of the substance in the condensed state is ρ, then a layer of thickness Pm/ρ grows in unit time on the area dS. Hence, the condensation rate is

TABLE 1. Component Composition of the Plasma Jet (T = 40,000 K)

Concentration of particles, m^{-3}	Concentration of electrons, N_e, m^{-3}						
	$1\cdot10^{23}$	$2\cdot10^{23}$	$5\cdot10^{23}$	$7\cdot10^{23}$	$8\cdot10^{23}$	$1\cdot10^{24}$	$2\cdot10^{24}$
N_F^{3+}	$2.4\cdot10^{20}$	$2.5\cdot10^{20}$	$2.5\cdot10^{20}$	$2.3\cdot10^{20}$	$2.2\cdot10^{20}$	$2.3\cdot10^{20}$	$2.0\cdot10^{20}$
N_F^{2+}	$2.7\cdot10^{22}$	$5.8\cdot10^{22}$	$1.3\cdot10^{23}$	$1.7\cdot10^{23}$	$1.9\cdot10^{23}$	$2.2\cdot10^{23}$	$3.5\cdot10^{23}$
N_F^{+}	$2.4\cdot10^{22}$	$1\cdot10^{22}$	$5.24\cdot10^{22}$	$9.5\cdot10^{22}$	$1.2\cdot10^{23}$	$1.7\cdot10^{23}$	$5\cdot10^{23}$
N_F	$6\cdot10^{17}$	$5\cdot10^{18}$	$6.4\cdot10^{18}$	$1.6\cdot10^{20}$	$2.3\cdot10^{20}$	$4.2\cdot10^{20}$	$2.4\cdot10^{21}$
N_C^{4+}	$7.3\cdot10^{18}$	$4.6\cdot10^{18}$	$2.6\cdot10^{18}$	$2.2\cdot10^{18}$	$1.9\cdot10^{18}$	$1.6\cdot10^{18}$	$1.1\cdot10^{18}$
N_C^{3+}	$5.3\cdot10^{21}$	$6.1\cdot10^{21}$	$7.8\cdot10^{21}$	$8.2\cdot10^{21}$	$8.3\cdot10^{21}$	$8.5\cdot10^{21}$	$9.5\cdot10^{21}$
N_C^{2+}	$1.3\cdot10^{22}$	$2.7\cdot10^{22}$	$7.9\cdot10^{22}$	$1.2\cdot10^{23}$	$1.3\cdot10^{23}$	$1.7\cdot10^{23}$	$3.5\cdot10^{23}$
N_C^{+}	$1.4\cdot10^{20}$	$5.9\cdot10^{20}$	$4.3\cdot10^{21}$	$8\cdot10^{21}$	$1.1\cdot10^{22}$	$1.7\cdot10^{22}$	$6.9\cdot10^{22}$
N_C	$2.4\cdot10^{16}$	$2\cdot10^{17}$	$3.5\cdot10^{18}$	$9.1\cdot10^{18}$	$1.4\cdot10^{19}$	$2.8\cdot10^{19}$	$2.2\cdot10^{20}$

$$v_c \approx \frac{Pm}{\rho} = \frac{Nv_n dS}{\omega L^2}\frac{m}{\rho}. \tag{1}$$

Reaching the substrate, the greater part of the energy contained in the plasma flow participates in film formation and heats the substrate. This energy is a function of the density and temperature of the plasma (including the energy of random motion, ionization, dissociation, and excitation of the particles) and its plasmadynamic velocity. The surface of the evaporated-on substrate can be heated by the flow of the erosion plasma to a magnitude determined by the substrate material and the condensate composition, which basically limits the condensation rate of films by their destruction. Ultimately, the condensation rate is a function of the overall reflection and reevaporation coefficient k:

$$v_c = (1-k)\,\frac{Nv_n dS}{\omega L^2}\frac{m}{\rho}. \tag{2}$$

A plasma that is used for substance condensation in a vacuum can attain an electron concentration of the order of 10^{24} m^{-3} and a temperature of $4\cdot10^4$ K. Multiply charged ions are also formed at such temperatures. In Eq. (2), the concentration N is taken to mean the concentrations of atoms and ions of all sorts that can be obtained from either experimental measurements or the equilibrium composition of the plasma. With allowance for the plasma composition Eq. (2) takes the form

$$v_c = (1-k)\,\frac{v_n dS}{\omega L^2}\frac{1}{\rho}\sum_{a=1}^{r}\sum_{z=0}^{s} N_{az}\,m_{az} = (1-k)\,\frac{v_n dS}{\omega L^2}\frac{1}{\rho}\sum_{az} N_{az}\,m_{az}, \tag{3}$$

where r is the number of chemical components and s is the highest observed degree of ionization. The summation is initially taken for particles of sort a over the different degrees of ionization, and afterward all sorts of particles are summed up.

If particles of one sort are present in the plasma, the summation is made only over the degrees of ionization, i.e.,

$$\sum_{az} N_{az}\,m_{az} = \sum_{z} N_z\,m_z.$$

Let us evaluate the maximum possible (at k = 0) condensation rate for a plasma-forming substance of Teflon $(CF_2)_n$. We adopt a velocity of the plasma flow of 10^4 m/sec, a density of the substance in the condensed state equal to the initial one of $2.2 \cdot 10^3$ kg/m^3, an electron concentration of 10^{24} m^{-3}, a temperature of $4 \cdot 10^4$ K, a solid angle of 1, a distance to the substrate of 10^{-1} m, and $dS = 10^{-4}$ m^2. The calculation of the equilibrium composition for such conditions is presented in Table 1. Using these data, from Eq. (3) we find a maximum possible condensation rate of $7 \cdot 10^{-4}$ m/sec.

The rate of condensation of the erosion plasma, whose composition is specified by the Teflon material, on a metal surface was measured experimentally and is about $6 \cdot 10^{-4}$ m/sec. Such favorable agreement between the calculated and experimental values of the condensation rate can also be incidental, since the process of plasma production has a pulsed character and the plasma outflow from the discharge volume confined by the dielectric lasts longer than the discharge current (the condensation time was taken according to the duration of the discharge current).

The condensation rate obtained is several orders of magnitude larger than the traditional one and is comparable to the deposition rate obtained by electron-beam and laser (pulsed) evaporation [10].

Thus, a pulsed source of erosion plasma that depends for its operation on an electric discharge over the surface of a dielectric with a spatial limitation of the discharge volume at a decreased pressure is a fairly efficient generator of erosion plasma from a dielectric material with a low content of impurities of the electrode material and is promising for use in vacuum plasma technology.

The author is grateful to V. S. Burakov and L. Ya. Min'ko for their discussion of the results and for some valuable remarks and to G. O. Aver'yanova for her assistance in determining the condensate thickness.

NOTATION

N_{az}, concentration of the ions of the sort a and the charge z; T, temperature; S, area; $\vec{n}$, unit vector of the normal to the surface element dS; v_n, projection of the plasma velocity; v_c, condensation rate; ω, solid angle; P, particle-flux density; L, length; m_{az}, mass of the ion of the sort a and the charge z; ρ, substance density; k, overall reflection and reevaporation coefficient, which is the ratio of the particle flux reflected and reevaporated by the body to the particle flux that has impinged on the body. Subscripts: n, normal; c, condensation; a, sort of the ion; z, ion charge.

REFERENCES

1. L. Ya. Min'ko, V. B. Avramenko, and A. M. Kuz'mitskii, in: *Proc. XVIth Int. Conf. "Phenomena of Ionized Gases,"* Vol. 1, Düsseldorf (1983), pp. 289-290.
2. V. B. Avramenko, A. M. Kuz'mitskii, and L. Ya. Min'ko, *Teplofiz. Vys. Temp.*, **20**, No. 6, 1052-1056 (1982).
3. V. B. Avramenko and A. M. Kuz'mitskii, *Teplofiz. Vys. Temp.*, **22**, No. 1, 31-34 (1984).
4. V. B. Avramenko, A. M. Kovalev, and A. M. Kuz'mitskii, in: *Abstracts of Reports Submitted at the Ist Seminar on Atomic Spectroscopy*, Moscow (1990), p. 84.
5. V. B. Avramenko, A. M. Kovalev, and A. M. Kuz'mitskii, in: *Proc. VIIIth All-Union Conf. on the Physics of Low-Temperature Plasma*, Pt. II, Minsk (1991), pp. 129-130.
6. V. B. Avramenko and A. M. Kuz'mitskii, *Vakuum. Tekh. Tekhnol.*, **1**, No. 2, 41-43 (1991).
7. *Proceedings of the IIIrd All-Union Conference on Plasma Accelerators* [in Russian], Minsk (1973).
8. S. D. Grishin, L. V. Leskov, and N. P. Kozlov, *Plasma Accelerators* [in Russian], Moscow (1983).
9. N. N. Antropov, V. K. Blagovestov, L. G. Burova, et al., in: *Abstracts of Reports Submitted at the VIIth All-Union Conf. on Plasma Accelerators and Ion Injectors*, Khar'kov (1989), pp. 183-184.
10. N. N. Rykalin, A. A. Uglov, and I. V. Zuev, in: *Treatment of Materials. Handbook* [in Russian], Moscow (1985), pp. 402-407.