Journal of Engineering Physics and Thermophysics, Vol. 79, No. 4, 2006

DYNAMIC AND SPECTROSCOPIC CHARACTERISTICS OF THE ABLATION PULSED PLASMA SOURCE AT ATMOSPHERIC PRESSURE

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UDC 537.52

This paper presents the results of optical, spectroscopic, and electrophysical studies of plasma obtained with the aid of a combined two-stage, electric-discharge system at atmospheric pressure. A comparative study of such plasma sources with the use of pure dielectric insertions and insertions with metal disposition on their working surface has been made. The considered variants of pulsed sources operating in the air permit obtaining under these conditions relatively dense low-temperature (6000–9000 K) plasma streams of a definite composition.

At present, various pulsed electric-discharge sources of plasma streams are known (see, e.g., [1–5]). Wide use and prospects for future application of pulsed plasma sources require detailed studies of the physics of the working process and improvement of the methods for generation of high-energy plasma streams. In particular, the development of high-intensity optical sources and the use of plasma streams for various engineering and technological purposes necessitate generation and investigation of dense pulsed plasma streams in the air at atmospheric pressure. Among the first works on the obtaining and investigation of such streams are [6–9]. In these works, an electric-discharge device consisting of a central and a ring electrode located in a discharge chamber made of a dielectric material was used. In [2], the results of complex studies of a pulsed plasma generator operating at atmospheric pressure were generalized.

In the last few years, a powerful pulsed electric discharge in pure argon at atmospheric and higher pressures has been investigated [10]. The aim was to develop an effective radiation source in the short-wavelength region of the spectrum for use in microelectronics. The explosion of tungsten microconductors has also been investigated because of the interest in it in the fundamental and applied sections of experimental physics (for obtaining powerful soft x-ray radiation pulses) [11].

In [12], a plasma source, which is essentially a combined two-stage plasmodynamic system where the role of the first stage is played by a laser source of erosion plasma (light-ablation plasma generator) and the second stage incorporates an electric-discharge source (electroablation plasma generator) is described. In [13, 14], to obtain ablation (erosion) plasma streams, a generator operating on the basis of electric explosion of conductors and ablation of electrodes and dielectric insertions, which was a two-stage electric-discharge system, was used. The present paper gives the results of the optical, spectroscopic, and electrophysical investigations of an analogous discharge system. Comparative studies of such plasma sources with the use of pure dielectric insertions and insertions with metal deposition on their working surface are also interesting.

Description of the Facility and Experimental Techniques and Procedures. The investigations were carried out on an experimental facility with a cylindrical discharger (Fig. 1). The facility allowed two variants of operation.

In the first variant, the main discharge occurs between the central hollow electrode 1 and the nozzle-insertion 2. The central hollow electrode is common for the main and igniter dischargers. As the second igniter electrode, either the central rod electrode 3 or the outer ring electrode 4 are used.

In the second variant, discharge occurs, as in the first one, between the central hollow electrode and the nozzle-insertion. However, the working surface of the central electrode is not the face but its inner surface (Fig. 1a). Ignition occurs through the ring electrode 4 by the wire passing through the dielectric insertion. In this variant of operation of the facility, one could vary the discharge volume and use dielectric insertions from different materials: fluoroplastic, cloth-based laminate, paraffin, and acrylic plastic. The electrodes were made of copper, brass, and steel.

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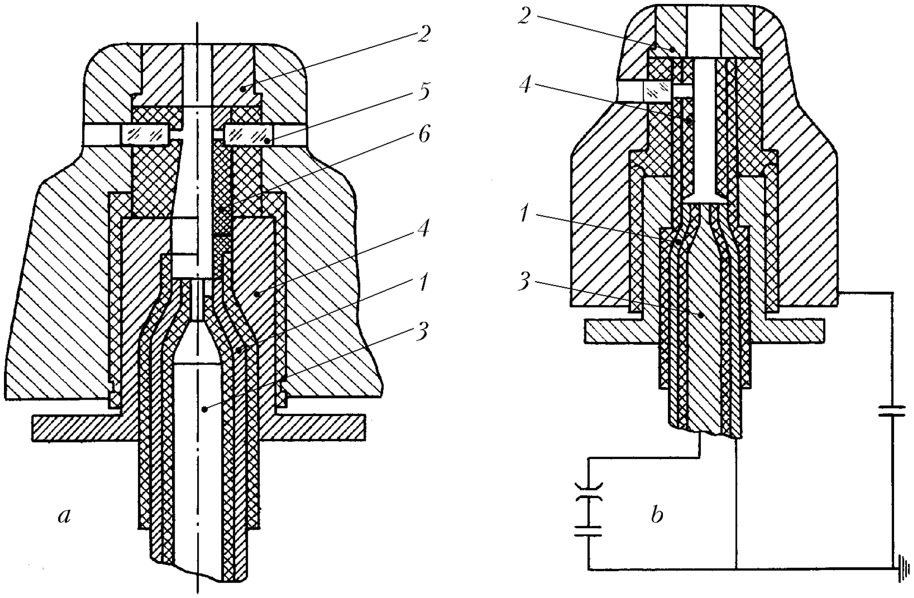

Fig. 1. Diagram of the discharger: (a) 1) central hollow electrode; 2) nozzle-insertion; 3) igniter electrode; 4) outer ring electrode; 5) optical windows; 6) dielectric insertion; (b) 1) central hollow electrode; 2) nozzle-insertion; 3) igniter electrode; 4) dielectric insertion.

The investigations were carried out for two discharge volumes differing about twice (the length of the cylindrical insertion and the inner diameter were decreased). As an energy storage system, a battery consisting of 13 IM-5-150 capacitors of total capacity 1950 μF was used. The operating voltage was 2–5 kV, the maximum discharge current was up to 100 kA, and the discharge time was 300 μsec. To initiate the main discharge (variants I and II), the discharge of a 24-μF capacitor at voltages of 2–5 kV was used. It should be noted that besides playing its main role, the igniter discharger also acted as a preliminary erosion plasma generator.

To elucidate the influence of the plasma-forming material on the plasma parameters and the discharge characteristics, we performed comparative studies of the plasma inside the discharge chamber of cylindrical geometry on the basis of a fluoroplastic insertion with aluminum deposition and without it under identical discharge conditions. The identical of the discharge conditions were provided as follows. In both cases, to ignite the main discharge, we used an auxiliary discharge. It was provided between the central electrode 1 and the rod electrode 3 (Fig. 1b). The plasma formed acted as an initiating pulse and set up the main discharge between the central electrode 1 and the ring nozzle 2. As an energy storage system, we used a battery consisting of 18 IM-5-150 capacitors with a total capacity of 2700 μF. Aluminum was deposited on the inner surface of the fluoroplastic insertion 4 so that a clearance was formed between the surface with deposition and the central electrode. The discharge on the surface with deposition occurs in the same discharge volume as in the case of the usual discharge on a dielectric.

We used spectroscopic methods to investigate the plasma in the discharge volume and high-speed photo- and spectrography for the plasma jet formed. The time-integral spectra of plasma radiation were obtained with the aid of an ISP-51 spectrograph with a camera of F = 270 mm, and the time-resolved ones — by a combination of an ICP-51 spectrograph and a high-speed photorecorder (HPR). Continuous recording of the plasma jet radiation was carried out with focusing of its image on the entrance slit of the waiting photorecorder (WPR-2) or the high-speed camera of the HPR. For current and voltage measurements, a Rogowski loop and voltage dividers were used.

Experimental Studies of the Radiation Characteristics of Discharge and Plasma Parameters in the Discharge Chamber. In studying the properties of the erosion plasma obtained with the aid of the combined electric-discharge system, it is interesting to determine both the plasma parameters in the discharge chamber and the parameters of the plasma jets.

In the spectroscopic studies, primary consideration was given to the emission spectra of the plasma formed inside the discharge chamber, which made it possible to determine the qualitative composition of the plasma and evaluate its parameters. We also made a comparative study of the spectra for different operating conditions of the facility and with the use of different materials as dielectric insertions.

In the first variant of operation of the electric-discharge device (see Fig. 1a), in the emission spectra of the plasma inside the discharge chamber, we observed continuous radiation and absorption lines of the elements entering into the composition of the electrode materials: FeI, CrI, and MnI (in this variant steel electrodes were used; c = 600–800 μF, U = 3–5 kV). With decreasing quantity of energy accumulated in the storage system there is a marked change in the spectrum: only the emission spectrum of atoms of elements of the electrode material is observed; continuous radiation is not registered.

The second variant of operation of the electric-discharge device was investigated in more detail. A comparative study of the radiation spectra of the plasma inside the discharge gap at two discharge volumes was made.

Qualitative analysis of the emission spectra of the plasma at a large volume of the discharge gap shows that mainly copper lines, as well as individual lines of iron, chrome, and barium ions, are registered. In this case, it is very difficult to determine the plasma parameters by the spectral lines, because the intense continuum hinders the use of weak emission lines, and the other lines are self-reversal lines. Some ideas about the temperature conditions in the plasma formed can be obtained from the qualitative analysis of the spectra with a variation of energy accumulated in the storage system. For instance, at a voltage of 2 kV in the plasma radiation spectrum a line of CuI at 578.2 nm (the energy of the upper level is 3.79 Ev) is observed and the 570.0-nm line (the energy of the upper level is 3.82 Ev) is not registered; with increasing voltage both lines are registered. The determination of the relative intensities of the CuI lines at 515.3 and 510.5 nm indicates that the intensity of the second line is much higher than that of the first line. The calculation of the temperature dependence of the intensities of these lines shows that such an intensity ratio for the Boltzmann distribution of radiating atoms over the energy levels can take place at temperatures not exceeding $(5–6)\cdot 10^3$ K.

With decreasing discharge volume the plasma emission spectrum changes noticeably. Both the continuous radiation and the lines of the elements entering into the composition of the electrode materials are highly intensive. Qualitative analysis shows that in the spectrum mainly the lines of copper atoms, as well as individual lines of atoms of fluorine, sodium, barium, iron, zinc, and barium ions are observed. It should be noted that the emission spectra of the plasma formed by discharges with different dielectric insertions (fluoroplastic, cloth-based laminate, acrylic plastic, glass-cloth-base laminate, paraffin) under the investigated discharge conditions (U = 5 kV, C = 1950 μF) almost do not differ from one another. An important fact is the presence of a continuum and a discrete emission spectrum of the elements of the electrode material. The material of the dielectric insertions is only represented by the lines of some elements entering into their composition.

The presence of an intense emission spectrum of the copper atom in the case of using copper electrodes has made it possible to determine the concentration of charged particles in the plasma formed in the discharge gap. The results of measurements of the electron concentration N_e by the Stark broadening of the CuI line at 453.1 nm with the use of dielectric insertions from different materials are as follows (in 10^{16} cm^{-3}): 5.0 for fluoroplastic, 3.8 for cloth-based laminate, 5.2 for paraffin, and 4.0 for acrylic plastic. It should be noted that these values are averaged along the line of sight and over a large time interval and do not characterize the maximum values of the electron concentration but are only used for comparison.

Since the line chosen for the diagnostics experiences some self-absorption, the results of measurements should be considered as the upper limit of the concentration of charged particles in the region of the line luminescence. It is clear from the foregoing that the concentrations of charged particles determined in the plasma formed by discharges with dielectric insertions from different materials do not differ markedly (the measurement error is 30–40%).

The intensive continuous radiation of the plasma formed in the discharge gap was used to estimate the temperature of electrons on the assumption of local thermodynamic equilibrium. The investigation of the frequency dependence of the continuum emissivity (in the region of frequencies higher than the threshold frequency of positive plasma ions) makes it possible to determine the plasma temperature from the slope of the straight line which is a graph of this dependence. The estimate of the temperature obtained from the slope of the straight line in the region of $\nu = (0.66–0.77)\cdot 10^{-15}$ sec^{-1} was equal to $6\cdot 10^3$ K (Fig. 2). In this case, the measurement error was ~25% because of the narrow frequency range in which measurements are possible. Continuous sweep of the spectrum has shown that

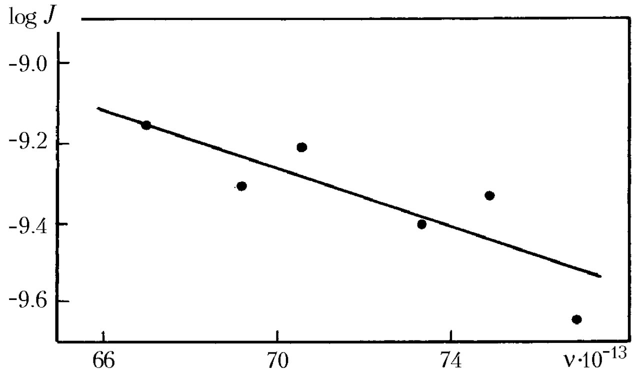

Fig. 2. Logarithm of continuous spectrum intensities versus frequency for continuous radiation of plasma (fluoroplastic insertion).

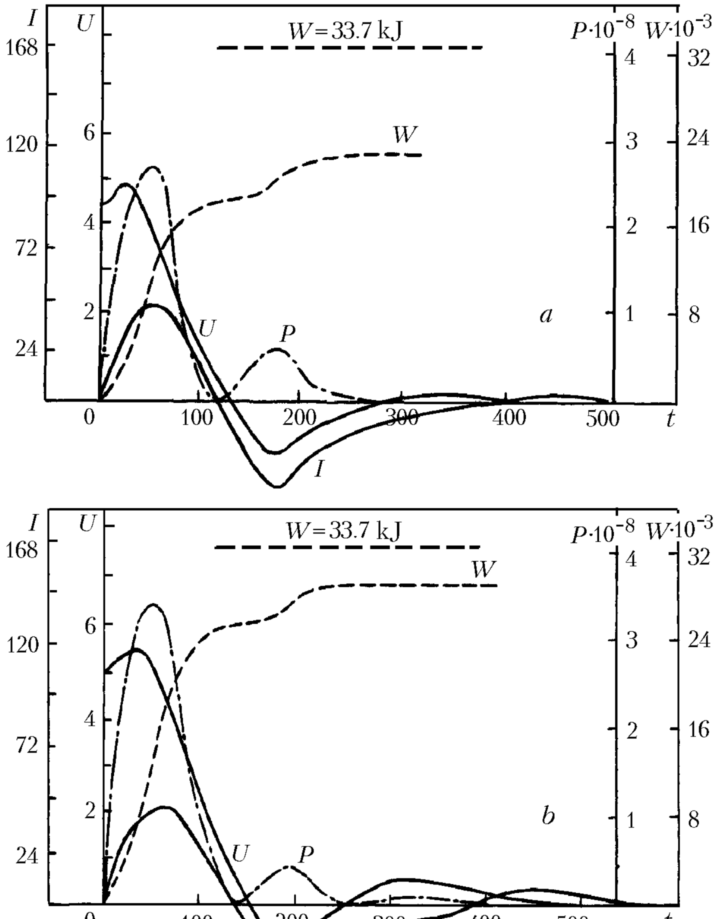

Fig. 3. Oscillograms of current I and voltage U and power P and energy W contributing to the discharge: a) with aluminum deposition on the inner surface of the fluoroplastic insertion; b) without disposition. t, μsec.

continuous radiation is observed throughout the discharge time and, therefore, the temperature value obtained is averaged over the discharge time.

The comparative spectroscopic studies of plasma with the use of dielectric insertions without deposition and with aluminum deposition have shown that in all cases an intense continuum is present. The AlI lines with the use of

TABLE 1. Parameters of Plasma Jets for Different Experimental Conditions

Discharge volume	Kind of surface	v, km/sec	P_1, atm	T_e, K
Large	Without deposition	10	35	7000
	With deposition	15	45	—
Small	Without deposition	14	45	8900
	With deposition	17	95	8700

dielectric insertions without deposition are low-intensity (aluminum in small quantities enters, as an additive, into the composition of the electrode material; the electrodes are copper); in the case of aluminum deposition, lines are observed in the absorption, and their complete self-reversal is characteristic, which points to a sharp increase in the quantity of aluminum getting into the plasma.

It should be noted that while at smaller contributions of energy to the discharge (~25 kJ) the presence of the discrete emission spectrum has made it possible to take measurements of the concentration of charged particles by the broadenings of the lines, now it is impossible to carry out plasma diagnosis by the emission lines because of the highly intense continuum. Basic measurements of the parameters were made with the use of the continuum. The temperature measurement data are presented in Table 1, which also gives the effluent velocities of plasma jets and the values of the nozzle exit section pressure.

In all cases, the temperature is low and varies only slightly; it somewhat decreases with increasing discharge volume. This causes a redistribution of the intensities of the lines and edges of molecular bands — with increasing active volume the molecular bands are intensified. An increase in the quantity of energy stored in the storage system leads to an increase in the continuum intensity. Only the absorption lines stand out markedly against it. The sharp increase in the continuum intensity cannot be explained by the temperature change alone and points to an increase in the number of particles in the operating plasma. In this case, exact determination of the plasma density entails great difficulties (including the lack of data on the quantitative relation between components of erosion products). However, using the pressure and temperature values obtained, one can estimate the upper limit of the total particle number density in the plasma: the maximum value is $\sim 5 \cdot 10^{19}$ cm^{-3}. Comparison of the current and voltage oscillograms with aluminum deposition and without it has shown that the discharge time in both cases is the same. The calculated graphical values of instantaneous powers and energies contributed to the discharge gap with aluminum deposition are somewhat lower (Fig. 3) [12].

Investigation of the Dynamics of Plasma Streams at Atmospheric Pressure. Since the discharge occurs in a limited volume at atmospheric pressure, there is a marked increase in the pressure in the discharge chamber compared to the ambient pressure. A supersonic plasma jet emanating under underspreading conditions is formed. Such jets at large noncalculations ($n = P_1/P_2$) are characterized by the formation of a normal shock wave. According to [15], the relation between the distance to the normal shock wave l and the pressure ratio in the nozzle P_1 in the environment P_2 is given by the formula

$$l \approx 0.64 d \left(P_1/P_2\right)^{1/2} .$$

Hence, having determined from experiment the distance to the shock wave, one can estimate the nozzle exit section pressure. To this end, we carried out continuous (slit) photorecording of the generated plasma jets in different variants of operation of the facility.

From the photoscans it is seen that the plasma efflux does not follow the current change: it approaches the quasi-stationary state. The efflux time of the plasma jet varies with the discharge volume (pressure). A decrease in the discharge volume leads to a reduction in the efflux time.

We have also investigated underspread jets formed during the operation of the electric-discharge device with a small discharge volume with the use of dielectric insertions from different materials. The maximum pressure values are as follows: P_1 = 150 atm for fluoroplastic, 155 for cloth-based laminate, 130 for paraffin, and 130 for acrylic plastic (the discharge parameters are: U = 5 kV, C = 1950 μF). It is seen that the pressure in the nozzle exit section differs insignificantly upon replacement of the dielectric material.

Comparative studies of the plasma jets of the electric-discharge device with a cylindrical discharge chamber based on a fluoroplastic insertion with aluminum coating and without it under identical conditions have shown that in the general case the plasma jets are discrete. In the case of aluminum deposition, the discreteness is more pronounced.

Discreteness of plasma jets has made it possible to measure their efflux velocity (see Table 1). In the case of aluminum deposition, some increase in the plasma efflux velocity (in a large volume) and the pressure in the discharge gap (especially in a small volume) is observed.

Thus, the investigations made have shown that the considered variants of pulsed plasma sources operating at atmospheric pressure in the air permit obtaining under these conditions dense low-temperature erosion plasma streams of definite composition. The spectroscopic studies point to a relatively great contribution to the plasma composition of electrode erosion products; the use of various materials for dielectric insertions does not lead to a considerable difference in the parameters of the plasma formed. The composition of the plasma obtained can be varied by depositing a plasma-forming material (metal) on the surface of the dielectric insertion. Comparative studies of the discharge characteristics and the plasma parameters with metal deposition and without it under identical conditions show that the pressure in the discharge volume and the plasma efflux velocity increase, while the instantaneous powers and energies contributed to the discharge are somewhat lower in this case. And the total particle number density in the plasma increases (according to estimates, for the small-value variant it reaches about 10^{19} cm^{-3}), and the temperature remains low (for the investigated operating conditions, 6000–9000 K).

NOTATION

C, capacity of capacitor, μF; d, nozzle diameter, cm; F, focal length, mm; I, current intensity, kA; J, radiation intensity, rel. units; l, length, cm; N_e, electron concentration, cm^{-3}; P, power, W; P_1, pressure in the nozzle exit section, atm; P_2, ambient pressure, atm; T, temperature, K; t, time, sec; U, voltage, kV; v, efflux velocity of plasma, km/sec; W, energy, J; ν, radiation frequency, sec^{-1}. Subscript: e, electron.

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