The Influence of the Geometry and Power of a Pulsed Capillary Discharge on the Properties of Erosive Plasma

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Abstract. The results of the spectral study of a pulsed capillary discharge in the range of the relative capillary lengths of \( l/d = 5 \) and the discharge power densities of \( q_S = 1 - 100 \) kW/mm\(^2\) are presented. The longitudinal profiles of the electron number density and temperature inside and on a short distance outside the capillary are measured. A good qualitative and quantitative agreement between the measured parameter profiles and the results of calculation based on the model of the expendable nozzle, which is valid for discharges in the "long" capillaries, was found. It is shown that a decrease in the relative length of the capillary, starting from \( l/d < 2.5 \), leads to a discrepancy between the experimental and calculated parameters profiles due to the increasing contribution of the electrode's evaporated substance to the total mass balance.

1. Introduction
A pulsed capillary discharge is known as a relatively simple and efficient method of obtaining plasma over a wide range of pressures, temperatures, and charged particles concentrations [1]. Depending on the method of the working body supply, one can distinguish the discharge in a gas-filled or in an initially empty capillary. In the latter case, the plasma composition is determined by the substance ablated from the capillary wall and electrode surface. The partial contribution of each source in the total mass balance depends on the power fluxes to the capillary wall and electrode, the ratio of their surfaces and the physico-chemical properties of the used materials. In two limiting cases, when the contribution from one source dominates, a capillary discharge with an evaporating wall (CDEW) and a capillary discharge with an evaporating electrode (CDEE) are distinguished. The conditions for these types of discharges are realized in "long" (\( l/d > 3 \)) and "short" (\( l/d < 1 \)) capillaries, respectively. In the intermediate case - \( 1 < l/d < 3 \) - the partial contribution of both sources to the total mass balance is comparable.

Most of the theoretical and experimental works have been devoted to the study of discharges in "long" capillaries, in which the ablated substance from the capillary wall act as the main source of the working body. Gas dynamics of plasma in such capillary is described by the model of expendable nozzle [2]. One-dimensional CDEW models for the parameters averaged over the capillary cross section (the mass density and the temperature) were considered in [3,4]. The uniform distribution of the plasma temperature and mass density over the radius is taken as the initial prerequisite in these models. However, these prerequisites are not met in real conditions. So the spatial separation of the discharge onto a central high-temperature zone and a low-temperature layer adjacent to the capillary...
wall and containing a weakly ionized plasma is necessary to achieve a balance of mass and energy introduced into the capillary and carried away from it by plasma jets [5,6]. Subsequently, one-dimensional models of a two-zone capillary discharge were proposed in [7–10]. Recently, two-dimensional models have been proposed that take into account the features of heat, mass and radiant energy transfer for a spatially inhomogeneous plasma inside the capillary [11,12].

At the same time, the number of experimental works devoted to the study of the discharge structure inside the capillary is small. This situation, first of all, is connected with large optical thickness of the erosive plasma, whose blackbody radiation at high pressures (p>50 bar) restrict the use of spectral methods to study its internal structure. Another limiting factor is the capillary geometry, whose cylindrical surface (through which the observation is provided) acts as a scattering lens that leads to a distortion of the real spatial picture of plasma emission. Therefore, the use of spectral methods for studying the discharge structure inside the capillary is limited to diagnostic of the paraxial discharge zone if the optical thickness of plasma is not too large.

The aim of the work is the experimental study of the influence of the capillary geometry and the discharge power on the properties of erosive plasma, as well as an assessment of the suitability of the used spectral diagnostic methods for determining the main plasma parameters (the electron number density and temperature) inside the capillary.

2. The object and the methods of research

The object of research is a capillary arrester, whose detailed description is given elsewhere [13]. Perspex is used as a capillary wall material (chemical formula C₈H₅O₃). The depth and the initial diameter of a capillary are respectively $h = 5$ mm and $d = 1$ mm. A capacitive storage device with series-connected inductor is used for power supply of discharge. The algorithm of power supply approximately corresponds to the sine half-wave. The main parameters of discharge circuit are the following: the stored energy $Q = 80$ J, the amplitude of discharge current $I_m = 60 – 450$ A, duration of discharge pulse $\tau_d = 1 – 9$ ms. Researches were carried out in the range of the capillary diameter $d = 1 – 3.2$ mm that corresponds to the range of the discharge surface power density (the power divided by the cross-section of the capillary) $q_S = 1 – 100$ kW/mm².

During the experiments, the 2D-matrix spectra of plasma radiation emitted from the paraxial zone of discharge inside and outside the capillary were recorded on the ICCD matrix of the fast gate Andor iStar camera (minimal camera gate 100 ns) mounted in the output focal plane of the MS-257 spectrograph (width of the entrance slit $\delta = 20$ μm). The spectra observed through a previously polished external wall of the capillary. The spectral interval $\Delta \lambda = 650 – 685$ nm was chosen for 2D-matrix spectra recording. This interval contains the hydrogen line $H_\alpha$ (used for determination of the electron number density by the linear Stark effect), the doublet of the ionic carbon lines C II 657.8 nm and 658.3 nm, the multiplet of ion C II lines of 678–682 nm, and the rather intense continuum (inside the capillary), which can be used to determine the electron temperature. The ability to use the method of "Boltzmann exponent" to determine electron temperature in the paraxial zone of the plasma jet from the relative population of excited states of carbon ions, and also the rather high accuracy of this method was shown in [14]. The application of this method inside the capillary is difficult because the strong broadening and merging those lines with the continuum. Therefore, the method of the relative intensities of the $H_\alpha$ line and the continuum is mainly used in the present work to estimate the electron temperature. Evaluation of the radiation reabsorption from both the $H_\alpha$ line and the continuum under experimental conditions indicates the suitability of this method for estimating the electron temperature inside the capillary with an error of less than 20% increasing with power input.

3. The results of research

The longitudinal profiles of the main plasma parameters (the electron number density and temperature) along the discharge centerline are obtained in the range of surface power density of $q_S = 1 – 100$ kW/mm² (figure 1) using the recorded 2D spectra and the ratio $\frac{\varepsilon_{H_\alpha}}{\varepsilon_{cont}} = f(T_e)$ [15] ($\varepsilon_{H_\alpha}$, $\varepsilon_{cont}$
– the intensities of $H_\alpha$ line and continuum, respectively). Change in discharge power density in the
selected range permits to reveal the main features in the spatial distribution of plasma parameters in a
supersonic, transonic and subsonic outflow mode from the capillary. It should be noted that the surface
power density $q_S$, expressed as the power divided by the cross-section of the capillary is more
convenient parameter for analyzing the gas dynamics of plasma flow, rather than volumetric power
density (power divided by the capillary volume). In particular, the threshold value of the discharge
power density $q_S^{thr}$, corresponding to the transition from subsonic to supersonic mode, is very weakly
dependent parameter on the capillary length and the discharge circuit parameters, which makes it
possible to compare the results of experiments obtained by different authors under different
conditions. This was first noticed by the authors of [16]. The threshold value of surface power density
can be easily determined from the diagrams in figure 1 by the position of the Mach disk, which closely
approaches the capillary edge (the position indicated as $M = 1$). The threshold surface power density
determined in this way, $q_S^{thr} = 15 - 20$ kW/mm$^2$, is in good quantitative agreement with the results
obtained in [16].

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig1.png}
\caption{The profiles of (a) electron number density and (b) temperature along the discharge
centerline. The arrows indicate: the threshold power density $q_{crit}$, which corresponds to a transition
from supersonic to subsonic flow regime of the jet ($M = 1$); the position of the capillary outlet
(indicated as “exit”); the margin of spatial domain where the anode vapours prevail ($\Delta Z_a$).}
\end{figure}

The results of temperature measurements are in good quantitative agreement with the results
obtained by other methods. In particular, the temperature in the expansion section of the plasma jet is
$T_e = 1.7 - 2.5$ eV, which agrees with enough accuracy (~20%) with the results obtained by the
method of relative intensities of ionic carbon lines [14]. The electron temperature inside the capillary
(at maximum values of the surface power density $q_S = 100$ kW/mm$^2$) reaches $T_e = 3.4$ eV, which is
in good agreement with the results obtained in [5,6]. Also, the measured temperature is in good
quantitative agreement with the estimates based on Saha equation, which is an additional confirmation
of the fulfillment of the local thermodynamic equilibrium, at least inside the capillary in the paraxial
discharge zone.

Inside the capillary, whose relative length exceeds $l/d > 2.5$, the profiles of electron number
density and temperature and also the pressure profile, restored from these data (taking into account the
relation $p \approx 2n_e k T_e$ valid for a strongly ionized paraxial zone of discharge consisting mainly of
electrons and hydrogen ions [13,17]), agree qualitatively with theoretical dependences obtained in [3]
for the model of expendable nozzle. The gas dynamics of such nozzle, according to the assumptions
made in [3], is determined solely by the flux of the evaporated substance from the capillary wall, and
the contribution of the evaporated substance from the electrode surface is neglected. So, the
relationships obtained within the framework of this model are valid for "long" capillaries only. The model is based on the relationships for the balance of mass and energy introduced into the capillary and carried away from it by a plasma jet. According to the basic assumptions [3], the electric power introduced into the discharge is equal, on the one hand, to the power carried away by the plasma jet, and on the other hand - to the power emitted by the arc and expended for the plasma creation. The mutual cancelling of these terms in the energy equation causes its transformation into the adiabatic equation, so the plasma flow inside the capillary is adiabatic. An example of the pressure profiles inside the capillary, restored from the spectral data and calculated for the model of expendable nozzle, is shown in figure 2. Good qualitative and quantitative agreement between the experimental profile and the model one is a strong argument in favor of the correctness of the theoretical model basic assumptions [3] that allow us to use relations obtained in this model for evaluation the plasma parameters in the paraxial discharge zone if the relative length of capillary exceeds \( \frac{l}{d} > 2.5 \).

![Figure 2](image)

**Figure 2** Pressure profiles inside the capillary along the discharge centerline: (1) restored from the spectral data, (2) calculated for the model of expendable nozzle [3]. Discharge parameters: \( \frac{l}{d} = 3.6, q_S = 55 \text{ kW/mm}^2 \).

At the same time, a decrease in the relative length of the capillary leads to a discrepancy between the measured and calculated parameters’ profiles. This discrepancy becomes particularly noticeable when the relative length of the capillary becomes less than \( \frac{l}{d} < 2.5 \). The discrepancy between the experimental and calculated profiles is observed in the vicinity of the internal electrode (anode) at a considerable distance (\( \Delta Z_a = 1.5 - 2 \text{ mm} \)) from its surface. The electron temperature profile is subjected to the greatest distortion: the measured temperature near the anode surface exceeds its calculated value by approximately \( \Delta T_e \approx 0.4 \text{ eV} \) (see figure 1b). At the same time, there is no visible distortion of the electron number density profile (see figure 1a). The analysis shows that the distortion of the electron temperature profile, increasing when the relative length of the capillary decreases, is due to increased fraction of the substance evaporated from the electrode surface in the total mass balance. In this case, the relationships obtained for "long" capillaries [3] cease to be satisfied. This conclusion is confirmed by the fact that the distortion of the temperature profile is reliably reproduced only in the case when the anodic spot of a large enough area (comparable with the capillary cross-section) is formed, which provides powerful jets of anode vapor. Such stationary anode spot is formed at high discharge currents (more than 300 A under experimental conditions). In the other cases - in the absence of anode spots or the formation of small spots randomly moving along the anode surface - the distortion of the temperature profile is not observed at all, or recorded irregularly, depending on how accurately the image of the anode spot coincides with the position of the spectrograph slit.

In the supersonic flow mode (\( M_a = 1 \) at the capillary outlet), the ratios of the pressure, electron number density and electron temperature at the bottom and at the outlet cross-section of the capillary
retain a constant value. These data, taking into account the relations obtained in [3], were used for the effective adiabatic index in the paraxial zone of discharge evaluation. Its value estimates as \( \gamma = 1.3 - 1.4 \).

We found that the static pressure at the capillary outlet in the subsonic regime \( (M_a \leq 1) \), as well as in the plasma jet (irrespective of the flow regime) systematically exceeds the ambient gas pressure. This excess is greater the shorter the duration of the discharge pulse. For example, the pressure in the jet reaches up to 3 bar for a short-pulse discharge \( (\tau_d = 1 \text{ ms}) \), while for a long-pulse discharge \( (\tau_d = 9 \text{ ms}) \) it almost equal to atmospheric pressure. The obtained result indicates that the main reason for the increased pressure in the plasma jet is the transient process of pressure equalization inherent to nonstationary flows, that is observed regularly in experiments [18,19] and finds the justification in the theoretical calculations [20].

4. Conclusions
The results of the spectral investigation of a pulsed capillary discharge in the range of the relative capillary lengths of \( l/d = 1.5 - 5 \) and the discharge surface power densities of \( q_s = 1 - 100 \text{ kW/mm}^2 \) are presented. The longitudinal profiles of the electron number density and temperature along the discharge centerline inside and on a short distance outside the capillary are measured. A good qualitative and quantitative agreement between the measured parameters profiles and their calculations based on the model of the expendable nozzle, which is valid for discharges in "long" capillaries, was found. It is shown that a decrease in the relative length of the capillary leads to a discrepancy between the experimental and calculated parameters profiles due to an increase in the fraction of the substance evaporated from the electrode surface in the total mass balance.

The obtained results confirm the principal possibility of using the combination of the half-width of the \( H_a \) line and the method of relative intensities of the \( H_a \) line and the continuum as an operative means of measuring the electron number density and temperature of plasma in the range of the studied parameters. The established relationship between the electrophysical and gas dynamic parameters of the plasma constitutes a good basis for the subsequent optimization of the plasma formation regimes in the capillary discharge, as well as the improvement of the spectral methods for microplasma objects diagnostics, in particular, for estimating important gas-dynamic parameter - the pressure - that is difficult to measure under these conditions using traditional methods.

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