The influence of spatial inhomogeneity of pulsed capillary discharge on the gas dynamics of multicomponent plasma

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Abstract. The results of experimental research of a pulsed capillary discharge with an evaporating wall in the power density range of \( q_s = 10 - 100 \) kW/cm\(^2\) obtained by using independent methods of diagnostics, including optical spectroscopy, the ballistic pendulum method, and direct measurement of pressure inside the capillary are presented. The analysis of experimental results, carried out with the help of a two-zone model of a capillary discharge, revealed the decisive influence of the discharge spatial inhomogeneity on the gas dynamics of a multicomponent plasma, which turns out to be substantially different in the high-temperature paraxial and low-temperature peripheral discharge zones. It is shown that the gas dynamics of the paraxial discharge zone corresponds to the regime of the ideal expendable nozzle with good accuracy, and the paraxial zone itself provides the main contribution to the creation of the jet momentum, in spite of the fact that more than 80\% of the evaporated substance is carried away from the capillary through the peripheral zone. It is shown that high losses in the plasma jet stagnation pressure, reaching up to 80\% relative to the pressure measured inside the capillary, belong to the peripheral discharge zone, in which the density and velocity, respectively, are two orders of magnitude higher and an order of magnitude lower than the corresponding values in the paraxial zone.

1. Introduction
The pulse capillary discharge with an evaporating wall (CDEW) is known as a method for obtaining highly ionized dense plasma [1]. The composition of the CDEW plasma is determined by the substance ablated from the capillary wall and electrodes surface. The presence of several chemical elements with different properties (mass, excitation and ionization energies, etc.) makes the physics of such a plasma more diverse in comparison with a single-component one. A feature of this type of discharge is the injection of the evaporated substance towards the capillary axis, and as a consequence, the spatial separation of the discharge into a paraxial high-temperature zone and a relatively low-temperature layer adjacent to the capillary wall. The difference between the temperatures is the reason of various component and ionization composition of plasma in these zones, namely: localization of electrons and ions of high ionization degree in the high-temperature zone [2] and the dominance of atomic and molecular components in the low-temperature periphery [3]. The processes of thermal diffusion that provide localization of lightweight components in the high-temperature zone and heavy components in the peripheral one contribute to the additional separation of the discharge by the masses of the constituent components. The near-wall layer plays an important role in the balance of mass and energy introduced into the discharge and carried away from it by the plasma jets [1,4,5], and its area is...
comparable with the cross-section of the paraxial zone [6,7]. According to estimates [4,6,7], the temperature in the near-wall layer is \( T = 3000 - 5000 \text{ K} \) that provides optimum conditions for the formation of polyatomic molecules and condensed particles [8,9].

Such spatial inhomogeneity of the CDEW in radial direction inevitably influences the gas dynamics of the plasma inside and outside the capillary. For example, low frictional losses in the paraxial zone of the jet because the sharp decrease in viscosity at \( T > 10000 \text{ K} \) provide its deep penetration into the dense gas [10], and high velocities in this zone contribute to its stability in perturbed atmosphere [11]. At the same time, the localization of condensed particles in the peripheral zone, and, as a consequence, decrease in viscosity, is able to destabilize the boundary layer and lead to the development of turbulence [12]. The low speed at the peripheral zone can be the reason of the jet momentum losses [1].

Despite the large number of experimental works devoted to the problems of the CDEW, the gas dynamics of the plasma in such discharge is studied insufficiently. In particular, there are no reliable data on such important gas-dynamic parameter as the plasma velocity. The use of direct methods of measuring the flow velocity by tracing the trajectories of plasma inhomogeneities cannot provide sufficient accuracy due to the different nature of these inhomogeneities and their spatial position. The use of the PIV method also does not lead to success due to the displacement of micron-sized particles onto the low-temperature peripheral zone. Moreover, the presence of these particles causes development of turbulence.

These difficulties cause the necessity of using non-intrusive diagnostic methods that do not disturb the flow pattern. Such methods, in particular, include the optical spectroscopy, the measurement of a jet momentum by the ballistic pendulum method, and direct measurements of the total pressure inside the capillary. These methods were used to perform complex diagnostics of a pulsed capillary discharge in the power density range of \( q_s = 10 - 100 \text{ kW/cm}^2 \) and to obtain the data necessary for estimating the most important gas-dynamic and thermodynamic parameters of a multicomponent plasma (pressure, density, temperature, velocity, Mach number) that is one of the main goals of this work. The set of experimental results obtained with the use of independent mutually complementary diagnostics methods creates the opportunities for estimating the effects connected with spatial inhomogeneity of the capillary discharge and their role in gas dynamics of plasma that is of particular interest for scientific and practical applications.

2. The object and the methods of research

The object of research is a capillary arrester, whose detailed description is given elsewhere [3]. Perspex is used as a capillary wall material (chemical formula \( C_3H_6O_2 \)). The depth and the initial diameter of a capillary are respectively \( h = 5 \text{ mm} \) and \( d = 1 \text{ mm} \). A capacitive storage device with series-connected inductor is used as a power supply. The values of capacity, inductance, voltage and the storage energy of a power supply are the following: \( C = 470 \mu \text{F}, L = 210 \mu \text{Hn}, U = 600 \text{ V}, Q = 80 \text{ J} \). The algorithm of power supply approximately corresponds to the sine half-wave. Typical parameters of the discharge are the following: pulse duration - \( \tau_d = 1 \text{ ms} \), peak current - \( I_m = 350 - 450 \text{ A} \), peak power \( N = 80 - 100 \text{ kW} \). During the preliminary experiments, the mass of substance evaporated from the capillary wall, as well as the pressure inside the capillary, have been measured. The mass of the evaporated substance was determined by monitoring the diameter of the capillary after each discharge pulse. The pressure inside the capillary was measured by a Honeywell strain gauge 19C200PG3K. Researches were carried out in the range of the capillary diameter \( d = 1 - 3.2 \text{ mm} \) that corresponds to the range of the discharge surface power density (the power divided by the cross-section of the capillary) \( q_s = 1 - 100 \text{ kW/mm}^2 \).

The pressure inside the capillary varies during the discharge pulse in accordance with the discharge power algorithm. The parameters of the plasma flow, which can be subsonic or supersonic outside the capillary (depending on the total pressure ratio \( N = P_0/P_\infty \), where \( P_0, P_\infty \) - the total pressure inside the capillary and the ambient gas pressure, respectively), are changed in an appropriate manner. The instantaneous image of the discharge obtained for \( N \sim 20 \), on which one can see the boundary of the
high-temperature paraxial zone of discharge inside the capillary, as well as the main elements of the shock-wave structure of the supersonic plasma jet (intercepting shock, reflected shock, Mach disk, triple configuration point), is presented in figure 1.

Figure 1 The instantaneous image of the pulsed capillary discharge: (1) boundary of capillary, (2) boundary of paraxial zone of discharge, (3) boundary of plasma jet, (4) intercepting shock, (5) triple configuration point, (6) reflected shock, (7) Mach disk. Total pressure ratio $N = P_0/P_\infty \approx 20$, camera exposure time $t = 1 \mu$s.

The ballistic pendulum method [13] is used to determine the momentum of the plasma jet from the measured values of deviation angle $\varphi$ and oscillation period $T$ of the pendulum: $p = \sqrt{2(1 - \cos \varphi)}Ms^\frac{T}{2\pi}$ ($M$ – mass of the pendulum, $g$ – acceleration of gravity, $s$ – distance from the rotation axis to the center of mass, $r$ – distance from rotation axis to center of force application). The ballistic pendulum is a massive body suspended on needle supports. The capillary arrest and current-carrying buses are rigidly fixed on the ballistic pendulum. The parameters of the ballistic pendulum satisfy the condition $T \gg \tau_d$. The thrust force is determined by the ratio $F = (P_0 - P_\infty)S_a$, (1) from which the stagnation pressure $P_0$ can be determined ($S_a$ – cross-section of the capillary).

The longitudinal profiles of the electron number density and temperature in the paraxial discharge zone inside and outside the capillary are obtained using optical spectroscopy. The 2D-spectra recording technique is described in detail in [3]. The spectral interval $\Delta \lambda = 650 - 685$ nm was chosen for 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. In the present work, the method of the relative intensities of the $H_\alpha$ line and the continuum is mainly used 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. The results of spectral diagnostics were used to estimate the plasma parameters in the paraxial discharge zone: the pressure $P_1 \approx 2n_e kT_e$, the mass density $\rho_1 = \frac{\mu_1 P_1}{RT_e}$ and the sound velocity $c_1 = \sqrt{\frac{\gamma RT_e}{\mu_1}}$.

3. The results of research
Dependences on the discharge power density of the pressures on the bottom ($P_0$) and on the outlet ($P_\alpha$) of the capillary, as well as the capillary pressure ratio ($N_{cap} = P_0/P_\alpha$), reconstructed from the results of spectral diagnostics, are presented in figure 2. The capillary pressure ratio remains approximately constant in the power density range corresponded to the supersonic regime of the
plasma jet (the Mach number at the capillary outlet is $M_a = 1$). The threshold power density, at which the flow regime changes, is approximately equal to $q^{thr}_s = 18$ kW/mm$^2$ and quantitatively consistent with the results obtained in [14]. It is easy to verify that the capillary pressure ratio is described with good accuracy by the relation $P_0/P_a = 1 + \gamma M_a^2$, valid for the expendable nozzle [15]. This makes it possible to estimate the effective adiabatic index, whose value is approximately $\gamma \approx 1.3 - 1.4$ (see figure 2), as well as the Mach number at the capillary outlet in the subsonic flow regime ($q_s < q^{thr}_s$).

Note that the pressure in the jet during its evolution exceeds the ambient gas pressure and only in the end of the discharge pulse approaches to the atmospheric pressure. Such feature is observed both in the supersonic and in subsonic flow regime. In particular, the exit pressure ratio in the subsonic flow regime ($M_a \leq 1$) reaches up to $n = P_a/P_\infty = 2 - 3$ (see figure 2). Moreover, the exit pressure ratio is the greater, the shorter the duration of the discharge pulse and vice versa. Such situation, obviously, is the consequence of nonstationarity of the pulsed flows, that is observed regularly in experiments [16,17] and finds the justification in the theoretical calculations [18].

![Figure 2 Dependences on the discharge power density $q_s$ of characteristic pressures, reconstructed from the results of spectral diagnostics: ($P_0$) pressure at the bottom of the capillary, ($P_a$) pressure at the capillary outlet, ($N_{cap} = P_0/P_a$) capillary pressure ratio.](image)

The dependences of the pressure at the bottom of the capillary $P_0^{spectr}(q_s)$ (The superscript is used for indication the method by which the parameter was obtained.), restored from the results of spectral diagnostics, and the pressure $P_0^{str}(q_s)$, measured inside the capillary by means of a strain gage qualitatively and quantitatively agrees with each other (figure 3). At the same time, the dependence of the stagnation pressure $P^{ballist}(q_s)$ of the plasma jet, restored from the data obtained by the ballistic pendulum method, differs from the $P_0^{spectr}(q_s)$ and $P_0^{str}(q_s)$ dependences both quantitatively and qualitatively. The ratio of these pressures reaches $P_0^{spectr}(q_s)/P^{ballist}(q_s) = 2 - 5$. Moreover, the dependence $P^{ballist}(q_s)$ contains a singularity that is expressed in a sharp change in its slope in the vicinity of the discharge power density of $q_s \approx 35$ kW/mm$^2$. The noted feature directly indicates that the results of the jet’s momentum measurement are determined by a combination of various factors, and the contribution of each individual factor is not predetermined and depends on the discharge power density. Both the processes inside and outside the capillary can act as such a factors. The latter ones, as a rule, are the sources of systematic errors of the plasma jet momentum measurement.

Nonstationarity of the pulsed jet and, as a consequence, the increased pressure inside the jet $P_{jet}$ in comparison with the ambient pressure $P_\infty$, is one of the most significant external factors leading to systematic errors. Accounting for this factor, however, does not influence significantly on the pressure ratio $P_0^{spectr}(q_s)/P^{ballist}(q_s)$, because replacing the last term in equation (1) from $P_\infty$ to $P_{jet}$ allows us to reduce the gap between $P_0^{spectr}$ and $P^{ballist}$ less than 20%. At the same time, account of this
and other external factors, allows to compensate only for the systematic error in measuring the jet momentum, but cannot significantly affect the very character of the dependence $P_{\text{ballist}}(q_S)$. Therefore, it seems that the loss in the jet momentum (and also the specific form of the dependence $P_{\text{ballist}}(q_S)$ related to this fact) is largely determined by the gas dynamics of the plasma inside the capillary, primarily by the spatial inhomogeneity of the flow.

**Figure 3** Dependences on the disc charge power density $q_S$ of the characteristic pressures obtained by various methods: ($P_0^{\text{spectr}}$) pressure at the bottom of the capillary, restored from the results of spectral diagnostics, ($P_0^{\text{str}}$) pressure, measured inside the capillary by a strain gage, ($P_{\text{ballist}}$) stagnation pressure of the plasma jet, restored from the data obtained by the ballistic pendulum method.

To verify this assumption, estimates of the plasma parameters at the section inside the capillary were made, taking into account the spatial separation of the discharge into the high-temperature paraxial and low-temperature peripheral zones. The initial system of equations includes the thrust force equation and the continuity equation

$$\frac{F}{S_a} = G_{a1}v_{a1}\phi + G_{a2}v_{a2}(1 - \phi) + P_a - P_{\text{jet}}$$  \hspace{1cm} (2)

$$G_a = \rho_{a1}v_{a1}\phi + \rho_{a2}v_{a2}(1 - \phi)$$  \hspace{1cm} (3)

where $\phi = S_1/S$ – reduced cross-section of the paraxial zone of discharge, $S_1, S_a$ – cross-section of the paraxial discharge zone and the total capillary cross-section, respectively, $G_{ai}, \rho_{ai}, v_{ai}$ – mass flow rate, mass density and velocity of plasma at the capillary outlet for $i$-th zone of discharge (the values of the index $i = 1, 2$ are used to denote the paraxial and peripheral discharge zones, respectively), $P_a, P_{\text{jet}}$ – pressures at the capillary outlet and in the plasma jet, respectively.

The initial data include:

- the results of measuring the thrust force $F(q_S)$ by the ballistic pendulum method;
- the results of measuring the mass flow rate $G_a(q_S) = \frac{\Delta m(q_S)}{\tau_d S}$ ($\Delta m$ – the mass of evaporated substance during the discharge pulse, $\tau_d$ – discharge pulse duration);
- the results of spectroscopic measuring the electron number density and temperature, and also the estimates of pressure restored from these data. These data are used to calculate the density, velocity of sound, and plasma velocity in the paraxial discharge zone at the capillary outlet (in the local thermodynamic equilibrium approximation). The value of the effective molecular mass in the paraxial zone $\mu_1 = 1.43$ was used in calculations, which corresponds to a fully ionized plasma whose stoichiometric composition is determined by carbon and hydrogen in the proportion $[C] : [H] = 1 : 5$.

Taking into account the results of spectral diagnostics (see figure 2), it is assumed that the gas dynamics of the plasma in the paraxial discharge zone corresponds to the model of an ideal
expendable nozzle assumed the absence of the pressure losses. Under these conditions, the dynamic pressure of the paraxial zone at the capillary outlet is determined by the relation

\[ H_{a1} = P_0 - P_a = \gamma M_{a1}^2 P_a = \rho_{a1} v_{a1}^2. \]  

(4)

This condition means that, in the absence of static pressure gradients over the capillary cross-section (grad \( P = 0 \)), the dynamic pressure losses occurs exclusively in the peripheral discharge zone. Thus, the condition for the equality of the dynamic pressures and Mach numbers in the paraxial discharge zone and the peripheral one, which is the basic assumption of the capillary discharge two-zone models \([6,7]\), is not satisfied in our case, so \( \rho_{a1} v_{a1}^2 > \rho_{a2} v_{a2}^2 \) and \( M_{a1} > M_{a2} \).

The temperature and effective molecular mass in the peripheral discharge zone, which determine the density and speed of sound in this zone, are specified as additional conditions necessary for solving a system of two equations (2)-(3) with three unknowns. The calculation was carried out for the following values of these parameters: \( T_{a2} = 3500 \) K, \( \mu_2 = 13.5 \). The condition for the complete dissociation of the ablating substance of the capillary wall, as well as estimates of the temperature in the peripheral zone, obtained in \([6,7]\) were used as criterion for choosing the temperature. The value of the effective molecular mass in the peripheral zone corresponds to a weakly ionized plasma whose stoichiometric composition is determined by carbon and oxygen in the proportion \( [C] : [O] = 3.4 : 2 \).

The solution of the system (2)-(3) makes it possible to determine the reduced area of the paraxial discharge zone \( \phi \), the velocity \( v_2 \) and the Mach number \( M_{a2} \) in the peripheral zone, the mass flow rate and dynamic pressure for each discharge zone. Results of calculation of some parameters are presented in figure 4. The qualitative course of the obtained dependences is determined primarily by the initial data \( F(q_S), C_0(q_S), \) and \( P_a(q_S) \), and, within the framework of accepted approximations, is not very sensitive to variations of the temperature and effective molecular mass in the paraxial and peripheral zones, which affect only the quantitative values of the calculated parameters. The analysis shows that the main contribution to the momentum of the plasma jet is provided by the paraxial discharge zone, the partial dynamic pressure of which \( (h_{a1} = H_{a1} \phi) \) is for 2-6 times higher than the corresponding value \( (h_{a2} = H_{a2}(1 - \phi)) \) for the peripheral zone (see figure 4). At the same time, more than 80% of the ablated mass is carried away from the capillary through the peripheral discharge zone. Such situation, in general, is due to a significant difference in the flow parameters in the two mentioned zones: by more than order higher speed and more than two orders lower mass density of plasma in the paraxial discharge zone if to compare with the peripheral one (figure 5). A significant difference in these parameters is facilitated by the inequality of Mach numbers \( (M_{a2} < M_{a1}) \), as well as the comparable cross-sections of these zones, whose ratio decreases with discharge power density decrease (see figure 4). We note that the course of the calculated dependence \( \phi(q) \) agrees with the experimental observations. Analysis of the images and spatial spectra of the discharge shows that the reduction in the power density (due to the increase in the capillary diameter, the other parameters (the capillary length and the energy deposited into the discharge) remain fixed) is accompanied not only by a decrease in the ratio of the cross-sections of the paraxial and peripheral zones predicted by the model, but also leads to the fact that this ratio varies along the capillary, and, the stronger, the lower the discharge power density (see figure 1).

The limitations of the two-zone model, as well as the assumptions about the constancy of the component composition in each zone and the temperature in the peripheral zone, do not allow us to indicate specific physical mechanisms responsible for the jet momentum losses. We suppose that the following processes provide the main contribution to the losses of the jet’s momentum: viscous friction in the boundary layer (the plasma viscosity in the low-temperature peripheral and high-temperature paraxial zone differ by more than order of magnitude \([10,19]\), as well as plasma-chemical transformations in the peripheral zone, proceeding with the absorption of energy. Among the latter processes, in particular, is the growth of cluster particles, a significant concentration of which in the erosive plasma finds experimental confirmation \([20,21]\). The contribution of both mechanisms to the jet momentum losses is determined by the thickness of the low-temperature peripheral zone that, in a first approximation, makes it possible to explain the results obtained in ballistic pendulum experiment.
Figure 4 Calculated dependencies on power density $q_S$: $M_{a1}$, $M_{a2}$ – Mach numbers, $h_{a1}/h_{a2}$ – ratio of partial dynamic pressures, $\phi$ – reduced cross-section of the paraxial discharge zone. Indices 1, 2 related to the paraxial and peripheral zone, respectively.

Figure 5 Calculated dependencies on power density $q_S$ of plasma parameters at the capillary outlet in the paraxial and peripheral discharge zone: $v_{a1}$, $v_{a2}$ – velocities, $\rho_{a1}$, $\rho_{a2}$ – mass densities.

4. Conclusions

Thus, the analysis of the results of complex research of pulsed capillary discharge with an evaporating wall, obtained on the basis of independent diagnostic methods, allows us to conclude that the spatial inhomogeneity of the discharge exerts a decisive influence on the gas-dynamic parameters of multicomponent plasma. Spatial separation of the discharge by the masses of its components, localization of lightweight components in the high-temperature paraxial zone, and heavy ones in the low-temperature peripheral zone, leads to the fact that the gas dynamics in these zones is significantly different. Estimates show that the detected high losses of plasma jet stagnation pressure should be attributed, mainly, to the peripheral discharge zone, the density and velocity in which, respectively, are two orders of magnitude higher and an order of magnitude lower than the corresponding values in the paraxial zone. The paraxial discharge zone, whose gas dynamics with good accuracy corresponds to the mode of an ideal expendable nozzle, provides the main contribution to the creation of a jet momentum, in spite of the fact that more than 80% of the evaporated substance mass is carried away from the capillary through the peripheral zone. We believe that the main sources of the stagnation pressure losses are viscous friction in the boundary layer and the endothermic processes of plasma-chemical transformations in the peripheral zone. A study of the role of these factors is the subject of future research.
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