Features of spatial distribution of the parameters on the initial section of a supersonic plasma jet, created by pulsed discharge in a capillary with ablative wall

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Abstract. The results of spectroscopic studies of the initial section of the supersonic plasma jet created by a pulsed discharge in the capillary with the ablative wall are presented. Features of the spatial distribution of the electron density and the intensity of the spectral components, which, in particular, caused by the high electron temperature in the hot central zone, exceeding the "normal" temperature, as well as significant non-isobaricity at the initial section of supersonic jet are revealed. The presence of the molecular components exhibiting their emission properties at the plasma jet periphery permit us to estimate the parameters of the plasma in the spatial domain, where "detached" shock waves of the supersonic jet are created.

1. Introduction

Pulsed discharge in a capillary attracts attention as a source of highly ionized dense plasma. The substance ablating from the capillary wall is used as the working body in this type of discharge, that permit to create the plasma jets with demanded chemical composition in a wide range of plasma parameters [1–10]. Our previous spectroscopy study of subsonic plasma jet created by a pulsed discharge in a capillary made from hydrocarbon polymer (polymethylmethacrylate—PMMA) [11] have shown that the structure of its initial part is characterized by explicit separation for the high temperature core, consisting preferably from hydrogen, and the low temperature peripheral domain, comprising atoms and molecules of ablating substance from the capillary wall and the electrodes' vapor and perhaps the cluster's component. The high volume fraction of hydrogen, determined by the composition of the ablating substance (PMMA), leads to the fact that the spatial distribution and quantitative parameters of the capillary discharge plasma in a hot near-axial zone (electron density and temperature, profiles of the radiation intensities of the spectral components) are close to the parameters of a stationary hydrogen arc at comparable discharge current and capillary sizes [12, pp 173–181]. Low-speed subsonic flow ($v \sim 100$–200 m/s) can be considered isobaric with sufficient approximation, so the spatial distributions of plasma parameters are determined predominantly by the temperature profile. Increasing the jet velocity causes deviation from the isobaricity that can make additional influence on plasma parameters. Flow non-isobaricity is particularly strongly expressed in supersonic jets, especially in the spatial domain occupied by the shock-wave structures [6,13–15].

Only few experimental studies devoted to this subject are available for today, but they, however, were conducted at significantly lower [6] and high [10] parameters of discharge. Therefore, the measurement of basic thermophysical and electrophysical parameters with high spatial and temporal resolution remains actual problem, whose solution allows us to clarify and to supplement the general concepts of the plasma jet created by the pulsed discharge in a capillary, as well as to determine the influence of the flow non-isobaricity on the plasma parameters. At the same time, the spectral diagnostics, perhaps, is the only suitable method for determining the gas-dynamic parameters of microjet flows, which allows us to get additional knowledge about the gas-dynamic picture for supersonic flows obtained earlier for pure gas streams [13–15] and weakly ionized plasma jets [6] of considerably larger scale. Objective of this work is determination of the plasma parameters of supersonic jet in the vicinity of central shock, where the influence of non-isobaricity is essentially strong.

2. The object of research and the results of spectral measurements

Supersonic plasma jet created by a pulsed discharge in a capillary gap is the object of our research. The capillary is fabricated from hydrocarbon polymer PMMA. Its initial diameter and depth are $d = 1$ mm and $h = 4$ mm respectively. The electrodes are fabricated from copper (internal electrode) and aluminum (external electrode). The capillary gap design, the scheme of experimental setup and the methods of researches are presented in detail in our previous works [2, 11]. The researches are conducted for the following parameters of the discharge pulse: pulse energy $Q \sim 80$ J, peak discharge current $I_d \sim 350$–400 A, voltage drop along the discharge gap $U_d \sim 200$–250 V, duration of the discharge pulse $t_d \sim 1$ ms, peak power $P \sim 100$ kW. Typical gas-dynamic parameters of plasma jet, obtained by flow visualization methods and analysis of shock-wave structures, are following: the Mach number $M \sim 2$–2.5, the degree of pressure ratio $n = p_{\text{out}}/p_{\infty} \sim 2$–10, the speed of the head of the jet $v_h \sim 300$–500 m/s, the pressure inside the capillary $p_{\text{in}} \sim 20$–40 bar, the pressure at the capillary outlet $p_{\text{out}} \sim 10$–20 bar.

The spectral equipment with high spatial (30–50 μm) and temporal (10-50 μm) resolution is used for detailed study of space-time evolution of short-pulse (1 ms) discharge with complex structure. The fast-gated ICCD camera Andor iStar (minimal exposition 100 ns) is mounted in the focal plane of MS-257 spectrograph (1800/mm and 2400/mm diffracting gratings, the entrance slit $\delta = 20$ μm) and used for spectral data registration. The inverse Radon procedure [16] is applied for transformation of the measured chordal intensities (integrated along the line of observation) and further calculation the real parameters' profiles in the transversal direction.

The spectrum of supersonic jet contains the intensive hydrogen lines of Balmer series H_α, H_β, H_γ, the lines of atomic carbon, the lines of excited copper atoms (the material of internal electrode), the lines of single-ionized copper Cu_{II}, carbon C_{II}, nitrogen N_{II}, oxygen O_{II} (figure 1). These spectral lines were used for calculation the electron density n_e (linear Stark broadening of H_α and H_β lines) and the electron temperature (the ratios of C_{II}, Cu_{II} lines). The lines of single-ionized copper and carbon are prevailed upon the atomic lines in the axis vicinity along initial part of the jet. The atomic lines of aluminum (the material of external electrode), oxygen, nitrogen, the violet band system of CN radical, the Swan band system of C_2 radical (ablating substance from the capillary wall) are presented on the jet's periphery. The violet band system of CN radical and the Swan band system of C_2 radical were used for calculation the vibrational ($T_v \sim 8$–9 kK) and the rotational ($T_r \sim 5$–7 kK) temperatures on the jet's periphery.

The presence of the lines of singly ionized atoms of ablating substance (carbon, oxygen) and of internal electrode (copper) with excitation energy about 20 eV, which are registered up to the distances of 50–70 mm from the capillary outlet, indicates the high electron temperature along this part—no less than 2 eV. The electron density along this part, obtained on the basis of the linear Stark effect for hydrogen lines H_α, H_β, is about $n_e = (1.5–2) \times 10^{17}$ cm^{-3}. The value of electron temperature determined by the ratio of ionic spectral lines C_{II} intensities is about

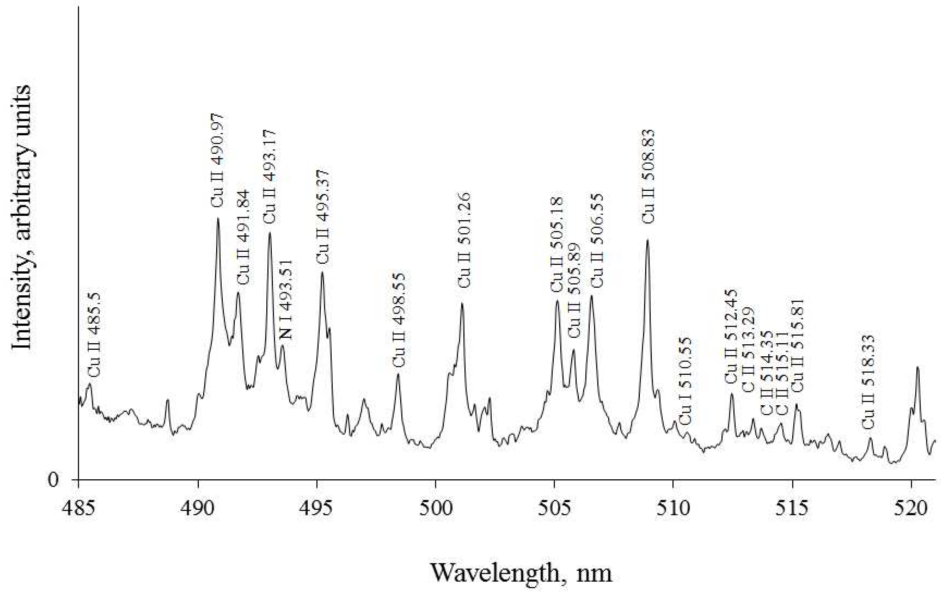

Figure 1. Detailed spectrum of the plasma in the rarefaction domain at the distance of $z = 2$ mm from the capillary outlet. Exposition duration of spectrograph camera is 5 μs.

$T_e \sim 2$ eV in the central shock vicinity ($z = 2.5$ mm) and about $T_e \sim 2.2$–2.5 eV at the distance of $z = 0.5$ mm from the capillary outlet. Using the ratio of $\mathrm{Cu_{II}}$ 248.9 nm ($E^* = 8.23$ eV) and $\mathrm{Cu_{II}}$ 254.4 nm ($E^* = 13.38$ eV) lines in the UV spectral band provides the similar values for the electron temperature in the capillary outlet vicinity ($z = 0.5$ mm)—$T_e \sim 2.4 \pm 0.2$ eV.

3. Transversal distribution of plasma parameters

The spatial inhomogeneity of the plasma is caused by significant temperature gradients and by non-isobaricity of supersonic flow. The greatest influence of these factors appears in the spatial domain occupied by shock-wave structures, characterized by the maximum pressure difference between the central and peripheral zones with an expected minimum on the jet axis. The transverse profiles of the electron density and the intensities of spectral components for this spatial area (in the vicinity of the central shock) are presented on figure 2.

The properties of investigated plasma in the "special" points and calculated dependences of these properties on the temperature and pressure under the assumption of local thermodynamic equilibrium (LTE) permit us to obtain the transverse profiles of temperature $T_e(r)$ and pressure $p(r)$ in different sections of the jet. These "special" points correspond to the "normal" temperatures [17] at which the maxima for electron density n_e and spectral components intensities $n^*_{\mathrm{H}_\alpha}$, $n^*_{\mathrm{H}_\beta}$, $n^*_{\mathrm{C}_2}$, $n^*_{\mathrm{C_{II}}}$ are achieved.

The additional calculation of the equilibrium composition of the plasma in the range of expected change of its temperature $T = 2$–3 eV, pressure $P_\Sigma = 0.2$–2 bar and a variable ratio of the partial pressures of H : C : O mixture, which initial stoichiometric composition ($C_5H_8O_2$) at the moment of the plasma creation corresponds to H : C : O = 53.3 : 33.3 : 13.3, is performed for determining the "normal" temperatures of the spectral components. The atoms (ions) of copper in a quantity of 0.1 volume percents are added to the mixture to account the possible role of the internal electrode material (observed in the radiation spectrum lines $\mathrm{Cu_I}$ and $\mathrm{Cu_{II}}$ were used for diagnostic purposes). The calculation takes into account that the total pressure of the plasma and the ratio of the partial pressures at different jet radii are variables in the test

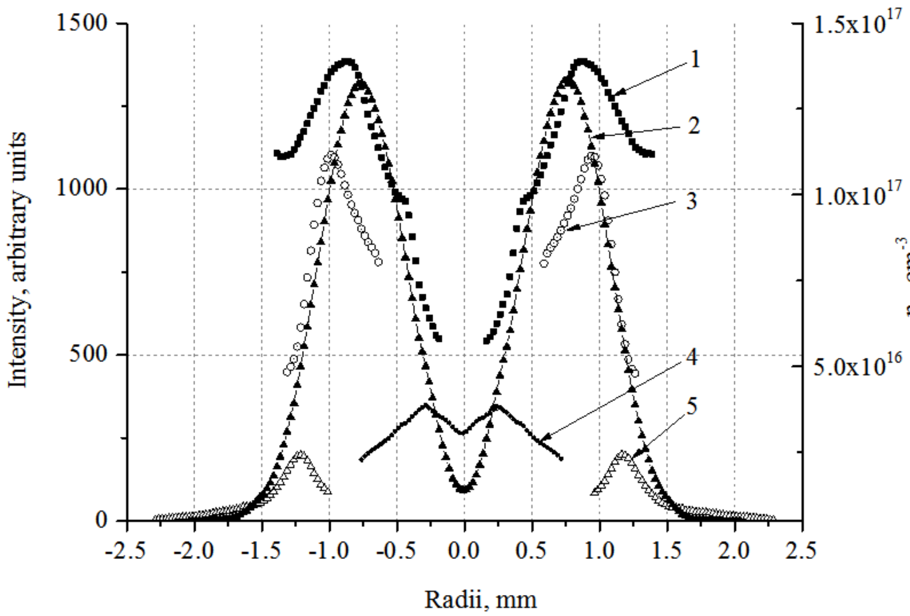

Figure 2. Transversal profiles of the electron density n_e and the radiation intensities of plasma spectral components in the vicinity of the central shock at a distance $z = 2.5$ mm from the capillary outlet: 1—n_e, 2—H_α, 3—H_β, 4—C_{II} 513.3 nm, 5—C_2 516.56 nm.

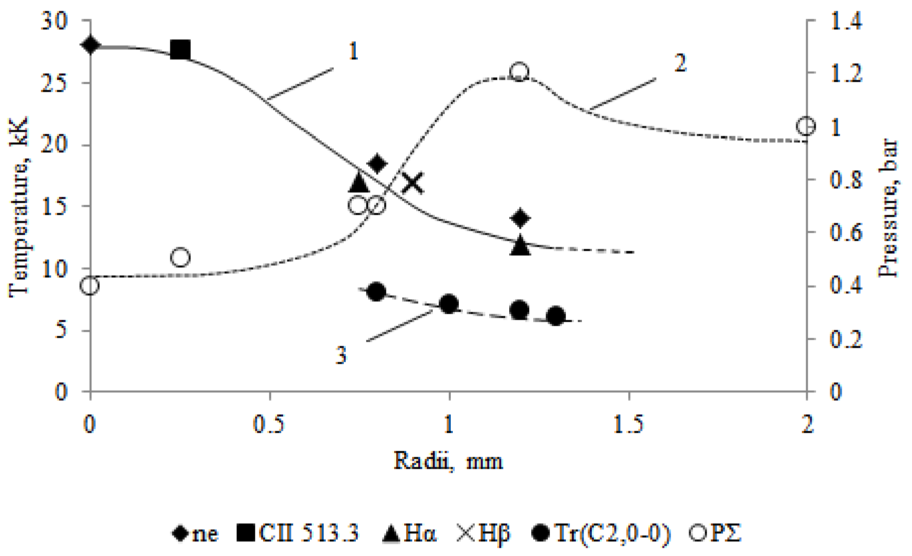

Figure 3. Transversal profiles in the vicinity of the central shock ($z = 2.5$ mm): 1—electron temperature, 2—pressure, 3—rotational temperature T_r ((0–0) band of C_2 radical).

medium, in particular: the light component (H, H^+) is concentrated in the axial zone, and the heavy (C, C^+, O, O^+, C_2, O_2)—on the periphery. Common consideration of the experimental curves $[H^*(3)](r)$ and $n_e(r)$ in relation to their calculated variations $[H^*(3)](p,T)$, $n_e(p,T)$ allows us to obtain a consistent change of $p(r)$ and $T_e(r)$ in the range of $r = 0$–1.2 mm. The results of $p(r)$ and $T_e(r)$ transversal profiles calculations in the vicinity of the central shock are plotted on figure 3. The central zone of the jet is strongly ionized ($n_e \simeq [\mathrm{H}^+] \gg [\mathrm{H}], [\mathrm{C}]$) and characterized by the temperature $T_e(r = 0) \sim 28$ kK, exceeding the "normal" value $T_N(\mathrm{H}_\beta, \mathrm{H}_\alpha)$. The electron temperature on the jet's periphery takes the value $T_e(r = 1.2\ \mathrm{mm}) \sim 10$–12 kK that is for 1.3–1.5 times higher than for subsonic jet [11]. Comparison of the electron temperature on the radius $r = 1.2$ mm with rovibrational temperatures T_r and T_v, obtained by processing the spectra bands of C_2 radical, indicates a significant difference (up for 2 times) between them (figure 3). As might be expected, the approach of single temperature LTE plasma is not satisfied for the peripheral zone of the erosion discharge, especially in the rarefaction domain.

Using the aforementioned procedure permits us to restore the pressure profile $p(r)$ in a rarefaction domain, which qualitatively and quantitatively agrees with results of measurements obtained for pure gas jets at close values of gas-dynamic parameters [13, 14]. The pressure reaches a minimum in the axial zone, where its value is $p(r = 0) = 0.4$ bar. The pressure value at the radius $r = 1.2$ mm (the Swan band maximum emission) is higher than the atmospheric pressure (1.2 bar), and outside the jet boundary ($r = 2$ mm) it closes to atmospheric value.

4. Conclusion

The high level of the electron temperature in the axial hot zone reaching $T_e \sim 2$–3 eV and exceeding the "normal" values ($T_e \sim 1.5$–2.3 eV) both for the electron density ($n_e \sim (1$–$2) \times 10^{17}$ cm^{-3}) and population levels of the main radiating spectral components, and also the non-isobaricity of supersonic flow cause the non-monotonic distribution of the plasma parameters in the transverse direction. The role of the flow non-isobaricity is particularly strong in the initial section of the jet—in the rarefaction domain, where the near-axial value of the electron density is much lower (approximately for 2.5 times) than at the jet's periphery. The plasma temperature is significantly lower in the peripheral zone, where the difference between the electron temperature ($T_e \simeq 12$–13 kK) and vibrational ($T_v \simeq 8$–9 kK) and rotational ($T_r \simeq 5$–7 kK) temperatures is observed. Restored on the basis of the spectroscopic measurements profile of the pressure in the rarefaction domain qualitatively and quantitatively agrees with results of measurements obtained for pure gas macrojets at close values of gas-dynamic parameters. The obtained results clarify and supplement the general concepts of the plasma jet created by the pulsed discharge in a capillary, and methods of spectroscopy of high spatial and temporal resolution can make a good basis for the diagnosis of small-scaled spatially inhomogeneous plasma objects.

Acknowledgments

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