Measurements of electron number density and temperature in a supersonic plasma jet by optical emission spectroscopy

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Abstract. The results of experimental studies of the shock-wave region of the supersonic plasma jet flow formed by a pulsed capillary discharge with a polymeric wall are presented. Using optical emission spectroscopy of high spatial resolution, a detailed picture of the evolution of the radial profiles of the electron number density and temperature along the initial section of an underexpanded plasma jet, starting from the capillary outlet and ending with the flow stagnation zone, has been obtained. It was found that the profiles of the electron number density and temperature reflect all the features of the shock-wave flow region, tracing the influence of intercepting, central and reflected shock waves.

1. Introduction
Supersonic plasma jets are widely used in various aerospace technologies [1–6], plasma chemistry, for processing and obtaining new materials [7,8], etc. Quite often, a pulsed discharge in a capillary with an evaporating wall turns out to be the most preferable method for the formation of supersonic plasma jets [9]. The working fluid in such a discharge is the substance of the capillary wall, which, under the influence of powerful heat fluxes, evaporates, ionizes and is ejected from the capillary in the form of a plasma jet. The gas-dynamic structure and parameters of the plasma jet substantially depend on the geometry of the electrical parameters of the discharge. Such specific features of the capillary discharge as the removal of electric current outside the capillary and the strong inhomogeneity of the plasma chemical composition due to the peculiarities of the inflow of the plasma-forming substance into the discharge volume [10–12] have a strong influence on the flow nature. These features, as a rule, are not taken into account when conducting experimental studies and numerical modeling, and the ratio of chemical elements is assumed to be unchanged in space and time [13–16]. This simplification can lead to a noticeable discrepancy between the experimental results and numerical simulation.

One of the reasons hindering the development of numerical models of capillary discharges is the lack of reliable experimental data required to confirm the results of numerical simulations. First of all, this refers to the initial section of the supersonic jet, which is characterized by large gradients of pressure, concentration, and temperature of charged particles. Experimental studies of capillary discharges were directed mainly towards studying the plasma inside a capillary, and only small efforts were made to study supersonic plasma jets in detail. Among the experimental studies in which the structure of the nonisobaric region was studied in the most detail, one can note the studies on determining the profiles of the number density and temperature of charged particles along the axis of a supersonic plasma jet [9,17,18] and in some of its cross-sections [9,19] using optical emission spectroscopy.
The aim of this work is to obtain a detailed picture of the spatial distribution of the main plasma parameters (electron number density and electron temperature) in the shock-wave section of a supersonic plasma jet formed by a pulsed discharge in a polymer capillary. The work is a continuation of previous research [9,19].

2. The object and the methods of research

The object of research is a supersonic plasma jet emerging into the ambient air atmosphere ($P=10^5$ Pa, $T=298$ K) from the open end of the capillary spark gap (figure 1). The main elements of the capillary spark gap are the following: the capillary bore, the internal electrode (anode), tightly mounted to the capillary inlet, and the external electrode (cathode). A copper rod with a diameter of 2.4 mm which mounted at a distance of 10-15 mm from the capillary edge is used as an external electrode. In order to obtain the most symmetric picture of the plasma parameters distribution in the transverse direction, as well as to minimize the influence of the external electrode on the flow pattern, the latter was placed strictly along the capillary axis. The capillary wall is made of polymethyl methacrylate, so the initial plasma composition determines by the chemical formula $C_5H_8O_2$. The initial diameter of the capillary bore is $d=1$ mm, and the depth is $h=5$ mm. The inner electrode is made of nickel. This choice was made because the absence of strong lines of Ni I and Ni II in the investigated spectral range, which makes it possible to minimize the undesirable effects of superposition of spectral lines, which significantly complicate the spectra processing. The capillary spark gap is driven by a pulse-forming network (PFN), which consists of capacitor banks charging to desired voltage, inductor and auxiliary network used for discharge ignition [20]. The capacitor banks with total capacitance of $C=470 \mu F$ are charged by rectifier circuit up to the voltages of $U=500-800$ V, so the energy input into the capillary spark gap is $Q=60-150$ J. The selected nominals of capacitors and the inductor ($L=210 \mu$Hn) provide the discharge current pulse corresponding to a sine half-wave with the discharge pulse duration of $\tau=1$ ms. The peak discharge current reaches $I_m=350-450$ A, and the voltage drop along the discharge is $U=150-250$ V. Typical waveforms of the discharge voltage and current are presented in figure 2.

Since the capillary diameter increases after each discharge pulse, it is highly desirable to be able to synchronously determine all the parameters of interest to us. In our case, these are the electron number density and electron temperature. This requirement presupposes the choice of a spectral interval containing the required number of emitters. The spectral interval 650-685 nm is the most suitable for...
this purpose (figure 3), which includes the contour of the hydrogen $\text{H}_\alpha \ 656.28 \text{ nm}$ line used to determine the electron number density based on the linear Stark effect, several singlet and multiplet lines of carbon ions ($\text{C II} \ 657.8 \text{ nm}, \ 658.2 \text{ nm}$ and $\text{C II} \ 678.36 \text{ nm}$), as well as a powerful continuum (mainly inside the capillary), which can be used for estimating the electron temperature. The highest accuracy in estimating the electron temperature can be achieved using the method of relative intensities of the emission lines of the carbon ion due to the significant, more than 6 eV, difference in the excitation energies of their upper levels. However, this method has some limitations. One of them is associated with the low emission intensity of the multiplet lines of the ion $\text{C II} \ 678.36 \text{ nm}$ at temperatures below $T_e<1.5 \text{ eV}$, and the other is associated with the destruction of the weakly bound $2s2p(^3\text{P})3p$ level (with an ionization energy of 1.9 eV) in plasma microfields [21,22]. The influence of the latter factor increases with an increase in the electron number density, and when the electron number density exceeds $n_e>10^{18} \text{ cm}^{-3}$ (the spectrum corresponding to this case is presented by the plot 2 in figure 3), the multiplet lines $\text{C II} \ 678.36 \text{ nm}$ become indistinguishable against the background of a powerful continuum. In this regard, we were forced to restrict the range of the discharge power density (power divided to the capillary cross section, $q = U_1/(\pi d^2/4)$) in order to be able to use this method of temperature estimation in the entire investigated volume of the plasma jet.

![Figure 3](image-url)

**Figure 3.** Emission spectra of the hydro-carbon plasma depending on the discharge power density: (1) $q=30 \text{ kW/cm}^2$ and (2) $q=80 \text{ kW/cm}^2$.

Plasma emission spectra were recorded on a CCD array (255x1024 pixels) of a high-speed Andor iStar camera mounted in the output focal plane of the MS-257 spectrograph. For this purpose, a sharp image of the selected cross-section of the plasma jet was projected onto the entrance slit (slit width is 50 µm) of the spectrograph. The spatial resolution of the recorded spectra is 20 µm per pixel. The temporal resolution is limited by the camera exposition, whose value did not exceed $\tau_{\text{exp}}<30 \mu\text{s}$, that is significantly less than the discharge pulse duration ($\tau=1 \text{ ms}$). The spectra were recorded at the moment when the discharge current reached its maximum (see figure 2).

To record the spectra, we selected several cross-sections perpendicular to the plasma jet axis, characterizing the rarefaction zone, the Mach disk, and the stagnation zone (see figure 1). However, since the dimensions characterizing the shock-wave structure of the flow were not known in advance (one of these dimensions is the distance between the Mach disk and the capillary edge), it was decided to record a series of spectra in each selected cross-section at different voltages of the power source. The meaning of this solution is that the position of the Mach disk relative to the capillary edge depends on the discharge power, which is adjusted by the voltage of the power source. Therefore, by adjusting the voltage of the power supply (in the range of 500-800 V with a step of 100 V) and, consequently, the Mach disk spatial position, it is possible to obtain a detailed picture of the evolution of transversal
parameters distribution along the jet axis without necessity of changing the physical position of the
capillary spark gap. Figure 4a shows the longitudinal profiles of the electron number density
corresponding to different power supply voltages. These profiles are obtained from the spectra registered
along the plasma jet axis. It can be seen that the higher the voltage of the power supply, the further from
the capillary edge the Mach disk is located. Figure 4b shows the same dependences in reduced units of
distance, \( \xi = x/x_C \) (\( x_C \) is the coordinate corresponding to the position of the Mach disk, determined as the
arithmetic mean distance between the positions of the minimum and maximum of the electron number
density relative to the capillary edge). With this representation, it can be seen that each dimensional
coorinate \( x \) corresponds to a range of dimensionless coordinates \( \xi(U,x) \) depended on the power supply
voltage \( U \) and distance \( x \) to the capillary edge. Thus, the technique used makes it possible to “smoothly
scan” rather short sections of the flow, which is fundamentally important for obtaining a detailed picture
of changes in plasma parameters, especially in the shock waves vicinity.

![Figure 4a](image1)
![Figure 4b](image2)

**Figure 4.** Electron number density profiles along the jet axis depending on the power source
voltage, plotted in (a) an absolute and (b) reduced units of distance. Profiles have been
reconstructed from the side-on 2D spectra, integrated along the line-of-sight. The vertical lines in
the plot (a) mark the axial positions of the plasma jet cross-sections, in which the transversal
profiles of the plasma parameters were determined. Each fixed position of the cross-section, marked
on the plot (a), corresponds to the interval of distances in reduced units of length, marked on the
plot (b) by a filled rectangle.

3. The results of research
The recorded spectra, after the inverse Abel transformation, were used to construct the profiles of the
electron number density and temperature in the selected cross sections of the plasma jet - starting from
the capillary edge and ending with the stagnation zone behind the Mach disk (figure 5 - figure 10). It
can be seen that, with distance from the capillary edge, not only the absolute values of the electron
number density and temperature change, but the very nature of the radial profiles of these parameters
also changes tracking the gas dynamics of the nonisobaric flow. The expansion of the plasma flow,
whose pressure at the capillary outlet is several times higher than the ambient pressure, is accompanied
by the formation of a shock waves system, including intercepting, central, and reflected shocks, that
influences the spatial distribution of the electron number density and temperature. In the immediate
vicinity of the capillary outlet, where the intercepting shock has not yet formed (\( \xi<0.1 \)), the radial
temperature course is characterized by monotonic decrease from the center to the periphery of the jet
(figure 5a). The nonmonotonic course of the electron number density with a characteristic maximum
located at a certain distance from the jet axis only tracks local change in temperature and pressure (figure
5b). In this case, the spatial position of the peripheral maximum corresponds to the value of the "normal"
temperature at a given pressure [23].
Figure 5. Transversal profiles of (a) the electron temperature and (b) electron number density in the vicinity of the capillary edge. Hereinafter the distance between the capillary edge and the plasma jet cross-section, in which the transversal profiles of the plasma parameters were determined, is indicated in the top of the plot.

Downstream, the profiles shape undergoes a significant transformation due to the influence of shock waves. So, in the range of reduced distances 0.1<\(\xi<0.7\) from the capillary edge, an intercepting shock wave changes significantly the radial course of electron number density and temperature (figure 6 and figure 7). As a result, the temperature profile becomes non-monotonic and includes not only a central, but also a peripheral maximum, whose spatial position coincides with the intercepting shock wave (figure 6a and figure 7a). An additional peripheral maximum due to the influence of the intercepting shock wave also appears on the radial profile of the electron number density. In some cases, this maximum is difficult to distinguish against the background of the concentration maximum corresponding to the "normal" temperature, especially if the spatial position of these two maxima coincides (figure 6b). However, in the middle of the rarefaction region, this maximum is easily observed (figure 7b). In this particular case, it is located closer to the jet axis than the maximum corresponding to the "normal" temperature.

Figure 6. Transversal profiles of (a) the electron temperature and (b) electron number density at the beginning of the rarefaction zone.
Before proceeding to the analysis of the transversal profiles in the region of the Mach disk location, let us to return once again to the longitudinal profiles of the electron number density calculated on the basis of side-on 2D spectrograms (figure 4). First of all, attention is drawn to the large extent of the transition region between the rarefaction and stagnation zones associated to that of the Mach disk. The width of this region, which is determined as the distance between the spatial positions of the maximum and minimum of the electron number density, reaches 1.5 mm, that is more than an order of magnitude larger than the maximum possible width of the viscous shock under the conditions of this experiment (<100 μm). This discrepancy is partly due to the fact that the profiles of the electron number density shown in figure 4 characterize the region of predominant emission of the Hα line and do not reflect the real course of the electron number density along the jet axis. However, the main reason for the large width of the transition region, in our opinion, is the curvature of the central shock, which is convex downstream. It is logical to assume that the beginning of the transition region corresponds to the intersection of the intercepting, central and reflected shock waves (triple Mach configuration), and its end is determined by the projection of the curved surface of the central shock onto the jet axis. The width of the transition region in dimensionless coordinates is 0.7<ξ<1.2 (figure 4b). This assumption is confirmed by the nature of the radial profiles of the electron number density and temperature in this region, which becomes more complex compared to the rarefaction region (figure 8). Thus, in some cases, it is possible to fix two peripheral maxima on the temperature profiles, one of which corresponds to a curved Mach disk, and the other to a reflected shock wave (the profile in figure 8a, corresponding to the reduced coordinate ξ=1.2). The character of the radial distribution of the electron number density becomes more complex (figure 8b). It is not always possible to clearly reveal the influence of the central and/or reflected shock waves on the radial profile of the electron number density because the complex flow structure in this region.

**Figure 7.** Transversal profiles of (a) the electron temperature and (b) electron number density in the middle of the rarefaction zone.
The next transformation of the transversal profiles of the electron number density and temperature occurs in the stagnation zone (figure 9). The substantially non-monotonic shape of the temperature profile, characterized by the presence of central and peripheral maxima at the end of the transition section (the profile in figure 9a corresponding to the reduced coordinate $\xi=1.03$), undergoes a transformation and becomes monotonic one with a single central maximum in the stagnation zone (profiles in figure 9a in the range of reduced coordinates $1.12<\xi<1.6$). And the course of the electron number density (as a rule, nonmonotonic) in the stagnation zone is caused only by the change in the local values of pressure and temperature along the jet radius (figure 9b). Such a character of the distribution of the electron number density and temperature is retained over a fairly extended region of the subsonic flow following the only one shock-wave section of the highly underexpanded supersonic jet. If the initial part of the jet contains several shock-wave sections, which is typical for weakly underexpanded supersonic jets, then the transversal profiles of parameters in the second and subsequent sections contain all the attributes of a supersonic flow typical for expansion zone. In this case, the radial course of the parameters is significantly determined by the influence of an intercepting shock wave, which is expressed in the appearance of additional peripheral maxima on the electron number density and temperature profiles (figure 10a and figure 10b).

Figure 8. Transversal profiles of (a) the electron temperature and (b) electron number density in the transition zone corresponding to the spatial position of the Mach disk.

Figure 9. Transversal profiles of (a) the electron temperature and (b) electron number density in the stagnation zone.
4. Conclusions
For the first time, on the basis of optical emission spectroscopy, the structure of a supersonic plasma jet formed by a pulsed capillary discharge with an evaporating wall has been studied in detail, and systematic data on evolution of the radial distribution of the electron number density and temperature along the nonisobaric plasma flow have been obtained. It was found that the electron number density and temperature profiles reflect all the features of the shock-wave flow region. In particular, they track the influence of intercepting, central and reflected shock waves, which influences the plasma parameters distribution and cause the appearance of additional peripheral maxima on the electron number density and temperature profiles. The results obtained can serve as a basis for the development and testing of theoretical and computational models of plasma jets formed in pulsed capillary discharges.

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Figure 10. Example of the transversal profiles of (a) the electron temperature and (b) electron number density in the rarefaction zone of the second barrel.
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