Nonsteady-state processes in a low-current discharge in airflow and formation of a plasma jet

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Abstract
The paper describes the investigations of a low-current discharge in airflow with the electrode configuration of coaxial plasmatron. An inner diameter of the plasmatron nozzle is of 0.5 cm and the mass airflow rate is from 0.1 to 0.3 g s\(^{-1}\). Typical averaged discharge current is varied from 0.06 to 0.2 A. In these conditions, due to airflow the so-called plasma jet forms in the plasmatron nozzle and at its exit. The total current in plasmatron mainly flows via the constricted plasma column of the glow discharge and only a small fraction of current is carried by the jet. The principal idea of the experiments is to reveal the mechanism of the jet formation and to elucidate how the nonsteady discharge regimes influence on the jet properties. We have proposed the method for the jet diagnostics, which is based on measuring the currents to the additional diagnostic electrodes located outside the nozzle. The obtained data show that the jet current forms due to electrons that are emitted from the boundary of plasma column. The temporal behavior of the jet current is determined by the position of the column inside the plasmatron nozzle, which changes with time. Hence, the term 'plasma jet' has to be used with care, since the charged particles in the jet area are the electrons. The estimated electron density in the jet is of about 10\(^9\) cm\(^{-3}\).

1. Introduction

In recent years, considerable interest has been attracted to the investigations of the low-current atmospheric-pressure discharges in gas flow [1–5]. A variety of the discharge types and the electrode configurations are used in the experiments [2, 3, 6–16]. The present paper deals with the glow-type discharge in airflow in the electrode system of the classical coaxial plasmatron [3, 17–22].

In such a discharge, the main fraction of the total current closes from the inner potential electrode to the grounded plasmatron nozzle via a constricted plasma column [3, 17, 19]. However, a weakly luminous region inside and at the exit of the nozzle forms, and this region is also able to carry some minor current. In most publications, this luminous region is associated with a low-temperature plasma jet [2].

The jet contains the chemically active particles that provide a basis for different applications, such as the modification of the surfaces [23–27] and the treatment of the biological objects [2, 28–30] to which the jet is directed. There are also investigations on generation of the nitrogen oxides in the discharges in airflow [17, 31, 32]. The systems where the discharge burns in the mixtures of air with the hydrocarbons are used for plasma-assisted combustion and for plasma-catalytic conversion of the hydrocarbons [3, 18–21, 33–40].

Although the term 'plasma jet' is widely used, we cannot advocate that the plasma is available in the numerous types of the jets. Anyway, as applied to the electrode configuration of the low-current plasmatron, we proceed from the supposition that the current through the jet closes to the plasmatron nozzle due to the electrons that are emitted from the glow discharge plasma column. In this situation, the column plays a role of a specific plasma cathode [41, 42].

The present paper deals with the elucidation of the problem how the discharge regimes in the plasmatron influence on the jet formation. The discharge investigations are based on measuring the voltage and current...
waveforms in the plasmatron whose nozzle consists of two sections and the currents to each section are measured separately. The time-resolved photographs of the discharge taken by a charge-coupled device (CCD) camera add the results of the voltage and current measuring. In the paper, we propose the method for the jet diagnostics at the exit of the plasmatron nozzle. The essence of the method is that the jet is directed to the additional electrodes outside the nozzle. The data on the currents to the diagnostic electrodes offer a possibility to interpret the mechanism of the jet formation and estimate an electron density in the jet.

2. Experimental setup and method of measurements

One of the experimental arrangements, which is intended for the investigations of the discharge regimes in the plasmatron, is shown in figure 1. The low-current discharge is sustained in a vortex airflow with the mass flow rate \( G = (0.1–0.5) \text{ g/s} \). The inner electrode of the plasmatron is the cathode and the grounded nozzle that consists of the sections 1 and 2 serves as the anode. The nozzle diameter \( D = 5 \text{ mm} \) and the length of each section is of 5 mm. The distance between the sections can be varied from \( \delta = 0 \) (when the sections are connected with each other) to \( \delta = 4 \text{ mm} \).

The discharge is powered by a dc voltage \( V_0 = (3–5) \text{ kV} \) connected to the electrodes via the ballast resistor \( R_b = 13.6 \text{ k}\Omega \) and coaxial cable whose capacitance \( C = 300 \text{ pF} \). In the setup under description, the cathode diameter is of 9 mm and the minimal gap distance between the electrodes in the coaxial part of the electrode system amounts to 1.5 mm. In such conditions the voltage \( V_0 = 5 \text{ kV} \) is not sufficient to provide the very first breakdown and to initiate the discharge in plasmatron. To initiate the discharge we use the additional pulsed power supply with the amplitude voltage up to 15 kV and pulse duration of 4 \( \mu \text{s} \).

The voltage at the electrodes of plasmatron \( V(t) \), that is the discharge burning voltage, and the currents are recorded by the oscillograph TDS-1012B. The currents flowing to the sections 1 and 2 of the plasmatron nozzle are taken from the current shunts \( R_{S1} = R_{S2} = 1 \text{ }\Omega \).

Plasmatron with two sections allows us to investigate the nonsteady-state phenomena in the temporal development of the discharge. As shown schematically in figure 1, the very first breakdown occurs at the instant \( t_0 \) in the coaxial part of the electrodes, and the current signal appears from the section 1. Under the effect of gas flow, the plasma column shifts along the coaxial part of the electrode system and after certain time interval the column becomes attached to the end of the cathode to the inner surface of the plasmatron nozzle. When the column occupies the place, which is conventionally denoted as position A, the current signal continues to be recorded from the shunt \( R_{S1} \). If the anode current attachment (the anode spot) travels to the section 2 (position B in figure 1) we record the current signal from the shunt \( R_{S3} \). Thus, from the current and voltage waveforms we are able to obtain information on the current attachment at each instant of time.

This information is added by the photographs taken via the exit aperture of the plasmatron nozzle by means of CCD camera. The characteristic feature of this experimental arrangement is that we use the plasmatron with a rather short length of the nozzle (of about 10 mm). At the nozzle diameter \( D = 5 \text{ mm} \), we can obtain the high-quality frames of the discharge structure inside the nozzle.

As mentioned earlier, the burning of discharge in the plasmatron is accompanied by formation of the luminous jet inside the nozzle and at its exit. The jet carries only a minor fraction of the total discharge current. However, the jet properties are of a great importance from the viewpoint of the discharge application. For the jet diagnostics outside the plasmatron, we used another setup whose schematic is shown in figure 2.

The diagnostic electrode system includes in itself the electrodes 3 and 4. The main idea of the investigation of the jet outside the nozzle is based on the measurements of the currents \( i_3(t) \) and \( i_4(t) \) taken from the current shunts \( R_{S3} \) and \( R_{S4} \). Since the current level is about several tens of microamperes, we use the shunts with a rather high resistances \( (R_{S3} = 1 \text{ k}\Omega \text{ and } R_{S4} = 10 \text{ k}\Omega ) \). It seems reasonable to note that in our experiments the electrode 3 is intended for the jet diagnostics. On the other hand, this electrode can be considered as certain
grounded substrate as far as the situation is typical for the setups in which the jet is directed to the substrate with the purpose of the surface processing [1].

The jet current appears due to a potential difference between the plasma column and the grounded electrode system. As shown in figure 2, electrode 3 represents a fine-meshed net. The net is spliced from a wire 0.3 mm in diameter and has an optical transparency of about 70 percent. Then, when a potential \( V_4 \) is applied to electrode 4, some electron current \( i_4(t) \) is able to flow in the interelectrode gap between the electrodes 3 and 4. As can readily be seen from the electric circuit, the total current via the jet is \( i_{jet}(t) = i_3(t) + i_4(t) \). In the experiments, a distance between the end of plasmatron nozzle and electrode 3 is varied from \( \Delta_1 = 5 \) mm to \( \Delta_1 = 15 \) mm. The gap length between the electrodes 3 and 4 can be varied in a range \( \Delta_2 = (1–5) \) mm.

As will be shown in the next section, with the nozzle length of 10 mm the discharge regimes are possible when the plasma column comes out the nozzle. Then the discharge can be intercepted to electrode 3. To prevent the interception and to provide the jet diagnostics at the exit of plasmatron, in these experiments we use the nozzle with a length of 20 mm. The other modification in design is that the minimum distance in the coaxial part of the electrodes has been decreased to 1 mm. In this case the voltage \( V_0 = 5 \) kV is quite sufficient to initiate the discharge.

3. Results of measurements and interpretation

3.1. The main features of the nonsteady-state discharge behavior in plasmatron

The principal goal of the experiments is to give interpretation of the waveforms, which we obtain when providing the jet diagnostics at the plasmatron exit. It turned out that the shapes of the waveforms are closely related to the nonsteady behavior of the discharge in the plasmatron nozzle. Then in this subsection, we present a summary of the data on the features of the discharge in the plasmatron.

Typical example of the waveforms for the conditions of the very first breakdown in the plasmatron and several seconds later after the breakdown are shown in figure 3. The waveforms are obtained at the setup shown in figure 1. The discharge is initiated at the instant \( t_0 \) so that the spark channel with a metal vapour cathode spot arises [19, 43–46]. The discharge burning voltage in the spark regime is practically equal to zero value. As far as the ballast resistor limits the discharge current, after some time the spark cathode spot extinguishes and the discharge starts sustaining in the glow mode. This transformation occurs at the instant \( t_1 \). The discharge burning voltage sharply increases to 350 V. This voltage is redistributed between the cathode voltage drop of the glow discharge \( V_c \approx 300 \) V, and the voltage drop at the positive column.

At the instant \( t_2 \), the glow-to-spark transition occurs. The mechanism of transition is associated with the development of the so-called explosive emission instability in the cathode layer of glow discharge [3, 47]. The arising metal vapour cathode spot bridges the cathode fall of the glow discharge [44–46]. Then we see the sharp decrease in the discharge burning voltage up to approximately 50 V. The subsequent sharp increases and decreases in the discharge burning voltage at the temporal stage up the instant \( t_3 \) are just related to the extinctions of the spots and to the new glow-to-spark transitions.

The plasma column moves along the coaxial part of the electrodes. The column displacement here and the discharge properties resemble that for the gliding arc or gliding glow discharge [9, 42, 48–50]. After a time interval of 4.6 ms, the discharge burning voltage begins to increase smoothly. This means that the plasma column length increases with time when the column is displaced in the position \( A \).

When the point of the column attachment at the anode reaches the section 2 (instant \( t_3 \)) we see that the current starts flowing to this section and the current to the section 1 disappears. During the process of the
displacement of the anode spot, the column length increases which leads to increasing the discharge burning voltage. At the instant \( t_4 \) the so-called repeated breakdown takes place \([19, 43, 44]\). The repeated breakdowns can be completed or noncompleted. In the first case, the breakdown is accompanied by the formation of the spark cathode spot. For the noncompleted breakdown, the newly originated discharge burns in the regime of constricted glow column without the formation of spark spot. For the particular case under discussion, we deal with the noncompleted breakdown and with the initiation of the new discharge at the section2.

The repeated breakdowns arise occasionally, so that at the same waveform we can see both types of the breakdowns. For example, the completed breakdown is observed at the instant \( t_5 \). Note that the current waveforms in this particular case show that the new plasma channel has been initiated at the section1. The subsequent repeated breakdown occurs at the instant \( t_7 \). The current waveforms demonstrate that during the time interval between \( t_7 \) and \( t_6 \) the discharge current initially flows to the section1 and at the instant \( t_6 \) shifts to the section2.

Now let us discuss the reasons for the repeated breakdowns. At the stage when the current flows via the plasma column of the constricted glow discharge, there exists a large gradient in the gas temperature at the boundary of the column. Due to diffusion process, the neutral particles, including the metastable exited particles, leave the column and are picked up by the vortex gas flow. Hence, these particles are available in the jet region. The column boundary serves as a plasma cathode, which emits the electrons and the emission electron current flows to the inner surface of the plasmatron nozzle through the jet area. Then we can speak of a kind of nonself-sustained discharge than carries a small fraction of the total discharge current. If the voltage at the gap is high enough, the process of avalanche ionizations begins to play an important role so that the repeated breakdown occurs. The availability of the metastable molecules encourages the gas ionization and the transition to spark.

The spark channel, arising as a result of the repeated breakdown, can sprout via the jet directly from the cathode surface \([19, 51]\). In this case, the new plasma column appears in parallel with the preceding column. Aside that the other scenario is possible, when the preceding plasma column serves as a peculiar cathode for the repeated breakdown \([42]\). The potential in the middle of the column for the glow discharge, whose cathode voltage drop is \( V_c \), can be estimated as

\[
V_p = \frac{V(t) - V_c}{2}.
\]  

As applied to the instant just before \( t_7 \), the discharge column is attached to the section2. The voltage between the cathode and the grounded nozzle achieves to \( V(t) = 1.4 \text{ kV} \) so that with \( V_c = 300 \text{ V} \) we obtain \( V_p = 550 \text{ V} \). Such a voltage seems to be sufficient to provide the breakdown from plasma column to the same section.

In the course of discharge operation, the gas in the jet is heated, which leads to changing in the external view of the waveforms. The waveforms after several seconds of the discharge operation (figure 3(b)) show that the nonsteady-state phenomena associated with the repeated breakdown occur mainly at the section2. The completed and noncompleted breakdown are also possible. For example, at the instants \( t_6 \) and \( t_9 \) we deal with the completed breakdowns. Nevertheless, in the particular conditions under discussion, the gas is still heated.
nonessentially. This is evidenced by the fact that an average time between the successive repeated breakdowns for figures 3(a) and (b) does not practically change and remains at a level of 0.8 ms.

The waveforms and the discharge photograph obtained after several minutes of the discharge operation are shown in figure 4. For the sake of convenience in interpretation, the figure also demonstrates the position of CCD camera (figure 4(a)) and the photograph of the plasmatron nozzle in the absence of discharge (figure 4(c)).

When the gas in the jet is heated to certain temperature $T_{\text{jet}}$, the directional gas velocity is increased as compared to the conditions at the plasmatron entrance where the temperature $T_0 = 300$ K. Since the mass airflow rate $G$ has to be constant, the gas velocity in the jet area obeys to the evident relation

$$v_{\text{jet}} = \frac{G}{\rho(T_{\text{jet}})S} = \frac{G}{\rho_0 S} \cdot \frac{T_{\text{jet}}}{T_0},$$

where $\rho_0$ is the gas density at the plasmatron entrance, $\rho(T_{\text{jet}})$ is the gas density in the jet region, and $S$ is the cross section of the nozzle aperture.

The gas is heated due to a power $Q = V_{\text{av}}I$ dissipated in the discharge and the maximum possible gas temperature in the jet can be readily estimated as

\[ T_{\text{jet}} \]
were \( V_a \) is the discharge burning voltage averaged over time, \( I \) is the averaged discharge current and \( c_p \) is the air specific heat.

The waveforms show that in the heated gas, the average time between the repeated breakdowns decreases. Typically, the repeated breakdowns are noncompleted and take place at the section 2. Based on the waveforms in figure 4(b) we can estimate that \( Q = 120 \) W and \( T_{jet} = 1500 \) K. Then the maximum possible directionnal gas velocity \( v_{jet} = 20 \text{ m s}^{-1} \). If the anode spot displaced with this velocity, the distance of the spot displacement over the nozzle surface in the time interval between \( t_1 \) and \( t_2 \) (\( \Delta t = 440 \mu s \)) would be \( \Delta x = 0.88 \) cm. From the experiment, we see that the anode spot passes a distance \( \Delta x \approx 0.5 \) cm, which is equal to the length of the section 2.

The reasons of such an inconsistence are rather evident. First, the gas flow velocity in the boundary layer near the inner surface of the nozzle has to be definitely lower than in the central part of the flow. Besides, the velocity obtained from equation (2) is overestimated as far as the estimate does not take into account the heat losses.

Figure 4(d) also shows the CCD frame, which covers the stage of the column displacement between the repeated breakdowns. The position of the camera allows us to take the photographs of the plasma column and of the anode surface. However, the bright cathode spot is not visible at the frame. At the beginning of the exposition (at the instant \( t_1 \)) we see the residual column from the preceding breakdown. At each time, the plasma column is attached to a bright place at the anode surface, which can be referred to as an anode spot [42]. It is seen that the anode spot moves over the section 2. As district to the cathode current attachment in the gliding glow discharge that moves over surface smoothly [9, 42], the anode spot displaces in a jump (stick-slip) manner. This means that the anode spot disappears in a previous place of attachment and originates in a new place down the gas flow.

As far as we use the vortex gas flow, the trace of the anode spots is not parallel to the discharge axis, but located over a spiral line. The rather uniform luminous region between the columns at the instants \( t_1 \) and the end of exposition is formed as a result of the motion of the plasma column during the exposition time.

The experiments show that in the cycle between the repeated breakdowns at the instants \( t_1 \) and \( t_2 \) the anode spot travels from the beginning of the section 2 to the end of this section. Hence, we have an information on the length of plasma column during its displacement. However, even if the direct observation of the discharge with temporal resolution is not provided, we are able to estimate the length of plasma column based on the results of paper [9]. In this paper, the careful study of the constricted plasma column in the gliding glow discharge has been carried out. In particular, it is shown that the electric field in the column depends on the discharge current and the related data are presented.

Let us consider, for example, the instant of time just before \( t_1 \) when the column length is maximal. The discharge burning voltage here \( V_d \approx 1500 \) V, the current \( i = 0.08 \) A and the voltage at the positive column \( V_{pc} = 1200 \) V. For such a current the electric field in the column \( E_{pc} = 910 \) V cm\(^{-1} \) [9], and we obtain that the column length \( l_{pc} = 1.3 \) cm that is the column is attached to the end of the section 2. At the instant just after \( t_1 \) (that is just after the repeated breakdown) we have \( V_d \approx 750 \) V, \( i = 0.14 \) A and \( V_{pc} = 450 \) V. For the current \( i = 0.14 \) A, the electric field in the column \( E_{pc} = 700 \) V cm\(^{-1} \) so that the column length \( l_{pc} = 0.64 \) cm. Hence, after the repeated breakdown at the instant \( t_1 \), the discharge is attached to the beginning of the section 2.

In the above-discussed case, we have demonstrated the discharge mode, in which the anode spot displaces over the inner surface of the nozzle. However, in the same conditions, the other scenario is possible when the anode spot attaches to the end of the nozzle so that the plasma column comes out the nozzle under the action of the gas flow and acquires a bent form. This situation is shown in figure 5.

The length of the column also increases in these conditions due to airflow. Typically, at a moment of repeated breakdowns the discharge burning voltage reaches of about 1900 V or larger. The characteristic feature of this mode is that in the time interval between the successive breakdowns the anode spot is located at the same place of the nozzle end as shown in figure 5 where the exposition time \( \Delta t_1 = 100 \mu s \). An increase in the column length with time is provided due to bending of the column in the gas flow.

The averaged power dissipated is the discharge estimated is \( Q = 120 \) W and the maximum possible directionnal gas velocity at the plasmatron exit can be estimated from the equation (3) as \( v_{jet} = 22 \text{ m s}^{-1} \). With this value of velocity, during the time \( \Delta t_1 = 100 \mu s \) the plasma column outside the nozzle could pass a distance \( \Delta x = 0.22 \) cm. The photograph shows the trace, which appears due to the column displacement, with a width of \( \Delta x = 0.2 \) cm. Then we can speak of a good agreement between experiment and estimation of jet velocity in the central part of the nozzle.

The exposition time \( \Delta t_2 = 100 \mu s \) relates to the interval inside of which the repeated breakdown occurs. At the photograph, we see the trace that remains due to movement of the preceding column and the new plasma channel corresponding to new repeated breakdown. It is notable that in this mode of operation the column of
repeated breakdown sprouts to the edge of the plasmatron nozzle. The further increase in the column length is provided because of its bending in the airflow.

3.2. The diagnostics of the jet at the plasmatron exit

In the experiments on the jet diagnostics, we intentionally used the plasmatron with the nozzle length increased to 20 mm. Then the conditions when the plasma column comes out the nozzle is prevented. The plasma column remains inside the plasmatron and is not able to be intercepted to the diagnostic system. Note that just such regimes are typical for the experiments where the metal substrates are processed by the jet.

The waveforms of voltage $V(t)$ and currents to the sections 1 and 2 several minutes later of the discharge initiation jointly with the frame of CCD camera in the scenario when the anode spot is attached to the end of the nozzle. $V_0 = 2850$ V, $R_b = 13.6$ kΩ, airflow rate $G = 0.1$ g s$^{-1}$, distance between the sections $\delta = 0.3$ mm, plasmatron nozzle diameter $D = 5$ mm. Zero lines at the waveforms are shown by the horizontal arrows at the left.

Figure 5. The waveforms of voltage $V(t)$ and currents to the sections 1 and 2 several minutes later of the discharge initiation jointly with the frame of CCD camera in the scenario when the anode spot is attached to the end of the nozzle. $V_0 = 2850$ V, $R_b = 13.6$ kΩ, airflow rate $G = 0.1$ g s$^{-1}$, distance between the sections $\delta = 0.3$ mm, plasmatron nozzle diameter $D = 5$ mm. Zero lines at the waveforms are shown by the horizontal arrows at the left.

The results of the preceding subsection show that we can estimate the length of the plasma column at each instant of time from the waveforms $V(t)$ and $i(t)$ and current to the diagnostic electrode $i_3(t)$ are shown in figure 6. Electrode 3 in this experiment was solid and the total jet current was equal to $i_3(t)$.

The results of the preceding subsection show that we can estimate the length of the plasma column at each instant of time from the waveforms $V(t)$ and $i(t)$. As applied to figure 6, the averaged power dissipated in the discharge $Q = 165$ W, and the maximum possible gas temperature at the discharge axis $T_{\text{jet}} = 1950$ K. It is evident that just before the instant $t_1$ the column length seems to be maximum. The discharge burning voltage $V_d = 1600$ V, the current $i = 0.12$ A and the voltage at the positive column $V_{\text{pc}} = 1300$ V. Taking into account
that the electric field in the column in the conditions under discussion \( E_{pc} = 750 \text{ V cm}^{-1} \) [9], we estimate the column length \( l_{pc} = 1.7 \text{ cm} \). In the experiments with the plasmatron nozzle 2 cm in length, we see that the minimum distance, to which the plasma column approaches to the plasmatron exit, is about 0.5 cm. Thus, the estimate demonstrates a good agreement with experiment.

As a result of the repeated breakdown at the instant \( t_1 \), the anode current attachment turns out to be inside the plasmatron nozzle at a distance from the cathode of about 0.6 cm. After that, the cycle of the displacement of the anode spot over the nozzle surface up to the instant of the next repeated breakdown \( t_4 \) takes place.

Proceeding from the above-said we can give an interpretation of the waveform \( i_3(t) \) and propose a method of estimation of an electron density in the jet. When the plasma column length is maximum the electron current \( i_3(t) \) has a maximum value. This current flows due a potential difference between the plasma column, which plays a role of emitting boundary, and the grounded diagnostic electrode 3. The distance between the plasma column located in the position \( B \) and electrode 3 can be taken as \( d \approx 1.5 \text{ cm} \). According to equation (1), the plasma potential can be taken as \( V_p \approx 650 \text{ V} \), so that the average electric field in the gap \( d \) is \( E = 430 \text{ V cm}^{-1} \).

Knowing the electric field, and current density via the jet \( j_{jet} = i_{jet}/S \) we can roughly estimate an electron density \( n \) in the jet by means of the expression

\[
 n = \frac{j_{jet}}{e \mu E}, \tag{4}
\]

where \( \mu \) is the electron mobility.

The mobility of electron in air at the normal conditions \( \mu_0 = 400 \text{ cm}^2 \text{ V}^{-1} \text{ c} \). The airflow in the jet is heated and the neutral particle density is decreased as compared to the normal conditions. Then for the electron mobility is reasonable to use the following expression: [3, 44]

\[
 \mu = \frac{T_{jet}}{T_0} \mu_0, \tag{5}
\]

Taking into account that the jet current just before the instant \( t_1 \) is \( i_{jet} = 50 \mu \text{A} \), the current density \( j_{jet} \approx 2 \cdot 10^4 \text{ A cm}^{-2} \), and the electron mobility \( \mu = 2.6 \cdot 10^5 \text{ cm}^2 \text{ V}^{-1} \text{ c} \), we obtain the electron density in the jet \( n \approx 10^9 \text{ cm}^{-3} \).

The presented estimate of the electron density proceeds from the supposition that the electric field distribution over the jet is uniform so that we use the average electric field \( E = V_p/d \) in the calculation. However, the regimes of the current passage are possible when the electric field in the jet area is distorted due to an excess space charge of the electrons. In these regimes, the electric field in a vicinity of the diagnostic electrode 3 turns out to be higher than the electric field at the plasmatron exit. Then it should be additionally noted that we do not take this effect into account and deal with an averaged electron density in the jet.

At the instant \( t_1 \) the repeated breakdown occurs and new plasma channel arises in the position \( A \). The capacitance of connecting cable is discharged via this channel and the discharge burning voltage becomes
plasmatron nozzle is reduced to positive column of the constricted glow discharge with the burning voltage of sharply and we see this fast decreasing at the waveform. It is evident, that for the instant of breakdown the current to diagnostic electrode 3 has to drop practically zeroes. It is evident, that for the instant of breakdown the current to diagnostic electrode 3 has to drop sharply and we see this fast decreasing at the waveform.

However, during a short time the plasma channel of the repeated breakdown acquires the properties of the positive column of the constricted glow discharge with the burning voltage of \( V_d = 700 \text{ V} \) and with the current \( i = 0.17 \text{ A} \). This column carries the main fraction of the current in plasmatron, and we would suppose that the column \( A \) completely shunts the column \( B \). In such a supposition, the emitting plasma boundary turns out to be inside the plasmatron nozzle and the current to electrode 3 should be extremely low.

Nevertheless, we see a noticeable current to electrode 3 in the time interval between \( t_1 \) and \( t_2 \). The reason seems to be as follows. After the breakdown at the instant \( t_1 \), the column \( B \) does not disappear instantly and the discharge burning voltage is also applied to this column. We can speak of a residual plasma column remaining from the preceding breakdown. This column moves in the gas flow together with the new column \( A \), and continues to play a role in the emitting of electrons that flow to electrode 3. Then the waveform \( i_3(t) \) shows the current which is provided by the residual plasma column \( B \). This temporal stage is sustained approximately up to the instant \( t_2 \).

After \( t_2 \) the preceding column decays completely and we see that the current \( i_3(t) \) becomes rather low. At the same time, the anode spot of the column \( A \) displaces over the nozzle surface and the new plasma column approaches to the nozzle exit. The distance between the emitting boundary and electrode 3 is reduced with time and after the instant \( t_3 \) we see that the current \( i_3(t) \) increases again.

Figure 7 shows the waveforms for the conditions in which the distance between the electrode 3 and plasmatron nozzle is reduced to \( \Delta x = 6 \text{ mm} \). The current to electrode 3 becomes essentially high as compared to figure 6. This is quite understandable since the gap between the end of the plasmatron nozzle and the diagnostic electrode 3 is decreased.

Another feature of the waveform \( i_3(t) \) is that the different temporal stages between the repeated breakdowns are illustrated more distinctively. The current before the repeated breakdown \( t_1 \) is of \( 0.18 \text{ A} \), and the calculated length of the plasma column \( l_{pc} = 1.6 \text{ cm} \). Just after \( t_1 \), the current to electrode 3 shows the sharp current drop associated with the formation of the plasma channel in the position \( A \). After that, the stage when the current \( i_3(t) \) is sustained due to existence of the residual plasma column \( B \) is observed.

The duration of the stage when the current \( i_3(t) \) flows from the residual column is \((t_2-t_1) = 400 \mu\text{s}\). With the gas velocity in the boundary layer near the nozzle surface of about \( 10 \text{ m/s} \), we obtain a distance \( \Delta x \approx 0.4 \text{ cm} \), which the anode current attachment passes during the discussed stage. Thus, the emitting plasma of the residual column approaches to the plasmatron exit, and this location ensures a large value of the current \( i_3(t) \). This value can be even higher than the current just before the repeated breakdown. Such a case is characteristic of the repeated breakdown \( t_5 \).

Figure 7. The waveforms of voltage \( V(t) \) and current \( i(t) \) jointly with the waveform of the current \( i_3(t) \) to electrode 3. \( V_0 = 5000 \text{ V}, R_0 = 20 \text{ k}\Omega, \text{ airflow rate} G = 0.1 \text{ g s}^{-1}, \text{ distance of the diagnostic system from the end of the nozzle} \Delta x = 6 \text{ mm} \). Zero lines at the waveforms are shown by the horizontal arrows at the left.
For the data in figure 8, the averaged discharge current decreases to $I = 0.06$ A, the averaged discharge burning voltage increases to $V_{av} = 1650$ V, so that $Q = 100$ W and the maximum gas temperature $T_{jet} = 630$ K. Due to a high mass airflow rate, the gas velocity is mainly determined by the value $G = 0.3$ g s$^{-1}$ and amounts at least $v_{jet} = 12$ ms.

At the waveform $i_4(t)$ we also observe that each repeated breakdown is accompanied by the sharp drop in current. However, in these conditions, the current provided by the residual plasma column $B$, is larger than the current just before the repeated breakdown. Then we conclude that with a high gas velocity the residual plasma column approaches to the position in immediate vicinity of the nozzle exit.

In the case when the voltage $V_4$ is applied to electrode 4, the current $i_4(t)$ is available. The shapes of $i_4(t)$ and $i_3(t)$ are practically similar each other. This is easy to understand, as far as the current $i_3(t)$ represents a fraction of the jet current and appears due to the electrons that are extracted via the meshed electrode 3.

In the further consideration, it seems reasonable to introduce the notion of the current–voltage characteristics $I_3(V_3)$ and $I_4(V_4)$. The currents are calculated from the corresponding waveforms by means of averaging the signals $i_3(t)$ and $i_4(t)$ over time. Then we take the waveforms for a certain value of $V_4$, make averaging and obtain the values $I_3$ and $I_4$ for the given $V_4$. It should be noted that changing the voltage $V_4$, does not influence on the discharge in the plasmatron.

The current–voltage characteristics constructed on the basis of the waveforms similar to presented in figure 8 are shown in figure 9.

As noted above, the jet current $I_{jet}$ flows as the electron emission current from the plasma column. In the presence of voltage $V_{av}$, the current $I_{jet}$ is divided between the electrodes 3 and 4. The current to electrode 3 is recorded from the shunt $R_{S3}$ and the current to electrode 4 is recorded from the shunt $R_{S4}$. In such a representation, we imply that the current $I_4$ flows under the potential difference $(V_p + V_4)$.

As shown in figure 9, increasing the voltage $V_4$ leads to decreasing the fraction of the jet current flowing to electrode 3. However the total jet current has to obey the condition $I_{jet} = I_3 + I_4$. In this consideration, the minimum current taken from the shunt $R_{S3}$ is determined by a geometric transparency of the meshed electrode 3 and cannot be lower than $0.3I_{jet}$. The current to electrode 4 cannot be higher than $0.7I_{jet}$. Just such a regime is realized up to a voltage $V_4$ of about 1400 V.

When the voltage $V_4$ reaches of 1500 V and higher, the current $I = I_3 + I_4$ begins to increase. We suppose that this increase is associated with the process of ionization multiplication in the gap between the electrodes 3 and 4. Because of ionization, the additional electrons appear in the gap. The ions, which are originated in the course of ionization, partly flow through the meshed electrode 3 to the plasma cathode thus providing the neutralization of the electron space charge between the plasma cathode and electrode 3. As a result of neutralization, the electron jet current increases, which is reflected in the current–voltage characteristic $I_4(V_4)$.

Aside that, some fraction of the ions comes to electrode 3 and generates a current in the electrode system between electrode 4 and grounded electrode 3. This current is subtracted from the current flowing via the shunt $R_{S3}$ so that we can have even the situation when the current recording from the shunt $R_{S3}$ becomes zeroes.
It is of interest to estimate the reduced electric field $E_4/n_a$ in the gap between the electrodes 3 and 4 starting from which the impact ionization reveals itself. The neutral particle density in the gap is reduced as compared to the normal conditions. For the temperature $T_{jet} = 630$ K, the neutral particle density becomes $n_a = 1.35 \times 10^{19}$ cm$^{-3}$ so that with $V_4 = 1500$ V and $E_4 = 3750$ V/cm, we obtain $E_4/n_a = 2.8 \times 10^{16}$ V·cm$^2$. This value is definitely low in order that the classical avalanche ionization comes into play [9, 52, 53]. Then we should suppose that the jet contains rather high densities of the exited metastable molecules [43] and the ionization is provided by the processes with their participation.

4. Conclusion

The paper describes the results of investigations of a low-current discharge in airflow with the electrode configuration of coaxial plasmatron. An inner diameter of the plasmatron nozzle is of 0.5 cm and the mass airflow rate varies from 0.1 to 0.3 g s$^{-1}$. Typical averaged discharge current is from 0.06 to 0.2 A and the averaged power dissipated in the discharge is at a level up to 200 W or less.

In these conditions, due to airflow the so-called plasma jet forms in the plasmatron nozzle and at its exit. The total current mainly flows via the constricted plasma column of the glow discharge and only a small current is carried by the jet. One of the features of the discharge in airflow is that the current is sustained in the nonsteady-state regime. The length of the plasma column increases with time and the discharge burning voltage increases respectively. At a certain voltage, the repeated breakdown over a short distance occurs and the new plasma column appears. The channel of the repeated breakdown sprouts to the plasmatron nozzle from the preceding plasma column via the jet area.

The principal idea of the experiments is to reveal the mechanism of the jet formation and to elucidate how the nonsteady discharge regimes influence on the jet properties. We have proposed the method for the jet diagnostics, which is based on measuring the discharge currents to the additional diagnostic electrodes located outside the nozzle. The obtained data show that the jet current forms due to electrons that are emitted from the boundary of the glow discharge plasma column. Then the temporal behavior of the jet current is determined by the position of the column inside the plasmatron nozzle, which changes with time. The estimated electron density in the jet amounts of about $10^{9}$ cm$^{-3}$.

As applied to this paper, the additional grounded electrode at the plasmatron exit is intended for the jet diagnostics. On the other hand, the situation is typical for the setups in which the jet is directed to the grounded substrate with the purpose of the surface processing. Then in the similar experiments, we have to take into account that the electron current inevitably flows to the surface, which is subjected to processing.

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