Influence of air flow speed on main characteristics of nonstationary pulsed discharge, created with help of stationary power source

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Abstract. The work is devoted to the investigation of a non-stationary pulsating transverse-longitudinal discharge created with the help of a stationary power source. The influence of the velocity of subsonic and supersonic airflows on main characteristics of the discharge is studied.

1. Introduction
Nowadays, low-temperature gas-discharge plasma in a flow is widely used in scientific research and various technological applications [1, 2]. To initiate and stabilize combustion of air–hydrocarbon fuels in a supersonic flow, we applied various types of discharge, namely, dc pulsed transverse discharges [3-6], freely localized microwave discharged produced by a focused electromagnetic radiation [7-9], and surface microwave discharges excited on a dielectric antenna [10, 11]. To optimize the burning of gaseous and liquid fuels under supersonic airflows it is necessary to know the parameters of the plasma used for the ignition and stabilization of the combustion of hydrocarbon fuels. The parameters of self-sustaining microwave discharges have been well studied. This work is devoted to research of the parameters of the discharge pulsating in a supersonic flow, which is essentially a nonstationary discharge generated using a DC voltage source.

2. Experimental setup
The experimental setup includes a vacuum chamber, a high-pressure air receiver, a system for generating a supersonic flow, a rectangular wind tunnel with an attached air duct, the high-voltage power supply to create the gas-discharge plasma, the synchronization system, and diagnostic equipment. The main part of the experimental setup is the 3-m-long evacuated metal cylindrical chamber with an inner diameter of 1 m. The wind tunnel was placed inside the pressure chamber. The longitudinal length of the channel was 50 cm. The supersonic flow in the wind tunnel was created by filling the pressure chamber with air through a specially shaped Laval nozzle. To prevent thermal choking a wind tunnel with a variable section was used; the ratio of the output section $S_2 = 38.1 \text{ cm}^2$ to the input section $S_1 = 3 \text{ cm}^2$ equals $S_2/S_1 = 12.7$.

A pulsed discharge was excited between two well streamlined electrodes, the cross section of which was an elongated rhomb with rounded vertices (the maximum thickness and width of the electrodes did not exceed 1 mm and 5 mm, respectively). The design of the electrode unit was described in [4, 5]. The minimum distance between the electrodes was varied from 0.1 to 3 mm. The electrodes were mounted inside the diverging wind tunnel. A special configuration of the electrodes made possible to easily excite
a pulsed discharge without its additional initiation in a wide range of chamber pressures of $p = 10–760$ Torr. The main experiments were carried out in an open working chamber at atmospheric pressure. The discharge was produced using a power source with an output voltage of up to 5 kV and a discharge current of up to 20 A, the pulse duration being of up to 2 s. The air flow rate was varied from 50 to 140 g/s, flow speed varied from 150 to 550 m/s. The experiments were performed using a diagnostic complex consisting of digital spectrographs, a high-speed video camera, pressure gauges, digital photo cameras, oscilloscopes, and computers.

3. Experimental results
It was shown that non-stationary pulsating discharge produced by a stationary power source is a thin pulsating channel drawn in the form of a plasma loop down the direction of the high-speed airflow propagation. In the experiments, two discharge maintenance regimes were implemented. In the first case, the plasma loop reaches its maximum possible length without intermediate repeated breakdowns. In the second case, several additional repeated breakdowns are realized. In both modes, the process of drawing a discharge loop along the flow is repeated periodically.

Application of a dc voltage to the electrodes leads to air breakdown along the shortest path between them. The formed plasma channel begins to glide over the electrodes downstream the air flow. While moving in the interelectrode gap, the plasma channel undergoes deformation. The velocities at which the anode and cathode spots move along the electrodes are lower than the flow velocity in the central part of the channel. First, the anode spot reaches the tip of the first electrode and is fixed on it, and, then, the cathode spot is fixed at the tip of the second electrode. At the same time, the plasma channel continues to stretch out downstream the flow. Since the channel length grows, the voltage drop across the channel increases until it reaches the threshold for the second breakdown, which occurs along the shortest path between the electrodes and shunts the plasma channel. Then, the discharge glow begins to decrease and the discharge plasma gradually decays. By that time, a new plasma channel has already formed and the process repeats.

Figure 1 illustrated the dynamics of the development of a pulsating discharge created in a subsonic airflow $v = 275$ m/s. The video frame rate is 32 kHz, the exposure time of one frame is 2 μs. The air flow is directed from the top to down, the time increases from left to right. It is seen that under these conditions, the regime of discharge maintenance is implemented without intermediate breakdowns during the development of one loop.

![Figure 1 Dynamics of the development of a pulsating discharge created in a subsonic airflow](image)

Discharge pulsations in a supersonic flow manifest themselves as oscillations of the gap voltage, discharge current, and plasma glow. Oscillations of the voltage and plasma glow are especially strong. The results of experimental studies carried out at various airflow velocities have shown that the magnitude of the current pulsation depends strongly on the flow velocity. Moreover, for fixed values of the output voltage of the power source, internal and ballast resistances, the maximum value of the discharge current $i_{\text{max}}$ remains constant both for subsonic and supersonic air flow velocities. Then, the minimum value of ripple current $i_{\text{min}}$ is highly dependent on the flow speed. The strongest pulsations, reaching 50% of the maximum value of the $i_{\text{max}}$ current, appear at low subsonic airflow velocities in
the aerodynamic channel, whereas in supersonic airflows, the current ripples are smoothed, their magnitude decreases monotonically and $\Delta i = 5\%$ at $v = 550$ m/s. Figure 2 shows a fragment of the time dependences of the current and the voltage across the discharge gap. We see that the modulation of the voltage reaches 100%, while the modulation of the discharge current is about 45%, because, at any time, there is plasma bridging the electrodes. The length of the plasma bridge varies in time, but the bridge is destroyed only after the repeated breakdown and formation of a new plasma bridge. In the voltage waveform (figure 2, curve 2), the moments of repeated breakdowns are clearly seen.

![Figure 2](image.png)

**Figure 2** Fragment of the time dependences of the discharge current (1) and gap voltage (2) for a discharge with a duration of $\tau = 2$ s in a subsonic air stream. Flow velocity is 275 m/s

The repeated breakdown can also occur between the anode and cathode parts of the plasma channel or between the electrodes. In any case, the repeated breakdown leads to the shunting of the remaining part of the channel. Depending on the experimental conditions, one to five repeated breakdowns can occur during one cycle of the formation and development of the plasma loop. The process of stretching of the discharge loop downstream the air flow repeats periodically, i.e., the given form of a dc discharge produced in an air flow is, in fact, an unsteady pulsating discharge. In figure 3 shows the dynamics of the development of a pulsating discharge plasma loop created in a subsonic airflow by means of a stationary power source when the discharge is realized with two additional intermediate repeated breakdowns. Air speed is 200 m/s, maximum discharge current is 9.8 A.

![Figure 3](image.png)

**Figure 3** Dynamics of the development of a pulsating plasma loop created in a subsonic airflow when the discharge is realized with two additional intermediate repeated breakdowns

It was obtained that for any fixed values of the velocities of subsonic and supersonic air flows, the pulsation frequency is almost independent of the discharge current, varying within 100 Hz with a change in the discharge current from 2 to 16 A. In contrast, in the experiment observed a strong discharge pulsation frequency dependence on the air speed. The dependence of the pulsation frequency of the plasma loop on the airflow velocity at a discharge current of 15.5 A is shown in figure 4. It can be seen
that an increase in the flow velocity from 100 m/s to 520 m/s results in a significant 40-time increase in the pulsation frequency from 50 Hz to 2 kHz.

![Figure 4](image-url)

**Figure 4** Pulsation frequency of the plasma loop as a function of the flow rate at \( I_{\text{max}} = 15.5 \text{ A} \)

In figure 5 shows the dependence of the maximum achievable voltage \( U_{\text{max}} \) on the discharge gap on the airflow velocity. In the case of subsonic streams, as the velocity of the air flow increases, the discharge voltage remains approximately constant for any fixed value of the current, and the voltage in the discharge decreases with increasing discharge current. In going to a supersonic flow, \( U_{\text{max}} \) sharply decreases with increasing velocity, and the explicit dependence on \( U(i) \) disappears.

![Figure 5](image-url)

**Figure 5** Dependence of the maximum attainable value of the voltage across the discharge gap on the airflow rate for different values of the pulsed discharge current \( I_{\text{max}} \): 1 – 5.2, 2 – 9.8, 3 – 15.5 A

The dependence of the maximum distance on which the front boundary of the plasma loop extends down the air flow, on its velocity for different values of the discharge current, is shown in figure 6. It can be seen that as the flow rate increases, the maximum achievable length of the plasma loop decreases linearly, and at any speeds the distance to which the loop extends increases with increasing of discharge current. The total length of the plasma channel is equal to the sum of the lengths of the cathode and anode parts of the loop.
Figure 6 The distance covered by the front boundary of the plasma loop down the airflow, depending on its speed for different maximum values of the pulsed discharge current $i_{\text{max}}$: 1– 5.5, 2– 15.5 A.

The dependence of the electric field intensity averaged over time and the length of the channel in pulsating discharge plasma on the airflow velocity for different values of the discharge current is shown in figure 7.

Figure 7 Electric field in pulsating discharge vs the airflow velocity. The maximum value of the discharge current $i_{\text{max}}$: 1– 5.5, 2– 9, 3– 15.5 A

It can be seen that the electric field increases with increasing flow velocity because the necessary condition for the plasma loop of a transverse-longitudinal discharge in a high-speed flow to remain closed onto the cathode is the increase in the drift velocity of positive ions, which is possible only if the electric field increases [12]. For small current the field grows faster than for large $i$. Thus, with an increase in the flow velocity from 200 to 500 m/s, the field doubles from 40 to 85 V/cm at $i_{\text{max}} = 15.5$ A, whereas for $i_{\text{max}} = 5.5$ A the electric field grows three times from 90 to 260 V/cm. For a fixed flow velocity, an increase in the discharge current leads to a decrease in the electric field in the discharge channel. The similar dependence $E(i)$ was obtained in [13].

4. Conclusions
It is shown that a pulsating discharge produced by a dc power source in a high-speed air flow operates in the form of a thin pulsating channel in the shape of a plasma loop stretched downstream the flow. Discharge exists in two regimes: without and with intermediate breakdows during the development of one loop. The pulsation frequency of the plasma loop monotonically increases from 50 Hz to 2 kHz.
when flow velocity changes from 30 m/s to 520 m/s. The electric field strongly depends on the flow velocity and the magnitude of the discharge current, varying in the range of 30-260 V/cm.

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