Air ionization degree of the plasma in a nonstationary pulsed discharge in subsonic and supersonic flows

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Abstract. The degree of gas ionization in a nonstationary pulsating discharge created using a stationary power source in subsonic and supersonic air streams is determined. It was experimentally obtained that when the flow velocity is changed from 150 m/s to 520 m/s, the plasma electron density near the electrodes (z = 1 cm) varies from $10^{15}$ cm$^{-3}$ to $3.7\times10^{16}$ cm$^{-3}$ at an unchanged discharge current of 15.5 A, and the gas temperature rises from 400 K to 1250 K. It is shown that in pulsating discharge plasma the degree of gas ionization is of the order of $10^{-4}$ at low subsonic airflow, and with an increase in the flow velocity it increases sharply and reaches a value of $10^{-2}$ at velocity of 500 m/s.

1. Introduction
The non-equilibrium low-temperature plasma of a pulsating discharge is optimal from the point of view of its application in different areas of supersonic plasma aerodynamics. Fundamental works in the field of plasma aerodynamics are studies of the properties of transverse electric dc discharges in supersonic air flows carried out by A.I. Alferov [1-2]. At present, intensive researches relating to the development of new ways to improve the efficiency of gaseous and liquid fuels combustion in a high-speed air flow are underway. In various laboratories it is proposed to use plasma technology for the purpose of reducing the fuel induction period, increasing the completeness and stabilizing supersonic combustion. That allows optimizing the combustion of air-hydrocarbon fuels in high-speed air flows without using mechanical stagnant zones. Different gas discharges are used to create the plasma in high-speed flow, among them: high-voltage nanosecond discharges [3-6], transverse and longitudinal electrode discharges [7-15], high-frequency discharges created either in the chamber volume or on the dielectric surface, spark, arc, glow, corona discharges, barrier, sliding arc [16] and laser discharges, as well as freely localized microwave discharges [17-22], microwave discharges created by a surface wave on a dielectric body [23-28].

The paper presents the results of studies of the main plasma parameters of a non-stationary pulsating transverse-longitudinal discharge created in subsonic and supersonic air flows using a stationary power source.

2. Experimental installation and diagnostic methods
The test setup includes a vacuum chamber, a high-pressure air receiver, a system for generating a supersonic flow, a rectangular wind tunnel with a variable section, high-voltage power supply, synchronization system, and diagnostic equipment. The wind tunnel was placed inside the 3-m-long
evacuated metal cylindrical chamber with an inner diameter of 1 m. The ratio of the output section $S_2 = 38.1$ cm$^2$ to the input section $S_1 = 3$ cm$^2$ of wind tunnel equals $S_2/S_1 = 12.7$. The longitudinal length of the wind tunnel was 50 cm. 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 changed from 150 to 550 m/s. A pulsed discharge was excited between two well streamlined electrodes. The design of the electrode unit was described in [10, 11]. The minimum distance between the electrodes was varied from 0.1 to 3 mm.

The experiments were performed using the diagnostic complex consisting of digital spectrographs, high-speed video camera, pressure gauges, digital photo cameras, oscilloscopes, and computers. Parameters of high-speed flow (velocity, second mass flow consumption, temperature and density) were experimentally determined from the measured values of static $p_1$ and total $p_0$ pressures, respectively, in the wind tunnel and receiver containing compressed air. The main parameters of the pulsating discharge were determined using an automated system for collecting and processing information. This system allowed real-time recording of signals from electrical probes, pulse pressure sensors, thermocouple sensors; photodiode multiplier; digital spectrograph; low resistance, the voltage drop in which is proportional to the magnitude of the discharge current; high-voltage divider, which makes it possible to measure the voltage across the discharge gap. The emission spectrum of the gas-discharge plasma was recorded with the Avantes double-channel spectrograph AvaSpec-2048-2-DT, with an inverse linear dispersion is equals of 0.05 nm/mm for the first spectral channel and 0.32 nm/mm for the second one. Averaging was performed for the exposure time $\tau = 20$ ms, the frame repetition rate was 20 Hz, i.e., for one start with duration of $t = 2$ s up to 40 spectra are consistently recorded. The gas temperature in the plasma channel of a pulsating discharge was determined by the spectral method from the bands of cyanogen and molecular nitrogen ion. At first, model distributions over the rotational levels of the CN and molecular nitrogen ion at different gas temperatures were calculated taking into account the instrumental function of the spectrograph. Various effects that lead to the broadening of spectral lines in the discharge plasma were also taken into account. Then, the experimentally obtained spectrum was compared with the calculated results. The gas temperature was considered to be equal to the temperature at which the best agreement between the calculated results and experimental data was achieved. The electron concentration was measured by the Stark broadening of the spectral lines $H_\alpha$ and $H_\beta$ of the Balmer hydrogen series (for $n_e < 10^{16}$ cm$^{-3}$ we used only $H_\beta$ line, for $n_e > 10^{16}$ cm$^{-3}$ we used $H_\alpha$ and $H_\beta$ lines). The absolute sensitivity of the spectrographs was calibrated using special tungsten filament lamp, the radiation intensity which is determined by the temperature of the tungsten ribbon, depending on the magnitude of current flowing through the lamp.

3. Experimental results

The panoramic emission spectrum of a pulsating discharge in a supersonic air flow, recorded at the distance of $z = 1$ cm from the electrode tips is shown in figure 1 at the discharge current of $i = 15.5$ A. A distinctive feature of the spectrum is the presence of an intense continuum, which may electron bremsstrahlung from ions or atoms and/or recombination emission. Estimates show that, under these experimental conditions, the intensity of bremsstrahlung caused by electron–ion collisions exceed the intensity of bremsstrahlung caused by electron–neutral collisions. It is well known that the intensity of the recombination spectrum depends non-monotonically on the wavelength, whereas the measured intensity of the continuous spectrum depends monotonically on $\lambda$. The electron temperature in the plasma channel was determined by comparing the measured spectrum with the bremsstrahlung spectrum calculated for different electron temperatures. It has been shown that at the discharge current of $i = 10.8$ A the electron temperature decreases downstream the flow from 13000 K at distance from electrodes $z = 1$ cm to 7000 K at $z = 5$ cm. It has been also shown that at $z = 1$ cm the electron temperature increases from 10000 K to 15000 K as the discharge current rises from 2 to 16 A. It was shown experimentally that, upon adding a small amount of propane to the air flow, the electron temperature decreases abruptly to 3000 – 5000 K.
Figure 1 Panoramic emission spectrum of a dc pulsating discharge in a supersonic air flow, recorded at a distance of $z = 1$ cm from the electrodes

To measure the air ionization degree direct link electron concentration with half-width of a spectral line $\Delta \lambda$ is used. The line broadening occurs not only because of the Stark effect, but also due to the Doppler effect, the finite lifetime of the excited atom, the pressure effects, and the apparatus function of the spectral instrument. The apparatus function for the spectrograph was determined experimentally. From the experimentally obtained values $\Delta \lambda$, the Stark component was calculated in accordance with contour theory and empirical dependence [29].

It was experimentally obtained that the electron concentration at a distance of 1 cm from the electrodes increases almost forty times from $10^{15}$ cm$^{-3}$ to $3.7 \times 10^{16}$ cm$^{-3}$ with an increase in the flow velocity from 150 m/s to 500 m/s (figure 2). As the distance from the electrodes is increased to 3 cm, $n_e$ decreases by approximately 2-3 times at all flow velocities, but also increases linearly with increasing of air stream speed. A high level of electron concentration is also observed in the channel plasma of a microwave discharge at high air pressures [30].

Figure 2 Dependence of the electron density on the velocity of the airflow in the pulsating channel discharge plasma at various distances from the electrodes $z = 1$ cm (1) and $z = 3$ cm (2). $i = 15.5$ A.

It has been experimentally shown that the electric field intensity linearly increases by 2-3 times with an increase in the flow velocity from 200 m/s to 500 m/s. The increase in the electric field strength with increasing flow velocity is explained by the fact that in order to close the plasma loop to the cathode under conditions of a transverse-longitudinal discharge in a high-speed flow, it is necessary to increase the drift velocities of positive ions, and this is possible only with an increase in the electric field. The
growth in the electric field leads to an increase in the ionization frequency and accordingly increases the electron density.

In figure 3 shows the time evolution of the electron concentration measured at a distance of $z = 1$ cm downstream of the electrodes, with different values of the discharge current and a fixed value of the flow velocity $\nu = 500$ m/s. The exposure time of the spectrograph is 20 ms. Twenty spectra were recorded during the duration of the discharge current pulse $t = 2$ s. It can be seen that at a fixed flow rate the electron density increases with increasing discharge current and the instability of the concentration does not exceed 5-10% during the discharge current pulse.

![Figure 3](image1.png)

**Figure 3** Electron concentration in a pulsating discharge plasma vs time for different values of the discharge current $i$, A: 1 - 2.3, 2 – 5.5, 3 – 9.8, 4 – 12.5, 5 – 14.5, 6 – 15.5 and fixed air velocity $\nu = 500$ m/s

To determine the degree of gas ionization, in addition to the electron density, it is also necessary to know the concentration of air molecules in the heated plasma channel. Initially, the dependence of the gas temperature on velocity of a high-speed flow was calculated without creating a discharge in it. The resulting relationship is shown in figure 4 (dotted curve 1).

![Figure 4](image2.png)

**Figure 4** Dependence of the gas temperature on flow velocity without creating a discharge in it (dotted curve 1), in a pulsating discharge channel plasma (point 2) and calculated by the elastic heating mechanism (dot-dashed curve 3) with a discharge current $i = 15.5$ A. Distances from the electrodes $z = 1$ cm.
Then the gas temperature in the channel plasma of the pulsed discharge was measured at \( z = 1 \) cm and different flow rates. This dependence (points 2) is presented in figure 4. It can be seen that the gas temperature in the plasma channel near the electrodes increases from 450 K to 1250 K with an increase in the airflow velocity from 250 m/s to 500 m/s.

![Figure 5](image)

**Figure 5** Dependence of the concentration of air molecules on flow velocity without creating a discharge in it (curve 1) and in a pulsating discharge channel plasma (point 2) at \( i = 15.5 \) A, \( z = 1 \) cm.

![Figure 6](image)

**Figure 6** Dependence of the air ionization degree in a pulsating discharge plasma on the air flow velocity at \( i = 15.5 \) A, \( z = 1 \) cm.

The gas heating model took into account various processes leading to gas heating in weakly ionized plasma, such as energy transfer into translational degrees of freedom under elastic collisions of electrons with molecules, rotational-translational and vibrational-translational relaxation, vibrational-vibrational exchange, and quenching of electronically excited states of molecules. Estimates show that, in the highly ionized plasma of a pulsating discharge, the main mechanism for gas heating is heating due to elastic interactions [18]. Numerical simulations of gas heating via elastic collisions without allowance for the power loss due to the convective heat transfer in a high-speed flow shows that, at an electron density of \( 10^{15} \) cm\(^{-3}\), the air heating rate is \( dT_g/dt = 27 \) K/\( \mu \)s. For an air flow velocity of 150 m/s, this corresponds to an increase in the gas temperature in the pulsating discharge by about 180 K. At velocity of 500 m/s and \( n_e = 3 \times 10^{16} \) cm\(^{-3}\), the air heating rate is \( dT_g/dt = 810 \) K/\( \mu \)s, which corresponds to an increase in the gas temperature in a pulsating discharge by about 1600 K. These results satisfactorily agree with the experimental data (figure 4).
With the help of these data, the concentration of air molecules in a heated plasma channel of a pulsating discharge was determined (figure 5).

Taking into account the obtained data on the concentrations of electrons and air molecules, the degree of ionization of the plasma in a nonstationary pulsating discharge created using a stationary power source in subsonic and supersonic air flows was determined. The dependence of the air ionization degree in the pulsating discharge plasma on the air flow velocity is shown in figure 6.

4. Conclusions
At low subsonic airflow rates, the degree of gas ionization in pulsating discharge plasma is of the order of 0.01%, with the flow velocity increasing, the degree of ionization of the gas sharply increases and reaches a value of 1% at flow velocity of 600 m/s. The obtained results show that near the electrodes the plasma channel of the nonstationary pulsating discharge is a strongly ionized medium.

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