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# SHADOW METHOD FOR MEASURING THE AVERAGE ELECTRON DENSITY IN AN IONIZED GAS FLOW INDUCED BY A HIGH-FREQUENCY BARRIER DISCHARGE

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*The electron density distribution in an ionized gas flow induced by a high-frequency barrier discharge has been investigated by an optical method. It has been shown that ion acceleration occurs mainly near the minima of the electron density, and the extremes in the temperature distribution are in antiphase with the corresponding extremes of the electron density.*

***Keywords:*** *aerodynamic drag, barrier discharge, shadow method.*

**Introduction.** Investigations aimed at creating a plasma flow upstream from a blunt body in order to decrease the aerodynamic drag have been carried out since the early 1980s [1–4]. The results obtained have found application in the present-day aircraft industry and initiated experiments on the use of a near-surface plasma for increasing the economic efficiency and controllability of airborne vehicles by varying their aerodynamic characteristics during flight in the atmosphere.

High-frequency pulsed discharges were investigated in [5–8]. Aerodynamic models in the form of conical cylinders (opening of $30^{o}$) with base diameters from 40 to 80 mm had a pointed electrode on the top for the concentration of the electric field strength. The results of experiments with a Mach number M = 2 showed a decrease in the aerodynamic drag by about 6% at a diffusive discharge and its insignificant changes at a filamentary discharge.

Of the inhomogeneous discharges, the microwave one is of greatest interest. It can be diffusive and filamentary depending on the gas pressure. The filamentary discharge at the center of the model directed counter to the flow is the most effective one [9–15].

The anomalous dynamics of shock waves in a weakly ionized plasma of the glow discharge was investigated experimentally for both nonequilibrium molecular gases (e.g., for air and nitrogen) and monatomic gases (such as argon and xenon) [16, 17]. In these experiments, plasma was formed at a pressure of 15–30 torr, and its electron temperature was usually a few electron-volts at a degree of ionization of the order of $10^{-6}$–$10^{-5}$. In some cases, to determine the influence of charged particles on the dynamics of shock waves, a magnetic field, longitudinal or transverse with respect to the direction of propagation of the shock wave, was used. Abnormally high velocities of shock waves were observed in the plasma simultaneously with a considerable dispersion and decay of the shock wave.

The force of the static magnetic field always acts orthogonally to the charged particle velocity and cannot produce any force effect either on individual particles or on the flow in general. The problem is to create an electrically charged medium at atmospheric pressure and form an effective configuration of electric fields suitable for initiating and using the above effects in such areas as decreasing the drag, heat transfer, lift or flow separation.

In [14], the initiation of a flow along a flat surface was investigated by the methods of electrohydrodynamics for low-velocity air flows (from 11 to 17.5 m/sec). To create a thin plasma layer on the surface of a plate, high-voltage direct current (20–40 kV) was used. By controlling the electric field intensity, the flow was shifted along the plate to cause changes in the boundary layer thickness. The ionic wind on a dc flat plate was used to correct the discharge shape in order to provide a small decrease in the drag (about 5%) for the turbulent boundary layer at longitudinal Reynolds numbers of $\sim 10^{6}$ [12]. In pulsation discharges sustained by short high-voltage pulses (pulsating corona discharge), the ionization efficiency can be several times that of the homogeneous glow discharge, since the strong electric field applied for a short time heats electrons to higher energies [13].

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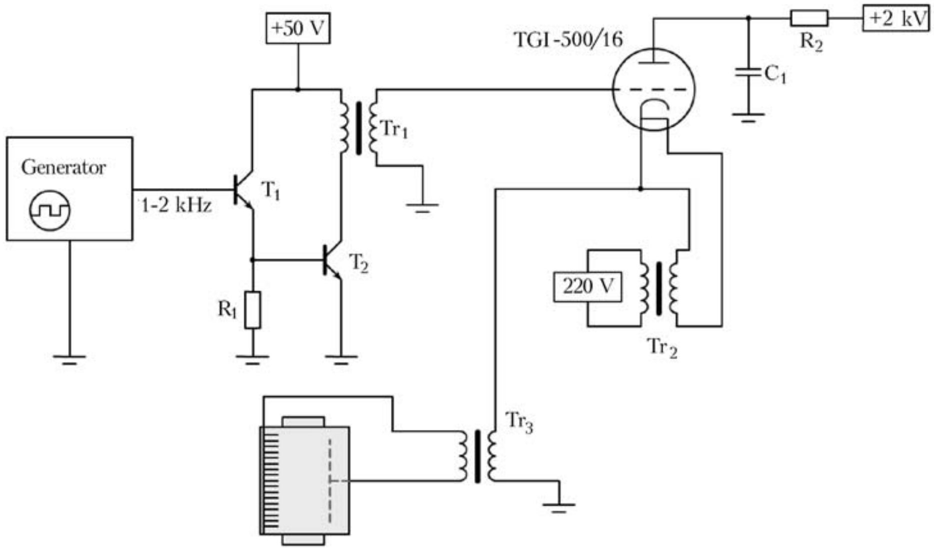


Fig. 1. Electrical feed circuit of the barrier discharge.

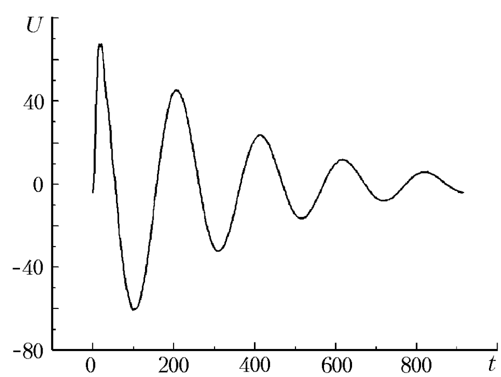


Fig. 2. Oscillogram of periodic voltage on discharge electrodes. *U*, kV; *t*, μsec.

The homogeneous glow discharge at 1 atm permits installing on the wings and the fuselage of an airplane glow plasma discharge actuators requiring energy of the order of a few dozen watts per square meter [18–25]. They can provide an electromagnetic coupling between the electric field in the plasma and the neutral gas in the boundary layer [26] that is strong enough to cause effects important from the point of view of aerodynamics: an increase or a decrease in the aerodynamic drag on a flat plate [27–29], regrouping of the stream near the wing at high angles of attack, peristaltic induction of neutral gas flow by the moving electrostatic wave on the surface of a flat plate containing plasma actuators fed by multiphase voltage sources [30, 31].

In computational modeling of the process of ionized gas flow past a surface, an important role is played by information on the distribution of electrons in the modeled flow. The aim of the present work was to measure by the optical method the electron density distribution in an ionized gas flow induced by a high-frequency barrier discharge.

**Experimental Equipment and Measuring Techniques.** For the object of investigation, we used a 10-mm-thick smooth Kaprolon plate with surface dimensions 180 × 120 mm. On the pointed front edge on either side of the plate, a system of needle electrodes spaced at 3 mm was mounted. The electrodes were set parallel to the surface at a height of 3 mm. The second electrode represented a portion of fluoroplastic-insulated copper wire built into the plate parallel to the front edge at a distance of 40 mm from the ends of the needle electrodes.

The high-frequency barrier discharge was formed by feeding a high a.c. voltage to the electrodes. The electrical feed circuit of the discharge is given in Fig. 1. Rectangular pulses of duration 5 μsec and repetition frequency 1–2 kHz were applied to the input of the circuit controlling the operation of the TGI1-500/16 thyratron assembled from transistors $T_1$ and $T_2$ and a radio-frequency transformer $Tr_1$. In the process of operation of the thyratron, the energy stored in the capacitor $C_1$ discharged periodically into the primary winding of the Tesla coil $Tr_3$. The secondary wind-

Fig. 3. Photograph of the barrier discharge on the plate.

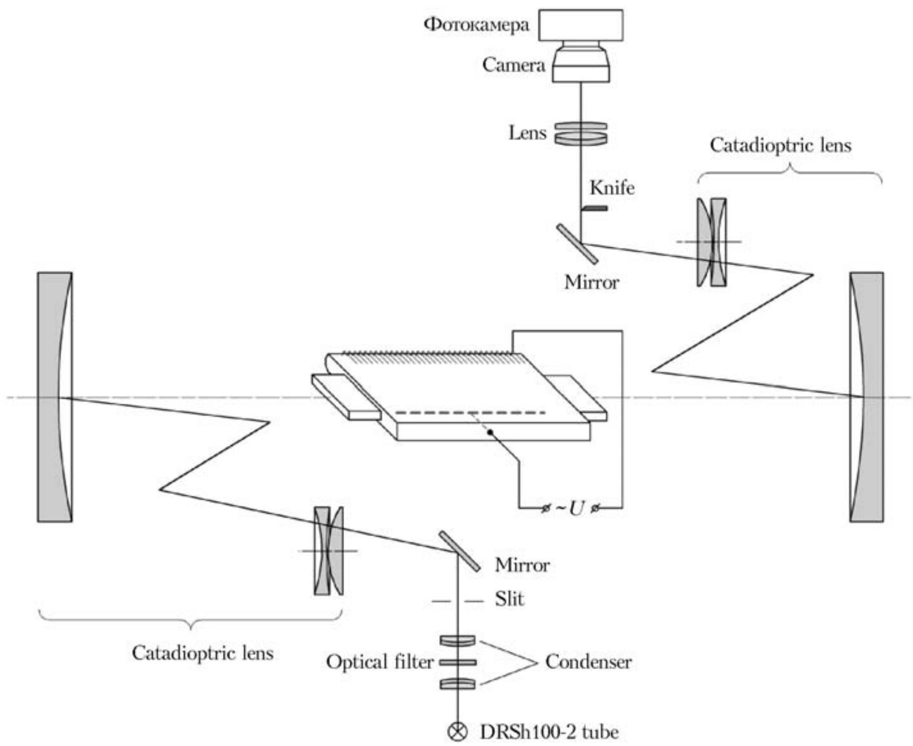


Fig. 4. Optical scheme of the experimental setup.

ing of the coil was connected to the discharge electrodes of the investigated plate. Depending on the magnitude of the capacitor $C_1$ discharge, the amplitude value of voltage on the discharge electrodes varied over the 70–140 kV range.

Figure 2 shows a typical oscillogram of the periodic signal of the voltage on the discharge electrodes.

As a result of the interaction of charged particles with the field of electrodynamic mass forces, a directed gas flow (whose velocity ranged from 5 to 10 m/sec) was initiated in the discharge with the formation of a turbulent boundary layer on the plate surface (Fig. 3).

The averaged electron density concentration was investigated by the direct-shadow knife and slit method [32]. The optical scheme of the experimental facility is given in Fig. 4.

Experiments were performed on an IZK-463 mirror-meniscus holographic interferometer operating in the regime of a shadow device. The focal length of the receiving part is $F$ = 3213.5 mm at a diameter of the observed field of 800 mm. The width of the slit in the illuminating part of the instrument $\Delta x$ = 0.1 mm. The slit was set parallel to the plate surface. To average turbulent pulsations in the flow, photography of shadow patterns was carried out at ex-

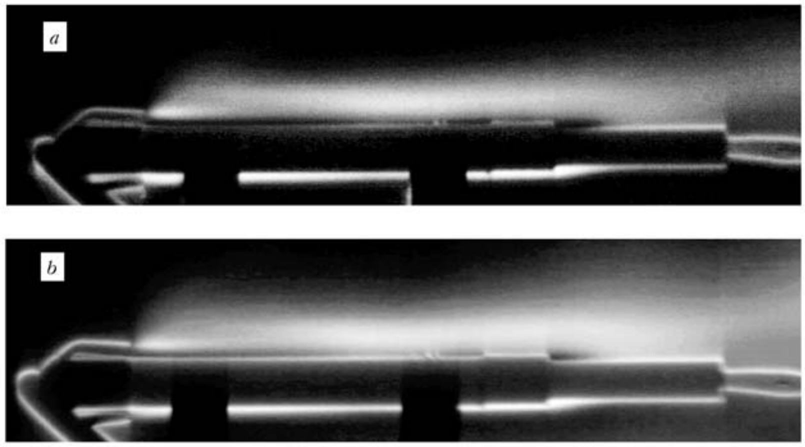


Fig. 5. Shadow patterns of the boundary layer on the plate for two wavelengths: a) blue light; b) red light.

posure times $\Delta t$ = 2 sec. In the illuminating part of the device, two optical filters with maximum transmission of light at wavelengths $\lambda_r$ = 640 nm and $\lambda_b$ = 420 nm were set alternatively. Figure 5 shows the shadow patterns of the boundary layer on the plate for two wavelengths.

**Results of Measurements and Discussion.** In the case of sufficiently small angles of deflection of light in the investigated optical inhomogeneity (e.g., at propagation of light in a turbulent gas flow), the Euler equation can be written in the simplified form [32]

$$\tan \varepsilon_x \approx \int_{z_1}^{z_2} \frac{d \{\ln [n (x, y, z)]\} dz}{dx}, \quad \tan \varepsilon_y \approx \int_{z_1}^{z_2} \frac{d \{\ln [n (x, y, z)]\} dz}{dy} . \tag{1}$$

If in investigating the two-dimensional boundary layer on the plate its surface is parallel to the optical axis of the shadow device, and the slit in the illuminating part of the device is set parallel to the plate surface, it may be assumed approximately that the function $\frac{\partial n}{\partial x}$ does not depend on the $z$ coordinate and the $\frac{\partial n}{\partial y}$ value is negligibly small. In so doing, the system of equations (1) transforms into the equation

$$\varepsilon_x = \frac{1}{n_0} \frac{\partial n}{\partial x} (z_2 - z_1) . \tag{2}$$

The $\varepsilon_x$ value is determined by the results of photometric measurements of shadow patterns from the formula

$$\frac{\Delta I}{I_0} = \frac{\varepsilon_x F}{\Delta x} , \tag{3}$$

where $l_0$ is found from the shadow pattern obtained in the absence of the Foucault knife.

At a known value of the refractive index in the unperturbed zone, the absolute values of the refractive index in the turbulent boundary layer can be obtained by integrating Eq. (2):

$$n (x, y) = n (x_0, y) = \int_{x_0}^{x} \frac{\partial n}{\partial x} (x, y) \, dx . \tag{4}$$

The refractive index of the plasma is determined from the relation [33]

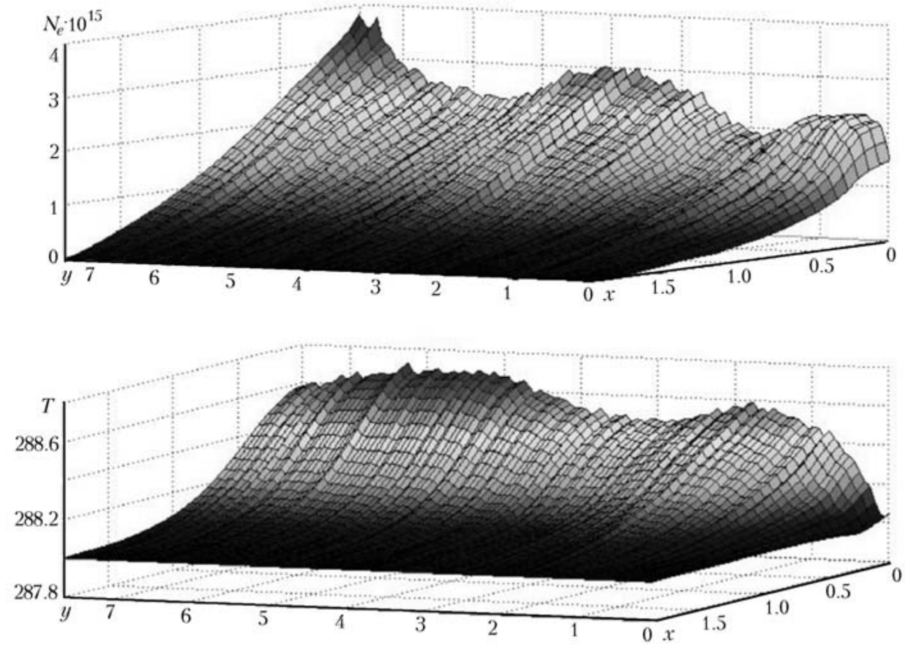


Fig. 6. Two-dimensional distributions of the averaged values of the temperature and the electron density in the boundary layer. $N_e$, cm$^{-3}$; $T$, K; $x$, $y$, cm.

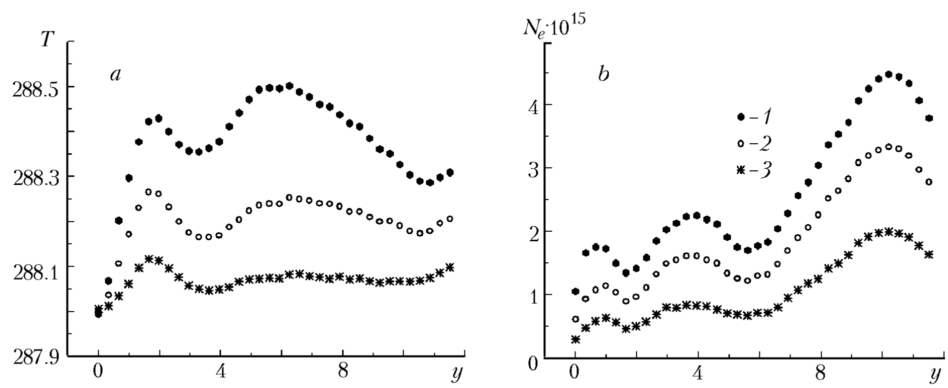


Fig. 7. Distributions of the averaged temperature (a) and electron density (b) along the flow: 1) $x$ = 10 mm; 2) 6; 3) 3. $T$, K; $N_e$, cm$^{-3}$; $y$, cm.

$$n - 1 = k\rho\,(1 + \beta T) - K\lambda^2 N_e\,, \quad K = \frac{\pi e^2}{2 m_e c^2}\,. \tag{5}$$

Writing Eq. (5) for two wavelengths $\lambda_r$ = 650 nm and $\lambda_b$ = 420 nm and using the Cauchy dispersion formula for the refractive index of air [34]

$$n - 1 = \frac{1}{10^6}\left[64.328 + \frac{29498.1}{146 - 10^6/\lambda^2} + \frac{255.4}{41 - 10^6/\lambda^2}\right], \tag{6}$$

we finally obtain a system of two equations for two unknown quantities: the temperature and the electron density [35]. The two-dimensional distributions of the average values of the temperature and the electron density in the boundary layer are shown in Fig. [6]. The distributions of the average values of the temperature and the electron density along the flow for three distances from the plate surface are given in Fig. 7.

**Conclusions.** The obtained values of the electron density are comparable in modulus to the corresponding values for the glow discharge. The wavy character of the change in the electron density along the flow is due to the formation of space charges leading to a potential redistribution, which reflects the inhomogeneous character of the Joule heating of air by the discharge current. This phenomenon is analogous to the formation of the Faraday dark space in the glow discharge. Ion acceleration in the induced gas flow occurs mainly in the vicinity of electron density minima. The extremes in the temperature distributions are in antiphase with the corresponding extremes of the electron density.

Thus, in the investigated discharge several alternating regions are formed: in the vicinity of electron density minima, heating of ionized gas prevails, and in the vicinity of maxima, acceleration of charged ions occurs.

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## NOTATION

$c$, velocity of light in free space, m/sec; $e$, electron charge, C; $F$, focal length of the lens, mm; $I$, radiation intensity, W/m$^2$; $k$, Gladstone–Dale constant, m$^3$/kg; $m_e$, electron mass, M, Mach number; $n$, refractive index of the medium; $t$, time, sec; $T$, averaged temperature of electrons, K; $N_e$, electron density, m$^{-3}$; $U$, voltage on discharge electrodes, kV; $x$, $y$, Cartesian coordinates; $\beta$, thermal coefficient of volumetric expansion, K$^{-1}$; $\varepsilon$, angle of deflection of light, seconds of arc; $\lambda$, probing radiation wavelength, nm. Subscripts: 0, initial value; 1, 2, input and output points of probing radiation; b, blue light; $l$, plate length along the flow; r, red light; $W$, profile aerodynamic drag.

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