POSITIVE COLUMN OF A GLOW DISCHARGE IN FLOWING NITROGEN

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UDC 537.527

The study of an electrical discharge in a moving medium is of interest in connection with its use for the creation of an inversely populated gaseous medium in lasers (performed in [1, 2], where certain regularities in the behavior of a discharge in a gas flow are discussed). The purpose of the present work is to explain the dependence of discharge characteristics on such parameters as the degree of preionization, velocity, and density in the gas flow. Calculations were made for a transverse discharge in a flow of preionized nitrogen.

The basic equations describing the motion of electrons and ions in the medium are the following:

equations of motion,

$$n_e\mathbf{V}_e = n_e\mu_e\mathbf{E},\qquad n_i(\mathbf{V}_i - \mathbf{V}_a) = n_i\mu_i\mathbf{E}, \tag{1}$$

where the last equation does not include diffusion and inertia for ion motion, which estimates show is valid at sufficiently high pressure (for the conditions in this paper, at $p \geq 50$ mm Hg);

equations for particle conservation,

$$\operatorname{div} n_e\mathbf{V}_e = \Gamma,\ \operatorname{div} n_i\mathbf{V}_i = \Gamma,\qquad \Gamma = n_e\mathbf{V}_e p(\alpha/p) - \beta n_e n_i,\ \alpha/p = f(E/p). \tag{2}$$

The ionization function $\alpha/p = f(E/p)$ is assumed to be the same as that in a gas in which the vibrational and electronic levels of the molecules are not excited.

This assumption is valid if one can neglect stepwise ionization from electronically excited states, which is justified for the conditions in a glow-discharge plasma and if the electron energy distribution function in the region of the ionization energy is the same as that in the unexcited gas. Since a change in the distribution function because of collisions of the second kind can be produced mainly by the interaction of vibrationally excited molecules with electrons having an energy less than 3 eV, it can be expected that perturbation of the distribution function in the energy region above the ionization potential of nitrogen (15.6 eV) will be insignificant.

The equation for the electric field has the form

$$\operatorname{rot} \mathbf{E} = 0. \tag{3}$$

In addition, quasineutrality, $n_e \simeq n_i$ is assumed, which is valid at densities $n_e \geq 10^8$ cm^{-3} under the conditions of the present problem; this density is achieved only immediately in the discharge zone and beyond it. At lower values $n_e \leq 10^8$ cm^{-3}, violation of quasineutrality will lead to distortion of the field from n_e at the entrance to the discharge region, but the fact that the discharge characteristics (as will be shown below) do not depend on the density n_0 in the incoming flow up to values $n_0 \leq 10^8$ cm^{-3} makes it possible to overlook violation of the condition $n_e \simeq n_i$.

Using the equations of motion and of particle conservation, one can show that the relation

$$\operatorname{div} n_e\mathbf{V}_e = 0,\qquad V_a\frac{\partial n_e}{\partial x} = \Gamma \tag{4}$$

is satisfied correctly within a quantity of the order of $V_i/V_e \simeq \mu_i/\mu_e \ll 1$. We introduce the stream function in the following manner:

Zhukovskii. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 2, pp. 18-22, March-April, 1977. Original article submitted April 5, 1976.

$$n_e V_{ey} = \partial\Phi/\partial x,\ n_e V_{ex} = -\partial\Phi/\partial y. \quad (5)$$

With the help of Eqs. (1) and (3)-(5), we finally obtain the system of equations

$$\begin{gathered}
\frac{\partial^2\Phi}{\partial x^2} + \frac{\partial^2\Phi}{\partial y^2} - \frac{\partial\Phi}{\partial x}\frac{\partial \ln n_e}{\partial x} - \frac{\partial\Phi}{\partial y}\frac{\partial \ln n_e}{\partial y} = 0, \\
V_a \frac{\partial n_e}{\partial x} = p n_e \mu_e E f(E/p) - \beta n_e^2, \\
E = \left(\left(\frac{\partial\Phi}{\partial x}\right)^2 + \left(\frac{\partial\Phi}{\partial y}\right)^2\right)^{1/2} \Big/ n_e\mu_e.
\end{gathered} \quad (6)$$

Boundary conditions for Eqs. (6) were taken in the form

$$\begin{gathered}
n_e = n_0 \ \text{for}\ x = -L, \\
\Phi = 0 \ \text{for}\ x \leqslant -L, \\
\Phi = ja/e \ \text{for}\ x \to \infty, \\
\left.\frac{\partial\Phi}{\partial x}\right|_{y=\pm b/2} = \begin{cases} 0 & \text{for}\ |x - a/2| > a/2, \\ j/e & \text{for}\ |x - a/2| < a/2. \end{cases}
\end{gathered} \quad (7)$$

These conditions correspond physically to the fact that the gas is preionized by one or another means, for example, by an electron beam or a supplementary discharge, at a distance L upstream from the electrodes, and that the current density at the electrodes is assumed constant, which is achieved, for example, by subdividing them, and thus near-electrode phenomena are eliminated from consideration.

The solution of Eqs. (6) in conjunction with the conditions (7) was performed numerically on a computer by the adjustment method. The calculations were performed for the following parameter values: a = 0.5-1 cm, $j = 10^{-4}$-1 A/cm^2, $n_0 = 10^5$-10^{11} cm^{-3}, p = 50-200 mm Hg, $V_a = 10^4$-$5 \cdot 10^4$ cm/sec, L = 0-2a, and b/2 = 1.5 cm.

Physical characteristics of the gas, $\mu_e = V_e/E$, $\alpha/p = f(E/p)$, and β, were taken from [3-5]. Experimental data for the ionization intensity α/p were generalized by means of the empirical relation $\alpha/p = A \exp(BE/p)$ as suggested in [4]. Since for typical values of the parameter E/p = 10-40 V/cm · mm Hg, under problem conditions the greater portion of the discharge energy goes into excitation of vibrational and electronic levels in gas molecules, change in gas density because of heating in the discharge region can be compensated by insignificant expansion or compression of the channel.

Calculated along with the current density and electric field intensity were the quantities $U = 1/a \int_0^a dx \int_{-b/2}^{+b/2} E_y dy$, $W = e \int_{-b/2}^{y} dy \int_{-\infty}^{+\infty} (d\Phi/dx) E_y dx$, which are, respectively, the average value of the potential difference

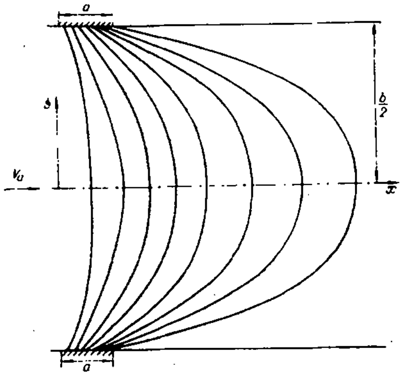

Fig. 1

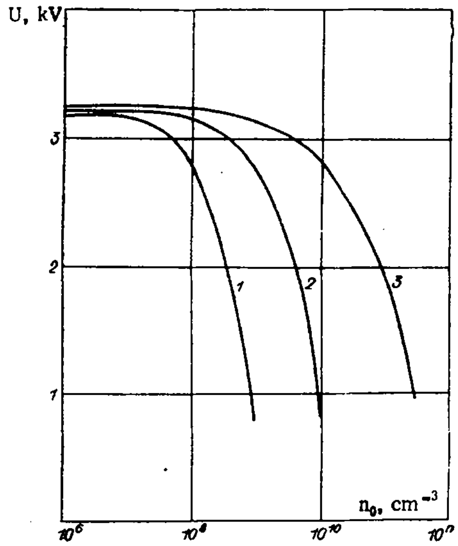

Fig. 2

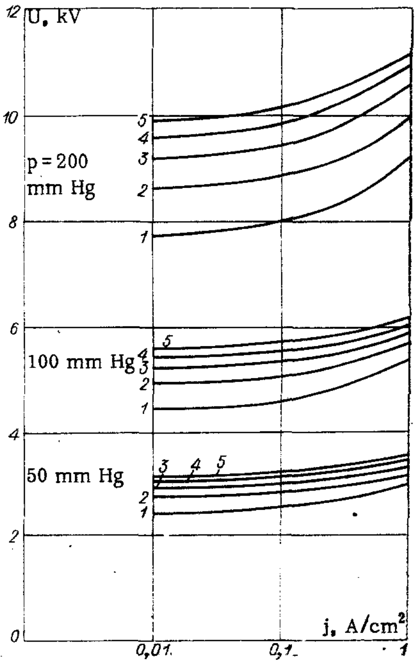

Fig. 3

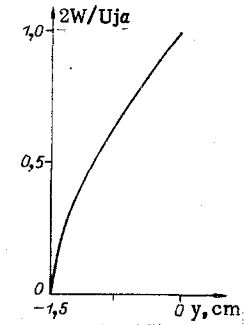

Fig. 4

between electrodes of opposite polarity and the value of the electric power released in the layer $(-b/2, y)$. The results of the calculations are illustrated in Figs. 1-4. The downstream shift of current lines caused by charge drift (Fig. 1: a =0.5 cm, b/2=1.5 cm, $V_a = 4 \cdot 10^4$ cm/sec, $j = 10^{-2}$ A/cm², L=a, n_0=0, p=50 mm Hg) leads to a rise in the voltage across the discharge gap as the flow velocity increases. The dependence of voltage on velocity turns out to be nearly linear in this case. The effect of the initial electron density n_0 on the value of the voltage across the discharge gap becomes marked [Fig. 2: 1) $j = 10^{-3}$ A/cm²; 2) $j = 10^{-2}$ A/cm²; 3) $j = 10^{-1}$ A/cm²; a = 0.5 cm; $V_a = 5 \cdot 10^4$ cm/sec; p = 50 mm Hg; L=a] only upon reaching certain values of n_0. Under the conditions here, the value of n_0 needed to reduce the striking voltage of the discharge by a factor of two can be estimated from the empirical relation

$$n_0 \simeq Cjb/eU_0\mu_e,$$

where U_0 is the striking voltage of the discharge in the absence of preionization and the quantity C depends insignificantly on the geometric dimensions a, b, and L and the ratio p/V_a. The value of C for the conditions specified above falls within the range 0.5-0.9.

Volt-ampere characteristics for various velocities and gas pressures are shown in Fig. 3 [1) V_a =100 m/sec; 2) V_a = 200 m/sec; 3) V_a =300 m/sec; 4) V_a =400 m/sec; 5) V_a =500 m/sec; a =0.5 cm; b/2=1.5 cm; n_0=0].

The linear nature of the variation of the quantity 2W/Uja as a function of y (Fig. 4: a =0.5 cm, b/2=1.5 cm, $V_a = 4 \cdot 10^4$ cm/sec, $j = 10^{-2}$ A/cm², p=50 mm Hg, n_0=0) is evidence that the release of power in various layers of gas flowing through the discharge region occurs fairly uniformly.

Since the voltage across the discharge gap depends weakly on the current density at the electrodes, one can expect the volt-ampere characteristics to maintain their form of behavior for another choice of near-electrode conditions also, particularly for solid electrodes in the region of current densities corresponding to a normal glow discharge.

LITERATURE CITED

1. V. I. Alferov and A. S. Bushmin, "Electrical discharge in a supersonic flow of air," Zh. Éksp. Teor. Fiz., 44, No. 6, 1776 (1963).
2. V. Yu. Baranov, A. A. Vedenov, and V. G. Niz'ev, "Electrical discharge in a gas flow," Teplofiz. Vys. Temp., No. 6, 1156 (1972).
3. S. C. Brown, Elementary Processes in Gas-Discharge Plasma [Russian translation], Atomizdat, Moscow (1961), p. 62.

4. V. L. Granovskii, Electrical Current in a Gas [in Russian], Nauka, Moscow (1971), p. 74.
5. B. M. Smirnov, Atomic Collisions and Elementary Processes in Plasma [in Russian], Atomizdat, Moscow (1968), p. 324.

DECELERATION OF A STRONG SHOCK WAVE BY A TRANSVERSE MAGNETIC FIELD AT SUBSTANTIAL MAGNETIC REYNOLDS NUMBERS

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UDC 538.6

Strong ionizing shock waves can be used for obtaining strong magnetic fields and high-powered short-duration pulses of electrical energy. The motionless gas ahead of the wave front is cold and nonconducting, while behind the front the gas moves at high speed and has considerable electrical conductivity because of its high temperature. The interaction of the high-velocity conductive stream produced by the ionizing shock wave with the magnetic and electric field can be utilized in various applications, one of which is magnetic cumulation, i.e., transformation of the energy of the wave into the energy of a compressed magnetic field and its subsequent utilization for various purposes [1]. Another subject of great interest is the utilization of ionizing shock waves moving in a transverse magnetic field for studying the effects of the T layer [2].

A theoretical investigation of the interaction of an ionizing shock wave with a transverse magnetic field at substantial magnetic Reynolds numbers can be carried out in the most complete form by using direct finite-difference methods which presuppose the utilization of implicit conservative calculation schemes [3, 4].

Analytic solutions of such problems are only partial solutions and serve to make clear only the qualitative aspects of the processes taking place.

One of the modifications of the numerical methods for solving the problem of the interaction of an ionizing shock wave with a magnetic field is based on singling out a hyperbolic subsystem from the original equations and solving this subsystem by the method of characteristics in combination with a direct numerical solution of the other equations. Although such an approach imposes additional restrictions on the calculation model for the problem (no viscosity, etc.), it makes it possible to use an explicit difference scheme for solving a nonlinear hyperbolic subsystem, which makes the time required for solving the problem on an electronic computer considerably shorter than the computation time for direct difference algorithms.

1. Calculation Model and Transformation of the Original System of Equations. We consider a model (Fig. 1) similar to the current grid used in the experiments of [5]. There is a plane region bounded by a highly conductive Π-shaped frame, into which a strong ionizing shock wave enters with velocity $\mathbf{w}(w, 0, 0)$. Within the frame, for $x \geq 0$, we have a magnetic field $\mathbf{B}_e(0, B_e, 0)$. The conductive gas behind the wave moves with velocity $\mathbf{u}(u, 0, 0)$. Because of the Faraday effect, in this gas there are currents with density $\mathbf{j}(0, 0, j)$, closing along the frame, which strengthen the magnetic field $\mathbf{B}(0, B, 0)$ within the frame and decelerate the gas and the shock wave. The energy of the shock wave is transformed into magnetic field energy and Joule losses in the gas.

The model described above also corresponds to a coaxial channel with a relatively small gap along the radius (the z direction in Fig. 1).

In the analysis given below we shall neglect the Hall effect, since the pressure behind the wave front is high; we shall also neglect the electrical boundary effects, since the electrical connection is short-circuited. These assumptions enable us to use a one-dimensional approximation in solving the problem.

The interaction of the gas behind the wave front with the magnetic field is described by nonstationary equations of motion, continuity, and energy, Maxwell's equations, and Ohm's law, which in dimensionless form, for an ideal perfect gas, are

Moscow. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 2, pp. 22–28, March–April, 1977. Original article submitted October 9, 1975.