STEADYING THE INSTABILITY OF A GLOWING DISCHARGE IN A LONGITUDINAL AIR STREAM

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We have studied experimentally the temperature of a gas and the strength of the electric field for a glowing discharge in a longitudinal stream of air. We have derived a two-dimensional distribution of the reduced field strength E/N in the gas discharge tube. Numerical studies have been conducted into the kinetics of a dry-air plasma. We have calculated the ionization factors, and the factors for adhesion and separation of electrons. Through comparison of experimental and theoretical data we propose a model for the contraction of the glowing discharge with an adhesive instability mechanism.

The glowing discharge plasma used extensively in various power installations is generated, as a rule, in gases containing electronegative impurities. The presence of the latter may lead to a significant increase in the density (within the plasma) of negative and positive ions. In this case, the basic characteristics of the discharge [the distribution of electric fields in the positive column (PC), the volt-ampere characteristic (VAC), etc.] will be determined to a considerable extent by the elementary processes associated with the creation and destruction of ions, i.e., adhesion, separation, and recombination. Glowing discharge (GD) in air at pressures above 20 torr is an example of such a situation [1].

In a glowing-discharge plasma in air the negative ions promote instability, the generation of noise and oscillations, and these significantly make more difficult experimental studies of the discharge [2]. We are familiar with a number of mechanisms for the ionization-energy instability whose development with an increase in gas pressure and applied power may lead to a contraction in the phase discharge [3]. Choosing the most probable contraction mechanism in each specific case becomes possible through comparison of the efficiency of the elementary processes in the charged-particle balance. For a glowing discharge in a stream of air a discontinuous transition from the positive column from the three-dimensional states to a statically contracted state, such as described in [2-4], is characteristic. However, despite the fact that the contraction effect has been known for a comparatively long period of time, there presently actually exists no completed model of this effect [4].

In the present study we have investigated the diffusion and contraction states of a discharge in a flow of air. We propose a model for the static contraction regime of a glowing discharge.

Discharge Chamber and Experimental Method. Selection of a specific discharge chamber (DC) was governed by the possibility of achieving a stable glowing discharge over a broad range of variations in the velocity of the plasma-forming gas, in pressure, and in current. The discharge chamber consists of a copper rod cathode, anode, and a dielectric interelectrode tube. The electrodes are 3 mm in diameter and the tube has a diameter of 25 mm. The interelectrode distance $l = 40$ mm. The electrodes were initially conditioned for 2-3 h in a powerful anomalous discharge at low pressures in order to cleanse and degas their surfaces, thus ensuring replicability of the results. Atmospheric air was used as the plasma-forming gas. The gas entered the discharge zone through a central orifice from the cathode. The gas flow rate was measured by means of RS-5 and RS-7 flowmeters. The measurement error for the gas flow rate did not exceed 3-4%. The pressure of the gas in the gas-discharge chamber was measured by means of a U-shaped mercury manometer. The distribution of the electric-field potential of the discharge in the air stream was determined by means of a single floating probe. The potential measurements were conducted relative to a grounded anode; the relative measurement error at the anode did not exceed 10% and diminished markedly in the direction toward the cathode. Direct measurements of strength E in the column were conducted with a double probe. The absolute value of the strength vector was recorded by a compensation procedure [5]. The plasma temperature was determined by means chromel—copel thermocouples [5], as well as with the aid of an ISP-30 quartz spectrograph on the basis of the molecular hydroxyl bands [6]. The relative error in the determination of temperature, when taking into consideration the class of measurement-device accuracy, did not exceed 7%.

Experimental Results. A diffuse glowing discharge in a stream of air is characterized by weak uniform luminescence, entirely filling the interelectrode region, and it exhibits an ascending VAC [7].

Figure 1a (curve 1) shows the distribution of the electric field strength E along the positive discharge column in a stream of air. Analysis of the data shows that E changes slightly along the GD column and an insignificant drop in E is noted in the midsection of the PC.

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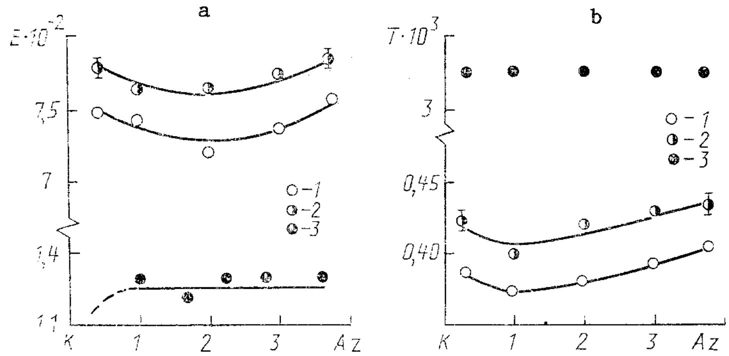

Fig. 1. Electric field strength distribution (a) and temperature distribution (b) over the length of a glowing discharge chamber: 1) I = 15 mA; 2) I_{cr} = 18-19; 3) I = 200. P = 6650 Pa, V = 100 m·sec^{-1}. E, V·cm^{-1}; T, K; z, cm.

Figure 1b (curve 1) shows the distribution of the axial value for the gas temperature along the PC. In the initial section of the PC there is a slight drop in temperature, and we then have a monotonic increase.

Figure 1 (curves 2) shows analogous results for the so-called critical current I_{cr} = 18-19 mA. Any further increase in current leads to discharge contraction. The dependence of the current contraction on pressure and gas flow rate is presented in [7]. It should be noted that the direct measurements of the electric field of the GD in air at critical current were made difficult by initiation of premature discharge contraction on introduction of the electrostatic probe into the interelectrode gap.

We investigated the distribution of field strength and gas temperature over the radius of the PC. The experimental results suggest constancy for E over the radius of the diffusion GD in a longitudinal gas flow. The distribution of the gas temperature over the radius is satisfactorily approximated in the form

$$T = T_w + (T_0 - T_w)\,[1 - (r/R)^2],$$

where for our case the wall temperature T_w = 290 K.

GD with contracting PC characteristically exhibits descending VAC [7]. The positive column in this case is characterized by a high value for the gas temperature and low electric-field strength.

Figure 1a (curve 3) shows results from the experimental determination of E on the axis of the contracting PC (I = 200 mA). As we can see, the strength of the electric field along the column is constant. Analysis of the data demonstrates that E in the transverse direction varies in an inconsequential manner and in first approximation it may be assumed to be constant.

In GD with contracted PC virtually the entire power introduced into the discharge is expended on heating, as a result of which we observe high values for the gas temperature in the column. The change in temperature along the positive column is insignificant in this case (Fig. 1b, curve 3).

Analysis of the results obtained in studies of the radial distribution of gas temperature in a DC with contracting GD at various pressures shows that the temperature drops insignificantly at the periphery of the discharge, and as the pressure is increased the area occupied by the discharge diminishes, while the temperature of the gas in the current filament rises.

The reduced electric-field strength E/N serves as a universal parameter by means of which it becomes possible to undertake a comparative study of diffusion and contracting GD. Figure 2 shows the spatial distribution of E/N in DC at a critical current value (I = I_{cr} = 18-19 mA). It exhibits a saddle shape with a bend observed at the z/l = 0.25 section of the channel axis. The virtual straightening out of E/N occurs near the periphery of the column along a discharge with min E/N = (4.5-4.6)·10^{-6} V·cm^2. The distribution of E/N in the diffusion regime at I = 15 mA exhibits an analogous structure with E/N at the periphery equal to (4.2-4.3)·10^{-16} V·cm^2.

In GD with contracting PC E/N is virtually uniform in the current filament and in terms of order of magnitude is ≈ 10^{-16} V · cm^2. (We neglect the insignificant reduction in E/N at the boundary of the column.)

Thus, in diffusion GD in a stream of air we observe a slow rise in the parameter E/N as the discharge voltage increases, and as a critical value is attained the discharge is transformed into a contracted regime with a small E/N.

The distribution of the concentration was calculated from the equation of state for an ideal gas P = NkT in the assumption of constancy for the pressure in the DC.

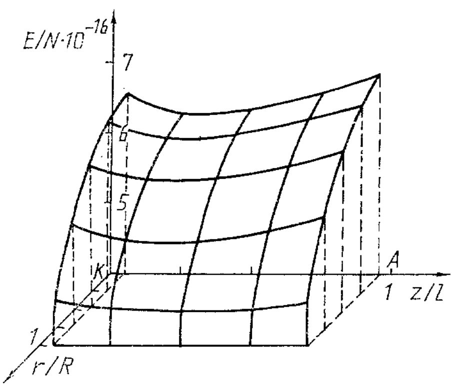

Fig. 2

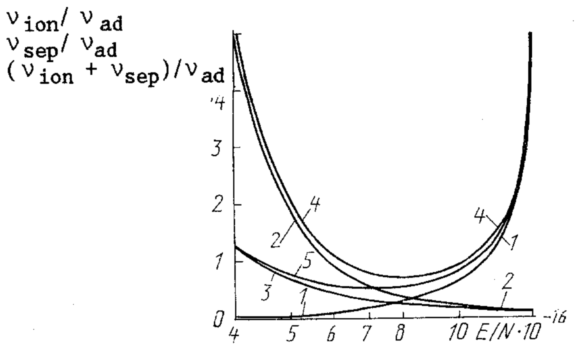

Fig. 3

Fig. 2. Spatial distribution of reduced electric field strength in GD chamber: 1) I_{cr} = 18-19 mA; p = 6650 Pa, V = 100 $m \cdot sec^{-1}$. E/N, $V \cdot cm^2$.

Fig. 3. Kinetic constants as functions of the parameter E/N: 1) ν_{ion}/ν_{ad}; 2) ν_{sep}/ν_{ad}; T_o = 0; 3) ν_{sep}/ν_{ad}, T_o = 0.4 eV; 4) $(\nu_{ion} + \nu_{sep})/\nu_{ad}$, T_o = 0; 5) $(\nu_{ion} + \nu_{sep})/\nu_{ad}$, T_o = 0.4 eV.

Kinetics of the GD Plasma in Air. As was indicated in the introduction, the properties of a discharge in air and, consequently, the reduced strength of the electric field, are determined by elementary processes, i.e., the excitation and ionization of neutral components, adhesion, and separation of electrons. Let us examine the kinetics of a GD plasma for the case of a simple two-component composition of air, i.e., N_2:O_2 = 0.79:0.21. This simplification can physically be explained as follows. As is well known, the primary components of air are nitrogen, oxygen, and water. The concentration of remaining components is insignificant. The rates of reactions with water molecules in air are considerably lower than those of the remaining processes and exhibit greater indeterminacy [8].

In a dry-air plasma the primary ion form is N_2^+, O_2^+, and O^- [2]. In addition to the ions, the GD plasma contains oscillation excited molecules whose oscillating temperature may reach 5000 K. The ion composition of the GD plasma in air at $E/N < 7 \cdot 10^{-16}$ $V \cdot cm^2$ is determined by the processes of oxygen ionization, and at $E/N > 7 \cdot 10^{-16}$ $V \cdot cm^2$ by the ionization of nitrogen molecules [9]. Consideration of the oscillation excitation of nitrogen molecules enabled us to ascertain the increase in the coefficients of N_2 and O_2 ionization with an increase in T_o for $E/N < 7 \cdot 10^{16}$ $V \cdot cm^2$.

The adhesion of electrons to the O_2 molecules represents one of the main channels for the loss of electrons in a weakly ionized plasma containing oxygen. In the range $E/N \gtrsim 10^{-16}$ $V \cdot cm^2$ the following process [10] is primary:

$$e + O_2 \rightarrow O^- + O.$$

It follows out of an analysis of the data from [9] that the adhesion coefficient increases with an increase in E/N and reaches a maximum when $E/N = (8\text{-}12) \cdot 10^{16}$ $V \cdot cm^2$, then falling slightly. With an increase in the oscillation excitation of the nitrogen molecules the adhesion coefficient for electrons to O_2 increases.

The destruction of the negative ions occurs in ion-molecular reactions of electron separation, paired and triple recombination of positive and negative ions. The predominant process for the destruction of negative oxygen ions in the air plasma is the reaction [9]

$$O^- + O_2 \rightarrow O_3 + e \text{ with } K_n = 1 \cdot 10^{-18} \, m^3/sec \, (T = 300 \, K).$$

Figure 3 shows the ratio of the frequencies of oxygen and nitrogen ionization to the adhesion frequency ν_{ion}/ν_{ad}, where $\nu_{ion} = \nu_{O_2} + \nu_{N_2}$ (curve 1), and the frequency of separation to the frequency of adhesion ν_{sep}/ν_{ad} (curves 2 and 3) as functions of the reduced electric field strength E/N for various oscillation temperatures T_o of nitrogen molecules. These data have been derived on the basis of a solution of the Boltzmann equation with consideration of inelastic collisions of the second kind. Greater details regarding the computational method can be found in [11].

For discharge in dry air the ratio of the ionization frequency and the frequency of adhesion increases sharply with an increase in E/N (curve 1). When $E/N = 10.5 \cdot 10^{-16}$ $V \cdot cm^2$ the ratio ν_{ion}/ν_{ad} is equal to 1. In the region $E/N < 10.5 \cdot 10^{-16}$ $V \cdot cm^2$ the rate of electron adhesion exceeds the rate of ionization. The change in the oscillatory temperature T_o for the nitrogen has no effect on the ν_{ion}/ν_{ad} ratio, which suggests their proportional dependence on T_o. For the dependence of ν_{sep}/ν_{ad} on E/N we have presented two curves at T_o = 0 (curve 2) and at T_o = 0.4 eV (curve 3). With $E/N \geq 5.8 \cdot 10^{-16}$ $W \cdot cm^2$ the inequality $\nu_{sep}/\nu_{ad} \leq 1$ is satisfied for any T_o. With an increase in T_o the ν_{sep}/ν_{ad} ratio is equal to 1 for smaller E/N.

Thus there exists a region $E/N = (5.8\text{-}10.5)\cdot 10^{-16}$ V·cm^2 for $T_o = 0$ and a region $E/N = (4.5\text{-}10.5)\cdot 10^{-16}$ V·cm^2 for T_o = 0.4 eV, in which the concentration of negative ions n_- considerable exceeds the n_e electron concentration. This is in agreement with the results from [2], where the experimental ratios $E/N \geq 20$ are given.

Model of GD Contraction in a Flow of Air. Based on the experimentally derived distribution of the reduced electric-field strength E/N in the DC and on the relationships between the frequencies of ionization, adhesion, and electron separation with respect to E/N we can construct a model for GD contraction in a stream of air.

Let us examine E/N at the critical current (I_{cr} = 18-19 mA). In this case, in the DC we have $E/N = (4.5\text{-}6.8)\cdot 10^{-16}$ V·cm^2. min $E/N = (4.5\text{-}4.6)\cdot 10^{-16}$ V·cm^2 is achieved at the periphery of the chamber. At these values the frequency of adhesion is greater than the ionization frequency and the separation frequency (at T_o = 0.4 eV) (see Fig. 3) and the discharge is situated in a region in which the quantity of negative ions n_- exceeds the quantity of electrons n_e, which leads to a contraction of the discharge. We should note that when $E/N < 7\cdot 10^{-16}$ V·cm^2, $\nu_{ion} \ll \nu_{ad}$ (curve 1 in Fig. 3), so that at these values of E/N the primary mechanism regulating the relationship between n_e and n_- is electron separation. With $E/N < 4.5\cdot 10^{-16}$ V·cm^2, $\nu_{sep} > \nu_{ad}$, and consequently, $n_e > n_-$; once this condition is satisfied at the periphery of the discharge, it is stable (which is achieved at I = 15 mA). Thus it can be assumed that if $n_- > n_e$ in the entire discharge (including at the periphery) or if the frequency of adhesion is greater than the frequencies of ionization and separation, discharge contraction sets in, and the primary mechanism regulating discharge stability is separation. This is in agreement with [1, 12], where the high value of separation for discharge in oxygen is indicated. From this it follows that the criterion (presented in [2, 13]) for GD contraction $(\nu_{ion} - \nu_{ad}) \leq 0$ at the periphery of the discharge calls for refinement. Separation must be taken into consideration.

Let us introduce the parameter $K = (\nu_{ion} + \nu_{sep})/\nu_{ad}$. Figure 3 (curves 4 and 5) shows K as a function of E/N for T_o = 0 and T_o = 0.4 eV. We can see from an analysis of the theoretical data that $K \leq 1$ when $E/N = (4.5\text{-}10.5)\cdot 10^{-16}$ V·cm^2 (T_o = 0.4 eV), and here $n_e < n_-$. When $I = I_{cr}$ = 18-19 mA, $E/N = (4.5\text{-}4.6)\cdot 10^{-16}$ V·cm^2, K = 1. Consequently, the parameter $K = (\nu_{ion} + \nu_{sep})/\nu_{ad}$ may serve as the critical parameter and when $K \leq 1$ discharge contraction sets in. Moreover, it shuld be noted that the increase in the oscillatory excitation of the nitrogen T_o leads to contraction at low E/N, which comes about as a consequence of the increase in the adhesion frequency as T_o rises.

This model makes it possible to provide a physical explanation for the contraction mechanism in GD in air. The increase in the discharge voltage leads to an increase in the number of negative ions, and when $n_- > n_e$ the primary current carriers are the heavy positive and negative ions, which leads to the heating of the gas (with maximum heating observed at the channel axis) and this leads to thermal contraction.

Thus, this model of contraction with the adhesion mechanism of instability makes it possible, having calculated the kinetics of the plasma of a mixture of electronegative gases, to determine E/N at which GD contraction takes place.

NOTATION

l, interelectrode distance; R, tube radius/ I_{cr}, critical current of glowing discharge; I, current; E, electric-field strength; T_w, wall temperature; T_0, temperature at column axis; T, temperature; p, pressure; N, concentration; r, radial coordinate; z, longitudinal coordinate; ν_{ion}, frequency of ionization; ν_{ad}, frequency of electron adhesion to oxygen molecules; ν_{sep}, frequency of electron separation; n_-, concentration of negative ions; n_e, concentration of electrons; T_o, oscillating temperature of nitrogen molecules.

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RADIAL DISTRIBUTION OF ELECTRON CONCENTRATION IN A COMPRESSED LAYER

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We present results obtained in the measurement of electron concentrations in compressed layers, derived in the plasma deceleration of an end-face Hall accelerator with a flat solid barrier, and these measurement results were then compared with analogous measurement results obtained in free flows.

The study of the parameters in plasma jets has been stimulated by their extensive utilization in a number of branches of science and engineering [1, 2]. The present study continues the investigation to determine the parameters of a plasma generated by an end-face Hall accelerator (EHA) [3-5]. In [5] we find an experimental determination of the electron concentration in free plasma flows. At the same time, in the streamlining of the barrier by hypersonic plasma flows a deceleration zone is established, where the plasma parameters are significantly different from the corresponding parameters in a free jet, a fact which must necessarily be taken into consideration in evaluating the action of a plasma flow onto the surface of a solid. In this connection, results from such investigations are of particular interest. The process of gas-jet deceleration has been studied rather fully [6, 7], and it may serve as a characteristic as well for weakly ionized plasma flows. However, there exists virtually no theoretical and experimental studies into the processes of interaction with solid barriers on the part of plasma jets exhibiting a high level of ionization.

Here we have studied transverse luminescence spectra and we have determined the electron concentrations in compressed layers. For the purposes of this investigation, we chose EHA operating regimes in which measurements similar to those in a free jet were conducted: the magnetic-field induction $B = 1$ T in the discharge zone, the discharge current $J = 2200$, 2600, and 3000 A, the working gas flow rate $G_\Sigma = 10$ g/sec (8.5 g for air and 1.5 g for nitrogen), and the vacuum-chamber pressure $P_{ch} = 1.2 \cdot 10^3$ Pa. Here the velocity of the plasma was approximately 10-15 km/sec. This velocity was determined from pressures measured in the operating sections of the flow by means of a combined Pitot—Prandtl fitting, and from the deceleration enthalpy.

To produce a compressed layer along the path of the plasma jet a flat barrier fabricated in the form of a hollow copper cylinder with a diameter of 120 mm was set up perpendicular to the axis of the jet. The axis of the cylinder coincided with the axis of the flow. The barrier was cooled by pumping water through the inside cavity of the cylinder. The barrier diameter was chosen on the basis of jet dimensions. The barrier was positioned at a distance of $L = 140$ and 170 mm from the outlet of the accelerator nozzle. Depending on the discharge current and the working cross section, the thickness of the compressed layer was varied within limits of 25-30 mm. The radiation spectra for the compressed layer were recorded at sections removed from the plane of the barrier surface through a distance of 10 mm. One such photograph of the compressed layer is shown in Fig. 1.

A spectroscopic analysis of the plasma composition demonstrated that the radiation spectrum is sensitive to the magnitude of the energy introduced into the discharge, but the qualitative composition of the spectra remains unchanged both for the free jet and for the compressed layer. We should take note, however, that the intensity of radiation for the spectral lines of the compressed layer exceeds by factors of 15-20 the corresponding values for the free jet.

The luminescence spectra for the compressed layer in the 430-580 nm wavelength band consists primarily of isolated lines of NI and NII nitrogen atoms and ions. None of the lines for the elements contained in the composition of the barrier were seen. The hydrogen line H_β is observed in each of the cases, and its presence is probably associated with the existence of a small admixture of water vapors in the supply system (Fig. 2). It is noticeably broadened on the spectrum of the compressed layer. In order to determine the electron concentrations we employed a method based on the broadening of the H_β line as a consequence of the

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