NUMERICAL INVESTIGATION OF THE GROWTH OF GLOWING DISCHARGES IN TWO-DIMENSIONAL GEOMETRY

G. G. Gladush and A. A. Samokhin

UDC 537.525

It is known that a breakdown in gases can take place in two fundamental ways: by diffusion (the Townsend breakdown) or by forming a narrow current channel (the streamer breakdown). At present there are no reliable criteria for one or another of these mechanisms to occur. It is also an open question as far as the pressure region p < 10 mm Hg [1] is concerned. Even in the case of special preionization it is not always possible to avoid the streamer stage breakdown. It is obvious that the fundamental cause of a streamer breakdown is related to higher intensity of the electric field around the localized zone of higher conductivity [2]. In [3] the superiority was shown of using numerical methods in the analysis of an axisymmetric cathode directed streamer between two flat electrodes in nitrogen. In the present article the results are described of computations carried out to find out whether a mechanism is feasible for fusing the discharge at any early stage of ignition for the geometry of a flat electrode plane, which is the most favorable to an anode-oriented streamer. This effect was investigated within the framework of a nonstationary system of three equations in which the ionization processes, the recombinations in the balance of charged particles as well as the effect if space charge on the electric-field distribution have been taken into account [4]. One has ignored the diffusion, which is also favorable to the streamer breakdown.

With regard to the electron concentration n_e, the ion concentration n_i, and the electric-field potential φ the following system of equations is valid:

$$\begin{aligned} \partial n_e/\partial t + \operatorname{div}\mathbf{j}_e &= \alpha j_e - \beta n_e n_i, \quad \mathbf{j}_e = \mu_e n_e \nabla\varphi, \\ \partial n_i/\partial t + \operatorname{div}\mathbf{j}_i &= \alpha j_i - \beta n_e n_i, \quad \mathbf{j}_i = -\mu_i n_i \nabla\varphi, \\ -\Delta\varphi &= 4\pi e(n_i - n_e), \end{aligned}$$

where α is the first Townsend coefficient; β, recombination coefficient; μ_e, μ_i, the mobility coefficients for the electron and ion components; e, electron charge (e > 0).

The boundary conditions imposed on the electron concentration on the cathode and of the ion concentration on the anode correspond to the loss of electrons from the cathode by an ion flow (γ process) and to the lack of ions on the anode:

$$j_e|_c = \gamma j_i|_c, \quad j_i|_a = 0.$$

A given potential difference U is maintained between the cathode and the anode. On the remaining dielectric boundary of the discharge chamber, the normal component of the electric field is made to vanish since the characteristic time of physical processes (the Maxwell time) is less than the characteristic time in our problem. The following boundary conditions are, therefore, imposed on the potential:

$$\varphi|_c = 0, \ \varphi|_a = U, \ \partial\varphi/\partial n|_{\text{diel}} = 0.$$

The geometry of the electrodes enables one to limit the considerations to a two-dimensional description. The computations are carried out for a flat rectangular region. One side of the rectangle represents the anode, and on the opposite dielectric boundary in the middle of the flush mounting there is a narrow cathode. The distance between the electrodes is 1 cm, the size of the anode is 2 cm, the size of the cathode is 0.2 cm. The discharge space between them is filled with nitrogen, whose data are known [4]. The potential difference is U = 500 V, the gas pressure in the chamber is p = 5 mm Hg. The discharge is assumed to be symmetric relative to the straight line that is perpendicular to the electrodes' surface in the middle of the chamber.

Moscow. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 5, pp. 49-54, September-October, 1978. Original article submitted September 20, 1977.

0021-8944/78/1905-0614$07.50

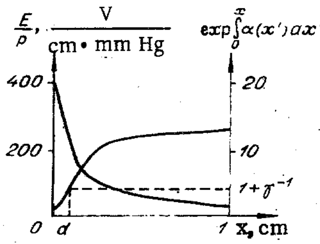

Fig. 1

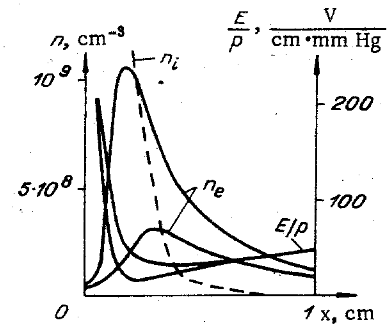

Fig. 2

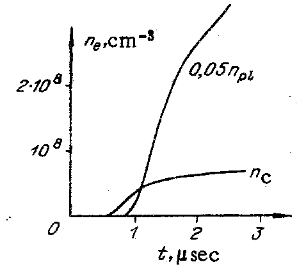

Fig. 3

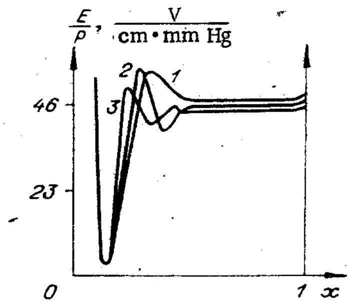

Fig. 4

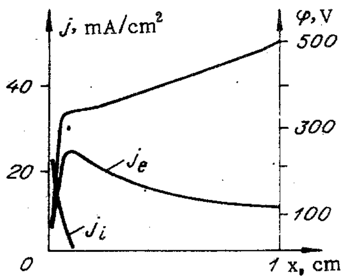

Fig. 5

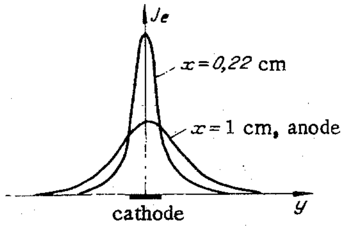

Fig. 6

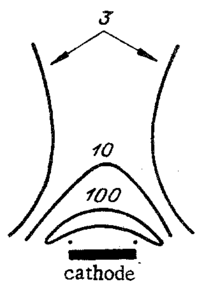

Fig. 7

The discharge was induced by a narrow layer of plasma near the cathode with the concentration of 10^8 cm^{-3}. During the period of ≈ 0.6 μ sec there is only a slight distortion of the electric field and the discharge flows in a known vacuum field. Until the effects of the space charge show up, the change in the electron concentration of electrons and ions along each line of the field force can be described by a system of two nonstationary and one-dimensional linear equations if recombinations are ignored. An analytic investigation within the framework of this simplified system shows that the sought quantities grow exponentially with the characteristic time τ whose value can be obtained from the integral equation

$$\gamma^{-1} = \int_0^{s_a} \alpha(s) \exp\left\{\int_0^s \alpha(s')\,ds' - \frac{t_{ie}(s)}{\tau}\right\} ds,$$

$$t_{ie}(s) = \int_0^s \{v_i^{-1}(s') + v_e^{-1}(s')\}\,ds',$$

where ds is the length element of the force line measured from the cathode; v_i and v_e are the drift rate of ions or electrons, respectively. For the distribution of the vacuum field on the symmetry axis (Fig. 1, t = 0) the time is $\tau = 0.2$ μsec and is approximately equal to the transition time of the ions from the breakdown boundary to the cathode. The distance d between the breakdown boundary and the cathode is determined by the equation

$$\ln(1+\gamma^{-1}) = \int_0^d \alpha(s)\, ds$$

and on the symmetry axis of the system it is equal to 0.08 cm. It follows from the solution that the zero density point of the space charge remains at the same location and can be found almost in the middle between the electrodes, its coordinate s_0 being given by the equation

$$\tau = \alpha^{-1}(s_0)/v_e(s_0),$$

which indicates that the growth in the electron density due to the drift from the cathode is equal to the rate of ion formation due to ionization processes at a given point. Since the plasma density grows exponentially, one would expect that in a time commensurate with τ the effects of the space charge would begin to appear. As the intensity of the electric field grows near the cathode, the rate of electron generation also increases, and the reduction in the potential drop reduces correspondingly the rate of ion formation; moreover, the point s_0 shifts towards the cathode. The correctness of the above considerations has been confirmed by numerical calculations.

With the space charge increasing, the quasineutrality requirement becomes essential and the electron flow is determined by the ion distribution. Since the drift time of the ions from the anode to the cathode (15 μsec) considerably exceeds τ, therefore the ion formation at each point takes place basically through ionization processes whose intensity starts to lag behind the formation rate of the electrons near the cathode with the appearance of the potential drop. A situation arises as a result, namely, that the conductivity in the space is insufficient to direct all the formed electrons from the cathode to the anode. Near the cathode the least intensity of the electric field can be found which limits the electron current to the chamber. A rapidly increasing concentration peak of locked electrons is superimposed on the ion distribution (Fig. 2, $t_1 = 0.9$ and $t_2 = 1$ μsec) the latter being displaced below the maximum of the ion concentration. Although the ions keep growing in number, the electron concentration increases even more rapidly at the maximum and at the instant 1.6 μsec it is comparable to the ion concentration. The discrepancy between the conductance in the space and the rate of electrons forming near the cathode diminishes in the course of time, since the surplus of electrons accumulated near the cathode compensates the positive charge of the ions and shortens the generation zone at the expense of generating a quasineutral plasma of high concentration. Thus, in ≈ 1.5 μsec after the appearance of the effects of the space charge, a quasistationary state is established with a characteristic time determined by the formation rate of the ions (Fig. 3, where the concentration of the electrons has been shown on the cathode n_c and in the space n_{pl} at the distance $x = 0.5$ cm from the cathode against time).

During the process of the discharge attaining the quasistationary state over the time interval from 1.1 to 1.6 μsec the forming of inhomogeneities in the distribution of the electric field was observed on the symmetry axis. Subsequent to the forming of the first deep minimum of the intensity near the cathode, the maxima and minima occurred successively (Fig. 4, where $1 - t_1 = 1.15$ μsec, $2 - t_2 = 1.35$ μsec, $3 - t_3 = 1.55$ μsec). The point at which the inhomogeneity arises is displaced in the course of time towards the anode, though each individual peak moves in the opposite direction from the anode to the cathode. The field distribution becomes, in the course of time, smooth (on the symmetry axis it is virtually constant) and attains in space the equality of the electron and ion concentrations. The characteristic time of this effect is, in accordance with the computations, much longer than the electron transit time and much shorter than the ion transit time. The distribution of the electrons advancing from the cathode into space thus has a chance to adjust itself to the electric field distribution, the ions forming at every point due to ionization. In the one-dimensional case, provided recombinations are ignored, one obtains the following system of equations describing the development of the field and of the conduction in space:

$$\begin{aligned} \partial n_i/\partial t &= \mu_e \alpha(E) J_e(t), \\ \partial E/\partial x &= 4\pi e\{J_e(t)/E - n_i\}, \end{aligned} \qquad (1)$$

where E is the absolute value of the intensity of the electric field ($J_e = n_e E$); the coordinate x is measured from the cathode.

If the ionization coefficient is a power of intensity, and also if the electric current depends on time, then there exists a self-consistent solution of (1) which qualitatively confirms the map of the forming of an oscillating electric field obtained by computations.

Within 2 μsec from the appearance of the effects of the space charge, the potential jump near the cathode reached 300 V with the full current of 5 mA/cm flowing through the system (Fig. 5, t = 2.6 μsec). The maximal value of the intensity on the symmetry axis is reached at the cathode and it is equal to 1300 V/cm · mm Hg the current density on the cathode being 25 MA/cm^2. The quasineutral plasma is now formed within the space with the ion concentration falling monotonically from the cathode to the anode, from $8 \cdot 10^9$ to $4 \cdot 10^9$ cm^{-3}. In the larger part of the volume, the ions are formed at the point due to ionization processes although in the region of minimal intensity of the electric field the deciding factor is the transition of ions over the field from the space points with higher E/p. On the symmetry axis the field intensity in the volume varies within the limits 37-38 V/cm · mm Hg increasing close to the anode to 44 V/cm · mm Hg. Across the discharge the intensity falls monotonically towards the chamber boundaries. With a reduction in the specific conductivity in the direction towards the anode, the effective width of the conductive zone increases (Fig. 6, t = 2.6 μsec), the integral current across a section of the column remaining unchanged. On the boundary separating the potential jump close to the cathode and the plasma in the volume, a narrow layer of quasineutral plasma is found with the concentration which is higher by one order than in the volume. The maximal value of the ion density is $1.6 \cdot 10^{11}$ cm^{-3} (Fig. 7, t = 2.6 μsec). In view of the edge effect, the electron flow density is not maximal at the center of the cathode but on its boundaries. Since the conductivity of the chamber rapidly falls at the lower dielectric boundary in the direction towards the side boundaries, therefore, the electrons formed at the edges of the cathode flow to the center into the region of the highest conductivity. Thus, there is a tendency for a redrawing of the flow next to the cathode.

The estimates carried out under the assumption of slow changes of E/p in the volume show that the ionization equilibrium is reached in 15-20 μsec. Within this time the effects due to the heating of the gas will become substantial.

The obtained results of the computations in two dimensions fully confirm the present concepts with regard to the mechanism of the flow passing through the gas. On the other hand, a number of interesting features have also come to light.

As a result of the lack of uniformity in the electric field, the system arrives at the state of a quasistationary cathode during the time 1.5-20 μsec; the electric current generated next to the cathode passes through the column with virtually no amplification though the conductivity in the column grows with time. When getting into the quasineutrality region in the volume, the discharge passes through an unstable stage which manifests itself as an oscillating electrical field arising on the symmetry axis. The quasineutrality zone forms the main part of the interval and its width is comparable with the distance between the electrodes. However, the current conducting channel is noticeable already in this zone, constituting 2-3 widths of the cathode. At the cathode between the region of the space charge and the column a narrow, sicklelike layer of high density plasma (plasma cathode) is formed with a clearly distinguishable intensity minimum. However, ahead of this layer no significant amplification of the electric field can be noticed as a result of the screening by the plasma column compared with the field in the column which could have been brought to the streamer breakdown.

Of course, to be able to realize such a mechanism one needs a considerable difference between the ionization rates in the space and at the cathode (by means of geometry selection or higher pressures), or one has to take into account the run up of the internal degrees of freedom of the molecules at the cathode.

The authors would like to express their thanks to A. A. Vedenov, A. P. Napartovich, and A. N. Starostin for their unceasing interest in this work and useful discussions.

LITERATURE CITED

1. G. Roeter, Electron Avalanches and Breakdown in Gases [Russian translation], Mir, Moscow (1968).
2. É. D. Lozanskii and D. B. Firsov, Theory of Sparking [in Russian], Atomizdat, Moscow (1975).
3. A. J. Davies, G. J. Evans, P. Townsend, and P. M. Woodison, "The numerical simulation of axially symmetric discharges between plane parallel electrodes," in: Fourth International Conference on Gas Discharges (1976).
4. S. Braun, Elementary Processes in Plasma of Gas Charge [Russian translation], Atomizdat, Moscow (1961).