EFFECT OF PREIONIZATION ON THE DEVELOPMENT OF A SELF-SUSTAINING DISCHARGE IN GASES

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The problem of obtaining a uniform gas discharge in large volumes is of great interest in connection with development of lasers based on molecular gases. For gas-discharge lasers in which the active medium is pumped by a self-sustaining discharge with preliminary ionization of the gas, two groups of instabilities leading to filamentation of the volume discharge can be distinguished. The first group includes instabilities that are related to the input of a certain amount of energy into the gas, for example, ionization or overheating-ionization instabilities [1]. The second group of physical processes leading to spark breakdown of the gas at the intial stage of the discharge is less well studied, especially on a theoretical level. The problem of the necessary conditions for homogeneous breakdown of gas was examined in [2-4], where it was shown that a homogeneous discharge can be obtained with a quasistreamer breakdown mechanism, when neighboring electronic avalanches overlap. In this case, the important circumstance that the discharge developes in an inhomogeneous electric field, arising due to the positive ionic volume charge, is taken into account only approximately. In order to understand completely the processes leading to spark breakdown of a gas, it is necessary to study in detail the spatial-temporal distribution of the electric field and charged particle densities in the interelectrode gap.

The development of a self-sustaining discharge in fields exceeding the static breakdown field was examined in [5-7]. Since the use of a high discharge voltage involves certain technical difficulties and a decrease in the efficiency of the entire laser system, in order to create gas-discharge lasers, it is especially interesting to investigate the discharge in fields E less than the static breakdown field E_{st}. The importance of a significant decrease in the breakdown voltage of a gas located in a stationary ionizing radiation field is demonstrated in [8, 9]. A discharge in air with preionization at $E < E_{st}$ was investigated theoretically and experimentally in [10].

In this paper, we examine the development of a uniform discharge with preionization in nitrogen. We investigate the dependence of the discharge formation time on the degree of preionization, gas pressure, and electric field intensity. The problem of the conditions for the appearance of spark breakdown of the gas is examined.

In order to describe the dynamics of a self-sustaining discharge, we used a system of equations including the transport equation for charged particles, the Poisson equation for the electric field, and equations for the source feeding the discharge:

$$\frac{\partial n_e}{\partial t} + \frac{\partial}{\partial x} v_e n_e = \alpha |v_e| n_e - \beta n_e n_i; \quad (1)$$

$$\frac{\partial n_i}{\partial t} + \frac{\partial}{\partial x} v_i n_i = \alpha |v_e| n_e - \beta n_e n_i; \quad (2)$$

$$\partial E/\partial x = 4\pi e(n_i - n_e); \quad (3)$$

$$L\partial I/dt + RI = U - U_d, \quad CdU/dt = -I, \quad (4)$$

with the following initial and boundary conditions:

$$n_e(t=0) = n_i(t=0) = n_0(x),$$

$$I(t=0) = 0, \quad U(t=0) = U_d(t=0) = U_0, \quad n_i(x=d) = 0,$$

$$\int_0^d E dx = -U_d, \quad |v_e| n_e(x=0) = \gamma_i |v_i| n_i(x=0) + \gamma_p \int_0^d \alpha |v_e| n_e dx.$$

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Here, the cathode is located at the point $x = 0$; the anode is located at the point $x = d$; n_e and n_i are the electron and ion concentrations; n_0 is the initial concentration of the plasma, created by preionization; I is the current in the external circuit; U is the voltage on the capacitor, which is the source feeding the discharge; U_d is the discharge voltage; v_e and v_i are the electron and ion drift velocities; α and β are the coefficients of ionization and recombination; L, C, and R are the inductance, capacitance, and resistance of the circuit feeding the discharge; γ_i is the coefficient of ion-electronic emission; γ_p is the coefficient of photoemission.

The system of equations (1)-(4) does not include diffusion of electrons and ions, since it was shown in [7] that diffusion has an insignificant effect on the behavior of the discharge. Heating of the gas is also neglected, i.e., the neutral particle density is assumed to be constant. This assumption is justified at the initial stage of the discharge, when the change in the gas temperature is small.

In order to approximate the coefficients α, β, μ_e and $\mu_i (v_e = -\mu_e E,\ v_i = \mu_i E)$ analytically in nitrogen, we used the following expressions [11]:

$$\alpha/p = A \exp(-Bp/|E|), \quad A = 0.066\ \text{cm}^{-1}\cdot\text{Pa}^{-1}, \qquad (5)$$
$$B = 2{,}06\ \text{cm}^{-1}\cdot\text{Pa}^{-1}\cdot\text{V} \quad \mu_e p = 379{,}9\cdot 10^5\ \text{cm}^2\cdot\text{Pa}\cdot\text{V}^{-1}\cdot\text{sec}^{-1},$$
$$\mu_i = 10^{-2}\mu_e, \quad \beta = 2\cdot 10^{-7}\ \text{cm}^{-3}\cdot\text{sec}^{-1},$$

where μ_e, μ_i are the electron and ion mobilities; p is the gas pressure.

In the calculations discussed below, the value of the coefficient of photoemission was taken as equal to 10^{-5}, while that of the ion-electronic emission was taken as equal to 10^{-2}. The initial distribution of the plasma density created by preionization was given by the function

$$n_0(x) = N \exp(-x/\lambda) \Big/ \int_0^d \exp(-x/\lambda)\, dx,$$

where N is the total plasma concentration per unit area and λ is a characteristic dimension of the ionization inhomogeneity. The inductance and resistance of the discharge supply circuit were chosen to be quite small and the discharge voltage equalled the voltage on the capacitance, whose value was taken as equal to $C = 3\cdot 10^{-10} S$, where S is the area of the electrodes (cm^2).

If the system of equations (1)-(4) is written in dimensionless variables E/E_0, n_e/n_p, n_i/n_p, I/I_p, U/U_0, x/d, t/τ_i, where $E_0 = U_0/d$; $n_p = \alpha_0 v_0/\beta$; $v_0 = \mu_e E_0$; $\alpha_0 = \alpha(E_0)$; $I_p = Sev_0 n_p$; $\tau_i = 1/\alpha_0 v_0$, then it is possible to separate some dimensionless parameters, which are convenient to use in interpreting the results obtained. In what follows, we shall show that the magnitude of the dimensionless parameters $\alpha_0 d = \tau_0/\tau_i$ and $\varkappa = 4\pi eN/E_0$, where $\tau_0 = d/v_0$ is the time of flight of electrons in the interelectrode gap, has the greatest effect on the development of the discharge.

Two characteristics of the system of equations describing the discharge in the gas are the presence of small parameters γ_i, μ_i/μ_e, $E_0/4\pi e n_p d$ and the strong dependence of the ionization coefficient on the electric field intensity. In an experiment, this leads to the existence of near-electrode layers with high electric field and charged particle concentration gradients and, in numerical calculations of the discharge, to certain difficulties in solving the system of equations (1)-(4). Satisfactory computational accuracy can be achieved by using a nonuniform grid with automatic selection of the spatial step size. Due to the strong decrease in the step size along the spatial coordinate h in the near-electrode layers, integration of Eqs. (1) and (2) using an explicit scheme leads to large expenditures of machine time, since the temporal step size h must satisfy the condition for stability of the explicit scheme $\tau < h/v_e$. For this reason, in order to integrate Eqs. (1) and (2), we used an implicit scheme with first-order accuracy and in order to determine the solution at the i-th step in time, in the divergence terms, the electric field was given at the i-th step, while in the right sides of (1) and (2), E, n_e, and n_i were given at the (i-1)-st step. Equations (1) and (2) can be solved directly together with (3) only with very small τ. This is related to the fact that insignificant errors in calculating n_e and n_i, in view of the smallness of the parameter $E_0/(4\pi e n_p d)$, lead to large errors in determining E from Eqs. (3) [7]. For this reason, in this paper, in order to determine the electric field intensity, we used the equation for conservation of current rather than Eq. (3):

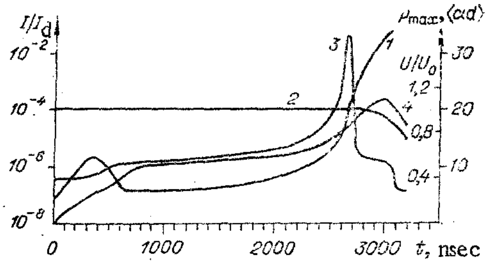

Fig. 1.

$$-\frac{1}{4\pi}\frac{\partial E}{\partial t}+e\left(n_e v_e - n_i v_i\right)=\frac{I}{S},$$

which follows from the system (1)-(4). The last equation was solved using a special scheme:

$$E(t+\tau)=\exp\left(-4\pi\sigma(t+\tau)\tau\right)\left(-\frac{I}{S}\,\frac{\exp\left(4\pi\sigma(t+\tau)\tau\right)-1}{4\pi\sigma(t+\tau)}+E(t)\right)$$

($\sigma = e(n_e\mu_e + n_i\mu_i)$ is the conductivity of the gas), which permits using a relatively large time step size ($4\pi\sigma\tau > 1$). The system of difference equations was solved by iteration. The time step size was chosen automatically from the condition that the relative changes in n_e, n_i and E be small at each step. It should be noted that the solution of Eqs. (1) and (2) by difference methods can lead to large computational diffusion, so that in a number of calculations, Eq. (1) was solved by the method of characteristics. The method of characteristics is useful for large gradients in the initial plasma concentration, but it leads to large expenditures of machine time at the stage of the discharge with developed near-electrode layers. In order to monitor the accuracy of the algorithm for solving the system of equations (1)-(4), calculations were carried out with smaller time and spatial step sizes, as well as test calculations for cases when the analytic solution of (1)-(4) is known. The test calculations were carried out for the case $L = R = \mu_e = \mu_i = 0$, i.e., the system (1)-(4) is written in the form

$$\begin{gathered}\partial n_e/\partial t=\partial n_i/\partial t=\alpha\,|v_e|\,n_e-\beta n_e^2,\\ n_e(t=0)=n_i(t=0)=n_0,\ \partial E/\partial t=I/(CSd),\\ E(t=0)=-U_0/d.\end{gathered} \tag{6}$$

Comparison of the solution of the system of equations (1)-(4) with solution (6) is of interest in itself in order to understand the processes occurring in a gas discharge. Test calculations were also performed for another limiting case, when $E \ll E_{st}$, $R = L = 0$, $C = \infty$ and a constant electron current is given at the cathode. Then, the system of equations (1)-(4) describes the distribution of the electric field and charged particle density in a gas diode and the stationary solution of (1)-(4) is known. For calculations with kinetic coefficients α, μ_e, μ_i for the mixture $CO_2:N_2 = 1:7$, proposed in [6], the disagreement between our results and the results of [6] turned out to be less than 5%. The test calculations as a whole demonstrated the satisfactory accuracy of the algorithm for solving the system of equations describing a nonstationary one-dimensional discharge in a gas proposed here. In this case, the average time for solving (1)-(4) on a BESM-6 computer was 5-10 min.

Figure 1 shows the dependence of the discharge current, discharge voltage, and $\langle\alpha d\rangle = \int_0^d \alpha \times (E)dx$ (curves 1-3, respectively) on time with $E/p = 0.3$ V/cm/Pa, $p = 2.03\cdot10^4$ Pa, $d = 5.6$ cm, $\lambda \gg d$ and $N = 2.5\cdot10^7$ cm^{-3}. The spatial distribution of the electron density (a), electric field intensity (b), ionization intensity of the gas (c), and the value of $\int_0^x \alpha dx$ at different times (t = 250 nsec (1), t = 1500 nsec (2), t = 2500 nsec (3), t = 2620 nsec (4), t = 2650 nsec (5), t = 2700 nsec (6), t = 2750 nsec (7)) with the same discharge parameters and degree of preionization are shown in Fig. 2. The results of our calculations show that the discharge passes through four characteristic stages.

At the first stage, the discharge current increases for some time due to ionization amplification, and then decreases due to convective transport of electrons out of the discharge gap. The positive ionic charge formed at the same time distorts the electric field

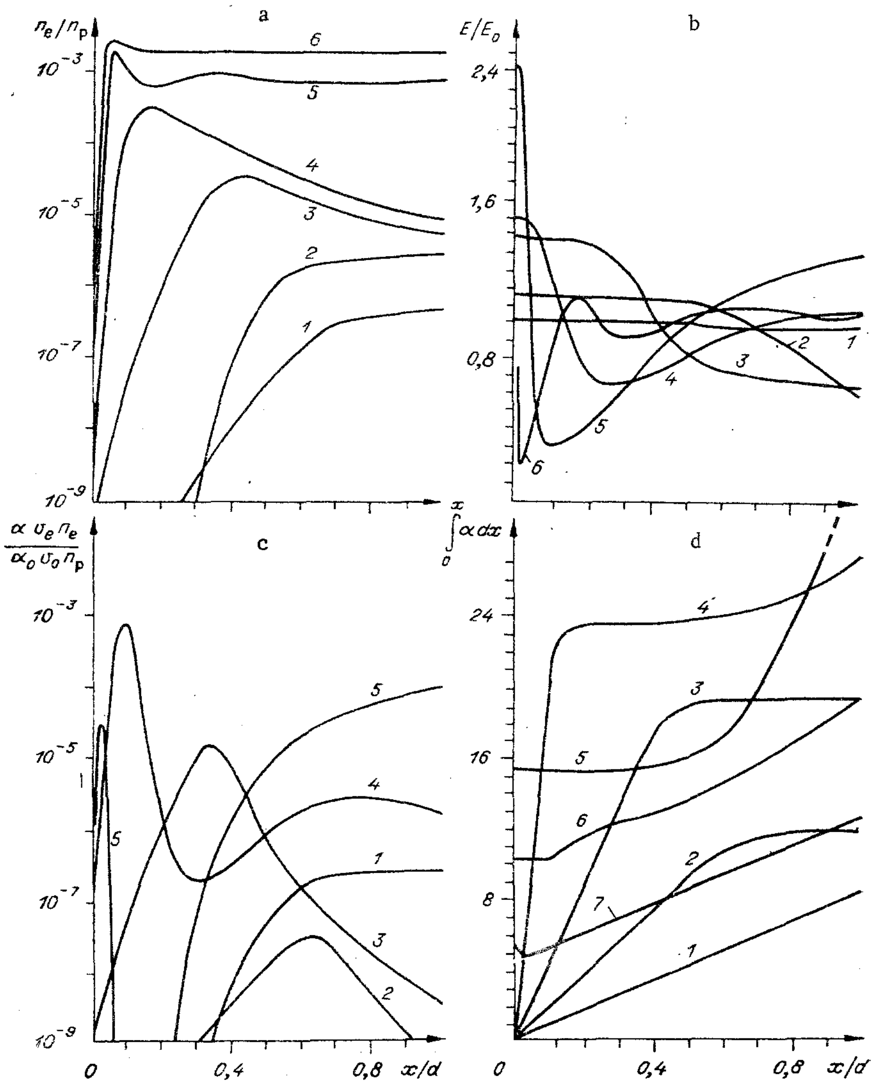

Fig. 2.

and $\langle \alpha d \rangle$ increases. We note that the value of $\langle \alpha d \rangle$, established after the completion of the first stage of the discharge, is determined not only by the magnitude of the parameters $\alpha_0 d$ and $\varkappa$, but also by the nature of the spatial distribution of the plasma, created by preionization. The increase in plasma concentration at the cathode leads to an increase in $\langle \alpha d \rangle$ due to the fact that an electron starting at the cathode forms the maximum number of ions. In calculations, where the primary plasma was created primarily at the anode, an appreciable increase was observed in the electrical strength of the gap and delay time for breakdown. The characteristic time of existence of the first stage of the discharge equals the flight time τ_0.

At the second stage of the discharge, there is further accumulation of ions in the interelectrode gap and $\langle \alpha d \rangle$ increases due to the distortion of the electric field. The electric field intensity decreases monotonically from cathode to anode, while the maximum intensity of ionization of the gas moves toward the cathode. Electrons at this stage of the discharge form at the cathode primarily due to ion-electronic emission. For the development of the discharge, it is necessary that the electron current through the anode exceed the ion current through the cathode. Therefore, the value of $\langle \alpha d \rangle$ after the first stage of the discharge is completed must satisfy the Townsend criterion $\gamma_i(\exp\langle \alpha d \rangle - 1) > 1$. For small values of $\langle \alpha d \rangle$, the time of existence of the second stage of the discharge makes a considerable contribution to the total time for the development of the discharge. It should be noted that the presence of the first two stages is characteristic for a discharge with relatively small parameters $\alpha_0 d$ and $\varkappa$. For larger values of these parameters, the first stage of the discharge goes over directly into the third stage over a time shorter than the flight time.

At the third stage of the discharge, a near-cathode layer that supplies electrons to the discharge gap is formed. It is well known that in the cathode layer, occupying with relatively small discharge currents ($E_0/(4\pi e n_d d) \ll 1$) a small part of the discharge gap, the ion density and electric field intensity increase sharply. As a result, the condition for the discharge to be self-sustained $\gamma_i\left(\exp\int_0^{x_c}\alpha(E)\,dx-1\right)=1$, where x_c is the length of the cathode layer, is satisfied on the cathode layer. Our calculations show that during the formation of the cathode layer, the value of $\langle\alpha d\rangle$ can greatly exceed $\langle\alpha d\rangle = \ln(1/\gamma_i + 1)$, necessary for the existence of a self-sustained discharge. For this reason, at this stage of the discharge, in principle, it is possible for a streamer to form and for the discharge to change over from the volume stage into the spark stage. An analysis of the development of the discharge at the third stage is quite complicated, since it occurs over times comparable to τ_0 and is characterized by a large nonuniformity of the electric field and charged particle density. Starting from the computational results, we shall give a qualitative description of the processes occurring at the third stage of the discharge.

At any time, the interelectrode gap can be arbitrarily separated into three regions. In view of the strong dependence of the coefficient of ionization on the magnitude of the electric field, the effective multiplication of electrons occurs in the first region $x < x_*(t)$, where the electric field intensity is maximum. In this case, the ionization intensity has a maximum at the boundary of the first region. Accumulation of ions in region II ($x \sim x_*(t)$) leads to a decrease in the field in the vicinity of $x_*(t)$ and an increase in the field at the cathode, i.e., the boundary of the first region shifts toward the cathode. The passage of an ionization wave is accompanied by an increase in αd. In region III ($x > x_*(t)$), the gas ionization is small, so that the ion density remains unchanged, while the electron density is determined by convective transport out of region I. Since the electron multiplication factor in region I increases with time, the density of electrons entering from region I, beginning with some time, exceeds the density of ions formed at the time of passage of the ionization wave. For this reason, at the third stage, the field intensity in region III begins to increase, while in region II, a minimum is observed in the electric field intensity. An increase in the field leads, starting at a definite time, to intense ionization of the gas in region III. Due to the increase in the conductivity of the gas, the electric field intensity and the charged particle density in the interelectrode gap level off. The value of $\langle\alpha d\rangle$ drops sharply, while the value of $\langle\alpha x_c\rangle=\int_0^{x_c}\alpha dx$ in the cathode layer ($x_c \ll d$) ensures that the discharge is self-sustained. The nature of the time dependence of $\langle\alpha d\rangle$ at the third stage of the discharge is determined primarily by the electric field intensity and gas pressure. When $\varkappa$ increases and λ decreases, the maximum value of $\langle\alpha d\rangle$ decreases somewhat.

Due to the low conductivity of the gas at the first three stages, the discharge voltage with our parameters of the supply sources remains unchanged. The role of recombination processes in the balance of the charged particle density is also insignificant. For this reason, for $\lambda \gg d$, the spatial-temporal distribution of the electric field and charged particle density in the variables x/d and t/τ_i must depend only on the values of the parameters E/p, $\alpha_0 d$, $\varkappa$ and constants γ_i, γ_p, μ_i/μ_e. Neglecting recombination and assuming the discharge voltage is constant, the system of equations (1)-(4) in dimensionless variables $n_e' = n_e d/N$, $n_i' = n_i d/N$, $z = (E_0 - E)/Bp$, $x' = x/d$, $\tau = t/\tau_i$ with the coefficients μ_e, μ_i, α approximated by (5) can be represented for $\lambda \gg d$ in the form

$$\frac{\partial n_e'}{\partial\tau}+\alpha_0 d\frac{\partial}{\partial x'}(1+\varepsilon z)\,n_e=\exp\left(\frac{z}{1+\varepsilon z}\right)n_e'(1+\varepsilon z),$$

$$\frac{\partial n_i'}{\partial\tau}-\alpha_0 d\frac{\partial}{\partial x'}\frac{\mu_i}{\mu_e}(1+\varepsilon z)\,n_i'=\exp\left(\frac{z}{1+\varepsilon z}\right)n_e'(1+\varepsilon z),\quad \frac{\partial z}{\partial x'}=\varkappa_*(n_e'-n_i')$$

with the following initial and boundary conditions:

$$n_e'(\tau=0)=n_i'(\tau=0)=1,\quad \int_0^1 z\,dx'=0,\quad n_i'(x'=1)=0,$$

$$n_e'(x'=0)=n_i'(x=0)\,\gamma_i\frac{\mu_i}{\mu_e}+\frac{\gamma_f\alpha_0 d}{1+\varepsilon z(x=0)}\int_0^1\exp\left(\frac{z}{1+\varepsilon z}\right)(1+\varepsilon z)\,n_e'dx'.$$

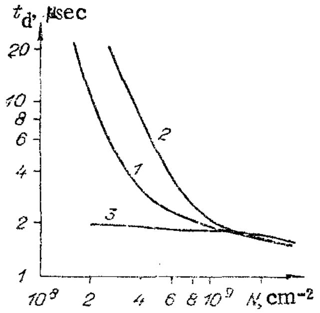

Fig. 3.

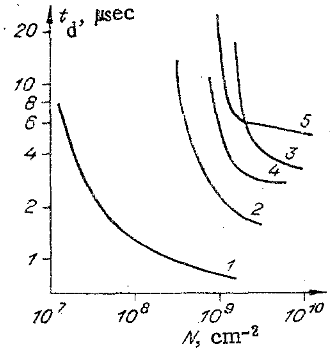

Fig. 4.

For small field distortions $\varepsilon z \ll 1$ ($\varepsilon = E_0/pB \sim 0.1$–$0.2$), the parameters $\alpha_0 d$ and $\varkappa_* = 4\pi eN/Bp$ must play a determining role in the development of the discharge at the first three stages. Our calculations showed that for identical $\alpha_0 d$ and $\varkappa_*$, but different E_0/p, the time dependences of $\langle\alpha d\rangle$ and the discharge current differ at the first three stages by only $\sim$10%. The magnitude of the parameter ε can affect the development of the discharge for small pd, since the value of $\alpha_0 d$ increases when pd decreases with ε remaining constant.

At the fourth stage, the development of the discharge is satisfactorily described by the system of equations (6) neglecting the divergence terms. Although the process of formation of the cathode layer continues at this stage of the discharge as well, the cathodic voltage drop becomes much less than the voltage on the electrodes. Since the last stage has been quite well studied, we shall only note the fact that the development of the discharge at this stage is practically independent of $\varkappa$. The delay time in the current maximum, related to the voltage drop on the capacitance, relative to the termination of the third stage of the discharge, is proportional to τ_i.

We define the total time for development of the discharge as the delay time in the current maximum, and we define the time for formation of the cathode layer as the delay time in the maximum of $\langle\alpha d\rangle$. The dependence of the discharge development time t_d on N with E/p = 0.27 V/cm/Pa, p = $2.03 \cdot 10^4$ Pa, and d = 5.6 cm is shown in Fig. 3 (curve 2: λ = 1 cm; curve 1: $\lambda \gg 1$). This figure also shows t_d as a function of N for a calculation of the discharge using the system of equations (6). For $N \gtrsim 10^9$ cm^{-2} the time of formation of the cathode layer makes a small contribution to t_d and the total time for formation of the discharge approximately coincides for all three cases. The dependences of the time for development of the discharge on N with d = 5.6 cm, $\lambda \gg d$ and different values of p and E/p are presented in Fig. 4 (1: p = $2.03 \cdot 10^4$ Pa, E/p = 0.3 V/cm/Pa; 2: p = $2.03 \cdot 10^4$ Pa, E/p = 0.27 V/cm/Pa; 3: p = $2.03 \cdot 10^4$ Pa, E/p = 0.24 V/cm/Pa; 4: p = $1.01 \cdot 10^4$ Pa, E/p = 0.27 V/cm/Pa; 5: p = $0.5 \cdot 10^4$ Pa, E/p = 0.27 V/cm/Pa). A characteristic of the graphs presented, especially for small p and E/p, is the existence of some N_*. For $N \gtrsim N_*$, the discharge development time depends weakly on N, while for $N \lesssim N_*$ a decrease in N leads to a sharp increase in t_d. Similar behavior of the dependence of the discharge development time on N was observed in theoretical and experimental studies of a discharge in air with $E < E_{st}$ [10].

Let us examine the possibility of filamentation of the discharge at the initial stage with $\alpha_0 d \lesssim 20$. The necessary conditions for ignition of a uniform discharge with $\alpha_0 d \gtrsim 20$ were studied in [2-4]. Since the filamentation of the discharge is a process that is largely three-dimensional, the one dimensional model of the discharge only gives qualitative information about the mechanism of the transition of the discharge out of the volume stage into the spark stage.

In the streamer model of the appearance of spark breakdown of the gas, an electron starting at the cathode must form an avalanche with a total number of particles $N_s \sim 10^8$ [12, 13]. We shall describe the process of avalanche formation from a single electron in the form

$$\partial P/\partial t + v_e \partial P/\partial x = \alpha |v_e|, \quad P|_{x=0} = 0,$$

where P is the multiplication factor in a single avalanche and e^P is the number of particles in the avalanche. In the last equation, the electric field intensity was determined from calculations of a one-dimensional discharge. Streamer breakdown of a gas is possible for $P_{max} \sim \ln N_s \sim 20$. The necessary condition for quasistreamer gas breakdown with $P_{max} \gtrsim 20$ is overlapping of neighboring electronic avalanches [2, 3]. Using the diffusion theory [12], the radius of the streamer head r_s can be estimated from the equation $r_s = \sqrt{6Dl_s/v_e}$, where D is the coefficient of diffusion. Then the neighboring avalanches overlap, if $(n_e/N_s)\pi r_s^2 l_s > 1$ [3]. Here, n_e is the density of electrons at a distance l_s from the cathode, where the condition $P(l_s) \geqslant 20$ is satisfied. The time dependence of P_{max} (curve 4) with $E/p = 0.3$ V/cm/Pa, $p = 2.03 \cdot 10^4$ Pa, $d = 5.6$ cm, $\lambda \gg d$, and $N = 2.5 \cdot 10^7$ cm^{-2} is presented in Fig. 1. The criterion for the possibility of the formation of a streamer $P_{max} \geqslant 20$ is satisfied at $t = 2800$ nsec, but the electron density at these times satisfies the condition for overlapping of neighboring avalanches. It should be noted that the development of a streamer with $E < E_{st}$ in the volume of the discharge is inhibited, since the condition $P_{max} \geqslant 20$ is attained only with large field distortions, i.e., with a high charged particle concentration. However, for $P_{max} \geqslant 20$, streamer breakdown can occur on the boundary of the discharge, where the electron density is much lower. The problem of the time for transition of the streamer into a spark channel, which can cause filamentation of the volume discharge, remains unsolved. When E/p and pd decrease, the value of P_{max} decreases and the streamer cannot arise.

If the time for formation of the cathode layer depends strongly on the plasma concentration, then filamentation of the discharge can occur due to spatial inhomogeneities in the plasma created by preionization. Since the characteristic time for increase in current at the fourth stage of the discharge equals τ_i, the development of the discharge in a separate filament can determine the development of the discharge in the volume with $\Delta t_d > \tau_i$. Here, Δt_d is the fluctuation in the delay time of the discharge, due to fluctuations in the initial plasma concentration ΔN. Remaining within the scope of the one-dimensional model, we can write $\Delta t_d \sim (\partial t_d/\partial N)\Delta N$ and the condition for homogeneous breakdown of the gap can be written in the form

$$\frac{\Delta N}{N} \frac{t_d}{\tau_i} \frac{\partial \ln t_d}{\partial \ln N} \leqslant 1. \quad (7)$$

Since the time of formation of the discharge depends strongly on the degree of preionization with $N \leqslant N_*$, filamentation of the discharge is possible with $N < N_*$. For example, for $\Delta N/N \sim 0.1$ condition (7) is not satisfied for $E/p = 0.27$ V/cm/Pa, $p = 2.03 \cdot 10^4$ Pa, $d = 5.6$ cm, if $N \leqslant 8 \cdot 10^8$ cm^{-2}. The quantity N_* depends strongly on E/p. This agrees well with the fact that in the experiments in [4, 14, 15], the lower limit on the voltage necessary for homogeneous breakdown of the gas is practically independent of N. As the gas pressure decreases, the value of N_* changes little, while the region in which filamentation of the discharge is possible, becomes smaller (see Fig. 4). For this reason, starting from the model proposed for the filamentation of the discharge, it may be assumed that for small gas pressures either a uniform breakdown occurs or the discharge does not form at all. As the gas pressure and the value of $\alpha_0 d$ increase, spark breakdown of the gas is possible over a wide range of variation of N.

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ELECTRIFICATION OF AEROSOL PARTICLES MOVING IN A ONE-DIMENSIONAL CORONAL DISCHARGE

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The electrification of dispersed aerosol particles as the latter move through the region of a one-dimensional, unipolar coronal discharge is analyzed in the approximation of electrohydrodynamics [1, 2]. The problem of such a discharge in a stationary gas was solved in [3], while it was solved for gas motion at a constant velocity in [4]. A numerical investigation on a computer of the problem of a one-dimensional coronal discharge in an aerosol and the charging of its particles in the case when the aerosol moves in the direction of ion motion was carried out in [4], where the influence of the charging of aerosol particles on the coronal discharge is also taken into account.

In the present work we consider cases when the aerosol moves in the direction of ion motion or opposite to it, while the aerosol particles do not affect the coronal discharge. An exact analytical solution of the problem of particle charging is found in this formulation, it is investigated, and simple asymptotic expressions are obtained for the dependence of the particle charge on the local value of the electric field strength and the aerosol velocity.

1. Let us consider one-dimensional steady flow of an aerosol consisting of a gas and initially uncharged, dispersed liquid particles through the region of a unipolar coronal discharge between two plane grid electrodes placed perpendicular to the stream. For determinacy we assume that the collector electrode is grounded (we take its potential as zero), while to create the coronal discharge a system of needles, which start to display corona at an emitter potential Φ_0, is installed on the emitter electrode. Let the distance L between the collector and the emitter be sufficiently large and let nonuniformity of the electric field near the grid electrodes be neglected. We choose the Cartesian coordinate system x, y, z so that the emitter and collector lie in the planes x = 0 and x = L. We are confined to the case when the influence of the electric field on the motion of the gas and aerosol particles is small. For this it is sufficient to satisfy the inequalities

$$|qE|L/\rho u^2 \ll 1, \quad qbE^2L/(\rho c_V T|u|) \ll 1,$$
$$\min\left(|QE|/(6\pi\mu a|u|), \quad |QE|L/mu^2\right) \ll 1,$$

where q is the electric charge density of ions in the region of the unipolar coronal discharge; b is their mobility (b > 0 for a positive coronal discharge while b < 0 for a negative one); u and E are the projections of the gas velocity and the electric field strength onto the x axis; ρ, μ, c_V, and T are the density, viscosity, specific heat, and temperature of the gas (its relative permittivity is taken as one); Q, m, and a are the electric charge,

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