ELECTRIC STRENGTH AND ELECTRICAL CONDUCTIVITY OF A VOLUME DISCHARGE IN THE PRESENCE OF EXTERNAL IONIZATION

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A study of the properties of the electric strength and electrical conductivity of a gas gap subjected to the action of an external ionizing radiation is of interest in connection with the engineering application of a triggered volume discharge [1] and with questions of gas insulation in an ionizing radiation field.

It is a feature of the electric strength of a gap under the action of a high intensity ionization source that breakdown can develop for an undervoltage η [$\eta = (U_0 - U_*)/U_0$, U_0 is the static breakdown voltage, U_* is the breakdown voltage in the presence of ionizing radiation] of some tens of a percent. The breakdown process is characterized by the fact that as a result of the development of instability the volume semi-self-maintained discharge passes to a spark discharge. The breakdown development time τ has a marked dependence on the applied voltage and varies within the limits of several orders of magnitude.

Current flow in the stage of semi-self-maintained discharge is characterized by a high electrical conductivity. According to [2] this is explained by the fact that a layer forms in the neighborhood close to the cathode which acts as an emitter with an infinite emissivity. For a high enough intensity of ionizing radiation the layer thickness Δd and the potential drop U_K across it satisfy the inequalities $\Delta d \ll d$ and $U_K \ll U$ (where d is the interelectrode distance, and U is the applied voltage). The presence of an emitter layer and the absence of a distorted field in most of the gap ensure a high electrical conductivity.

The present paper attempts to explain the instability (for $\tau \sim 10^{-7}$ sec) of a volume semi-self-maintained discharge, triggered by a constant external ionization source on the basis of Townsend ionization in an inhomogeneous field, and also discusses the role of shock ionization in ensuring the emissivity of the layer close to the cathode, taking as an example the calculation of the conductivity current when an external pulsed ionization source acts.

§1. The development of a current in an air gap under the action of a constant and uniform ionization source is considered in order to find a possible explanation of triggered discharge for finite values of η. The initial system of equations as well as the boundary and initial conditions have the form

$$\frac{\partial q_+}{\partial t} = \alpha(E) j_e + \frac{\partial j_+}{\partial x} + Q, \quad \frac{\partial q_-}{\partial t} = \beta(E) q_e - \frac{\partial j_-}{\partial x},$$
$$\frac{\partial q_e}{\partial t} = \alpha(E) j_e - \frac{\partial j_e}{\partial x} - \beta(E) q_e + Q, \quad \frac{\partial E}{\partial x} = -4\pi(q_+ - q_- - q_e),$$
$$j_-(0,t) = j_+(0,t) = 0, \qquad j_e(0,t) = \gamma_+ j_+(0,t) + \gamma_f \int_0^d \alpha(x,t) j_e(x,t)\,dx, \tag{1}$$
$$\int_0^d E(x,t)\,dx = U = \text{const}, \quad q_-(x,0) = q_+(x,0) = q_e(x,0) = 0,$$
$$j(t) = \frac{1}{d}\int_0^d [j_e(x,t) + j_+(x,t) - j_-(x,t)]\,dx,$$

where j_+, j_-, j_e, and q_+, q_-, q_e are the current and charge densities for positive and negative ions and electrons, $\alpha(E)$ and $\beta(E)$ are the impact ionization coefficient and sticking probability, Q is the specific charge produced in the gas by the external ionization source, γ_+ and γ_f are the coefficients of secondary ionization at the cathode as a result of ion impact and photoionization, and j is the discharge current density in the gap.

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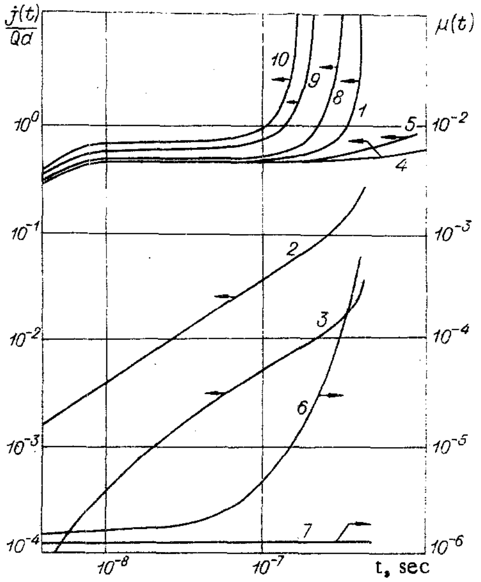

Fig. 1

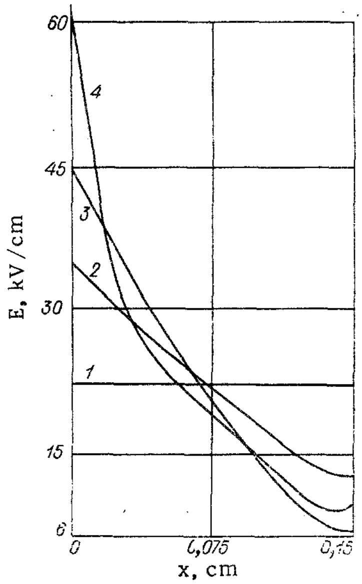

Fig. 2

In solving the system of equations numerically for the coefficient $\alpha(E)$ well-known empirical expressions [3] were used which are valid in the appropriate intervals of variation of E/p. The adherence process is described by the coefficient $\beta(E) = (ep/m_e\mu_e)h(E)$, where e, m_e, and μ_e are the charge, mass, and mobility of the electrons. The graphical dependence given in [4] was used for the sticking probability $h(E)$. Recombination was neglected since the time τ for instability to develop with the values of the parameters used in the problem is much less than the recombination time.

The system (1) was solved numerically by means of a representation in finite differences [5]. The coordinate Δx and time Δt step lengths were chosen from the condition that the solution be stable ($\Delta t \lesssim \Delta x/v_e(E)$). Moreover, an additional choice of values of Δx and Δt was made on the empirical grounds that the increment of the variable functions be small compared with their absolute values at each coordinate and time step.

Figure 1 gives calculated curves for the discharge current (in dimensionless variables j/Qd) and gas amplification coefficient $\mu(t)$ which characterize the effect of impact ionization and field distortion on the time variation of current in a plane-parallel gap of distance $d = 0.15$ cm ($\Delta x = d/50$, $\Delta t_0 = 10^{-9}$ sec, $\gamma_+ = 0$, $\gamma_f = 1.5 \cdot 10^{-5}$). Curves 1-3 describe the discharge current j and the current of positive j_+ and negative j_- ions, respectively, for $U = 3.3$ kV and $Q = 3 \cdot 10^8$ R/sec (the current density j_d of an equivalent beam of elqctrons creating a charge Q in air for $p = 760$ mm Hg is determined from the formula $j_d = 6.6 \cdot 10^{-12}Q$ A/cm^2). It can be seen from these curves that the total current j is basically determined by the electron component. Curve 4 describes a current j for $\alpha = 0$ (the parameters U and Q correspond to curve 1). Comparison of curves 1 and 4 shows that the sharp increase in current for $t \sim 4 \cdot 10^{-7}$ sec is connected with the multiplication of electrons as a result of impact ionization. The fact that the current increase as a result of this process occurs for $U < U_0$ [$\mu_0 \equiv \gamma(e^{\alpha_0 d} - 1) \ll 1$] is explained by the distortion of the field which results from the formation of a fairly large specific charge in the gas by the external source $Q \gtrsim U/4\pi d^2\tau$ ($Q \gtrsim 2 \cdot 10^8$ R/sec for $U \approx 4$ kV, $d \approx 0.15$ cm, and $\tau \approx 3 \cdot 10^{-7}$ sec). This distortion leads to an increase in the quantity $\int_0^d \alpha(x, t)\,dx$ compared with the initial value of $\alpha_0 d$.

In order to determine the effect of the volume charge on the process of impact ionization the current j is calculated for $U = 3.3$ kV and a fairly small specific ionization Q ($Q = 10^2$ R/sec) when it is known that field distortion can be neglected (curve 5). In this case there is no sharp increase in current. The slow current growth described by curves 4 and 5 is caused by the accumulation of positive ions in the gap as a result of the action of the constant ionization source. Curves 6 and 7 give a time change of the gas amplification coefficient $\mu(t) \equiv \gamma\left(e^{\int_0^d \alpha dx} - 1\right)$ for $Q = 3 \cdot 10^8$ R/sec and $Q = 10^2$ R/sec, respectively (U = 3.3

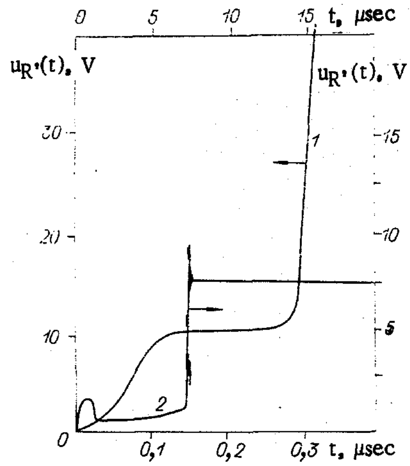

Fig. 3

kV). The increase in μ for $Q = 3 \cdot 10^8$ R/sec confirms the conclusion that the sharp increase in current is caused by the amplification of impact ionization as a result of field distortion. When the applied voltage is increased the development time of breakdown decreases as can be seen from curves 8–10 [8) U = 3.6 kV; 9) U = 4.2 kV; 10) U = 4.2 kV; $\beta \to \beta/3$].

The field distribution for $Q = 3 \cdot 10^8$ R/sec, U = 3.3 kV, and at different times preceding the sharp increase in current, is shown in Fig. 2 (curves 1–4 refer to times $t = 0$, $1.7 \cdot 10^{-7}$, $3.02 \cdot 10^{-7}$, $4.0 \cdot 10^{-7}$ sec). Thus, by considering only the particle balance allowing for the action of a space charge we can obtain the development of current under conditions when a constant and uniform ionization source acts in a semi-self-maintained gap ($\eta \lesssim$ 30%) and for times $\tau \sim 10^{-7}$ sec.

The calculated curves 1, 8, and 9 in Fig. 1 are close to the experimentally observed discharge current oscillograms. In the experimental determination of the triggered breakdown of an air gap a circuit was used which included a reservoir capacitor (C = 1100 pF), a discharge gap (C_1 = 1 pF) with stainless-steel electrodes, and a load resistance of R = 1 kΩ. An electron accelerator producing an electron beam ($E_e \approx 1$ MeV) with a rise time of $\sim 10^{-7}$ sec and a pulse length of $\sim 10^{-6}$ sec was used as an ionization source. The electron beam was in a direction parallel to the plane of the electrodes. Oscillograms of the voltage $U_{R'}(t)$ on a resistance R' = R/14 were recorded. For the parameter chosen for the measuring circuit the difference between the discharge current in the gap and the current in the external circuit can be neglected for $t \gtrsim 10^{-7}$, so that the oscillogram of the voltage $U_{R'}(t)$ is proportional to the current pulse in the gap, and $j(t) = U_{R'}(t)/R'S$, where the area of the electrodes is $S = 1.5$ cm^2.

The discharge current pulse shape depends on the applied voltage U. If the value of U is less than some limiting value U_*, the current pulse in the gap has the same form as the electron beam pulse. For $U > U_*$ an instability is observed to develop which leads to spark breakdown. Two characteristic discharge current oscillograms in the presence of breakdown are given in Fig. 3. Curve 1 (d = 0.12 cm, $Q = 10^9$ R/sec, U = 3.6 kV, E/p = 40 V/cm·mm Hg, $\eta \sim$ 30%) refers to the case when the development time of breakdown τ is less than the electron pulse length T, so that the formation of the breakdown occurs under the conditions of action of a constant ionization source. It is just to this case that the calculation of discharge current given above applies. The satisfactory agreement, as regards the time for breakdown to develop, between calculated (curve 8 in Fig. 1) and experimental (curve 1 in Fig. 3) data for close values of Q and d shows that it is possible to explain breakdown in a semi-self-maintained gap ($\eta \leq$ 30%) as a result of the amplification of impact ionization in a nonuniform field.

As η is increased the development of breakdown proceeds after the electron irradiation is switched off at the stage of the retarded component of current (curve 2 in Fig. 3, d = 0.2 cm, $Q = 7 \cdot 10^8$ R/sec, U = 3.2 kV, η = 48%, and E/p = 27 V/cm·mm Hg), and the breakdown retardation time after removal of the electron beam varies within the limits of several orders of magnitude. If we assume that while the ionizing radiation is acting the coefficient μ approaches unity as a result of the field distortion, the current should be maintained as a result of secondary ionization processes after the source is switched off, and the current curve

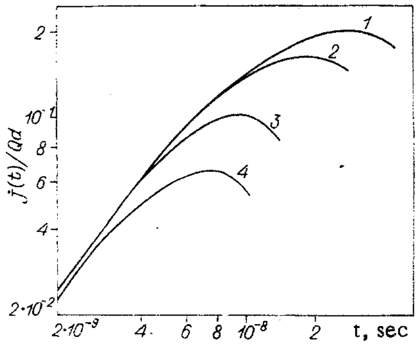

Fig. 4

should be characterized by periodic spikes just as in the case of current oscillations in the generation of electron cascades for $\mu_0 \approx 1$ [6]. The monotonic nature of change of the retarded current component and also the large time for breakdown to develop (exceeding the ion flight time by an order of magnitude in particular cases) apparently indicates that a treatment of system (1) which does not allow for energy balance [7], and also sticking processes [6], is inadequate for explaining the instability mechanism for a semi-self-maintained space charge with breakdown development times of $1\text{-}10^3$ μsec.

§2. Approximate treatments of electrical conductivity are based on the assumption [2] that the field in the gap is equal to $E = U/d$, with the exception of the layer next to the cathode in which it increases linearly, and the layer parameters [Δd, $E(0)$ — the field at the cathode] are obtained from the condition that the multiplication of electrons in the layer as a result of volume impact ionization and secondary ionization at the cathode should ensure that the current in the gap is continuous.

By contrast, in [8] the field distribution in a volume discharge triggered by an electron beam is obtained by numerical solution of the self-consistent problem including the continuity equation for electrons and Poisson's equation. Calculation of the field distribution in [8] is restricted to times $t \leq 7.7 \cdot 10^{-9}$ sec. For these times the field is distorted only in a narrow region near the cathode. The comparison in [8] of theoretical variants which allow for and neglect impact ionization shows that in the case where the external source is uniform throughout the volume impact ionization does not affect the field distribution. Apparently, this result is connected with small time adopted in the treatment. If the time $t \ll d/v_e$, then because of the small layer thickness ($\Delta d \sim v_e t$) the reduction of potential in the layer $U_K \sim E(0)\Delta d \ll U$ and the field outside the layer is weakly distorted when the condition $\int_0^d E(x)\,dx = U$ is taken into account.

For large times ($t \sim d/v_e$) the field outside the layer depends on the emissivity of the layer near the cathode, and, in particular, on the impact ionization in the layer, if this process determines the electron emission from this region. Unfortunately, for large Q the algorithm used in the calculation is very sensitive to the choice of steps Δx and Δt, and in order to obtain a solution corresponding to the physical content of the problem the calculations must be carried out for small values of Δt ($\Delta t \sim 1/Q^n$, $n < 1$), which increases the computation time considerably.

The system of equations (1) was solved numerically in order to calculate the conductivity current and field distribution in an air gap ($p = 760$ mm Hg, $d = 0.2$ cm, $E/p = 10$ V/cm·mm Hg) when pulsed ionizing radiation of the form $Q(t) = Q_0\{\exp[-t/\tau_1] - \exp[-t/\tau_2]\}$, $\tau_1 = 2 \cdot 10^{-8}$ sec, $\tau_2 = 10^{-9}$ sec.

In the calculation the coordinate step Δx was equal to $d/100$, and the initial value of the time step Δt_0 was 10^{-10} sec. Curves 1-4 in Fig. 4 for $Q = 10^2$, 10^{10}, 10^{11}, 10^{12} R/sec, respectively, give the discharge current j in dimensionless units of j/Qd at time $t \simeq t_1$, where t_1 is the time for the current to reach a maximum, while $\gamma_+ = 0.02$ and $\gamma_f = 0$. The corresponding field distribution for the same values of Q is described by curves 1-4 of Fig. 5. On passing from $Q = 10^2$ R/sec to $Q = 10^{10}\text{-}10^{12}$ R/sec the current amplitude in relative units of j/Qd varies by a factor of the order of unity regardless of the radical redistribution of the field.

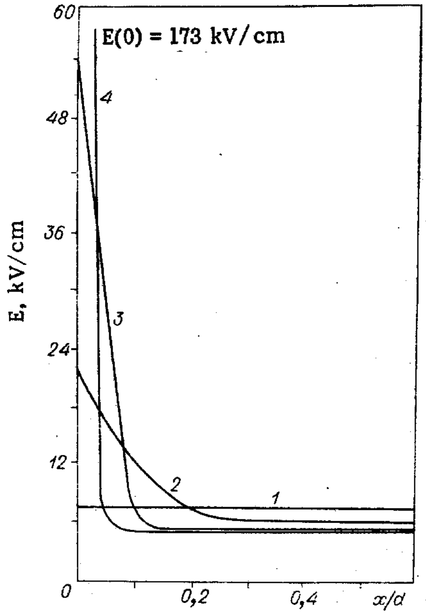

Fig. 5

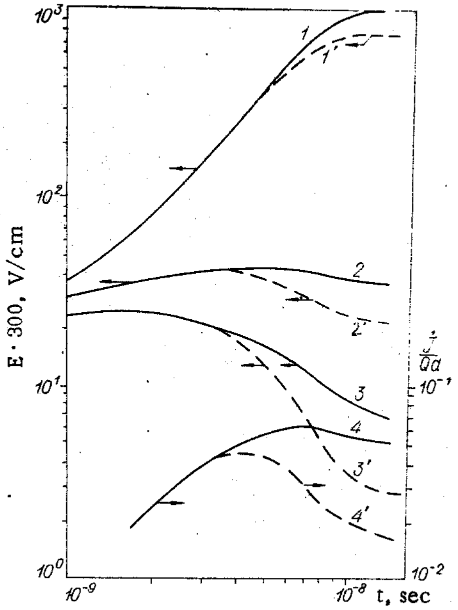

Fig. 6

The fact that as the strength of ionization Q increases the current amplitude j/Qd decreases and the field outside the layer is reduced compared with its initial value indicates that the discharge is screened by the layer near the cathode. Comparison of theoretical variants for $\alpha = 0$ and $\alpha \neq 0$ shows that for $Q \lesssim 10^{11}$ R/sec the contribution from impact ionization to the current amplitude and the field distribution is negligibly small. In addition, for $Q = 10^{12}$ R/sec a finite difference is observed both in the field distribution as well as in the time for the current to vary depending on whether impact ionization is included in the treatment or not.

The time change of the field at the cathode, the anode, and at the center of the gap is shown in Fig. 6 for $Q = 10^{12}$ R/sec ($\gamma_+ = 0$, $\gamma_f = 1.5 \cdot 10^{-5}$) when $\alpha \neq 0$ (curves 1-3) and when $\alpha = 0$ (curves 1'-3'). Curves 4 and 4' give the current pulse for $\alpha \neq 0$ and $\alpha = 0$, respectively. When $\alpha \neq 0$ the current decreases more slowly in time as the external ionization decreases than in the case when $\alpha = 0$, which is connected with the multiplication of electrons in the layer by the cathode as a result of impact ionization. Compared with the case $\alpha = 0$ taking impact ionization into account results in the field at the cathode and at the center of the gap increasing, and the thickness of the layer near the cathode decreasing. Although, for example, in the case of curve 4 of Fig. 4 the mean electron density reaches a value of $n_e \sim j/v_e(d/2) \sim 10^{12}$–$10^{13}$ cm^{-3}, nevertheless the parameters of the layer near the cathode in an air gap are such that the emission of electrons from the layer as a result of impact ionization and secondary processes at the cathode results in a fairly weak compensation for screening of the field at the center of the gap.

For large Q the field at the cathode increases sharply, in particular, in the case of curve 4 of Fig. 5 and curve 1 of Fig. 6, $E(0) \sim (2\text{-}3) \cdot 10^5$ V/cm. When the increase of the real field at the cathode as a result of surface roughness is taken into account field emission is possible. This process can become more important in the creation of an emitter layer near the cathode compared with impact ionization.

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EQUILIBRIUM AND STABILITY OF THE SEPARATION SURFACE BETWEEN A LIQUID DIELECTRIC AND A PERFECTLY CONDUCTING LIQUID

A. I. Zhakin UDC 531.51:538.4

We consider a stationary container (Fig. 1) completely filled with two perfectly immiscible liquids, one of which is a perfect conductor, and the other a dielectric with a dielectric constant ε. We assume that the container walls are perfect conductors, both liquids are at the same temperature, and the liquid–liquid interface has no points in common with the container walls.

We introduce the following notation: $\Omega_1(\Omega_2)$ is the region occupied by the conductor (dielectric); $S_1(S_2)$ is the container wall adjoining the conductor (dielectric); Γ is the surface of separation of the liquids; **n** is a unit vector normal to Γ, directed into the region Ω_1 ; $\mathbf{n}_i$ is a unit vector normal to S_i and directed into the region $\Omega = \Omega_1 + \Omega_2$; ρ_i is the density of the conductor (dielectric); σ is the surface tension in the liquid–liquid interface; φ is the electric potential; **r** is the radius-vector to a point; and V_i is the volume of region Ω_i.

We assume that the electric field results from a potential difference U between S_1 and S_2 and that the external forces have a potential Π_i in Ω_i (i = 1, 2).

1. Condition for Equilibrium of Liquids in a Container

In deriving the equilibrium conditions we start from the variational principle that the potential energy has a stationary value. The potential energy is

$$W = \sigma \int_{\Gamma} d\Gamma + \sum_{i=1}^{2} \int_{\Omega_i} \Pi_i d\Omega - \frac{\varepsilon}{8\pi} \int_{\Gamma} \varphi \frac{\partial \varphi}{\partial n} d\Gamma + \text{const.} \tag{1.1}$$

Let **h(r)** be the displacement of a liquid particle. We assume that **h(r)** is a twice continuously differentiable function, continuous in Ω, having no normal component on S and a continuous normal component on Γ,

$$\operatorname{div} \mathbf{h}(\mathbf{r}) = 0 \qquad (\mathbf{r} \in \Omega); \tag{1.2}$$

$$\mathbf{h}(\mathbf{r})\mathbf{n}_i = 0 \qquad (i = 1, 2;\ \mathbf{r} \in S = S_1 + S_2); \tag{1.3}$$

$$\lim_{\mathbf{r}_1 \to \mathbf{r}} \mathbf{h}(\mathbf{r}_1)\mathbf{n} = \lim_{\mathbf{r}_2 \to \mathbf{r}} \mathbf{h}(\mathbf{r}_2)\mathbf{n} \qquad (\mathbf{r} \in \Gamma,\ \mathbf{r}_1 \in \Omega_1,\ \mathbf{r}_2 \in \Omega_2). \tag{1.4}$$

We assume that U = const in virtual displacements of a liquid particle. This is possible only if there is an external energy source [1].

Using the formulas for the variations of the area of a surface and a unit vector normal to a surface [2] we obtain an expression for the first variation of the potential energy in the form

$$\delta W = \int_{\Gamma} \left(-2\sigma H + \frac{\varepsilon}{8\pi} \left(\frac{\partial \varphi}{\partial n} \right)^2 \right) N d\Gamma + \sum_{i=1}^{2} \int_{\Omega_i} \nabla \Pi_i \mathbf{h} d\Omega,$$

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