BREAKDOWN OF THE NEAR-ELECTRODE LAYER IN A FLOW OF IONIZED GAS

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An electric discharge in a flow of ionized gas is widely used in many physics and engineering problems. Among them are problems associated with current flow in various magnetohydrodynamic devices (generators, accelerators), arc shunting in a plasmatron, physical experiments in shock tubes, etc. It is known that with cold electrodes providing the contact between the plasma and the external circuit and relatively high pressures, two modes of current flow occur: at low current, the discharge is of a distributed nature; as the applied voltage increases, the discharge abruptly shifts into a discharge with a clearly developed cathode spot at some critical current density (we call this form of discharge an arc discharge). Existing experimental data [1-20] refers to varying experimental conditions. Furthermore, the critical voltage (or current) at which the transition of the discharge from a distributed discharge to an arc discharge occurs varies within very broad limits. From an analysis of the experimental data, a condition is formulated which the discharge parameters satisfy at the time of transition from a distributed discharge to an arc discharge.

We consider a discharge in a current of hot, ionized gas flowing along a cold metal wall. The hot core of the flow is separated from the cold wall by a gas-dynamic boundary layer. For certain conditions near the wall, a layer is formed within the boundary layer in which the charged-particle density is different from an equilibrium distribution and the existence of significant space charge is possible. Let the wall be an electrode (cathode) through which contact is made with an external electrical circuit which provides current flow through the gas. The structure of the nonequilibrium layer and of the space-charge layer near the electrode depend on the density of the current passing through the layer, on the parameters of the gas flow, and on the wall temperature.

We assume the wall is sufficiently cold so that there is no thermoemission from its surface, and we limit ourselves to conditions in which the following relation holds between the characteristic lengths in the various layers near the electrode:

$$\lambda_i \ll d \ll l_i \lesssim \delta \tag{1}$$

where λ_i is the mean free path for an ion, d is the thickness of the space-charge layer, l_i is the thickness of the layer with nonequilibrium thermal ionization, and δ is the thickness of the gas-dynamic boundary layer. Satisfaction of the condition (1) requires a relatively high gas pressure and low gas temperature near the wall (the latter determines the recombination rate). The relations (1) are satisfied for a broad class of experimental conditions.

Electrons are not present in the space-charge layer under these conditions, and the ions are in a state of mobility [1]. Furthermore, there is the following relation between current density and potential drop in the layer [1]:

$$jV = \frac{\mu_i}{12\pi} E_w^3, \quad E_w = (ad)^{1/2}, \quad a \equiv \frac{8\pi}{\mu_i} j \tag{2}$$

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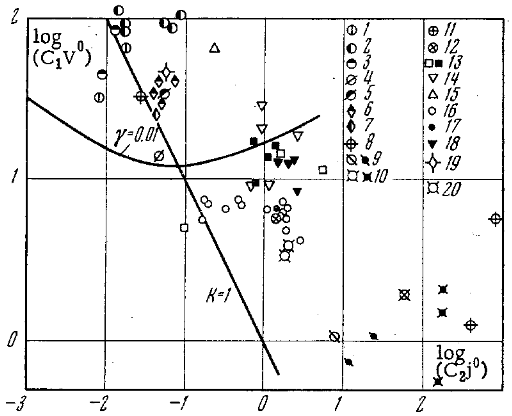

Fig. 1

Here, $j=j_i$ is the current density, which is equal to the ion current density, V is the potential drop in the layer, μ_i is the ion mobility, E_w is the electric field intensity at the electrode surface (at $x=0$), and d is the thickness of the space charge layer, which depends on current density.

To obtain from Eqs. (2) equations for the volt–ampere characteristics of the discharge, it is necessary to determine the function $d=d(j)$. This relation and also the current density under specific discharge conditions (point on the volt–ampere characteristic) can be determined by matching the solutions of Eqs. (2) in the space-charge layer and the solutions in the region of the boundary layer external to that layer.† The equation for the volt–ampere characteristic obtained from such a solution gives a relation between current density and potential drop in the discharge for any current density. As shown by experiment, however, only the initial portion of this characteristic (at low currents) is actually realized. At a certain current density, the discharge shifts into a discharge with a cathode spot (we call this phenomenon breakdown), the characteristic of which must be described by another solution.

The selection of the transition point (breakdown) on the volt–ampere characteristic of the discharge and the construction of the relation between parameters at the time of breakdown must be based on additional considerations. This can be done either theoretically, from an analysis of the physical processes and of the distribution of parameters in the discharge, or empirically, from generalization of the experimental data.

The condition

$$E_w = E^0 = 3 \cdot 10^4 \text{ V/cm} \tag{3}$$

obtained in [1] is an example of a semiempirical relation which determines the time of breakdown for the conditions being considered. Condition (3) was obtained from an analysis of experimental data on breakdown of the near-electrode layer in air and in combustion products at a pressure of ~1 atm using Eqs. (2).

To generalize condition (3) for the breakdown of the near-electrode layer in a flow of ionized gas, we analyzed breakdown experiments conducted in a flow with added potassium [1-7], in a flow of "pure" gases in shock tubes, [8-17, 19, 20], and also investigations of arc shunting in a plasmatron [18]. Despite the difference in experimental conditions, the pre-breakdown mode in these experiments is characterized by the following general features:

1) absence of emission from the cathode;

2) a plasma is the anode for the discharge from which ions are supplied; the steadiness of the discharge (continuity and constancy of the ion flux from the plasma) is ensured by the plasma flux far from the electrode within the core of the flow;

3) there is a velocity field which influences ion motion in the space-charge layer if the thickness of that layer becomes comparable to the thickness of the boundary layer;

4) a marked nonuniformity of gas properties near the electrode surface associated with the formation of hydrodynamic boundary layers is typical;

5) the gas contains easily ionized contaminants, impurities, excited atoms, etc., associated with the use of special gas mixtures and with the method for the production of an ionized plasma flux (heating, electric-discharge shock tube, etc.).

To analyze the experimental data [1-20] on the basis of Eqs. (2), we introduce the dimensionless variables

$$j^* = C_2 j, \quad V^* = C_1 V, \quad C_1 = 3/2U_i, \quad C_2 = 8\pi\lambda_e^3/\mu_i U_i^2 \tag{4}$$

† Examples of such solutions were constructed in the dissertation of V. N. Mikhailov, "Near-electrode effects in a plasma containing added alkali metal," and will not be discussed here.

Here, λ_e is the mean free ionization range of an electron near the surface of the electrode and U_i is the ionization potential of the gas. In the variables (4), Eqs. (2) are written in the form

$$j^* V^* = K^3 \tag{5}$$

$$K = \frac{E_w \lambda_e}{U_i} = \frac{2}{3} \frac{V}{d} \frac{\lambda_e}{U_i} \tag{6}$$

The thickness of the space-charge layer is

$$d = K^2 \lambda_i^* / j^* \tag{7}$$

If the temperature gradient near the wall is large, the variation of λ_i and μ_i may be considerable within the bounds of the space-charge layer. If we neglect the longitudinal velocity of the ions (with respect to the electrode), the variability of temperature and density across the space-charge layer can be taken into account in Eqs. (4)-(7) by the introduction of values averaged over the layer.

In the actual analysis of the experimental data, the results of which are given below, it was assumed

$$\mu_i \rho \sqrt{T} = \text{const}, \qquad \langle \mu \rangle = \text{const} / \langle \rho \rangle \sqrt{\langle T \rangle} \tag{8}$$

Here $\langle \rho \rangle$ and $\langle \mu \rangle$ are average values of density and mobility where

$$\langle \rho \rangle = \frac{1}{d} \int_0^d \rho \, dx \tag{9}$$

In the calculation of $\langle \rho \rangle$, the pressure across the space-charge layer was assumed constant and the temperature distribution was varied in accordance with the mode of flow in the boundary layer.

For laminar flow in shock-tube experiments, it was assumed

$$T(x) = T_w (1 + Cx)^{1/(n+1)}, \qquad T_\infty = T_w (1 + C\delta)^{1/(n+1)} \tag{10}$$

The quantity C is determined by the thermal flux in the channel wall. Unfortunately, insufficient data for the determination of the parameters C and n is given in most shock-tube papers, and, therefore, values for these quantities obtained in [21] were used in the analysis of the experimental results.

For a turbulent flow, it was assumed the temperature distribution was linear within the limits of the laminar sublayer and $T = T_\infty$ at the external boundary of this sublayer. The thickness of the laminar sublayer was calculated from gas-dynamic equations [22].

The average mean free path is

$$\langle \lambda_e \rangle = 1 / A_1 \langle \rho \rangle \tag{11}$$

where A_1 is the tabulated value of the quantity in the equation for the first Townsend coefficient

$$\alpha = A_1 \rho \exp(-B_1 \rho / E) \tag{12}$$

The results from various experiments on breakdown of the near-electrode layer analyzed by using the variable (4) and Eqs. (7)-(10) are given in Fig. 1 (the points correspond to the current and voltage, j° and V°, at the time of breakdown; the notation is defined in Table 1). The great spread of the points plotted in Fig. 1 may be associated not only with the spread in the values of j° and V° from experiment to experiment under identical conditions (see [1]) but also with inaccuracy in the analysis of the data because of the absence of direct measurements important for the analysis of parameters in most of the papers. Despite this, one can note a tendency toward a reduction in the dimensionless voltage as the dimensionless current rises at the breakdown points.

The data shown in Fig. 1 corresponds to breakdown in air, combustion products, argon, nitrogen, and helium with and without added potassium. The range of pressures and temperatures in the core of the flow is ~ 10-760 mm Hg for p and ~ 2500-11,600°K for T. Experiments were conducted both in applied and induced electric fields with the magnetic field varying in the range $B \sim 0$-$1.5 \cdot 10^4$ G. The resultant current density and voltage at the time of breakdown fall within the limits $j^\circ \sim 10^{-4}$-1 A/cm² and $V^\circ \sim 10$-700 V. Analysis of Fig. 1 leads to the conclusion that for the majority of experiments, despite the considerable variation in experimental conditions, the value of the parameter K [Eq. (6)] at the time of breakdown varies within the rather narrow limits

TABLE 1

Notation	1	2	3	4	5
Reference	[1]	[1]	[2]	[3]	[4]
Working gas	air	air + K	combustion products + K	combustion products	combustion products + K
Notation	6	7	8	9	10
Reference	[5]	[6]	[7]	[8]	[8]
Working gas	combustion products + K	air + K	combustion products + K	argon	helium
Notation	11	12	13	14	15
Reference	[9, 10]	[11]	[12]	[13, 14]	[13, 14]
Working gas	argon	argon	argon	argon	air
Notation	16	17	18	19	20
Reference	[15]	[16]	[17]	[18]	[19]
Working gas	argon	argon	argon	argon	air

$$0.8 \leqslant K \leqslant 4.5 \tag{13}$$

The data from [9, 10, 20] are an exception (the points from [20] are not shown in Fig. 1 because they fall outside the boundaries of the figure). Analysis of the relations between the fundamental characteristic lengths δ, d, and λ_i in these experiments shows that $d \sim \lambda_i$ for them. Therefore, the conditions under which that set of points was obtained are such that this data cannot be analyzed by the method described above because the assumptions imposed on the theoretical model (2) are not satisfied.

Considering the statistical nature of the breakdown phenomenon and the small variation (13) of the parameter K at the time of breakdown in various gases and under various experimental conditions, one can advance the following conditions for the breakdown of the near-electrode layer*

$$K = K_{\min} = 1 \tag{14}$$

The curve corresponding to Eq. (14) is shown in Fig. 1. The physical meaning of the breakdown condition (14) is that breakdown sets in at the time when a random electron acquires an energy equal to the ionization potential between two collisions in the near-electrode layer, i.e., acquires the capability of ionizing gas atoms by collision.†

The form of condition (14) indicates that breakdown of the near-electrode layer under the conditions discussed is of a volume nature. The relatively minor role of surface processes is indicated by the fact that within the accuracy of the measurements there is no effect of electrode material on the breakdown phenomenon (electrodes of copper, steel, aluminum, tungsten, and nickel were used in these experiments; the surface temperature of the electrode did not exceed 500-600°K).

The values of the quantity K at the time of breakdown for experiments involving a magnetic field can be differentiated, generally speaking, from the corresponding values for B = 0 because the magnetic field can lead to a change in the effective frequency of ionizing collisions for an electron.

*The relation $\lambda_c \gg d$ holds for the conditions in [8, 11] and for some data in [12, 15]. On the basis of the physical meaning of the breakdown condition (14), it is necessary to replace the quantity λ_e by d in expressions for the parameter K when analyzing this data.

† The condition (14) agrees in form with the condition for gas breakdown in a high-frequency field [23].

To evaluate the possible effect of a magnetic field on the breakdown phenomenon and the corresponding change in the critical value of the electric field intensity, one can turn to the physical significance of condition (14). The critical electric field intensity can vary if the electron mean free path along the field and the energy acquired by the electron between two collisions varies correspondingly (it is assumed the magnetic field has no effect on ion motion $-\omega_i\tau_i \ll 1$). Such a variation in energy will be important if the ratio λ/R (λ is the electron mean free path in the absence of a magnetic field and R is the Larmor radius for the electron) becomes significantly greater than one. In this case, the electron mean free path along the electric field will be determined by the quantity R, the critical field intensity increases, and it will be necessary to determine it from the condition

$$K_B = ER / U_i \tag{15}$$

If it is assumed the electrons created by ionization have zero initial velocity, the Larmor radius will be determined by the maximum of the velocities

$$v_D = \frac{cE}{B}, \quad v = \frac{eE}{2m}\tau, \quad \frac{v}{v_D} = \frac{\omega\tau}{2}$$

Here, v_D is the drift velocity, v is the average electron velocity between collisions, and τ is the time between electron collisions in the near-electrode layer. For $\omega\tau \ll 1$, we have $v_D \gg v$ and

$$\frac{\lambda}{R} \sim \frac{v\tau eB}{mcv_D} \sim \frac{(\omega\tau)^2}{2} \ll 1$$

It then follows that when $\omega\tau \ll 1$, the characteristic electron range along the field is determined by the quantity λ and the magnetic field should have no effect on the critical electric field intensity.

For $\omega\tau \gg 1$, the Larmor radius depends on the velocity $v \gg v_D$ and

$$\frac{\lambda}{R} \sim \frac{v\tau eB}{mcv} \sim \omega\tau \gg 1$$

Under these conditions, the characteristic electron range along the field is determined by the quantity R and the critical electric field intensity should depend on the magnetic field in the following manner [see Eq. (15)]:

$$E_B = \omega\tau\, E_0 \tag{16}$$

where E_0 is the critical electric field intensity in the absence of a magnetic field and at the same gas density, E_B is the critical intensity with a magnetic field present.

In the experiments with a magnetic field mentioned above, we find

$$B \lesssim 10^4\ \text{G}, \quad E \gtrsim 10^4\ \text{V/cm}, \ \lambda \lesssim 10^{-4}\ \text{cm},$$
$$\tau \sim (2\lambda m / eE)^{1/2} \lesssim 10^{-12}\ \text{sec}, \omega \sim eB / mc \lesssim 2 \cdot 10^{11}\ \text{sec}^{-1}$$

Consequently, $\omega\tau \ll 1$ for these experiments, and the critical electric field intensity should not depend on the magnetic field. This is confirmed by the fact that the quantity K calculated for them does not depend on the magnetic field (within the spread of the experimental data; see Fig. 1 where points corresponding to experiments involving a magnetic field are plotted).

Note that the breakdown condition (14) is different from the corresponding conditions for the transformation of a non-self-sustaining discharge into a self-sustaining Townsend glow discharge [24, 26], the transformation of a glow discharge into an arc discharge [25, 26], and from the conditions for a spark breakdown [26]. As an illustration, a curve is shown in Fig. 1 corresponding to the condition for transformation into a Townsend discharge, $1 - \gamma[\exp(\alpha d) - 1] = 0$ for $\gamma = 10^{-2}$ with α and d calculated from the solution of Eqs. (2).

The relation between parameters at the time of transition from one form of discharge to another should depend on the physical nature of the original discharge. It is therefore natural that the form of the breakdown condition for this discharge differ from the breakdown conditions for other discharges (in particular, those mentioned above).

There is interest in the investigation of the physical processes leading to the transformation of the distributed discharge discussed into an arc discharge and in an explanation of the kinetic meaning of the breakdown condition (14).

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