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

G. A. Lyubimov

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:

$$\lambda_i \ll d \ll l_i \ll \delta$$

(1)

where $\lambda_i$ 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 $\delta$ 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]:

$$jV = \frac{\mu_i}{12\pi} E_w^3, \quad E_w = (ad)^{\alpha}, \quad a = \frac{8\pi}{\mu_1^2}$$

(2)
Here, \( j = j_0 \) is the current density, which is equal to the ion current density, \( V \) is the potential drop in the layer, \( \mu_1 \) 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

\[
E_w = E^0 = 3 \times 10^4 \text{ V/cm}
\]

(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 \( \sim 1 \) 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:

\[
j^* = C_1 j, \quad V^* = C_1 V, \quad C_1 = 3/2U_i, \quad C_2 = 8x\lambda_s/\mu_1 U_i^3
\]

(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.