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## Abstract

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# DYNAMICS OF THE CHANGE IN THE FRACTION OF ELECTRON CURRENT IN THE NEAR-CATHODE REGION OF AN ARC DISCHARGE

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The question of the ratio of the magnitudes of the electron $j_e$ and ion $j_i$ currents in the cathode spot at the electrode surface is of great importance for interpreting the mechanism of cathode processes in an electric arc ([1]). The fraction of electron current $S = j_e/(j_e + j_i)$, for a given total current $j = j_e + j_i$, determines the electric field at the cathode, while the ionic component of the current $j_i$ mainly determines the local heating of the cathode. These two processes are currently used to explain the mechanism of emission of the electrons required to sustain the discharge.

Until now (see the review in ([1])), the question of the fraction of electron current has been determined on the basis of stationary models of the cathode spot. On the other hand, it is known that in a number of cases cathode spots move irregularly, disappear, and arise again at different points of the cathode surface. In this case the lifetime of an elementary spot is very short ($\sim 10$ $\mu$sec). Naturally, under these conditions, as well as at the moment of development of "stationary" spots, nonstationary thermal and electrical processes may prove to be essential.

Below, the nonstationary problem of the development of a cathode spot is solved on the basis of the model proposed in ([2]).

In accordance with this model, the magnitude of the ion current is determined mainly by the diffusion of ions arriving from the ionization region. In this case, the problem of the nonstationary change in the fraction of ion current reduces to the solution of the nonstationary diffusion equation, under the condition that there is a source of ions arising from the process of ionization of neutral atoms by electrons emitted from the cathode:

$$\partial n_i/\partial t = D\,\partial^2 n_i/\partial x^2 + \alpha N_{e0} e^{-\alpha x}. \tag{1}$$

Here $n_i$ is the ion concentration; $\alpha = n_a\sigma_i$ is the product of the concentration of neutral atoms $n_a$ and the ionization cross section $\sigma_i$; $D \sim V_{iT}/3n_a\sigma_{pn}$ is the diffusion coefficient, which is determined through the resonant charge-exchange cross section $\sigma_{pn}$ and the magnitude of the thermal velocity of ions $V_{iT}$; $N_{e0}$ is the flux of electrons emitted by the cathode per unit surface area.

The boundary condition for equation (1) is obtained from the condition of balance of ions at the electrode surface:

$$\frac{\partial n_i}{\partial x} = \frac{1}{D}\,\frac{n_i V_{iT}}{2} \equiv h n_i \quad \text{for } x = 0. \tag{2}$$

We shall assume that at the initial instant the gas near the cathode is not ionized,

$$n_i(0, x) = 0. \tag{3}$$

The temperature $T$, the concentration of neutrals $n_a$, the flux of emitted electrons $N_{e0}$, and also the concentration of ions $n_i$ at the initial instant are determined by the breakdown conditions. These quantities may change during the development of the spot, and to determine them it is necessary to solve the nonstationary problem, supplementing equation (1) with the equation of heat conduction, emission

etc. (see, for example, ([3])). In order to estimate the qualitative aspect of the phenomenon, we shall regard $D$, $n_a$, $N_{e0}$ as constant and the gas at the initial instant as nonionized—the condition (3).

The solution of equation (1) under conditions (2), (3) is represented in the form ([4])

$$\begin{aligned} n_i(x,t) = \frac{N_{e0}(\alpha+h)}{D\alpha h}\Bigg\{ & \frac{\exp(\mu^2 t - \alpha x)}{2(1+A)}\,\Phi^*\left(\mu\sqrt{t} - \frac{\alpha x}{2\mu\sqrt{t}}\right) - \frac{\exp(-\alpha x)}{1+A} \\ & - \frac{\exp(\mu^2 t + \alpha x)}{2(1-A)}\,\Phi^*\left(\mu\sqrt{t} + \frac{\alpha x}{2\mu\sqrt{t}}\right) \\ & + \frac{A^2\exp(\mu^2 t/A^2 + \alpha x/A)}{1-A^2}\,\Phi^*\left(\frac{\mu\sqrt{t}}{A} + \frac{\alpha x}{2\mu\sqrt{t}}\right) + \Phi^*\left(\frac{\alpha x}{2\mu\sqrt{t}}\right)\Bigg\}, \end{aligned} \tag{4}$$

$$A = \alpha/h = \frac{2}{3}\sigma_i/\sigma_{pn}, \qquad \alpha = n_a\sigma_i, \qquad \mu^2 = n_a V_{iT}\sigma_i^2/3\sigma_{pn},$$

Fig. 1

Figure 1: Fig. 1

Fig. 2

Figure 2: Fig. 2

$$\Phi^*(\xi) \equiv 1 - \Phi(\xi).$$

Here $\Phi(\xi)$ is the error function.

In the limit as $t \to \infty$ we obtain the concentration distribution for the stationary case ([2]):

$$n_i(x, \infty) = \frac{N_{e0}(h+\alpha)}{D\alpha h} - \frac{N_{0e}}{D\alpha} e^{-\alpha x}. \tag{5}$$

According to (5), the ion concentration in the stationary regime varies from the value $2N_{0e}/V_{iT}$ at the cathode surface to $N_{0e}(h+\alpha)/D\alpha h$ upon moving away from the cathode (Fig. 1). It follows from (5) that the decrease in ion concentration near the cathode as a result of the departure of the ion flux to the cathode begins at distances $\sim (2 \div 3)/n_a\sigma_i$. After the saturation region, a region of decreasing ion concentration should be observed. This part of the curve was considered neither in ([2]) nor in the present work, but could be obtained if a term describing the loss of ions as a result of recombination were added to the right-hand side of equation (1). Thus, the distribution of ion concentration near the cathode in the stationary regime contains a saturation region, whose extent along the discharge axis is determined by the ratio of the cross sections of the processes of electron-impact ionization and ion recombination.

**Fig. 1**

**Fig. 2**

In the nonstationary regime, as solution (4) shows, the ion concentration is distributed nonmonotonically. To illustrate this, Fig. 1 gives plots of the concentration distribution at various instants of time. The calculations were carried out for conditions close to the cathode spot on copper ($\sigma_i = 2.5 \cdot 10^{-16}$ cm$^2$ ([8]), $\sigma_{pn} = 10^{-14}$ cm$^2$ ([10])) at the boiling temperature.

Since in the diffusion region the ion diffusion coefficient $D = D_i$, determined by the charge-exchange cross section, is much smaller than the electron diffusion coefficient $D_e$, determined by the gas-kinetic cross section, then

the current in this region is predominantly electronic, and

$$j \sim j_e = -D_e \frac{\partial n_e}{\partial x} - \frac{n_e e E}{kT} D_e. \tag{6}$$

It follows from this that, for a nonmonotonic distribution of the ion concentration, characteristic of the initial stage of the discharge, the electric field near the electrode will also be distributed nonmonotonically. This fact may possibly explain phenomena associated with the presence of a potential "hump" near the cathode ([5]).

The fraction of the electron current at the electrode surface is determined in the nonstationary regime by the relation

$$S = \frac{j_e}{j_e + j_i} = \frac{N_{e0}}{N_{e0} + D\,\partial n_i/\partial x\big|_{0,t}}. \tag{7}$$

Using the solution (4), we bring this expression to the form

$$S(t) = \left[2 - \frac{\exp(\mu^2 t)}{1-A}\,\Phi^*(\mu\sqrt{t}) + \frac{A^2 \exp(\mu^2 t/A^2)}{1-A}\,\Phi^*\left(\frac{\mu\sqrt{t}}{A}\right)\right]^{-1}. \tag{8}$$

For the stationary case, formula (8) gives $S(\infty) = 0.5$, which agrees with the conclusions of work ([2]).

The dependence of the quantity $S$ on time for the conditions adopted in the calculation of Fig. 1 is presented in Fig. 2. This dependence shows that the fraction of the electron current falls from unity to the stationary value 0.5 in a time $\sim 10$ $\mu$s.

As is known, field electron emission is impossible at a low fraction of electron current ([1]). Under stationary conditions, at small $S$, there exists a thermofield electron spot ([6]).

On the other hand, over the short ($\sim 10$ $\mu$s) time of spot development it is difficult to expect heating of the cathode-spot region to temperatures at which substantial thermofield electron emission is possible. The decrease in the fraction of electron current apparently must lead to a violation of the conditions for existence of a cathode spot with the field-emission type of emission already at a time when the conditions for existence of a thermofield-emission type of spot do not yet exist. Thus, the time required to reach the stationary value of the electron-current fraction determines the limiting time of existence of a field-emission spot at one location in the absence of appreciable local heating of the electrode.

Heating of the cathode surface can lead to the formation of a thermofield electron spot ([6]). However, surface heating requires (see, for example, ([9])) considerably longer times ($\sim 10^2 \div 10^3$ $\mu$s).

The experiments described in ([7]) showed that the lifetime of field-emission cathode spots is 5-10 $\mu$s. Consideration of the data ([1]) leads to an analogous conclusion. According to ([7]), the transition to slowly moving thermofield electron spots occurs over a time from several hundred to several thousand microseconds, i.e., on the order of the heating time of the region of the cathode surface on which cathode spots of this type may be concentrated. In this case, as shown in ([7]), thermofield electron spots, as a rule, arise on a region of the cathode surface previously heated by formerly existing field-emission spots.

Thus, it may be concluded that, apparently, the stationary value of $S$ proves unattainable in the case of a field-emission spot and can be reached only upon transition to the thermofield-emission mechanism.

On a heated surface, a thermofield electron spot can exist only at a low fraction of electron current $S = 0.5 \div 0.7$ (which

close to the stationary value—see Fig. 2), since the high surface temperature can be maintained only by the ionic component of the current.

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*Note: Figure translations are in progress. See original paper for figures.*

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