THE ELECTRIC FIELD ON THE SURFACE OF AN ELECTRODE IN THE CATHODE SPOT OF AN ARC DISCHARGE

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Abstract

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THE ELECTRIC FIELD ON THE SURFACE OF AN ELECTRODE IN THE CATHODE SPOT OF AN ARC DISCHARGE

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According to Langmuir' s concepts ([1,2]), in the space near the cathode, under the influence of the space charge formed by positive ions, an electric field arises which causes cold emission of electrons from the cathode as a result of the Schottky effect, and also because of the narrowing of the potential barrier. The first expression for the electric field at the cathode that takes into account the presence of ambipolar ion and electron currents was proposed in ([2,3]). All emission models that currently exist and are considered in connection with the creation of a theory of cathode processes are based on this expression, which is usually called Mackeown' s equation:

$$E_c^2 = 16\pi i \left[(1-S)(M/2e)^{1/2} - S(m/2e)^{1/2}\right] u_c^{1/2}, \tag{1}$$

where i is the current density in the cathode spot, E_c is the electric field on the surface of the cathode, and S is the fraction of the electron current.

However, the legitimacy of applying equation (1) under one or another set of conditions is, as a rule, not justified.

In deriving equation (1), the assumption is introduced that, over the length h on which the cathode voltage drop is realized, electrons and ions move without collisions. Thus, the question of the applicability of equation (1) is first of all a question of the fulfillment of the relation

$$h \ll \min\{l_i, l_e\}, \tag{2}$$

where l_i and l_e are the mean free paths of an ion and an electron in the gas near the cathode spot.

Let us estimate the magnitude of h for the conditions of a vacuum arc, on the basis of solution (2). Since the cathode fall has a value of ~ 15 V, while the plasma electrons have on average an energy less than ~ 1 eV, they are reflected from the potential barrier at the outer boundary of the cathode-fall region, and their space charge can be neglected in estimating h. The ions incident on the cathode of a vacuum arc are ions produced from vapors of the cathode material, and therefore it may be assumed that the probability of their neutralization is sufficiently high and, consequently, the flux of ions reflected from the surface of the cathode spot may be neglected.

Thus, we shall assume that the space charge in the cathode-fall region is determined by the current density of electrons i_e leaving the cathode spot, and by the current density of ions i_i arriving from the region in which ions are generated by ionization. Owing to the fact that the cathode fall is sufficiently large, in solving the problem of the distribution of the parameters in the space-charge layer where the cathode fall is realized, the initial velocities of the charged particles may be neglected.

Under these assumptions, the problem of determining the potential distribution in the cathode-fall region reduces to the equation:

$$\frac{d^2u}{dx^2} = -4\pi\rho_e = -i_e 4\pi \left(\frac{m}{2e}\right)^{1/2} \left[\frac{1-S}{S}\left(\frac{M}{m}\right)^{1/2}\left(\frac{1}{u}\right)^{1/2} - \left(\frac{1}{u_c - u}\right)^{1/2}\right], \tag{3}$$

where ρ_e is the charge density, M is the ion mass, m is the electron mass, u_c is the cathode potential, e is the electron charge, and S is defined by the expression

$$S = i_e/(i_e + i_i) = i_e/i. \tag{4}$$

Practically all known theories of emission from the cathode of a low-pressure arc use a value of S lying within the range $0.5 \leq S \leq 0.99$. In this case, throughout almost the entire cathode-fall region the second term of the expression in brackets in equation (3) is appreciably smaller than the first. Neglecting this term, we integrate the simplified equation (3). We then obtain the following estimate for the dimensions of the space-charge region, which in the present case is determined only by the ionic component of the current,

$$h = \frac{u_c^{3/4}}{3\sqrt{\pi}\,(M/2e)^{1/4} i^{1/2}(1-S)^{1/2}}. \tag{5}$$

The simplification of equation (3) that we have made essentially means that, in determining the magnitude h, we have neglected the narrow region immediately near the electrode, whose dimensions are smaller than the space-charge region by the factor by which the quantity

$$\frac{1-S}{S}\left(\frac{M}{m}\right)^{1/2}$$

is less than unity.

The electron mean free path l_e can be found from the magnitude of the total effective cross section for collision of an electron with atoms of the cathode material. Unfortunately, the number of measurements carried out in this region is extremely limited. However, comparison with available data, for example ([4]), shows that the total scattering cross section is sufficiently close to the gas-kinetic cross section for an electron–atom collision, calculated for the collision model "hard sphere—material point," $\sigma_e \sim 5 \cdot 10^{-16}$ cm^2.

Under the conditions considered for an arc burning in vapors of the cathode material, the ion-atom collision cross section will be very large, since in such a collision resonant charge exchange takes place. An estimate of the resonant charge-exchange cross section by the formulas of ([5]) for ion–atom collisions in the cathode-fall region (ion energy ~ 15 eV) gives the value $\sigma_{\mathrm{rn}} \sim 8 \cdot 10^{-15}$ cm^2.

An estimate of the mean free paths of electrons and ions on the basis of the cross sections given above, and comparison of them with the value of h, determined by (5) for $S \sim 0.5$, shows that condition (2) is satisfied in the cathode-spot region of a vacuum arc at current densities exceeding $5 \cdot 10^4$ A/cm^2; moreover, the current density required from the standpoint of (2) increases with increasing S. Consequently, at smaller current densities the Mackeown equation (1) cannot be used.

Usually, in the theoretical consideration of the emission mechanism, the quantity S in equation (1) is specified on the basis of various considerations ([9]). In the theory of Lee and Greenwood ([6]) it was likewise impossible to determine S directly from the solution of the system of equations, since the system was mathematically not closed. In that case S was determined with the aid of additional conditions, as a result of which a certain set of values of S was obtained.

Let us try to determine the quantity S on the basis of other considerations, based on the phenomenon of charge exchange in the near-cathode region. For definiteness, let us consider an arc in copper vapor. In the region near the cathode spot, ions are formed as a result of impact ionization by emitted electrons ($E_e \sim 15$ eV). The ions formed either are neutralized on the elec-

electrode, or recombine in the volume of the gas. We shall assume that the ion concentration everywhere in the cathode region is much smaller than the neutral concentration n_a. This assumption (a very essential one for the quantitative estimates carried out below) makes it possible to use the available data on the cross sections of various processes in the cathode region to determine the corresponding mean free paths.

The ionization process is governed by the ionization cross section, whose experimentally measured value at the indicated cathode fall is $\sigma_i = 2.5 \cdot 10^{-16}$ cm^2. In the present case the recombination process proceeds by triple collisions, and its cross section is $\sigma_r \sim 10^{-21}$ cm^2.

The mean free path of an electron is determined by its collisions with neutrals, and the cross section of this process is $\sigma_e \sim 5.1 \cdot 10^{-16}$ cm^2. The mean free path of an ion in the gas (the ion energy is small) is determined by the charge-exchange process, whose cross section ([5]) is $\sigma_p \sim 10^{-14}$ cm^2.

Thus, over distances of several electron mean free paths in the gas, all emitted electrons undergo ionization. The recombination process is unimportant in the ionization region and occurs at distances of many electron mean free paths. Finally, in the ionization region the ions undergo many collisions and, owing to the charge-exchange process, the "ion gas" is rapidly Maxwellized. Consequently, the motion of ions in the ionization region may be described by a diffusion equation with a function for ion "birth" due to impact ionization:

$$d\Gamma_i/dx = F(x), \tag{6}$$

$$\Gamma_i = \mu_i n_i E - D_i dn_i/dx, \qquad D_i \sim v_T/3n_a\sigma_p. \tag{7}$$

Here Γ_i is the diffusion flux of ions; D_i, μ_i are the diffusion coefficient and mobility of the ions; n_i, v_T are their concentration and thermal velocity; E is the electric-field strength in the gas outside the cathode fall.

The birth function $F(x)$ in (6) is determined under the conditions considered as

$$F(x) = n_a\sigma_i N_e = n_a\sigma_i N_{e0}\exp\{-n_a\sigma_i x\}. \tag{8}$$

Here $N_e(x)$ is the number of emitted electrons at a given point x that are capable of ionizing, calculated under the assumption of single ionization (the probability of secondary ionization by one and the same electron is extremely small ([7])); N_{e0} is the number of electrons emitted by the cathode per unit time from unit area; n_a is the neutral concentration, which, by virtue of the assumption of a small degree of ionization ($n_i \ll n_a$), is taken to be constant, $n_a = \text{const}$.

The use of the diffusion approximation is associated with a limitation on the magnitude of the electric field in the gas,

$$E \ll kT/el_i. \tag{9}$$

At current densities of the order of 10^5 A/cm^2, the temperature at the surface of the cathode spot reaches such a value ([8]) that the neutral concentration arising as a result of evaporation ($n_a \sim 10^{19}$ cm^{-3}) limits the ion mean free path, because of resonant charge exchange, to a value of the order of 10^{-5} cm or still less. In this case inequality (9) is satisfied, since it requires $E \ll 10^4$ V/cm, which practically always occurs.

If the recombination process is neglected ($\sigma_r \sim 10^{-21}$ cm^2), then the natural boundary condition for equation (6) will be $\Gamma_i(x = \infty) = 0$. Substituting (8) into (6) and integrating it under this condition, we obtain

$$\Gamma_i = -N_{e0} \exp\{-n_a \sigma_i x\}. \tag{10}$$

It follows directly from this that at $x = 0$, $\Gamma_i(0) = N_{e0}$, i.e., the flux of emitted electrons is equal to the ion flux. Thus, do-

for the electron current

$$S = 0.5. \tag{11}$$

In order to estimate the magnitude and distribution of the ion concentration, let us substitute into (10) the expression for Γ_i from (7) and set $E = 0$ in the resulting equation. The ion balance at the electrode surface gives the boundary condition for this equation: $2\Gamma_i = n_i v_\tau$ at $x = 0$. Integration of the resulting equation gives

$$n_i = n_{i0} + \frac{N_{e0}}{n_a \sigma_{iD} i} \{1 - \exp[-n_a \sigma_i x]\}, \tag{12}$$

$$n_{i0} = 2N_{e0}/v_\tau, \qquad n_{i\infty} = n_{i0} + N_{e0}/n_a \sigma_{iD} i.$$

Using (12) and (9), it is easy to show that the ion flux associated with the electric field in (7) is small in comparison with the ion flux due to the concentration gradient if $E < 10^4$ V/cm. Thus, under the assumptions adopted, the concentration distribution is described by (12).

An estimate of the ion concentration from formulas (12) shows that at current densities $i \gtrsim 10^5$ A/cm^2 the quantity $n_{i\infty} \gtrsim 10^{19}$ cm^{-3}. Thus, the assumption of a small degree of ionization in the near-cathode region can be satisfied only at low current densities ($i \sim 10^3$ A/cm^2). Under these conditions $S = 0.5$, and, as simple considerations based on the energy balance show, the spot operates in the thermionic regime. We note that, as was shown above, at such current densities one cannot use the Mackeown equation (1).

To explain and quantitatively describe arc spots with high current densities, two approaches are possible.

First, if the spot is stationary, then for its description one may use the stationary solution of the diffusion problem formulated above, but with variable diffusion coefficients ($n_a \neq$ const, determined by the diffusion equation for the neutral component). In this case the value of S will apparently be greater than 0.5. We emphasize that such an explanation of high current densities in the spot inevitably leads to high degrees of ionization in the near-cathode region.

Another possible explanation for the existence of spots with high current density (auto-electronic spots) is nonstationarity. It is possible that auto-electronic spots exist only in the initial stage of the discharge, and then either arise in a new place or pass into thermionic spots with a low current density. For a quantitative description of nonstationary auto-electronic spots it is necessary to solve the nonstationary diffusion problem. It is clear that in such a solution the value of S will be greater than its stationary value, since at the initial moment some of the ions diffuse into the gas from the ionization region.

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