MUTUAL RELATIONSHIP OF ADSORPTION PROCESSES ON THE SURFACE OF A CATHODE AND THE PROCESSES TAKING PLACE IN THE PARTS OF A HEAVY-CURRENT PLASMA DISCHARGE CLOSE TO THE ELECTRODES

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The effect of alkali metal vapor on the work function of the cathode material in various MHD installations has as yet been little studied [1]. Nor has the mutual influence of adsorption processes on the cathode surface and processes taking place in the parts of a plasma discharge close to the electrodes, although this information is extremely vital in order to make a correct determination of the emission characteristics of cathodes in plasma. The manner in which the electrode becomes coated with the plasma material determines the work function of the electrode and thus the discharge current density and cathode potential drop φ_s. On the other hand, the degree of coverage of the cathode with the adsorbed particles depends substantially on the value of φ_s. In this paper we shall propose a method of calculating the emission characteristics of cathodes during a heavy-current plasma discharge allowing for the mutual influence of the processes in question. The problem is solved in a one-dimensional setting for an automatic thermionic-emission discharge (discharge of the "spotless" type).

Using the fundamental adsorption equation [2] and also the Frenkel formulas [3] for the time spent by particles on an adsorbent surface, we may derive an equation for the degree of coverage of a cathode surface with adsorbed material:

$$\theta = \frac{Nh}{\sigma_m k T_w} \exp\left\{\frac{Q(\theta)}{kT_w}\right\} \tag{1}$$

where $\theta = \sigma/\sigma_m$ is the dimensionless degree of coverage, σ is the density of the coating, i.e., the number of adsorbate atoms (or ions) per unit surface area of the substrate, σ_m is the density of the coating corresponding to the existence of a monolayer of plasma material on the cathode surface, T_w is the temperature of the cathode surface, N is the flow of heavy particles from the plasma per unit surface of cathode per unit time, h is Planck's constant, k is Boltzmann's constant, q is the elementary electric charge, and $Q(\theta)$ is the heat of sorption of the adsorbed atoms.

When the adsorption of plasma particles takes place mainly in the form of ions, the formulas of [4] may be used to determine the dependence of Q on θ.

Numerical or graphical solution of Eq. (1) gives the relationship $\theta = \theta(T_w, N)$. Hence on the basis of [5] we may find the change taking place in the work function for any specific pair of materials (adsorbate–substrate) as a function of the temperature T_w and the value of N. In order to determine the value of θ we may use the Zwicker formula for the Richardson constant [5].

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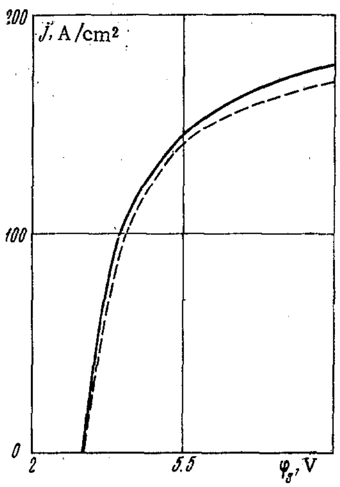

Fig. 1

When the plasma contains particles of two or more substances, we may approximately consider that for $\theta \ll 1$ the resultant change in the work function equals the sum of the changes in work function due to the individual plasma components.

In order to solve the problem we then require relationships describing the processes taking place in the region next to the cathode, and also a relation for determining the temperature T_w.

For the first of these requirements we may use the relationships given in [6, 7], with the one difference that the value of the work function Φ in [6, 7] should be replaced by the quantity $\Phi - \Delta\Phi(T_w, N)$, where $\Delta\Phi(T_w, N)$ is determined as just indicated.

The temperature of the cathode surface was approximately determined from the energy-balance equation at the surface of the cathode, which takes the form

$$Q_i + Q_a^+ + Q_e - Q_t - Q_a^- - Q_p - Q_{ra} - Q_c - Q_v = 0 \tag{2}$$

Here Q_i is the energy carried from the plasma to the cathode by the flow of ions; Q_a^+ is the energy carried to the cathode by neutral plasma atoms; Q_e is the energy carried to the cathode by virtue of the plasma electrons; Q_a^- is the heat carried away by reflected neutral atoms; Q_p is the heat carried away by virtue of surface ionization; Q_{ra} is the heat carried away from the cathode by radiation; Q_c is the heat carried away into the structure of the apparatus (assumed known); Q_v is the heat carried away by evaporation of the cathode material.

In carrying out the calculations the value of Q_i was determined from

$$Q_i = q^{-1} j_{ic} [2kT_i + q(\varphi_s + V_i)]$$

Here V_i is the ionization potential of the plasma; j_{ic} is the current density of the ions passing from the plasma to the cathode; T_i is the temperature of the plasma ions.

Using the results of [8], for the quantity Q_a^+ we have

$$Q_a^+ = 4n_0 \sqrt{\frac{kT_a}{2\pi m_a}}\, kT_a$$

where n_a, T_a, m_a are the concentration, temperature, and mass of the neutral atoms.

The remaining terms take the form

$$Q_e = q^{-1} j_e [2kT_e + q\Phi - \Delta\Phi(T_w, N)], \quad Q_a^- = n_a \left[\sqrt{\frac{2kT_a}{\pi m_a}} - \right.$$
$$\left. - \beta \exp\left(-\frac{q\varphi_s}{kT_w}\right)\right] kT_w, \quad Q_p = n_a \sqrt{\frac{2kT_a}{\pi m_a}}\, \beta \exp\left(-\frac{q\varphi_s}{kT_w}\right) qV_i$$
$$Q_{ra} = \varepsilon\sigma T_w^4, \quad Q_v = m^\circ W$$

Here ε is the emissivity of the cathode, σ is the Stefan–Boltzmann constant, m° is the rate of evaporation of the cathode material, W is the heat of evaporation of the cathode material, j_e is the electron current from the plasma to the cathode, T_e is the temperature of the plasma electrons.

The simultaneous solution of the equations in the region close to the cathode and Eqs. (1) and (2) by an iteration method offers the possibility of determining all the interesting characteristics of the region next to the cathode as regards adsorption processes on the cathode surface.

In carrying out the calculations, we took tungsten as cathode (substrate) material, with $A = \text{const} = 70\ \text{A} \cdot \text{cm}^{-2} \cdot \text{deg}^{-2}$, and lithium as adsorbate. The temperature of the electrons in the plasma T_e was taken as 10^4 °K, $T_i = T_a = 4 \cdot 10^3$ °K. In determining the flows of ions from the plasma to the cathode, we allowed for the results of [8]. Figure 1 shows some typical volt/ampere characteristics of the region close to the cathode, allowing for the dynamic adsorption of plasma material on the cathode surface with $n_i = 2 \cdot 10^{15}$ cm^{-3} (continuous line), and also without allowing for adsorption (broken line). Figure 2 shows the dependence

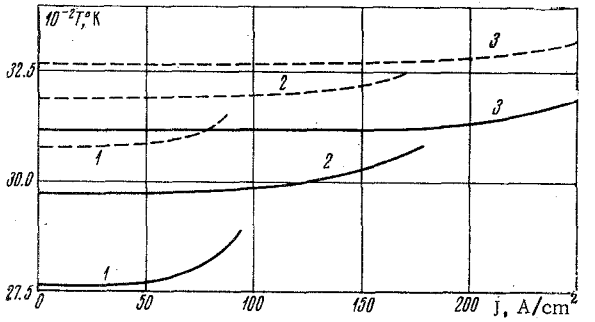

Fig. 2

of the cathode surface temperature on the current density at the cathode allowing for dynamic adsorption for various concentrations of ions in the plasma (curves 1 correspond to $n_i = 10^{15}$ cm^{-3}, curves 2 to $2 \cdot 10^{15}$cm^{-3}, curves 3 to $3 \cdot 10^{15}$ cm^{-3}) (continuous lines), and also without allowing for adsorption (broken lines). We see from an examination of these graphs that, on allowing for dynamic adsorption, for a fixed voltage drop in the cathode layer there is a slight increase in the current density and also a considerable reduction in the cathode temperature (by the order of 200°C). This result is quite easily explained. We find, in fact, on estimating the terms in the energy-balance equation for the conditions here envisaged, that the main access of energy to the cathode is attributed to the bombardment of the cathode surface by plasma ions accelerated in the region of the potential drop. The main loss of energy from the cathode arises from thermionic emission. Since the quantity Q_i is independent of the work function of the cathode material, the removal of energy by the emission electrons should to a first approximation remain constant on varying Φ. When Φ falls by an amount $\Delta\Phi$, the energy required to release one electron diminishes by an amount proportional to $\Delta\Phi$. On the other hand, according to the Richardson–Dushman formula, the flux of emission electrons increases exponentially with rising $\Delta\Phi$. The total removal of energy by the emission electrons may be kept constant by reducing the intensity with which the emission current density rises, i.e., by reducing the cathode surface temperature.

It follows from a consideration of the graph $T_W = f(j)$ and the volt/ampere characteristics that an increase in the concentration of the ions in the plasma leads to a rise in cathode temperature and to a reduction of the voltage drop in the layer close to the cathode. An increase in the ion concentration also leads to a reduction in the effect of adsorption on the characteristics of the processes occurring close to the cathode. Apart from the obvious cause (the increase in the temperature T_W), this is a consequence of the increase in the contribution of the ion current (on which adsorption processes have no influence) to the total current of the system.

The fact that the temperature T_W depends on the current density j indicates that processes taking place in the regions next to the electrodes have a major effect on the degree of coverage θ. Conversely, any calculation of the region next to the electrodes without allowing for the effects of adsorption processes may lead to serious errors.

Thus, even for the discharge conditions here envisaged, which are characterized by a high cathode surface temperature T_W, adsorption processes and the mutual relationship between these and the processes taking place on the cathode surface and close to the cathode play a major part and must be considered when calculating the characteristics of plasma discharges.

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