VOLTAGE – CURRENT CHARACTERISTICS OF THE ELECTRODE BOUNDARY LAYER IN A THERMALLY NONEQUILIBRIUM DENSE PLASMA

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The contact between a thermally nonequilibrium dense plasma and the emitter electrode in a subsonic MHD generator channel is considered. Only the three-particle recombination reaction is treated, in the absence of any magnetic field. The electrode layer is divided into two regions – quasineutral and space-charge areas. The equations which describe the electrophysical processes in these regions are solved numerically on a BÉSM-6 computer. The results are presented in the form of voltage–current curves for the electrode boundary layer at various temperature values for the wall, main flow, and electrons.

The operating characteristics of MHD devices depend on the electrical conductivity of the plasma, and it is therefore important to know how to increase this quantity within the limits set by the materials employed.

The interaction between the plasma and electric field usually produces a state where the electron temperature is different from that of the ions and neutrals, and since the plasma conductivity depends on the electron temperature, this nonequilibrium ionization in the plasma is of special interest. An attempt has been made in [1-3] to show theoretically and experimentally that nonequilibrium ionization occurs in an argon plasma with potassium seeding. Similar nonequilibrium conditions have been studied for rare gases with alkali-metal seeding [4, 5].

The effect of an increased electron temperature near the surface of an insulating wall has been considered in [6, 7] on the assumption that the electron density is in equilibrium across the boundary layer. The density was determined from the Saha equation at the given electron temperature. A similar assumption is valid for an electrode wall in the main flow and in some part of the boundary layer. Near the wall itself the electron densities will be determined by the finite recombination rates [8], and if the nonequilibrium ionization extends into a sufficiently large region of the boundary layer ($l_{sh} \sim 0\ (\delta_T)$), it is necessary to take into account the interaction between the boundary and electrode layers because the temperature of the heavy particles (ions), the seeding atoms, and the main gas will differ from that of the conducting-wall surface.

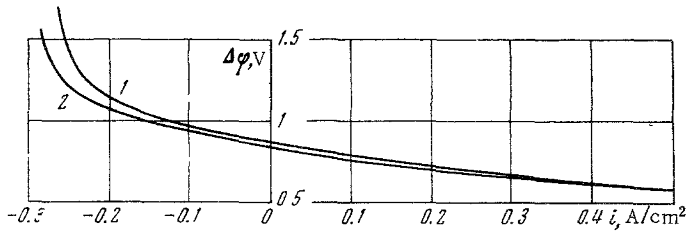

Fig. 1

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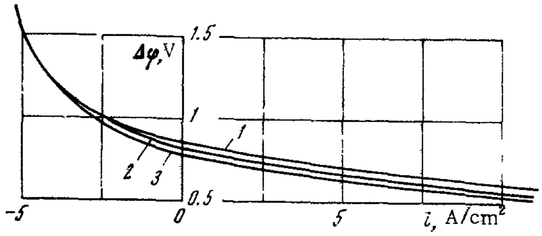

Fig. 2

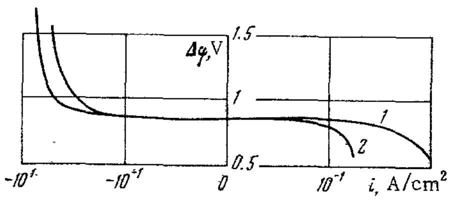

Fig. 3

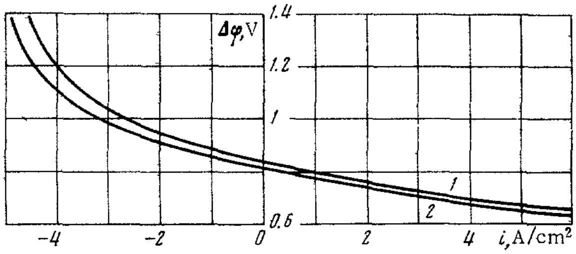

Fig. 4

In this paper we study an electrode boundary layer with allowance for the diffusion, ionization, and recombination of the charged particles for given temperature and velocity distributions in the main gas. We consider a dense plasma at a pressure of P = 1 atm so that the temperatures of the ions and main gas may be taken to be equal. In its general form the problem requires the simultaneous solution of the diffusion and Poisson equations together with the magnetogasdynamic equations for the boundary layer. For a small degree of ionization and a small magnetic-interaction parameter, however, the equations for determining the velocity and temperature of the main gas separate and can be solved independently.

We introduce the following assumptions: 1) The plasma is quasineutral (except in the electrode layer); 2) all the plasma components (except the electrons) are in thermal equilibrium; 3) the electrode surfaces absorb charged particles moving towards them. The surfaces produces thermoionic and thermoelectronic emission; 4) the Debye radius is much greater than the electron mean free path; 5) there is no magnetic field; 6) only three-particle recombination need be considered; 7) radiation effects can be neglected; 8) the electron temperature is constant; 9) we can neglect the variation of all quantities along an electrode.

The electrode layer can now be divided into three regions [8] in which the charged-particle density, the electric field, and the particle fluxes are described by the following dimensionless equations.

In the space charge region

$$\frac{dN_i}{dy} = \frac{N_i G}{\tau_i} - j_i, \quad \frac{dN_e}{dy} = -\frac{N_e G}{\tau_e} - \varepsilon j_e$$
$$\frac{dj_i}{dy} = 0, \quad \frac{dj_e}{dy} = 0, \quad \frac{dG}{dy} = N_i - N_e\ . \tag{1}$$

In the quasineutral region ($N_i = N_e = N$)

$$\frac{dN}{dy} = -\frac{\tau_i j_i + \varepsilon \tau_e j_e}{\tau_i + \tau_e}, \quad \frac{dj_i}{dy} = N(1 - N^2)$$
$$\frac{dj_e}{dy} = N(1 - N^2), \quad G = \frac{(j_i - \varepsilon j_e)}{\tau_i + \tau_e}\frac{1}{N}\ . \tag{2}$$

In the unperturbed plasma

$$N_i = N_e = 1, \quad G = \frac{(j_i - \varepsilon j_e)\tau_i \tau_e}{\tau_i + \tau_e}\ . \tag{3}$$

We now introduce the boundary conditions. In the main flow:

$$y \to \infty, \quad N \to 1, \quad G \to \frac{(j_i - ej_e)\tau_i\tau_e}{\tau_i + \tau_e}.$$

In the diffusion approximation, i.e., in a sufficiently dense gas, the charged-particle density on a wall N_{mw} is usually taken as zero. It is clear, however, that N_{mw} must depend on the diffusion fluxes from the plasma to the electrode and also (when thermal emission occurs) on a density of the emitted current,

$$N_{iw} = \frac{-2j_{iw} + 4_{i,\,em}}{\vartheta_i}, \qquad N_{ew} = \frac{-2j_{ew} + 4j_{e,\,em}}{\vartheta_e} \tag{4}$$

$$j_{e,\,em}e = AT_w^2 \exp\left[-e\left(\varphi_A - \sqrt{eF_w}\right) / KT_w\right]$$

$$j_{i,em}e = BT_w^2 \exp\left[-E_a / KT_w\right].$$

The systems (1) and (2) have been integrated on a BÉSM-6 computer by the Runge–Kutta technique. The solutions of (1) and (2) were found for a certain value of electric field at the electrode surface, and the boundary values of the ion and electron-current densities were varied to derive a solution which satisfied the following matching condition for the two systems at the boundary between the quasineutral and space-charge regions:

$$\left| (N_i' - N_e') / (N_i' + N_e') \right| < \delta \quad \text{at } \infty \quad N' < \delta.$$

The values of the ion- and electron-diffusion coefficients, the three-particle recombination coefficient, the electron work function, and the diffusion activation energy were taken from [9-11]. As a particular example we took the flow of air with a 1% seeding of potassium in a subsonic MHD generator channel. We used the temperature distribution for an incompressible laminar boundary layer [12].

The results are illustrated in Figs. 1-4. Figure 1 shows the effect of the thickness of the temperature boundary layer on the voltage–current curves of the electrode layer for $\delta_T = 0.59 \cdot 10^{-3}$ and $0.75 \cdot 10^{-2}$ m (curves 1 and 2, respectively; $T_0 = 2400$°K, $T_e = 2400$°K, $T_w = 2000$°K); Fig. 2 gives the effect of temperature of the main gas in the flow for $T_0 = 2000$, 2500, and 2800°K (curves 1-3, respectively; $T_e = 2800$°K, $T_w = 2000$°K); Fig. 3 shows the influence of electron temperature for $T_e = 2400$ and 2800°K (curves 1 and 2, respectively; $T_0 = 2400$°K, $T_w = 2000$°K); and Fig. 4 gives the effect of the wall temperature for $T_w = 2000$ and 2400°K (curves 1 and 2, respectively; $T_0 = 2500$°K, $T_e = 2800$°K).

The equilibrium electron density calculated from the Saha equation for an electron temperature of 2400°K and a main flow temperature of 2000°K is $n_{ep} \approx 1.1 \cdot 10^{20}$ m^{-3}, and for nonequilibrium ionization the electron density is equal to this value at the boundary of the electrode layer; for a potential drop of 1 V across this layer the density falls to a value of $n_{ew} = 4 \cdot 10^{17}$ m^{-3} near the electrode surface.

The results in Figs. 2-4 were obtained for the same point on the electrode surface (the thickness of the temperature boundary layer was taken to be $2.15 \cdot 10^{-3}$ m for a main flow temperature $T_0 = 2400$°K, a wall temperature $T_w = 2000$°K, and an electron temperature $T_e = 2800$°K).

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