CALCULATION OF THE THERMALLY NONEQUILIBRIUM NEAR-ELECTRODE REGION IN AN ALKALI-METAL-SEEDED PLASMA

V. I. Belykh

UDC 538.4.533.9

Distribution of parameters in the region of disturbance of a plasma near the surface of an electrode is considered based on diffusion equations. Thermoelectronic and thermionic emission from the electrode surface, the Schottky effect, and volume ionization and recombination are borne in mind. Two regions are assumed in the solution, namely, the region of ambipolar diffusion and the region of the space charge. A comparatively simple geometry for the discharge gap, given in the form of two infinite plane-parallel electrodes, is considered. A comparison is carried out with calculations for a thermally balanced region of a plasma disturbance.

Much attention has recently been paid to the study of near-electrode processes in a plasma due to the development of methods for directly transforming energy (kinetic into electrical and conversely), while the analysis of near-electrode phenomena has been based on the supposition that electron temperature is constant [1-3].

In this work, a model of the near-electrode layer is studied that takes into account diffusion, ionization, and recombination, and in which the hypothesis that electron temperature is constant is removed. Electron temperature is determined from the energy balance of the electron gas, described in the form

$$\sigma E^2 = \frac{3}{2}\delta n_e k\nu (T_e - T_g). \tag{1}$$

We assume that the plasma is a mixture of a gas with high ionization potential whose pressure is sufficiently high ($p_g \sim 1$ atm), and of vapors of an alkali metal seed ($p_a \sim 10^{-2}$ atm). It is also assumed that ion and neutron temperatures coincide and are equal to the electrode temperature ($T_i = T_g = T_W$).

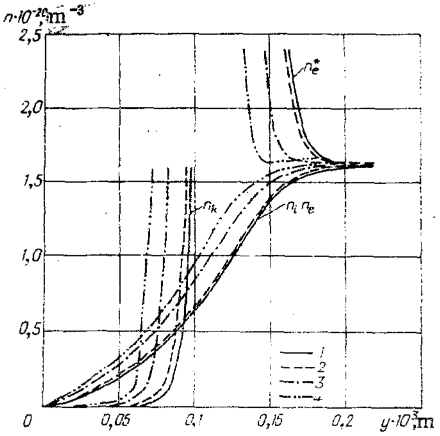

Fig. 1

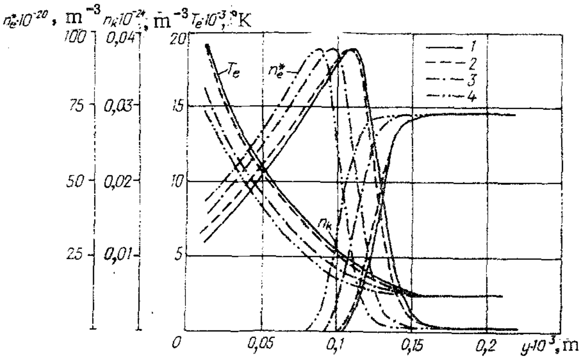

Fig. 2

Zhukovskii. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 1, pp. 13-17, January-February, 1976. Original article submitted November 21, 1974.

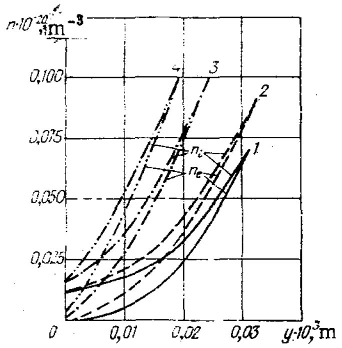

Fig. 3

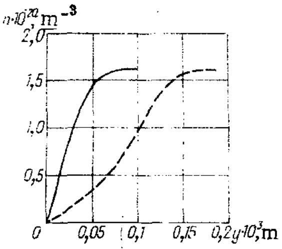

Fig. 4

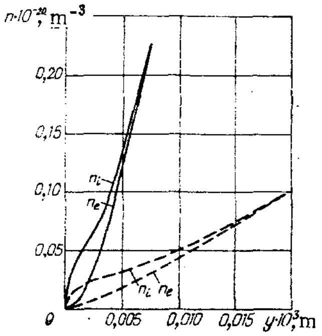

Fig. 5

Under these hypotheses, the near-electrode layer divides into three regions [1], in which the concentration of charged particles, electric field strength, and particle fluxes are described by the following dimensionless equations:

for the region of the space charge

$$\frac{dN_i}{dy} = N_i G - j_i D_i^{-1}, \tag{2}$$

$$\frac{dN_e}{dy} = - N_e G \tau_e^{-1} - j_e D_e^{-1},$$

$$\frac{dj_i}{dy} = \frac{dj_e}{dy} \equiv 0, \quad \frac{dG}{dy} = N_i - N_e;$$

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

$$\frac{dN}{dy} = \frac{j_i D_i^{-1} + j_e \tau_e D_e^{-1}}{1+\tau_e}, \tag{3}$$

$$\frac{dj_i}{dy} = \frac{dj_e}{dy} = \alpha_r N \left\{ \frac{(N_e^*)^2}{N_k^*} [N_{k0} - (1+\tau_e) N] - N^2 \right\},$$

$$G = \frac{\left(j_i D_i^{-1} - j_e D_e^{-1}\right) \tau_e}{1+\tau_e} \cdot \frac{1}{N};$$

for the region of undisturbed plasma

$$N_i = N_e \equiv 1, \tag{4}$$

$$G = \frac{\left(j_i D_i^{-1} - j_e D_e^{-1}\right) \tau_e}{1+\tau_e}.$$

Variables such as the diffusion coefficients of the ions D_i and electrons D_e, the recombination coefficient α_r, seed pressure p_a, and equilibrium electron concentration N^*_e, which are determined from the following equations, also occur in Eqs. (2)-(4). The diffusion coefficient is given by:

$$D_i = \left(\sum_{s \neq i} N_s Q_{is}^1 \right)^{-1},$$

$$D_e = \left(\frac{m_i}{m_e} \tau_e \right)^{1/2} \left(\sum_{s \neq e} N_s Q_{es}^1 \right)^{-1};$$

the recombination coefficient [4] by

$$\alpha_r = \tau_e^{-4.765};$$

the Saha equation [5] is

$$(N_e^*)^2 = C N_k^* \tau_e^{3/2} \exp\left(- \frac{e\varphi_i}{kT_e} \right);$$

and the equation of state is given by

$$p = \sum_s p_s = k \sum_s n_s T_s.$$

In this work we will use collision cross sections that have been previously obtained [6-8],

$$Q_{ek}=4\cdot 10^{-18},$$

$$Q_{eN_2}=4{,}5565\cdot 10^{-20}+2{,}81786\cdot 10^{-23}T_e-4.99704\cdot 10^{-27}T_e^2+3{,}30643\cdot 10^{-31}T_e^3,$$

$$Q_{iN_2}=2.39\cdot 10^{-17}T_g^{(1.756\cdot 10^{-5}T_g-0{,}5)},$$

$$Q_{ei}=\frac{\pi}{2}\left[\frac{e^2}{4\pi\varepsilon_0}\frac{1}{kT_e}\right]^2\ln\Lambda,$$

$$\Lambda=3\lambda_D\left[\frac{4\pi\varepsilon_0}{e^2}\right]kT_e,$$

$$\lambda_D^{-2}=\frac{1}{\varepsilon_0}\sum_s\frac{n_s q_s^2}{kT_s},$$

where Q_{ek}, Q_{eN_2}, and Q_{iN_2} are in m^2, while temperature is in °K.

The boundary conditions on the electrode surface, i.e., for the system (2), are given by

$$N_{iw}=\frac{-2j_{iw}+4j_{i\mathrm{em}}}{v_i},$$

$$N_{ew}=\frac{-2j_{ew}+4j_{e\mathrm{em}}}{v_e},$$

where $j_{i\mathrm{em}}$ and $j_{e\mathrm{em}}$ are the thermal emission densities,

$$j_{e\mathrm{em}}=AT_w^2\exp[-e(\varphi_\mathrm{a}-\sqrt{eE_w})/kT_w],$$

$$j_{i\mathrm{em}}=BT_w^2\exp\left[-\frac{E_\mathrm{a}}{kT_w}\right].$$

Exact analytic solution of Eqs. (1)-(3) is impossible, so they were integrated on a computer using the Runge–Kutta method. The computation procedure reduces to finding a solution satisfying matching conditions for the solution of the systems of equations (2), (3)

$$\left|\left(\frac{dN_i}{dy}-\frac{dN_e}{dy}\right)\Big/\left(\frac{dN_i}{dy}+\frac{dN_e}{dy}\right)\right|\leqslant\delta_1,$$

$$|(N_i-N_e)/(N_i+N_e)|\leqslant\delta_1$$

on the boundary of the quasineutral region and the region of the space charge and

$$\frac{dN}{dy}\leqslant\delta_2$$

on the boundary of the quasineutral region and the region of undisturbed plasma. This solution is given for definite values of the electrode temperature and the electric field strength at the electrode surface by varying the boundary values of the densities of the ion and electron fluxes.

Figures 1-5 illustrate the results of the calculation. The working mixture was nitrogen at atmospheric pressure containing 1% potassium. The distribution of charged-particle concentration as well as the electron and ion concentration distributions, calculated using the Saha method, is depicted in Fig. 1; Fig. 2 depicts the distributions of the electron temperature and ion and neutron concentrations calculated using the Saha method; Fig. 3 depicts the distributions of ion and electron concentrations in the region of the space charge. Curves 1 in Figs. 1-3 correspond to a current density of 78.64 A/m^2, while $i=-14.29$ A/m^2 for curves 2, $i=-1190$ A/m^2 for curves 3, and $i=-3273$ A/m^2 for curves 4. The distribution of concentrations in the near-electrode layer and in the region of the space charge, respectively, as a current of density $i=-3273$ A/m^2 passes is depicted in Figs. 4 and 5 for comparison in the cases of a constant and a variable electron temperature. The unbroken curves correspond to constant electron temperature equal to the electrode temperature, while the dashed-dot curves correspond to variable electron temperature. The temperature of the electrodes was set equal to 2400°K for all the computational results. The potential drop $\Delta\varphi$ in the near-electrode layer was 1.2 V in the case of a constant electron temperature and 4.35 V in the case of a variable electron temperature.

LITERATURE CITED

1. G. A. Lyubimov and V. N. Mikhailov, "Analysis of the region of plasma disturbance near an electrode," Izv. Akad. Nauk SSSR, Mekh. Zhidk. Gaza, No. 3 (1973).

2. V. N. Mikhailov, "Calculation of the near-electrode region in an alkali-metal-seeded plasma," Zh. Prikl. Mekh. Tekh. Fiz., No. 4 (1971).
3. V. I. Belykh, "Calculation of the volt–ampere characteristics of an electrolyte boundary layer in a thermally unbalanced plasma," Zh. Prikl. Mekh. Tekh. Fiz., No. 5 (1974).
4. T. A. Koll and E. E. Zukoski, "Recombination rates and nonequilibrium electrical conductivity in seeded plasmas," Phys. Fluids, 9, No. 4, 780 (1966).
5. J. L. Kerrebrock, in: Proceedings of the Second Symposium on Engineering Aspects of MHD, Philadelphia (1961).
6. G. W. Garrison, "Electrical conductivity of a seeded nitrogen plasma," AIAA J., 6, No. 7, 1264 (1968).
7. R. E. Weber and K. E. Tempelmeyer, "Calculation of the D-C electrical conductivity of equilibrium nitrogen and argon plasma with and without alkali metal seed," AEDC-TDR-64-119 (July, 1964).
8. S. T. Demetriadis and G. S. Argyropoulos, "Ohm's law in multicomponent nonisothermal plasmas with temperature and pressure gradients," Phys. Fluids, 9, No. 11, 2136 (1966).

EXISTENCE REGION FOR ARCING CONDITIONS WITH NEGATIVE ANODE POTENTIAL DROP

N. S. Merniov and V. A. Petrosov

UDC 533.932:621.3.036.6

Conditions for ignition of a high-current arc with negative anode potential drop U_a is investigated, and the region within which these conditions exist and causes for a transition into conditions with positive U_a are studied. It is noted that a regime with negative U_a is most preferable for most plasma units.

Two regimes are observed in working with different plasma units (MHD generators, plasmotrons, plasma accelerators, etc.) when investigating and using high-current arcs, namely, regimes with positive and with negative anode potential drop U_a [1]. Though these two regimes are often encountered when working with the same unit (one regime may pass into the other), they possess a number of distinctive properties.

The discharge is practically always uniformly distributed throughout the surface of the electrode in the regime of negative U_a, while it is tightened into a braid and contracted with positive U_a. Discharge current increases with minimal voltage increase for a negative U_a (we are speaking here of a highly developed high-current arc), while a small increase in current is accompanied by a significant increase of voltage for positive U_a, a large part of the voltage increment falling within the near-electrode zone [1, 2]. The current density through the electrode and the total heat release with positive U_a is greater than with negative U_a, other conditions being equal. Moreover, this refers to the specific heat flow in the anode spot. A number of studies have recently appeared (for example, [3-5]) in which it was discovered that heat release on the anode is less than that calculated for arcing with negative U_a, which is apparently due to an increase in the effective work function of the anode material in contact with the plasma [5-7]. No such effect is observed with positive U_a.

It is well known that a regime with positive U_a occurs in many plasma units (this has been proposed by investigators). For example, the anode drop is positive in high-current plasma accelerators. The opinion that atmospheric arcs burn with positive U_a has been widespread.

At the same time, a comparison of these properties of the two regimes implies that the regime with negative U_a is more preferable (from the point of view of decreasing energy losses in the construction, solving electrode-cooling problems, optimally organizing the working process in the unit, etc.). Therefore an investigation into the ignition regime for a high-current arc with negative anode drop, a study of the region within which this regime exists, and an explanation of the causes and conditions for a transition into a regime with positive U_a constitute the most important problems.

Moscow. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 1, pp. 17-24, January-February, 1976. Original article submitted November 21, 1974.