NEAR-ELECTRODE LAYERS AT "HOT" ELECTRODES

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Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 4, pp. 45–53, 1965

References [1, 2] present a definite approach to the problem of theoretically describing the near-electrode layers for a change of potential at "hot" electrodes located in a weakly-ionized gas stream. There it was assumed that the degree of gas ionization near the electrode and its temperature are such that the Debye length computed from parameter values near the surface of the electrode is smaller than the mean free path of the charged particles ($d \leqslant l$). In this case, the problem of the near-electrode layer is separate from the problem of the distribution of quantities in the gas stream and its solution is used to formulate the boundary condition. Moreover, in solving the problem of the near-electrode layer, we can assume collision-free motion of the charged particles throughout this layer.

In the indicated references the near-electrode layer problem was not solved. The quantities necessary for formulating the corresponding boundary conditions were assigned on the basis of physical considerations.

In this article, some of the assumptions of [1, 2] are refined on the basis of the solution of model problems and a more detailed analysis of the effects in question. It is shown, in particular, that the theory is inadequate for describing near-electrode layers at electrodes made from a material that is a poor neutralizer for ions.

On the basis of an analysis of solutions of model problems of the near-electrode layer for both "ion-absorbing" and "ion-reflecting" surfaces, an attempt is made to construct a semi-empirical theory of the near-electrode layer. For certain cases, experimental data are compared with calculated data and, in particular, the experimental constants needed to construct the theory are determined.

Although the experimental and calculated data seem to agree, one should remember that the amount of data is still insufficient to make a final decision on the quality of the proposed theory. It is necessary to perform special carefully organized experiments to study near-electrode layers under different conditions. On the basis of an analysis of such experiments the experimental constants of the theory must be determined and then substituted in the calculation formulas. The results of such experiments may considerably modify our ideas about the phenomena taking place in near-electrode layers and may possibly require improvements in the theory.

1. One of the most important assumptions in [1, 2] was that the electric field at the electrode surface has the form

$$E = \varphi / d, \tag{1.1}$$

where φ is the change of potential in the near-electrode layer and d is the Debye radius computed from the parameters near the electrode. This assumption is equivalent to ignoring the space-charge distribution in the layer and to fixing the thickness of the layer according to the Debye length.

To estimate the effect of the near-electrode layer structure on the magnitude of E and the layer thickness, let us consider an idealized problem. Let the gas parameters near the electrode be such that $d < l$ (l is the mean free path of the charged particles). If the gas in question consists of the basic gas and an easily ionized additive ($\leqslant 1\%$) for $T \geqslant 2000°$ K, $p \sim 1$ atm, and equilibrium conditions, then the number of charged particles is not large and their mean free path for collision with neutral particles proves to be less than the mean free path for collisions with each other. Here, $l \geqslant 10^{-3}$ cm, and the Debye length for these conditions is $d \leqslant 10^{-4}$ cm. Consequently, if the layer thickness is of the order of d, within the layer the charged particles move without collisions under the conditions in question.

Let the electrode surface be such that all the ions incident on it are neutralized ("absorbing" surface). The coefficient for reflection of ions from the surface depends on the type of ion and the surface material; however, for neutralization, it is necessary that $\Phi < U_i$ (Φ is the electrode work function, U_i is the ionization potential of the ionized atoms) [3].

Let us take the diode problem as a model. Assume that the cathode emits an electron current of density j_e and absorbs all ions incident on it. The anode is at the same temperature and emits an electron current j_e and ion current j_i equal to the flow of charged particles from the plasma. If we assume that equilibrium conditions exist at the outer boundary of the layer, then

$$j_e = ne\left(\frac{kT}{2\pi m_e}\right)^{1/2}, \quad j_i = ne\left(\frac{kT}{2\pi m_i}\right)^{1/2}, \tag{1.2}$$

where n is determined from the Saha formula.

We assume that the particles begin their movement from the cathode and the anode at zero velocity (we can show that allowance for finite particle velocities does not significantly change the magnitude of E at the cathode surface if $T \sim 2000°$ K and the potential difference across the diode is greater than 1 V). Then the charged particle distribution in the layer is given by the expressions (see, for example, [4])

$$\begin{gathered} n_i = \frac{j_i}{e}\left(\frac{m_i}{2e(\varphi - V)}\right)^{1/2}, \\ n_e = \frac{1}{e}\left(\frac{2\pi m_e}{kT}\right)^{1/2}\left[j_e \exp\left\{\frac{(V - \varphi)e}{kT}\right\} + \frac{j_c}{2\sqrt{\pi}}\left(\frac{m_e}{2eV}\right)^{1/2}\right]. \end{gathered} \tag{1.3}$$

Here V is the potential at the point in question, φ is the anode potential, and the cathode potential is taken to be zero.

For $\varphi \geqslant 1$ V and $T \sim 2000°$ K, the electron density is basically determined by the emitted electrons j_c; therefore, the potential distribution in the layer is described by

$$\begin{gathered} \frac{d^2V}{dx^2} = 4\pi e(n_e - n_i) = 4\pi j_i\left(\frac{m_i}{2e\varphi}\right)^{1/2}\left(\frac{\beta}{\sqrt{\tau}} - \frac{1}{\sqrt{1 - \tau}}\right), \\ \beta = \frac{j_c}{j_i}\left(\frac{m_e}{m_i}\right) \equiv \frac{j_c}{j_e}, \qquad \tau = \frac{V}{\varphi}. \end{gathered} \tag{1.4}$$

For the foregoing electrode operating conditions, in MHD devices $\beta \ll 1$. Moreover, the electric fields at the outer boundary of the layer, which determine the current in the gas, are much smaller than the electric fields at the electrode surface which, as will be seen below, are of an order greater than 10^3 V/cm. Here the boundary condition for equation (1.4) has the form

$$E_a = -\frac{dV}{dx} = 0 \quad \text{for } V = \varphi\,. \qquad (1.5)$$

The electric field at the electrode surface corresponding to the solution of equation (1.4) for condition (1.5) has the form [5]

$$E = \left(\frac{2}{\sqrt{\pi}}\right)^{1/2}\left(\frac{kT}{e\varphi}\right)^{3/4}\frac{\varphi}{d} \qquad (1.6)$$

while the layer thickness is given by

$$L = \left(\frac{8}{9}\sqrt{\pi}\right)^{1/2}\left(\frac{e\varphi}{kT}\right)^{3/4} d\,. \qquad (1.7)$$

Relationships (1.6), and (1.7) show that for our case of an ideally absorbing electrode surface, the electric field at the electrode surface is less than (1.1), since $kT/e\varphi \ll 1$ and the layer thickness is much greater than the Debye length. Here we must take $L \leqslant l$, and not $d \leqslant l$, as the condition of applicability of the given model.

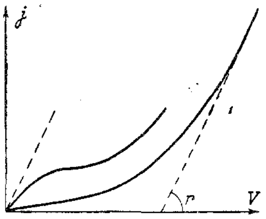

Fig. 1

If the electrode surface partially reflects the incident ions, the conditions are created for the accumulation of ions in a "potential well" near the cathode. In these conditions the electric field at the surface of the electrode depends upon the number of "trapped" ions and their distribution and will, in general, be greater than the field determined by (1.6). The processes occurring at the electrode surface when ions are neutralized and reflected have received neither much theoretical nor much experimental attention [3]. These problems have gone almost unstudied as far as the conditions of electrode operation in MHD devices are concerned. Moreover, the distribution of quantities in the layer is evidently determined by the reflection coefficient and the type of reflection of the ions from the electrode surface, which depend upon the surface material and the nature of the ions.

In this connection, it is still not possible to solve the problem of the near-electrode layer with allowance for these effects. (Similar problems were considered in [6, 7] for conditions characteristic of plasma thermoelements under some constraints.) Nevertheless, it is of interest to examine the other limiting case, the opposite of that considered above.

Consider the problem of a diode when the cathode completely reflects incident ions and assume that the particle distribution near the electrode, including "trapped" particles, is the equilibrium distribution. (The solution of a similar problem without allowance for trapped particles is given in [4].) In this case, the electron and ion densities are given by the expressions

$$n_e = n\exp\left\{\frac{e(V-\varphi)}{kT}\right\},\quad n_i = n\exp\left\{-\frac{e(V-\varphi)}{kT}\right\}, \qquad (1.8)$$

where n is the particle density at the outer boundary of the layer. The electron density associated with particles emitted from the cathode can be ignored for the same reasons ($\beta \ll 1$) as in the previous example.

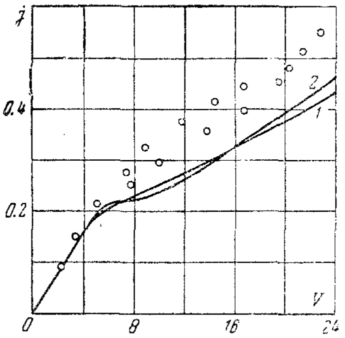

Fig. 2

In this case the potential distribution is described by

$$\frac{d^2V}{dx^2} = 8\pi ne\,\mathrm{sh}\left[\frac{e(V-\varphi)}{kT}\right]. \qquad (1.9)$$

The solution of equation (1.9) with boundary condition (1.5) yields the following expression for the electric field at the electrode surface and the thickness of the charged layer:

$$E = 2\frac{\varphi}{d}\left(\frac{kT}{e\varphi}\right)\left(\mathrm{ch}\left[\frac{e\varphi}{kT}\right]-1\right)^{1/2}, \qquad L \sim d\,. \quad (1.10)$$

The solution of (1.10) shows that small changes in potential in the near-electrode layer ($\varphi \sim 1$ V) produce an increase in the fields at the electrode surface so great that a considerable increase in emission current becomes possible due to the Schottky effect and field emission.

These limiting cases and an analysis of relations (1.6) and (1.10) suggests that a semi-empirical relationship of the form

$$E = \beta\frac{\varphi}{d}\left(\frac{e\varphi}{kT}\right)^{\alpha} \qquad (1.11)$$

should be used as the first approximation for E in calculating the effect of the near-electrode layers on the characteristics of MHD devices.

Here the quantities α and β, which apparently depend only upon the properties of the electrode material and the nature of the ions, must be determined experimentally from an analysis of the current-voltage characteristics of the MHD devices.

Note that if we assume that the electric field at the electrode surface is not explicitly dependent upon current density, then by dimensional analysis we can obtain a relationship of the form $E = \varphi d^{-1} f(e\varphi/kT)$.

Equation (1.11) corresponds to approximation of the function f by a power series.

It is clear that the quantities α and β are not equivalent. The quantity α determines the rate of growth of the electric field with increase in the change of potential in the near-electrode layer. The quantity β has only a slight effect on the electric field and an even slighter effect on the final results of calculating the function $\varphi_+ = \varphi_+(j, T, \ldots)$ [1, 2]. In this connection, it is clearly desirable to set $\beta \cong 1$ initially.

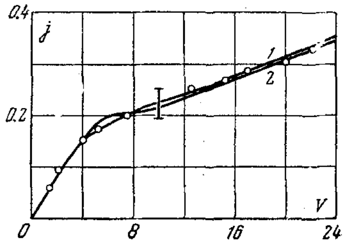

Fig. 3

Functions (1.10) may be approximated satisfactorily enough for calculation purposes in the 1–2 V interval by the expression $E = 0.25\varphi d^{-1}(e\varphi/kT)^3$. Therefore, the change in α is limited, evidently, to the interval $-3/4 < \alpha < 3$. The theory of [1, 2] corresponds to a value $\alpha = 0$.

For surfaces which are good ion absorbers, α is small and the change in potential φ_+ at the positive electrode (electrode from which electrons enter the stream) is high for $j > j_c^*$ (j_c^* is the thermoemission current). In these conditions, impact ionization at the outer boundary of the layer is important, for it increases the ion current. The basic relations for calculating the change in potential have the form given in [2]. In this case, a characteristic saturation interval will be present on the current-voltage characteristic of the MHD device (see below).

When the surface is a good ion reflector ($\alpha \geqslant 1$), the electric fields grow very rapidly; in this case, even at high currents, the change in potential in the near-electrode layer is small. In these conditions, impact ionization is not important and the ion current can be ignored. The relation for calculating the change in potential in the near-electrode layers now has the form (compare with [2]):

$$j = \frac{\pm j_c^* \exp\{4.39 T^{-1} \sqrt{E}\} \mp j_e \exp\{-e\varphi_\pm / kT\}}{1 - {}^1/_2 (1 - \psi\{\sqrt{2e\varphi_\pm / kT}\})}. \quad (1.12)$$

Owing to the strong growth of current due to the electric field, there is no saturation interval on the current-voltage characteristic.

Figure 1 shows the qualitative form of the current-voltage characteristics on absorbing (curve 1) and reflecting (curve 2) surfaces.

Analysis of the scanty available experimental data (see below) shows that potassium ions are apparently neutralized strongly on graphite and weakly on tungsten.

2. One result of the formation of near-electrode layers is that the change in potential in the gas stream differs from the potential difference across the electrodes [1]. Therefore, in studying the over-all characteristics of MHD devices, it is convenient to treat the near-electrode layers as a certain resistance

$$r^\circ = \frac{\varphi_+ - \varphi_-}{j} \quad (2.1)$$

depending upon the current density. For example, the equation of the current-voltage characteristic in the problem of the passage of a current through an ionized gas will have the form

$$j(r + r^\circ) = jr + \varphi_+ - \varphi_- = V, \quad (2.2)$$

where r is the internal resistivity of the gas space.

The slope of the characteristic at the origin is [8]

$$\left.\frac{dV}{dj}\right|_{j=0} \approx r + 2\frac{kT}{e}\frac{1}{j_c^* + j_i}. \quad (2.3)$$

We may draw some conclusions from this relationship with respect to the measurement of electrical conductivity by the electrode method. If the measuring electrodes are good ion absorbers (graphite), they have a relatively small work function ($\Phi < U_i$) and $j_c^* \sim \sim j_i$. Under these conditions, the second term in (2.3) is not large for $T \geqslant 2000°$ K and the angle of inclination of the characteristic at the origin will not differ greatly from r for a suitable distance between electrodes [8, 9] (Fig. 1).

On the other hand, if the electrodes are good ion reflectors (tungsten), they have a high work function ($\Phi \geqslant U_i$) and the ion current at the surface is small (in the limiting case all ions are reflected and $j_i = 0$). Under these conditions, the second term in (2.3) may be quite large, so that for a device of reasonable dimensions $r \lesssim 2kT/ej_c^*$ (for example, $2kT/ej_c^* \cong 300$ ohms for tungsten at $T = 2000°$ K). Clearly, it is now impossible to measure the electrical conductivity from the slope of the current-voltage characteristic at the origin (Fig. 1).

However, since the electric field increases very radpily at the reflecting surface with increase in the change of potential in the near-electrode layer, r° decreases rapidly with increase in current. For example, when the calculations are based on (1.10) and $T \sim \sim 2000$–$2500°$ K, $\varphi_+ - \varphi_-$ increases quite rapidly to a value of ~2 V and remains practically constant with current increase. A similar pattern is also observed when (1.11) is used for the calculation with $\alpha < 3$ (see below); but, of course, the value of $\varphi_+ - \varphi_-$ increases and becomes more temperature-sensitive than at $\alpha = = 3$. Since the value of $\varphi_+ - \varphi_-$ increases rapidly at the beginning and then changes only slightly with increase in current, it is clear that r° → 0 as the current increases. In this case the angle of inclination of the current-voltage characteristic at large currents must correspond to the internal resistance r, while the segment cut off by the line $rj + \varphi_+ - \varphi_- = V$ on the V axis gives the change of potential in the near-electrode layers at high currents.

3. Reference [2] gave a formula for calculating the change of potential in near-electrode layers at ion-absorbing surfaces with allowance for impact ionization of atoms at the outer boundary of the layer. The structure of the impact ionization term in this formula is

$$\frac{n_k Q_k}{n_k Q_k + n_a Q_a} c_k(\varphi_+ - U_k), \quad c_k = 0 \text{ for } \varphi_+ < U_k. \qquad (3.1)$$

Here n_k, n_a are the particle concentrations in the additive and the basic gas, Q_k and Q_a are their cross sections for collision with beam electrons emitted by the electrode and accelerated in the near-electrode layer, c_k is the experimental constant of impact ionization, U_k is the ionization potential of the additive, and φ_+ is the change of potential in the near-electrode layer at the positive electrode.

It was assumed in [2] that for the purposes of specific calculations $Q_a = 2 \cdot 10^{-3} Q_k$ [10] (basic gas is argon, additive is potassium). We know [3] that the cross section for electron-neutral collision depends on the electron energy. The foregoing relationship between cross sections holds at low electron energies (less than 1 eV). At high energies ($\geqslant$5 eV), the cross sections for argon, and other basic gases are close to the gas-kinetic value and are of the order of 10^{-15} cm^2. For potassium at energies of $\sim$5 eV, $Q_k \sim 0.3 \cdot 10^{-13} - 10^{-14}$ cm^2 and it decreases fairly slowly with increase in energy.

Upon comparing the cross sections for collision of basic gas atoms and additive, we see that in the conditions under consideration at an additive concentration $\leqslant$ 1%, the total collision cross section is principally determined by the basic gas atoms ($n_k Q_k + n_a Q_a \sim n_a Q_a$). Therefore, the effectiveness of impact ionization is directly proportional to the additive concentration.

The quantity (3.1) is the ratio of the additive ionization cross section to the total collision cross section for emitted electrons. If for the constant c_k we take the value obtained in electronics for measurements in alkali metal vapors at low temperatures, then $c_k \sim 10^{-3}$. On the other hand, the value of c_k obtained from analysis of the experimental current-voltage characteristics using the formulas of [2] is of the order $c_k \sim 0.4$, i.e., roughly two orders greater.* If, however, the experimental data are reduced with allowance for (1.6), then a still greater value of c_k is obtained (see below).

The increase in c_k for alkali metal atoms when alkali metal vapors are present in small quantities in a gas with a higher ionization potential (operating conditions for MHD devices) may be due to the following circumstance. In the conditions under consideration for additive concentrations $\leqslant$1% and pressure p $\sim$ 1 atm, the mean free path for ionizing electrons (electrons accelerated in the near-electrode layer) colliding with basic gas atoms is roughly $n_a Q_a / n_k Q_k \sim$ $\sim$ 10 times less than the mean free path for collision with additive atoms. In this case, the beam of accelerated electrons is strongly scattered at atoms of the basic gas, the electron energy changing only slightly on collision. It is clear that the probability of ionization of the additive may increase due to the impact of electrons scattered by basic gas atoms and to stepwise ionization.

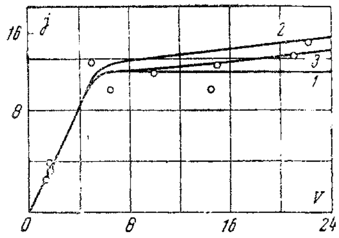

Fig. 4

The problem of the increase in ionization probability under these conditions must be solved experimentally. An indirect possibility of determining the constant c_k is to study the current-voltage characteristics of the gas space obtained in special experiments. The experimental data available [8, 9] still do not enable us to obtain a final value for c_k, as will be seen below.

4. Reference [2] gives a comparison of calculated and experimental [8] current-voltage characteristics for the problem of passage of a current through an ionized gas. Experimental points [8] corresponding to the following conditions are plotted in Fig. 2: the working gas is argon with 0.4% potassium additive; T = 2200 ± 200° K, p $\sim$ 1 atm; the electrodes are graphite. The calculated curve 1 [2] plotted on this figure corresponds to the following values of the parameters:

$$j_{\text{э}} = 0{,}095\ A/\text{cm}^2 \quad r = 24.1\ \text{ohms} \qquad (4.1)$$

$$c_k = 0.4, \quad \alpha = 0, \quad T = 2200°\ \text{K}.$$

Here α is the exponent in (1.11). The values in (4.1) were determined by analyzing the oscillogram [8] corresponding to a 0.2% potassium additive [2] (curve 1 in Fig. 3).

Since in [8] graphite is used for the electrodes (there is no mention of the emission properties in this article), i.e., an ion-absorbing surface, the formulas for calculating the change of potential in the near-electrode layer at such a surface contain two experimental constants: α and c_k. It is clear, therefore, that the analysis of the experimental data (particularly when the electrode work function is not known) with the aim of determining the experimental constants

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* This value is different from the one given in [2]. The difference is due to the fact that the expression given in [10] for the relation between the collision cross sections for atoms of the additive and the basic gas was used in [2] for determining c_k. The above-mentioned value is obtained if c_k is determined from an analysis of the same experiments [2, 8] taking for the cross sections the orders of magnitude indicated above.

may be done in more than one way. For example, Fig. 3 gives the calculated curve 2 corresponding to the following values of the parameters:

$$j_{\text{э}} = 0.125\ \text{A/cm}^2,\ r = 24.1\ \text{ohms}, \qquad (4.2)$$
$$c_k = 1.2, \quad \alpha = -{}^3/_4, \quad T = 2200^\circ\ \text{K}.$$

Both curves in Fig. 3 lie within the spread of the experimental points (the dispersion is indicated in the figure). The calculated curve for 0.4% potassium is given in Fig. 2 (curve 2) for the values of the parameters (4.2).

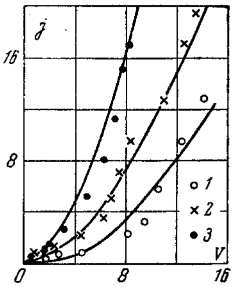

Fig. 5

Clearly, both calculated curves describe the experimental data equally well [8]. The final selection of values for α and c_k will be possible only after a great number of special experiments have been analyzed.

Unfortunately, we cannot make a final selection of the values of the constants even after analyzing the experimental data of [9] for $\alpha = 0$, $c_k = 0.4$ and $\alpha = -3/4$, $c_k = 1.2$ (Fig. 4). Curve 1 in Fig. 4 corresponds to the theory according to which the near-electrode layer is replaced by a potential discontinuity surface; curve 2 corresponds to the values $\alpha = 0$, $c_k = 0.4$ and curve 3 to the values $\alpha = -3/4$, $c_k = 1.2$. Under the experimental conditions in question (low temperature, small additive concentration, poor emitter), both the potential discontinuity theory and the theory developed above yield values that give a good description of the experimental data.

Let us now consider the current-voltage characteristic obtained by passing a current through argon containing about 0.5% potassium with tungsten used as the electrode material, i.e., a good ion reflector.

Figure 5 gives the experimental points obtained for various electrode and gas temperatures.* Unfortunately, these data correspond to a random set of gas and electrode temperatures and the resistance of the gap was not measured independently.

An approximate estimate of the gap resistance from the measured values ($T_1^* = 2300^\circ$ K, $T_2^* = 2200^\circ$ K, $T_3^* = 2400^\circ$ K) of the flow core temperature (measured by the heat balance method and corresponding quite accurately to the mean gas temperature at the working section inlet) shows that the resistances corresponding to the series of points 2 and 3 differ by a factor of two. The resistance corresponding to the series of points 1 must be somewhat greater, since in this case the flow is cooled near the electrode. If, in accordance with the foregoing considerations, we estimate the resistance from the angle of inclination of the characteristic at large currents, we obtain

$$r_1 \approx 6\ \text{ohms},\ r_2 \approx 4\ \text{ohms},\ r_3 \approx 2\ \text{ohms}\ . \qquad (4.3)$$

These values are found to agree with rough estimates from the temperature and are used in the subsequent calculations.

If the angle of inclination of the characteristic at the origin for the temperature values measured experimentally ($T_1^\circ = 1750^\circ$ C, $T_2^\circ = 2000^\circ$ C, $T_3^\circ = 2300^\circ$ C) is computed, at $j_i = 0$, from (2.3) we obtain values for points 2 and 3 which are much lower than their experimental counterparts. We may assume that the cathode temperatures were inaccurately measured (by an ordinary pyrometer, which is not too accurate, particularly at high temperatures). In this connection, (2.3) was used to determine the cathode temperature. The following results were obtained:

$$T_1 \approx 2100^\circ\ \text{K}, \qquad T_2 \approx 2200^\circ\ \text{K}, \qquad T_3 \approx 2300^\circ\ \text{K}. \qquad (4.4)$$

One series of points was used to determine the constant α in (1.11). We obtained the value

$$\alpha \approx 1.2\ . \qquad (4.5)$$

Using (4.3)–(4.5), two other characteristics were computed from (1.12) and (2.2). The results are represented by the curves in Fig. 5.

Figure 5 shows that the curves thus computed are in good with the experimental data when the cathode temperatures are equal to (4.4).

An analysis of the formulas shows that it is impossible to make all three characteristics coincide with the experimental data by varying α if the cathode temperatures are taken equal to the measured values. Moreover, if the experimentally measured cathode temperatures are used, then characteristics 2 and 3 are almost straight lines and do not have the bend at the origin characteristic for the experimental curves. Thus it seems probable that the cathode temperatures were not measured accurately.

The above comparison of the experimental and calculated current-voltage characteristics and the values of the experimental constants is preliminary in nature. Future experiments will show how well the developed theory corresponds to the physical content of the problem. These experiments may change and refine our ideas about the effects taking place in the near-electrode layer and require an improvement in the theory. Nevertheless, it is possible to use the theory in its present stage as a working method for analyzing experimental data and performing preliminary calculations.

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* These data were obtained by N. M. Maslennikov who courteously allowed us to publish them.

REFERENCES

1. G. A. Lyubimov, "Change in electric potential near the channel walls for motion of an ionized gas in a magnetic field," PMTF, no. 5, 1963.

2. G. A. Lyubimov, "Some problems in the theory of the near-electrode layer for a change of potential," PMTF, no. 4, 1964.

3. V. L. Granovskii, Electric Currents in Gases [in Russian], Gostekhizdat, 1952.

4. T. E. Luzzi and R. A. Gross, "Magnetogasdynamic boundary conditions at a conducting wall," Phys. Fluids, vol. 7, no. 8, 1964.

5. I. Langmuir, "The interaction of electron and positive ion space charges in cathode sheaths," Phys. Rev., vol. 33, no. 6, 1929.

6. R. Ya. Kucherov and R. E. Rikenglaz, "Kinetic theory of a diode filled with rarefied plasma," Zh. tekhn. fiz., vol. 32, no. 10, 1962.

7. E. B. Sonin, "Effect of near-electrode regions on the electrical resistance of a weakly-ionized plasma," Zh. tekhn. fiz., vol. 33, no. 7, 1963.

8. Z. Croitoru and A. Montardy, "Phénomènes de contact, tenseur de conductivité et temperature des électrons dans un gaz ionisé," Rev. gen. électr., vol. 72, 1963.

9. G. Y. Mulluney, P. H. Kydd, and N. R. Dibelins, "Electrical conductivity in flame gases with large concentration of potassium," J. Appl. Phys., vol. 32, no. 4, 1961.

10. R. I. Rosa, "Physical principles of magnetohydrodynamic power generation," Phys. Fluids, vol. 4, no. 2, 1961.

20 June 1965 Moscow