THEORETICAL INVESTIGATION OF A LOW-PRESSURE ARC DISCHARGE IN A CYLINDRICAL DIODE

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Using systematic numerical calculations of an arc discharge in a coaxial interelectrode gap, the potential drops and the electron density and temperature are obtained as a function of the current density, the plasma pressure, the azimuthal magnetic field, and the interelectrode distance. General conclusions are drawn from the relations obtained.

The low-pressure discharge has been investigated in many theoretical and experimental papers, for example [1-3].

In this investigation we consider the change in the plasma parameters in a cylindrical diode with an azimuthal magnetic field as a function of the discharge conditions. The inner cylindrical electrode is taken as the cathode, the external one as the anode. The azimuthal magnetic field is produced by an electric current flowing coaxially with the diode. The problem is solved in the one-dimensional formulation, which corresponds to the case when the main discharge parameters have transverse gradients, which are much greater than the longitudinal gradients, and radial diffusion currents play the main part. The composition of the plasma is assumed to be in thermodynamic disequilibrium, the ionization-recombination processes have a collisional character, and complete ion recombination occurs at the electrodes. It is assumed that the electrons have a distribution which differs slightly from Maxwellian, and the gas-dynamic transfer equations are assumed to be completely applicable to the electron gas. It is also assumed that the mixture of ions and atoms forms a single-temperature gas of heavy particles. With the exception of narrow layers at the electrodes the quasi-neutrality condition is satisfied in the plasma. In the heat balance, the losses of energy due to radiation are insignificant.

Unlike that in [1, 3] the theoretical calculation is made on the basis of the more accurate system of transfer equations obtained in [4, 5] in the 13-moment approximation. In this it is assumed that $\sqrt{\varepsilon/\theta} \ll 1$, where ε is the electron–ion mass ratio, and θ is the ratio of the temperatures of the heavy-particle gas and of the electrons. The equations are written for the one-dimensional axisymmetric case, and in the ion conservation equation a term is added to allow for the creation of particles. This kinetic term, which describes the change in the number of ions per unit volume due to ionization-recombination processes, takes the form

$$\Gamma = K_1 n_e (n_a - n_a^\circ)$$

for a single-temperature plasma of the usual form [3]. Here K_1 is the ionization rate factor, n_e is the electron density, n_a is the atom density, and n_a° is the equilibrium atom density for the actual electron density. The equilibrium density n_a° is calculated taking into account the two-temperature nature of the plasma from the statistical relation in [6]. The change introduced in the previously employed method of calculation leads to the fact that the equilibrium state in a two-temperature plasma, obtained from a calculation of the ionization-recombination process, will be in agreement with the statistical calculation. The boundary conditions take into account the physical arrangement used in [7, 8]. However, the expression for the ion current to the walls is twice that used in these

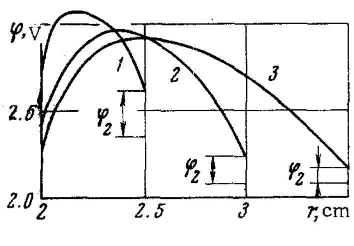

Fig. 1

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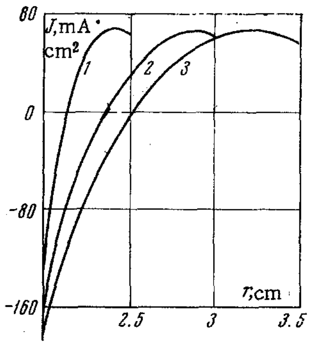

Fig. 2

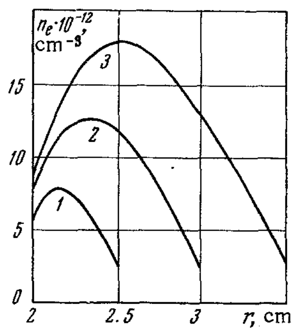

Fig. 3

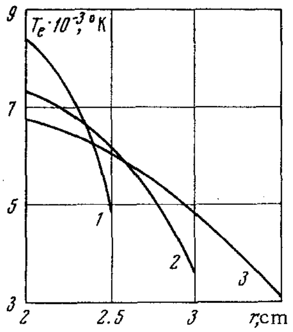

Fig. 4

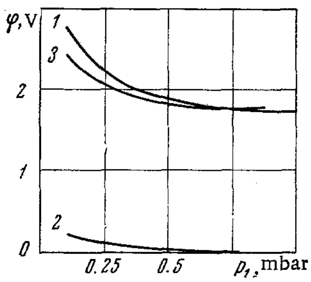

Fig. 5

papers because of our assumption that the ions at the external boundary of the Langmuir layer move in a single direction.

The boundary value problem formulated reduces to the solution of the Cauchy problem for a system of ordinary differential equations with subsequent accurate solutions by the Newton iteration method. To obtain the initial solution (which does not satisfy the whole system of boundary conditions) of the Cauchy problem over the whole assigned interval of the interelectrode gap, we used the random search method to find the extremum of functions of many variables.

This investigation of a low-pressure arc discharge in a cylindrical diode applies to a lithium plasma, which has an ion mass $m = 11.52 \cdot 10^{-24}$ g, and an ionization potential $V = 5.39$ eV. The gas-kinetic diffusion cross section in the temperature range from 2000 to 10,000°K was taken to be in the limits $Q_{ea} = (2.4\text{-}3.2) \cdot 10^{-14}$ cm², and $Q_{ai} = (6.6\text{-}8.5) \cdot 10^{-14}$ cm², and the ionization rate factor $K_1 = 2 \cdot 10^{-17}\text{-}7.9 \cdot 10^{-9}$ cm³/sec. We took the radius of the internal electrode to be unchanged at $r_1 = 20$ mm, the anode and cathode temperatures $T_1 = T_2 = 2700$°K, and the thermionic emission current density $j_0 = 1.47$ A/cm².

The results of the numerical solution of the above boundary value problem on a computer in the range of pressures $p_1 = 0.1\text{-}0.3$ mbar, current density $j_1 = 1.10\text{-}2.17$ A/cm², magnetic inductions $B_1 = 15\text{-}50$ G, and interelectrode gaps $L = 5\text{-}15$ mm are shown in Figs. 1-11 (the distance r is measured from the axis of symmetry). A check of the solution using the criterion given in [9] showed that under these conditions, in regions of the discharge in which recombination plays an important part, the latter is of greater value in triple collisions than recombination by radiation. The temperature of the heavy component of the plasma under these conditions differs very little from the electrode temperature. Analysis showed that the pressures assumed in the calculations, $p_1 > 0.1$ mbar for a value of the interelectrode gap $L > 5$ mm, lie in the region of permissible values for which this system of equations can be used.

For Figs. 1-4, $p_1 = 0.1$ mbar, $j_1 = 1.3$ A/cm², and $B_1 = 50$ G; curve 1 corresponds to L = 5 mm, curve 2 corresponds to L = 10 mm, and curve 3 corresponds to L = 15 mm. The potential in the plasma is calculated with respect to the cathode, and φ_1 and φ_2 are in effect the cathode and anode potential drops.

An investigation of the change in the plasma parameter distribution as a function of the interelectrode gap L (Figs. 1-4) showed that for a given current density j_1 and pressure p_1 at the cathode as L increases there is an increase in the maximum electron density $n_e{}^*$, the electron density at the cathode n_{e1}, the

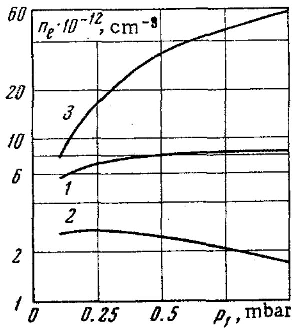

Fig. 6

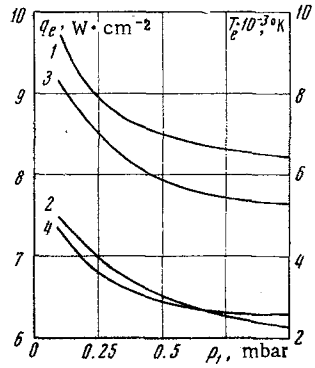

Fig. 7

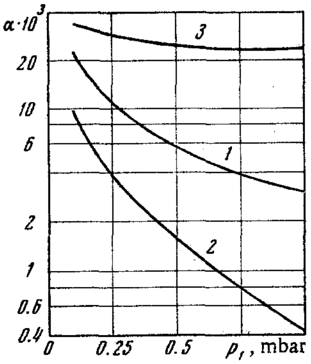

Fig. 8

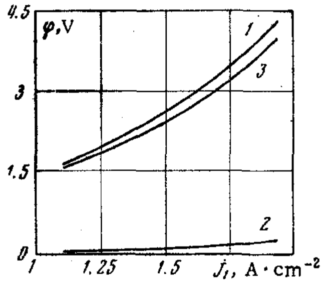

Fig. 9

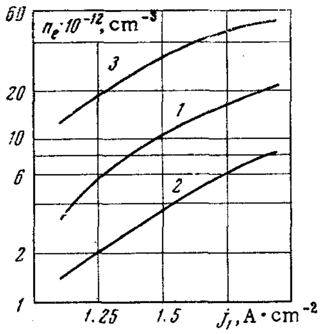

Fig. 10

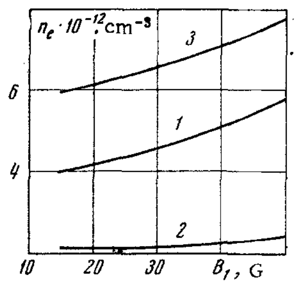

Fig. 11

maximum potential in the plasma with respect to the external boundary of the Langmuir layer at the cathode $\varphi^* - \varphi_1$, and the relative dimensions of the region of recombination adjacent to the anode $\Delta r/L$; the electron temperatures T_e and the potential differences in the Langmuir cathode and anode layers φ_1 and φ_2 fall; the electron density at the anode n_{e2} remains practically unchanged; and there is a slight change (a tendency to fall) in the ion diffusion current j_2.

For Figs. 5-8, $j_1 = 1.3$ A/cm^2, $B_1 = 50$ G, and $L = 5$ mm; for Figs. 9 and 10, $p_1 = 0.3$ mbar, $B_1 = 50$ G, and $L = 5$ mm; and for Fig. 11, $p_1 = 0.1$ mbar, $j_1 = 1.3$ A/cm^2, and $L = 5$ mm. In Figs. 5 and 9, curves 1 and 2 show the potential drop in the layers adjacent to the cathode and anode, and curve 3 shows the over-all potential difference; in Figs. 6, 10, 11, and 8, curves 1 and 2 represent the electron density and the degree of ionization at the external boundary of the Langmuir layer at the cathode and anode respectively, and curve 3 shows the maximum value of the density and degree of ionization; in Fig. 7, curves 1 and 2 represent the energy flow (taking into account the ionization energy), and curves 3 and 4 represent the electron temperature at the cathode and anode.

Systematic calculations of the discharge for a constant interelectrode gap L with a constant current density j_1 and magnetic induction B_1 at the cathode (Figs. 5-8) showed that as the pressure p_1 is increased the maximum electron density n_e* and the electron density at the cathode n_{e1} increase, the density at the anode n_{e2} has a maximum at a certain pressure, and the electron temperature T_e and the degree of ionization α decrease; the electron density and temperature at the cathode, in the range of parameters investigated continuously remain above the corresponding values at the anode.

An increase in the current density (Figs. 9 and 10), like an increase in the magnetic field (Fig. 11), gives rise to an increase in the electron densities n_{e1} and n_{e2}, the electron temperature at the cathode T_{e1}, the potential differences in the layers adjacent to the electrodes φ_1 and φ_2, and a drop in the electron temperature at the anode T_{e2}; the overall potential difference U increases with the current.

The above investigation shows that numerical investigation of a gas discharge using a computer is very fruitful. The material presented should facilitate further theoretical work on gas discharges using computational methods, for the successful use of which general ideas on the behavior and orders of magnitude of the discharge parameters are needed.

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