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Abstract

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ON THE QUESTION OF THE NATURE OF AN ARC DISCHARGE IN AN ATMOSPHERE OF INERT GASES

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The overwhelming majority of works devoted to the study of a low-current arc discharge have been carried out in an air atmosphere. The existence of thermal equilibrium in this case has been established beyond dispute. But it is still unclear whether the plasma of an arc discharge in an atmosphere of inert gases is an equilibrium plasma. All authors who have experimented with such a discharge assume *a priori* that equilibrium exists in it and that, consequently, it can be characterized by a temperature (see, for example, ([1–4]), as well as the works cited there). On the other hand, the assumption has been expressed ([5,6]) that the plasma of an arc discharge in an atmosphere of very pure inert gases may prove to be nonequilibrium owing to the smallness of the effective cross sections of noble-gas atoms, as compared with the cross sections of metal atoms, for collisions of the second kind with electrons. The question of the existence of thermal equilibrium could be settled definitively by investigating the distribution of the atoms participating in the discharge over excited levels, which in an equilibrium plasma should obey Boltzmann' s law:

$$\lg\frac{N_0}{g_0}-\lg\frac{N_i}{g_i}=5040\frac{E_i}{T},$$

where N is the population of the level; g is its statistical weight; E is the excitation energy in electron-volts; T is the equilibrium temperature of the plasma. Thus, if the values E_i are plotted along the abscissa axis and $\lg\frac{N_i}{g_i}$ along the ordinate axis, then for all levels, including the ground level, the points should lie on a single straight line. From the slope of the straight line one can find T.

We began the investigation with a direct-current arc burning between pure carbon electrodes at a current of 4 A in atmospheres of helium and argon with an admixture of hydrogen, and of neon (the pressure was atmospheric). The absolute and relative intensities were measured for 3 hydrogen lines (H_α, H_β, H_γ), 8 helium lines, and 14 neon lines, for which the transition probabilities are known.

Figure 1

Figure 1: Figure 1

The distribution of the intensities of these lines over the radius of the arc column was also studied. The accuracy of the calculated value of the absolute or relative population of a certain level is practically equal to the accuracy with which the absolute or relative intensity of the corresponding line was measured, and amounts to 30% for absolute population and 7-10% for relative population. N_0 is practically equal to the total number of atoms of the given species N; in turn, $N = 291\, n/T_2$, where n is the concentration of atoms of the given species at 18°C, which, as a rule, was known to us. Since the gas temperature T_2 in a low-current arc is known to lie within the limits from $2 \cdot 10^3$ to $2 \cdot 10^4$ °K, we can estimate N_0, in any case, with an accuracy to within an order of magnitude.

Let us dwell on the principal experimental results.

1) In Fig. 1 we have plotted the values obtained by us of $\lg \frac{N_i}{g_i}$ for hydrogen, helium, and neon in the case when the arc burned in a mixture of these gases (95% He, 5% Ne, 0.01% H_2), for hydrogen and helium (an arc in pure helium with an admixture of $\sim$ 0.01% H_2), and for helium (an arc in technical helium: $\sim$ 98% He, $\sim$ 1% H_2).

Fig. 1. Population of the excited levels of H, He, and Ne atoms. The dashed straight lines pass (on the ordinate axis) through the calculated values $\lg \frac{N_0}{g_0}$.

In all cases the populations of the hydrogen and helium levels practically did not change. On the same graph are plotted the data obtained by A. K. Sukhovanchenko for hydrogen: by asterisks—an arc in technical helium, and by triangles—an arc in pure argon with an admixture of $\sim$ 0.2% H_2. The magnitude of the maximum error is practically equal to the thickness of the lines drawn on the graph.

From the graph it is seen that the experimental points lie well on straight lines, but these straight lines do not pass through $\lg \frac{N_0}{g_0}$, but intersect the ordinate axis at a point that corresponds to a pressure of tens of billions of atmospheres. The dashed lines indicate straight lines passing approximately through the middle of the group of experimental points and through $\lg \frac{N_0}{g_0}$. The slope of these straight lines corresponds to $\sim 11 \cdot 10^3$ °K. The slopes of the actually obtained straight lines (for the excited levels) coincide for all atoms and give a temperature of $\sim 3.5 \cdot 10^3$ °K. It is clear that at such a low temperature thermal excitation of inert gases and hydrogen is practically absent. Thus, the distribution of H, He, and Ne atoms over excited levels does not obey the Boltzmann law, and the mechanism of excitation of the atoms is not thermal.

Figure 2

Figure 2: Figure 2

Fig. 2. Distribution of the intensities of the lines of H, He, and the C_2 band over the radius of the arc column at a current of 4 A. The ratio of the intensities of the H_α and H_β lines (horizontal straight line) does not depend on r.

2) Figure 2 shows the distribution over the radius of the arc column of the intensities of the hydrogen lines, the helium line $\lambda 5876$ Å, and the C_2 band $\lambda 5165$ Å. -

a characteristic feature is the fact that helium lines (excitation energy ~ 23 eV) and C_2 bands (dissociation energy 5.6 eV) are excited simultaneously at the center of the arc. Molecular bands of CN, CH, and H_2 are also excited rather intensely at the center of the arc. If the mechanism of excitation of the lines of He, Ne, Ar, and H were thermal, then all molecules in the zone of appreciable emission of these lines would be practically completely dissociated.

3) The half-width of the hydrogen lines in all our experiments is less than 2–3 Å. This indicates a low concentration of ions (electrons) in the discharge and, consequently, a low gas temperature. Let us recall that at gas temperatures $\sim 10^4$ °K the half-width of the hydrogen lines (Balmer series) is 10–15 Å.

All the facts listed above irrefutably indicate that **there is no thermal equilibrium in the column of a low-current arc burning between carbon electrodes at normal pressure in an atmosphere of inert gases.**

Let us recall that in works ([5], [6]) the possibility of the absence of equilibrium was attributed to the smallness of the effective cross sections of noble atoms for deactivating collisions with electrons. Calculations show that they are indeed 1-2 orders of magnitude smaller than the corresponding cross sections for atoms of metals, N, and O. However, taking only this factor into account is still insufficient for understanding the peculiarities of the arc discharge in an atmosphere of inert gases. It is also necessary to take into account that the resonance radiation of noble atoms and hydrogen is practically entirely absorbed in the column itself; consequently, the energy lost in the column to radiation is very small. Apparently, two main mechanisms of atomic excitation operate simultaneously in the arc column: photoexcitation from the ground level and stepwise excitation from metastable levels in collisions with electrons, as well as photoionization with subsequent recombination, in which the atom proves to be excited. These processes make it possible to interpret the value obtained by us, $T = 3.5 \cdot 10^3$ °K, as the "temperature" of the electron gas. It is possible that it is equal to the kinetic "temperature" of atoms and molecules in the column of the arc discharge. We are at present carrying out the corresponding calculations.

A certain influence toward bringing the system closer to equilibrium may be exerted by metal atoms introduced into the discharge, as well as by an increase in the electron concentration through a sharp increase in the current strength in the discharge. These investigations are also being carried out by us at present.

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Note: Figure translations are in progress. See original paper for figures.