THERMAL CONDITION IN PLASMA FLOWS OF A COAXIAL-ELECTRODE HALL ACCELERATOR

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Results of electron temperature determination in free jets of plasma of a coaxial-electrode Hall accelerator are reported. The recombination structure for population of upper energy levels of a nitrogen ion is established and the degree of population departure of these levels from the equilibrium conditions is determined.

The electron temperature and concentration in plasma jets (mainly argon) of magnetoplasmadynamic accelerators at different operating conditions are determined in few investigations [1-4]. The radial distribution of these quantities in plasma flows of a powerful Hall accelerator is given in [5, 6]. Analysis of the results obtained in [1-6] has shown that in a plasma jet, both of argon and air, the electron concentration decreases at a distance from the nozzle exit-section of the accelerator, increases with the discharge current and its profiles have, as a rule, one central maximum. However, the data on the plasma temperature reported in these works are to be refined. In [3, 6], a conclusion is substantiated on a nonequilibrium state of the investigated plasma. Apparently, it may be extended to other works [1, 2, 4], since the given maximal electron concentrations are not high: $n_{emax} \leq 10^{14}$ cm^{-3}, which is almost an order of magnitude less than n_{emax} obtained in [6].

The present work offers the results of temperature measurements by a spectroscopy technique from relative and absolute radiation intensities of spectral lines of NI and NII in plasma flows of a coaxial-electrode Hall accelerator at the discharge currents I = 2200, 2600, 3000 A and a working gas flow rate of G = 10 g/sec (8.5 g, air; 1.5 g, nitrogen).

The electron temperature is determined from the Saha–Boltzmann equation [7] in the assumption of a single ionized plasma

$$2\left(\frac{2\pi m_e kT_e}{h^2}\right)^{3/2}\frac{u_z}{g_i}\exp\left(-\frac{\Delta E_{z-1,i}}{kT_e}\right)=\frac{n_e n_z}{n_{z-1,i}}\approx\frac{n_e^2}{n_{z-1,i}}. \tag{1}$$

Here $n_{z-1,i}$ is the population of the i-th excited state of an atom (for neutral, z = 1); $n_z \approx n_e$ is the electron concentration experimentally measured earlier [6]; g_i is the statistical weight of the i-th excited state; $\Delta E_{z-1,i}$ is the binding energy of the i-th level; u_z is the statistical sum over the states of an NII ion.

The contribution of NII ions has been evaluated beforehand. In the spectra of accelerator plasma jets at the known pressures from 60 to 100 Pa, the lines NI and NII fully prevail under investigated operation conditions. This has allowed evaluation of the upper bound of the temperature from the ratio of line intensities NII/NI. It turns out that $T_e \leq 18 \times 10^3$ K and, respectively, the concentration ratio is $n_z/n_{z+1} \approx 10_2$ under LTE conditions. Obviously, under nonequilibrium conditions this value will be even higher. Here, it is also assumed that molecules and molecular ions may be neglected. Errors due to these simplifications are insignificant for the partial LTE (pLTE) conditions as compared to the errors in determination of the free electron concentration [6].

Equation (1) implies that highly excited levels of an atom are in equilibrium with free electrons. An electron concentration n_e, starting from which the pLTE condition is fulfilled, is determined by the expression [8]

$$n_e \geqslant 7\cdot 10^{18}\frac{z^7}{n^{17/2}}\left(\frac{kT}{z^2 E_H}\right)^{1/2}, \text{ cm}^{-3}, \tag{2}$$

where n = n_{eff} is the quantum number of the energy level; E_H is the ionization energy of a hydrogen atom. The corresponding

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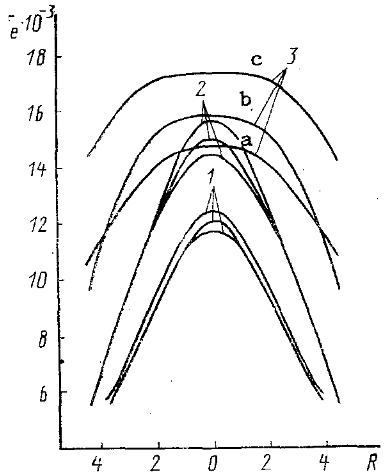

Fig. 1

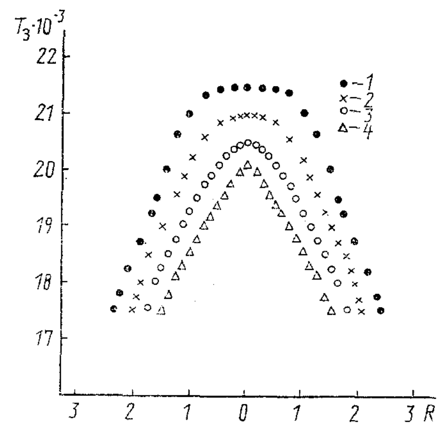

Fig. 2

Fig. 1. Radial electron temperature distribution in a free jet, L = 130 mm: 1) I = 2200 A; 2) 2600; 3) 3000; a) 561.6 nm; b) 528.1; c) 493.5. T_e, K; R, cm.

Fig. 2. Population temperature for the line λ = 501.6 nm: 1) I = 3000 A (L = 130 mm); 2) 2600 (130); 3) 2200 (130); 4) 2200 (160).

calculations, based on electron concentrations experimentally obtained earlier, have shown that the nitrogen atom level may be in equilibrium with free electrons, the excitation energy of which is $E \geq 12$ eV. Therefore for T_e determination we used the following lines of the nitrogen atom NI: 561.6 nm (E_{ex} = 13.94 eV), 556.4 (13.99), 535.6 (13.24), 528.1 (13.27), 520.1 (13.99), 493.5 nm (13.20 eV). Their absolute intensities were employed to determine the excitation n_i of the corresponding excited states. The presence of an optically thin layer was controlled by the absolute intensity of lines NII 568.6, 567.6, and 566.6 nm of the multiplet $^3P^0-^3D$. Results of the radial distribution $T_e(R)$ in the section L = 130 mm are shown in Fig. 1. As is seen, with an increase of discharge current strength, the near-axis values of T_e increase. A character of T_e distribution faithfully copies the electron concentration distribution. In the section with L = 160 mm we did not determine $T_e(R)$ because of the absence of data on radial distribution of an electron concentration. Attempts were made to evaluate the temperature from axial concentrations [6] which were (8-10) $\times$ 10^3 K, respectively, for current 2200-3000 A.

For the spectral lines of nitrogen atoms and the ions NI and NII, experimentally obtained population levels have been compared with those calculated under LTE conditions at the known pressures in the jet. It has turned out that for the nitrogen atom levels ($E \approx 13$ eV) relative populations are close to unity and, correspondingly, $T_e \approx T_p$, where T_p is the population temperature determined from the Boltzmann equation [8]. At a distance from the axis, $T_p > T_e$ which is connected with the existence of the pressure gradient along the radius.

The excited levels of the nitrogen ion NII are distinguished by a more complicated behavior. The values of T_p, determined experimentally for a group of levels including values from 20.7 to 27.7 eV, change in the central part of a plasma jet from $20 \cdot 10^3$ to $22 \cdot 10^3$ K. Minimal T_p values are recorded, as a rule, in the group of lines with E = 20.7 and 20.9 eV. For other levels, no regularity is established in changing the axial T_p values with E_{ex}. With increasing current strength, numerical values of the axial population temperature, found from the radiation intensity of one of the spectral lines, somewhat increase as a rule. At the permanent position of the considered section, an increase of a current strength causes appearance and further increase of the region with a practically constant T_p (Fig. 2). At a distance from the nozzle exit section, with the discharge current strength being invariable, the temperature profiles $T_p(R)$ become more sharp, which is attributed to a decrease of the region where spectral lines display deexcitation.

The available data on absolute intensities of NII lines also allow calculation of populations of the corresponding excited levels for ions. The dependence of calculated values of $\ln(n_i/g_i)$ for the central part of a plasma jet on the excitation potential E_{ex} of energy levels are shown in Fig. 3. Analysis of the obtained results has revealed that in our case practically a linear dependence of $\ln(n_i/g_i)$ on E_{ex} is observed for each operation mode of the accelerator. A departure from a linear dependence is observed at I = 2200 A for a group of lines with a minimum excitation energy. The presence of the indicated linear depen-

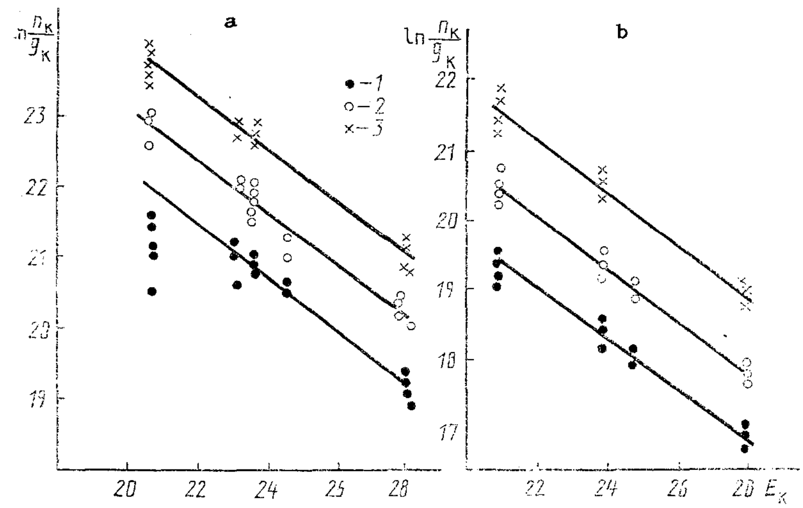

Fig. 3. Population of the ion NII levels as a function of the excitation potential in cross-sections with L = 130 mm (a) and 160 (b): 1) I = 2200 A; 2) 2600; 3) 3000.

dence permits us to determine the distribution temperature T_R for combinations of the group of highly excited states from a slope of the straight lines in Fig. 3. At the all discharge current values and for both sections of the plasma jet it has been equal to T_R = (28-30)$\cdot 10^3$ K on the axis and smoothly falling along the radius to (18-20)$\cdot 10^3$ K. The error in its determination is 10-15%. From mutual arrangement of the straight lines in Fig. 3 it follows that population of any energy level appreciably grows with an increase of the discharge current strength and a decrease of the distance from the nozzle exit section of the accelerator.

Thus, the nitrogen ion states, approaching the second ionization boundary ($E_{ion} \approx 29{\cdot}59$), are characterized by a quasi-Boltzmann particle distribution with respect to energy states with the temperature $T_R > T_e$. At a distance from the second boundary of ionization, a departure from the quasi-Boltzmann distribution is observed which manifests itself in slowing down of the $\ln(n_i/g_i)$ rise for the lines with the excitation energy $E_{ex} \approx 20.7$ eV, especially appreciable at I = 2200 A. Analogous T_R calculations for a nitrogen atom have failed because of the absence of the lines with a large difference in their excitation energies in the spectrum.

The inequality $T_R > T_e$ is indicative of the recombination character of the population of energy levels [9]. It is likely that due to the low pressure in the plasma jet the processes of triple recombination of ions with electrons prevail. An intensity of the recombination processes is evidenced by the presence of a continuum in the central part of the plasma jet within the entire investigated spectrum region. Earlier, from the radiation power of the recombination continuum an electron concentration in the investigated plasma flows has been determined [6]. The recombination character of the population of the upper energy levels of NII specifies their overpopulation. A ratio of experimentally found populations of excited levels of nitrogen ion NII to their equilibrium values for excitation energies from 20.7 to 27.7 eV varies from 10^3 to 10^6, respectively. With an increase of the current strength and the free electron concentration, the overpopulation of upper energy levels decreases.

We have evaluated the role of radiation processes in terms of the principles of impact-radiation kinetics. For each regime, those E_R energy ranges are found, within which the radiation processes are of importance. The obtained values of $E_R \approx 2$ eV agree well with the binding energy values obtained from formula (2). This allows the conclusion that the radiation output does not exert an essential influence on the excited levels of an NI atom, considered in the experiment, which confirms the assumptions made earlier. For NII ions, the radiation output causes essential depletion of the excited states which is confirmed by disturbance of the quasi-Boltzmann distribution at a distance from the second boundary of ionization.

NOTATION

n_e, electron concentration, cm^{-3}; I, discharge current, A; G, working gas flow rate, g/sec; n_z, population of the excited state, cm^{-3}; u_z, statistical sum over the states; T_e, electron temperature, K; T_p, population temperature, K; T_R, distribution temperature, K; E_{ex}, excitation energy, eV. Indices: e, electron component; i, excited level; z, ion charge.

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