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THERMAL STATE OF A PLASMA IN A COMPRESSED LAYER

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The results of an investigation of the thermal state of a plasma in a compressed layer under retardation conditions of the plasma flow of a coaxial Hall accelerator are reported and compared with analogous data for a free flow.

At present, plasma accelerators are of particular interest as sources of high-temperature gas flows since they provide, along with thermal, more effective electromagnetic acceleration of the plasma, thus permitting high velocities and enthalpies of retardation of plasma flows to be obtained. Therefore such apparatuses may be used successfully to investigate high-temperature heat and mass transfer processes in the case of entry of space vehicles into the atmospheres of planets at superorbital velocities. Investigations of the main parameters of plasma flows are also needed to compare the test conditions of heatproof materials with full-scale investigations. At the same time when a supersonic flow passes around a model of a material a stagnation zone develops in which the plasma parameters may differ substantially from the corresponding parameters in a free jet. This fact must be accounted for in evaluating the effect of a plasma flow on a frontal surface of the material.

In the present paper we give results of measurement and investigation of the radial distribution of the temperature of the electrons in a compressed layer. In the investigations, we chose the operating conditions of a coaxial Hall accelerator (CHA), which were adopted for analogous measurements in a free jet [1]: the magnetic induction in the discharge zone $B = 1$ T, the discharge current $J = 2200$, 2600, and 3000 A, the flow rate of the working gas $G_\Sigma = 10$ g/sec (8.5 g – air, 1.5 g – nitrogen), the pressure in the vacuum chamber $P_{\text{ch}} = 1.2 \cdot 10^3$ Pa. In [2, 3] we reported results of the radial distribution of the concentration of the electrons in a free jet and in a compressed layer.

To create a compressed layer, a hollow 120-mm-diameter copper cylinder [3], as a flat obstacle, was placed in the path of a plasma jet. The stagnation zone was distinguished as a bright 30–35-cm-thick spherical segment adjacent to the frontal surface of the cylinder. Radiation spectra of the compressed layer were recorded in a section located at a distance of 10 mm from the plane surface of the cylinder.

Spectroscopic analysis of the plasma composition showed than the radiation spectrum is sensitive to the magnitude of the energy contributed to the discharge, but the qualitative composition of the spectra remains unchanged for both the free jet and the compressed layer. However the radiation intensities of the spectral lines of the compressed layer are 15–20-fold higher than the corresponding values for the free jet. In the spectra, lines NII are most intense. Along with the latter, lines NI of nitrogen occur due to 4s–4p transitions. Lines NI corresponding to transitions from higher levels 5p–4s, for which the probabilities of transitions are approximately an order of magnitude smaller, were not observed. The low intensity of lines NI indicates the strong single ionization of the plasma. The maximum intensities of lines NI are shifted along the radius toward the periphery. With an increase in the current strength, the ratio of the intensities of the lines NII/NI increases, thus indicating an increase in R and in the concentration of singly charged ions [4].

The electron temperature was determined by the Saha–Boltzmann formula relating the population of the i-th excited state of an atom to the ground state of an ion and the total electron density. In [1] we substantiated

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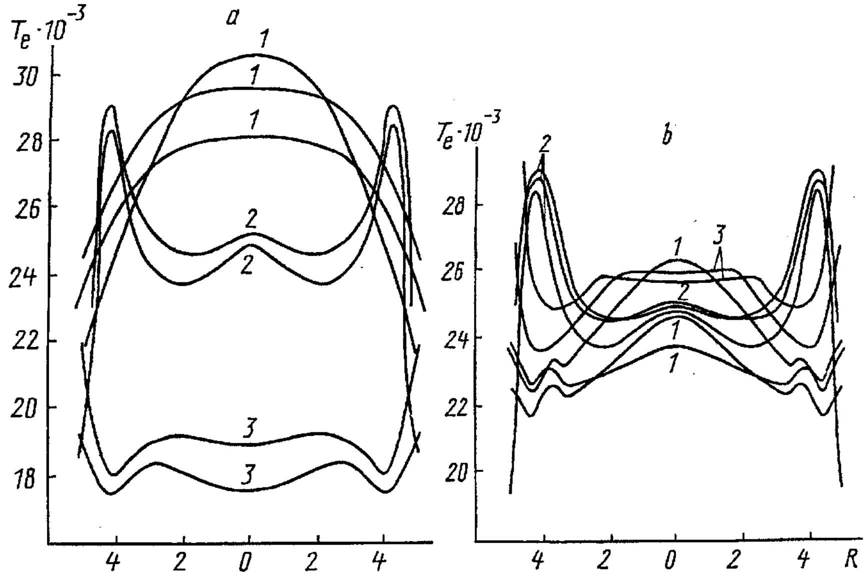

Fig. 1. Radial temperature distribution of electrons in the compressed layer, $L = 130$ mm (a), 160 (b): 1) $J = 2200$ A (561.6 nm; 528.1; 493.5); 2) 2600. T_e, K; R, cm.

the applicability of the model of partial local thermodynamic equilibrium (LTE) for the plasma conditions of a Hall accelerator. For comparison, using n_e and T_e obtained under the assumption of partial LTE, we calculated the equilibrium composition of the plasma at a prescribed P.

Figure 1 shows $T_e(R)$ calculated for different lines NI. The profiles have a complicated nature and depend on the structure of the compressed layer. The temperature maxima are mainly on the periphery, where a shock wave reaches the investigated section. In a compressed layer with $J = 2200$ A and $L = 130$ mm the T_e maximum produced by the distinct compression zone in the region of the cathode jet is clearly seen. The T_e maxima for the shock wave under these conditions are outside the recorded region. The maximum temperature difference on the axis, compared to the free jet, is $\Delta T = 20 \cdot 10^3$ K. In a shock wave T_e will naturally be substantially higher. Comparing T_e at the center of the compressed layer for two sections, it should be noted that away from the nozzle section the electron temperature depends only slightly on the strength of the discharge current, unlike the section $L = 130$ mm. With $J = 2600$ A a shock wave with a thickness of 8–10 mm and the maximum $T_e = 3010^3$ K is distinctly seen.

Using the known pressures at the center of the compressed layer, we calculated the equilibrium composition of the plasma. The experimental values below the equilibrium ones and their difference increased with the strength of the discharge current and with departure from the nozzle section [4]. For the lines of the nitrogen atoms and ions we compared the experimental values of populations of levels and the theoretical data under LTE conditions. The population of a level under equilibrium conditions is uniquely related to the population temperature T_z by the Boltzmann formula. In the free jet with $J = 2200$ A the relative populations of the levels of a nitrogen atom (E_{ex} ~ 13 eV) are close to 1 and, correspondingly, $T_e \approx T_z$ [1]. At some distance from the axis, $T_z > T_e$, which is due to neglect of the pressure gradient along the radius. With an increase in the discharge current the underpopulation of the excited levels of an atom attains $n_{i-1}/n^0_{i-1} \sim 10^{-2}$ for $J = 3000$ A and, correspondingly, $T_e > T_z$. With an increase in the discharge current and the distance from the nozzle section the population temperature calculated for the all observed atomic lines hardly changes in both the free jet and the compressed layer. However, in the compressed layer, where the electron temperature is substantially higher, the underpopulation of the atomic levels attains $\sim 10^{-6}$ and the maxima of the radiation lines are displaced from the center to the periphery, thus indicating the strong single ionization.

The behavior of the excited levels of the ion NII is more complicated. The values of T_z on the axis determined for the levels 20.7–30.12 eV of a nitrogen ion increase, in accordance with the discharge current

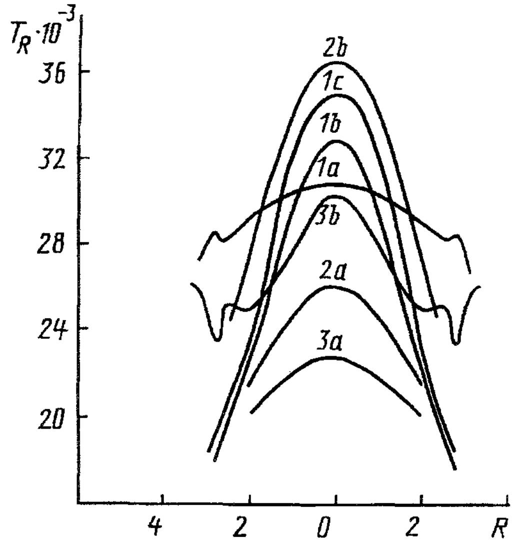

Fig. 2. Temperature of the distribution of the excited levels of the nitrogen ion NII as a function of the discharge current strength in the compressed layer (a, b), $L = 130$ mm (a), 160 (b): 1) $J = 2200$ A; 2) 2600; 3) 3000 and in a free jet (c), $L = 130$ mm, $J = 2200$ A. T_R, K; R, cm.

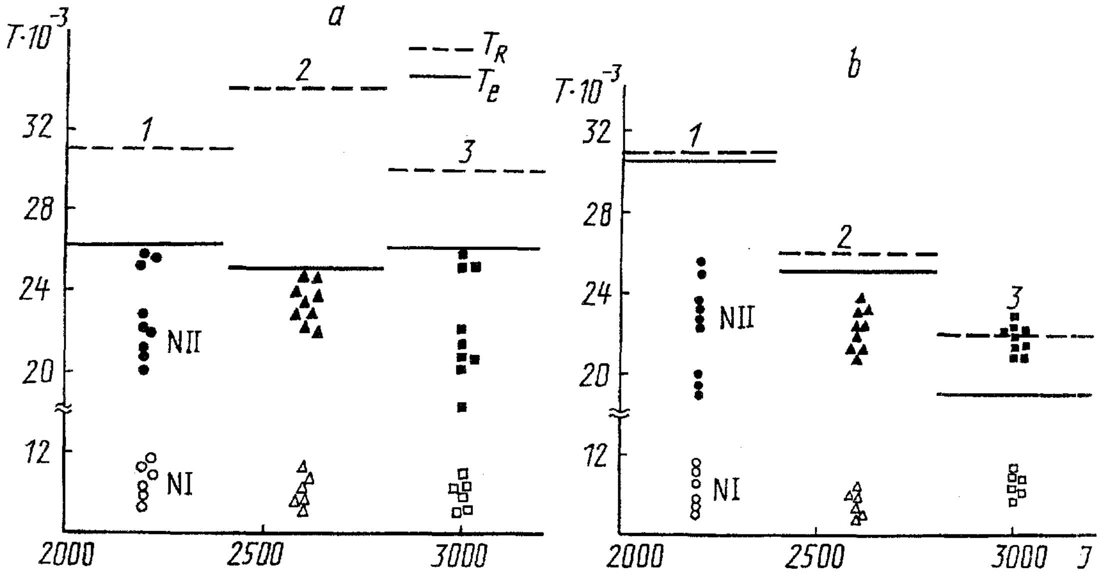

Fig. 3. Temperatures of the distribution T_R, the population of atoms and ions T_z and the electronns T_e on the axis in the compressed layer under different operating conditions of the accelerator: $L = 130$ mm (a), 160 (b); 1) $J = 2200$ A; 2) 26500; 3) 3000. T, K; J = A.

strength, from $(18-22) \cdot 10^3$ K for the free jet to $(20-26) \cdot 10^3$ K for the compressed layer. Minimum values are recorded, as a rule, for the group of lines with lower excitation energies. With the section being unchanged, an increase in the current strength leads to the appearance and subsequent increase of a region with a practically constant T_z. In the compressed layer, the population temperature of levels NII is almost independent of the distance and the strength of the discharge current, but it depends, as a rule, on the excitation energy of the level. This fact allowed us to establish the temperature of the distribution of the group of highly excited states (Fig. 2) for different operating conditions of the source. For illustration, Fig. 3 gives T_z, T_e, T_R values on the axis in the compressed layer in two sections. As a rule, $T_R > T_e > T_z$, but this difference depends on the operating conditions of the source and the distance from the nozzle section. In the section $L = 130$ mm this difference is insignificant: ionization is balanced by recombination. The above inequality is indicative of the recombination nature of the population of levels NII in the central region. Enhanced processes of recombination are confirmed by the presence of a continuum in the central part of the jet over the entire spectrum. We have employed its radiation power to determine the electron concentration in a free jet [2]. Individually, we would like to consider the regime $J = 2600$ A with the shock wave: here $T_e > T_R$, and ionization prevails over recombination. In a free jet, the levels of a nitrogen ion are highly overpopulated, $n_i/n_i^0 \sim 10^4$. For the compressed layer, the dependence of the population of a level on the binding energy and the electron concentration (the model of shock-radiation kinetics [5]) is clearly seen. For each operating regime an energy interval of E_R may be established above which the excited levels are in equilibrium with free electrons ($T_e \approx T_z$, $n_i/n_i^0 \sim 1$) and below which the levels are underoccupied due to the high radiation yield ($T_e > T_z$, $n_i/n_i^0 \sim 10^{-2}$). The value of E_R may be determined by the formula

$$E_R = [n_e/(4.5 \cdot 10^{13})]^{1/4} T_e^{-1/8},$$

where n_e, cm^{-3}; T_e, eV. The higher the binding energies of a level, the higher its underoccupation relative to the equilibrium state.

In conclusion, the investigations carried out show that in the plasma of a Hall accelerator partial local thermodynamic equilibrium is realized in the investigated regimes, where electron concentrations are such that collision processes prevail local thermodynamic equilibrium is realized in the investigated regimes, where electron concentrations are such that collision processes prevail only starting from the *k*-th excited state, while for lower levels radiation processes dominate.

NOTATION

n_e, electron concentration, cm^{-3}; J, discharge current, A; G_Σ, flow rate of the working gas, g/sec; n_i, population of an excited state, cm^{-3}; T_e, electron temperature, K; T_z, population temperature, K; T_R, distribution temperature, K; E_{ex}, excitation energy, eV; L, distance from the nozzle section, mm. Subscripts: e, electron component; i, ion charge.

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