Spatial Distribution of a Small Readily Ionized Additive in the Plasma of a Thermoelectronic Laser Energy Converter

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Abstract—The spatial distribution of a small additive of readily ionized atoms was studied in plasma of a continuous optical discharge (COD) between electrodes of a thermoelectronic laser energy converter. It is shown that the additive both in the equilibrium core of the COD and in nonequilibrium near-electrode plasma regions is driven toward the periphery of the discharge. As a result, the concentration of this additive at the electrodes is several orders of magnitude higher than that at the discharge center. © 2005 Pleiades Publishing, Inc.

Introduction. Experimental [1] and theoretical [2–4] investigations of the process of thermoelectronic laser energy conversion showed that practically significant characteristics can be achieved provided that the converter has an emitter ensuring a thermoelectron current. The presence of a readily ionized additive—in particular, cesium vapor—into the interelectrode space filled with an inert gas.

Under the conditions of operation of a thermoelectronic laser energy converter, the temperatures of electrons and the heavy plasma components (ions and neutral species) in the central region (core) of a continuous optical discharge (COD) are nearly equal and the discharge plasma is virtually equilibrium. In the narrow (10−2 cm thick) near-electrode regions, an increase in the heat flux density carried by heavy particles and in the ion current density make the electron and ion temperatures different and lead to a drop in the density of charged particles, so that plasma in these regions becomes nonequilibrium [2, 5].

The presence of a readily ionized additive in the interelectrode space may, besides decreasing the work function of the emitter and collector, give rise to processes (both in the equilibrium COD core and in the nonequilibrium near-electrode regions) significantly influencing the laser energy conversion. In order to estimate the role of these processes, it is necessary to know the distribution of atoms and ions of the additive in the interelectrode space of the energy converter. This paper considers the features of this distribution on a qualitative level in the case of a small concentration of the additive, whereby it is possible to ignore its effect on the parameters of the working inert gas and electrons.

COD core. Let us consider an axisymmetric thermoelectronic laser energy converter with an inner electrode (emitter) of external radius $r_1$ and an outer electrode (collector) of internal radius $r_2$. The COD maintained in the interelectrode space is weakly inhomogeneous along the axis of symmetry coinciding with the z axis. Taking into account the high degree of ionization for the additive in the COD core, the radial profile of the density of additive ions can be described by the relation

$$n_{1}(a) = \frac{n_{1}(T_{1})}{n_{1}(T)} \left[ \frac{T_{1}}{T} \right]^{1+k_{T}(T)} e^{-\int_{r_{1}}^{r_{2}} J_{T_{1}} \left( \frac{r_{1}}{r} \right) n \frac{1}{n T} dr}, \quad (1)$$

where $n_{1}(a)$ is the ion density, $n$ is the electron density, $T$ is the plasma temperature, $J_{T_{1}}$ is the ion flux density, $k_{T}(T)$ is the thermal diffusion ratio for electrons, $u_{e}$ is the electron mobility, and $e$ is the electron charge; the subscripts $T_{1}$ and $T_{2}$ refer to the quantities characterizing the near-emitter (inner) and near-collector (outer) boundaries of the COD core.

In the absence of a current via discharge, the additive ion concentration in the COD core decreases from its boundaries to the center in inverse proportion to the electron density and to approximately the square of the plasma temperature ($k_{T} = 0.7$). Since the plasma temperature $T_{M}$ at the COD core center weakly depends on the regime of operation of the energy converter, the ratio of the additive density at the COD core boundary to that at the core center increases with decreasing plasma temperature at the core boundary. An increase in the discharge current up to $J_{T_{1}} = 400 \text{ A/cm}^{2}$ does not produce qualitative changes in the distribution of additive ions in the COD core, albeit somewhat decreasing...
Let us consider the case of not very high temperatures which these regions are flat and thin and the electron trode COD regions will be described within the frame-boundaries. As can be seen, the concentration of cesium atoms rapidly be lower by one to two orders of magnitude than at the density of cesium ions in the middle of the COD core can be seen, the concentration of cesium atoms rapidly.

The near-electrode COD regions. The near-electrode COD regions will be described within the framework of a one-dimensional model [5], according to which these regions are flat and thin and the electron temperature variations within these regions are ignored. Let us consider the case of not very high temperatures of plasma at the COD core boundaries, whereby the main working gas in the near-electrode regions is weakly ionized. Distributions of the density of electrons (and the working gas ions) \( n \), the temperature \( T \) of the heavy plasma components, and the electric field potential \( \varphi \) in the near-electrode regions have been recently studied in [5]. The flux densities of additive ions and neutrals obey the relations

\[
\frac{d j_i^{(a)}}{dx} = \frac{d j_j^{(a)}}{dx} = -\frac{\Gamma_i^{(a)}}{x},
\]

\[
j_i^{(a)} = -D_i^{(a)} \frac{d n_i^{(a)}}{dx} - n_i^{(a)} u_i^{(a)} \frac{d \varphi}{dx},
\]

\[
j_a^{(a)} = -D_a^{(a)} \frac{d n_a^{(a)}}{dx}.
\]

Here, \( n_i^{(a)} \), \( n_a^{(a)} \) are the concentrations and \( j_i^{(a)}, j_a^{(a)} \) are the flux densities of the additive ions and atoms, respectively; \( \Gamma_i^{(a)} \) is the additive ionization–recombination velocity [6]; \( D_i^{(a)}, D_a^{(a)} \) are the diffusion coefficients for the additive ions and atoms, respectively; and \( u_i^{(a)} \) is the mobility of additive ions.

At a boundary between the quasi-neutral plasma and the Langmuir layer \( (x = 0) \), Eqs. (2) are supplemented by the well known boundary conditions for the flux densities of additive ions and atoms [6] and for the total concentration of these ions and atoms, \( n_i^{(a)} = n_i^{(a)} + n_a^{(a)} \).

At the near-electrode COD core boundary \( (x \rightarrow \infty) \), we use the condition of equilibrium for the additive. Here and below, the subscript “1” refers to the values of variables at the boundaries between the quasi-neutral plasma and the Langmuir layer and the subscript “2” refers to the near-electrode boundary of the COD core.

Using relations (2), we obtained a system of two equations of the first and second order, which were numerically solved using the Runge–Kutta method. The calculation procedure was analogous to that used in [5].

Figure 2 shows the characteristic profiles of the dimensionless concentrations of cesium ions \( n_i^{(a)} = n_i^{(a)} / n_{i1} \) and atoms \( n_a^{(a)} = n_a^{(a)} / n_{a1} \) and the electric field strength \( E = (d\varphi/dx)/(d\varphi/dx) \) in the near-electrode regions of a thermoelectronic laser energy converter operating at an argon pressure of \( 5 \times 10^4 \) Pa, electrode temperature of \( T_e = 1000 \) K, and a thermionic current of \( J_e = 0 \). The profiles are potted versus a dimensionless coordinate \( x = x/L_f \), where \( L_f \) is the ionization relaxation length for the working gas. The latter value, calculated under the conditions set at the near-electrode boundary of the COD core, characterizes the width of the near-electrode region [5]. As can be seen, the concentration of cesium atoms rapidly drops with increasing distance from the electrode, which is explained by intense ionization. The concen-