Model of the cathode region of a plasma photoelectric converter of concentrated solar radiation.

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Abstract. A model of the cathode region of a plasma photoelectric converter of concentrated solar radiation in the regime of an open external circuit is considered. Plasma is analyzed in sodium vapor at a pressure of $10^4$ - $10^5$ Pa. The necessary optical power is calculated for creating plasma in the state of Local Thermodynamic Equilibrium (LTE), whose temperature is in the range 4000-4500 K. This temperature provides a small internal resistance of the plasma voltage source. A large value of radiative heat conduction coefficient ensures a small temperature drop between the central part and the plasma LTE boundary near the walls of the converter. The model of a Non-LTE zone near the wall of the cathode is analyzed to specify the boundary conditions in the energy balance equation for LTE plasma. The thermal non-equilibrium plasma model resulted in the electron temperature gradient in the Non-LTE zone. The energy losses of electrons in the ionization layer near the cathode are counterbalanced by the thermal conductivity of the electron gas. The specificity of the conditions under consideration consists in the non-local nature of the balance of the electron temperature in the Non-LTE zone.

1. Introduction
The requirements for operating modes of a plasma photovoltaic converter (PPVC) were formulated, it was shown that a high efficiency energy conversion of concentrated solar radiation can be achieved \cite{1}. The PPVC model is based on the concept of a heat pipe. The sodium vapor fills the cathode region of the PPVC. The anode region is filled with an inert gas with a small admixture of sodium.

In accordance with the proposed model, the solar radiation is focused inside the cathode region of the PPVC, which has the form of a cylinder. The length of the cylinder $L$ is determined by the absorption conditions of solar radiation and should be $L=(10\div15)$ cm. For the normal operation of the heat pipe, its diameter $D$ should be two or three times smaller than the length $D=(5\div6)$ cm.

The operating pressure is determined by the condition of the minimum contribution of the radiation losses to the total energy balance of the plasma. An earlier analysis showed that the pressure satisfying this requirement belongs to the range $p=(10^4 \div 10^5)$ Pa. For the heat pipe working cycle, the wall temperature of the cathode $T_w$ must exceed the saturated vapor temperature at the indicated pressure ($T_w>900$ K).

One of the conditions for efficient operation of the PPVC is a low internal resistance, which is determined by the conductivity of the plasma. The conductivity of the plasma depends on the...
temperature of the electrons. The performed calculations showed that the temperature of the electron gas in the bulk plasma volume ($T_p$) should reach the value $T_p=4500$ K [1].

This paper is devoted to estimating the power of focused solar radiation, which is necessary to maintain these plasma parameters in the cathode region of the converter. The power estimation is carried out based on the calculation of the energy losses coming from the plasma to the cathode wall in the regime of an open external circuit.

2. Statement of the problem

Under the conditions under consideration, most of the plasma volume in the cathode region of the PPVC is in Local Thermodynamic Equilibrium (LTE). LTE is broken near the wall, where a nonequilibrium layer is formed. Self-consistent processes of relaxation of temperature and electron concentration, temperature of heavy particles (atoms and ions), and emission of radiation from the plasma determine the energy flux carried away from the plasma.

The equations describing the LTE state of plasma and plasma in a relaxation state differ substantially. LTE plasma is described by the heat balance equation. When solving this equation, calculating the chemical composition of the plasma and analyzing the various mechanisms of thermal conductivity plays an important role. The plasma in the state of relaxation is described by a system of differential equations, where the relationship between the relaxation parameters is decisive.

A separate description of LTE plasma and nonequilibrium plasma result in substantially simplifying the mathematical solution of the problem. First, it is possible to use large mesh grids when implementing numerical algorithms in the region of LTE plasma. Secondly, one-dimensional flat geometry can be used to describe a nonequilibrium layer. Thirdly, the partition of the nonequilibrium layer into a number of sub-layers allows one to take into account consistently or neglect different relaxation processes.

After separately finding the parameters of LTE plasma and relaxing plasma, it is necessary to link the solutions at the boundary. The matching of the solutions at the boundary between LTE and nonequilibrium plasma is carried out using boundary conditions that reflect the continuity of the particle and energy flux. The boundary conditions reflect the specifics of the problem under consideration. Such an approach has been successfully used in the simulation of the plasma of a thermionic converter [2] and in the numerical modeling of a high-pressure arc discharge in argon [3].

3. The nonequilibrium layer

3.1. Structure of the nonequilibrium layer.

The nonequilibrium layer can be conditionally divided into several sub-layers with different properties [4]. Each sub-layer is described by its set of equations. The layers are joined by boundary conditions. The division of the near-cathode non-equilibrium plasma layer into sub-layers with different properties reflects the fact that different physical mechanisms become significant at different length scales.

3.1.1. A space charge layer.

A layer of space charge directly joins the wall, in which the plasma quasi-neutrality condition is violated ($n_e \neq n_i$), where $n_e$ and $n_i$ are the electron and ion concentrations, respectively. The thickness of the sheath is given by the local Debye length ($L_D$). The potential jump in the space-charge layer ($\varphi_{ch}$) in the regime of an open external circuit and the absence of electron emission from the cathode surface (cold cathode approximation) is determined by the following formula:

$$\varphi_{ch} = \frac{k_B T_{ec}}{e} \ln \left( \frac{M_i}{M_e} \right)$$

(1)

where $k_B$ is the Boltzmann constant, $T_{ec}$ is the electron temperature at the boundary of the space charge layer, $e$ is the elementary charge, $M_i$ and $M_e$ are the masses of the ion and electron, respectively.
3.1.2. An ionization layer.

The ionization layer joins the space-charge layer, in which the quasi-neutrality condition of the plasma \( n_e=n_i \) is satisfied. In this layer, the escape of charged particles to the wall predominates over bulk recombination processes. The ionization layer theory is well developed when the mean free path of the ion \( \lambda_i \) is less than the characteristic length \( L_i \) of the ionization layer \( \lambda_i < L_i \), which is satisfied in the range of plasma parameters under consideration. The solution of the balance equation for charged particles assuming no variation of the gas \( T_g \) and electron \( T_e \) temperatures in the ionization layer allows calculating the electron energy flux \( P_e \) carried away to the cathode wall [2]:

\[
P_e(T_e, T_w) = D_a \frac{\dot{n}}{\sqrt{2L_i}} (E_i + e\Delta\varphi_c + 2kT_e / e)
\]  
(2)

where \( D_a = D_i (1 + T_e / T_w) \) is the ambipolar diffusion coefficient; \( D_i \) is the diffusion coefficient of ions; \( T_w \) is the temperature of the cathode wall, \( \dot{n}(T_e, T_w) \) is the concentration of charged particles at the boundary of the ionization layer calculated under the assumption of Partial Local Thermodynamic Equilibrium (PLTE); \( E_i \) is the ionization potential of the atom, \( \Delta\varphi_c \) is the potential difference between the cathode and the boundary of the ionization layer: \( \Delta\varphi_c = \varphi_a + \varphi_{ch} \). It consists of the potential jump in the space charge layer and an ambipolar potential difference in a quasi-neutral plasma \( \varphi_a \):

\[
\varphi_a = T_e\ln \left( \frac{\dot{n}}{n_i} \right)
\]  
(3)

where \( n_i \) is the concentration of charged particles at the boundary of the quasi-neutral plasma and the space-charge layer near the cathode. To find \( n_i \), one can use the quadratic equation [2]:

\[
n^2 + \frac{\sqrt{2L_i}}{D_a} \gamma \frac{2kT_e}{M_i} n_c - \dot{n}^2 = 0
\]  
(4)

where, for the conditions under consideration, \( \gamma = 0.71 \). The ionization length is calculated by the formula:

\[
L_i = \frac{1}{\dot{n}} \sqrt{\frac{D_a}{\alpha_{rec}(T_e)}}
\]  
(5)

where \( \alpha_{rec} \) is the three bodies recombination coefficient of charged particles. For the conditions under consideration, the inequality \( L_i > L_D \) holds, which is the justification for taking into account the space charge layer in the form of a boundary condition in the analysis of the ionization layer.

Formulas (1-5) enable calculating the flux density carried to the cathode by charged particles as a function of the electron temperature at the boundary of the ionization layer. Figure 1 shows the calculated graph at \( T_w = 950 \) K. It can be seen from the above results that in the temperature range \( T_e \sim (3000 \div 4500) \) K the flux varies by three orders of magnitude. The strong dependence of the energy flux on the electron temperature at the boundary of the ionization layer determines the main feature of the problem under consideration.
3.1.3. A layer of partial local thermodynamic equilibrium.

Between the ionization layer and the LTE plasma is a layer in which the diffusion of charged particles to the wall can be neglected. The temperatures of electrons and heavy particles differ inside this layer ($T_e \neq T_g$). The concentration of charged particles $n_0$ is determined by the condition of local equilibrium:

$$n_0^2(T_e, T_g) = N_{Na} \frac{g_i}{g_a} \left( \frac{2\pi M_i k_b T_e}{h^2} \right)^{3/2} \exp \left( -\frac{E_i}{k_b T_e} \right)$$

where $N_{Na}$ is the concentration of neutral sodium atoms, $g_i$ and $g_a$ are the statistical weights of ions and atoms, respectively, and $h$ is the Planck’s constant. To calculate the concentration of charged and neutral particles, equation (6) is supplemented by the condition of constant pressure: $p = k_b [T_g (N_{Na} + n_0) + T_e n_0]$.

In the analysis of the PLTE region in an electric arc, the electron temperature variation is often neglected, which greatly simplifies the simulation [4]. The heating of electrons in the arc is due to the operating electric current. The energy received from an external voltage is spent on ionization of atoms and heating of heavy particles. As a result, a local electron temperature balance is established. The role of the thermal conductivity of the electron gas is reduced to equalizing the electron temperature in the region under consideration.

Under the conditions of PPVC in the regime of the open external circuit, there is no heating of the electrons due to the operating current. The design of the PPVC is such that radiation from an external source does not reach the sidewalls of the cathode [1]. Optical energy can be absorbed in the ionization layer only after re-radiation by the bulk plasma. However, the efficiency of converting the energy of excited atoms to the kinetic energy of electrons in the ionization layer is small. This is due to the fact that the rate of quenching of excited atoms in collisions with electrons is small because of the relatively small concentration of electrons near the wall in comparison with the bulk plasma. The rate of radiative decay of excited states is large, since the role of the radiation trapping effect decreases near the wall.

All of this governs the main mechanism that ensures the energy flux into the ionization layer is the thermal conductivity of the electron gas. This means that an electron temperature gradient must exist in the PLTE region, which distinguishes the conditions under consideration from arc discharges.
4. The balance of the electron temperature in the PLTE region.

Let us consider the cathode part of the PPVC in the form of a cylinder with a diameter $D=6$ cm and a length $L=12$ cm. If we neglect the $T_e$ relaxation in the PLTE region, then the electron energy flux is $P_e(T_e)=1000$ W/cm$^2$. In this case, about 200 kW is required to maintain the heat balance in the cathode region of the PPVC, which is not possible with existing solar concentrators.

Allowance for the $T_e$ relaxation in the PLTE region can substantially reduce the required fluxes for plasma generation. Let us turn to the equation of the electron gas energy balance for calculating the spatial dependence of the electron temperature in the PLTE region.

The equation of the electron temperature balance for the conditions under consideration has the form [5]:

$$
\frac{dT_e}{dx} + D_{\delta n} n_e \frac{dn_e}{dx} = \frac{3}{2} \delta \nu_e (T_e - T_g) - H_{in}(x) \tag{7}
$$

Where $\chi_e$ is the thermal conductivity of electrons, $\nu_e$ is the frequency of the energy losses in collisions with heavy particles, $\delta=2M_e/M_i$ is energy transfer coefficient for elastic collisions, $H_{in}$ is the rate of energy release in inelastic collisions of electrons with excited atoms and molecules. The excited particles concentrations are determined by the radiative energy transfer. Equilibrium between atoms and molecules in a gas is maintained by the processes: $Na + Na \leftrightarrow Na_2$. The relationship between the number densities of atoms and molecules depends on the dissociation energy of the molecule $(D_W)$ and the gas temperature $T_g$ [2]: $[Na]^2/([Na_2]) = \exp(-D_W/kT_g)$. It can be seen that a relatively high content of molecules requires a high density of atoms and a low gas temperature. These conditions are realized near the cathode wall. The relative content of $Na_2$ molecules exceeds 7% for saturated sodium vapors at the temperature of $T_g=900$ K. Molecules have wide absorption bands compared to the line absorption spectrum of atoms. Thus, molecules play a decisive role in the formation of optical absorption in the near-wall regions. The lower the wall temperature, the higher the concentration of molecules and the lower the flux of radiation leaving the plasma. It should be noted that the kinetics of molecules near the cathode wall is non-equilibrium, which is due to the complicated mechanism of evaporation and condensation in the heat pipe. All of this leads to the fact that the calculation of $H_{in}$ is a complex and ill-defined task.

The collision transport frequency of electrons with sodium atoms $\nu_{ea}$ depends weakly on collision energy and has a large value due to the high polarizability of alkali atoms ($\nu_{ea}=4.2 \cdot 10^7 N_{Na},$ sec$^{-1}$) [1]. The thermal conductivity coefficient taking into account electron-atomic and electron-ion collisions in the case of dependence of the frequency of electron-atom collisions with respect to the electron energy is given by the formula [5]: $\chi_e = 5nT_e/[2M_e(\nu_{ea} + 1.87\nu_{ei})]$. In this paper, we analyze the temperature range of electrons $T_e\leq 4500$ K, which corresponds to the ionization degree of less than 7%. Accordingly, the inequality holds: $\nu_{ei} \approx 0.2\nu_{ea}$. Consequently, in the zeroth approximation one can neglect the effect of electron-ion collisions on the coefficient of thermal conductivity of the electrons. Therefore, the expression for the thermal conductivity of electrons has the form: $\chi_e=(5/2)D_e n$, where $D_e=T_e/(M_e\nu_{ea})$ is the coefficient of free electron diffusion. The second term in Eq. (7) describes the energy transfer associated with the radial hydrodynamic velocities of the electrons that are determined by the rate of ambipolar diffusion. The contribution of the second term compared with the first term is small ($D_e<\ll D_e$) under the considered conditions. Thus, the contribution of the second term can be neglected at the initial stage of the analysis of equation (7). In this work, the ionization rate of atoms in collisions with electrons $H_{in}$ was calculated in the framework of the diffusion approximation: $H_{in}(T_e) = 1.6 \cdot 10^{-5} E_n T_e^{-3} \exp(-E_n/kT_e)$ . The given formula is characterized by a strong dependence on the electron temperature. Calculation showed that the rate of energy loss during ionization of atoms is significantly higher than the rate of energy loss in elastic collisions in the considered electron temperature range $T_e \geq 3000$ K. This allows us to neglect the first term on the right-hand side of Eq. (7) at the initial stage of the analysis.

We use the following expressions as the boundary conditions [2]:
If \( x \to \infty \) then \( T_e \to \hat{T}_p \) \hspace{1cm} (8)

\[
\chi_e \frac{dT_e}{dx} \bigg|_{x=0} = P_e(T_{ec})
\]

Equation (8) reflects the asymptotic tendency of the electron temperature to the plasma LTE temperature at the boundary of the non-equilibrium layer (\( \hat{T}_p \)). Equation (9) reflects the fact that, under the considered conditions, the energy flux into the ionization layer is determined by the thermal conductivity of the electron gas.

Let us consider a homogeneous equation:

\[
\frac{d}{dx} \left( \frac{5}{2} D_e n \frac{dT_e}{dx} \right) = 0
\]

When calculating the derivative \( \partial n / \partial T_e \), we take into account only the sharpest (exponential) temperature factor in the equation (6):

\[
\frac{\partial n}{\partial T_e} = \frac{n}{2T_e} \left[ \frac{E_i}{T_e} \right]
\]

As a result, equation (10) takes the form:

\[
\frac{E_i}{2T_e^2} \left( \frac{dT_e}{dx} \right)^2 + \frac{d^2 T_e}{dx^2} = 0
\]

We consider the following function as the zeroth approximation to the solution of equation (12):

\[
T_{e0}(x) = \hat{T}_p - \left( \hat{T}_p - T_{ec} \right) \exp \left( -\frac{x}{T_{tc}} \right)
\]

where \( L_{te} \) is the characteristic length of the electron temperature relaxation in the PLTE plasma layer. The above dependence \( T_{e0}(x) \) satisfies the boundary condition (8). To find two unknown parameters \( (T_{ec} \) and \( L_{te} \), two equations are needed. One of them is equation (9). We suggest using the following condition as the second equation:

\[
\frac{dT_{e0}}{dx} \bigg|_{x=0} = \frac{E_i}{2T_{e0}} \left( \frac{dT_{e0}}{dx} \right)^2 dx
\]

Equation (14) reflects the requirement that the sum of the average values of the first and second terms on the left-hand side of equation (12) should be zero. The integral on the right-hand side of (14) is calculated analytically. As a result, equation (14) reduces to an algebraic equation for finding the electron temperature at the boundary of the ionization layer near the cathode \( T_{ec} \):

\[
\left( \hat{T}_p - T_{ec} \right) = \frac{E_i}{2} \left( \frac{\hat{T}_p}{T_{ec}} - 1 \right) - \ln \left( \frac{\hat{T}_p}{T_{ec}} \right)
\]

As can be seen from (15), the electron temperature drop in the PLTE plasma layer is determined by two parameters: the ionization potential of the atom \( (E_i) \) and the electron temperature at the boundary of the non-equilibrium layer and the LTE plasma \( (\hat{T}_p) \). The solution Eq. (15) for \( \hat{T}_p=4500 \) K gives the value \( T_{ec}=3518 \) K. Consequently, a significant temperature difference of about 1000 K is realized in the PLTE region. Using the found value of \( T_{ec} \), we can calculate the right-hand side of Eq. (2) and thereby determine the energy flux density carried to the cathode by charged particles: \( P_{eC0}=33 \) W/cm\(^2\).

The calculation showed that a decrease in \( \hat{T}_p \) leads to a decrease in \( T_{ec} \).

It follows from the above estimates that the electron temperature relaxation in the PLTE region has reduced the energy flux in comparison with the isothermal case by a factor of 35. The total energy flow to the cathode wall, indicated geometric dimensions is 7 kW. Such powers of focused solar
radiation are realizable for existing optical systems with about x3500 concentration ratio, which makes the statement of the proof-of-experiment feasible.

Substituting (13) into equation (9), we obtain an expression for calculating $L_{Te}$:

$$ L_{Te} = \chi_e(T_{ec}) \left( \frac{T_p - T_{ec}}{P_{ac0}(T_{ec})} \right) $$  \hspace{1cm} (16)

We have obtained the value $L_{Te}=2.75 \cdot 10^{-3}$ cm for $T_p=4500$ K. For the conditions under consideration, the length of the thermal relaxation exceeds the length of ionization relaxation: $L_{Te} / L_i = 5.7$. This circumstance justifies the allowance for the ionization layer in the form of the boundary condition (9) in the analysis of the PLTE region of the plasma.

The function (13) will satisfy the energy balance if the integral of $H_{in}(x)$ is equal to the value $P_{ac0}$ found. However, depending on the mathematical form of the function $H_{in}(x)$, the exact solution of the inhomogeneous equation (7) may differ from (13). The solution of the model problems will enable finding out how much equation (15) is suitable for finding the $T_{ec}$ value. The sensitivity of the value of $T_{ec}$ to the form of the model function $H_{in}(x)$ requires separate consideration.

5. LTE plasma region.

In this region, the concentration of charged particles is determined by formula (6), the temperatures of electrons and heavy particles are equal ($T_e=T_g$).

To analyze the radial distribution of the LTE plasma temperature ($T(r)$), we use the heat balance equation. In cylindrical coordinates, the balance equation for the LTE plasma temperature takes the form [6]:

$$ \frac{1}{r} \frac{d}{dr} \left( \chi(T) r \frac{dT}{dr} \right) + \rho(r) = 0 $$  \hspace{1cm} (17)

here $\chi$ is the coefficient of thermal conductivity of LTE plasma, $\rho(r)$ [W/cm$^3$] is the specific power of optical pumping. The boundary condition on the axis ($r=0$) reflects the symmetry of the problem: $\frac{dT}{dr}|_{r=0}=0$. The boundary conditions near the wall ($r=R$) are the continuity of the heat flux $P(T_p)$ at the plasma LTE boundary and the non-equilibrium layer:

$$ \chi(T_p) \left. \frac{dT}{dx} \right|_{x=R} = P(T_p) $$  \hspace{1cm} (18)

Under the considered conditions, the thermal conductivity coefficient $\chi(T)$ can be represented as the sum of three terms: $\chi(T)=\chi_d(T)+\chi_e(T)+\chi_r(T)$, where $\chi_d(T)$ is the coefficient of thermal conductivity due to the neutral component [7]. $\chi_d(T)$ is coefficient of thermal conductivity of the electron gas, taking into account collisions of electrons with neutral atoms and sodium ions [5]. $\chi_e(T)$ is coefficient of radiative heat conduction. The calculation showed that the overall thermal conductivity of electrons and atoms $\chi_{ea}=\chi_d+\chi_e$ can be characterized by the total thermal conductivity, which has the following temperature dependence: $\chi_{ea}(T) = 9.13 \cdot 10^{-11} T^{1.983}$ [W/(K cm)]. Calculation of $\chi_e$ for LTE of sodium plasma was carried out in [8] for $p=10^5$ Pa. The value of $\chi_e=86$ W/(cm$^2$K) is obtained, which varies only slightly in the temperature range $T=[3500: 5000]$. The analysis showed that the results of [8] can be used as an upper estimate of the coefficient of radiative heat conduction. In a subsequent paper [9], it was shown that the question of the nature of intense luminescence and significant absorption in the infrared spectrum in dense vapor of alkali metals remains open. The experimental absorption coefficient can exceed the calculated values by two or three orders of magnitude. Even with these observations, the radiative thermal conductivity remains two or three orders of magnitude greater than the thermal conductivity, due to the chaotic motion of atoms and electrons. Therefore, in carrying out further estimates we shall take into account only the radiative thermal conductivity, assuming that $\chi_e=1$ W/(cm K).
Let us estimate the difference between the temperature at the axis $T_0$ and the temperature at the plasma LTE boundary. We define the distribution of heat release over the cross section $\rho(r)$ in the form [6]:

$$\rho(r) = \rho_0 \left[ 1 - \left( \frac{r}{R} \right)^\alpha \right]$$

(19)

where $\alpha$ is the calculation parameter, which allows simulating the width of the focusing spot of external radiation. The parameter $\rho_0$ is related to the flux at the plasma LTE boundary using the formula:

$$\rho_0 = \frac{2P(\hat{T}_p)}{R} \left( \frac{\alpha + 2}{\alpha} \right)$$

(20)

The solution of equation (17) results in finding the required temperature $T_R = T(R) = T_R$ at the boundary of the LTE plasma:

$$T_R = T_0 - \frac{2P(\hat{T}_p)}{\chi_R} \left[ \frac{\alpha + 2}{\alpha} \right] \left[ \frac{1}{4} - \frac{1}{(\alpha + 2)^2} \right]$$

(21)

As seen from (21), the temperature difference between the axis and the LTE plasma boundary $\Delta T = T_0 - T_R$ is proportional to the power drawn from the plasma, to the radius of the device and inversely proportional to the thermal conductivity of the plasma. The value of the $\alpha$ parameter has little effect on the temperature drop. We estimate the value of $\Delta T$, assuming that the radiation flux of energy at the plasma LTE boundary is equal to the energy flux at the boundary of the ionization layer: $P(\hat{T}_p) = P_{C0}(T_{c0})$. Calculation by formula (21) for $\alpha=2$ and $R=3$ cm gives the value $\Delta T = 70$ K.

This evaluation has several important consequences. The high value of the radiative heat conductivity leads to the fact that the radial temperature difference between the axis and the periphery of the LTE plasma will be small (of the order of several tens of degrees). This leads to a high value of plasma conductivity averaged over the radius, which favorably affects the output characteristics of the converter, reducing its internal resistance. The ambipolar potential difference in the LTE plasma $\Delta \phi$ between the axis and the boundary of the near-wall non-equilibrium region is determined by the ionization potential $E_i$ and the logarithm of the temperature ratio: $\Delta \phi \approx 0.5 E_i \ln(T_0/T_R)$. The $\Delta \phi$ value under these conditions is small $\Delta \phi \approx 0.1$ V. It was shown earlier [1] that a small ambipolar potential difference in the cathode region increases the output voltage of the PPVC.

6. The discussion of the results.

The energy balance in the cathode region of the PPVC was analyzed. The plasma of sodium vapor was considered in the LTE state at a pressure ($10^4$-$10^5$) Pa and the temperature of the bulk plasma of 4500 K. It was shown that for these parameters the main mechanism effecting the plasma thermal conductivity is the radiative transfer of energy. It was shown that the temperature difference between the PPVC axis and the plasma LTE boundary in the near-wall region is less than 100 K. This leads to the high averaged plasma conductivity and the small ambipolar potential difference in the LTE plasma, which increases the efficiency of the direct photoelectric conversion.

The analysis showed that under the considered conditions, the radiative energy transfer sharply decreases in the non-equilibrium layer separating the LTE plasma from the cathode walls. This leads to a small contribution of radiation losses to the overall energy balance. The complex effect of radiative energy transfer on plasma parameters was discussed earlier in the literature. It was noted that consideration physical processes occurring in an arc, it is incorrect to solve the energy balance equation in an arc, taking into account only the radiation emission from the system at a given temperature and not taking into account its effect on the temperature distribution profile itself, for example, the mechanism of radiative heat conductivity [10]. Actually, this scenario is realized in the conditions under consideration.
The analysis of the electron temperature balance has shown that in the non-equilibrium layer, the electron temperature drop is realized, which leads to a significant decrease in the energy flux to the cathode wall as compared to the isothermal approximation. A more accurate prediction of the energy flux to the cathode wall requires a joint self-consistent analysis of the relaxation of the temperatures of electrons and heavy particles.

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