KINETICS OF HEAT TRANSFER FROM A RAREFIED PLASMA TO A SPHERICAL PARTICLE EMITTING THERMOELECTRONS

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It is shown that thermoelectron emission from the surface of a particle leads to a substantial increase in the intensity of heat transfer from a plasma.

It is known that the laws governing plasma heating of particles of a material have a connection with gas ionization, participation of electrons and ions in transfer processes, and the associated electrization of particles [1-10]. The magnitude of the charge (potential) acquired by each particle is determined by the local parameters of the plasma, for example, the temperature and pressure, the size of the particle, and the intensity of elementary processes proceeding on its surface, such as recombination of electrons, neutralization of ions, thermoemission, etc. Build up of the charge on the particle continues until the fluxes of negative electrons and positive ions moving in its electrostatic field compensate each other. Under conditions where the thermoelectron emission from the particle surface is insignificant [3-10], the equilibrium (floating) potential of the particle is negative ($\varphi_f<0$) owing to the fact that the thermal velocity of plasma electrons significantly exceeds the velocity of ions ($\bar{v}_e/\bar{v}_i \sim (m_i T_{e\infty}/m_e T_{i\infty})^{1/2} >> 1$). At high temperatures of the material or low densities of the charge carriers in the gas phase (in a weakly ionized or in a strongly rarefied plasma) the flux of thermoelectrons emitted by the particle leads to a decrease in the absolute value or a change of sign of the floating potential φ_f. Such behavior of the potential of the particle exerts the strongest effect on the frequency of the collisions of plasma electrons with the particle surface and on the heat flux transferred by the electrons. This can lead to a substantial change in the contributions of each species of charge carriers to the total thermal balance.

The present work gives a kinetic description of heat transfer to a thermoelectron-emitting spherical particle when at rest in a rarefied collisionless ($Kn = l_j/R >> 1$) plasma. It is assumed that molecules, electrons, and ions of the plasma, moving to the side with respect to the particle, in an unperturbed region at infinity as well as thermoelectrons, emitted by the particle, at the surface obey one-sided Maxwellian velocity distributions with parameters determined by the corresponding temperatures and densities and with zero mass velocity. The density of thermoelectrons near the surface is specified in such a way that the thermoemission current found for the given distribution function coincides with that calculated from the classical Richardson formula [11]. The velocity distribution functions at an arbitrary point of space and the macroscopic parameters of the plasma (densities, temperatures, fluxes, etc.), determined as moments of distribution functions of corresponding orders, are not known beforehand and are found during solution of the problem. The thermoelectron emission current is considered to be limited, so that the particle potential remains negative. The efficiencies of recombination of electrons and neutralization of ions of the plasma on the particle surface are assumed to be equal to unity. The law of diffuse scattering has been selected for molecules and neutralized ions reflected by the particle. Heat transfer is considered in a regime which is quasi-stationary with respect to the floating potential of the particle, since the time of build-up of charge on the particle turns out to be extremely small as compared with the characteristic times of the thermal and hydrodynamic processes [3-5].

In the thermal balance on the surface of a particle placed in the plasma, the following mechanisms of energy transfer should be taken into account: 1) transfer of kinetic energy by each plasma component (molecules, electrons,

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and ions) to the particle surface with allowance for retardation of electrons and acceleration of ions in the local electrostatic field of the particle; 2) transfer of the potential energies of charge states as a result of recombination of electrons and neutralization of ions on the surface; 3) heat losses associated with diffuse reflection of molecules and neutralized ions from the particle; 4) heat losses due to thermoemission of electrons, including both kinetic and potential energy losses.

The corresponding expressions for the thermal fluxes of molecules, ions, and electrons are written in dimensionless form as

$$q_a = 1 - \tau_s, \tag{1}$$

$$q_i = e_i^- + j_i^- \left(\frac{1}{2} w_i - \tau_s\right), \tag{2}$$

$$q_{e,Te} = e_e^- + \frac{1}{2} j_e^- w_e - j_{Te}\left(\frac{1}{2} w_e + \tau_s/\tau\right). \tag{3}$$

Here $q_h = Q_h/E_h^0$, $q_{e,Te} = Q_{e,Te}/E_e^0$, $e_j^- = E_j^-/E_j^0$, $j_j^- = J_j^-/J_j^0$, $j_{Te} = J_{Te}/J_e^0$, $\tau = T_{e\infty}/T_{h\infty}$, $\tau_s = T_s/T_{h\infty}$, $w_j = W_j/kT_{j\infty}$, $W_e = \Phi_e$, $W_i = I_i - \Phi_e$, $E_j^0 = N_{j\infty}kT_{j\infty}(2kT_{j\infty}/\pi m_j)^{1/2}$, $J_j^0 = N_{j\infty}(kT_{j\infty}/2\pi m_j)^{1/2}$, $J_{Te} = (A_R/e)T_s^2\exp(-\Phi_e/kT_s)$.

In a number of cases, the thermal balance given above should additionally take into account heat losses associated with radiation [12] and evaporation [13] of the particle.

Determination of the charge and energy fluxes transferred by electrons and ions, which depend on the spatial distribution of the potential in the plasma and the floating potential of the particle, is reduced to solution of the kinetic problem, which includes the Poisson equation for the electrostatic potential and the Boltzmann-Vlasov equations for the velocity distribution functions. The Poisson equation, the boundary conditions for the potential, and the balance of charge fluxes on the surface of the emitting particle are written in dimensionless form as

$$\frac{d^2y}{dx^2} = \frac{1}{x_D^2 x^4}(n_i - n_e - n_{Te}), \tag{4}$$

$$y(x=0) = 0, \; y(x=1) = y_f, \tag{5}$$

$$j_e^- - j_{Te} = (\mu/\tau)^{1/2} j_i^-, \tag{6}$$

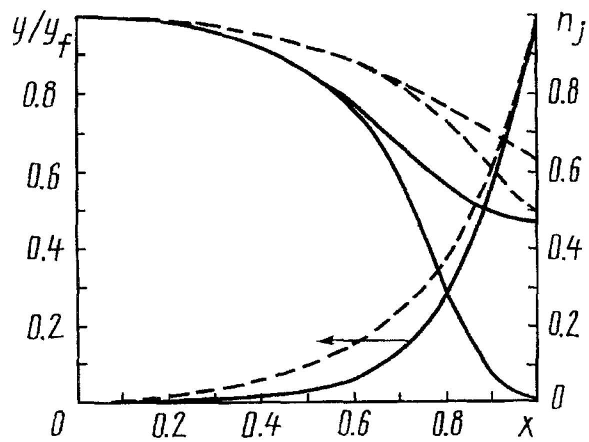
where $x = R/r$; $y = -e\varphi/kT_{e\infty}$; $y_f = -e\varphi_f/kT_{e\infty}$; $n_j = N_j/N_{j\infty}$; $x_D = r_D/R$; $\mu = m_e/m_i$; $r_D = (kT_{e\infty}/4\pi e^2 N_{e\infty})^{1/2}$.

The relationship of the densities $n_j(x)$ and fluxes j_j^-, e_j^- of electrons and ions with the plasma potential $y(x)$ in a free-molecular regime can be found from the Boltzmann-Vlasov equations by analyzing the possible trajectories of their motion in the field of a charged particle [14-16]. For electrons and ions with Maxwellian velocity distributions in the unperturbed region of the plasma far from the particle the corresponding formulas are given, e.g., in [8, 10, 15]. For the spatial distribution of the density of thermoemission electrons $n_{Te}(x)$ a similar approach gives the following result:

$$n_{Te} = \frac{1}{2} j_{Te}\left(\frac{\tau}{\tau_s}\right)^{1/2}\left[\operatorname{erfc}\left(\frac{\tau(y_f - y)}{\tau_s}\right)^{1/2}\exp\left(\frac{\tau(y_f - y)}{\tau_s}\right) - (1 - x^2)^{1/2}\operatorname{erfc}\left(\frac{\tau(y_f - y)}{\tau_s(1 - x^2)}\right)^{1/2}\exp\left(\frac{\tau(y_f - y)}{\tau_s(1 - x^2)}\right)\right]. \tag{7}$$

The thermoemission current j_{Te} is considered to be a parameter in the above relations and is regarded as given.

Analytical results can be obtained only in the limiting cases of a weakly and strongly screening plasma when the fluxes incident on the particle are calculated from the momentum and energy conservation laws without resorting



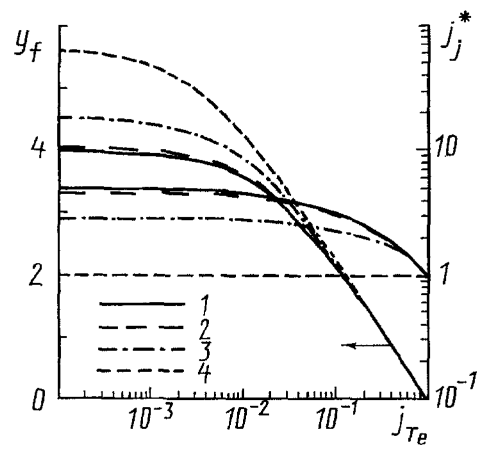


Fig. 1. Spatial distributions of the potential y/y_1 and densities of electrons $n_e + n_{Te}$ and ions n_i in the vicinity of a particle in an argon plasma at the Debye screening parameter $x_D = 0.1$ and for different thermoemission fluxes. Solid lines—$j_{Te} = 0$, $y_f = 4.51$; dashed lines—$j_{Te} = 0.4$, $y_f = 0.90$. The upper branches of the concentration curves are n_i, the lower branches are $n_e + n_{Te}$

Fig. 2. The dimensionless floating potential of a particle y_t and charge fluxes $j_i^* = j_{e,Te}^* \equiv j_e^* - j_{Te}^*$ as functions of the thermoemission current j_{Te} in an argon plasma at different parameters of Debye screening: 1) $x_D = \infty$; 2) 1; 3) 0.1; 4) 0.

to the Poisson equation. The relations which, together with Eqs. (2), (3), and (6), determine the electronic and ionic heat transfer acquire the form

$$j_i^- = 1 + \tau y_f,\ e_i^- = 1 + \tau y_f + \frac{1}{2}(\tau y_f)^2,\ j_e^- = \exp(-y_f),\ e_e^- = \exp(-y_f)$$

in the case of weak Debye screening ($x_D \gtrsim 1$, a particle with a thick layer of space charge) and

$$j_i^- = 1,\ e_i^- = 1 + \frac{1}{2}\tau y_f,\ j_e^- = \exp(-y_f),\ e_e^- = \exp(-y_f)$$

in the case of strong Debye screening ($x_D \ll 1$, a particle with a thin layer of space charge).

For an arbitrary ratio between the particle radius R and the Debye radius r_D, the kinetic problem is solved numerically by a method of successive approximations that is similar to one suggested in [16] for a cylindrical electrostatic probe and used in [10] in application to the case of a spherical particle in a rarefied plasma.

Results of numerical simulation illustrating the effect of thermoemission on the processes of charge transfer and heat transfer to a spherical particle in an argon plasma are presented in Figs. 1-3. Since in traditional processes of plasma treatment of materials the plasma temperature greatly exceeds the temperature of the particles, the ratio $\tau_s = T_s/T_{h\infty}$ turns out to be small and exerts little effect on the results, thus allowing use of the thermoemission flux rather than the particle temperature as an independent free parameter. Computations were carried out for the following values of the dimensionless parameters: $\tau = T_{e\infty}/T_{h\infty} = 1$; $\tau_s = T_s/T_{h\infty} = 0.3$; $\Phi_e/k\,_eT = 4.5$; $I_i/kT_{i\infty} = 15.8$.

It is seen from Fig. 1 that as the intensity of thermoemission grows, the total concentration of electrons near the surface increases. Since the quasi-neutrality condition must be maintained in the plasma volume and because of the decrease in the velocity of directed motion, the density of ions also increases. In this case, the spatial distribution of the potential becomes flatter.

As the emission current grows, the absolute value of the floating potential decreases (Fig. 2). The weakening of the collecting field causes a decrease in the ion current which is equal to the total flux ofelectrons, including the plasma and emission electrons: $j_i^* = j_{e,Te}^* \equiv j_e^* - j_{Te}^*$ where $j_j^* = J_j/J^*$, $J^* = N_{e\infty}(kT_{e\infty}/2\pi m_i)^{1/2}$.

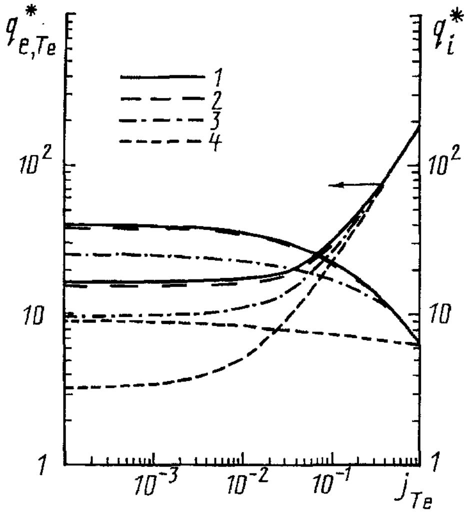


Fig. 3. Dimensionless heat fluxes of electrons $q^*_{e,Te}$ and ions q^*_i as functions of the thermoemission current j_{Te} in an argon plasma at different parameters of Debye screening (designations 1-4 are the same as in Fig. 2).

The effect of thermoelectronic emission on heat transfer to a spherical particle in a plasma is illustrated in Fig. 3. The thermoemission leads to a decrease in the ionic and an increase in the electronic thermal flux. It is essential that, in comparison with the case of a nonemitting particle ($j_{Te} = 0$; $y_f = 4$-5.6), under the conditions of developed thermoemission ($j_{Te} \approx 1$; $y_f \approx 0$) sharp growth in the heat flux of electrons $q^*_{e,Te}$, takes place, by about 20-100 times, depending on the screening properties of plasma, whereas the ionic heat flux q_i^* decreases only 2-3 times (here $q_j^* = Q_j/E^*$, $E^* = N_{e\infty}kT_{e\infty}(2kT_{e\infty}/\pi m_i)^{1/2}$). The thermoemission-induced enhancement of the electronic heat flux makes itself felt most appreciably in a strongly screening plasma ($x_D \ll 1$), since in this case the change in the floating potential of the particle is maximal.

The reasons for the enhancement of electronic heat transfer to an emitting particle are the following. If there is no emission from the surface, the flux of plasma electrons incident on the particle is limited by a high negative potential. In this case, the main contribution to the heat flux of electrons is attributable to the energy of the charge state Φ_e. Thermoemission leads to a lowering of the height of the potential barrier and to an increase in the frequency of collisions of plasma electrons with the particle surface. The energy brought by the "hot" electrons of the plasma $\sim kT_{e\infty}$ greatly exceeds the energy removed by the "cold" electrons of the material $\sim kT_s$. Under the conditions of developed thermoemission the total heat flux of electrons is already determined by the energy of thermal movement $\sim kT_{e\infty}$, rather than by the work function Φ_e. Actually, with growth of the intensity of thermoemission, a rapid increase in the flux of kinetic energy of the plasma electrons colliding with the particle surface occurs, whereas the component of the electron heat flux associated with transfer of the energy of the charge state slowly decreases, since the total flux of electrons remains equal to the flux of ions. The energy, evolved on the surface of electrons, of the charge state from the additional flux due to the decrease in the potential barrier height is compensated by losses on the emission of thermoelectrons.

Thus, heat transfer from a plasma to a particle is enhanced in the course of thermoelectronic emission from the particle surface due to the contribution of the kinetic energy of "hot" plasma electrons to the total heat balance because of the decrease in the absolute value of the floating potential of the particle. This phenomenon can play an important role in heating the particles of refractory materials in a rarefied low-temperature plasma.

NOTATION

A_R, Richardson constant; e, electron charge; E_j^-, density of flux of kinetic energy; I_i, ionization energy; J_j^-, number flux density of plasma particles; J_{Te}, density of flux of thermoelectrons; k, Boltzmann constant; l_j, free-path length; m_j, mass; N_j, number density; Q_j, heat flux density; r, spatial coordinate; r_D, Debye radius; R, particle radius; T_j, temperature; $\bar{v}$, mean thermal velocity; φ, plasma potential; φ_j, floating potential of a particle; Φ_e, electron work function. Subscripts: a, molecules; j = e, i; e, plasma electrons; i, ions; h, heavy particles of a plasma (molecules and ions); s, surface; Te, thermoelectrons; ∞, unperturbed region of a plasma far from a particle. Superscript: -, direction to the side with respect to a particle.

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