KINETICS OF HEAT TRANSFER BETWEEN A SPHERICAL PARTICLE AND A RAREFIED PLASMA.

2. MONOENERGETIC ION APPROXIMATION

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A kinetic description of heat transfer to a spherical particle from a plasma with allowance for charge-transfer processes is given in the monoenergetic ion approximation.

The kinetic description of the interaction of a material particle with a rarefied plasma, allowing for the participation of both neutral molecules and charges — electrons and ions — in the transfer processes and for electrization of the particle, comes down to a simultaneous solution of the Boltzmann—Vlasov equations for the velocity distribution functions and the Poisson equation for the electrostatic potential. These equations are analyzed together with the condition of equality of the fluxes of electrons and ions colliding with the particle, which determines the equilibrium (floating) potential of the particle, $\varphi_f < 0$, acquired by it in the plasma due to the considerable difference between the thermal velocities of the charge carriers $[\bar{v}_e/\bar{v}_i \sim (m_i T_{e\infty}/m_e T_{i\infty})^{1/2} \gg 1]$. The main complexities in solving the kinetic problem are associated with calculating the macroscopic characteristics (densities, charge fluxes, etc.) of the ions, since the effective potential of their interaction with the charged particle has a complicated form [1, 2]. Simplifying model distributions — the cold ion [3] and monoenergetic ion [4] approximations — have therefore become widely popular. Heat transfer between a spherical particle and a rarefied plasma in the cold ion approximation has been described in [5].

In the present paper we give the results of calculations of heat transfer to a spherical particle of radius R, at rest in a rarefied collisionless ($R \ll \ell_j$) plasma, under the assumption of a monoenergetic ion velocity distribution.

The formulation and an algorithm for numerical solution of the problem of the potential distribution of plasma in the vicinity of a charged particle have been given in [5]. The equations in [5] for the density and the charge and energy fluxes of the electrons, which have a Maxwellian velocity distribution in the unperturbed part of the plasma far from the particle, also remain valid. For ions with a monoenergetic distribution function

$$f_{i\infty} = \frac{m_i^2 N_{i\infty}}{4\pi (2m_i \mathscr{E}_0)^{1/2}} \delta(\mathscr{E} - \mathscr{E}_0) \quad (1)$$

the expressions for the dimensionless densities $n_j = N_j/N_{j\infty}$ and for the fluxes of charge $j_j^- = J_j^-/J_j^0$ and kinetic energy $e_j^- = E_j^-/E_j^0$ take the form

$$n_i = \frac{1}{2}\left(1 + \frac{\pi}{4}\tau y\right)^{1/2} - \frac{1}{2}(1 - 2\theta)\left(1 + \frac{\pi}{4}\tau y - j_i^- x^2\right)^{1/2}, \quad (2)$$

$$j_i^- = (\tau/\mu)^{1/2} j_e^-, \quad (3)$$

$$e_i^- = \frac{2}{\pi} j_i^- \left(1 + \frac{\pi}{4}\tau y_f\right), \quad (4)$$

where

$$\theta = \begin{cases} 1 & \text{for } (x/2)(dy/dx) - y \leqslant 4/(\pi\tau), \\ 0 & \text{for } (x/2)(dy/dx) - y > 4/(\pi\tau); \end{cases}$$

$x = R/r$; $y = -e\varphi/kT_{e\infty}$; $y_f = -e\varphi_f/kT_{e\infty}$; $\mu = m_e/m_i$; $\tau = T_{e\infty}/T_{i\infty}$; $j_j^0 = N_{j\infty}(kT_{j\infty}/2\pi m_j)^{1/2}$; $E_j^0 = N_{j\infty}kT_{j\infty}(2kT_{j\infty}/\pi m_j)^{1/2}$.

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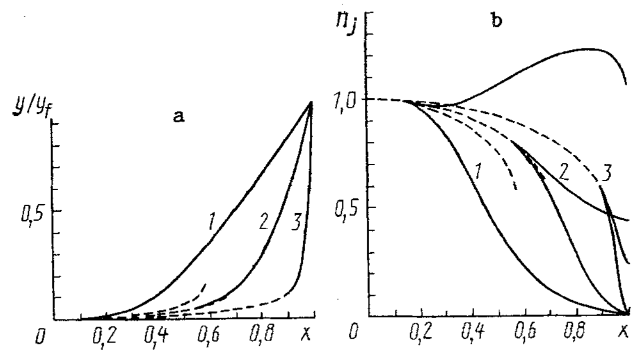

Fig. 1. Spatial distributions of potential y/y_f (a) and of densities n_j of charge carriers (b) in the vicinity of the particle in a one-temperature (τ = 1) argon plasma; the upper branches are curves of density n_i and the lower branches are of density n_e; dashed lines: quasi-neutral solutions: 1) x_D = 1, y_j = 4.15; 2) 0.1 and 4.51; 3) 0.01 and 5.02.

The ion energy $\mathscr{E}_0$ must be of the order of the ion temperature $kT_{i\infty}$. Since the ion temperature is definitely not a part of the monoenergetic distribution function (1), the choice of the proportionality factor between these quantities is not unique. In the present paper we use the relationship $\mathscr{E}_0 = (4/\pi)kT_{i\infty}$ adopted in probe theory [1, 2], which makes the ion fluxes to an uncharged particle in the absence of an electric field calculated for Maxwellian and monoenergetic distributions coincide [1, 2]. In the limit $\tau = T_{e\infty}/T_{i\infty} \to \infty$, Eqs. (2)-(4) change into the corresponding equations [5] for the cold ion approximation.

The dimensionless total heat fluxes $q_j = Q_j/E_j^0$, with allowance for the contribution to heat transfer from the energy of charge states of electrons ($W_e = \Phi_e$) and ions ($W_i = I_i - \Phi_e$), for diffuse scattering of molecules and neutralized ions by the surface of the particle are calculated as

$$q_a = 1 - \tau_s, \tag{5}$$

$$q_e = e_e^- + \frac{1}{2} j_e^- w_e, \tag{6}$$

$$q_i = e_i^- + j_i^-\left(\frac{1}{2} w_i - \tau_s\right), \tag{7}$$

where $w_j = W_j/kT_{j\infty}$ and $\tau_s = T_s/T_{h\infty}$.

The results of numerical calculations of the transfer of charge and energy to a particle in an argon plasma with $\tau = T_{e\infty}/T_{i\infty} = 1$ are given in Figs. 1 and 2. In Fig. 1 we show the influence of the ratio of the Debye radius $r_D = (kT_{e\infty}/4\pi e^2 N_{e\infty})^{1/2}$ to the particle's radius R on the spatial distributions of plasma potential and electron and ion densities. In Fig. 2 we give the dependence on the Debye screening parameter $x_D = r_D/R$ of the dimensionless particle potential $y_f = -e\varphi_f/kT_{e\infty}$ and the dimensionless fluxes of charge $j_j^* = J_j^-/J^*$ and kinetic energy $e_j^* = E_j^-/E^*$ of electrons and ions [$J^* = N_{e\infty}(kT_{e\infty}/2\pi m_i)^{1/2}$, $E^* = N_{e\infty}kT_{e\infty}(2kT_{e\infty}/\pi m_i)^{1/2}$]. The bends in the curves (Fig. 2) correspond to the transition to the regime of orbital motion of ions [1, 2, 4] with weak Debye screening, when the electron and ion fluxes depend only on the particle's potential φ_f but not on the spatial distribution $\varphi(r)$ of the plasma potential, and hence on $x_D = r_D/R$.

In the limiting cases of a strongly and a weakly screening plasma, the particle's potential and the fluxes of charge and energy to it can be found analytically:

$$j_e^* = j_i^* = e_e^* = 1/\tau^{1/2},\ e_i^* = \frac{2}{\pi\tau^{3/2}}\left(1 + \frac{\pi}{4}\tau y_f\right),\ y_f = -\frac{1}{2}\ln(\mu/\tau)$$

for strong screening ($x_D \ll 1$) and

$$j_e^* = j_i^* = e_e^* = \frac{1}{\tau^{1/2}}\left(1 + \frac{\pi}{4}\tau y_f\right),\ e_i^* = \frac{2}{\pi\tau^{3/2}}\left(1 + \frac{\pi}{4}\tau y_f\right)^2,$$

$$\exp(-y_f) = (\mu/\tau)^{1/2}\left(1 + \frac{\pi}{4}\tau y_f\right)$$

for weak screening ($x_D \gtrsim 1$).

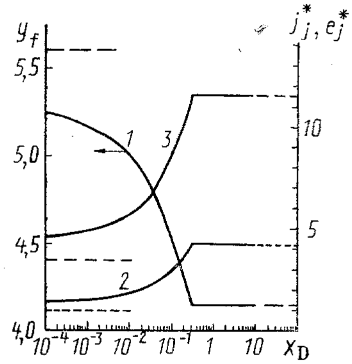

Fig. 2

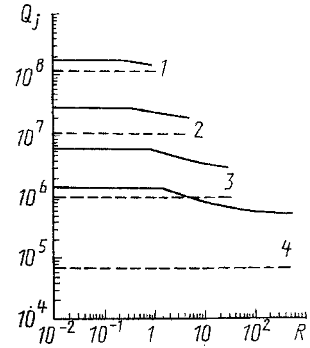

Fig. 3

Fig. 2. Dimensionless floating potential of the particle and dimensionless fluxes of electron and ion charge and energy for a one-temperature (τ = 1) argon plasma as a function of the Debye screening parameter; dashed lines: limiting values in a strongly and a weakly screening plasma; 1) y_f; 2) $j_i^* = j_e^* = e_e^*$; 3) e_i^*.

Fig. 3. Heat transfer to a metallic particle in a one-temperature argon plasma with $T_{j\infty} = 10^4$ K at different pressures: p = 10^5 (1), 10^4 (2), 10^3 (3), and 10^2 Pa (4); solid lines: $Q_t = Q_a + Q_e + Q_i$; dashed lines: Q_a. Q_j, W/m²; R, μm.

For the monoenergetic ion approximation in a one-temperature (τ = 1) argon plasma, these limiting values are $y_f \simeq 5.60$, $e_e^* \simeq 1$, and $e_i^* = 3.44$ for $x_D \ll 1$ and $y_f = 4.15$, $e_e^* = 4.26$, and $e_i^* = 11.56$ for $x_D \gtrsim 1$.

The role of plasma effects in heat transfer to metallic particles of different sizes is illustrated in Fig. 3, in which we give the results of calculations for a one-temperature argon plasma with $T_{j\infty} = 10^4$ K at different pressures (p = 10^2-10^5 Pa). Under these conditions the plasma parameters vary within the following limits: degree of ionization $\eta \simeq 0.3$-0.01; Debye radius $r_D \simeq 0.6$-0.09 μm; mean free path $\ell_j > 4000$-2 μm. The contribution of the electron and ion fluxes, determined by the difference between the $Q_t = Q_a + Q_e + Q_i$ and the Q_a curves, is considerable in all cases, despite the fact that the degree of ionization may be fairly low. Plasma processes have the strongest influence on heat transfer to small particles, the electric field of which is weakly screened by the plasma.

The high efficiency of heat transfer to the particle from the plasma in comparison with a hot molecular gas is determined by the following factors: 1) the participation of electrons and ions in transfer processes and electrization of the particle in the plasma; 2) penetration into the plasma of the electric field of the charged particle, which affects the motion of electrons and ions; 3) the contribution of the energy of charged states of electrons and ions to heat transfer.

NOTATION

e, electron charge; energy; E_j^-, flux density of kinetic energy; I_i, ionization energy; J_j^-, number flux density of plasma particles; k, Boltzmann constant; ℓ_j, mean free path; m_j, mass; N_j, calculated density; p, pressure; Q_j, heat flux density; r, spatial coordinate; r_D, Debye radius; R, particle's radius; T_j, temperature; $\bar{v}$, average thermal velocity; $\delta(z)$, delta function; η, degree of ionization; φ, plasma potential; φ_f, floating potential of the particle; Φ_e, electron work function. Indices: a, molecules; e, electrons; i, ions; h, heavy plasma particles (molecules and ions); s, surface; ∞, unperturbed region of plasma far from the particle; -, direction toward the particle.

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MUTUAL THERMAL EFFECT OF DEPOSITED PARTICLES ON THE STRENGTH OF A PLASMA COATING

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An analytical expression is derived for the strength of a coating to resist separation. The probability density of incidence of the deposited particles is given as a function of position on the basis of a known experimental dependence.

Particles adhering to a substrate have roughly the shape of a disk of radius R and height h with R/h ~ 100 [1]. The adhesion strength Σ per unit base area of such a disk is greater the longer the solidification time t_0 of the disk and the higher the contact temperature T_K [1]. If the flow rate G (kg/sec) of the plasmatron is high, then some of the particles are not able to cool off prior to subsequent particles impinging onto them. Therefore, the cooling time of the deposited layer is increased, which leads to an increase in Σ. Below, we calculate Σ allowing for the mutual thermal influence of the deposited particles.

Let the deposited coating consist of N disks of particles and their projection onto the substrate lie in the deposition spot S(x, y), where x and y are the coordinates on the substrate. For the convenience of further calculations, we shall introduce the auxiliary unitary functions E_i and $\Phi(N; A_k)$, i, k = 1, 2, ..., N. Let

$$E_i = \begin{cases} 1, & \text{if} \quad (x, y) \in C_R(\xi_i, \eta_i), \\ 0, & \text{if} \quad (x, y) \notin C_R(\xi_i, \eta_i), \end{cases} \tag{1}$$

where ξ_i, η_i are coordinates on the substrate of the projection of the center of the disk $C_R(\xi_i, \eta_i)$ of radius R.

Let

$$\Phi(N; A_k) = (1 - |e_{a_1 a_2 \ldots a_N}|) \prod_{j=1}^{K} E_{a_j} \prod_{S=k+1}^{N} (1 - E_{a_S}), \tag{2}$$

where $e_{a_1 a_2 \ldots a_N}$ is the Levi-Civita symbol, the absolute value of which is equal to unity if there are identical indices and zero if all indices are different, $A_k = (a_1, a_2, \ldots, a_k)$, and a_k is the number of disks. From Eqs. (1) and (2) it follows that $\Phi(N; A_k)$ equals unity only in the vicinity of the intersections of the projections of disks $a_1, a_2, \ldots, a_k$ and equals zero over all the remaining regions S(x, y).

As an example, Fig. 1 shows a picture of intersection of the projection of three disks in the deposition spot S(x, y) for N = 3. In this case, the following functions Φ are not identically zero:

$$k = 1{:}\ \Phi(3; 1) = E_1(1 - E_2)(1 - E_3);\ \Phi(3; 2) = (1 - E_1) E_2 (1 - E_3);$$
$$\Phi(3; 3) = (1 - E_1)(1 - E_2) E_3;$$
$$k = 2{:}\ \Phi(3;\ 1, 2) = \Phi(3;\ 2, 1) = E_1 E_2 (1 - E_3);\ \Phi(3;\ 1, 3) =$$
$$= \Phi(3;\ 3, 1) = E_1(1 - E_2) E_3;\ \Phi(3;\ 2, 3) = \Phi(3;\ 3, 2) = (1 - E_1) E_2 E_3;$$
$$k = 3{:}\ \Phi(3;\ 1, 2, 3) = \Phi(3;\ 3, 2, 1) = \Phi(3;\ 2, 1, 3) =$$
$$= \Phi(3;\ 2, 3, 1) = \Phi(3;\ 1, 3, 2) = \Phi(3;\ 3, 1, 2) = E_1 E_2 E_3.$$

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