10. Ya. L. Al'pert, A. V. Gurevich, and L. P. Pitaevskii, Artificial Satellites in a Rarefied Plasma [in Russian], Moscow (1964).
11. Yu. A. Koshmarov and Yu. A. Ryzhov, Applied Dynamics of a Rarefied Gas [in Russian], Moscow (1977).
12. B. V. Alekseev and V. A. Kotel'nikov, The Probe Method of Plasma Diagnostics [in Russian], Moscow (1988).
13. G. Korn and T. Korn, Handbook of Mathematics [in Russian], Moscow (1974).

HEAT TRANSFER OF NONSPHERICAL PARTICLES IN A RAREFIED PLASMA JET. 2. DIELECTRIC PARTICLES

A. G. Gnedovets and A. A. Uglov

UDC 533.915.2

Processes of charge and energy transfer onto a dielectric particle of an arbitrary shape in a rarefied plasma current are studied.

In [1] a description of the heat transfer of a metallic (conducting) particle of an arbitrary shape in a rarefied plasma flux is presented, and it is shown that the effectiveness of heat transfer is connected with the sharing of the plasma electrons and ions in the transport processes and in the charging of a particle in the plasma up to a negative potential which is constant over its surface, and is also connected with the orientation of the particle in the jet.

In the present work the heat transfer of a nonspherical dielectric (nonconducting) particle by a jet of a rarefied highly shielded plasma is considered. A significant difference in the interaction with the plasma flux of the dielectric and metallic particles consists in the fact that the surface of a nonconducting particle is not an equipotential, such as in the case of a metallic conductor, and in equilibrium is established such a surface potential distribution that the frequencies of impact of negative electrons and positive ions are equalized at each point of the surface of the particle of the dielectric.

Determination of the velocity distribution functions of molecules, electrons, and ions of the plasma, and of the fluxes they transport, the chosen system of coordinates, and the assumed symbols all correspond to [1]. For particles of dielectrics of an arbitrary shape the formulas for the current density and heat flux density obtained in [1] for metals remain correct, with the only distinction that in the case of a nonconducting particle the floating potential ϕ_f is not constant at all points of the surface. The local value of the potential ϕ_f is determined from the condition of balance of electron and ion current densities, described below in the dimensionless form

$$j_e^- = (\mu_e/\tau_e)^{1/2} j_i^- . \tag{1}$$

In a subsonic (s < 1) jet the distribution of dimensionless potential $y_f = -e\phi_f/kT_e$ over the surface of a nonconducting particle is given by the relationship

$$y_f = y_f^0 - \pi^{1/2} s_n - (1-\pi/2) s_n^2, \tag{2}$$

where

$$y_f^0 = -(1/2)\ln(\mu_e/\tau_e);\ s_n = -s(\sin\theta_0\cos\alpha + \cos\theta_0\cos\gamma).$$

The determination of the total heat flux incident from the plasma onto the particle is reduced to the calculation of the surface integral of the density of the energy flux of the transported molecules, electrons, and ions of the plasma, taking into account the stationary potential distribution. The dimensionless heat fluxes are presented in the form:

$$\langle q_h \rangle = \langle e_h^- \rangle + \langle j_h^- \rangle \left(\frac{1}{2} w_h - \tau_s\right),$$

A. A. Baikov Institute of Metallurgy, Academy of Sciences of the Ukrainian SSR, Moscow.
Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 60, No. 5, pp. 715-719, May 1991. Original article submitted March 14, 1990.

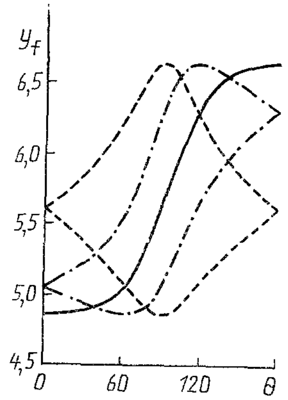

Fig. 1. The distribution of dimensionless potential $y_f = -e\phi_f/kT_e$ along the surface of an ellipsoidal dielectric particle (a/c = 2) for various angles of incidence θ_0 in an argon plasma jet (s = 0.5). The solid lines are for $\theta_0 = 0$, the dot-dash lines are for $\theta_0 = 45°$, and the dashed lines are for $\theta_0 = 90°$. The lower branches of the curves are for $\psi = 0$ and the upper are for $\psi = 180°$. θ_0 is in degrees.

$$\langle q_e \rangle = \langle e_e^- \rangle + \frac{1}{2} \langle j_e^- \rangle w_e. \tag{3}$$

In particular, for dielectric particles, namely for ellipsoids of revolution (spheroids) in a subsonic jet the constituents of the fluxes in (3) with an accuracy up to terms ~s^2 are written thus

$$\langle j_h^- \rangle = 1 + \langle s_n^2 \rangle ,$$

$$\langle j_e^- \rangle = (1 + \langle s_n^2 \rangle) \exp (- y_f^0),$$

$$\langle e_h^- \rangle = 1 + \frac{1}{2} s^2 + \frac{3}{2} \langle s_n^2 \rangle + \frac{1}{2} z_h \tau_e [y_f^0 + (y_f^0 - 1 - \pi/2) \langle s_n^2 \rangle], \tag{4}$$

$$\langle e_e^- \rangle = (1 + \langle s_n^2 \rangle) \exp (- y_f^0),$$

where $\langle s_n^2 \rangle = s^2 (\sin^2 \theta_0 \langle \cos^2\alpha \rangle + \cos^2\theta_0 \langle \cos^2\gamma \rangle); \; z_a = 0, \; z_i = 1.$

The results of numerical evaluations of the processes of charge exchange and energy exchange of the dielectric particles, namely of the ellipsoids of revolution by a rarefied flux of single-temperature ($T_g = T_h = T_e$) argon plasma are presented in Figs. 1 to 3. In order for it to be possible the comparisons are presented for these values of dimensionless parameters: $\Phi_e/kT_e = 4.5$; $I_i/kT_i = 15.8$; and $\tau_s = T_s/T_h = 0.1$.

The distribution of the local floating potential over the surface of the dielectric particle located in the plasma flux is nonequilibrium. In as much as the electron current compensates the ionic current at all points on the particle surface, the dimensionless potential $y_f = -e\phi_f/kT_e$ is a minimum as viewed from the side of the incident current, where the ion collision frequency with the surface is a maximum, and grows in the "shadow" (stern) region. A change of the orientation of the particle in the jet leads to a corresponding redistribution of the potential (Fig. 1). The local floating potential very strongly influences the intensity of the electron current. In distinction from the case of a metallic particle the distribution of transported electron heat flux density over the surface of the dielectric particle becomes substantially nonuniform (Fig. 2). Molecular, ion, and electron fluxes are maximum at the bow and minimum at the stern zone of the particle.

The intensity of heat transfer of the particle from the plasma is connected with the velocity of the incident flux, and with the shape and orientation of the particle in the jet (Fig. 3). For small angles of incidence ($\theta_0 \sim 0$) an increase of the relative velocity s of the plasma flux leads to an increase of the number of impacts with a particle of molecules,

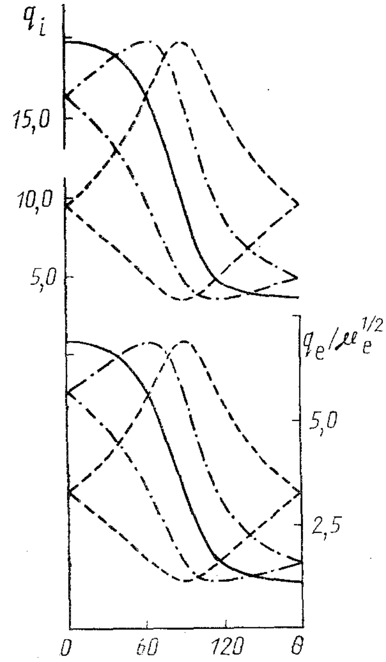

Fig. 2. The distribution of dimensionless heat flux $q_j/\mu_j^{1/2}$ of electrons (j = e), and ions (j = i) on or along the surface of an ellipsoidal dielectric particle (a/c = 2) for various angles of incidence θ_0 in an argon plasma jet (s = 0.5). The solid lines are for $\theta_0 = 0$, the dot–dash lines are for $\theta_0 = 45°$, and the dashed lines are for $\theta_0 = 90°$. The upper branches of the curves are for $\psi = 0$, the lower are for $\psi = 180°$.

ions, and electrons and of the fluxes of energy transported by them for oblate disk shaped particles (a/c > 1) and practically does not influence these parameters for prolate needle shaped particles (a/c < 1), in as much as the velocity of the flux is directed along a large part of their surface. The opposite situation occurs for large angles of incidence ($\theta_0 \sim 90$), when with the growth of the velocity ratio s the intensity of the heat transfer to prolate needle shaped particles increases more noticeably. It must be said that in spite of substantial differences in the character of the distribution of the local macroparameters, calculations lead to similar results for total heat fluxes toward particles of metals and dielectrics, which is a consequence of the averaging of the flux densities over the surface.

In a quiescent or stationary plasma (s = 0) independently of the shape of the particle and of whether its material is conducting or nonconducting, the floating potential y_f and the density of heat flux q_j are constant over the surface. In the examined example of a one temperature argon plasma $y_f = 5.60$; $\langle q_a \rangle = q_a = 1 - \tau_s = 0.90$; $\langle q_e \rangle = q_e = 3.69 \cdot 10^{-3}\,(1 + 0.5\,w_e) = 3.25\,\mu_e^{1/2}$; $\langle q_i \rangle = q_i = 3.80 + 0.5\,w_i - \tau_s = 9.35$. In a strongly rarefied plasma a decoupling of the temperatures of electrons and of ions ($T_e > T_i$) leads to an increase of the dimensionless floating potential of a particle y_f. In the case of a particle, quiescent or stationary in a two temperature argon plasma with $\tau_e = T_e/T_i = 10$, the potential of a particle becomes equal to $y_f = 6.75$, but the heat fluxes of electrons and ions are evaluated thus $\langle q_e \rangle = q_e = 1.17 \cdot 10^{-3}\,(1 + 0.5\,w_e)$; $\langle q_i \rangle = q_i = 34.8 + 0.5\,w_i - \tau_s$.

Significantly, thanks to the contribution into the heat transport of the energy of the charge state of electrons and ions, which significantly exceeds the average energy of thermal motion of a plasma particle and corresponds to the work function and ionization energy, the role of electron and ion flux in the total heat balance is found to be important even in a plasma with a quite low degree of ionization, in as much as $\langle q_i \rangle + \langle q_e \rangle/\mu_e^{1/2} \gg \langle q_a \rangle \sim 1$. In an example corresponding to that given in [2, 3], in argon in the pressure range $P_g \sim 10^2$ to 10^5 Pa plasma effects lead to a noticeable increase of the rate of particle heating, starting with temperatures $T_g \sim 6 \cdot 10^3$ to 10^4 K.

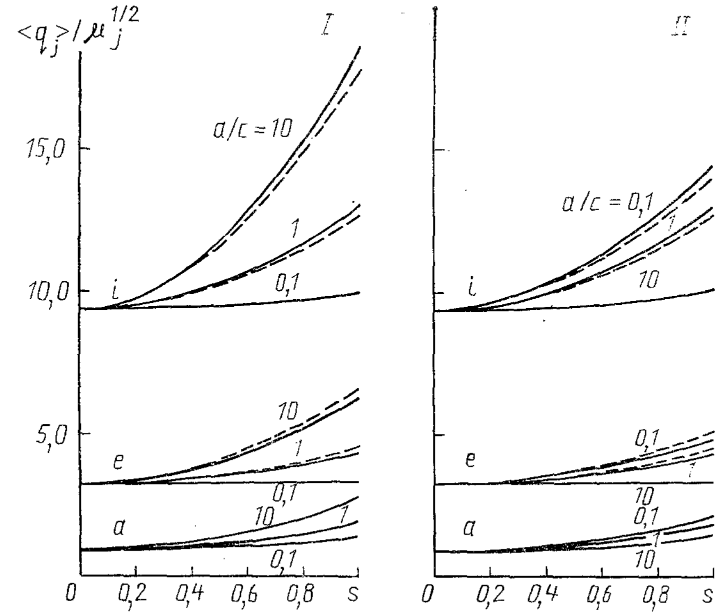

Fig. 3. The dependences of dimensionless heat flux $\langle q_j \rangle / \mu_j^{1/2}$ of molecules (a), electrons (e), and ions (1) upon the velocity ratio of an argon plasma jet for ellipsoidal metallic (solid lines) and dielectric (dashed lines) particles of various shapes (numbers at the curves are the values of a/c). Figure 3I is for $\theta_0 = 0$ and Fig. 3II is for $\theta_0 = 90°$.

The calculations presented in this work show that for modelling of plasma heating of particles of arbitrary shape it is necessary to consider their orientation in the jet. The forces acting on the particle and determining the history of its motion are due to the transfer of momentum by heavy components of the plasma, namely by molecules and ions [4, 5]. In a strongly screened plasma the description of this process for molecules and ions is the same. The motion of nonspherical bodies in rarefied molecular fluxes was considered earlier in [6-8].

NOTATION

a, b, c are the semimajor axes of the ellipsoid; e is the electron charge; I_i is the ionization energy; $J_j^{\pm}$, $E_j^{\pm}$, Q_q are the densities of the currents or fluxes of the number of plasma particles, kinetic energy, and heat; $J_j^0 = N_j(kT_j/2\pi m_j)^{1/2}$, $E_j^0 = N_j kT_j(2kT_j/\pi m_j)^{1/2}$ are the densities of the fluxes of particles of the plasma and of kinetic energy, calculated for noncharged stationary particles; k is Boltzmann's constant; m_j is the mass; N_j is the number density; P_j is the pressure; S_p is the surface area of the particle; T_j is the temperature; V is the velocity of the plasma flux relative to a particle; $W_a = 0$, $W_e = \Phi_e$, $W_i = I_i - \Phi_e$ are the energy of the charge state; r, θ, ψ are the spherical coordinates; cos α, cos β, cos γ are the direction cosines; θ_0 is the angle of incidence; ϕ is the potential; Φ_e is the electron work function. The dimensionless quantities $j_j^{\pm} = J_j^{\pm}/J_j^0$; $e_j^{\pm} = E_j^{\pm}/E_j^0$; $q_j = Q_j/E_j^0$; $s = V/(2kT_h/m_h)^{1/2}$; $w_j = W_j/kT_j$; $y_f = -e\varphi_f/kT_e$; $z_a = 0$, $z_i = 1$, $z_e = -1$; $\mu_j = m_j/m_h$; $\tau_e = T_e/T_h$; $\tau_s = T_s/T_h$; ⟨ ⟩ signifies averaging over velocity, for example: $\langle q_j \rangle = (1/S_p)\int q_j \, dS_p$. The indices have the following meaning: a is for molecules (atoms), e is for electrons, i is for ions, h is for heavy plasma particles (molecules and ions); g is plasma (gas); n is the normal component; p is for particle; s is for surface; +(−) are the directions away from (from the viewpoint of) a particle.

LITERATURE CITED

1. A. G. Gnedovets and A. A. Uglov, Inzh. Fiz. Zh., 60, No. 5, 709-715 (1991).
2. X. Chen and P. He, "Plasma chemistry and plasma processing," 6, No. 4, 313-333 (1986).
3. A. G. Gnedovets, Inzh.-Fiz. Zh., 58, No. 1, p. 95 (1990).

4. A. A. Uglov, A. G. Gnedovets, and Yu. N. Lokhov, Teplofiz. Vys. Temp., 20, No. 4, 621-626 (1982).
5. X. Chen and X-g. Chen, "Plasma chemistry and plasma processing," 9, No. 3, 387-408 (1989).
6. Yu. A. Koshmarov and Yu. A. Ryzhov, Applied Dynamics of a Rarefied Gas [in Russian], Moscow (1977).
7. H. Rohatschek and W. Zulehner, J. Colloid Interface Sci., 119, No. 2, 378-382 (1987).
8. D. Besnard and F. H. Harlow, Int. J. Multiphase Flow, 12, No. 6, 891-912 (1986).

THEORY OF RANDOM MOTION OF PARTICLES IN A SUSPENSION

A. N. Latkin

UDC 532.545

We estimate the self-diffusion coefficient of particles in a moving suspension, taking into account pseudoturbulent and Brownian fluctuations.

Heat and mass transport in dispersed systems depend, to a large degree, on the random motion of the particles, which is caused by different physical factors. For quasilaminar motion fluctuations result from ordinary Brownian motion and from concentration fluctuations of the particles produced by the flow of the continuous phase (so-called pseudoturbulent motion). If the particles are sufficiently small, the only significant contribution to their random motion is isotropic Brownian motion, which depends on the concentration of the dispersed phase. Hence diffusion processes in suspensions are quite different from self-diffusion of a single particle in a pure liquid. Brownian motion is described in [1] for low concentrations. The results of [1] are generalized in [2] to higher concentrations. As the particle radius increases, pseudoturbulent motion begins to play an important role. Pseudoturbulent motion was considered in [3], neglecting Brownian fluctuations. From the results of [3] one can compute the mean square velocity fluctuation of the particles and the self-diffusion coefficients of the medium and the dispersed particles. However, because of nonlinear collective interactions in dispersions, Brownian motion (which smoothes out concentration fluctuations) can be important in diffusion, even when the amplitude of Brownian motion is relatively small. A simple superposition of Brownian and pseudoturbulent motion is not correct in concentrated suspensions because of the nonlinearity of the processes. In the present paper pseudoturbulent diffusion is considered for the same assumptions used in [3], but with the effect of the Brownian motion of the particles taken into account.

Because of the anisotropy of pseudoturbulence, one must consider the self-diffusion tensor. The principal components of this tensor can be represented in the form [2]

$$D_{11} = D_{11}^{(p)} + D^{(b)},\ D_{22} = D_{22}^{(p)} + D^{(b)}, \tag{1}$$

where the superscripts (p) and (b) refer to pseudoturbulent and Brownian motion, respectively. Here the first Cartesian coordinate is chosen to lie along the average relative velocity u of the phases of the suspension. Using the theory of [3], the following relations for the principal self-diffusion coefficients were obtained in [2]:

$$D_{11}^{(p)} = \frac{(au)^2}{D_{11}^{(p)} - D_{22}^{(p)}} S(\rho)\,[1 - z)^2 I_0 + 2z(1 - z) I_2 + z^2 I_4],$$
$$D_{22}^{(p)} = \frac{(au)^2}{2\,(D_{11}^{(p)} - D_{22}^{(p)})} z^2 S(\rho)\,[I_2 - I_4], \tag{2}$$
$$S(\rho) = 3\left[\frac{2}{9\pi}\right]^{2/3} \rho^{4/3} \left(1 - \frac{\rho}{\rho_*}\right)\left[\frac{d \ln M(\rho)}{d\rho}\right]^2,$$

A. S. Gorkii Urals State University, Sverdlovsk. Translated from Inzhenerno-fizicheskii Zhurnal, Vol. 60, No. 5, pp. 720-724, May, 1991. Original article submitted November 27, 1989.