HEAT TRANSFER OF NONSPHERICAL PARTICLES IN A RAREFIED PLASMA JET. 1. METAL PARTICLES

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

During modelling of processes of plasma processing in dispersed particles of materials the generally accepted approximation seems to be that in which the particles are regarded as spherical and the plasma is regarded as a hot molecular gas [1, 2]. The particles of the processable powder, however, may have an irregular shape [3], but for quite high temperatures of the plasma, corresponding to an appreciable ionization of the gas, effects begin to appear which are connected with participation of the charges, electrons and ions, in transport processes and with charging of the particles [4-9].

The present work is devoted to the description of the kinetics of heat transfer of convex nonspherical metallic (conducting) particles with a jet of a tenuous low temperature plasma. For calculation of the heat flux the methods of molecular gas dynamics [10-12] are applied, during which the behavior of molecules, electrons, and ions are studied separatedly, which allows one to establish the contribution each of these plasma components makes to the total heat balance. We consider a plasma which is lightly filled with powder ($N_n^{-1/3} \gg \bar{a}$), which is also in a free molecular ($\ell \gg \bar{a}$) and highly shielded ($r_D \ll \bar{a}$) regime, that is, we use the approximation of an isolated particle with a thin layer of plasma surrounding it. It is assumed that the temperature of a particle does not exceed the melting point, but the level of ionization and the concentration of the charge carriers $N_e = N_i$ in the plasma is quite high, therefore thermoemission of electrons from the surface of the particles is not considered. The enumerated restrictions allow one to perform an analytic description of the interaction of particles with a plasma flux, and they occur in a wide range of parameters of the processes of plasma processing of materials. For example, at a temperature of an argon plasma $T_g \sim 10^4$ K in the pressure range $P_g \sim 10^2$-10^5 Pa the plasma characteristics are changed over the following ranges: $\eta \sim 2.5 \cdot 10^{-1} - 8.5 \cdot 10^{-3}$; $\ell \sim 4 \cdot 10^{-3} - 2 \cdot 10^{-6}$ m, $r_D \sim 5 \cdot 10^{-7} - 9 \cdot 10^{-8}$ m. Therefore the results obtained in the present work are applied for the description of heat transfer from a jet of low temperature plasma at reduced pressure with particles of micron size.

A particle in a plasma experiences collisions with molecules, electrons, and ions, as a result of which there occurs a transfer of momentum, energy, and charge. The plasma electrons recombine on the surface and are scattered by the surface of the particles in the form of neutral molecules. As a result of substantial difference in the average thermal velocities of electrons and of ions of the plasma ($\bar{v}_e/\bar{v}_i \sim (m_i/m_e)^{1/2} \gg 1$) a particle becomes charged, namely it acquires an excess negative charge (potential), and a local electric field forms near it which retards the electrons and accelerates the ions. The time of accumulation of the charge proves to be extremely small in comparison with the characteristic time of heating of the particles in the plasma [4-7], therefore heat transfer takes place in a regime which is quasi-stationary with respect to the potential. Considering that the surface of a metallic particle is an equipotential, the quantity of the equilibrium (floating) potential ϕ_f of the particle is determined from the condition of equality of the accumulated total flux of electrons and ions. Such is a qualitative description of the process.

The chosen coordinate system is presented in Fig. 1.

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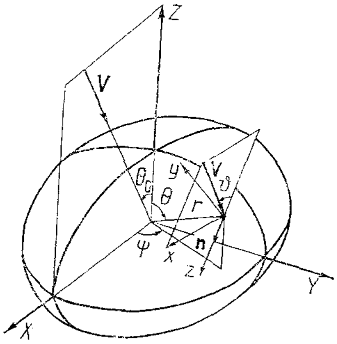

Fig. 1. The coordinate system.

For strong Debye shielding, the electric field of a particle practically does not penetrate into the plasma, and the velocity distribution functions of the molecules, electrons, and ions driven onto the side of a given point of the surface of the particle on the outer boundary of a thin layer of space charge are describable thus:

$$f_j^- = N_j\left(\frac{m_j}{2\pi kT_j}\right)^{3/2}\exp\left\{-\frac{m_j\left[(v_x+V\sin\vartheta)^2+v_y^2+(v_z-V\cos\vartheta)^2\right]}{2kT_j}\right\},\quad v_z\geqslant 0;\ j=a,\ e,\ i. \tag{1}$$

The velocity distribution functions of the diffusely reflected by the surface heavy particles of the plasma (molecules and neutralized ions) are

$$f_h^+ = N_h^+\left(\frac{m_h}{2\pi kT_s}\right)^{3/2}\exp\left[-\frac{m_h(v_x^2+v_y^2+v_z^2)}{2kT_s}\right],\quad v_z<0;\ h=a,\ i, \tag{2}$$

where the densities N_h^+ are determined from the condition that molecules do not accumulate on the surface: $J_h^- + J_h^+ = 0$. For a "cold" nonemitting particle $f_e^+ = 0$. Corresponding flux densities of plasma particles $J_j^\pm$ and of the kinetic energy $E_j^\pm$ transported by them is evaluated in the following way:

$$J_j^- = \int_{-\infty}^{\infty}dv_x\int_{-\infty}^{\infty}dv_y\int_{v_{jm}}^{\infty}v_z f_j^- dv_z,$$

$$J_h^+ = \int_{-\infty}^{\infty}dv_x\int_{-\infty}^{\infty}dv_y\int_{-\infty}^{0}v_z f_h^+ dv_z, \tag{3}$$

$$E_j^- = \int_{-\infty}^{\infty}dv_x\int_{-\infty}^{\infty}dv_y\int_{v_{jm}}^{\infty}v_z\left[\frac{1}{2}m_j(v_x^2+v_y^2+v_z^2)-z_je\varphi_f\right]f_j^- dv_z,$$

$$E_h^+ = \int_{-\infty}^{\infty}dv_x\int_{-\infty}^{\infty}dv_y\int_{-\infty}^{0}v_z\frac{1}{2}m_h(v_x^2+v_y^2+v_z^2)f_h^+ dv_z.$$

Here $z_a = 0$, $z_i = 1$, $z_e = -1$, $v_{am} = v_{im} = 0$, $v_{em} = (-2e\phi_f/m_e)^{1/2}$ that is, it is considered that upon passing through the thin layer of space charge the ions additionally accumulate and the electrons lose energy $-e\phi_f$, in which case the surface of the particle may acquire merely electrons with an energy sufficient for overcoming the potential barrier.

The density of the total heat flux Q_j incident onto the particle from the plasma, apart from the transmitted or transfered kinetic energy, likewise includes the separate part due to collisions with the surface of the charge state energy of the electrons and ions:

$$Q_j = E_j^- + E_j^+ + J_j^- W_j, \tag{4}$$

where $W_a = 0$, $W_e = \Phi_e$, $W_i = I_i - \Phi_e$.

The expressions for the flux density may be written in the form

$$J_j^\pm = J_j^0\, j_j^\pm,\quad E_j^\pm = E_j^0\, e_j^\pm,\quad Q_j = E_j^0\, q_j, \tag{5}$$

where the fluxes J_j^0 and E_j^0 correspond to uncharged particles in the stationary plasma

$$J_j^0 = N_j(kT_j/2\pi m_j)^{1/2},\quad E_j^0 = N_jkT_j(2kT_j/\pi m_j)^{1/2},$$

and the formulas for the dimensionless current densities $j_j^\pm$, $e_j^\pm$, q_j are written thus

$$j_j^- = \exp\left[-(c_{jm} - s_{jn})^2\right] + \pi^{1/2} s_{jn} \operatorname{erfc}(c_{jm} - s_{jn}),$$

$$e_j^- = \left[1 + \frac{1}{2}(s_j^2 + c_{jm}^2 + c_{jm}s_{jn})\right] \exp\left[-(c_{jm} - s_{jn})^2\right] + \frac{1}{2}\pi^{1/2} s_{jn}\left(\frac{5}{2} + s_j^2\right) \operatorname{erfc}(c_{jm} - s_{jn}) + \frac{1}{2} z_j j_j^- \tau_e y_f,$$

$$j_h^+ = -j_h^-,\ e_h^+ = j_h^+ \tau_s,\ q_h = e_h^- + j_h^-\left(\frac{1}{2} w_h - \tau_s\right), \tag{6}$$

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

Here $\tau_e = T_e/T_h$, $\tau_s = T_s/T_h$, $y_f = -e\varphi_f/kT_e$, $w_j = W_j/kT_j$, $s_j = V/(2kT_j/m_j)^{1/2}$, $s_{jn} = s_j \cos\vartheta$, $c_{jm} = v_{jm}/(2kT_j/m_j)^{1/2}$, $c_{am} = c_{im} = 0$, $c_{em} = y_f^{1/2}$. The parameter $\tau_e = T_e/T_h$ we will introduce for the purpose of keeping track of the fact that the plasma is of reduced pressure and a decoupling of the electron temperature T_e from the temperature of heavy molecule and ions T_h is possible.

The projection of the velocity $V = (-V \sin\theta_0,\ 0,\ -V\cos\theta_0)$ of the plasma flux onto the inward normal $n = \{\cos\alpha,\ \cos\beta,\ \cos\gamma\}$ toward the surface of a particle is $V_n = Vn$, therefore $s_{jn} = -s_j(\sin\theta_0 \cos\alpha + \cos\theta_0 \cos\gamma)$.

In the case of subsonic jets ($s_h < 1$) the formulas for the current densities one may simplify, using the relationships

$$j_h^- = 1 + \pi^{1/2} s_n + s_n^2,\ j_e^- = \exp(-y_f),\ e_e^- = \exp(-y_f), \tag{7}$$

$$e_h^- = 1 + \frac{5}{4}\pi^{1/2} s_n + \frac{1}{2}s^2 + \frac{3}{2}s_n^2 + \frac{1}{2} z_h j_h^- \tau_e y_f.$$

Here we introduce the symbols $s = s_h$, $s_n = s_{hn}$, and consider that $s_e \ll s_h \equiv s$.

The total currents and heat fluxes transmitted from the plasma to the particle is found via evaluation of integrals of the corresponding flux densities (3)-(7) over the surface of the particle and by analogy with (5) they may be represented in the form:

$$\int J_j^{\pm} dS_p = S_p J_j^0 \langle j_j^{\pm} \rangle,$$
$$\int E_j^{\pm} dS_p = S_p E_j^0 \langle e_j^{\pm} \rangle, \tag{8}$$
$$\int Q_j dS_p = S_p E_j^0 \langle q_j \rangle.$$

The formulas for the evaluation of the dimensionless total heat flux take the form:

$$\langle q_h \rangle = \langle e_h^- \rangle + \langle j_h^- \rangle \left(\frac{1}{2} w_h - \tau_s\right), \tag{9}$$

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

Here it is assumed that a particle is a thermal point ($Bi \ll 1$; $\tau_s = \mathrm{const}$).

Entering into the expression for the currents is the potential of the metallic particle ϕ_f which is constant on its entire surface and is determined from the condition of equality of the total currents carried by electrons and ions as the solution to the equation

$$\langle j_e^- \rangle = (\mu_e/\tau_e)^{1/2} \langle j_i^- \rangle, \tag{10}$$

where $\mu_j = m_j/m_h$.

The evaluation of the total current and energy flux for particles of arbitrary shape may be performed by a numerical integration. Simple analytic expressions are obtained for subsonic ($s < 1$) jets and for particles, the form of which one may approximate using ellipsoids of revolution (spheroids) $X = a \sin\theta \cos\psi$, $Y = a \sin\theta \sin\psi$, $Z = s \cos\theta$ with semimajor axes $a = b$ and c. In this case the dimensionless currents or fluxes, with an accuracy to terms $\sim s^2$, are represented thus:

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

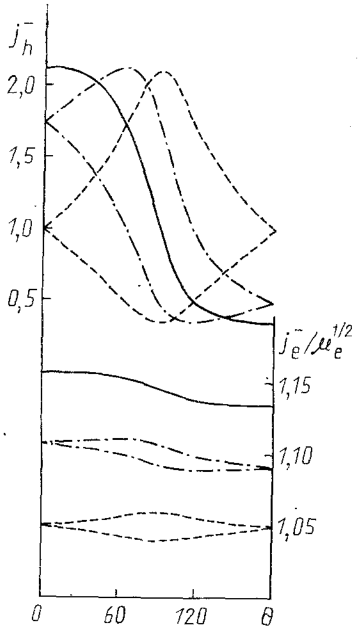

Fig. 2

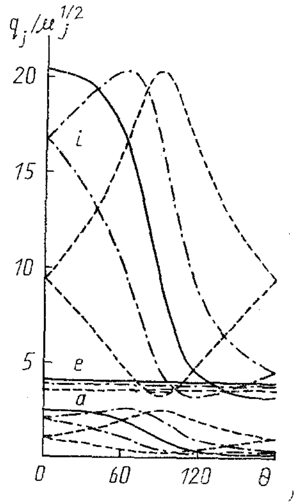

Fig. 3

Fig. 2. The distribution of the dimensionless current $j_j^-/\mu_j^{1/2}$ of heavy plasma particles (molecules and ions, j = h = a, i) and electrons (j = e) across the surface of an ellipsoidal metallic particle (a/c = 2) for various angles of incidence of an argon plasma jet (s = 0.5). The solid lines are for $\theta_0 = 0$, dots and dashes are for $\theta_0 = 45°$, and the dotted lines are for $\theta_0 = 90°$. The upper branches of the curves are for $\psi = 0$ and the lower are for $\psi = 180°$. θ is in degrees.

Fig. 3. The distribution of dimensionless heat flux $q_j/\mu_j^{1/2}$ of molecules (a), electrons (e), and ions (i) upon the surface of an ellipsoidal metallic 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 $\psi = 180°$.

$$\langle e_h^- \rangle = 1 + \frac{1}{2} s^2 + \frac{3}{2} \langle s_n^2 \rangle + \frac{1}{2} z_h \tau_e [y_f^0 + (y_f^0 - 1) \langle s_n^2 \rangle], \tag{11}$$

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

Here

$$y_f = y_f^0 - \langle s_n^2 \rangle, \quad y_f^0 = -(1/2) \ln (\mu_e/\tau_e),$$

$$\langle s_n^2 \rangle = s^2 (\sin^2\theta_0 \langle \cos^2\alpha \rangle + \cos^2\theta_0 \langle \cos^2\gamma \rangle),$$

$$\langle \cos^2\alpha \rangle = (1/S_p) \int \cos^2\alpha dS_p, \quad \langle \cos^2\gamma \rangle = (1/S_p) \int \cos^2\gamma dS_p.$$

Expressions for the direction cosines of an ellipsoid are given, for example, in [13].

The surface integrals entering into (11) are evaluated in terms of elementary functions, however the corresponding formulas are somewhat inconvenient and are not given here. Simple relationships are accurate for the following special cases:

$$\int \cos^2\alpha dS_p = \pi^2 ac \left(\frac{1}{2} - \frac{1}{4} \varepsilon^2 \right),$$

$$\int \cos^2\gamma dS_p = \pi^2 ac\varepsilon^2 \left(1 - \frac{4}{\pi}\varepsilon\right),$$

$$S_p = \pi^2 ac \left(1 + \frac{1}{2}\varepsilon^2\right)$$

for prolate spheroid (needle-shaped particles), $\varepsilon = a/c \ll 1$;

$$\int \cos^2 \alpha dS_p = 2\pi a^2\varepsilon^2 \left[\ln\left(\frac{2}{\varepsilon}\right) - \frac{1}{2}\right],$$

$$\int \cos^2\gamma dS_p = 2\pi a^2 \left[1 - \varepsilon^2 \ln\left(\frac{2}{\varepsilon}\right)\right],$$

$$S_p = 2\pi a^2 \left[1 + \varepsilon^2 \ln\left(\frac{2}{\varepsilon}\right)\right]$$

for oblate spheroid (disk-shaped particle), $\varepsilon = c/a \ll 1$;

$$\int \cos^2\alpha dS_p = \frac{4}{3}\pi a^2,$$

$$\int \cos^2\gamma dS_p = \frac{4}{3}\pi a^2,$$

$$S_p = 4\pi a^2$$

and for a sphere, $a = b = c$.

The results of a numerical modelling of the heat transfer to an ellipsoidal metallic particle (with semimajor axes $a = b$ and c) from a jet of a single-temperature ($T_g = T_h = T_e$) argon plasma are presented in Figs. 2 to 4. The calculations were conducted with the following values of the dimensionless parameters: $s = V/(2kT_h/m_h)^{1/2} = 0.5$, $\Phi_e/kT_e = 4.5$, $I_i/kT_i = 15.8$, $\tau_s = T_s/T_h = 0.1$. These conditions correspond to heat exchange of the metal particles with a temperature $T_s \sim 10^3$ K with a plasma with a temperature $T_g \sim 10^4$ K and a velocity of the relative motion $V \sim 10^3$ m/sec.

The equilibrium (floating) potential of a particle is connected with the rates of transfer onto it of electron and ion charges. The distribution of frequencies of impact of heavy ions over the surface of a particle and the total current of the charge transported by them depends upon the shape of the particle and its orientation in the jet. The collision frequency of light moving electrons is practically constant over all the surface of the parti-

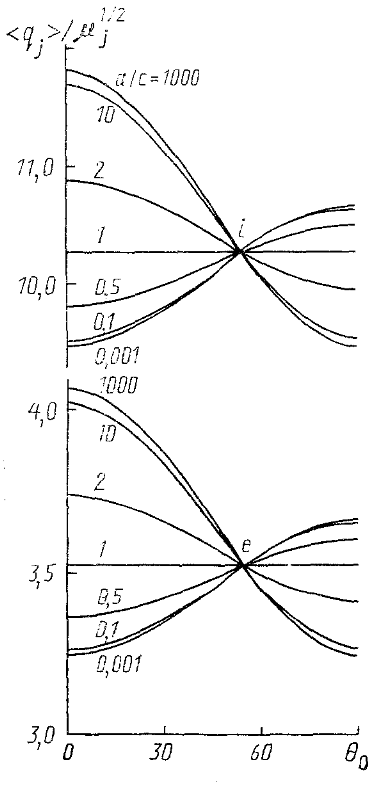

Fig. 4. The dependence of dimensionless heat flux $\langle q_j \rangle/\mu_j^{1/2}$ of electrons (e) and ions (i) upon the angle of incidence θ_0 for ellipsoidal metallic particles of various shapes (the numbers at the curves are the values are the values of a/c) in an argon plasma jet (s = 0.5).

cle (Fig. 2). Upon the orientation of the particle depends merely the intensity of the electron current, in as much as the negative charge transferred by them must compensate the current of positive ions accumulated on the entire surface of the particle. In the presented case of an oblate spheroid ($a/c = 2$) for a variation of the angle of incidence θ_0 from 0 to 90° the effective cross section for the capture of ions by the particle decreases, which leads to a weak increase of the dimensionless particle potential $y_f = -e\phi_f/kT_e$ from 5.47 to 5.53.

The character of the heat transfer from the plasma flux to the particle is determined by the characteristics of the transfer of molecules, electrons, and ions to its surface. Because of "shadow" effects the distribution of densities of heat flux transported by the heavy components of the plasma, namely molecules and ions, is nonuniform, and there appears a significant difference in the heat liberation in the bow (exposed to or turned to the incident plasma flux) and the stern region of the particle (Fig. 3). The intensity of the electron heat transfer is invariant over all the surface and is connected mainly with the value of the floating potential, which is determined by the frequency of collision of electrons and the particle.

The influence of the shape of the metallic particle and its orientation in the plasma jet on the intensity of the heat transfer is shown in Fig. 4. For an oblate ellipsoid (disk shaped particle, $a/c > 1$) an increase of the angle of incidence θ_0 leads to a decrease of its effective cross section of capture of plasma particles, and the thermal fluxes decrease. The reverse picture is observed for prolate ellipsoids (needle shaped particles, $a/c < 1$): an increase of angle θ_0 corresponds to an increase of its effective cross section and of the intensity of heat transfer.

NOTATION

$\bar{a}$ is the characteristic dimension of a particle; a, b, c are the semimajor axes of the ellipsoid; e is the electron charge; $f_j^{\pm}$ are the velocity distribution functions; I_i is the ionization energy; $J_j^{\pm}$, $E_j^{\pm}$, Q_j are the densities of the fluxes of the number of plasma particles, kinetic energy, and heat; k is Boltzmann's constant; ℓ is the free path length; m_j is the mass; n is the inward normal to the surface; N_j is the number density; P_j is the pressure; r_D is the Debye radius; s is the velocity ratio; S_p is the surface area of the particle; T_j is the temperature; v is the velocity of the plasma particles; V is the velocity of the plasma flux relative to a particle; x, y, z is the Cartesian system of coordinates connected with an arbitrary point on the surface of a particle; X, Y, Z is the Cartesian coordinate system connected with the center of mass of a particle; r, θ, ψ are spherical coordinates; cos α, cos β, cos γ are the direction cosines; η is the level of ionization; ϑ is the angle between the vectors n and V; θ_0 is the angle between the axis Z and the vector V (the angle of incidence); ϕ is the potential; Φ_e is the electron work function. The indices have the following meaning: a is for molecules, e is for electrons, i is for ions, h is for heavy plasma particles (molecules and ions); g is plasma (gas); m is the minimum value; n is the projection onto the inward normal; p is for particle; s is for surface; +(−) are the directions from (from the viewpoint of) a particle.

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

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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:

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

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