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INTERACTION BETWEEN A SPHERICAL PARTICLE AND ATMOSPHERIC PRESSURE CURRENTLESS ARGON PLASMA

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The interaction between a spherical particle of radius $10^{-5}-10^{-3}$ m and atmospheric pressure currentless argon plasma was studied numerically within the hydrodynamic approach. The nonlinear problem was solved taking into account the temperature dependencies of transport and kinetic coefficients. A two-temperature model, which considers plasma thermal and ionization non-equilibrium near the particle, was used. The boundary condition for electron heat flux on the outer boundary of the space charge sheath is discussed in detail. The spatial distributions of plasma characteristics, such as temperature and number density, near the particle were determined and analyzed. The heat flux from plasma to the particle was calculated over a wide temperature range of singly ionized argon plasma.

Keywords: *Atmospheric pressure argon plasma; Currentless argon plasma; Plasma numerical modeling; Spherical particle in plasma; Plasma-particle interaction*

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1. INTRODUCTION

The interaction between fine condensed matter particles and plasma has been of interest in plasma physics for many years. Low-pressure plasma containing fine particles is commonly referred to as dusty or complex plasma [1, 2, 3]. The study of dusty plasma often focuses on particle charge, potential, and interactions between particles [4, 5, 6, 7], as well as the propagation of various types of waves and solitons [8, 9, 10, 11].

Atmospheric-pressure thermal plasma [12, 13] containing fine metal particles occurs in many technical plasma processes, such as plasma spraying, plasma transferred arc (PTA) surfacing [14, 15, 16], spheroidization of metal powders [17, 18], and gas metal arc welding (GMAW) [19]. For the research and development of these processes, it is important to understand both the thermal effect of plasma on the particles and the influence of particles on plasma characteristics.

In the present study, we consider currentless plasma, which corresponds to the conditions of plasma spraying [14, 15], where thermal plasma is used to heat and melt dispersed material before depositing it on a surface. However, the obtained results may also be useful for current-carrying plasma, which is used, for example in PTA surfacing. Our recent study showed that for particles with a radius of up to $\sim 10^{-3}$ m, the thermal effect of plasma on the particle does not significantly depend on the plasma current but rather on its temperature, which is determined by the current.

In Refs. [20, 21], the heat flux from atmospheric-pressure plasma to a particle was studied, taking into account the thermal and ionization nonequilibrium of the plasma, the violation of quasineutrality near the particle surface, and rarefaction effects over a wide range of Knudsen numbers. However, the inverse effect of the particle on the characteristics of the surrounding plasma was not considered in these studies. Such effects were examined in our previous works [22, 23, 24].

In the present study, we used a modified boundary condition for the electron heat flux and accounted for an additional mechanism of ion heat transfer to the particle. Additionally, particles with a radius of $a = 10^{-3}$ m were considered, corresponding to the droplet size of electrode metal in GMA welding. The influence of particles of this size on plasma characteristics is expected to be more pronounced.

2. MODEL AND BASIC EQUATIONS

Atmospheric-pressure currentless argon plasma with a temperature $T_0 = 6-18$ kK is considered. In this temperature range, the density of multiply charged argon ions is much lower than that of singly charged ions. We study the interaction of such a plasma with a single stationary spherical particle (either metal or dielectric) of radius $a = 10^{-5}-10^{-3}$ m placed in it. The particle surface adsorbs electrons (e) and ions (i) from plasma, which then recombine on the surface and desorb as argon atoms (a). It means that there are electron, ion and atom fluxes $\mathbf{J}_\alpha = n_\alpha \mathbf{v}_\alpha$ near the particle (n_α is the number density and $\mathbf{v}_\alpha$ is the velocity). Since the mobility of electrons is much higher than that of ions, the initially neutral particle gains a negative electric charge, which increases until the electron and ion fluxes become equal $\mathbf{J}_i = \mathbf{J}_e$ in the stationary state. Also, we consider plasma at rest relative to the particle, i.e. the mass-average plasma velocity is zero $m_e\mathbf{J}_e + m_i\mathbf{J}_i +$

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$m_a \mathbf{J}_a = 0$ that gives $\mathbf{J}_a = -\mathbf{J}_i$. Thus, only one flux density is independent, and we will consider the ion flux density, which satisfies the following continuity equation

$$\nabla \mathbf{J}_i = \omega_i = k_i n_e n_a - k_r n_e^2 n_i. \tag{1}$$

Here ω_i is the production rate of ions due to ionization-recombination reactions, obviously $\omega_i = \omega_e = -\omega_a$; k_i and k_r are the ionization and recombination rate constants, respectively.

Desorbed atoms have a temperature equal to the temperature of the particle surface $T_s \ll T_0$. Due to efficient energy transfer between ions and atoms (heavy particles h) they share the same temperature, T_h. Since energy transfer between heavy particles and electrons is slow, T_h differs from the electron temperature T_e i.e., the plasma is not in thermal equilibrium nor, consequently, in ionization equilibrium near the particle. A spatial distribution of plasma particle density and temperature is established around the spherical particle.

The momentum equations for plasma particles have the form [25]:

$$-\nabla p_\alpha - n_\alpha Z_\alpha e \nabla \varphi + \sum_\beta \nu_{\alpha\beta} \mu_{\alpha\beta} n_\alpha n_\beta (\mathbf{v}_\beta - \mathbf{v}_\alpha) - C_\alpha^{(e)} n_\alpha k \nabla T_e = 0. \tag{2}$$

Here $\alpha, \beta = e, i, a$; $p_\alpha = n_\alpha k T_\alpha$ is the partial pressure of α plasma component, where k is the Boltzmann constant; T_α is the temperature; Z_α is the particle charge number ($Z_e = -1$, $Z_i = 1$, and $Z_a = 0$); e is the elementary charge; φ is the distribution of electric potential in plasma; $\nu_{\alpha\beta}$, $\mu_{\alpha\beta} = m_\alpha m_\beta/(m_\alpha + m_\beta)$ are the momentum transfer collision rate and the reduced mass of particle species α and β, respectively, where m_α is the mass of a particle of species α. The last term in (2) is thermal diffusion force due to electron temperature gradient, where $C_\alpha^{(e)}$ are the thermal diffusion coefficients. The thermal diffusion force due to heavy particle temperature gradient can be neglected [26].

The space charge layer (sheath) is formed around the charged particle in plasma. The thickness of the sheath l_{sh} is of the order of Debye length that is $r_D \sim 10^{-7}$ m for the considered plasma parameters [22]. The considered particle radii are much greater than the sheath thickness $a \gg l_{sh}$. Thus, we study plasma outside the sheath, where it is quasineutral $n_e = n_i$.

The sum of partial pressures of all particle species is constant and equal to atmospheric pressure p_0, i.e. $n_e k T_e + n_i k T_h + n_a k T_h = const = p_0$. Taking into account that $n_e = n_i$, we obtain the expression for atom number density

$$n_a = \frac{p_0}{k T_h} - n_i \left(1 + \frac{T_e}{T_h}\right). \tag{3}$$

Equations (2) for electrons and ions ($\alpha = e, i$), taking into account that $\mathbf{J}_e = \mathbf{J}_i$, can be rewritten as

$$-k \nabla (n_i T_\alpha) - n_i Z_\alpha e \nabla \varphi - \gamma_\alpha \mathbf{J}_i - C_\alpha^{(e)} n_i k \nabla T_e = 0, \tag{4}$$

where $\gamma_e = \nu_{ea} \mu_{ea} (n_i + n_a)$ and $\gamma_i = \nu_{ia} \mu_{ia} (n_i + n_a)$.

By adding equations (4) we eliminate the term with $\nabla\varphi$ and obtain the expression for ion flux

$$\mathbf{J}_i = -\frac{k}{\gamma_e + \gamma_i} \left((T_e + T_h) \nabla n_i + n_i \nabla T_h + \tilde{C}_i^{(e)} n_i \nabla T_e \right), \tag{5}$$

where $\tilde{C}_i^{(e)} = 1 + C_e^{(e)} + C_i^{(e)}$. Substitution of Eq (5) and $n_e = n_i$ into continuity equation for ion flux density (1) gives the second order differential equation.

Substituting equation (5) into one of the equations (4) allows us to obtain the potential gradient distribution in the plasma near the particle.

$$\nabla \varphi = \frac{k}{e\,(\gamma_e + \gamma_i)\, n_i} \left[(\gamma_i T_e - \gamma_e T_h) \nabla n_i - \gamma_e n_i \nabla T_h + \left(\gamma_i + \gamma_i C_e^{(e)} - \gamma_e C_i^{(e)} \right) n_i \nabla T_e \right]. \tag{6}$$

The heavy particle temperature gradient in plasma leads to the appearance of heat flux $\mathbf{q}_h = -\lambda_h \nabla T_h$, which satisfies the following continuity equation [25]

$$\nabla \mathbf{q}_h = -e \mathbf{J}_i \nabla \varphi + \kappa_{eh} n_i k (T_e - T_h), \tag{7}$$

where λ_h is the thermal conductivity coefficient of heavy particles; κ_{eh} is the energy exchange frequency.

The heat flux for electrons [26] contains additional terms that describe energy transfer between electrons and heavy particles due to their relative drift.

$$\mathbf{q}_e = -\lambda_e \nabla T_e + k T_e n_e \left[A_i^{(e)} (\mathbf{v}_e - \mathbf{v}_i) + A_a^{(e)} (\mathbf{v}_e - \mathbf{v}_a) \right] = -\lambda_e \nabla T_e + k T_e A_a^{(e)} \mathbf{J}_i (1 + n_i/n_a), \tag{8}$$

where $A_\alpha^{(e)}$ are the kinetic coefficients. It was taken into account in (8) that $\mathbf{J}_a = -\mathbf{J}_i$, $\mathbf{J}_e = \mathbf{J}_i$ and $n_e = n_i$.

The continuity equation for electron heat flux is [25]

$$\nabla\left(\mathbf{q}_e + \frac{5}{2}kT_e\mathbf{J}_i\right) = e\mathbf{J}_i\nabla\varphi - \kappa_{eh}n_i k(T_e - T_h) - U_i\omega_e. \tag{9}$$

The first terms on the right-hand sides of Eqs. (7) and (9) describe the heat transfer between plasma particles and electric field, the second terms describe the energy exchange between electrons and heavy particles. The last term describes the power released in ionization-recombination processes ($U_i = 15.75$ eV is the argon ionization potential.)

The considered problem has a spherical symmetry, so it is one-dimensional in the spherical coordinate system placed in the center of the particle. All vector functions have only radial nonzero components that depend on single variable r. For instance, the electron flux takes the form $\mathbf{J}_i = (J_{ir}(r), 0, 0)$, where $J_i = J_{ir}$. We have three unknown functions of single variable $n_i(r)$, $T_h(r)$, and $T_e(r)$ along with three differential equations (1), (7) and (9). The system of equations should be supplemented with proper boundary conditions, which are discussed in the next section.

3. BOUNDARY CONDITIONS

As it was mentioned above, we consider quasineutral plasma, i.e. outside the sheath. The boundary conditions are set on the sheath outer boundary, which is denoted with letter S on the figure 1. The values of functions on this surface are denoted with subscript s, for instance $n_i\big|_S = n_i(a + l_{sh}) = n_{is}$.

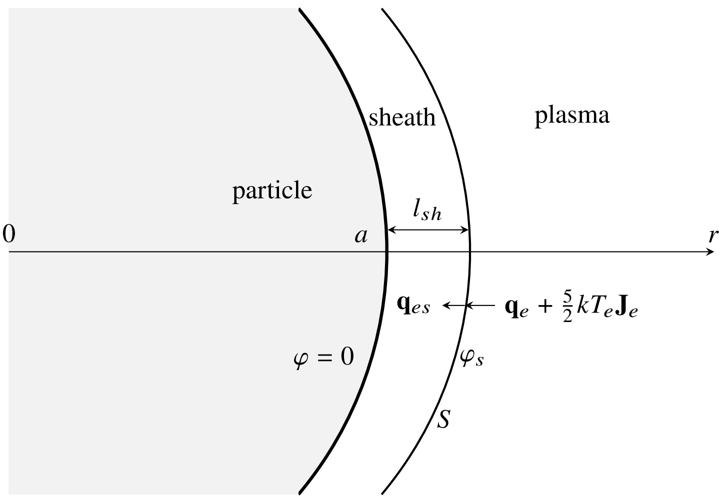

Figure 1. Scheme of the problem

The normal component of ion flux on surface S is

$$J_i(a + l_{sh}) = J_{is} = -n_{is}v_B, \tag{10}$$

where $v_B = \sqrt{k(T_{es} + T_{hs})/m_i}$ is the Bohm velocity. It has a negative sign because it is directed opposite to the r-axis. Neglecting ion collisions with atoms within the sheath and taking into account that $l_{sh} \ll a$, we can write $J_i(a + l_{sh}) = J_i(a)$.

The boundary condition for the electron flux can be derived from the electron velocity distribution function. At the sheath outer boundary, it takes the form

$$f_s(\mathbf{v}) = f_{sn}(v_n)f_{st}(\mathbf{v}_t), \tag{11}$$

where v_n is the component of velocity along the $\mathbf{e}_r$ (normal to surface), $\mathbf{v}_t$ is the component perpendicular to $\mathbf{e}_r$ (tangential to surface) and

$$f_{st}(\mathbf{v}_t) = \frac{m_e}{2\pi kT_{es}}\exp\left(-\frac{m_e v_t^2}{2kT_{es}}\right), \tag{12}$$

$$f_{sn}(v_n) = \begin{cases} 0, & v_n > v_{n0}, \\ \sqrt{\frac{m_e}{2\pi kT_{es}}}\exp\left(-\frac{m_e v_n^2}{2kT_{es}}\right), & v_n < v_{n0}. \end{cases} \tag{13}$$

where $v_{n0} = \sqrt{2e\varphi_s/m_e}$ and $\varphi_s = \varphi(a + l_{sh})$. The potential of the particle surface is considered to be zero.

The electron flux density on sheath outer boundary is

$$J_e(a+l_{sh}) = J_{es} = n_{es}\int d\mathbf{v}\, v_n f_s(\mathbf{v}) = n_{es}\int_{-\infty}^{v_{n0}} dv_n v_n f_{sn}(v_n)\int d\mathbf{v}_t f_{st}(\mathbf{v}_t) = -\frac{n_{es}\bar{v}_{es}}{4}\exp\left(-\frac{e\varphi_s}{kT_{es}}\right), \quad (14)$$

where $\bar{v}_{es} = \sqrt{8kT_{es}/\pi m}$ is the mean thermal velocity of electrons.

Equating the currents $J_{es} = J_{is}$ we obtain from Eqs. (14) and (10) expression for the sheath potential

$$\varphi_s = -\frac{kT_{es}}{e}\ln\left(\frac{4v_B}{\bar{v}_{es}}\right). \quad (15)$$

Since $v_B \ll \bar{v}_{es}$ the value of φ_s is positive in order to decrease the electron flux $n_{es}\bar{v}_{es}/4$ to the value of ion flux.

Temperature of heavy particles is equal to the temperature of the particle surface

$$T_h(a+l_{sh}) = T_s. \quad (16)$$

There is an energy flux from plasma to the particle, thus, in general, T_s is a function of time. Since the characteristic time for plasma parameter establishment is much shorter than the time for a temperature change of the particle surface [22], we can consider the temperature of the particle surface as constant and study the stationary distribution of plasma characteristics near the particle.

The boundary condition for the electron temperature is determined by the electron heat flux. The electron heat flux from the sheath outer boundary to the particle is

$$q_{es} = n_{es}\int d\mathbf{v}\, v_n\frac{m_e v^2}{2}f_s(\mathbf{v}) = n_{es}\int_{-\infty}^{v_{n0}} dv_n\int d\mathbf{v}_t v_n\frac{m_e}{2}(v_n^2+v_t^2)f_{sn}(v_n)f_{st}(\mathbf{v}_t) =$$

$$n_{es}\int_{-\infty}^{v_{n0}} dv_n f_{sn}(v_n)v_n\left(\frac{m_e v_n^2}{2}+kT_{es}\right) = J_{es}(e\varphi_s+2kT_{es}). \quad (17)$$

It should be equal to the electron heat flux from plasma to S, that gives the boundary condition

$$\left(q_e+\frac{5}{2}J_e kT_e\right)_{r=a+l_{sh}} = J_{es}(e\varphi_s+2kT_{es}). \quad (18)$$

Thus, we have three conditions on the sheath outer boundary: (10), (16), and (18). Another set of conditions is determined far away from the particle where plasma is unperturbed, i.e. it is in thermal equilibrium $T_h\big|_{r=\infty} = T_e\big|_{r=\infty} = T_0$ and ionization equilibrium. The ratio between ion n_{i0} and atom n_{a0} number densities in the state of ionization equilibrium for quasineutral plasma ($n_{i0} = n_{e0}$) is defined by the Saha equation

$$n_{i0}^2/n_{a0} = S(T_0) = 12\left(\frac{2\pi m_e kT_0}{h^2}\right)^{3/2}\exp\left(-\frac{U_i}{kT_0}\right), \quad (19)$$

which together with expression (3) for atom number density gives

$$n_{i0} = S(T_0)\left(\sqrt{1+\frac{p_0}{S(T_0)kT_0}}-1\right). \quad (20)$$

For numerous practical applications, it is important to know the heat flux from plasma to the particle. The heat flux density on the particle surface q_p consists of the several components. The electron component can be determined from the following reasoning.

The electron velocity distribution function on the particle surface ($r = a$) is

$$f_a(\mathbf{v}) = f_{an}(v_n)f_{at}(\mathbf{v}_t), \quad (21)$$

where

$$f_{at}(\mathbf{v}_t) = \frac{m_e}{2\pi kT_{ea}}\exp\left(-\frac{m_e v_t^2}{2kT_{ea}}\right), \quad (22)$$

$$f_{an}(v_n) = \begin{cases} 0, & v_n > 0, \\ \sqrt{\frac{m_e}{2\pi kT_{ea}}}\exp\left(-\frac{m_e v_n^2}{2kT_{ea}}\right), & v_n < 0. \end{cases} \quad (23)$$

The electron heat flux on the particle surface is

$$q_{ea} = n_{ea} \int d\mathbf{v}\, v_n \frac{m_e v^2}{2} f_a(\mathbf{v}) = 2J_{ea} kT_{ea}. \tag{24}$$

Since the sheath is collisionless, then $J_{ea} = J_{es} = J_{is}$ and $T_{ea} = T_{es}$. Thus electron component of the heat flux on the particle surface is given by

$$q_{pe} = -2J_{is} kT_{es}. \tag{25}$$

Since J_{is} is negative (see Eq. (10)), the minus sign was added to ensure that q_{pe} is positive.

The difference between energy fluxes (18) and (24) equals to $J_{es}e\varphi_s$ it is due to electrons energy loss in the sheath electric field. On the other hand, ions gain additional energy $-J_{is}e\varphi_s$ from electric field in the sheath. Also, on the sheath outer boundary ions have directed velocity v_B and corresponding kinetic energy $m_i v_B^2/2$. Thus, the heat flux component due to the kinetic energy of heavy particles is

$$q_{ph} = \lambda_h \nabla T_h \big|_{r=a+l_{sh}} - J_{is}\left(e\varphi_s + \frac{m_i v_B^2}{2}\right). \tag{26}$$

When an ion reaches the particle surface, it recombines and releases energy equal to the ionization potential U_i. The corresponding heat flux component is

$$q_{pi} = -J_{is} U_i. \tag{27}$$

Finally, the total heat flux on the particle surface consists of the three components

$$q_p = q_{pe} + q_{ph} + q_{pi}. \tag{28}$$

4. RESULTS AND DISCUSSION

For spatial distributions of ion number density $n_i(r)$ and temperatures $T_h(r)$ and $T_e(r)$, the system of three differential equations (1), (7), and (9) was solved numerically on the segment $[a, b]$. Since $l_{sh} \ll a$, the left boundary of the computation segment was taken equal a. The right boundary $b \gg a$ is where plasma unperturbed, i.e. $n_i(b) = n_{i0}$ and $T_h(b) = T_e(b) = T_0$. Numerical calculations were performed using the FlexPDE program (ver.7.22) in which the finite element method is realized. The transport and kinetic coefficients used in the equations can be found in the appendix of [22]. Note that there is a misprint in equation (A19) of [22] for the energy exchange frequency; the correct formula is given in equation (19) of [27]. The dependence of these coefficients on T_e, T_h, and n_i was taken into account in the calculations, meaning that a fully nonlinear problem was solved.

The temperature distribution in plasma with $T_0 = 1.4$ kK near the particle with $T_s = 1$ kK is presented in figure 2a). According to boundary condition (16) the temperature of heavy particles (dashed line) is equal T_s for $r = a$. Due to heat transfer between heavy particles and electrons, their temperature also decreases. The electron temperature on the sheath outer boundary T_{es} is considerably less then T_0, namely $T_{es} = 13070$, 11465 and 9212 K for $a = 10^{-5}$, 10^{-4}, and 10^{-3} m,

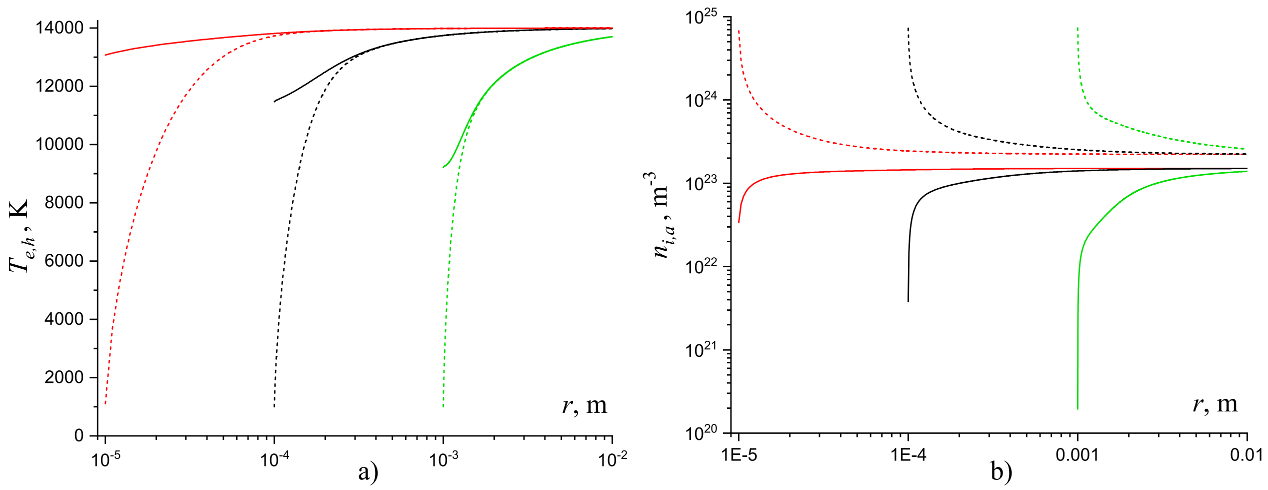

Figure 2. Spatial distributions of: a) electron temperature T_e (solid lines) and heavy particle temperature T_h (dashed lines), b) ion number density n_i (solid lines) and atom number density n_a (dashed lines), for $a = 10^{-5}$, 10^{-4}, and 10^{-3} m, $T_0 = 1.4$ kK and $T_s = 1$ kK

respectively. At some distance from the particle, plasma becomes isothermal $T_e = T_h$, however, the temperature is still less than T_0. The decrease of electron temperature near the particle leads to the decrease of plasma ionization, i.e. to the decrease of n_i. This effect is more pronounced for larger particles (see solid lines in figure 2b). The ion number density on the sheath outer boundary is equal to $n_{is} = 3.35 \times 10^{22}$, 3.74×10^{21} and 1.92×10^{20} m^{-3} for $a = 10^{-5}$, 10^{-4}, and 10^{-3} m, respectively. Since the plasma pressure is constant, the decrease of n_i is compensated by the increase of atom number density n_a, see Eq. (3). The sheath potential is higher for smaller particles $\varphi_s = 5.23$, 4.58 and 3.67 V, respectively.

Table 1. Electron temperature T_{es}, ion number density n_{is}, Bohm velocity v_B, ion flux J_{is}, and potential φ_s on the sheath outer boundary S, heat fluxes from plasma to the particle surface q_p and heat power $4\pi a^2 q_p$ for various unperturbed plasma temperatures $T_0 = 6 - 18$ kK, $a = 10^{-4}$ m, and $T_s = 1$ kK.

T_0 (kK)	T_{es} (kK)	n_{is} (m^{-3})	v_B (m/s)	J_{is} (m^{-2}s^{-1})	φ_s (V)	q_p (W/m^2)	$4\pi a^2 q_p$ (W)
6	5.920	2.34×10^{17}	1200	-2.81×10^{20}	2.35	5.04×10^{6}	0.634
8	7.770	1.46×10^{19}	1351	-1.98×10^{22}	3.09	8.68×10^{6}	1.09
10	9.300	1.89×10^{20}	1464	-2.76×10^{23}	3.71	1.55×10^{7}	1.95
12	10.500	1.11×10^{21}	1547	-1.72×10^{24}	4.19	3.16×10^{7}	3.97
14	11.470	3.74×10^{21}	1611	-6.03×10^{24}	4.58	6.40×10^{7}	8.04
16	12.250	7.64×10^{21}	1660	-1.27×10^{25}	4.90	1.05×10^{8}	13.2
18	12.980	1.12×10^{22}	1706	-1.91×10^{25}	5.19	1.43×10^{8}	18.0

The difference $T_0 - T_{es}$ grows with temperature of unperturbed plasma T_0 (see table 1). The ion number density on the sheath outer boundary n_{is} also grows with T_0 as well as the Bohm velocity. According to boundary condition (10) $J_{is} = -n_{is} v_{Bs}$, one can directly verify that this condition is satisfied. The ion flux density increases by five orders of magnitude as T_0 rises from 6 kK to 18 kK, while the sheath potential increases from 2.35 to 5.15 V.

The heat flux density and the heat power on the particle surface are presented in the last two columns in table 1 and in figure 3. For $T_0 \leq 10$ kK, the total heat flux is almost entirely provided by the kinetic energy of heavy particles q_{ph} (26). For $T_0 > 10$ kK, the heat flux due to recombination of ion on the particle surface q_{pi} becomes significant that is explained by the substantial increase of J_{is}. The electron heat flux is minor in the considered temperature range.

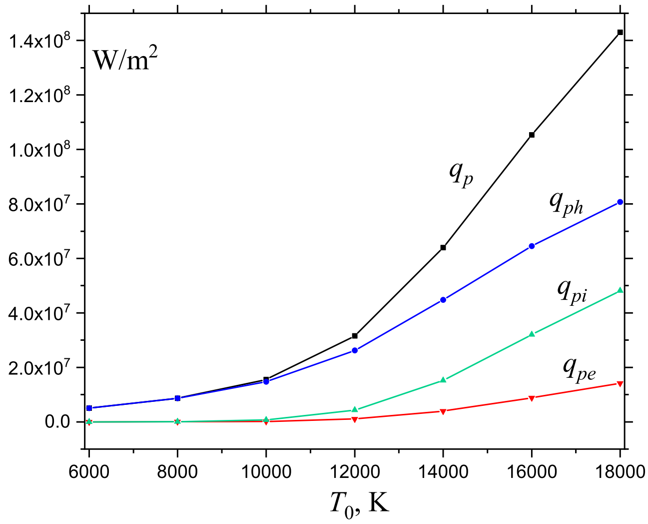

Figure 3. The heat flux on the particle surface q_p and its components q_{ph} (26), q_{pi} (27), and q_{pe} (25)

5. CONCLUSIONS

The electron heat flux at the outer boundary of the sheath, which is formed near charged spherical particle, is given by $J_{es}(2kT_{es} + e\varphi_s)$, where J_{es} is the electron flux density, T_{es} is the electron temperature, and φ_s is the sheath potential. Electrons transfer part of their energy to the electric field in the sheath and their heat flux on the particle surface becomes equal to $2J_{es}kT_{es}$ (assuming that electron flux and temperature are constant within the sheath).

The electron temperature near the particle surface is lower than the temperature of unperturbed plasma. The difference $T_0 - T_{es}$ increases with T_0 and it reaches ≈ 5 kK for $a = 10^{-4}$ m and $T_0 = 18$ kK. In contrast, for $T_0 = 6$ kK $T_{es} \approx T_0$.

The heat flux from plasma to the particle surface depends non-linearly on T_0. The increase of temperature from 6 KK to 18 kK leads to the increase of q_p almost in 30 times. The main contribution to the heat flux comes from the kinetic energy of heavy particles, while the contribution from electron kinetic energy reaches a maximum of approximately 10% at T_0=18 kK. The energy released by ions during their recombination on the particle surface becomes significant for $T_0 >$ 10 kK accounting for up to one-third of the total heat flux at T_0=18 kK.

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ВЗАЄМОДІЯ СФЕРИЧНОЇ ЧАСТИНКИ З БЕЗСТРУМОВОЮ АРГОНОВОЮ ПЛАЗМОЮ АТМОСФЕРНОГО ТИСКУ

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Чисельно вивчалася взаємодія сферичної частинки радіусом 10^{-5} – 10^{-3} м з безструмовою аргоновою плазмою атмосферного тиску в рамках гідродинамічного підходу. Нелінійна задача розв'язувалася з урахуванням температурної залежності транспортних і кінетичних коефіцієнтів. Використовувалася двотемпературна модель, яка враховує теплову та іонізаційну нерівноважність плазми поблизу частинки. Детально обговорюється гранична умова для теплового потоку електронів на зовнішній межі шару просторового заряду. Визначено та проаналізовано просторові розподіли характеристик плазми поблизу частинки, таких як температура та концентрація. Розраховано тепловий потік від плазми до частинки в широкому діапазоні температур однократно іонізованої аргонової плазми.

Ключові слова: *аргонова плазма атмосферного тиску; безструмова аргонова плазма; чисельне моделювання плазми; сферична частинка в плазмі; взаємодія плазма-частинка*