The effect of electron emission processes on micro- and nanoparticle charges in the dusty plasma for engineering applications

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Abstract

In this paper, the charge-balance, the energy-balance and the moment equations and Poisson’s equation have been used to describe the charging process for a dust particle in the undisturbed plasma taking into account the emission variety (secondary electron, electron-ion, thermal-field electron and photoelectron types) in the intermediate regime of ion motion. Such an approach was associated with the fact that the dust-particle charge specified by the parameters of the above-mentioned plasma depends heavily on electron emission from the particle surface. Collisions between ions and atoms as well as ionization also essentially affect the formation of the ion flux onto the surface of dust particles. The computational procedure we propose has allowed solving the chosen set of equations for an arbitrary relationship between the ion mean free path, the particle radius and the Debye length. The electron emission was shown to decrease the absolute value of the dust-particle charge. Moreover, the collisions with atoms lead to the ion flux deceleration onto the particle surface whereas the depth of the disturbance space of plasma increased with decreasing the ionization frequency.

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Introduction

Dusty plasma is an ionized gas containing charged particles of condensed matter. This type of plasma can be used to fabricate fundamentally new nanostructured and composite materials. The electric charge that dust particles can acquire in the discharge plasma is one of the major problems in dusty plasma physics [1]. Despite the fact that a number of works take into account the effects of collisions and of ionization of the gas atoms in calculating the ion current onto the surface of particles [2,3], no theory has been developed for describing the charging of dust particles under transient conditions that cannot be fully explained by either the drift-diffusion approximation [4] or the orbital-motion-limited approximation [5]. The rapidly evolving methods of molecular dynamics [6–8] or the particle-in-cell Monte Carlo collision method [9] prove to be too difficult for modeling real problems. Solving such problems is complicated by
the presence of various types of electron emission processes (secondary and electron-ion types, photo and thermal-field types) from the surface of dust particles.

This study considers the regime of ion migration onto the surface of the dust particle using the moment equations and Poisson’s equation. This approach makes it relatively easy to take into account the processes of electron emission from the surface of a dust particle.

The system of moment equations and Poisson’s equation

To describe the charging process of a spherical dust particle of radius \( a \) under transient conditions, we shall use the particle balance equations, the equations of motion and Poisson’s equation [10] in spherical coordinates:

\[
\frac{1}{r^2} \frac{d}{dr} r^2 n_i u_{irt} = n_e z_e, \quad n_e u_{ert} = n_i u_{irt},
\]

\[
T_e \frac{d n_i}{d s} = -en_e E_r - m_e n_i u_{ert} v_{ea},
\]

\[
m_i n_i u_{irt} \frac{d u_{irt}}{dr} + T_i \frac{d n_i}{d r} = en_i E_r - m_i v_{ia} n_i u_{irt} - m_i u_{irt} n_e z_e,
\]

\[
\frac{1}{r^2} \frac{d}{dr} r^2 d \varphi = -\frac{e}{\varepsilon_0} (n_i - n_e),
\]

where \( r \) is the coordinate, \( n_i(e) \) is the ion (electron) concentration, \( u_i(e) \) is the radial directed velocity of ions (electrons), \( z_e \) is the ionization frequency, \( E_r \) is the electric field intensity, \( T_i(e) \) is the temperature of ions (electrons) in energy units, \( m_i(e) \) is the mass of ions (electrons), \( v_{i(e)} \) is the frequency of ion (electron) collisions with atoms, \( e \) is the elementary charge, \( \varepsilon_0 \) is the dielectric constant.

As the radial directed velocity of electrons is slow compared to the random one, neglecting the inertial term and bulk friction forces (\( v_{ea} = 0 \)) allows to obtain a simple equation for the motion of electrons (2) with the temperature \( T_e \). In this case, the electrons obey the Boltzmann distribution regardless of the regime of ion motion onto the surface of the dust particle. Thus, the density of the electron current onto the particle follows the expression

\[
J_{ew} = \sqrt{\frac{T_e}{2\pi m_e}} n_e \exp \left( \frac{e\varphi_w}{T_e} \right),
\]

where \( n_e \) is the electron concentration at the boundary of the perturbed region, \( \varphi_w \) is the potential of the dust particle surface.

Let us introduce the dimensionless quantities:

\[
s = r/a, \quad N_i = n_i/n_e, \quad N_e = n_e/n_e, \quad U_i = u_{irt}/u_0, \quad \eta = -e\varphi/T_e, \quad Z = eaE_r/T_e,
\]

where \( u_0 = \sqrt{T_e/m_i} \).

Then Eqs. (1)–(4) take the following form:

\[
\frac{d N_i}{d s} = \frac{n_i N_e}{U_i} - 2 \frac{N_i}{s} - \frac{N_i d U_i}{U_i d s},
\]

\[
\frac{d N_e}{d s} = -N_e Z,
\]

\[
N_i U_i \frac{d U_i}{d s} + T_i \frac{d N_i}{d s} = N_i Z - \delta_i N_i U_i - \delta_i N_e U_i,
\]

\[
\frac{d Z}{d s} = \frac{1}{\alpha^2} (N_i - N_e) - \frac{2Z}{s}, \quad Z = \frac{d \eta}{d s}.
\]

The dimensionless similarity parameters \( \alpha = \lambda_d/a, \quad \delta_i = a v_{ia}/2u_0, \quad \delta_i = a z_e/u_0 \) are determined by the charging regimes of the dust particles; \( \lambda_d = \sqrt{\varepsilon_0 T_e/2n_e} \) is the electron Debye length [11]; \( \tau = T_e/T_d \) is the normalized electron temperature used in the calculations of atom (ion) temperature, with

\[
T_a \approx T_i = 0.026 \text{ eV (300 K)}.
\]

The quasi-neutrality of the plasma is violated near the dust particle. The characteristic scale of the perturbed region of the plasma is the electron Debye length \( \lambda_d \). The ratios between the characteristic lengths of the problem, namely \( \alpha, \lambda_d \) and \( \lambda_{ia} \), describe a particular charging regime of the dust particles in the discharge plasma. Here \( \lambda_{ia} = 1/\sqrt{2n_i/\varepsilon_0} \) is the free path of the ion, \( n_a \) is the atom concentration, \( \sigma_r \) is the averaged transport cross-section of the ion-electron collisions [12], \( v_{ia} = \sqrt{8\lambda_{ia}/\pi m_a / \lambda_{ia}} \).

The potential, the electric field and the radial directed velocity are equal to zero at the boundary of the perturbed region (let us denote it as \( r_0 \)), while the ion and electron concentrations may differ [1], i.e.,

\[
u_{ir}(r_0) = 0, \quad \varphi(r_0) = 0, \quad E_r(r_0) = 0,
\]

\[
n_i(r_0) = n_{io}, \quad n_e(r_0) = n_{eo}.
\]

For an isolated particle, \( n_{io} = n_{eo} = n_0 \), where \( n_0 \) is the concentration of charged particles in unperturbed plasma; besides, the thickness \( r_0 \) of the perturbed region for that particle is not known in advance.

The charge (the potential) of the particle in the steady-state case is determined by the charge balance equation [1]:

\[
J_{we} - J_{ew} + J_{em} = 0,
\]

where \( J_{em} \) is the total current density of the emitted electrons.
The ion current density on the surface $J_{iw}$, as well as the surface potential are determined through solving a system of differential equations in the perturbed region. The required value $r_0$ is found by the optimization method (described in Ref. [13]) from the minimal value of the objective function

$$(J_{iw} - J_{eu} + J_{em})^2.$$  

This approach allows to determine the size of the perturbed region and obtain the distribution of the plasma parameters in this region, as well as the expression for the density of the ion current onto the particle surface

$$J_{iw} = n_{i0} \bar{u}_0 N_{iw} U_{iw},$$

where $N_{iw}$ and $U_{iw}$ are the normalized concentration and the ion velocity on the particle surface.

In a plasma crystal, the thickness $r_0$ may exceed the radius of the Wigner–Seitz cell

$$r_d = (3/4\pi n_d)^{1/3},$$

where $n_d$ is the concentration of dust particles.

In this case, the particle cannot be regarded as isolated, so the following ion concentration should be chosen as the optimized parameter at the boundary of the Wigner–Seitz cell:

$$n_{i0} = n_i(r_d) > n_{e0}$$

for the negative charge of the dust particles and $n_{i0} < n_{e0}$ for their positive charge. The quasi-neutrality of the Wigner–Seitz cell is thus maintained.

**The balance equations of particle charge and energy**

The balance equations of charge and energy on the particle surface [14] were solved simultaneously to determine the secondary, ion-electron, photoelectron and thermal field emission processes:

$$J_i = J_e - P_j \left[ \bar{r} J_e \kappa_r + \bar{d} J_e \kappa_d + \gamma J_e \kappa_\gamma + Y J_p h \kappa_pe + J_{e}\kappa_w \right],$$

$$J_a \alpha_a 2(T_W - T_a) + J_e P_j \kappa_w 2T_W + a_0 \sigma_0 T_W^4$$

$$= J \left[ E_a + \alpha_i (e_{iw} - 2T_W) - P_j e_{\gamma} \kappa_\gamma \right]$$

$$+ J_e \left[ 2T_W - P_j (\varepsilon_{iw} + \varepsilon_{d} \kappa_d) \right]$$

$$+ J_{ph} \left( E_{ex} - P_j e_{pe} \kappa_{pe} \right),$$

where $J_i$, $J_e$, $J_{ph}$, $J_{th}$ and $J_a$ are the densities of ion, electron, resonant photon, thermal-field electron and atom currents onto the particle surface (the wall factor $W$ is omitted to simplify the expression); $T_W$ is the temperature of the dust particle surface; $\bar{r}$ and $\bar{d}$ are the secondary-electron emission coefficients for the elastically backscattered and the true secondary electrons, averaged over the electron energy distribution function (EEDF) [15]; $\gamma$ is the coefficient of the potential ion-electron emission; $Y$ is the quantum yield for the photoelectric effect; $P_j$ is the probability of an electron escaping from the rough surface of the dust particle without a repeated collision [16]; $\alpha_a$ and $\alpha_i$ are the accommodation coefficients of atoms and ions [17]; $\sigma_0$ is the Stefan–Boltzmann constant; $a_0$ is the integrated absorptivity of a dust particle (the emissivity coefficient); $e_{iw}$, $e_{\gamma}$, $\varepsilon_{d}$ and $\varepsilon_{pe}$ are the kinetic energy quantities of ions and secondary electrons during ion-electron emission, and of true secondary electrons and of photoelectrons; $E_{ex}$ is the excitation energy of the resonant levels.

The factor $\kappa$ is equal to unity if the charge of the dust particle is negative and to $\exp(-e\varphi_w/T)$ if it is positive, as the emitted electrons experience additional deceleration. The temperature $T$ takes the values $T_e$, $T_k$, $T_T$ and $T_{pe}$ [14] for the respective processes and $T_w$ for the thermal-field emission electrons.

The left-hand side of the energy balance equation contains the terms taking into account the cooling of the dust particle by atoms, thermal electrons and radiation, while the right-hand side contains the terms taking into account the heating of the dust particle by

Fig. 1. The calculated curves of the absolute value of the surface potential of the smooth dust Al2O3 particle in neon plasma versus the ratio between the temperature values of electrons and atoms for the parameter values of (12) without emission taken into account (the dashed line) and with all types of emission take into account (the dotted line) according to the OML theory. The corresponding curves were calculated by our proposed technique under the $a \ll \lambda_d \ll \lambda_{iw}$ conditions and for the following cases: with ion-electron emission and photoemission factored in (2); with secondary (3) and thermal-field (4) emission factored in; with all types of emission (5) factored in, and without emission (1).
10

Fig.

Table 1
Expressions and calculated formulae for current densities and energies of different types of particles.

<table>
<thead>
<tr>
<th>Particle type</th>
<th>Particle current density</th>
<th>Calculated formula for ( J ), cm(^{-2})·s(^{-1} )</th>
<th>Particle energy, eV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atoms</td>
<td>( J_a = n_a \sqrt{\frac{I_a}{2\pi m_a}} ) ( \times \exp \left( \frac{ex}{kT} \right) )</td>
<td>( 2.69 \times 10^8 n_a \sqrt{\pi} ) ( \exp \left( \frac{ex}{kT} \right) )</td>
<td>( 2T_a = 0.052 )</td>
</tr>
<tr>
<td>Electrons</td>
<td>( J_e = n_e \sqrt{\frac{I_e}{2\pi m_e}} ) ( \times \exp \left( \frac{ex}{kT} \right) )</td>
<td>( 2.69 \times 10^8 n_e \sqrt{\pi} ) ( \exp \left( \frac{ex}{kT} \right) )</td>
<td>( 2T_e = 0.052 )</td>
</tr>
<tr>
<td>Ions</td>
<td>( J_i = n_i \sqrt{\frac{I_i}{2\pi m_i}} ) ( \times \exp \left( \frac{ex}{kT} \right) )</td>
<td>( 6.76 \times 10^8 n_i \sqrt{\pi} ) ( \exp \left( \frac{ex}{kT} \right) )</td>
<td>( E_{ex} )</td>
</tr>
<tr>
<td>Photons</td>
<td>( J_{ph} = \frac{Q_{ex}}{h} ) ( \times \exp \left( \frac{ex}{kT} \right) )</td>
<td>( 6.76 \times 10^8 n_i \sqrt{\pi} ) ( \exp \left( \frac{ex}{kT} \right) )</td>
<td>( 2T_i = 0.052 )</td>
</tr>
<tr>
<td>Thermal field emission electrons</td>
<td>( J_{te} = \frac{2\pi^2 e^2}{h^2} \sqrt{\frac{n_i T_i}{n_e \eta}} )</td>
<td>( 8.74 \times 10^{21} \frac{[E_e V]^{1/2}}{\kappa V} )</td>
<td>( 2T_e = 0.052 )</td>
</tr>
</tbody>
</table>

Notations. \( Q_{ex} \) is the constant excitation rate of the spontaneously decaying resonance levels \( \beta \); \( \eta \) is the ionization rate; \( h \) is the Planck constant. The rest of the notations are listed in the text.

Fig. 2. Distributions of the charged particle concentrations in plasma \( (a) \) and of the absolute value of the potential and the ion directed velocity \( (b) \) depending on the radial coordinate, obtained by the optimization method with \( \lambda_d/a = 1 \) and in the value range of \( \alpha u_0/\nu_0 \) from \( 10^{-5} \) to \( 10^{-3} \) for different values of \( \alpha u_0/2\nu_0 \): 0.1 \( (1) \); 1 \( (2) \); 10 \( (3) \). The groups of curves lying higher in Fig. 2a refer to ions, and those lying lower refer to electrons.
ions, electrons and resonant photons and the cooling by the respective secondary electrons.

Table 1 lists the particle current densities and particle energies carried onto or from the surface of the dust particle that were used in the calculations.

Calculation results

Fig. 1 shows the calculated curves of the normalized potential of a smooth dust particle surface versus \( \tau = T_e / T_a \), with the above-listed emission processes factored in separately and together. The calculations were performed based on the orbital-motion-limited (OML) theory and on the proposed technique under conditions corresponding to the OML approximation.

We examined aluminum oxide (Al\(_2\)O\(_3\)) particles in a neon (Ne) discharge under the following parameters:

\[
a = 1.5 \mu \text{m}, \quad n_a = 10^{16} \text{cm}^{-3}, \quad n_{e0} = 10^{11} \text{cm}^{-3}, \quad T_a = T_i = 300 \text{ K}.
\]

These parameters were used to calculate the potentials excluding emission and including all types of emission (see Fig. 1).

The potential values were obtained on the basis of the OML theory without emission taken into account (the dashed line) and with all of the above-mentioned types of emission taken into account (the dotted line). The solid lines describe the results obtained by the proposed technique, with each type of emission considered separately; results without emission taken into account and with the combined influence of all emission types taken into account were also obtained.

A comparison of the obtained data shows that the results of the calculation by the described technique are close to those described by the OML theory. It has been shown that the secondary, ion-electron emission and photoemission from the surface of the smooth particle reduce the absolute value of the potential of the dust particle surface in the whole considered electron temperature range. The effect of thermal field emission on the potential begins at \( T_e / T_a \approx 300 \) and increases with an increase in the electron temperature.

The thermal field emission flux becomes substantial as the surface temperature reaches a certain value, namely

\[
T_e \geq (W_0 - e\Delta \varphi) / (50 - \ln (n_{e0}, \text{ cm}^{-3})).
\]
The calculations show that the surface roughness reduces the effect of electron emission, and in fact at a sufficiently high degree of roughness (~0.8) emission can be neglected ($P_f \leq 0.325, \alpha_0 \geq 0.822, \alpha_i \geq 0.956$[14]).

The proposed technique was used to calculate spatial distributions for the concentrations of charged particles (ions and electrons) in plasma, for the absolute values of ion directed velocity, and for the potential in the region where the plasma was perturbed by the dust particle (Fig. 2). Vertical lines are the coordinates of the boundaries of the perturbed regions for each specific case. The calculations were performed for an isolated particle in a neon discharge without emission taken into account, with $\lambda_d/a = 1$, for the values $\delta_e = \alpha v_{ia}/2u_0$ from 0.1 to 10 and $\delta_i = a z_e/u_0$ in the range from $10^{-5}$ to $10^{-3}$, which are typical for the discharge conditions. An increase in the collision frequency leads to a decrease in the concentration and the directed velocity of ions, which is due to the growing influence of the collision term in the equation of ion motion. A decrease in ion concentration and velocity means a decrease in ion current density, which in turn leads to a decrease in electron current density (according to the charge balance equation) and, consequently, to an increase in the absolute normalized value of the potential on the surface of the dust particle and in its vicinity.

A change in the ionization rate of the isolated particle does not affect the calculated plasma parameters, as the influence of the bulk friction caused by ion-atom collisions by far exceeds the influence of the friction caused by the ionization in the considered range of values $v_{ia} \gg z_e$ (this effect is not observed in the figures). However, a decrease in the ionization rate leads to an increase in the thickness of the perturbed region.

Fig. 3 shows the graphs for the concentration distributions of ions and electrons, and of the absolute values of the potential and the radial velocity of ions, which show the transition from an isolated particle to a dense plasma-dust structure.

These graphs were obtained for the parameter values $\lambda_d/a = 1$ and $av_{ia}/2u_0 = 1$. Curves 1, corresponding to the distributions for the isolated particle, were obtained for $a z_e/u_0 = 0.001$. Curves 2 ($a z_e/u_0 = 0.01$) and 3 ($a z_e/u_0 = 0.1$) correspond to the distributions in the Wigner–Seitz cell, with an increased frequency $z_e$.

In this case, the ionization rate for the value $a z_e/u_0 = 0.1$ (curves 3) is higher than that for the 0.01 value (curves 2); respectively, in the second case, the
cell radius $r_{d2}$ is less than in the first one ($r_{d1}$). The values of the corresponding normalized radii are given in the caption to Fig. 3.

Conclusion

This paper uses the moment equations and Poisson's equation to describe the charging process of the dust particle. We have proposed a technique for solving this system of equations, allowing to obtain the ion current density and the potential on the surface of the dust particle, as well as the thickness of the plasma perturbation region and the distributions of the plasma parameters in this region taking into account collisions, ionization, electron emission and surface roughness.

The obtained calculation results demonstrate that ion-atom collisions reduce the density of the ion current onto the particle surface and lead to an increase in the absolute value of the potential (the charge). A reduction in the ionization rate due to an electronic impact leads to an increase in the thickness of the perturbed region.

It was established that the electron emission and the surface roughness have a significant impact on the charging process of dust particles and reduce the absolute value of the potential of the dust particle surface. These processes must be taken into account in experiments and theoretical models.

References


