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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.

Keywords: Dusty plasma; Electron emission; Ion-atom collisions; Ionization; Nanoparticle charge.

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

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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:

$$\frac{1}{r^2}\frac{d}{dr}r^2 n_i u_{ir} = n_e z_e, \;\; n_e u_{er} = n_i u_{ir}, \tag{1}$$

$$T_e \frac{dn_e}{dr} = -e n_e E_r - m_e n_e u_{er} \nu_{ea}, \tag{2}$$

$$m_i n_i u_{ir} \frac{du_{ir}}{dr} + T_i \frac{dn_i}{dr} = e n_i E_r - \frac{m_i}{2}\nu_{ia} n_i u_{ir} - m_i u_{ir} n_e z_e, \tag{3}$$

$$\frac{1}{r^2}\frac{d}{dr}r^2\frac{d\varphi}{dr} = -\frac{e}{\varepsilon_0}(n_i - n_e), \tag{4}$$

where r is the coordinate, $n_{i(e)}$ is the ion (electron) concentration, $u_{i(e)r}$ 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), $\nu_{i(e)a}$ is the frequency of ion (electron) collisions with atoms, e is the elementary charge, ε_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 (($\nu_{ea}=0$) 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

$$J_{ew} = \sqrt{\frac{T_e}{2\pi m_e}} n_{e0} \exp\left(\frac{e\varphi_w}{T_e}\right), \tag{5}$$

where n_{e0} is the electron concentration at the boundary of the perturbed region, φ_w is the potential of the dust particle surface.

Let us introduce the dimensionless quantities:

$$s = r/a,\; N_i = n_i/n_{e0},\; N_e = n_e/n_{e0},\; U_i = u_{ir}/u_0,$$
$$\eta = -e\varphi/T_e,\; Z = eaE_r/T_e,$$

where $u_0 = \sqrt{T_e/m_i}$.

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

$$\frac{dN_i}{ds} = \delta_i \frac{N_e}{U_i} - 2\frac{N_i}{s} - \frac{N_i}{U_i}\frac{dU_i}{ds}, \tag{6}$$

$$\frac{dN_e}{ds} = -N_e Z, \tag{7}$$

$$N_i U_i \frac{dU_i}{ds} + \frac{T_i}{T_e}\frac{dN_i}{ds} = N_i Z - \delta_c N_i U_i - \delta_i N_e U_i, \tag{8}$$

$$\frac{dZ}{ds} = \frac{1}{\alpha^2}(N_i - N_e) - \frac{2Z}{s},\;\; Z = \frac{d\eta}{ds}. \tag{9}$$

The dimensionless similarity parameters $\alpha = \lambda_d/a$, $\delta_c = a\nu_{ia}/2u_0$, $\delta_i = az_e/u_0$ are determined by the charging regimes of the dust particles; $\lambda_d = \sqrt{\varepsilon_0 T_e/e^2 n_{e0}}$ is the electron Debye length [11]; $\tau = T_e/T_a$ 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 λ_d. The ratios between the characteristic lengths of the problem, namely a, λ_d and λ_{ia}, describe a particular charging regime of the dust particles in the discharge plasma. Here $\lambda_{ia} = 1/\sqrt{2}n_a\sigma_{tr}$ is the free path of the ion, n_a is the atom concentration, σ_{tr} is the averaged transport cross-section of the ion-electron collisions [12], $\nu_{ia} = \sqrt{8T_a/\pi m_a}/\lambda_{ia}$.

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.,

$$u_{ir}(r_0) = 0, \varphi(r_0) = 0, E_r(r_0) = 0,$$
$$n_i(r_0) = n_{i0}, n_e(r_0) = n_{e0}.$$

For an isolated particle, $n_{i0} = n_{e0} = n_0$, 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]:

$$J_{iw} - J_{ew} + J_{em} = 0,$$

where J_{em} is the total current density of the emitted electrons.