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Analysis of dusty plasma in the positive column of glow discharges*

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The radial distributions of ions, electrons and dust particles in the positive column of glow discharges are investigated in a triple-pole diffusion model. The dust particles are mainly trapped in the region around the column axis where the electrostatic potential is the highest. The presence of the dust particles results in the ion density increasing and the electron density decreasing in the dust-trapped region. The dust-trapped region is wider for a higher dust temperature or a smaller particulate radius. The ions and electrons in the dust-free region away from the column axis are in ambipolar diffusion.

Keywords: dusty plasma, positive column, diffusion
PACC: 5225Z, 5225F

1. Introduction

The presence of dust particles in low-pressure nonthermal plasmas, such as those used in plasma etching or deposition applications, has been recognized as a serious problem because of particle contamination in plasma processing. These particles result from sputtering of electrode and wall surfaces, gas phase nucleation and polymerization. Their size ranges from a few nanometres to tens of micrometres. They can be observed directly using laser scattering techniques.[1,3] The observation of dust has shown that the dust particles are trapped at the plasma–sheath boundary where the electrostatic, gravitational and ion drag forces reach a balance. The dust particles can also be trapped in the plasma region where the electrostatic potential field is maximum when the size of dust particles is so small that the gravitational force on them can be neglected. The trapped particles have been shown to be negatively charged.[3−5] Recently, laser Doppler velocimetry has been used in experiments to measure the dynamics of particles trapped electrostatically in rf plasma.[6] The results show that the kinetic energies, hence the temperature of the particles trapped in the system, can be much higher than the neutral gas, ion and electron temperatures. The particle charging process and levitating mechanism under the various forces have been studied extensively with theoretical and numerical models.[7−12] But the diffusion mechanism of ions, electrons and dust particles in the plasma region is not yet clear.

In this paper, we focus on the triple-pole diffusion problem of ions, electrons and dust particles in the positive column of glow discharges. The density distributions of ions, electrons and dust particles in the radial direction in the positive column of glow discharges are calculated with a diffusion model. The layout of the paper is as follows. After the introduction, the model of the triple-pole diffusion for ions, electrons and dust particles in the positive column of glow discharges is described and the basic equations are deduced. Then we solve the formalism numerically for various parameters, and show the results. We compare the density distributions of ions, electrons and dust particles for different sets of parameters and discuss the diffusion mechanism. Finally we give a brief summary of the paper.

2. Description of the model

2.1. Charging of dust particles

The charge of a dust particle in a plasma can be obtained by the electron and ion currents striking the

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dust particle. If the dust particle radius is smaller than the Debye length and the Debye length is less than an electron-neutral mean free path, the orbit motion limited theory[13] is used to calculate the charging currents. In the present model, we assume that the dust charge is constant in the region of cylindrical geometry and can be determined by the plasma parameters in the column axis. The assumption could be a good approximation because the dust particles would concentrate in the region around the column axis.

The electron current to the dust particle in the plasma is given by

$$I_e = -e\pi a^2 n_{e0}\left(\frac{8kT_e}{\pi m_e}\right)^{1/2}\exp\left(\frac{eU_d}{kT_e}\right), \quad \text{for } \frac{eU_d}{kT_e} \le 0, \tag{1}$$

where m_e, T_e and n_{e0} are the electron mass, temperature and density in the column axis respectively, and a and U_d are the particle radius and floating potential, respectively. Through the relation $U_d = q_d/4\pi\epsilon_0 a$, the particle charge q_d can be determined. The dust particles are negatively charged at this place.

The ion current to the dust particle in the plasma is written by

$$I_i = e\pi a^2 n_{i0}\left(\frac{8kT_i}{\pi m_i}\right)^{1/2}\left(1 - \frac{eU_d}{kT_i}\right), \tag{2}$$

where m_i, T_i, and n_{i0} are the ion mass, temperature and density in the column axis, respectively.

Requiring a zero net current on the dust particle $I_e + I_i = 0$ and using the quasi-neutral condition $n_{i0} = n_{e0} + n_{d0}\,|q_d|/e$ (n_{d0} is the density of dust particle in column axis), we can determine the dust charge number $Z = |q_d|/e$ from the plasma parameters.

2.2. Triple-pole diffusion model

We consider that the plasma in the positive column consists of ions, electrons and dust particles. The present model is analogous to the theory of electronegative plasma equilibrium.[14] For these charged species, we can write the flux equations as follows

$$\Gamma_i = -D_i\nabla n_i + n_i\mu_i E, \tag{3}$$

$$\Gamma_e = -D_e\nabla n_e - n_e\mu_e E,$$

$$\Gamma_d = -D_d\nabla n_d - n_d\mu_d E,$$

where D_i, D_e and D_d are the diffusion coefficients of ion, electron and dust particle respectively, and μ_i, μ_e and μ_d are the mobilities of ion, electron and dust particle, respectively. In equilibrium, the currents satisfy

$$\Gamma_i = \Gamma_e + \Gamma_d. \tag{4}$$

The quasi-neutral condition can be expressed as

$$n_i = n_e + Zn_d. \tag{5}$$

Using Eqs.(3)–(5) and using the ratio of dust particle to electron density $\alpha = n_d/n_e$, eliminating Γ_d, Γ_e, n_i, n_e and E from above formulae, an equation can be obtained

$$\Gamma_i = -D_{ai}\nabla n_i, \tag{6}$$

where a new diffusion coefficient is formally defined by

$$D_{ai} = \frac{(\mu_e + \mu_d\alpha)D_i + \mu_i(1+Z\alpha)D_e(\nabla n_e/\nabla n_i) + \mu_i(1+Z\alpha)D_d(\nabla n_d/\nabla n_i)}{\mu_e + \mu_d\alpha + \mu_i(1+Z\alpha)}. \tag{7}$$

However, because Eq.(6) is coupled to n_e and n_d , it cannot be solved for n_i independently. The three diffusion equations must be solved in this case. This is a difficult numerical procedure. If both electrons and dust particles are assumed to be in Boltzmann equilibrium just like the electronegative plasma,[14] the relation can be obtained as

$$\frac{\nabla n_d}{n_d} = Z\gamma\frac{\nabla n_e}{n_e}, \tag{8}$$

where $\gamma = T_e/T_d$ is the temperature ratio and T_d is the temperature of the dust particles. Since the transport coefficients are inversely proportional to the masses, the particle flux Γ_d is very small. According to Eq.(3), the assumption that the dusty particles are in Boltzmann equilibrium could be a good approximation. Differentiating Eq.(5), one obtains

$$\nabla n_i = \nabla n_e + Z\nabla n_d. \tag{9}$$

Combining Eqs.(8) and (9), we obtain the ratios

$$\frac{\nabla n_e}{\nabla n_i} = \frac{1}{1+Z^2\gamma\alpha}, \qquad \frac{\nabla n_d}{\nabla n_i} = \frac{Z\gamma\alpha}{1+Z^2\gamma\alpha}. \tag{10}$$

Substituting Eq.(10) together with the Einstein relations

$$\frac{D_i}{\mu_i} = \frac{kT_i}{e}, \qquad \frac{D_e}{\mu_e} = \frac{kT_e}{e}, \qquad \frac{D_d}{\mu_d} = \frac{kT_d}{Ze}, \tag{11}$$

into Eq.(7), we obtain

$$D_{ai} = D_i \frac{(1+\gamma T_d/T_i + Z\gamma\alpha T_d/T_i + Z^2\gamma\alpha)(1+\alpha\mu_d/\mu_e)}{(1+Z^2\gamma\alpha)[1+\alpha\mu_d/\mu_e + (1+Z\alpha)\mu_i/\mu_e]}. \quad (12)$$

Since μ_d/μ_e, $\mu_i/\mu_e << 1$, the second parentheses in both the numerator and the denominator are approximately equal to one, so that

$$D_{ai} = D_i \frac{1+\gamma T_d/T_i + Z\gamma\alpha T_d/T_i + Z^2\gamma\alpha}{1+Z^2\gamma\alpha}. \quad (13)$$

The steady-state ion continuity equation $\nabla \cdot \Gamma_i = \nu_{iz} n_e$ in cylindrical geometry is written as

$$-\frac{1}{r}\frac{\mathrm{d}}{\mathrm{d}r}\left[rD_{ai}(\alpha)\frac{\mathrm{d}n_i}{\mathrm{d}r}\right] = \nu_{iz} n_e, \quad (14)$$

where ν_{iz} is the average electron ionization frequency. Equation (14) cannot be solved directly because it depends on n_e, n_d and n_i. Integrating Eq.(8), one can obtain

$$\frac{n_e}{n_{e0}} = \left(\frac{n_d}{n_{d0}}\right)^{1/Z\gamma}. \quad (15)$$

Using Eqs.(5) and (15), we obtain the relations

$$n_e + Zn_{d0}\left(\frac{n_e}{n_{e0}}\right)^{Z\gamma} = n_i,$$

$$Zn_d + n_{e0}\left(\frac{n_d}{n_{d0}}\right)^{1/Z\gamma} = n_i. \quad (16)$$

Equation (16) determines that n_e and n_d are functions of n_i, so that Eq.(14) becomes

$$-\frac{1}{r}\frac{\mathrm{d}}{\mathrm{d}r}\left[rD_{ai}(n_i)\frac{\mathrm{d}n_i}{\mathrm{d}r}\right] = \nu_{iz} n_e(n_i). \quad (17)$$

We define the dimensionless quantities

$$N_i = \frac{n_i}{n_{i0}},\ N_e = \frac{n_e}{n_{i0}},$$

$$N_d = \frac{n_d}{n_{i0}},\ R = \frac{r}{l}, \quad (18)$$

where l is the radius of the positive column of the glow discharge. Using Eq.(18), we can write Eq.(16) as

$$N_e + FN_e^{Z\gamma} = N_i,$$

$$ZN_d + GN_d^{1/Z\gamma} = N_i, \quad (19)$$

where $F = Z(n_{e0}/n_{i0})^{-Z\gamma} n_{d0}/n_{i0}$ and $G = (n_{d0}/n_{i0})^{-1/Z\gamma}\ n_{e0}/n_{i0}$. The dimensionless ion continuity equation becomes

$$\frac{1}{R}\frac{\mathrm{d}}{\mathrm{d}R}\left[R\Omega(N_i)\frac{\mathrm{d}N_i}{\mathrm{d}R}\right] = -hN_e(N_i), \quad (20)$$

where

$$\Omega(N_i) = \frac{1+\gamma T_d/T_i + Z\gamma\alpha T_d/T_i + Z^2\gamma\alpha}{1+Z^2\gamma\alpha}, \quad (21)$$

and $h = l^2\nu_{iz}/D_i$. Equations (19) and (20) constitute a complete set of equations for the problem of the triple-pole diffusion with the boundary conditions

$$N_i(0) = 1, \quad \frac{\mathrm{d}N_i(0)}{\mathrm{d}R} = 0, \quad (22)$$

and

$$N_i(1) = 0\ . \quad (23)$$

The last condition shows that the ion density vanishes at the boundary (at $r = l$). Using Eq.(23), one can determine the dimensionless plasma parameter h.

3. Numerical results

We have numerically solved Eqs.(19) and (20) with the boundary conditions (22) and (23) to obtain the of density distributions of electrons, ions and dust particles in the radial direction. The parameters used throughout the paper for argon plasma are the plasma density $n_{i0} = 1.0\times10^{10}\mathrm{cm}^{-3}$, the electron temperature $kT_e = 2$ eV, and the ion temperature $kT_i = 0.025$eV. The numerical results for the different particle density n_{d0}, radius a and temperature kT_d are presented in Figs.1–4.

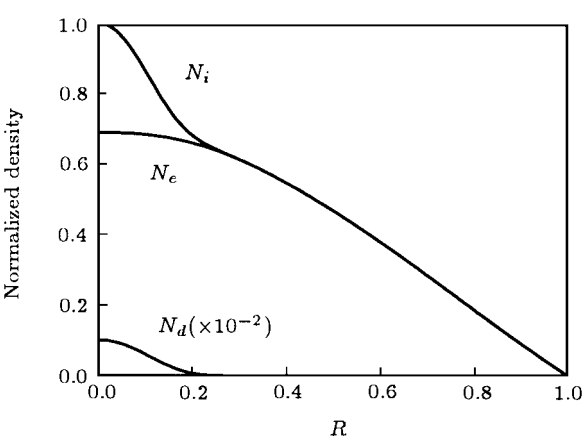


Fig.1. Density distributions of ions, electrons and dust particles for the parameters $n_{d0} = 1.0\times10^7\mathrm{cm}^{-3}$, $kT_d = 10$ eV, $a = 0.1$ μm, $Z = 309$ and $h = 465.35$.

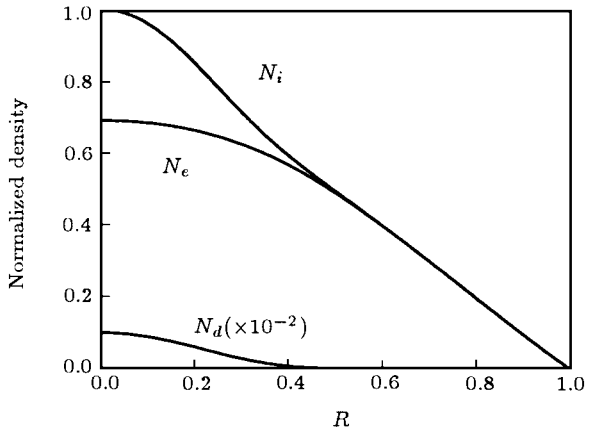


Fig.2. Density distributions of ions, electrons and dust particles for the parameters $n_{d0} = 1.0 \times 10^7 \mathrm{cm}^{-3}$, $kT_d = 50$ eV, $a = 0.1$ μm, $Z = 309$ and $h = 471.90$.

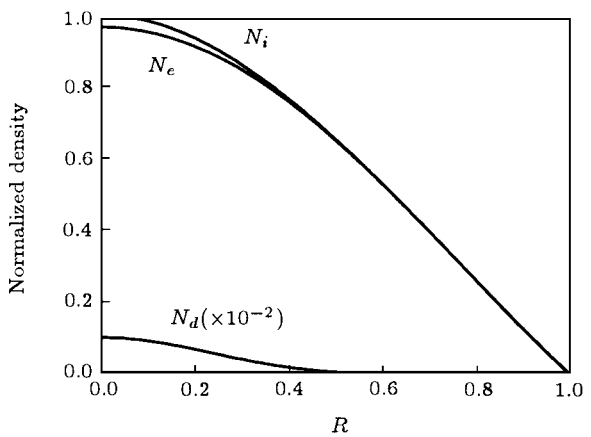


Fig.3. Density distributions of ions, electrons and dust particles for the parameters $n_{d0} = 1.0 \times 10^7 \mathrm{cm}^{-3}$, $kT_d = 10$ eV, $a = 0.01$ μm, $Z = 34$ and $h = 472.25$.

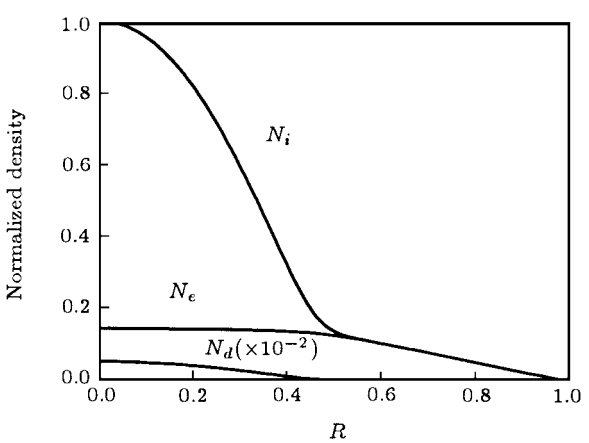


Fig.4. Density distributions of ions, electrons and dust particles for the parameters $n_{d0} = 5.0 \times 10^7 \mathrm{cm}^{-3}$, $kT_d = 10$ eV, $a = 0.1$ μm, $Z = 172$ and $h = 497.44$.

Figure 1 shows the density distributions of ions, electrons and dust particles for $n_{d0} = 1.0 \times 10^7 \mathrm{cm}^{-3}$, $kT_d = 10$ eV and $a = 0.1$ μm corresponding to $Z = 309$ and $h = 465.35$. It is shown that the dust particles are trapped in the region around the column axis. The maximum of the particle distribution is at the column axis where the electrostatic potential is the highest. The presence of the dust particles results in the increase of ion density and the decrease of electron density in the dust-trapped region because the dust particles are negatively charged. The ions and electrons in the dust-free region away from the column axis are in ambipolar diffusion. Figure 2 shows the density distributions of ions, electrons and dust particles for $n_{d0} = 1.0 \times 10^7 \mathrm{cm}^{-3}$, $kT_d = 50\,\mathrm{eV}$ and $a = 0.1$ μm corresponding to $Z = 309$ and $h = 471.90$. The trapping region of the dust particles is wider than that in Fig.1, which can be understood easily from the thermal diffusion mechanism of the dust particles. Figure 3 shows the density distributions of ions, electrons and dust particles for $n_{d0} = 1.0 \times 10^7 \mathrm{cm}^{-3}$, $kT_d = 10\,\mathrm{eV}$ and $a = 0.01$ μm corresponding to $Z = 34$ and $h = 472.25$. Because the charge number of the dust particle decreases for smaller particles, the trapping region of the dust particles is wider, but the influence of the dust particles on the ion and electron diffusion becomes weaker. Figure 4 shows the density distributions of ions, electrons and dust particles for $n_{d0} = 5.0 \times 10^7 \mathrm{cm}^{-3}$, $kT_d = 10\,\mathrm{eV}$ and $a = 0.1\,\mu\mathrm{m}$ corresponding to $Z = 172$ and $h = 497.44$. In this case, because the dust particle density increases, the trapping region of the dust particles becomes wider due to the diffusion of the dust particles and the negatively charged particles confine many more ions and fewer electrons in the dust-trapped region.

4. Conclusions

We have developed a triple-pole diffusion model for ions, electrons and dust particles in the positive column of glow discharges. The radial distributions of ions, electrons and dust particles are examined by numerical calculation. The dust particles are mainly trapped in the region near the column axis where the electrostatic potential is highest. The negatively charged dust particles result in many more ions and fewer electrons confined in the dust-trapped region. The ions and electrons in the dust-free region away from the column axis are in ambipolar diffusion. The trapping region of the dust particles becomes wider for a higher dust temperature or a smaller particulate radius. The effects of the negatively charged dust particles on the ion and electron diffusions are enhanced as the dust particle density increases.

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