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ON THE MECHANISM OF RADIAL SUSTENANCE OF DENSE DUSTY PLASMAS

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The mechanism of self-sustenance of dust structures in plasma of dc glow discharge in neon is simulated using the diffusion/drift model. The heat release in a discharge is considered. Radial profiles of electron number density, electric field and gas temperature are represented for different values of dust particle concentration in a discharge.

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1. Introduction

Last years dusty plasmas have got a wide application field as a working medium for different types of technical apparatus used for plasma surface modification and plasma coating [1-3]. The particles with the coatings that possess of the preset physicochemical characteristics and new surface properties are used or can be used in different modern industrial technologies and medicine [3], for example for the synthesis of biostructures consisting of supramolecular complexes on their surface [4]. The noble gases argon, helium and neon are used as a plasma-forming gas in these devices.

Recently the elongated dust structures containing a large number of dust particles were obtained in glow discharge plasma of argon [5]. We have observed the dust structures of 8 cm in length containing more than $1.6\text{x}10^6$ dust particles in a glow discharge in neon. Let us note that plasma of neon is used in the continued complex plasma experiment PK-4 on board of the International Space Station [6]. That shows the increasing possibilities for application of dc discharges in neon in plasma science and technologies.

The dust particles may be introduced in a plasma from the outside or be formed in the course of technological process and change both local plasma parameters (around themselves) and integral parameters of a discharge. Most frequently the surface of dust particles absorbs plasma particles, causes an additional losses in the plasma bulk and shifts the plasma ionization balance, requiring the additional energy input and increase of electron temperature for the maintenance of a discharge current.

In [7] we have reported that the introduction of dust particles in the positive column of glow discharge in neon lead to the noticeable increase of the longitudinal electric field strength and the corresponding increase of the electron temperature. Dust structures change the radial profiles of plasma components, resulting in the inversion of the radial electric field at high concentration of dust particles. In present paper we analyze the influence of dust structures on the characteristics of a discharge at higher values of a discharge current considering the heat release in a discharge, and the reverse influence of discharge electric field on the sustenance of dust structures in plasma.

2. Numerical model

We consider neon plasma consisting of neutrals, electrons, ions and metastable neon atoms. The lowest metastable state of 1s configuration is considered. The ionization proceeds by

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single electron collision with neon atom in the ground state, and by two successive collisions through the metastable state. We describe the plasma in frames of diffusion/drift approximation, considering the positive column with uniform gas density, basing on the idea of ambipolar diffusion of ions and electrons towards the tube walls in quasi-neutral plasma under the action of the electric field of discharge represented as a combination of invariable longitudinal component E_l, and self-consistent radial component E_r. Considering the losses of plasma particles on the surface of dust particles, the flow of electrons to the dust particle surface is calculated using the orbit motion limited approximation (OML), and the flow of ions is calculated with the account of the collisional enhancement of the ion current due to ion-neutral collisions in accordance with collision enhanced collection (CEC) model [8]. The ion and metastable temperatures were supposed to be equal to gas temperature, the mean electron energy and transport coefficients were obtained using the SIGLO Database [9] and the electron Boltzmann equation solver BOLSIG+ [10]. In more details the diffusion/drift model was described in [7]. Using this approach, we have found the radial distributions of ions, metastables and electrons and the electric field for the given dust particle distribution $n_d(r)$, the total discharge current I and pressure P.

To find the radial gas temperature profile in a discharge tube, we have neglected the convective and electron heat conduction terms and solved the steady-state one-dimensional heat conduction equation in the form:

$$\frac{1}{r}\frac{d}{dr}\left(r\lambda\frac{dT}{dr}\right)=-Q(r),$$

with the appropriate boundary conditions:

$$\left.\frac{d^2T}{dr^2}\right|_{r=0}=\left.\frac{dT}{dr}\right|_{r=0}=0,\ \left.\frac{dT}{dr}\right|_{r=R}=T_W,$$

Here Q is the rate of Joule heat release:

$$Q(r)=n_e(r)\mu eE_l^2,$$

$n_e(r)$ is the electron concentration, μ is the electron mobility, λ is the thermal conductivity of neon taken from [11], T_W is the temperature of the wall of the discharge tube with the radius R. Simulations were carried out for the discharge tube of R=16.5 mm i.d. with T_W =295 K, and dust particle size a=2.55 micron. In simulations, the dust particle distribution $n_d(r)$ was given by an axially symmetrical flat profile of size $r_d=R/2$ with dust particle concentration on the axis of the discharge tube n_d and exponential end blurring:

$$n_d(r)=n_{d,0},\ r\le r_d$$

$$n_d(r)=n_{d,0}e^{\frac{(r_d-r)}{0.1R}},\ r>r_d.$$

3. Results and discussion

In free discharge the undisturbed radial concentration profiles of plasma particles are close to Bessel distribution. Dust particles produce an additional electron losses in the plasma bulk, changing plasma ionization balance. For the maintenance of the discharge current, these losses should be compensated by the increase of ionization frequency through the increase of E_l and electron temperature. The increase of dust particle concentration leads to the case when the electron concentration on the outer face of dust cloud becomes higher than in the center of the tube, i.e. the maximum of electron profile shifts towards the tube wall, forming a local minimum in the center of discharge tube. In figure 1 the simulated radial distributions of electron concentration $n_e(r)$ are represented for four values of dust particle concentration $n_d(r)$. The calculated corresponding values of the longitudinal electric field strength E_l are: 5.85 V/cm in dust free discharge, 9.68 V/cm at $n_{d,0}=1.0\times10^{11}$ m^{-3}, 10.86 V/cm at $n_{d,0}=2.0\times10^{11}$ m^{-3}, and 11.4 V/cm at $n_{d,0}$=4.0×10^{11} m^{-3}. The essential increase of E_l in a discharge with dust particles was also observed in experiments [7] at lower pressure of neon.

While the longitudinal electric field increases with the increase of dust particle concentration, there appears the smoothing of electron concentration over the discharge cross section under the action of dust cloud and even the essential inverse electron concentration gradient at high values of n_d, represented in figure 1. At high n_d the strong depletion of electron concentration within the dust cloud causes the reverse flow of electrons from free discharge towards the tube axis and results in the inversion of the radial electric field. Following from this point, there appear the change of the electric force acting on the dust particles that is discussed below.

The increased electric field strength leads to the increase of Joule heat release, while the redistribution of electron concentration over the cross section of discharge tube causes the shift of its maximum towards the tube walls. The simulated temperature profiles are represented in figure 2 for the discharge conditions of figure 1. One can see that the increment of gas temperature on the axis of a discharge tube increases by about 50% in the presence of dust particles.

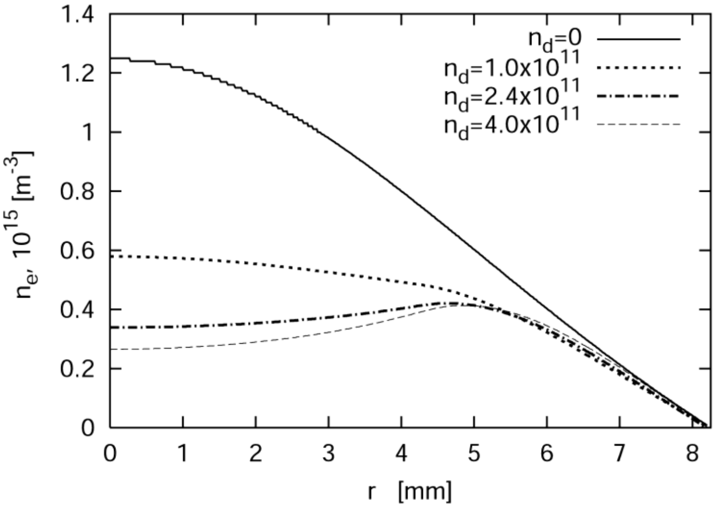

Fig. 1. Radial profiles of electron concentration $n_e(r)$ at various values of dust particle concentration $n_d(r)$, dust structure radius r_d=R/2, I=3.0 mA, P=0.9 torr

The temperature profile seems to be smoother than the Joule heat release profile that is proportional to $n_e(r)$ because of high enough value of thermal conductivity of neon. Still, the additional temperature gradient caused by formation of dust structures may have the reverse influence on the dust structures and cause the transformations of its shape.

Let us consider the forces acting on the dust particle in a discharge. The resulting force is a sum of three constituents: electric field force, thermophoretic force and ion drag force:

$$F(r) = F_e(r) + F_{th}(r) + F_i(r).$$

The radial electric field force is:

$$F_e(r) = -q(r)\, E_r(r),$$

where $q(r)$ is the charge of dust particle. The thermophoretic force is:

$$F_{th} = \frac{4PLa^2}{T}\frac{dT}{dr},$$

where P is the gas pressure and L is the atomic free path [11]. The ion drag force is:

$$F_i = m_d\, \nu_{di}\, u,$$

where m_d is a mass of dust particle, u is the ion flow velocity, and v_{di} is the momentum exchange rate (for details see [13]). The ion drag force magnitude is less than thermophoretic and electric forces, and the later are comparable in magnitude, except the region close to the tube wall, where the electric force strongly increases.

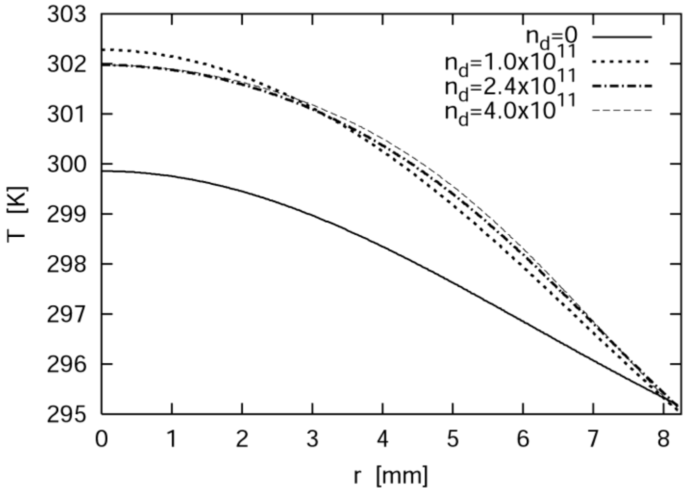

Fig. 2. Radial profiles of temperature at various values of dust particle concentration $n_d(r)$, discharge conditions of Fig. 1

The resulting force *F(r)* is represented in figure 3 for different values of $n_d(r)$. In figure 3 the force acting on a test dust particle with charge of $5x10^3e^-$ independent on radial dust particle coordinate, is represented. In other cases the dust particle charge depended on the radial coordinate accordingly to CEC model. One can see that the redistribution of electrons and the corresponding self-organizing of dust structures results in appearing of electric force directed inside the dust structure. This force keeps dust particles in equilibrium in a radial direction. The magnitude of this force increases with the growth of concentration of dust particles. Note, that the absolute value of the critical dust particle concentration in neon is of about $10^{11}m^{-3}$ that is higher than in air at the identical set of parameters, obtained earlier in [14]. The resulting force acting on a dust particle in a discharge is determined, for the most part, by the electric field force. On may conclude, consequently, that the mechanism of radial sustenance of dust particles in the discharge realizes through the self-consistent influence of dust particles on the discharge electric field configuration.

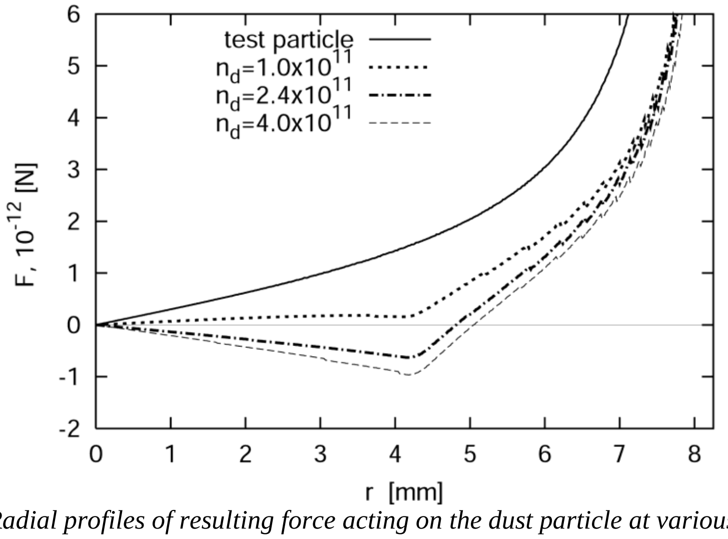

Fig. 3. Radial profiles of resulting force acting on the dust particle at various values of dust particle concentration $n_d(r)$, discharge conditions of Fig. 1

The motion of a dust particle in the radial direction is defined by its potential energy. Because the radial forces are proportional to the respective gradients:

$$F(r) = -\frac{dU}{dr},$$

then the total potential energy of a dust particle is:

$$U_r = -\int_0^R \left[F_e(r) + F_{th}(r) + F_i(r)\right]dr .$$

In figure 4 the potential energy of a charged dust particle as a function of the particle position is represented. Note that the high value of the potential energy of dust particle appear due to high value of its negative charge on the order of several thousands elementary charges and the radial electric field strength of several tens volts per centimeter. One can see that the arising additional force represented in figure 3, leads to the shift of the minimum of potential energy towards the wall of the discharge tube with the increase of the dust particle concentration. This should result in the formation of the ring dust structures (voids) that was observed earlier in air [15], and in the increase of the concentration of dust particles near the outer border of the dust structure [16].

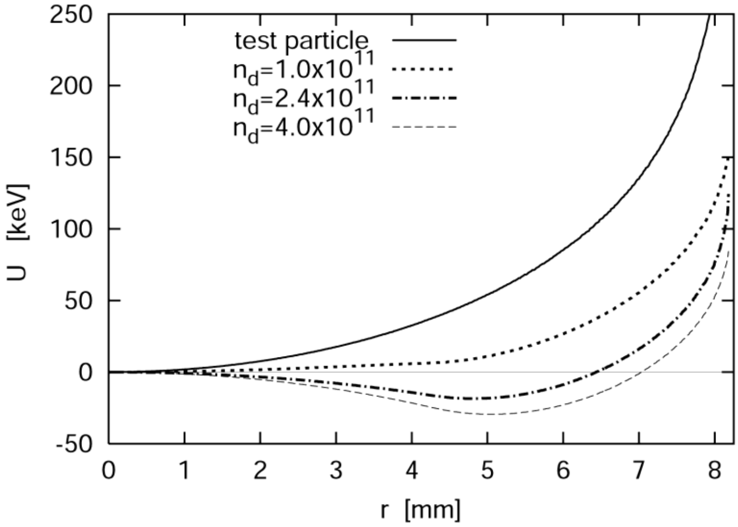

Fig. 4. Radial profiles of the dust particle potential at various values of dust particle concentration $n_d(r)$, discharge conditions of Fig. 1

4. Conclusions

In conclusion, one can see that the introduction of dust particles in the positive column of glow discharge in neon leaded to the noticeable increase of the longitudinal electric field strength that results the increase of the Joule heat release in the discharge. The arising additional temperature and concentration gradients result in the arising of the resulting force acting on the dust particle in a discharge and leading to the change of the position and shape of dust structures. The self-consistent electric field and thermophoretic forces play the major role in the formation of voids in dense dust structures.

Acknowledgments

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