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Dust particles influence on a stratified glow discharge

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In this work, the correlations between the parameters of a DC glow discharge and dust particles in a low-temperature plasma is studied. The formation of voids inside the dust cloud was studied, depending on the characteristics of the discharge (discharge pressure, type of gas and discharge current) and dust particles (quantity and size). We have demonstrated that the ion drag force could lead to the formation of voids in the center of the cloud of dust grains, which levitate in the field of a stratified positive column. It has also been demonstrated that the accumulation of dust particles affects the discharge plasma in a non-local way, i.e., the density distribution of dust grains and the charge of each individual particle depend on the plasma parameters outside the dust cloud. The presented qualitative estimates are important for understanding the processes occurring in complex plasma of a glow discharge.

Key words: dusty plasma, stratified glow discharge, voids in dusty plasma, Boltzmann equation for electron distribution function, Havnes parameter.
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1 Introduction

Dusty plasma is a complex medium that includes ionized gas and micron-sized solid particles that acquire a significant charge in this gas [1-3]. Such an environment can most often be found in outer space, but it is also common in industry (for example, in chemical deposition and coating processes). In laboratory conditions, dusty plasma is studied in the RF [4, 5] and in DC glow discharges [6-8]. There are also studies of dust particles in combined discharges of RF + DC [9-10]. As a result of extensive research, many interesting phenomena were discovered and studied in a dusty plasma, such as the ordering of dust particles into structures, phase transitions between different types of ordered structures, the formation of vortices in a dusty plasma, the propagation of sound waves, etc. [1-3].

The phenomenon of the appearance of large voids in a dust cloud under microgravity conditions in RF discharges is a well-known [11-12]. Various analytical models have been developed for its description [13-15]. Because of experimental, theoretical and numerical studies, it was found that the ion drag force, which arises due to the outflow of ions from the ionization source, is responsible for the formation of voids in the dust cloud [13].

In a dusty plasma obtained in laboratory conditions (both in direct current discharges and radio frequency discharges), the density of ions and electrons is $n_i \approx n_e \sim 10^7$-$10^9$ cm^{-3}, the density of dust particles is $N_d \sim 10^2$-10^8 cm^{-3}, the charge of each dust particle can vary in the range $eZ_d = (10^3$-$10^5)$ e. In the case when the Havnes parameter $P_H = Z_d N_d/n_e \ll 1$, the charge of dust grains is determined from the conditions in the plasma. At large P_H, local plasma distributions near dust particles (electron density, electric potential distribution, electron energy distribution function (EEDF)) change, which causes the average charge of charge of dust grains. The non-local effect of dust particles on the properties of a RF discharge, which is widely used in the semiconductor industry, was studied using particles in a cell method by J. P. Boeuf [16]. As a result of research, it was found that each dust particle is a sink for ions and electrons, which means that a cloud of high-density dust particles will have a significant effect on the properties of the plasma and the conditions of confinement of the dust grains themselves. However, this important phenomenon is often omitted in studies of dusty plasma in discharges. Moreover, so far in many works it is often assumed that the electron energy distribution function is Maxwellian.

At present day, a significant number of works have been published that are devoted to how dust grains affect plasma characteristics [16–28]. As a result of these studies, it was concluded that the loss of electrons and ions due to dust particles is compensated by ionizing collisions, therefore in the region containing dust particles, the averaged electric field increases. In [17–18], a self-consistent kinetic model was used, which showed that an increase in the concentration of dust grains leads to an increase in the ion density and an averaged electric field, as well as to a decrease in the electron density and the average charge of the dust particles of the cloud. However, it is worth noting that the number of dust particles in this model was set, and the effect of dust particles on the plasma was taken into account in the local approach.

In the case when the density of dust particles in the cloud is very high, its effect on the distribution in the discharge plasma becomes non-local [21-23]. One of the important consequences of this non-locality is that the average charge of particle grains depends on the fluxes of ions and electrons into the cloud from the plasma outside the cloud. In many articles, the characteristics of dust particles are studied without taking into account their influence on the parameters of a gas-discharge plasma. For example, the electric field that holds dust particles is usually considered constant and is specified as a parameter. The influence of a dust cloud on radial distributions in plasma was studied by a nonlocal kinetic model in [24–28]. The purpose of this work is to emphasize the non-local effect of dust particle accumulation on DC discharge plasma.

2 Kinetic approach for description of dusty plasma parameters

Based on the Boltzmann equation for EEDF, a self-consistent kinetic study of the influence of the density of dust particles N_d on the PC parameters of a low-pressure direct current glow discharge for a noble gas plasma was carried out. It should be noted that even without dust grains, a glow discharge in cylindrical tubes is a very complex non-equilibrium system of ions, electrons, and neutral atoms. At some initial parameters, the glow discharge self-organizes (stratification of the positive column), and nonlocal processes play an important role in this. The addition of dust particles to this complex system substantially complicates its description. A simplified model is considered here, which is able to isolate the main problems of the interaction of dust grain clusters and plasma parameters.

The charge of each specific dust particle is found from the OML approximation, that is, in the case in which the average mean free path of ions l_i in the plasma significantly exceeds both the dust grain size r_0 and the screening length λ_i. This work does not take into account the capture of ions by dust grain and, as a consequence of this, the occurrence of an additional collisional ion flux. In [29, 30], it was found that the capture of ions by a dust particle leads to screening of the charge of the dust particle and to a decrease in its charge. Nevertheless, this does not change the qualitative conclusions about the effect of the density of dust particles on the discharge parameters. It is also worth considering the non-Maxwellian character of EEDF in a non-equilibrium low-temperature dusty plasma.

In order to describe the formation of voids in dust clouds in a direct current discharge, a previously developed self-consistent kinetic model was used to calculate the radial distributions of dust plasma parameters [22-23]. In this model, it was assumed that a cloud of dusty spherical grains of radius $r_0 \sim 1$ μm has a certain distribution of radial density $N_d(r)$. The Boltzmann equation for the electron energy distribution function was used in the "two-term" approximation for the isotropic f_0:

$$\sqrt{\frac{m_e\varepsilon}{2}}\frac{\partial f_0}{\partial t}=\frac{1}{r}\frac{\partial}{\partial r}\left[\frac{r\varepsilon}{3H}\left(\frac{\partial f_0}{\partial r}-e_0E_z\frac{\partial f_0}{\partial\varepsilon}\right)\right]+$$
$$+\frac{\partial}{\partial\varepsilon}\left[\frac{\varepsilon}{3H}\left(-e_0E_r\frac{\partial f_0}{\partial r}+e_0^2\left(E_r^2+E_z^2\right)\frac{\partial f_0}{\partial\varepsilon}\right)\right]+ \tag{1}$$
$$+\frac{\partial}{\partial\varepsilon}\left[C(\varepsilon)f_0\right]-G(\varepsilon)f_0+$$
$$+S(f_0)+S_{ion}(f_0)+S_d(f_0),$$

and anisotropic (axial f_z and radial f_r) components related, respectively, to the similar components of the electric field, $E_r(r)$ and $E_z(r)$. Coefficients C, G, and S determine the energy lost in elastic and inelastic collisions. The value of E_z was calculated from the balance of the formation of ions and electrons as a result of ionization $S_{ion}(f_0)$ and their recombination on the surface of dust particles and on the walls of the discharge tube. Obviously, these processes are non-local. The radial j_{er} and axial j_{ez} current densities, electron density $n_e(r)$, ionization rate constants, and electron and ion absorption rates on the surface of dust particles were calculated from the Boltzmann equation. To calculate the ion density $n_i(r)$, the drift-diffusion equation is used with the conditions for their loss upon absorption on the surface of dust particles and the formation of ions in electron-atom collisions:

$$\frac{\partial n_i(r,t)}{\partial t}-\frac{1}{r}\frac{\partial}{\partial r}r\times \times\left(\mu_i n_i(r,t)E_r(r,t)-D_i\frac{\partial n_i(r,t)}{\partial r}\right)= =\nu_{io}(r,t)-\nu_{rec}(r,t) \quad (2)$$

In the absence of dust particles, in noble gases, the diffusion coefficients D_i and ion drift μ_i are determined only by charge exchange collisions and are related to each other by the Einstein relation. In the discharge where dust grains are located, the drift and diffusion coefficients depend both on the density of dust particles $N_d(r)$ and on the gas density N_g.

The density of dust particles $N_d(r)$ was calculated by the drift diffusion equation:

$$\frac{\partial n_d(r,t)}{\partial t}-\frac{1}{r}\frac{\partial}{\partial r}r\times \times\left(\mu_d n_d(r,t)F_d(r,t)-D_d\frac{\partial n_d(r,t)}{\partial r}\right)=0 . \quad (3)$$

It was assumed that the diffusion coefficients D_d and mobility μ_d of dust particles obey the Einstein relation. In this work, temperature T_d = 10 eV is used, due to the fact that the temperature of dust particles was not so significant for the results obtained. Dust grains are confined in the center of the tube and form a dust cloud. Due to the lack of sources of dust particles losses, we do not need to take the actual values of the mobility and diffusion coefficients only taking into account the Einstein relation between them. In the process of numerical calculation, the radial profile of the dust density is estimated, and in the final state, the radial flux of dust particles $j_{dr}(r)$ = 0. The total force F_{tot}, which affects the dust grain in the radial direction, is determined by the superposition of forces:

$$F_{tot}=F_E+F_{id}+F_{th}+F_{dd}, \quad (4)$$

where $F_E = -eZ_d(r)E_r(r)$ is electric force, $F_{id} \sim j_{ir}(r)$ is the ion drag force, F_{dd} is the repulsion forces of dust particles (calculated similarly to [22]), and $F_{th} \sim \Delta T$ is the thermophoretic force. The forces F_{id} and F_{th} are opposite in direction to F_E, which leads to the formation of voids in the central part of the dust cloud in the middle of the discharge tube under certain conditions. There are many works that are devoted to assessing the strength of ion drag force. In this work, F_{id} was taken as in [22]:

$$F_{id}=\frac{\sqrt{8\pi}}{3}n_i u_i v_{T_i} R_C^2 m_i\times \times\left[\Lambda(\beta_T)+\sqrt{\frac{2}{\pi}}\kappa\left(\frac{\lambda_D}{l_i}\right)\right]. \quad (5)$$

Here $\Lambda(\beta_T)$ is the modified Coulumb logarithm and κ(x) – a collisional function, the exact expressions are given in [22].

The equations for ions, electrons, and dust particles were supplemented by the Poisson equation, which calculated the self-consistent electric field $E_r(r)$:

$$\frac{1}{r}\frac{\partial(rE_r(r,t))}{\partial r}=4\pi e_0\left[n_i(r,t)-n_e(r,t)\right]. \quad (6)$$

Thus, a complete system of equations is obtained for the self-consistent determination of $n_e(r)$, $n_i(r)$, $N_d(r)$ и $E_r(r)$. In this paper, we solved the non-stationary case for ions, electrons, and dust particles based on the balance equations obtained using the Boltzmann equation for EEDF and the electric field obtained from the Poisson equation. At each time step, the charge number Z_d was determined from the condition of the balance of fluxes of ions and electrons on the surface of the dust grain ($I_e + I_i = 0$), taking into account the distribution functions of ions and electrons [22]. The axial electric field voltage was recounted at each time step using the feedback between the discharge current E_z and I_d. The procedure was repeated until the parameters of dust particles and plasma distributions completely converged. It is worth noting that the evolution of plasma parameters in time has not been considered here, since only the final convergent solution for the given parameters of the gas discharge is of interest.

3 Results and discussion

In the present work, we study a stratified positive column of a glow discharge in a quasi-2D arrangement. In the absence of dust grains in the tube, the axial electric field is E_z, and the electron current density on the tube axis is j_z. In the stationary state, the creation of new ions and electrons is completely compensated by their recombination on the tube wall, which is determined by the process of ambipolar diffusion. It is known that EEDF depends only on parameter E_z/N_g. If, however, micron-sized dust particles with a density of N_d are placed in the discharge, then ions and electrons will participate in the recombination on surfaces of both walls and dust particles, which for electrons can be considered in the Boltzmann equation for EEDF as volume recombination. Another of the main parameters affecting the distribution of dusty plasma is the total number of dust grains N_{tot}. In experiments, this parameter is difficult to control. The number of dust particles and the radial profile of their distribution in space are formed self-consistently. In the calculations, it is possible to establish various values of the total number of dust particles per unit length (per 1 cm) of the positive column, which is equal to the integral of the particle density over the cross section of the discharge tube.

Using calculations by this model, it was found that for values of the discharge current I_d < 8 mA, clouds of dust particles have the usual compact structures. In this case, voids in the cloud do not appear, and the N_d distribution has a uniform decaying radial profile with a maximum in the center of the discharge tube. With the increase of current I_d, the density of dust particles N_d in the center of the cloud decreases. At I_d > 10 mA, the particles in the cloud move away from the center of the discharge tube to the periphery. With a further increase in I_d, the radius of voids increases, and the cloud of dust particles has a “cup-shaped” structure without particles in the upper and central parts of the cloud. In Figure 1, dust particle density radial distributions for discharge currents 8 mA and 13.4 mA are presented.

An analysis of papers (see, for example, [22]) devoted to studies of the formation of voids in dusty plasmas shows that a void is formed in RF discharges when the electrostatic force becomes less than the ion drag force (assuming that other forces are negligible). If the ion drift $u_i = \mu_i E$ is proportional to the electric field strength E, the ratio of F_{id} and F_E can be represented as [22]: $|F_{id}/F_E| \sim \mu_i n_i Z_d$, i.e. the ratio is proportional to the charge of dust particles Z_d, ion density n_i and ion mobility μ_i,. An estimate in [22] showed that the condition $|F_{id}/F_E| > 1$ can be achieved at low gas pressures $\mu_i \sim 1/p$, high discharge currents $n_i \sim I_d$, and for large dust particles $Z_d \sim r_d$. In the case of a direct current discharge with cylindrical symmetry, voids are formed on the axis of the discharge tube. The radial component $F_{id}(r)$, as well as the radial component $F_{th}(r)$, expels dust grains from the center of the dust cloud to the periphery, despite the electrostatic force $F_E(r)$, which traps particles on the axis of the discharge tube. In voids, the condition $|F_{id}/F_E|>1$is satisfied. At Figure 2 radial distributions of the product of dust particle density and the forces acting on dust particles for discharge currents 8 mA and 13.4 mA are presented.

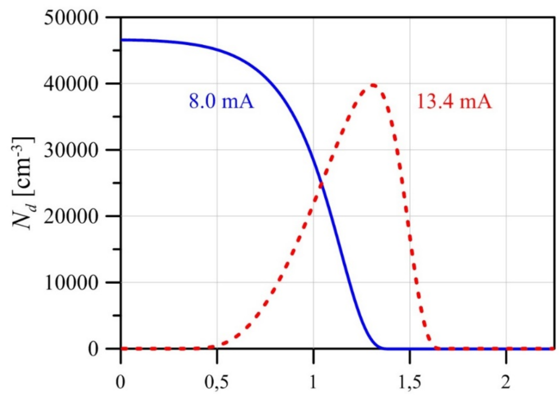

Figure 1 - Dust particle density radial distributions for discharge currents of 8 mA and 13,4 mA, gas pressure 0,38 Torr, dust particle diameter 2 µm. Solid line for I_d = 8 mA, dashed line for I_d = 13,4 mA.

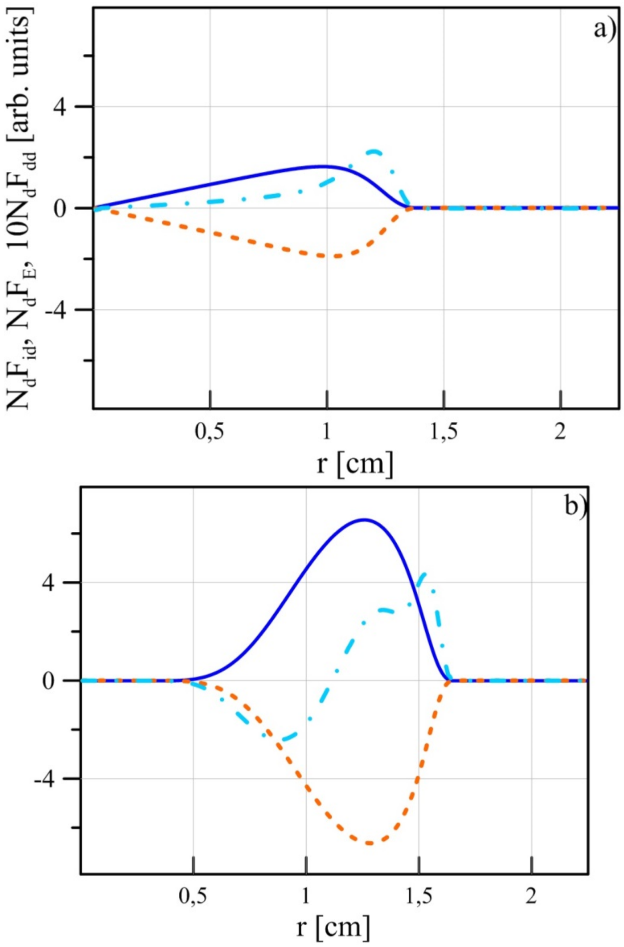

Figure 2 - Radial distributions of the product of dust particle density and the forces acting on dust particles: solid line for the ion drag force $F_{id}N_d$, dashed line for the electrostatic force F_EN_d , dashed dotted line for the interparticle repulsive force $F_{dd}N_d$. (a) I_d = 8 mA, (b) I_d = 13.4 mA.

4 Conclusions

It should be noted that the obtained conditions for the formation of voids are nontrivial. A simple increase in the discharge current (as well as a decrease in gas pressure or an increase in the particle radii or) by a factor of two will not lead directly to twice pronounced void. These parameters are highly dependent on each other self-consistently. If you increase the discharge current, then the electric field, axial and radial strengths, particle charge and other parameters will vary depending on each other.

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