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Abstract. The flight of aircraft at about orbital velocity in the upper atmosphere results in the problem of protecting the aircraft from drag flux of the dust grains. Under cosmic rays the upper atmosphere gas is ionized so the dust grains are charged here. Behavior of the dust ensemble highly depends on charge of grains, therefore, simulation of the ensemble properties requires the information about grain charge and about interaction potential. The similar problem also arises at simulation of MHD-generator characteristics on solid fuel basis, the problems for both the first case and the second one being essentially non-one-dimensional.

The present paper reports about the results of two-dimensional simulation of charging dust grains in argon plasma created by external ionization source at different applied uniform electric field strength varied from 0 to 1200V/cm. The system consisting of the electron and ion discontinuity equations and the Poisson equation was self-consistently solved. It is found that the external electric field had an obvious effect on charge accumulated by the dust grain despite the external electric field was distinctly smaller than dust grain field.

Introduction

At present in connection with extremely rapid development of microtechnology and technology of new material production the great interest is observed for studying the plasma with the condensed disperse phase [1-7]. One of the most significant parameters of the dusty plasma, determining its unique properties, is the charge collected by dust particulates. At the usual conditions in the plasma the charge of the dust particulates is negative due to significantly higher electron mobility. In estimating the charge and forces acting in the dust particulates the orbit motion limited approach (OML) is widely used at present. This approach is highly crude and has rather a limited region of applicability.

It is exactly inapplicable at elevated pressures where the collisions of electrons and ions with the neutral gas particles are not ignorable. The discharges at elevated pressures are widely used in the plasma-chemical setups and high power gas lasers. During the operation of these systems in the discharge medium the dust particulates appear either due to sputtering of electrodes or discharge wall, or due to polymerization of radicals created in the discharge zone. The dust particulates greatly, in some cases cardinally, change discharge characteristics and properties, the rates and even direction of the plasma-chemical processes. The interest to study the dusty plasma is also associated with the problem of invention of compact stationary radionuclide generator of electric power on the basis of plasma-dusty structure for aerospace and other applications [8,9]. Firstly, in such a generator the energy of the radionuclide decay is transformed to ultraviolet emission of excimer molecules, for example, of xenon. Secondly, with the wide gap photovoltaic transformer used, the ultraviolet emission energy is converted to electricity. But under these conditions the problem of photon transport in the gas medium with dust particulates arises. For solving this problem the creation of ordered dusty-plasma structures or of coulomb crystal of dust particulates is required.

Description of 2D model

One-dimensional simulation of dust particle charging in atomic and molecular gases at elevated pressures on the basis of diffuse-drift approach was performed in [10-13]. At fulfillment of the conditions [14-18]

\[ \lambda_e < r_0 + d, \quad \lambda_i < r_0 + d, \]  \(1\)

where \(\lambda_e, \lambda_i\) are the mean free paths of electrons and ions, respectively, \(r_0\) is the dust particle radius and \(d\) is the characteristic size of quasineutrality violation region, the transport processes of charged plasma particles could be considered in the diffuse-drift approximation. When the gas pressure is about atmospheric or higher, the mean free path of ions is usually the magnitude of about \(10^{-5}\) to \(10^{-6}\) cm, and that of electrons in the absence of electrical field is \(\lambda_e(10^{-4}\) to \(10^{-7}\) cm in inert gases (except neon), \(\lambda_e(10^{-4}\) cm in nitrogen and in air. In the electrical field the free path of electrons has quite complicated behavior in inert gases for the case of Ramzauer minimum in electron scattering cross-section, but does not exceed \(10^{-3}\) cm, however, and \(\lambda_e\) always drops with the growth in the electric field in air and in nitrogen. According to estimation the typical size for the region of quasi-neutrality violence in plasma is the magnitude of about \(10^{-3}\) cm for particles with the radius of \(10^{-4}\) cm. Therefore,
condition (1) for the particles, whose radius is greater than $10^{-4}\text{cm}$, under atmospheric or higher pressure is accomplished both in atomic and molecular gases.

For a stronger condition for electrons

$$\lambda_\omega << r_0 + d,$$  

(2)

where $\lambda_\omega$ is the length of electron energy relaxation, it is possible to use a local approximation [14] for determining such electron parameters as mobility, diffusion coefficient, rate coefficients of electron production and loss. For ions the length of free path and that of energy relaxation practically coincide because for neutral gas the mass of ions and that of particles are comparable. Estimation shows that condition (2) is practically always accomplished under atmospheric pressure for particles of $10^{-4}\text{cm}$ in radius or greater ones. For atomic gases under the considered conditions the opposite inequality is true:

$$\lambda_\omega >> r_0 + d.$$  

(3)

When this condition is accomplished the field of charged dusty particle weakly disturbs the electron distribution function, therefore, for this case it is possible to use the electron parameters calculated for the plasma without a dusty component.

The present work shows two-dimension calculations of the charging process for dusty particles in argon under atmospheric pressure. The gas ionization was performed by an external ionization source. Development of two-dimension model was basically brought by the necessity to solve the following two problems. Usually the dusty plasma is in the external electric field. For example, in a compact stationary radioisotope generator of electric energy on the basis of plasma dusty structures the external electric field is applied to execute formation and confinement of the levitating ordered structure of dusty particles. In this case the problem of charging the dusty particle becomes axially symmetrical which requires at least two-dimension model. The second problem, also axially symmetrical, is related to modeling the process of two-particle interaction. The present work is devoted to the solution of the problem mentioned the first.

The equation system which self-consistently describes the process of charging dusty particles consists of discontinuity equations for electrons and ions and of the Poisson equation. Let's consider cylindrical system of coordinates, its origin being at the center of the dusty particle and $z$-axis along the vector of the applied external field strength. Having the radius equal to the mean distance between particles $R = \left(\frac{3}{4\pi}n_d\right)^{1/3}$ and the height $2R$, the cylinder, in the center of which there is a dusty particle, is considered to be quasi-neutral. For the cylindrical system of coordinates the self-consistent system of equations for calculating dusty charges in the external field is as follows:

$$\frac{\partial n_e}{\partial t} + \frac{1}{r} \frac{\partial}{\partial r} \left( r D_e \frac{\partial n_e}{\partial r} - n_e k_e E_r \right) + \frac{\partial}{\partial z} \left( -D_e \frac{\partial n_e}{\partial z} - n_e k_e E_z \right) = R_e$$

$$\frac{\partial n_i}{\partial t} + \frac{1}{r} \frac{\partial}{\partial r} \left( r D_i \frac{\partial n_i}{\partial r} + n_i k_i E_r \right) + \frac{\partial}{\partial z} \left( -D_i \frac{\partial n_i}{\partial z} + n_i k_i E_z \right) = R_i$$

(4)

where $R_e = R_i = Q + k_{ion}n_e N - e_i \alpha n_i n_e$ are the sources for production and loss of electrons and ions, $E_e, E_z$ are the components of the vector of the self-consistent electric field strength for $z$- and $r$-axes, the components can be determined according to the last equation of system (4) by using the equation

$$E = -\nabla \phi,$$

which makes a relation between the potential and the vector of electric field strength, $n_e, n_i$ are the concentrations of electrons and ions, accordingly; $N$ is the concentrations of neutral particles; $Q$ is the rate of gas ionization by an external ionization source; $k_{ion}$ is the rate of gas ionization by intrinsic electrons of plasma; $\beta_\alpha$ is the coefficient of dissociate electron-ion recombination; $k_e, k_i$ are the mobility coefficients and $D_e, D_i$ are the coefficients of diffusion of electrons and ions, accordingly (in the present work the transport coefficients were...
considered to be constant, their magnitudes for both one-dimension and two-dimension models being determined by the external electric field.

The following boundary conditions were set for the end faces of the cylinder:

\[ n_e |_{z=R} = n_e |_{z=-R}, \quad n_i |_{z=R} = n_i |_{z=-R}, \]
\[ E |_{z=R} = E |_{z=-R}, \]
(5)

and lateral faces had Neumann conditions:

\[ \frac{\partial n_e}{\partial r} |_{r=0} = 0, \quad \frac{\partial n_i}{\partial r} |_{r=0} = 0, \quad \frac{\partial E}{\partial r} |_{r=0} = 0, \]
\[ \frac{\partial n_e}{\partial r} |_{r=R} = 0, \quad \frac{\partial n_i}{\partial r} |_{r=R} = 0, \quad \frac{\partial E}{\partial r} |_{r=R} = 0. \]
(6)

Formulation of the boundary conditions on the surface of a dust particle for the problem described here is a complicated task which is related to the violence of conditions for using the hydrodynamic approximation in the Knudsen layer and to the necessity to consider the molecular regime of charged particle transport. On the base of experimental data it is assumed that when electrons and ions are on the surface of a dusty particle their charge is absorbed with unity probability, therefore, there are zero boundary conditions on the surface of the dusty particle:

\[ n_e |_{z=\text{Dust}} = 0, \quad n_i |_{z=\text{Dust}} = 0, \quad E |_{z=\text{Dust}} = 0. \]
(7)

It was assumed that a dusty particle consisted of the conducting material. Polarization of dusty particle charge in the external field was given according to the analytical solution of the problem about the conducting ball in the external homogeneous field [12].

Solution of system (4) with boundary conditions (5-7) was performed according to the alternating-direction fully implicit method and the factorization method.

**Discussion of results**

In Fig.1 there is a comparison of results obtained according to one-dimensional and two-dimensional models of dusty particle charging process. There are graphs of charge evolution of dusty particle of 12\( \mu \)m in radius in non-self-sustained discharge in argon under atmospheric pressure, for the gas ionization rate of \( Q=1.5\times10^{17}\text{cm}^{-3}\text{s}^{-1} \) in Ar at the atmospheric pressure. Curve 1D (SS) is the result of the one-dimensional simulation according to [11-13]; 2D (SS) is the result of the two-dimensional spherical symmetric simulation with taking into account only the effect of the external field on the transport coefficients; 2D (AS) is the result of the two-dimensional axial symmetric simulation with taking into account all the effects due to the external field.

Fig.2 shows the dependence of the dust charge on the applied external field. As it was assumed the external field has a great effect upon the dusty particle charge. This is, first of all, due to heating up the electrons in the external field which two-dimensional models lead to nearly the same result, and taking into account the flows caused by external field and by plasma and dusty particle charge polarization results in the increase in the charge accumulated by a dusty particle.
results in the changes in transport coefficients, that is, in the growth in \( D_2/k_e \) ratio, which the charge is practically linearly dependent on \([8,9]\). As it is seen in Fig.2 one-dimensional and two-dimensional models give nearly the same result for low fields, for greater fields the charge in the two-dimension model grows much faster than that in the one-dimensional model.

The external field has a considerable effect upon the spatial distribution of ions and electrons. Fig.3 illustrates this effect for ions (on the left) and electrons (on the right). It should be noted that for \( \theta=\pi/2 \) (perpendicular-to-the-field direction) the distribution of charged particles practically coincides with that calculated according to the one-dimension model.

Fig.4 shows the charge distribution in the vicinity of a dusty particle, and Fig.5 show the distribution of the self-consistent field without the external field. In Fig.4 it is seen that the charge separation towards the field is greater than that along the field. It is due to the fact that the field created by the polarization of dusty particle charge by the external field is added to the field of the dusty particle charge, when \( \theta=\pi \), and is subtracted from the field of the dusty particle charge, when \( \theta=0 \), therefore, the total field along the \( \theta=\pi \) direction is greater than that along the \( \theta=0 \) one. It is seen in Fig.5 that for the region of maximal charge separation (up to \( \approx 30\mu m \) from the dusty particle center) the field of the charged dusty particle is greater than the external field, therefore, for the external field strength considered in this work the influence of polarization of the plasma and the own particle on the charge is low.

**Conclusion**

Therefore, the performed simulation showed that the external field had a considerable effect upon the charge accumulated by the dusty particle for the electric field strength up to 1200 V/cm. That basically occurred due to the increase in diffusion coefficient and electron mobility. Besides that, the external field creates redistribution of charges which can change the character of interaction of dusty particles due to dipole and higher moments. This is a subject for further research.

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