TWO-DIMENSIONAL SIMULATION OF DUST CLOUDS IN A PLASMA

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In this article has been carried numerical simulations of the interaction of the partically ionized argon plasma and a dust cloud, which is situated near the wall in a cylindrical vessel. The plasma and dust dynamics studied in the frame of two-dimensional hydrodynamics model, the charge of dust particles is determined acording to the orbit-limited probe model, the potential of the self-consistent electric field is described by Poisson equation. As a result simulations the spatial distributions of dust cloud parameters are obtained at different times.

PACS: 52.27.Lw

1. INTRODUCTION

The physics of dusty plasmas has been extensively studied in the last decade in view of practical applications in space, as well as laboratory situations. Particular attention has been paid to the study of collective processes, such as the formation of nonlinear structures like solitons, double layers, voids, vortexes and dust clouds with sharp boundary. These phenomena are observed in many capacitively coupled rf devices [1], dc glow discharged devices [2] and recently have been discovered in microgravity experiments [3]. A characteristic feature of bounded dusty plasmas with free boundaries is the expansion process. The one-dimensional expansion of an unmagnetized dusty plasma was examined by [4], [5]. It is necessary note that experimental results shown that dust clouds are not one-dimensional [3] and this feature may causes new phenomena.

In this article we investigate the temporal behavior of dust clouds in plasma near a solid wall using two-dimensional hydrodynamic model and a computer simulation.

2. MODEL

We consider partially ionized argon plasma in a cylindrical vessel (fig.1). The cloud of dust particles immersed into the plasma near the solid wall. The form of the dust cloud at initial time is a disk. In our model dust grains acquire a charge and influence the potential of the electric field φ, which is described by Poisson equation:

$$\Delta\varphi = -\frac{1}{\varepsilon_0}\left(en_i - en_e + q_d n_d \right).$$

The wall potential φ_0 at the bottom of the vessel (Fig.1) is floating. The other walls of the vessel are grounded ($\varphi = 0$).

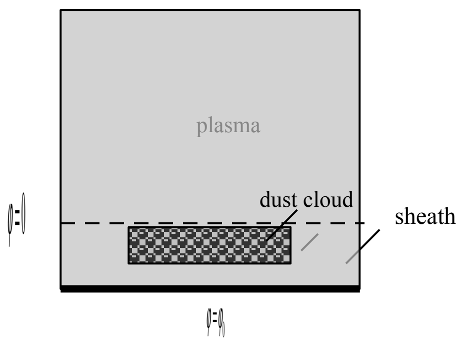

Fig.1

Electrons are assumed to be in a thermal equilibrium; therefore their density satisfies the Boltzmann distribution

$$n_e = n_{eo}\cdot\exp\left(\frac{e\varphi}{kT_e}\right),$$

where n_{e0} is the electron density far away from the charged wall.

Ions and dust particles are treated as a cold fluid, governed by the continuity and the momentum conservation equations

$$\frac{\partial n_i}{\partial t} + div\left(n_i \vec{w}_i \right) = -\frac{I_i}{e} n_d,$$

$$\frac{\partial n_i}{\partial t} + div\left(n_i w_h \right) = -Y_i n_d,$$

$$m_i n_i \left[\frac{\partial \vec{w}_i}{\partial t} + \vec{w}_i \nabla \vec{w}_i\right] = -en_i \nabla\varphi + \vec{F}_{id},$$

$$m_d n_d \left[\frac{\partial \vec{w}_d}{\partial t} + \vec{w}_d \nabla \vec{w}_d\right] = -q_d n_d \nabla\varphi - \vec{F}_{id} + \vec{F}_n.$$

The dust charge q_d is determined by the charging currents

$$\frac{\partial q_d}{\partial t} + \vec{w}_d \nabla q_d = (I_i - I_e).$$

Here n_i, n_d are ion and dust densities, $\vec{w}_i$, $\vec{w}_d$ are drift velocities of ion and dust fluids.

According to the orbit-limited probe model, the electron and ion charging currents I_e and I_i are determined by local electron and ion densities, as well as the potential difference between the grain surface and the local plasma. They are given by

$$I_e = -\pi r_d^2 e \sqrt{\frac{8kT_e}{\pi m_e}} n_e K_e(q_d),$$

$$I_i = \pi r_d^2 e \sqrt{\frac{8\,kT_i}{\pi m_i}} n_i \left(1 - \frac{eq_d}{r_d kT_i}\right),$$

where $K_e(q_d) = \exp\left(\frac{eq_d}{r_d kT_e}\right)$ when $q_d < 0$ and $K_e(q_d) = 1 + eq_d / r_d T_e$ when $q_d > 0$.

We assume that the forces on the dust consist of electrostatic force, ion drug forces, and neutral collision force. The ion-drag force $\vec{F}_{id}$ consists of the collection $\vec{F}_{id}^c$ and orbit $\vec{F}_{id}^o$ components. The collection force is a result of the momentum transfer from the ions collected by the particle, so that $F_i^c = n_i m_i \vec{w}_i |\vec{w}_i| \pi b_c^2$, and the orbit force is conditioned by momentum transfer from the ions of orbital motion around the grain

$$\vec{F}_i^o = n_i m_i \vec{w}_i |\vec{w}_i| 4\pi b_{\pi/2}^2 \Gamma,$$

where $b_{\pi/2} = eq_d / m_i w_i^2$ is the orbital impact parameter and $\Gamma = \ln[(\lambda_d^2 + b_{\pi/2}^2)/(b_c^2 + b_{\pi/2}^2)]^{1/2}$ is the Coulomb logarithm integrated over the interval from collection impact parameter to Debye radius λ_d. The neutral gas collision force $\vec{F}_n$ is given by:

$$\vec{F}_n = \frac{16\sqrt{\pi}}{3}\left(1 + \frac{\pi}{8}\right)\frac{r^2 n_n T_n}{w_{th}} \vec{w}_n,$$

where $\vec{w}_n$ is neutral gas velocity, w_{th} is neutral gas mean thermal velocity, n_n, T_n, and m_n are the neutral gas density, temperature, and mass, respectively.

The modified method of big particles [6] is used for the computer modeling of this problem. In this method the complex set of equations is separated on simpler components which describes separated physical processes. The general solution consists of additive members of time influences of each process on spatial parameter distributions. Each process is simulated with the corresponded minimum characteristic time what allows to obtain higher simulation precision.

3. RESULTS

We simulated the evolution of the two-dimensional dust cloud using the large particles method [5]. Calculations were carried out for following plasma parameters: $n_{io}=n_{eo}=10^{12} cm^{-3}, T_e = 1eV$, $r_d = 0.1\mu m$, $n_d=10^8 cm^{-3}$, $n_n=10^{16} cm^{-3}$. The length and the radius of the vessel are $L=10cm$ and $R_0=2.5cm$ corresponding.

Figure 2a shows the spatial distribution of dust density at $t\omega_{pi} = 300$ after the beginning of the dust cloud expansion. The dust density is normalized on the ion density in the unperturbed plasma; the spatial coordinate is normalized on Debye radius.

We can see that the density of dust particles is not uniform along radius. Its maximum is at axis of symmetry ($r = 0$). Expansion of dust cloud is carried out radially. The dust cloud doesn't expand along axial axis in consequence of the balance of electrical and viscosity forces. It is confirmed by fig.2b, where distributions of dust density along axial axis are shown. These distributions are invariable during the long time interval.

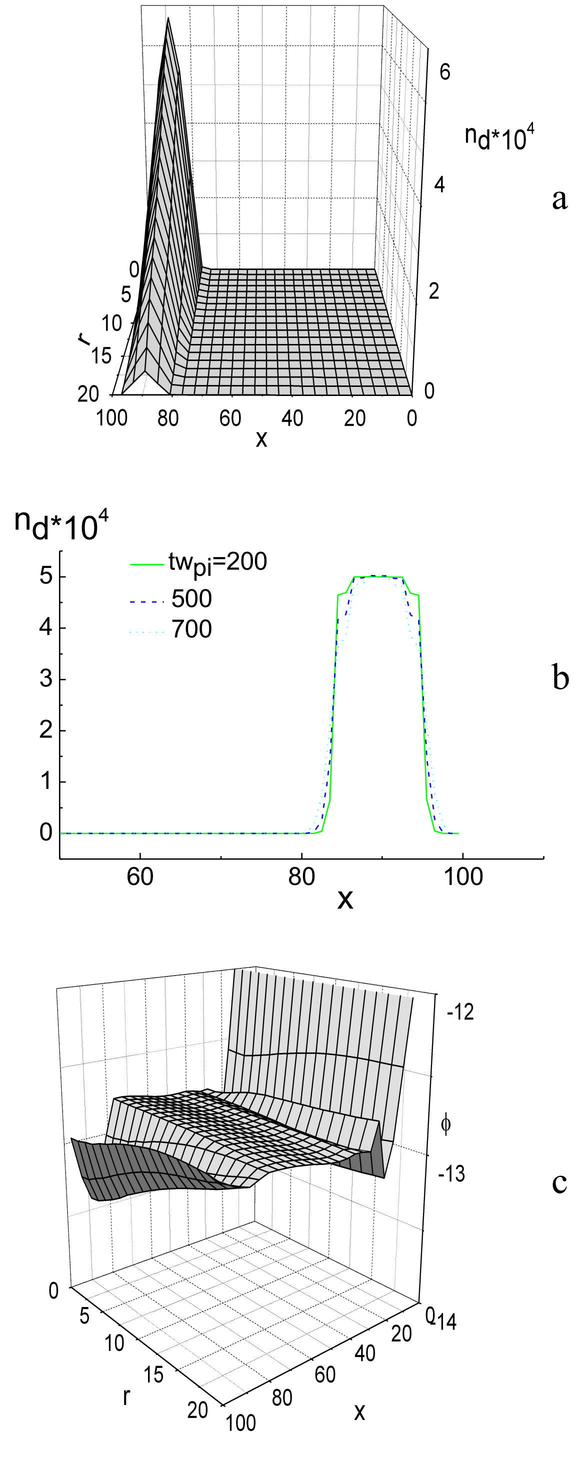

Fig. 2. The spatial distributions of dust density (a) and electrical potential (b) at $t\omega_{pi}$=300

The electrical potential φ is shown in figure 1b as a function of radius r and axial coordinate x. Here the potential is normalized on the characteristic potential $\frac{kT_e}{e}$. We can see that at the boundary of dust cloud double layers are formed. These double layers cause the capture of dust particles in some region near the wall.

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ДВУХМЕРНОЕ МОДЕЛИРОВАНИЕ ПЫЛЕВЫХ СГУСТКОВ В ПЛАЗМЕ

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Проведен численный расчет взаимодействия частично ионизированной аргоновой плазмы с пылевым сгустком, который образуется возле стенки в цилиндрической камере. Для описания динамики плазмы и пылевых частиц использовалась двухмерная гидродинамическая модель, заряд пылевых частиц определялся при помощи модели ограниченных орбит, а потенциал самосогласованного электрического поля описывался уравнением Пуассона. При анализе динамики пылевых частиц учитывались электрические силы, а также силы, обусловленные ионной вязкостью и трением с нейтральными частицами. В результате проведенного моделирования получены пространственные распределения параметров пылевого сгустка в различные моменты времени.

ДВУХВИМІРНЕ МОДЕЛЮВАННЯ ПИЛОВИХ ЗГУСТКІВ У ПЛАЗМІ

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Проведено числовий розрахунок взаємодії частково іонізованої аргонової плазми з пиловим згустком, що утворюється біля стінки в циліндричній камері. Для описання динаміки плазми і пилових частинок використовувалась двовимірна гідродинамічна модель, заряд пилових частинок визначався за допомогою моделі обмежених орбіт, а потенціал самоузгодженого електричного поля описувався рівнянням Пуассона. При аналізі динаміки пилових частинок враховувались електричні сили, а також сили, обумовлені іонною в’язкістю та тертям з нейтральними частинками. В результаті проведеного моделювання одержані просторові розподіли параметрів пилового згустку в різні моменти часу.