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The Behavior of Dust Particles Near Langmuir Probe

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In the present work the dynamics of dust particles near electric probe in gas discharge at different pressures was studied. Trajectories of dust particles near electric probe with taking into account of the ion drag force and neutral friction force were calculated numerically. The comparisons between experimental and calculated results showed the good agreement.

1 Introduction

Dusty plasma is an ionized gas containing particles of condensed matter. The presence of dust particles may significantly affect the parameters of the low-temperature plasma. Analysis of probe measurements in gas-discharge dusty plasma is not complete without understanding of the behavior of dust particles in the perturbed region near the probe [1, 2]. In this connection it is interesting to develop the mathematical model of the behavior of an individual dust particle near the probe which allows to study the important features of this phenomenon. This model requires the correct analysis of the forces acting on macroparticles. In this paper the electric force, ion drag force and neutral friction force were taken into account. Ion drag force is related with the momentum transfer from the ions current to the charged particle introduced into the plasma, it is very important factor in dusty plasmas [3].

2 Experimental setup

The motion of dust particles near the Langmuir probe was studied by the setup, based on a glow discharge. Gas discharge tube disposed vertically, the probe was injected into the plasma perpendicular to the positive column. The discharge in pure argon was created at pressures from 0.1 Torr to 0.3 Torr, and at electric current values of $0.5 - 3.0$ mA. The probe is a tungsten cylindrical electrode with the following linear parameters: diameter $d = 0.1$ mm, length $l = 2$ mm. To fix the trajectory a laser with a wavelength of 532 nm was used. A laser knife was produced by mean of the special optical system. It lightened the plane perpendicular to the camera. Recording of particles trajectories was performed with a CCD camera at 25 frames per second. After the negative potential had been given to the probe particles were injected into the plasma from container located at the top of the discharge tube. Potential of the probe is negative relatively to the plasma, so near the probe an ion layer sheath with a radius of several millimeters was formed [4]. Dust particles, flying through the ionic layer, behaved differently. Qualitatively one can say that at pressures from 0.1 Torr to 0.2 Torr the small deviation in trajectories of particles from initial directions was observed, at pressures larger than 0.2 Torr particles interacted with the probe more significantly, there were large angles of deviation. When a pressure in the discharge tube was about 0.3 Torr the most part of the particles after penetrating into the ionic layer had rotated around the probe about 1-2 times, and sticked to the probe.

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3 Simulation model

The dust particle moves under the influence of the electrostatic force, ion drag force and neutral friction force. Ion drag force is observed in the layer near the probe surface with a negative potential. Introducing polar coordinates r and θ in the plan of the trajectory and considering the center of the probe as a center of the reference system [1,2] the equation of motion can be written as:

$$M_d \frac{d^2 r}{dt^2} = -eZ_d \frac{dU(r)}{dt} + \frac{2K_0 p^2}{r^3} - \pi R_d^2 m_n n_n u_d v_{Tn} + \pi m_i n_i u_i v_s (b_c^2 + 4b_{\pi/2}^2 \Gamma), \tag{1}$$

$$\frac{d\theta}{dt} = \frac{p}{r^2} \left(\frac{2K_0}{M_d} \right)^{1/2}, \tag{2}$$

where $U(r)$ is the potential of the probe field, p is an impact parameter, K_0 is the initial kinetic energy of a dust particle, M_d is its mass, Z_d is its charge, m_n and n_n are mass and density of the neutrals, u_d and R_d are the velocity and radius of dust particle respectively, v_{Tn} is the thermal speed of neutrals, u_i is the ion drift velocity, $b_{\pi/2}^2 = eQ_d/4\pi m_i v_s^2$ is the scattering cross section of the Coulomb interaction between the ion and dust particle, $v_s = (8k_B T_i/\pi m_i + u_i^2)^{1/2}$, $b_c = R_d(1 - 2q_i\phi_s/m_i v_s^2)^{1/2}$ is the cross section of ion absorption by negatively charged macroparticle, $\Gamma = \frac{1}{2} ln(\lambda_D^2 + b_{\pi/2}^2)/(b_c^2 + b_{\pi/2}^2)$ is the standard Coulomb logarithm, λ_D is the Debye length.

Using the Poisson equation, the electric field distribution near the probe is:

$$\frac{1}{r}\frac{d}{dr}\left(r\frac{dU}{dr} \right) = -4\pi e[n_i(r) - n_e(r)] \tag{3}$$

Densities of electrons and ions are determined by the following expressions:

$$n_e = n_0 \exp\left[\frac{eU(r)}{kT_e} \right]. \tag{4}$$

$$n_i = n_0 \left\{ 1 - \frac{1}{\pi} \arcsin \frac{r_l}{r} \left[\frac{E_{0n} + eU(r_l)}{E_{0n} + eU(r)} \right]^{1/2} \right\} \quad for \quad r > r_l, \tag{5}$$

$$n_i = \frac{n_0}{\pi} \arcsin \frac{r_l}{r} \left[\frac{E_{0n} + eU(r_l)}{E_{0n} + eU(r)} \right]^{1/2} \quad for \quad r < r_l. \tag{6}$$

where E_{0n} is a quantity that approximately equals to ion temperature in plasma; r_l is so called limiting radius which is determined by the local maximum of the effective ion potential energy [1,2]. The charge of dust particles in the plasma is determined by the currents of electrons and ions on the surface:

$$\frac{dZ_d}{dt} = I_e + I_i. \tag{7}$$

Expressions for electron and ion currents obtained in the framework of orbit motion limited theory [5].

4 Numerical and experimental results

The experimental and numerical calculation were performed for the dust particle of radius 10 μm and mass of $2.1 \cdot 10^{-10}$ g, mass of the atoms (ions) of argon $m_i = 6.63 \cdot 10^{-23}$ g at the temperatures of electrons $T_e = 8.9\ eV$ and at room temperature of ions T_i. The value of $\gamma_d = K_0/k_B T_e$ denotes the reduced energy of dust particles, here K_0 is the initial kinetic energy of a dust particle. The Debye length and plasma density are D = 0.005 cm, $n_{e0} = 21.2 \cdot 10^{10}$ cm^{-3}. We used reduced parameter p/R_p, here $p = 150 - 500$ μm is the impact parameter, $R_p = 150$ μm is the radius of the probe.

It should be noted that in work [2] the trajectories of dust particles near the probe were calculated without taking into account ion drag and friction forces. In this work the rotation of dust particles in the ion layer around the probe was explained by phenomena of dust particles recharging (i.e., dust acquiring a positive charge) due to predominance of ion flux on the dust particle surface in ion layer. In work [2] the results obtained at pressure equals 0.1 Torr were presented. For higher pressure the results of calculations and experimental results did not agree. In this connection, in the present work the ion drag and friction forces are taken into account.

Theoretical and experimental results for different values of reduced initial kinetic energies $\gamma_d = K_0/k_B T_e$ are shown in figures 1,2.

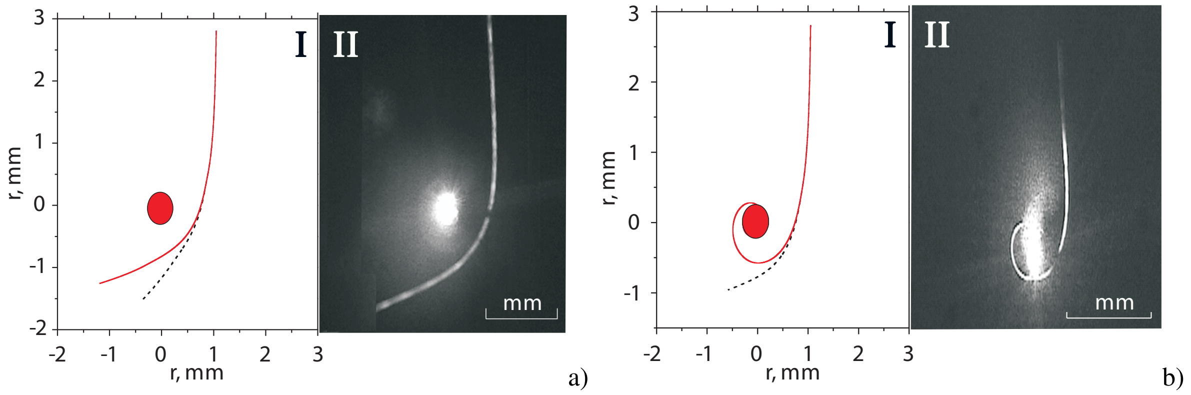

Fig. 1 Trajectories of dust particle at different initial kinetic energies. a) p/R_p=2; γ_d=12650 b) p/R_p=2; γ_d=15500. Comparisons of numerical (I) and experimental (II) results. *dash line* denotes the result obtained without taking into account of ion drag and neutral friction forces; *solid line* denotes the result obtained with taking into account of ion drag and neutral friction forces.

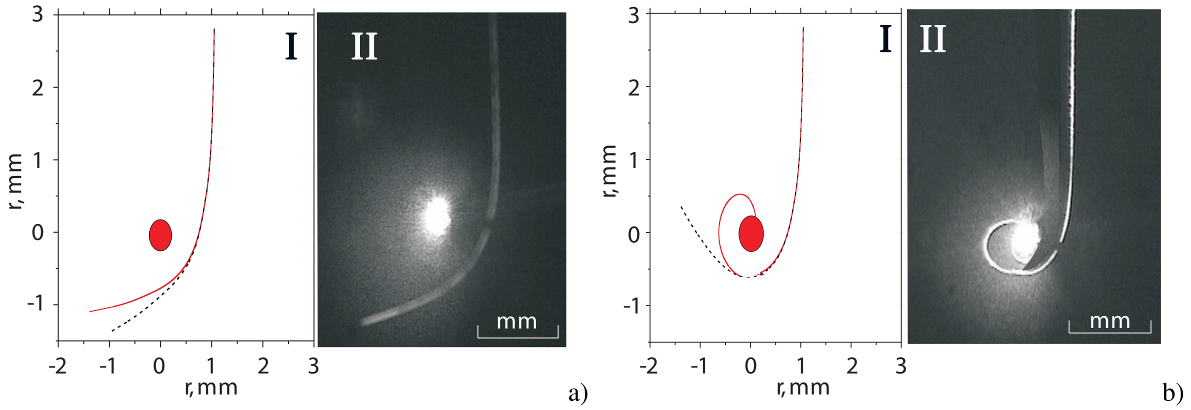

Fig. 2 Trajectories of dust particle with impact parameter $p/R_p = 2$ and initial kinetic energy $\gamma_d = 12620$ at different gas pressures. a) $P = 0.1$ Torr, b) $P = 0.3$ Torr. Comparisons of numerical (I) and experimental (II) results. *dash line* denotes the result obtained without taking into account of ion drag and neutral friction forces; *solid line* denotes the result obtained with taking into account of ion drag and neutral friction forces.

As one can see from these figures trajectories of dust particles near electric probe calculated on the basis of equation of movement taking into account the ion drag force and neutral friction force are in good agreement with experimental data. Ion drag force was taken into account in the sheath of the probe in radial direction. The experimental and numerical results show that with increasing of pressure in the discharge tube, the interaction between dust particles and the probe increases. In this case large scattering angles and the rotation of dust particles in the ion layer around the probe are observed with subsequent attachment to the probe.

5 Conclusion

For adequate description the behavior of dust particles near Langmuir probe it is necessary to into account ion drag and neutral friction forces. The obtained experimental trajectories can be used for developing the new methods of dusty plasma diagnostics

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