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Study of the Dust-Free Region Near an Electric Probe and the Dust Particles Oscillations in Dusty Plasma

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Key words Dust particles, electric probe, dust-free region, energy balance,dusty plasma, diffusion, velocity autocorrelation function, spectral function.

In this paper we consider the behavior of the dust particles around the electric probe with a negative potential. The size of the dust-free region , which depends on the probe potential, was experimentally determined. Theoretical calculation of the size of the dust-free region based on the energy balance was performed. Comparison of theoretical estimations with experimental results was made.

Also in this work the results of the theoretical investigation of the oscillations of the dust particles based on the Fourier analysis of the velocity autocorrelation functions are presented.It is shown that real and imaginary parts of the spectral function have maximum near the plasma frequency of the dust particles at large values of coupling parameter and small values of friction coefficient.

1 Introduction

A dusty plasma is an ionized gas which contains the micrometer-size charged grains of solid matter.This type of plasma is often found in nature and in many laboratory and technological devices. Experiments with dusty plasmas are carried out mostly in the gas discharges of various types. In a gas discharge plasma grains acquire a significant electric charge, and can form the dust structures similar to a liquid or to a solid. Also dusty plasma can be found in astrophysical objects such as comet tails and planetary rings. In space dust particles have charge due to the radiation impact.

Present time the intensive experimental and theoretical researches of dusty plasma properties are carried out. So, experimental study of the properties of dusty plasma near an electric probe gives interesting results. The study of the behavior of dust particles near an electric probe (or near electrode) with a negative potential gives the possibility to diagnose the buffer plasma properties by the visual easily measured experimental characteristics of dust structures obtained in these regions [1,2]. In work [3] the experimental observations of different trajectories of dust particles in the disturbed region around the electric probe had been carried out, on this basis a mathematical model of the interaction of the particles with the probe was constructed. In work [4] the same model was developed with taking into account the ion drag and the neutral friction forces. Part 2 of this paper presents data of the measuring of the dust-free region size around the electric probe in the experiments under different discharge conditions for various values of the electric potential applied on the probe. On the basis of the equality of the thermal energy of the dust particles and the energy of the electrostatic interaction between the particle and the probe the radius of the dust-free region was theoretically estimated. It was shown that the theoretical results are in a good agreement with experimental data.

Due to large different between size and mass of the dusty plasma components the computer simulation on the basis of the Langevin dynamics can be used. Langevin dynamics gives the opportunity to investigate microscopic and dynamic properties of the dusty particles. Recently the velocity autocorrelation functions and diffusion of the dust particles on the basis of the Langevin dynamics were investigated. As was shown, the velocity autocorrelation functions of the dust component in liquid state had oscillations around zero, which was interpreted as the localization of the particles. "Positive" oscillations appeared due to the collective effects in the strongly

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coupled system. In Part 2 of this work we present the results on the oscillation frequencies of the dust particles obtained based on the Fourier analysis of the velocity autocorrelation functions.

2 Study of the dust-free region near an electric probe in dusty plasma

The experiments were performed in the positive column of a glow DC discharge of argon. Discharge was obtained in a glass tube with length of 550 mm, and a diameter of 46 mm. Single cylindrical Langmuir probe was introduced to plasma perpendicularly to positive column.The probe is made of tungsten wire and has a length of 1 mm, diameter of about 150 microns. When the probe circuit had been turned on a potential Up, which is negative relatively to the plasma, was applied on the probe. Dust particles of Al_2O_3 with diameter 10 microns were injected into the plasma through the container, which is located on the top of the discharge tube. After inserting the probe in the discharge gap, the positive space-charge layer was formed around it. The dust particles fell down until they reached region near probe. Then particles with a relatively high kinetic energy to overcome barriers of ion layer moved toward probe along different trajectories in this region. Some of them performed rotations around probe and fell on probe surface [5,6]. But the particles that had a low thermal energy remain to levitate in some distance over probe. So, some region near probe was free from dust particles. Dimensions of this region depend on the voltage on the probe and the parameters of the surrounding plasma. When the absolute value of the voltage increases, the distance between the probe and a cloud of dust particles increases, too. The experimental results are shown in Figure 1.

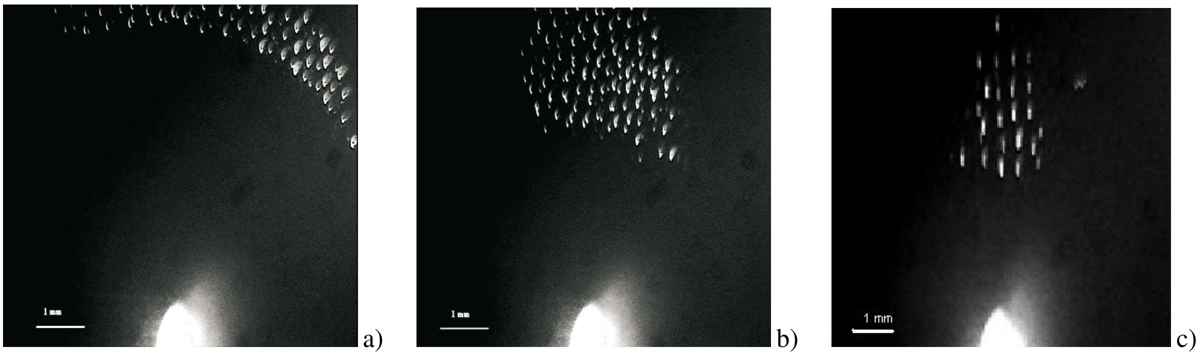

Fig. 1 Dust free region in the dependence on the voltage on the probe. a) Up= -260 V ;b) Up= -100 V; c) Up= -60 V;

The experimental data were obtained under different conditions of discharge. It was observed that with the increasing of the discharge current or (and) decreasing of the gas pressure in the discharge tube the distance between the probe and the dust particles decreases. The experimental curves of dependencies of dust-free region's radius on the probe voltage obtained at different pressure are shown in Figure 2.

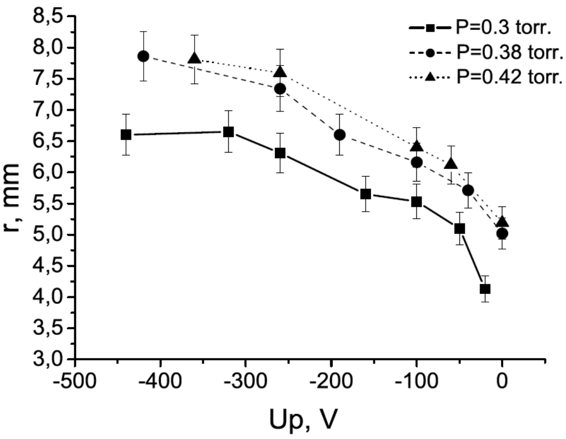

Fig. 2 Dependence of the dust-free region's radius on the probe potential Up at the different values of gas pressure.

In work [7], the distance between the probe and the dust particles was calculated by the balance of electric and ion-drag forces. We calculated the radius of dust-free region on the basis of the equality of thermal energy of the dust particles and the energy of the electrostatic interaction of the particles with the probe:

$$k_B T_d = Z_d e U(r) \tag{1}$$

where $k_B T_d$ and $Z_d e$ -temperature and charge of dust particles,$U(r)$ is the electric field of probe. In the case of an isotropic, weakly ionized and rarefied plasma, when the mean free path of the charged particles is much larger than the characteristic dimensions of the probe, the electric field is determined by the Poisson equation

$$\Delta U(\vec{r}) = -4\pi(n_i(\vec{r}) - n_e(\vec{r})) \tag{2}$$

According to work [8] there is an absorbing surface, which differs from the probe surface. Radius of the absorbing surface is the limitation radius r_l which defines the local maximum of the effective potential energy of the ions:

$$U_{eff}(r) = \frac{l^2}{2m_i r^2} + eU(r) \tag{3}$$

where m_i is the mass of ions, l is the angular momentum of ions. Then for large cylindrical probe $(R_0 >> r_d)$ when $\lambda >> R_0$ one can obtain [6]:

$$n_i = n_0 \left\{ 1 - \frac{1}{\pi} \arcsin \frac{r_l}{r} \left[\frac{E_0 + eU(r_l)}{E_0 + eU(r)} \right]^{1/2} \right\} \tag{4}$$

when $r > r_l$

$$n_i = \frac{n_0}{\pi} \arcsin \frac{r_l}{r} \left[\frac{E_0 + eU(r_l)}{E_0 + eU(r)} \right]^{1/2} \tag{5}$$

when $r < r_l$ (here and below the potential is taken as absolute values).

We introduced the following dimensionless parameters:

$$x = \frac{r}{r_l}, \gamma = \frac{E_0}{kT_e}, \varphi = \frac{eU(r)}{kT_e} \tag{6}$$

For the electron numerical density the Boltzmann distribution was taken. Then the Poisson equation in dimensionless variables can be written as:

$$\left(\frac{r_d}{r_l}\right)^2 \frac{\pi}{x} \frac{d}{dx} \left(x \frac{d\varphi}{dx} \right) = \arcsin \frac{1}{x} \left(\frac{1 + \frac{\varphi_l}{\gamma}}{1 + \frac{\varphi}{\gamma}} \right)^{1/2} - \pi e^{-\varphi} \tag{7}$$

One should take the following boundary conditions: $\varphi_{x=1} = \varphi, (d\varphi/dx)_{x=1} = -2(\gamma + \varphi), \varphi_{x=0} = eU_p/k_B T_e$. The equation for connection of φ_l with r_l one can find by substitution of the first and second derivatives of $U_{eff}(r_l)$ at $r = r_l$ into the equation (8), then

$$1 - 2e^{-\varphi_l} = 8 \left(\frac{r_d}{r_l}\right)^2 (\gamma + \varphi) \tag{8}$$

The equation (7) can be solved by the "shooting method": searching of such limitation potential φ_l, at which the curve of potential passes through known point $x = 0$, $\varphi = eU_p/k_B T_e$ (the potential on the probe surface). In the case of $r > r_l$ solution can be approximated by an analytical function (see [6]):

$$\varphi = \frac{1}{x^2}(\gamma + \varphi_l) - \gamma \tag{9}$$

In order to compare the theoretical estimation with experimental one the equations (7) and (8) were solved for the following discharge conditions: pressure in the discharge tube P=0.3 torr, T_e=5 eV, n_e=$7{\cdot}10^{11}$cm^{-3}, r_d=0.002

cm, Z_d=6000 and different values of U_p. Thus, we constructed the curves of the dependencies of $Z_d eU(r)$ on the potential on the probe surface, see Figure 3. Straight dotted line corresponds to the thermal energy of the dust particles, in this experiment T_d=5 T_e. Dust temperature was determined on the basis of the velocity distribution function measured in the experiment. The points of intersection of the dotted lines with the potential curves give us the distances between the dust cloud and the electric probe. These results were compared with experimental results at pressure in discharge tube P=0.3 torr, and at the values of the discharge current I_1=0.7 mA, I_2=1.3 mA, I_3=1.9 mA, which showed good agreement.

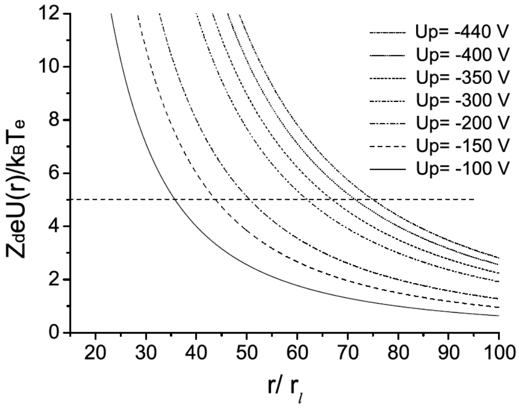

Fig. 3 Interaction energy of the dust particles and electric probe. The dotted line corresponds to the thermal energy of the dust particles.

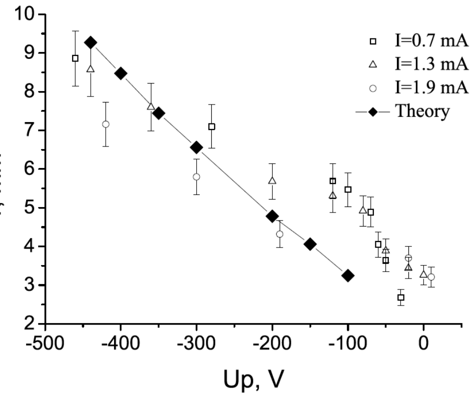

Fig. 4 Comparison of experimental data with theoretical results for different values of the discharge current. The pressure in the discharge tube P=0.3 torr.

3 On the diffusion and oscillations of the dust particles in the gas discharge plasmas

The method of the Langevin dynamics found its recent wide application in studies of dusty plasma properties. Simulation of the dust particles space-time trajectories was made on the basis of the following equations:

$$m_d \frac{d^2 \vec{r}_i}{dt^2} = \sum_j F_{int}(r_{ij}) \frac{\vec{r}_i - \vec{r}_j}{|\vec{r}_i - \vec{r}_j|} - m_d \nu_{fr} \frac{d\vec{r}_i}{dt} + \vec{F}_{br}(t), \tag{10}$$

where $F_{int}(r_{ij}) = -\partial\Phi/\partial r$ is a force acting on a selected i-th particle due to interaction with j-th particle, $r_{ij} = |\vec{r}_i - \vec{r}_j|$ is a distance between two grains, $\vec{F}_{br}(t)$ is the stochastic force due to interactions with neutrals, ν_{fr} is the friction coefficient dependent on buffer plasma pressure, m_d is mass of a dust particle. The Yukawa potential was chosen as interaction potential; in the dimensionless form it looks as:

$$\Phi(R) = \frac{\Gamma}{R} e^{-\kappa R} \tag{11}$$

here $\Gamma = (Z_d e)^2/(ak_B T_d)$ is the coupling parameter, $\kappa = a/r_D$ is the screening parameter, $a = (3/4\pi n_d)^{1/3}$ is the average distance between dust particles, $Z_d e$ and n_d are the charge and numerical density of the dust particles, respectively; T_d is temperature of the dust component. Set of 1024 dust particles were randomly distributed within a 3D cubic cell that was extended by periodical boundary conditions. Time is taken in the units of reverse plasma frequency of dust component $\omega_d = (4\pi n_d (Z_d e)^2/m_d)^{1/2}$. Number of the time steps $N_t = 30000$. Some performed tests of the temporal characteristics showed the validity of these parameters. The dimensionless friction parameter is $\theta = \nu_{fr}/\omega_d$. Simulations were performed for the dust particles system according to usual scheme [9-16].

On the basis of data obtained in computer simulation one can investigate the possible oscillation processes in dusty plasma. So called the velocity autocorrelation function

$$A(t) = \langle \vartheta(0)\vartheta(t) \rangle$$

can give the answer on the question about the oscillations presence [9]. In Figs. 5 and 6 one can see the velocity autocorrelation functions obtained for different values of the friction parameter in the regimes of strong and week coupling. As it is shown in Fig. 5 that the return movements of dust particles take place at large coupling parameter but the increase in the friction parameter decays it. On the contrary at small coupling parameter the increase in the friction parameter can cause the appearance of the week return movements (see Fig. 6). It can be explained by the buffer plasma fast decelerates the dust particles on the distances near initial position, so, the return force, which appears according to fluctuation dissipation theorem, is enough to make particle move a little back.

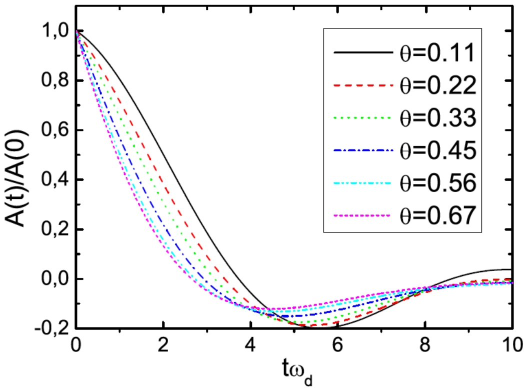

Fig. 5 The velocity autocorrelation function of the dust particles in regime of strong coupling $\Gamma = 100$, $k = 2$

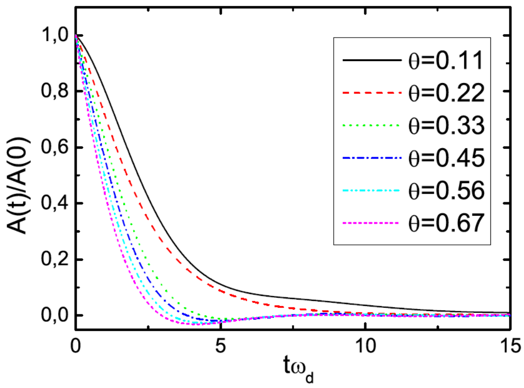

Fig. 6 The velocity autocorrelation function of the dust particles in regime of week coupling $\Gamma = 5$, $k = 2$

To obtain the oscillation frequencies of the dust particles the spectral function was investigated. According to work [17], spectral function $f(\omega)$ completely determines the behavior of the system under the action of a given perturbation:

$$f(\omega) = \int_0^\infty f(t)e^{i\omega t}dt, \tag{12}$$

here $f(t)$ is some function, which depends on the microscopic properties of the system.

One of the alternative methods for calculating $f(\omega)$ is the formalism of the dynamic autocorrelation functions. In this case, for example, the velocity autocorrelation function calculated on the basis of the computer simulations can be taken as a quantity characterizing the microscopic state of the system. So, spectral function of dust particles can be obtained by the Fourier transformations of the velocity autocorrelation function obtained in work [9]:

$$f(\omega) = 1/2\pi \int_0^\infty A(t)e^{-i\omega t}dt \tag{13}$$

The real part of the spectral function of the velocity autocorrelation function like the dynamic structure factor gives the possibility to determine the frequencies of the particles oscillations by the presence of the peaks in their charts. There is the connection between these functions, as noted in the book [18] the velocity autocorrelation function is associated with the autocorrelation part of the dynamic structure factor. The dynamic structure factor is determined by the correlations between the density fluctuations with the given wave vector. Based on data from the molecular dynamics method, it is calculated by the coordinates of the particles, and the theoretical methods of the dynamic structure factor obtaining are based on the structural characteristics of the particles, such as the direct correlation function. The velocity autocorrelation function is calculated based on the computer simulations data using the velocities of the same particles. An example of how to define the same value with a set of coordinates or a set of velocities is the diffusion coefficient, which can be obtained by the mean square displacement or on the basis of the Green-Kubo relations by the velocity autocorrelation function:

$$D = \frac{1}{3}\int_0^\infty A(t)dt. \tag{14}$$

From equation (14) one can see that $\lim_{\omega\to 0} Re(f(\omega))$ equals to the diffusion coefficient with accuracy within a numerical factor.

Imaginary part of the spectral function characterizes the energy dissipation in the system.

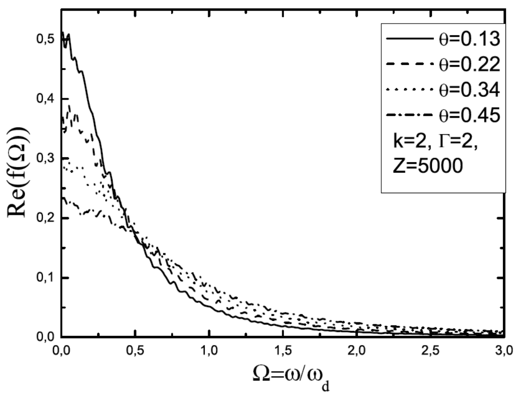

Fig. 7 The real part of the spectral function of the dust particles

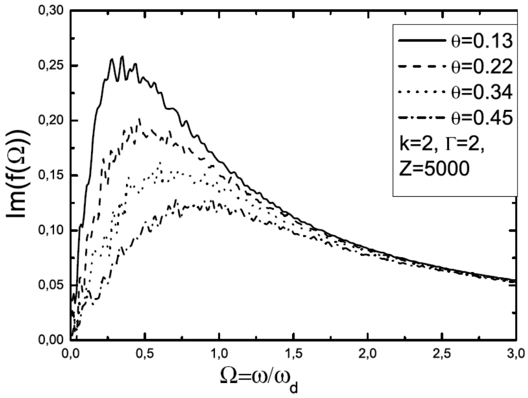

Fig. 8 The imaginary part of the spectral function of the dust particles

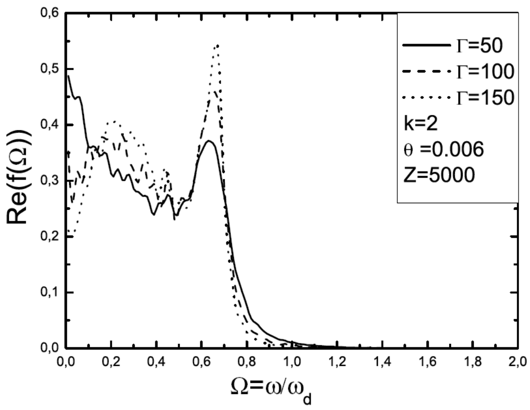

Fig. 9 The real part of the spectral function of the dust particles for different values of the coupling parameter

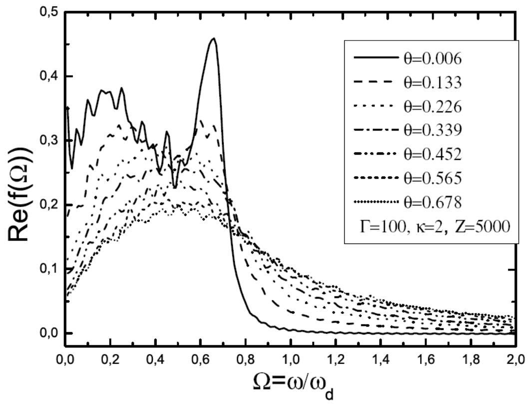

Fig. 10 The real parts of the spectral function of the dust particles for different values of the friction coefficient

Real and imaginary parts of the spectral function at $\Gamma = 2$ are presented in Figs. 7, 8. It is shown, that at low values of the coupling parameter the real parts of the spectral function are monotonic and there are no any oscillations in the system. As one can see from Fig. 7 values $\lim_{\omega\to 0} Re(f(\omega))$ reduce with increase in friction coefficient. In work [9] the decrease in the diffusion coefficient with increase in friction coefficient was shown. Real parts of the spectral function at large values of coupling parameter are presented in Figs. 9,10. Fig. 9 indicates the reduction of the diffusion coefficient at rising of coupling parameter, theoretically up to zero (crystal state). In this figure it is seen too, that at increase in the value of the coupling parameter a maximum rises on the curve of the spectral function, which is approximately located at the frequency near the plasma frequency of the dust component ω_d. But in Fig. 10 one can see, that even at high values of the coupling parameter with increase in the value of the friction coefficient the maximum disappears.

Imaginary parts of the spectral function at large values of coupling parameter are presented in Fig. 11. This figure shows that a maximum of the energy absorption approximately is located at frequency near the plasma frequency of the dust particles.

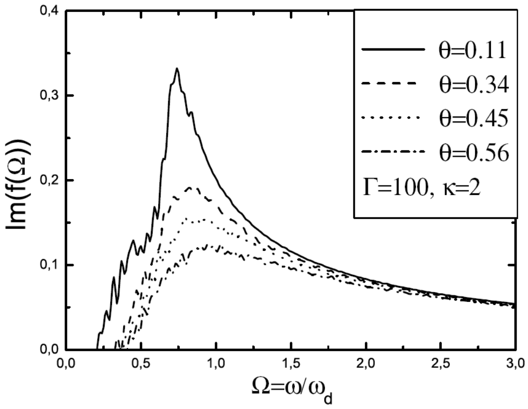

Fig. 11 The imaginary parts of the spectral function of the dust particles for different values of the friction coefficient

4 Conclusion

The radius of the dust-free region around of electrical probe was experimentally determined. Dependence of size of the dust free region area on the potential applied to the probe was investigated. Experimental results are in a good agreement with the results of the theoretical estimations. So, on the basis of the equality of the dust particles thermal and the electrostatic interaction energies of the particle with electric probe, it is possible to correctly describe the size of the area of the dust-free region around the probe. Thus, the theoretical results can be used hereafter for diagnostics of the dusty plasma parameters by experimentally observable and easily measured size of dust-free region.

The main result of computer simulation of the dust plasma presented in this work is the result of the spectral analysis of the velocity autocorrelation functions of the dust particles. It has shown that in the dusty system there are oscillations with frequency near plasma frequency of the dust component at large values of the coupling parameter and small values of the friction coefficient. Maximum of the energy absorption approximately is located at frequency near the plasma frequency of the dust particles too. Also it was shown that at small coupling parameter increase in friction parameter can cause the appearance of the return movement of dust particle.

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