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BEHAVIOUR OF THE MASS-TRANSFER EVOLUTION FUNCTION IN QUASI-2D SYSTEMS IN DUSTY PLASMA OF RF-DISCHARGES

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Introduction. The dusty plasma is an ionized gas that contains micron-sized particles of solid matter. This type of plasma is ubiquitous in nature (in space, in planetary atmospheres, etc.) and often appears in a number of technological processes [1, 2]. Laboratory dusty plasma is a good experimental model for studying the non-ideal systems and for testing the existing empirical and numerical results, because, owing to their size, dust particles may be observed via the video camera. The diffusion is the main mass-transfer process that defines the dissipation in the systems and their physical characteristics (the nature of interaction potentials, the phase state, the conditions for formation of instabilities, etc.). A study of this process for dusty plasma is of great interest [1-7]. The present work is devoted to the investigation of mass-transfer processes in quasi-two-dimensional (2d-) systems consisting of several dust layers (or a single one) that are usually observed in plasma of RF- discharge.

Basic equations. In diffusion measurements, the ratio of mean square displacement, $<\Delta l^2>$, to the observation time t is usually calculated. In the 2d- case, the diffusion constant can be obtained from the relationship $D = \lim_{t\to\infty} D(t)$, where [7]

$$D(t) = <<\Delta l^{2}>_{N}>_{t}/4t, \qquad (1)$$

and the brackets < > denote the ensemble (N) and time (t) average. It is valid for gases as well as for the liquid and the solid. For systems in the statistical equilibrium, this relation (with $t \to \infty$) is analogous to the well-known Green-Kubo formula

$$D_{G\text{-}K}(t) = \int_0^t \langle V_x(0)V_x(t)\rangle dt\,, \qquad (2)$$

where V_x is the velocity of the grains in some x- direction, and $<V_x(0)V_x(t)>$ is the velocity autocorrelation function. In a quasi-stationary system with the time increasing ($t \to \infty$), the $D(t)$ and $D_{G\text{-}K}(t)$ functions tend to the identical value of the D constant, which corresponds to the standard definition of the diffusion rate as one of the basic transfer rates.

For ideal gases, the Eqs. (1) - (2) have the simple analytical solutions that with $t \to \infty$ yield the value of diffusion coefficient, $D_0 = T/(\nu_{fr}M)$, for non-interacting grains; here M and T are the mass and kinetic temperature of a grain, and ν_{fr} is the friction coefficient. A behavior of the $D(t)$- and $D_{G\text{-}K}(t)$- functions in the ideal crystals may be obtained from the motion equation of a harmonic oscillator with some characteristic frequency ω_c:

$$\frac{D(t)}{D_o} = \frac{1-\exp(-\nu_{fr}t/2)\left(ch(\nu_{fr}t\psi)+sh(\nu_{fr}t\psi)/\{2\psi\}\right)}{2\xi_c^{\ 2}\nu_{fr}t}, \qquad (3a)$$

$$\frac{D_{G-K}(t)}{D_0} = \frac{\exp\left(-\nu_{fr}t/2\right)}{\psi}\cdot \mathrm{sh}\left(\nu_{fr}t\psi\right), \qquad (3b)$$

where $\psi=(1\text{-}8\xi_c^{\ 2})^{1/2}/2$ and $\xi_c = \omega_c/\nu_{fr}$. With $t \rightarrow \infty$, both expressions tend to zero, as the value of $<\Delta l^2>$ is constant for ideal crystals ($D = 0$). For liquid media, the exact analytic expression for $D(t)$ can't be obtained. Numerical simulations have shown that the behavior of $D(t)$- function in the liquids for the time less than some critical value ($t < 1/\omega_c$) is similar to the $D(t)$ for particles in solid [3]. This fact is in agreement with measurements of $D(t)$- function in dusty fluids [3, 4]. The best fitting of experimental $D(t)$- and $D_{G\text{-}K}(t)$- functions by the Eqs. (3a, b) allows simultaneously to retrieve the values of ω_c, ν_{fr} and T, and to estimate the coupling parameter of system as $\Gamma^* \sim M\omega_c^{\ 2}l_p^{\ 2}/T$ (where l_p is the mean interparticle distance) [3].

Experiments. The experimental study of the mass-transfer processes in dusty plasma, including the examination of relations (1) - (3), was performed in RF-discharge with the power W ~ 2- 20 W in argon at the pressure P ~ 5-30 Pa for the particles of formaldehyde melamine of different radiuses a (2.755 μm and 6.37 μm) with concentrations from 100 to 1600 cm^{-2}. The phase state of observed dust structures varied from the weakly correlated fluid to the crystal. The pair correlation functions $g(r)$ are presented in Fig. 1. The grains were registered with the help of high-resolution high-speed video camera, which allowed us to study the behavior of the systems at the small observation times and to determine the dust parameters.

The kinetic temperature of dust was varied from ~0.1 to 50 eV, and the effective coupling parameter – from Γ^*~ 2.5 (dusty fluid) to Γ^*~ 300 (dust crystal). The measured $D(t)$- and $D_{G\text{-}K}(t)$- functions (calculated from Eqs. (1) - (2)) are shown in Figs. 2a, b, c. The diffusion constants (D), obtained from both expressions with the time increasing ($t \rightarrow \infty$), were within experimental errors (~ 5 -7 %) for both the weakly correlated and crystal systems.

The comparison of the experimental $D(t)$- and $D_{G\text{-}K}(t)$- functions with the analytical expressions (3a, b) is also presented in Figs. 2a, b, c. It is easy to see that all experimental functions are in agreement with the theoretical predictions on small observation times ($t < 2/\omega_c$); in this time interval, the independent measurements of $D(t)$- and $D_{G\text{-}K}(t)$ are well approximated by Eqs.(3a, b) with the identical dust parameters (ω_c, ν_{fr} and T).

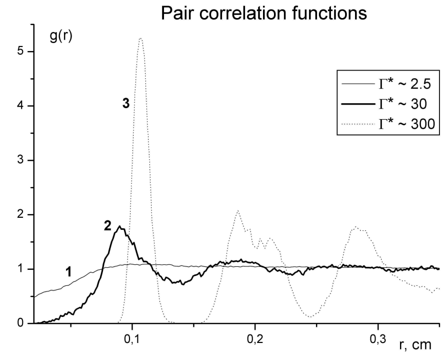
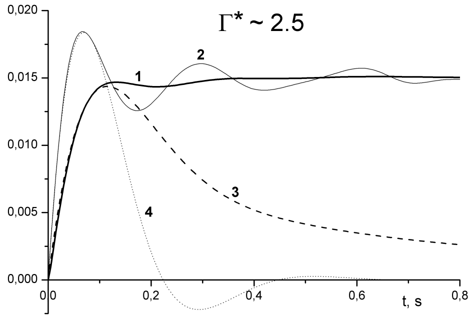
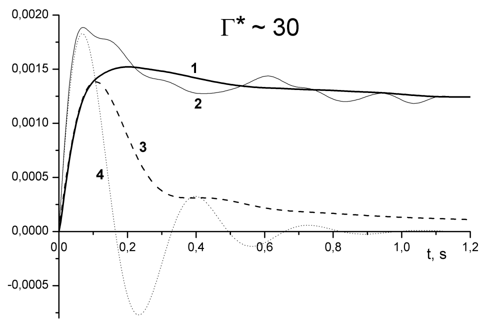


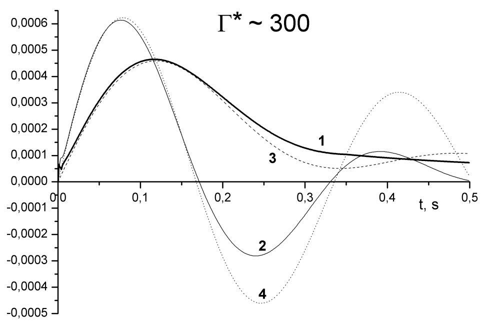
Figure 1. The $g(r)$ functions in dusty plasma with different parameters: **1** – a =2.755 μm, P = 5 Pa, W = 2 W; **2** – a =6.37 μm, P = 18 Pa, W = 4 W; **3** – a =6.37 μm, P = 4 Pa, W = 3 W.



(**a**)



(**b**)



(c)

Figure 2. Experimental $D(t)$- (**1**) and $D_{G\text{-}K}(t)$- (**2**) functions for dusty plasma with different parameters: (a) – a =2.755 μm, P = 5 Pa; W = 2 W; (b) – a =6.37 μm, P = 18 Pa; W = 4 W; (c) – a = 6.37 μm, P = 4 Pa; W = 3 W. Dashed lines (**3**) and (**4**) denote their approximations by the Eqs. 3a and 3b, respectively, with the dust parameters: (a) – $T = 2.6 \cdot 10^{-4}$ eV, $\nu_{fr} = 19$ s^{-1}, $\omega_c = 12$ s^{-1}; (b) – $T = 2.7 \cdot 10^{-4}$ eV, $\nu_{fr} = 10.5$ s^{-1}, $\omega_c = 14$ s^{-1}; (c) – $T = 8.8 \cdot 10^{-5}$ eV, $\nu_{fr} = 3.6$ s^{-1}, $\omega_c = 13.3$ s^{-1}.

Conclusion. The mass-transport of grains in RF- discharge was studied for the various parameters of dusty plasma (size, concentration and kinetic temperature of dust grains, pressure of the buffer gas, etc.). The diffusion constants were found from the Green-Kubo formula and from the mean-square displacement of the particles. The values of these constants, obtained from both formulas, were within experimental errors. (Thus we can conclude that the systems under study were in a statistical equilibrium.) The examination of the different analytical expressions for the mass-transfer evolution functions was performed. This examination has shown that the considered expressions may be used for a description of mass transfer on the small observation times and for the determination of the dust parameters under a wide range of the plasma conditions. Finally, we note that results of the present study can be used to develop new methods of passive diagnostics (without disturbing the system under study) for the various complex media (for dusty plasma, biological and medical solutions, biopolymers, etc.) [1, 8, 9].

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