TRANSPORT PROCESSES IN DUSTY PLASMA OF RF-DISCHARGE

O. S. Vaulina, X.G. Adamovich, O.F. Petrov, V. E. Fortov

Institute for High Temperatures, RAS, Moscow

1. Introduction

A study of the kinetic constants (diffusion, viscosity, etc.) for dusty plasma is of great interest [1-4]. When the deviations of the system from the statistical equilibrium are small, the kinetic constants can be found from Green-Kubo formulas that were established with the help of the theory of Markovian stochastic processes under an assumption of the linear reaction of the system on its small perturbations [5].

The collisions of grains with the gas neutrals have a dramatic effect on the dissipation of dust energy in weakly ionized plasma. Correct simulation of grain motions in dissipative media requires using the Langevin molecular dynamics method (LMDM) based on the solution of the differential equations with the stochastic force, $F_{\rm ran}$. Displacement of j-th particle along one coordinate, $x_j = x_j(t)$, for the time t, under an action of some potential F forces, can be written as

$$M \frac{d^2 x_j}{dt^2} = -M\nu_{fr} \frac{dx_j}{dt} + F + F_{ran} . \qquad (1)$$

Here M is the dust mass, and $\nu_{\rm fr}$ is the friction coefficient. In a statistical equilibrium ($<(dx_j/dt)^2> = <V_x^2> \equiv T/M$): $<F_{\rm ran}(t)> = 0$, and $<F_{\rm ran}(0)F_{\rm ran}(t)>= 2T\nu_{\rm fr}M\delta(t)$, and the Eq.(1) describes the Markovian processes. Here, T is the kinetic temperature of grains, $\delta(t)$ is the delta-function, and the brackets <> denote the ensemble and time averaging.

The diffusion is the basic mass-transfer process, which defines the losses of energy (dissipation) in the system. In equilibrium, diffusion constants may be obtained from the measurements of mean-square displacement of grains, $<x_j^2>=< x^2>$

$$D_{msd}(t) =< x^2>/(2t), \qquad (2a)$$

or, from the analyses of velocity autocorrelation functions, $<V_x(0)V_x(t)>$, (VAF)

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

With the increasing time ($t \to \infty$), both these mass-transfer functions ($D_{msd}(t)$, $D_{G\text{-}K}(t)$) tend to the same constant value D, which corresponds to the diffusion coefficient; and the relation (2b) is a particular case of the well-known Green-Kubo formulas.

The solutions of Langevin equation for non-ideal systems show that relations between $D_{msd}(t)$, $D_{G\text{-}K}(t)$, $<V_x(0)V_x(t)>$ and $< x^2>$ may be presented as [6]

$$D_{G\text{-}K}(t) = \frac{d\{tD_{msd}(t)\}}{dt} \equiv \frac{1}{2}\frac{d\langle x^2\rangle}{dt}; \quad <V_x(0)V_x(t)> = \frac{d^2\{tD_{msd}(t)\}}{dt^2} \equiv \frac{1}{2}\frac{d^2\langle x^2\rangle}{dt^2}. \qquad (3)$$

In doing so, the $D_{msd}(t)$- functions in the liquid systems for the short observation times ($t < 2/\omega_c$) are similar to those for harmonic oscillators, the motion of which may be described by a single characteristic frequency ω_c [6]

$$\frac{D_{msd}(t)}{D_o} = \frac{1-\exp(-\nu_{fr}t/2)\left(\cosh(\nu_{fr}t\psi)+\sinh(\nu_{fr}t\psi)/\{2\psi\}\right)}{2\xi_c^{\,2}\nu_{fr}t}, \qquad (4)$$

where $D_o = T/(\nu_{fr}M)$, $\psi = (1-8\xi_c^2)^{1/2}/2$, $\xi_c = \omega_c/\nu_{fr}$, and the ω_c value is proportional to the second derivative of a pair interaction potential U_{ip} at the point of the mean interparticle distance l_p [6,7]: $\omega_c = \{\,|\,a_o U_{ip}''\,|/(\pi M)\}^{1/2}$. Here $a_o \equiv 2$ for uniform 3d- systems with a *bcc*-lattice in their crystallization phase, and $a_o \approx 2.7$ for 2d- structures forming a hexagonal lattice during their crystallization.

As all the mentioned functions (VAF, D_{msd}, $D_{G\text{-}K}$) are connected by Eqs. (3) and are uniquely determined by the dust parameters (T, ω_c, ν_{fr}), it is possible to simultaneously determine all these parameters in experiments using the best fitting of the measured functions at the short observation times by the corresponded analytical solutions. The information on T and ω_c allows to estimate the effective coupling parameter Γ^* and the scaling parameter ξ, which determine the dust dynamics [6-8]: $\Gamma^* = a_1 l_p^2 U_{ip}''/(2T)$, $\xi = |\,a_2 U_{ip}''\,|^{1/2}(2\pi M)^{-1/2}\nu_{fr}^{-1}$, here $a_1 = a_2 \equiv 1$ for 3d- system; $a_1 = 1.5$, $a_2 = 2$ for 2d- case.

The kinematic viscosity, ν, of gases is comparable in magnitude with the diffusion coefficient, D. To determine the relationship between the viscosity and diffusion constants for dense fluids the Einstein-Stokes (E-S) relation is commonly used [2, 3]. The simulation of transfer processes with a wide scope of interaction potentials reveals that, the relations between the D and ν constants may be approximated by [3, 5]

$$\nu \cong l_p^2 T/(CMD), \qquad (5)$$

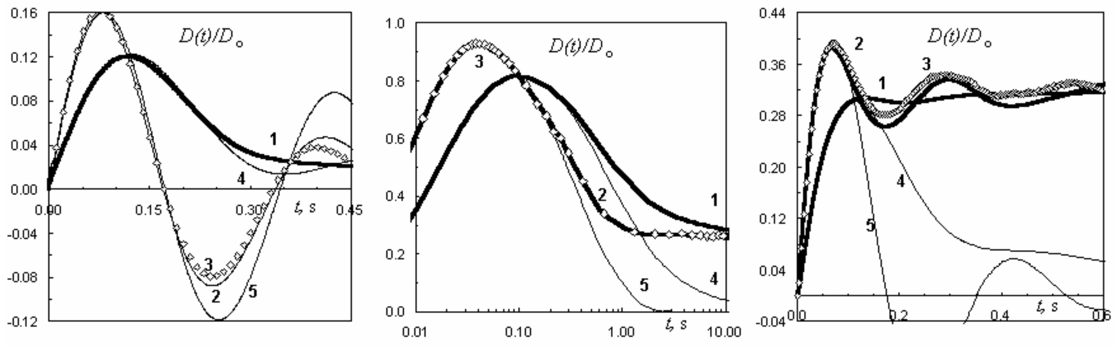
where C ≈ 8. Note, that to apply the results of simulation by LMDM for analyses of dynamics of the grains in plasma, one needs to examine, whether the considered Langevin model is valid under experimental conditions (i.e. to prove the validity of Markovian approach).

2. Experiments

The experimental study of the dust transport processes, including the examination of Eqs.(1)-(5), was performed in RF-discharge in argon at the pressure P ~ 0.03 – 0.5 Torr for mono-disperse grains (material density $\rho_p \approx 1.5$ g cm^{-3}, radiuses $a_p \approx 2.7$ μm and $a_p \approx 6.3$ μm). The grains were registered with the help of high-speed video camera, which allowed us to study the behavior of the systems at the short observation times, and to determine the dust parameters (T, ω_c and ν_{fr}) by the best fitting of the measured functions, $<V(0)V(t)>$, $D_{msd}(t)$ and $D_{G\text{-}K}(t)$, and the corresponding analytical solutions, Eqs. (3)-(4). The kinetic temperature of dust was varied from ~0,1 to 50 eV, and the coupling parameter from $\Gamma^* \sim 3$ (dusty fluid) to $\Gamma^* \sim 300$ (dust crystal).

The measured $D_{msd}(t)$ - and $D_{G\text{-}K}(t)$ – functions (calculated from Eqs. (2a,b)), are shown in Figs. 1 a, b, c. The diffusion constants (D), obtained from both expressions with the time increasing ($t \to \infty$) were within experimental errors (~ 5 %) for both the weakly correlated and crystal systems. The comparison of the experimental $D_{msd}(t)$ -, and $D_{G\text{-}K}(t)$ – functions with the analytical solution of Eqs. (3)-(4) is also presented in this figures. It is easily to see that all experimental functions are in an agreement with their theoretical prediction on the short observation times ($t < 2/\omega_c$); in doing so in this time interval, the measured $D_{msd}(t)$-, $D_{G\text{-}K}(t)$ are well approximated by corresponded analytical solutions with the similar retrieved dust parameters (ω_c, ν_{fr}, T).

For the measurements of viscosity constants we have used the technique detailed in [4]. The observed dust clouds were consisted of ~10-15 dust layers ~ 5 cm in diameter. The radiation of Ar^+ laser was used for a formation of cylindrical laminar flow of particles moved through an undisturbed area of the dust cloud. For the viscosity determination we have used the best fitting of measured dust velocity in laminar flow and the solutions of the Navier-Stokes equation. The diffusion constants were measured in undisturbed dust area. The results of examination of E-S relation for various experimental conditions show that the C values (see Eq.(5)) are close to 8 within 5-10% in the wide range of Γ^*(from ~ 30 to ~100).



(a) **(b)** **(c)**

FIGURE 1. The $D(t)/D_o$ functions: (**1**) – $D(t) \equiv D_{\text{msd}}(t)$; (**2**) - $D(t) \equiv D_{\text{G-K}}(t)$, Eq.(2b); (**3**, ◇) - $D(t) \equiv D_{\text{G-K}}(t)$, Eq.(3a), for various experiments: **(a)** - a_p = 6.3 μm, mono-layer, P = 0.03 Torr; **(b)** - a_p = 2.7 μm, mono-layer, P = 0.35 Torr; **(c)** - a_p = 2.7 μm, multi-layer system, P = 0.04 Torr. Curve **4** and curve **5,** Eqs.(3)-(4), are the corresponding solutions for the harmonic oscillator:
(a) -ω_c= 13 c^{-1}, ν_{fr} =3.5 c^{-1}, Γ^* ~310; **(b)** -ω_c= 9 c^{-1}, ν_{fr} =98 c^{-1}, Γ^* ~57; **(c)** -ω_c= 13 c^{-1}, ν_{fr} =11 c^{-1}, Γ^* ~ 6.

3. Conclusion

The experimental study of transport processes is presented for the dusty plasma in radio-frequency (RF-) capacitive discharge. Validity of the Langevin and Green-Kubo equations for the description of dynamics of dusty grains is verified. Experimental examination of the Einstein-Stokes relation between the viscosity and diffusion constants is carried out.

Acknowledgements

This work was partially supported by the RFFR (project no. 07-08-00290), by the Program of the Presidium of RAS and by the Russian Science Support Foundation.

References

[1] S. Nunomura, D Samsonov, S. Zhdanov, G. Morfill, Phys. Rev. Lett. 96, 015003 (2006).

[2] S. Ratynskaia, K. Rypdal, C. Knapek et al., Phys. Rev. Lett. 96, 105010 (2006).

[3] B. Liu, J. Goree, O. S. Vaulina, Phys. Rev. Lett. **96**, 015005 (2006)

[4] A. Gavrikov, I. Shakhova, A. Ivanov, et al., Physics Letters A 336, 378-383, (2005)

[5] N.H. March, and M.P. Tosi, Introduction to Liquid State Physics, World Scientific (1995).

[6] O. S. Vaulina, X.G., Adamovich, JETP (in press, 2008)

[7] O. S. Vaulina, S. V. Vladimirov, O. F. Petrov, V. E. Fortov, Phys. Plasmas 11, 3234 (2004).

[8] O. S. Vaulina, I.E. Drangevski, Physica Scripta T**73**, 577-586 (2006).