Transport of macroparticles in weakly ionized dusty plasma of gas discharges

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Abstract. Transport of macroparticles in dust fluids have been numerically studied for radial pair potentials of different types. Estimations of effective dust charges have been performed for dust particles in dc- and rf – discharges under microgravity and ground- based conditions.

In this work, the results of numerical simulations of particle dynamics in dust fluids (including the ordering of macroparticles and self-diffusion processes) are presented, and an application of these results for the dust diagnostics in laboratory plasma of rf- and dc- discharges is considered. The particle dynamics in dust fluids has been studied by three-dimensional Brownian dynamics method under periodic boundary conditions [1]. The transport characteristics were calculated for different dust temperatures T, and charges eZ, different types of pair potentials $\phi(r)$ of interparticle interaction, and ratio ξ of characteristic dust frequency ω_p to the friction coefficient ν_{fr}

$$\xi = \omega_p / \nu_{fr} \equiv \sqrt{\frac{eZ}{2\pi m_p}\phi''(r_o)} / \nu_{fr}, \quad (1)$$

in the limits of values typical for laboratory experiments. Here m_p is the dust mass, ϕ'' is the second derivative of pair potential $\phi(r)$ at the mean intergrain distance $r_o = n_p^{-1/3}$, where n_p is the dust concentration. We used in our calculations: the screening Yukawa potentials ($\phi = \phi_c \exp(-\kappa r/r_o)$, $\kappa = r_o/\lambda$, $\phi_c = - eZ/r$), the power functions ($\phi \propto \phi_c r_o^j/r^{j+1}$, $5>j>0.5$); the combination of Yukawa potentials with different screening lengthens λ; and the Yukawa potential combined with the power functions. Last two potentials were used for simulation of the reducing of screening with the distance from particle predicted in Refs. [2,3]. All modal potentials were isotropic (radial), repulsive and long-interacting: $2\pi|\phi'(r_o)| > r_o|\phi''(r_o)|$.

Pair correlation functions $g(r)$ and structure factors $S(k)$ were studied for analysis of ordering of macroparticles. The calculation shown that the order of macroparticles is independent on a friction (ν_{fr}) and fully determined by the ratio of ϕ''/T from the gas state of the system to the crystallization point where the *bcc*- lattices were formed for all considered cases. Thus, for analysis of phase state of dust systems we can use an effective coupling parameter $\Gamma^* = (Z^*e)^2/Tr_o$ with the effective particle charge

$$Z^*e = \{Ze\,\phi''/2n_p\}^{1/2} \quad (2)$$

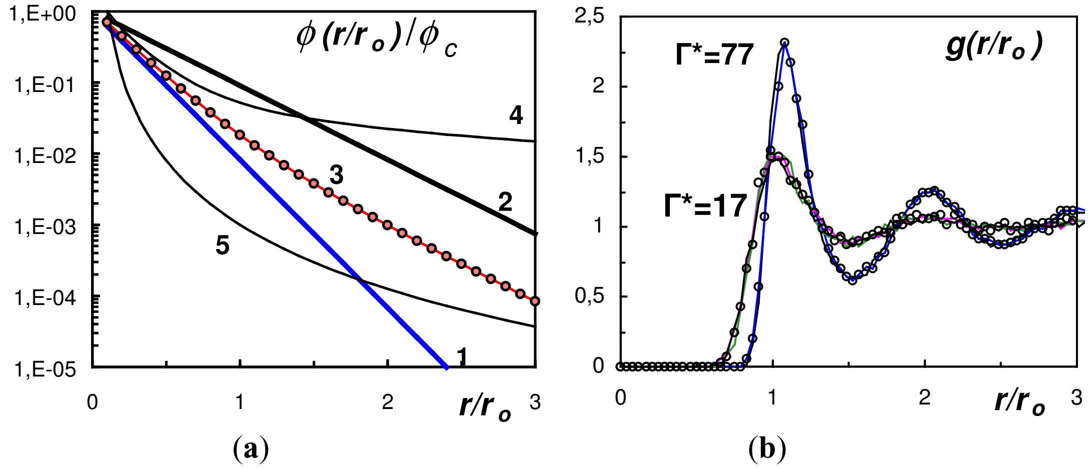


FIGURE 1. Ratio of ϕ to ϕ_c (a) and the pair correlation function g versus r/r_o for different $\phi(r)/\phi_c$:
1 - $\exp(-4.8r/r_o)$; **2** - $\exp(-2.4r/r_o)$; **3** - $0.1\exp(-2.4\, r/r_o)+\exp(-4.8\, r/r_o)$,
4 - $\exp(-4.8\, r/r_o) + 0.05r_o/r$; **5** - $0.05(r_o/r)^3$.

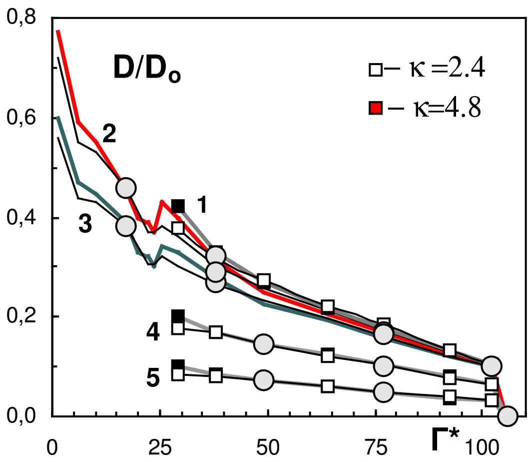


FIGURE 2. Ratio of D to the Brownian diffusion constant $D_o = T/m_p\nu_{fr}$ versus Γ^* for different ξ: **1** – 0.045; **2** – 0.14; **3** – 0.41; **4** – 1.22; **5** – 3.65. Circles are the points of calculations with different types of model potentials.

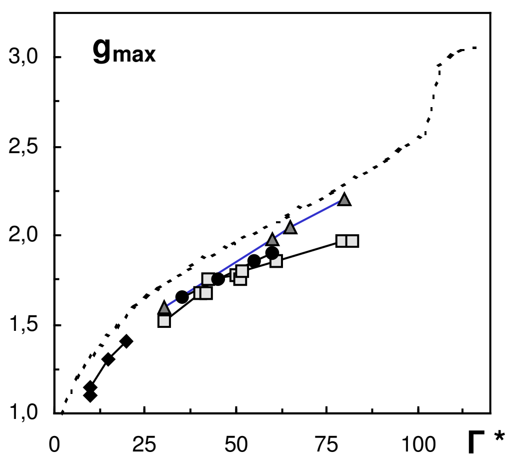


FIGURE 3. Values of first maximums g_{max} for correlation function versus the retrieved Γ^* for experiments in dc- (◊),(Δ) and rf - (❑), (o) discharges. Dashed line is the result of numerical simulations.

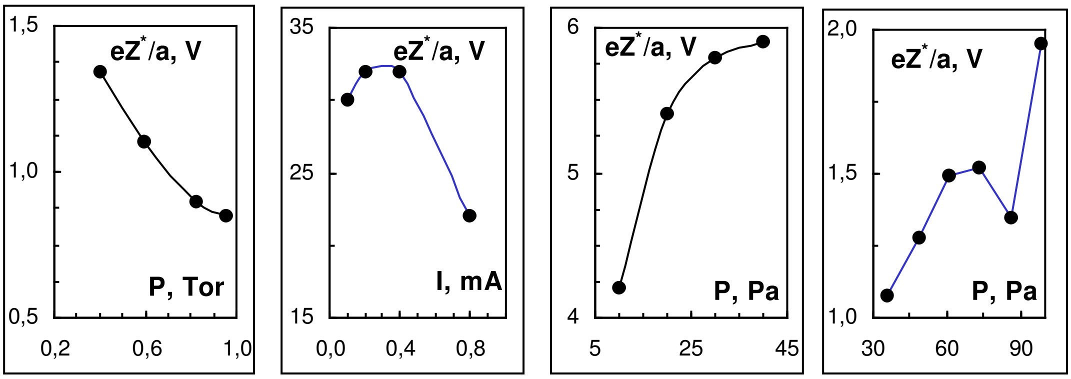
The illustration of pair correlation functions for different values of Γ^* are shown in Fig. 1 for different model potentials. It should be noted that for all cases, the melting point of lattices was observed for effective Γ^* about 106, where the first maximum of correlations functions was abrupt changed and the self diffusion coefficients D were fast reduced (see Fig. 2). Self-diffusion coefficients D were obtained for different pair potentials. Basic calculations were performed for Yukawa interactions. The calculations shown that two basic parameters are responsible for the particle dynamics in dust fluids: the effective coupling parameter Γ^* and the scaling parameter ξ (Fig. 2).

The dust temperature T, the pair correlation function $g(r)$ and the self-diffusion coefficients D can be measured for the dust clouds in plasma without additional external actions on the systems. Nevertheless, the measurements of these characteristics allow a determination of effective dust parameters (Γ^*, Z^*) only. Determination of pair potential $\phi(r)$ requires additional assumptions about its form. We will consider the determination of effective parameters Γ^*, and charges Z^* on base of dust diffusion measurements in weakly ionized plasma of gas discharges.

First experiment is the measurements in striations of dc- discharge (P = 0.4-1 Tor, the current I = 3mA, the electron temperature $T_e \approx$ 2-5 eV, the ion density $n_i \sim 5\ 10^9$ cm^{-3}) in neon (Ne) under ground-based conditions. The measurements were performed for small iron particles with the radius a = 1-3 μm. Basic purpose of these experiments was to study the dust structures the most close to the gas state. The effective coupling parameters Γ^* retrieved from diffusion measurements were varied from 10 to 20. Experiments in dc-discharge (Ne, P = 1 Tor, I = 0.1-1 mA, $T_e \approx$ 3-7 eV, $n_i \sim 5\ 10^9$ cm^{-3}) under microgravity conditions carried out on the Mir space station for big bronze particles. The mean dust size $\langle a \rangle$ = 65 μm was more than the mean free path length l_{in} of ion-neutrals collisions and above the ion Debay radius λ_i [4].

We studied dynamics of small (a =1-2.5 μm) Al_2O_3 particles in a single dust lay, which was formed above the ground electrode of rf- discharge (P = 10-40 Pa, the power W= 2-7 W, $T_e \approx$ 1-3 eV, $n_i \sim 10^9$ cm^{-3}) in argon. The effective coupling parameters were estimated. Nevertheless an application of our three-dimensional simulation for analysis of effective characteristic can be not valid in this case. Last measurements were carried out in rf- discharge (Ar, P = 36 - 98 Pa, W= 0.14-1 W, $T_e \approx$ 1-3 eV, $n_i \sim 10^9$ cm^{-3}, a =1.7 μm) under microgravity conditions in the scope of scientific international program (PKE-3) [5].

The first maximums g_{max} for measured correlation functions are presented in Fig. 3 versus effective Γ^* retrieved from diffusion measurements for all four experiments. The obtained Γ^* values are in a god agreement with the measurements of correlation functions $g(r)$. We can see also that the both the strongly correlated dust fluids and the weakly non-ideal dust structures can be formed under conditions of gas discharge plasma ($\Gamma^* \sim$ 10-85). Retrieved values of effective particle charges Z^* are presented in Figs. 4a-d. Under assumption of Yukawa interparticle interactions $Z^* = Z\ \{(1+\kappa+\kappa^2/2)\exp(-\kappa)\}^{1/2}$ and $(eZ/a) \approx$ 2-4 T_e, we can find that the dust screening lengths λ are about λ_i ion Debay radius for the small particles ($a < \lambda_i$) in bulk three-dimensional dust clouds (λ < 40 μm for ground-based dc- discharge, and λ < 90 μm for rf-discharge in microgravity). The value of λ for big bronze particles ($\langle a \rangle > \lambda_i$) is about electron Debay radius (λ > 700 μm). These results are in agreement with the numerical simulations presented in Ref. [2]. In the case of one-lay dust structures (ground-based rf- discharge), the retrieved value of λ > 400 μm is close to the electron Debay radius. But the determination of effective dust parameters on base of our calculations may be incorrect in this case.



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

FIGURE 4. The effective dust charges Z^* for different experiments in dc- (a),(b) and rf - (c), (d) discharges under (a),(c) ground-based and (b),(d) microgravity conditions.

To conclude, the transport of macroparticles in dust fluids have been numerically studied for radial pair potentials of different types. The parameters responsible for particle dynamics in dust fluids have been considered including an effective coupling parameter and a scaling parameter. Estimations of effective dust charges have been performed for macroparticles in dc- and rf – discharges under microgravity and ground- based conditions.

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REFERENCIES

1. O.S.Vaulina, S.V. Vladimirov, Plasma Phys. **9**, 835 (2002)
2. J.E. Daugherty, R.K. Porteos, M.D. Kilgore *et al*, J. Appl. Phys. **72**, 3934 (1992).
3. J.E. Allen, Phys. Scripta **45**, 497 (1992).
4. A.P Nefedov, O.S.Vaulina, O. F.Petrov *et al*, (to be published in JTEP)
5. T. Stuffler, G. Schmitt, H. Pfeuffer, *et al*., Proceed. of 52nd International Astronautical Congress 1-5 Oct 2001/Toulouse, France, IAF-01-J.6.02.