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Computer simulation of microscopic and transport properties of dusty plasma

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I. Introduction

Investigation of transport properties of dusty plasmas is the actual task. It is related to fundamental and practical problems as there are many devices where problem of removing of dust is important. Nowadays the most conventional potential of dust particles interaction is the Yukawa potential:

$$\Phi(r) = \frac{(Ze)^2}{r} e^{-r/r_D} \tag{1}$$

Some investigations of dusty plasma's transport properties were performed on the basis of that potential. The shear viscosity coefficient for 3 and 2 dimensional cases was calculated in works [1,2] by the Green-Kubo relation. In this method shear viscosity is obtained as time integral from autocorrelation function of microscopic stress tensor. Autocorrelation function can be calculated on the basis of computer simulation data, for example, the molecular dynamics simulation as in works [1,2]. However, the molecular dynamics method does not allow to investigate the dependence of shear viscosity on buffer plasma's pressure. In work [3] shear viscosity is considered as function of many parameters and the buffer plasma's pressure is among them. Authors of Ref. [3] obtained shear viscosity by the diffusion coefficient which had been calculated on the basis of the Langevin dynamics. It should be noted that in the Langevin dynamics one can take into account the pressure of buffer plasma through the friction coefficient.

In present work the shear viscosity of dust particles was calculated by the autocorrelation function obtained on the basis of the Langevin dynamics. All calculations were performed with the Yukawa potential.

II. Parameters and method

A method of the Langevin dynamics is well known for studies of dusty plasma properties [4, 5]. We considered N dust particles placed in the cubic box of side $l$with taking into account the boundary conditions. The equation of macroparticle motion has the following form

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

where $F_{int}(r_{ij}) = -\partial\Phi/\partial r$ is a force due to interaction with other grains, $r_{ij} = \left|\vec{r}_i - \vec{r}_j\right|$ is the distance between two grains, $\vec{F}_{br}(t)$ is random force, ν_{fr} is the friction coefficient depending on the plasma's pressure, m_d is the mass of a dust particle.

In the dimensionless Yukawa potential the coupling parameter $\Gamma = (Ze)^2/ak_BT$ and the screening parameter $\kappa = a/r_D$ are used. Here $a = (3/4\pi n_d)^{1/3}$ is the average distance between dust particles.

Dimensionless time τ is taken in units of inverse plasma frequency of dust particles: $\omega_p = \left(4\pi n_d(Ze)^2/m_d\right)^{1/2}$. In dimensionless friction and random forces parameter related with pressure $\theta = \nu_{fr}/\omega_p$ is used.

At first stage a system must come to the equilibrium state, it is quickly enough. We used thermostat for providing the constant temperature. After a system reaches the equilibrium state we record data on particles velocities and coordinates.

III. Autocorrelation functions

For determination of shear viscosity one needs to know autocorrelation function of microscopic stress tensor. We can write the off-diagonal component J^{xy} of this tensor as

$$J^{xy}(t) = \sum_{i=1}^{N} m v_{x,i} v_{y,i} - \sum_{i=1}^{N}\sum_{j>i}^{N}\sum_{N'} \frac{x_{ij}y_{ij}}{r_{ij}}\frac{d\Phi(r_{ij})}{dr_{ij}}, \quad (3)$$

where first term is the kinetic part and the second one is the potential part. All velocities are taken at time t. N' is number of all particles and their periodic images. Autocorrelation function can be obtained by the following expression

$$C_{shear}(t) = \langle J^{xy}(0)J^{xy}(t)\rangle, \quad (4)$$

where $\langle ... \rangle$ denotes statistical time averaging.

Autocorrelation functions of microscopic stress tensor obtained for different values of θ at $\Gamma = 2,\ \kappa = 0.5$ are presented in fig.1. It is shown with increase pressure autocorrelation function "forgets" initial conditions more quickly. It can be easily explained. It is known that at low values of coupling parameter the main part of autocorrelation function is the kinetic one [1,2]. At increasing pressure collisions with plasma particles become more frequent what leads to rapid falling of kinetic part and the total autocorrelation function as a result.
Autocorrelation functions for different values of θ at $\Gamma = 2,\ \kappa = 2$ are presented in fig.2. Here the comparison with result obtained in Ref.[1] is given.

IV. Shear viscosity of dust component

Shear viscosity can be evaluated by the following formula

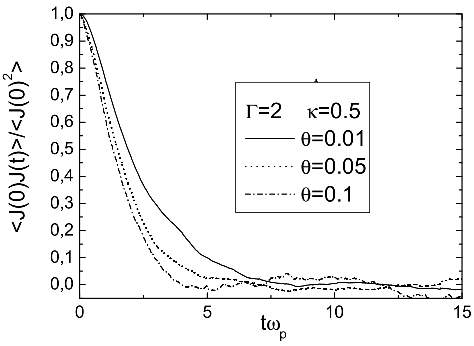

Figure 1: Autocorrelation functions of microscopic stress tensor for different values of parameter θ, $\Gamma = 2,\ \kappa = 0.5$.

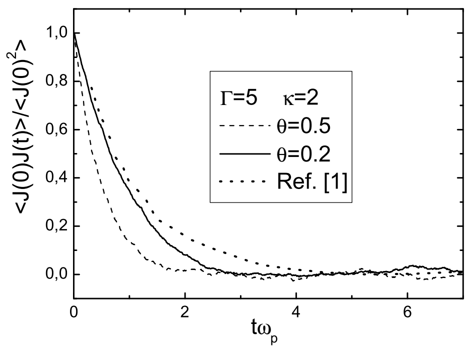

Figure 2: Autocorrelation functions of microscopic stress tensor for different values of parameter θ,$\Gamma = 5,\ \kappa = 2$.

$$\eta = \frac{1}{Vk_BT}\int_0^\infty C_{shear}(t)dt, \tag{5}$$

where V is area of the system.

Shear viscosity was calculated for different values of coupling parameter and θ. At changing θ we noted that viscosity can have complicated dependence from plasma pressure. We performed calculation with average distance between particles $a = 0.06\,cm$. According formulas (3),(4),(5) shear viscosity η^* can be presented as a sum of three terms – kinetic, potential and crossing (see Ref.[1]).

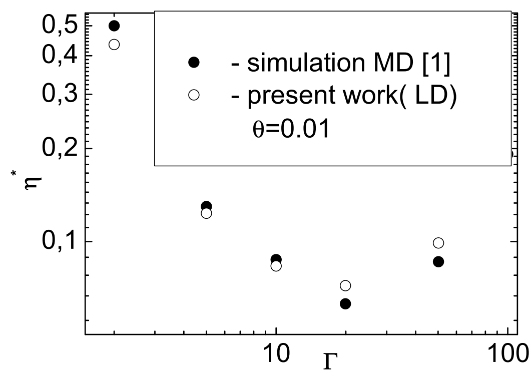

Figure 3: Dependence of reduced viscosity on coupling parameter.

In table 1 the values of reduced viscosity $\eta^* = \eta/mn_d\omega_pa^2$ and its kinetic, potential and crossing parts at $\Gamma = 2,\ \kappa = 0.5$ are given. It should be noted that values of kinetic, potential and crossing viscosities from Ref.[1] are presented in units of $\sqrt{3}mn_d\omega_Ea^2$ (ω_E is Einstein's frequency, $\omega_E \to \omega_p/\sqrt{3}$ at $\kappa \to 0$).

One can see that results obtained on the basis of the Langevin dynamics tend to data [1] at $\theta \to 0$ and viscosity decreases with increasing of θ.

It is true for small coupling parameters because in this case the main part of viscosity

Table 1: The reduced viscosity.

θ	η^*	η^*_{kin}	η^*_{pot}	η^*_{cross}
Results of this work				
0.01	0.4355	0.4550	0.0287	-0.0482
0.05	0.3817	0.3809	0.0310	-0.0302
0.1	0.2775	0.2652	0.0336	-0.0213
1	0.1225	0.1057	0.0376	-0.0208
Ref[1]				
θ	η^*	$\hat{\eta}_{kin}$	$\hat{\eta}_{pot}$	$\hat{\eta}_{cross}$
0	0.500	0.564	0.0246	-0.0583

is the kinetic one. The potential part of viscosity increases with increasing of θ.In the range $10 < \Gamma < 20$ both kinetic and potential parts become equal and after then the potential part becomes the dominating one. In this region the anomalous increasing of viscosity with increase of plasma pressure was observed experimentally [6]. Authors gave such explaining of this effect: at large pressure dust particles relax and tend to more regulated structure what increases viscosity of dust system. The calculated results of this work confirm this fact. At large values of coupling parameter a potential part of viscosity increases with increasing of pressure and the total viscosity also. Results for $\theta = 0.01$ at different Γ are presented in Fig.3. The comparison with data from Ref.[1] shows the small difference between results, more over these differences can be in interval of error, but one can see that values of viscosity obtained in this work lay under data [1] at $\Gamma < 10$and lay above them at $\Gamma > 10$. With increasing of pressure the difference will increase.

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