Study of Relation between Transport Coefficients in Dusty Plasma Systems

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The problems associated with the transport phenomena in the systems of interacting particles are of significant interest in various fields of science [1-9]. The self-diffusion, and viscosity constants are fundamental dynamic parameters. The determination of analytical relations for transport constants in strongly correlated systems can be useful for application of known hydrodynamic approaches in analysis of wave propagation, and formation of different instabilities [1, 2]. The laboratory dusty plasma (consisting of electrons, ions, neutral gas and solid macro-particles of micron sizes) is a good experimental model for studying of non-ideal systems, because, owing to their size, dust particles may be video filmed, which significantly simplifies the use of direct diagnostic methods.

It is customary to assume that dust particles in a plasma interact through the screened Coulomb potential, $\varphi = eZ\exp(-r/\lambda)/r$, where r is the distance, λ is the screening radius, and Z is the dust charge [4-9]. The numerical simulations [4, 5] of these systems demonstrate that, in the case of $\kappa < 6$, the value of effective coupling parameter, $\Gamma^* = (Z e)^2 (1+\kappa+ \kappa^2/2)\exp(-\kappa) /(T r_p)$ fully defines the form of the binary correlation function $g(r)$. The mass transfer in dissipative fluids are determined by two parameters: Γ^* and the scaling factor $\xi = \omega^*/ \nu_{fr}$, associated with the ratio of the frequency $\omega^* = eZ [(1+\kappa+ \kappa^2/2) \exp(-\kappa)\, n /(\pi m_p)]^{1/2} \equiv [T\Gamma^*/(\pi r_p^2 m_p)]^{1/2}$ to the friction frequency ν_{fr} (here m_p is the particle mass). In the case of a strongly coupled system with $\Gamma^* > 40$-50, the diffusion coefficient can be written as [5]

$$D \cong \frac{T\,\Gamma^*}{12\pi(\omega^* + \nu_{fr})m_p}\exp\left(-c\frac{\Gamma^*}{\Gamma^*_c}\right), \qquad (1)$$

where $\Gamma^*_c \cong 102$ is the crystallization point, $c \cong 2.9$ for $\xi \geq 0.41$, and $c \cong 3.15$ for $\xi \leq 0.14$.

To determine the relationship between the viscosity and self-diffusion constants for dense fluids the Einstein-Stokes relation is commonly used $\eta \cong T/(6\pi a_{eff} D)$ [2, 4], where a_{eff} is the effective radius of spherical molecule. Our search for approximation of η involved the numerical calculations in the Yukawa (for κ = 0.16 - 4.8) [7], and in the OCP models [8, 9], performed for vanishing viscosity ($\nu_{fr} \rightarrow 0$). In order to illustrate our results, the value of η was reduced to $\eta_o = \frac{\Gamma^*}{r_p^{\ 2}}\sqrt{\frac{\pi T m_p}{\Gamma_c^{\ *}}}$ (see Fig. 1). One can easily see that $\eta^* = \eta/\eta_o$ values are determined by the effective coupling parameters within numerical errors (~ 20%) in determination of shear viscosity [7-9]. Thus the numerical data have been approximated by the Einstein-Stokes relation with $a_{\rm eff}$(T) ≡ const, and the diffusion constants D was set proceeding from simulations for the disperse (ν_{fr} =0) [6], and dissipative ($\nu_{fr} \neq 0$) systems [5]. Normalized viscosity $\eta^* = \eta/\{\eta_o(1+\xi^{-1})\}$ is shown in Fig. 1. (Notice that $\eta^*=\eta/\eta_o$ in disperse case $\xi^{-1} = 0$). Best fitting of numerical data for Γ^* from ~ 1 to ~ 100 gives

$$\eta \cong T/(8.1\ r_d D). \qquad (2)$$

The mean square errors of this approximation (~ 20 %) are close to the magnitudes of numerical errors for simulations of viscosity.

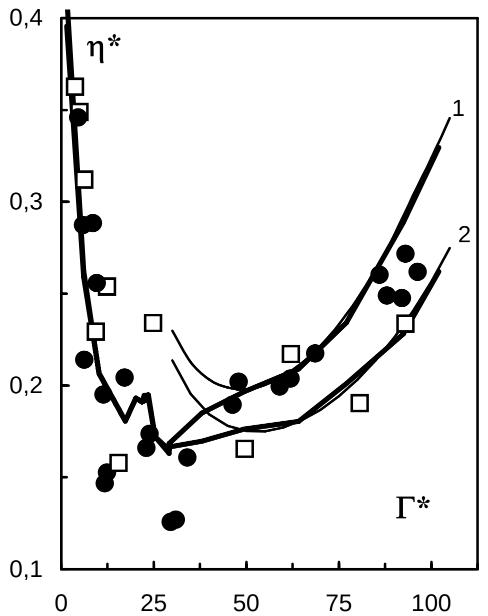

Fig. 1. Coefficient η^* vs. Γ^* obtained by Eq. (2) (thick lines), and by Eq. (3) (fine lines) for ξ: **1** – ≤ 0.14, **2** – ≥ 0.41; and the function $\eta^*(\Gamma^*)$ for disperse systems (ν_{fr} = 0) in OCP (□) [8, 9], and Yukawa models (●) [7] for κ = 0.16- 4.8.

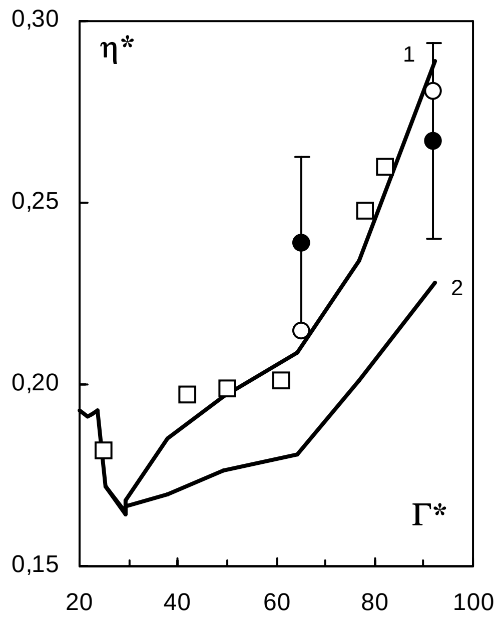

Fig. 2. Coefficient η^* vs. Γ^* for η obtained by Eq. (2) (lines): **1** – ξ ≤ 0.14, **2** – ξ ≥ 0.41; and the $\eta^*(\Gamma^*)$ values measured (●) and calculated (○;□) by Eq. (2) using measured parameters for different experiments: (○;●) -[3];(□) -[2].

Thus, taking into account Eq. (1), the analytical approximation for shear viscosity in the strongly correlated systems ($\Gamma^* > 40\text{-}50$) can be written as (see Fig. 1).

$$\eta \cong \frac{4.65(\omega^* + \nu_{fr})m_p}{\Gamma^* r_p} \exp\left(c \frac{\Gamma^*}{\Gamma^*_c} \right), \tag{3}$$

Let us analyze the data of experimental determination [3] of transport characteristics in dusty plasma presented in Table 1. The experiments were performed in rf- discharge under ground-based conditions for latex particles ($m_\mathrm{p} \cong 5.4\ 10^{-12}$ g). The estimations of viscosity constants, η^m, were obtained from Navier- Stokes equation by the best fitting of experimental velocity profile $V(y)$ of laminar flow of macro-particles moved through an undistributed area of dusty plasma under exposure to a beam of Ar^+ laser. The dust parameters (such as Γ^*, T, r_p and D) were measured in the undistributed dusty plasma [3]. The experimental errors were within 5-10%. The viscosity coefficients (η^c) were calculated from Eq. 2 with the help of measured parameters (T, D, r_p). The difference between the values of η^m and η^c is within the limits of experimental errors.

The results of experimental study of liquid dust structures under microgravity [2] are also presented in Table 1. The experiments were performed in rf- discharge with polymer particles ($m_\mathrm{p} \cong 3.1\ 10^{-11}$ g) for a wide range of $\Gamma^* \sim 25\text{-}82$ and were detailed in [2, 10]. The estimations of viscosity from Eq. (2) are shown that the η value is about the order of magnitude higher than under ground-based conditions. This difference can be result from the appreciable difference between the dusty structure parameters (n, T, m_p) in analyzed experiments.

Comparison of experimental results with the data of numerical simulations is shown in Fig. 2. We can see that the experimental values of viscosity are in a good accordance with the numerical simulations for the both experiments discussed. Thus we can assume that the shear viscosity for a dust systems is determined by the effective parameter Γ^*, and to take into account the energy dissipation due to the collisions of dust with the neutrals of gas the scaling factor ξ must be used. The Einstein-Stokes formula, Eq. (2), may be used for analysis of relation between the diffusion, and shear viscosity constants in a wide range of parameters of the coupled Yukawa, and dusty plasma systems.

Acknowledgments

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TABLE 1. Measured shear viscosity (η^m), and viscosity coefficients (η^c) calculated by Eq. 2 for different discharge (P is the gas pressure) and dusty structure (T, D, Γ^*, ξ, r_p) parameters.

P, mB	r_p, μm	T, eV	D 10^5, cm^2s^{-1}	Γ^*	ξ	$\eta^m 10^9$, Pa s	η^c 10^9, Pa s
Experiments [3]							
0.15	780	0.026	1.54	92	0.089	0.41	0.425
0.25	600	0.035	1.98	65	0.068	0.64	0.581
Experiments [2]							
0.36	200	0.51	7.45	25	0.174	-	5.52
0.49	200	0.24	1.85	50	0.133	-	7,57
0.61	200	0.27	1.0	82	0.147	-	13.2
0.73	200	0.37	1.75	61	0.124	-	11.5
0.86	215	0.4	2.0	42	0.083	-	7.11
0.98	220	0.48	1.25	78	0.110	-	13.8

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