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Dust Particles' Oscillations and Kinetic Temperature in Dusty Plasma

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The dispersive component of dusty plasma can be characterized by temperature as long as dusty subsystem tends to thermodynamic equilibrium. So, it is possible to introduce the concept of kinetic temperature (of dusty component) T_d. It can be equal to very high values close to the one of electronic temperature due to interaction between dust particles and electronic subsystem of plasma. Note that energy exchange between dust and neutrals is embarrassed on account of large difference in particles' masses and sliding effect [1, 2] under high vacuum conditions. Temperature T_d is important and characteristic parameter of dusty component. The question about accuracy of T_d determination is of certain interest. T_d is obtained from the comparison of empirical distribution function of macroparticles throughout velocity with Maxwell distribution. If the thermodynamic equilibrium is attained one can assign to the dusty subsystem the temperature T_d. Macroparticles distribution function F_v definition is performed by capturing a set of pictures of dusty structure with given frame frequency f_{frm}. Dusty component is a system of strongly interacting particles. Under conditions of solid state of dusty structure the macroparticles are oscillating near equilibrium positions. In liquid state the macroparticles' trajectories represent a Brownian broken line. Macroparticles in dusty "liquid" are oscillating with some frequency and amplitude as well in spite of translation motion. Evidently, in case of approximately equal frame frequency f_{frm} and characteristic frequencies of these oscillations large errors can occur in definition of function F_v and obtaining of temperature T_d as well.

Let us consider, for instance, harmonic oscillation with amplitude a and frequency ω of a particle along Ox axis. Let the particle's position to be defined by $x(t) = a \cos \omega t$. In some time $\tau = f_{frm}^{-1}$ the particle will assume the position $x(t+\tau) = a \cos \omega(t+\tau)$.

The ratio of mean square theoretical and experimental velocities is written:

$$\frac{\left\langle V_{exp}^2 \right\rangle}{\left\langle V_{th}^2 \right\rangle} = \left[\frac{2}{\omega\tau} \sin\left(\frac{\omega\tau}{2} \right) \right]^2 . \qquad (1)$$

According to approach in question velocities ratios indicated above are independent of the amplitude of oscillations and are defined by frame frequency f and oscillation frequency ω.

If frame frequency f is large ($\omega\tau \rightarrow 0$) experimental and theoretical mean square velocities coincide. But, if frame frequency f_{frm} is about oscillation frequency, the values of $\left\langle V_{exp}^2 \right\rangle$ and $\left\langle V_{th}^2 \right\rangle$ might differ greatly. It can cause sufficient errors in estimating of kinetic temperature T_d and also allows one to obtain via experiment characteristic frequencies and amplitudes of macroparticles oscillations performing capturing at different frame rates.

The present work is dedicated to dusty structures arising in plasma of capacitive RF discharge. The discharge was supported by RF generator with main frequency 13.6 MHz and power from 2 to 100 W. A cloud of monodisperse plastic particles 12.7 μm in diameter, immersed into the discharge, formed structures of different degrees of ordering. The dusty structure levitated near lower electrode in the potential hole, created by a ring 50 mm in diameter and 2 mm of height. Particles were illuminated by thin light beam of Ar^+ laser. Dusty structures were observed and recorded by CCD camera. The parameters of the latter were: spatial resolution: 1024 × 1024 pixels, frame rate range: $20-1000\ fps$. Argon was used as background gas. Its pressure was between 2 and 30 Pa.

In this experiments dusty structures with different values of effective nonideality parameter Γ^*, kinetic temperature T_d and macroparticles concentration was obtained. The regained values of T_d and $\left\langle V_{exp}^2 \right\rangle$ proved to be strongly dependent on frame frequency used in experiment. Thus the necessity arises of appropriate technique to define T_d and $\left\langle V_{exp}^2 \right\rangle$ independently of frame frequency. For the aim to obtain such a method the series of experiments was carried out during which the same structure was being observed with different frame rates.

In fig. 1 is shown the experimental dependence on frame frequency f_{frm} of obtained temperature T_d and mean square velocity $\left\langle V_{exp}^2 \right\rangle$:

$$\left\langle V_{exp}^2 \right\rangle = \varphi(f). \tag{2}$$

Three characteristic parts of curves (2): increasing one at low frame rates, constant one for intermediate rates and again increasing part for high frame rates. The first part appears due to principal impossibility of approximation of a macroparticle's trajectory by a line for any appropriate accuracy at low frame rate. The increase of $\left\langle V_{exp}^2 \right\rangle$ and consequently T_d with growing f represented by the third part of curves (2) can be explained if one takes into consideration the uncertainties in determination of macroparticles' position. Let us consider a macroparticle propagating along a line at a speed $V \sim 1$ ppf (pixel per frame) observed via CCD camera and analyzed by a computer. The mean square velocity equals $\left\langle V_{exp}^2 \right\rangle = \left(\Delta x \cdot f_{frm}\right)^2 \cdot \left(V/(f_{frm} \cdot \Delta x) + \theta\right)$, where θ – error in determination of a macroparticle's position, Δx – is length corresponding to one pixel. Thus one to be correct can assume that the constant value related to the second part of curves (2) represents real values of T_d and $\left\langle V^2 \right\rangle$ accordingly.

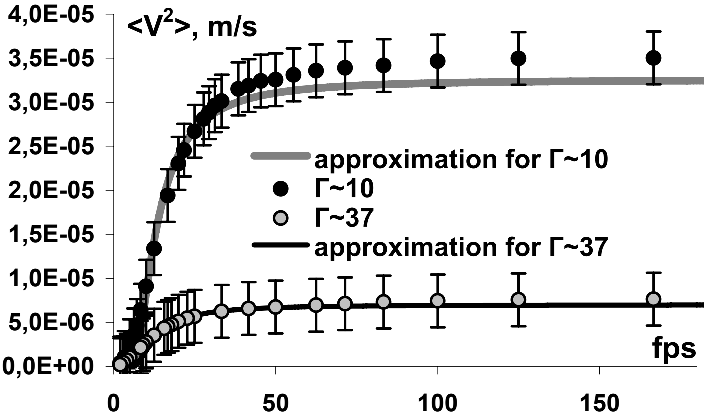

Figure 1. The empirical dependence of regained mean square velocity $\left\langle V_{exp}^2 \right\rangle$ on frame frequency f_{frm}:

Relation (1) apart from giving a correct method of obtaining T_d provides clues for understanding of dynamics and structure properties of dusty plasma. Empirical determination of dependencies $\omega_d = \omega_d(\Gamma^*, T_d, n_d)$ can lead to relation between Γ^* and T_d.

The value of $\omega_d^{\exp}$ was found by varying ω_d till $\left\langle V_{exp}^2 \right\rangle$ coincides with it value from relation (1). The result of this operation is shown at fig. 1. It is easily seen how close is the theory in question to the curve's parts 1 and 2.

What are those processes which correspond to the found oscillations? Let us estimate the order of value of plasma dusty frequency [see e.g. 4]:

$$\omega_d{}^{pl} = \left(\frac{4\pi n_d q_d^2}{m_d}\right)^{\frac{1}{2}},$$

where n_d is dusty concentration, m_d and q_d – mass and electric charge of a dusty particle correspondingly. For our case $n_d \sim 3.0 \cdot 10^3$ cm^{-3}, a macroparticle radius $r = 6.37 \cdot 10^{-4}$ cm, its density $\rho = 1.5$ g·cm^{-3}. The estimation for our experiment conditions of charge of a macroparticle is about ~ 10^4 e, where e is elementary charge. The estimation gives value

$\omega_d^{pl} \cong 20\ s^{-1}$. This value is close to the one obtained empirically for *solid-like* state dusty structure, but sufficiently differs from the experimental value for *liquid-like* state. Pro forma it can be explained by specific volume gap in "solid — liquid" transition.

Numerical values of Γ^*, T_d, ω_d^{pl}, $\omega_d^{\exp}$, a, and mean interparticle distance in dusty cloud r_d, are shown in Table 1.

Table 1. Data Obtained from Experiment

Γ^*	T_d, eV	r_p, µm	n_d, cm^{-3}	ω_d^{pl}, rad/s	$\omega_d^{\exp}$, rad/s	a, µm
10 ± 3	170 ± 4	825 ± 75	1800 ± 160	18 ± 2	38 ± 2	210
37 ± 3	39 ± 4	630 ± 40	4000 ± 200	27 ± 2	40 ± 4	100
90 ± 4	20 ± 2	820 ± 80	1800 ± 180	18 ± 2	38 ± 2	75
200 ± 15	14 ± 2	930 ± 90	1250 ± 120	15 ± 2	21 ± 3	110

This work is considered on developing of the techniques of kinetic temperature measuring for dusty component of plasma. It was shown that capturing of a dusty structure using standard frame rate can cause sufficient errors in determination of macroparticles' distribution functions and kinetic temperature T_d. On the basis of this technique characteristic low-frequency oscillations of macroparticles in dusty plasma were found and frequencies and amplitudes of them were determined. This frequency ω_d proved to be almost independent of the value of nonideality parameter right up till those values that correspond to "solid" state of a dusty structure. According to experimental results in the latter case dusty frequency ω_d was found to decrease.

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1. Fuchs N.A., The Mechanics of Aerosols, Pergamon Press, Oxford, 1964.
2. Gavrikov A., Shakhova I., Ivanov A., *et al.*, *Phys. Lett. A*, 336, 378 (2005).
3. Fillipov A.V. *et al.* *JETP* 123, 775 (2003)
4. Fortov V.E. *et al., UFN*, №5 (2004)