Experimental study of two-phase dust mono-layers forming in near-electrode area of RF- discharge

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The process of melting in two-dimensional systems is of great theoretical as well as practical interest. It qualitatively differs from the phase transition from the solid to the liquid state in three-dimensional systems. There are two main approaches in the melting theory for two dimensions that are based on unbinding of topological defects. The first of them is the Kosterlitz-Thouless-Halperin-Nelson-Young (KTHNY) theory, which predicts two phase transitions from the solid to fluid state via an intermediate state (so called “hexatic” phase) [1-3]. The second melting theory, the theory of grain-boundary-induced (GBI) melting [4, 5], predicts a single first-order transition from the solid to the fluid state without an intermediate phase for a certain range of values of the point-defect core energies.

Laboratory dusty plasma represents a good experimental model for investigation of properties of coupled systems. Dusty plasma is an ionized gas containing small grains of solid matter (dust) that becomes electrically charged. This plasma is very common in nature and is also generated during some technological processes. In dusty plasma, micron-size grains acquire a significant electric charge, and this can lead to the formation of dust structures (similar to a liquid or to a solid). Very important is that the separate grains in dusty plasma can be simply registered. This makes it a good experimental model for studying different strongly coupled systems, e.g. liquids, at the “kinetic” level, which is very important for testing the existing phenomenological models in the theory of liquid state, as well as for creating new models. The dusty plasma of rf-discharge is a good model of a quasi-two-dimensional system, as in the near-electrode area the confined layers of particles are formed.

The phase state of a two-dimensional system can be characterized by analyzing the peak decay rate g^s of its pair correlation function $g(l)$. For this purpose, the following approximations are used [6]: exponential

$$g^s = 1 + (g_{max} - 1)\exp\left[-\mu(l - l_{max})/l_p\right], \qquad (1)$$

and power-law

$$g^s = 1 + (g_{max} - 1)\left(1 + (l - l_{max})/l_p\right)^{-\eta} \qquad (2)$$

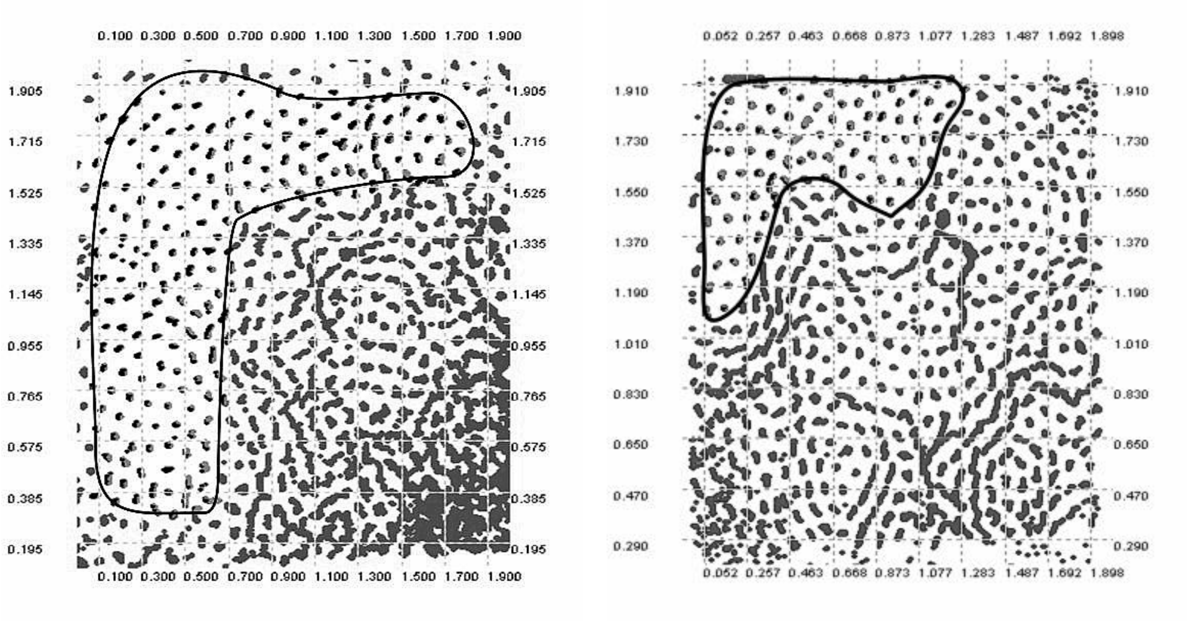
The dependence of the coefficients (η, μ) of these approximations on the effective parameter Γ^* was obtained in [7]. The authors of that work noted that both these approximations have small jumps of their parameters (η, μ) in the range of Γ^* from ~ 97 to ~ 110. In this case the parameters of these approximations practically don't change (η =1.6, μ = 0.6*)* for the interval 153 > Γ^* > 110, which can be associated with the range of existing of hexatic phase in the systems under consideration. As the effective coupling parameter Γ^* grows (Γ^* > 165), the perfect crystal is forming, and the decay of the pair correlation function can be described with the help of [6]

$$g^s \propto \left(l/l_p\right)^{-\eta}, \tag{3}$$

with η<1/3, for all the peaks of $g(l)$, excluding the first one.

We have analyzed the experiments with dusty plasma structures in the RF discharge in argon. The particle diameter was 5.5 мкм (density ρ_p = 1.5 g*cm $^{-3}$). The pressure of the buffer gas in experiments was changed from ~ 2 to ~ 20 Pa. The quasi-two-dimensional systems were studied, where the regions with different phase systems (dusty liquid and dusty crystal) co-existed. The effective coupling parameter Γ^* of the dusty systems under study was changed from 20 to 250.

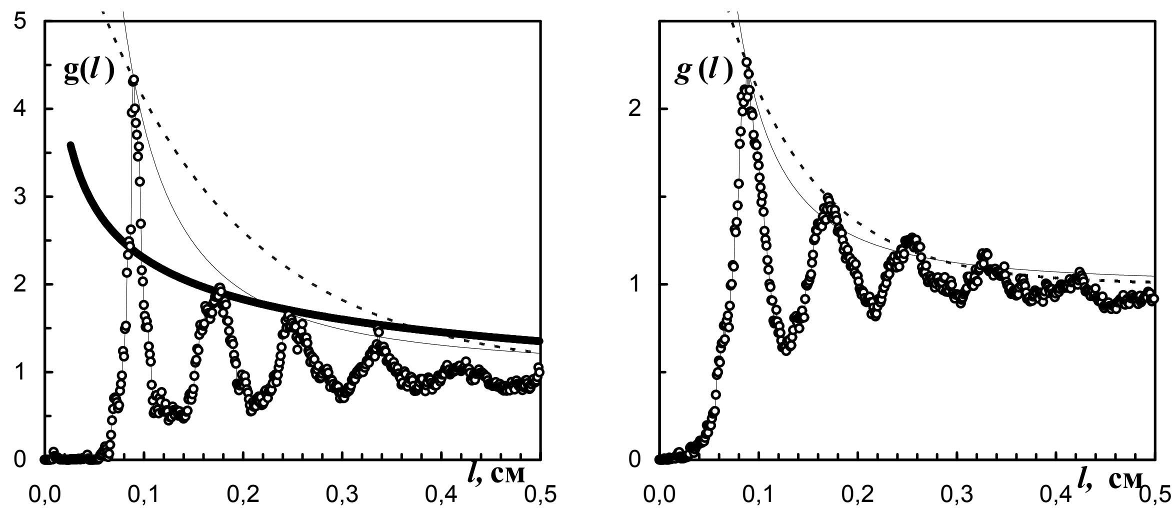
The video records of the behaviour of dust grains in the RF-discharge were processed with the computer program "Plasma"; as a result, the coordinates of each separate particle in horizontal plane in each registered moment of time were obtained. Then in each studied system the regions were selected with a homogeneous phase state (see Fig. 1); so for all the considered cases there were found more and less ordered regions. The Fig. 1(a), (b) represents the overlapping of frames of the video recording for the time interval Δt. In Fig. 1 a the crystal phase (Γ^* = 205) adjoins the liquid one (Γ^* = 55); in Fig. 1b the less ordered region is crystalline, but the macroscopic vortices can be distinctly seen in it, which can be a sign of the hexatic phase formation. With the help of the computer program "Dragon", based on the obtained coordinates of the dusty grains, we have drawn the pair correlation functions (PCFs, see Fig. 2), the velocity autocorrelation functions, the mass-transfer evolution functions and the velocity distribution functions of the dusty grains. The analysis of the magnitude of the first peak of the PCF, mass-transfer evolution functions and velocity autocorrelation functions allowed to estimate the effective coupling parameter of the marked regions.



(a) **(b)**

Fig 1. The dusty systems with co-existing phase states (overlapping of experimentally obtained frames for the certain time period Δt). The more ordered regions are marked. The numbers are the scaling in centimeters. (a) $\Gamma^* = 205$ and $\Gamma^* = 55$, $\Delta t = 2{,}1$ s; (б) $\Gamma^* = 250$ and $\Gamma^* = 130$, $\Delta t = 4{,}62$ s.

For the considered regions of dusty subsystems there were found the PCFs, the peaks decay rate was analyzed, and the comparison to the numerical results was done. The example of such comparison is shown in Fig. 2, where the part (a) corresponds to the more correlated region of the dusty subsystem, (b) – to the less correlated one.



(a) **(b)**

Fig. 2. The PCFs $g(l)$ of the dusty subsystem for (a) $\Gamma^* = 205$ and (b) $\Gamma^* = 55$ (line+markers). The dashed line corresponds to the exponential approximation (1), the thin line – to the power-law approximation (2), the thick line – to the power-law approximation (3).

In Fig. 3 one can see a comparison of the peak decay rate of the experimentally obtained PCFs with the numerical results of [7]. For each experiment there were found the best fitting parameters of the approximations (1) – (3).

It is easy to see that the exponential approximation (1) with the numerically obtained parameter μ is inadequate in case of the dusty crystal, because the approximation error is too large. This approximation fits satisfactory the behaviour of the systems with small Γ^* ($\Gamma^* < 50$). The approximation (3) can be used for the systems with $\Gamma^* > 150$, and the power-law approximation (2) can be used for all the considered values of Γ^* with satisfactory accuracy.

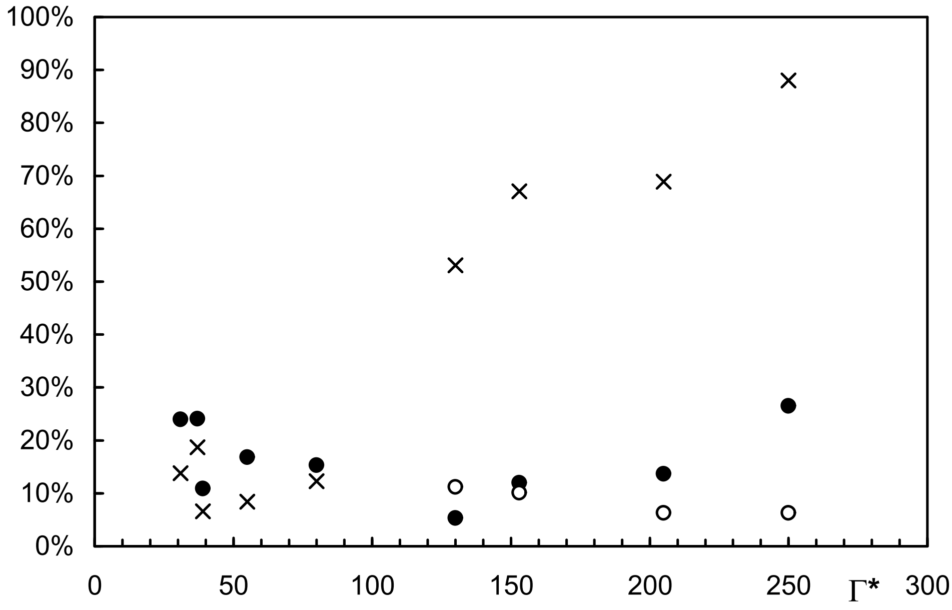


Fig. 3 The approximation error: ×- exponential (1), ● – power-law (2), ○ – power-law (3). The values of parameters μ and η in these approximations were taken from the numerical simulation [7].

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