Study of Diffusion Coefficient and Phase Transitions in Structures Formed by Dust Particles in RF-Discharge.

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1. Introduction.
Diffusion is the process caused by thermal movement of molecules. It is the basic transport process determining dissipation of energy in dust plasma structures. Systems where interaction between particles cannot be considered as small are of most interest for us. In this case dusty plasma behaviour is similar to a liquid. The theory of diffusion in a liquid is developed in two directions, one of them is based on analogy between a liquid and a solid structure, and another proceeds from the general principles of statistical physics. But also in this case it is not possible to receive correct estimations for relationship between diffusion coefficient and other parameters of system. The important step in the decision of the problem is the experimental study of dusty plasma parameters, diffusion coefficient and relations between them. It is necessary to note that the self-diffusion process determine the system's phase state and conditions of various waves and oscillations formation.

2. Experiment.
A schematic representation of the experiment is shown on the figure 1:

Experiments with a variation of parameters RF-discharge (RF-power (3-12 W) and gas pressure (0.07-0.7 torr)) were carried out.
The RF-discharge electrodes were made as two parallel plates of 19 cm diameter. A lower electrode is ground and powered upper electrode with centrally located hole of 5 cm diameter, is connected with high-frequency generator $f = 13.56$ MHz. The trap-ring of 5 cm diameter is centrally located on the lower electrode. This ring prevents a movement of particles to the edge of electrode. The discharge gap is 5 cm wide. This system is placed in vacuum chamber of 35 cm diameter and 50 cm height with four horizontal and one top observation windows. As a background gas we used argon.

In experiment we use polydisperse $\text{Al}_2\text{O}_3$ particles of 3-6 $\mu$m diameter and monodisperse plastic (MF) spheres of 4.05 $\mu$m diameter. The structures formed by dust particles in RF-discharge are suspended above lower electrode, where the electric field force balances the weight of the particle. A horizontally expanded laser beam from the HeNe-laser illuminates the levitating structures. The dust particles are viewed with a video camera.

3. Analysis.

The video signals are stored by a videotape recorder and transferred to computer. Using these data we receive value of diffusion coefficient $D(t)$:

$$ D(t) = \frac{< r(t)^2 >}{6t}, $$

where $r(t)$ is displacement of any particle depending of time,

$<$ > means average by ensemble.

Typical dependences of diffusion coefficient on time are shown on the figure 2.

![Figure 2(a, b). Typical time dependence of $D/D_0$:](image)

a) Pressure 0.07 torr, RF-power 5 Wt, $\Gamma = 66.9$;

b) Pressure 0.2 torr, RF-power 5 Wt, $\Gamma = 52.1$
It is conventional to use two coefficients of diffusion:

\[
D_S = \lim_{t \to 0} D(t), \quad D_L = \lim_{t \to \infty} D(t)
\]

\(t \to 0\) means that \(t\) is a small enough time, but it should be greater than characteristic time of dust particle’s collisions with neutrals.

It should be remarked that: \(D(t) \to D_0\), when \(t \to 0\).

Here \(D_0\) is a diffusion coefficient of non-interacting particles.

We use the numerical results [1]:

\[
D_L = a \frac{T}{m} \frac{T \Gamma^*}{\sqrt{\pi m L^2}} e^{-a r^*}
\]

Here \(\Gamma^* = \Gamma e^{\frac{k^2}{2}}(k^2 + k + 1), \quad k = \frac{T}{L_d}\)

\(L\) is a interparticle distance, \(L_d\) is a Debye radius, \(m\) is a mass of dust particle, \(\nu\) is a frequency of collision with neutrals, \(a\) is a constant depending on parameters of background gas, \(\Gamma\) is the ratio of the Coulomb potential energy to the particle kinetic energy, \(T\) is a kinetic energy (or temperature) of dust particles.

On the basis of the received experimental results we calculated \(\Gamma\), velocities of dust particles and their kinetic energy, interparticle distance and Debye length. This parameters are shown in table 1.

<table>
<thead>
<tr>
<th>(\Gamma)</th>
<th>(\nu) (eV)</th>
<th>(D) (cm(^2)/s)</th>
<th>(L_a) (mkm)</th>
<th>(P) (Pa)</th>
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</thead>
<tbody>
<tr>
<td>86.9</td>
<td>0.37</td>
<td>7.92E-05</td>
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</tr>
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<td>84.9</td>
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</tr>
<tr>
<td>66.9</td>
<td>0.28</td>
<td>9.34E-05</td>
<td>337.16</td>
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<td>60.7</td>
<td>0.27</td>
<td>7.68E-05</td>
<td>407.37</td>
<td>17</td>
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<tr>
<td>52.1</td>
<td>0.31</td>
<td>6.07E-05</td>
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<td>43.3</td>
<td>0.33</td>
<td>9.14E-05</td>
<td>286.17</td>
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<tr>
<td>35</td>
<td>0.41</td>
<td>5.41E-05</td>
<td>310</td>
<td>62</td>
</tr>
</tbody>
</table>

Table 1. Values of dusty plasma parameters for monodisperse particles (m=5.2\*10^{-14}kg).
The examples of correlation functions are shown on the figure 4:

![Fig. 4. Particles: monodisperse (MF), radius 2,025 mkm.](image)

a) Based on the experimental results $\Gamma = 86.9$, max/min = 5.9;

b) $\Gamma \sim 35$: Dark-numerical simulation results; Grey – experimental results

Image and correlation function of gaseous phase is shown on the figure 5:

![Fig.5 monodisperse particles, pressure of background gas = 0.13torr, RF-power = 12Wt](image)

4. Conclusion.

- Process of a diffusion in dust structures of RF-discharge plasma was studied.
- Noncontact diagnostic of dusty plasma was confirmed
- Values of the parameter $\Gamma$, velocities of dust particles, their kinetic energy, the diffusion coefficient, the interparticle distance were calculated, on the base of the experimental results.
- Correlation functions were obtained for different states of the system.

5. References.
