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Vortices in DC discharge dusty plasmas: one mechanism and 3D diagnostics.

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Abstract
3D measurements of dust vortices in a striation of a dc discharge were carried out and analyzed. The shape of the vortices is close to toroidal, and the particles at the top of the structure have a lower kinetic temperature than the ones at the bottom A possible mechanism of the formation of dc discharge dust vortices was considered. Analysis of the Rayleigh number of the dust vortices was carried out.

A dusty plasma is a partially ionized gas containing charged dust particles of micron size. The particles in gas-discharge plasmas are usually charged negatively by collecting electrons. The combined action of interaction between dust grains and dissipative processes in dusty plasmas can lead to the formation of both steady-state dusty structures (similar to fluids or solids) and complex dynamic configurations associated with large-scale transport processes.

Vortices are the most widespread type of self-organized systems. They are formed when a gas or a liquid is in turbulent motion. The dynamic dust structures (such as waves, or vortices) are steady concentration distributions of the moving particles. The directed speed of these particles should be not equal to zero. There are a lot of theories that explain the nature of formation of such structures. The influence of the forces of ionic attraction on the formation of vortical movement of dust particles under microgravity conditions was considered in [1]. In [2] a model to explain the occurence of vortical movement of dust particles in a field of action of nonelectrostatic forces has been offered.

In this paper, we consider one of the possible mechanisms of vortex formation that are about convection instabilities. A similar thing happens when a horizontal layer of a liquid is heated from below.

To measure dynamic characteristics of dust particles (trajectories and speed distributions) three-dimensional images of dust structures in a dc discharge were produced. For this purpose structures were lit by wide laser beam and recorded simultaneously by two synchronized video cameras with an angle between each other.

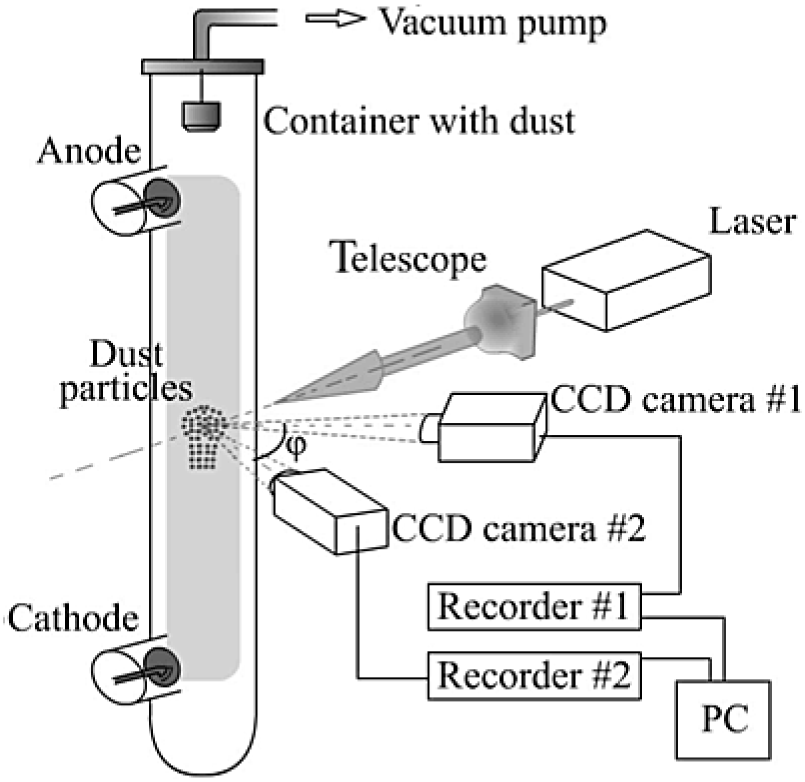

Figure 1. Schematic view of the experimental setup.

The experimental setup is schematically shown in figure 1.The discharge was generated in Ne at pressures p = 0.2–1Torr and currents I = 0.2–1.3 mA. Particles were stored in a container with a grid at the bottom and positioned above the anode. When the container was shaken the particles fell downwards through the grid. We used monodisperse melamine formaldehyde (MF) particles with a diameter of 2 μm and a density of 1.51 g cm^{-3}. With a tube of 5.5 cm in diameter we can obtain large dusty clouds of about 1 cm in size within a striation. In order to visualize the vortices we illuminated the particles with a He-Ne laser beam of λ = 532 nm. To record the scattered light from the particles two CCD video cameras were used at a frame rate of 25 fps.

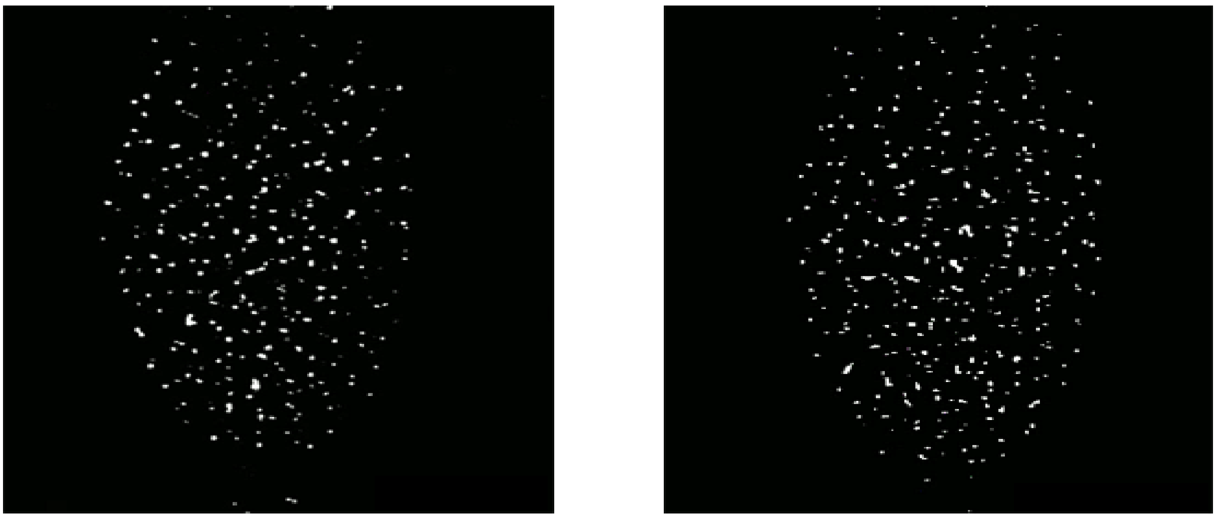

Figure 2. Dust convection in a striation of a cylindrical dc glow discharge from left and right video cameras

Figure 2 shows frames from the two synchronized CCD cameras, which have been processed by special computer programs to obtain a 3D model of dust vortices (Fig.3).

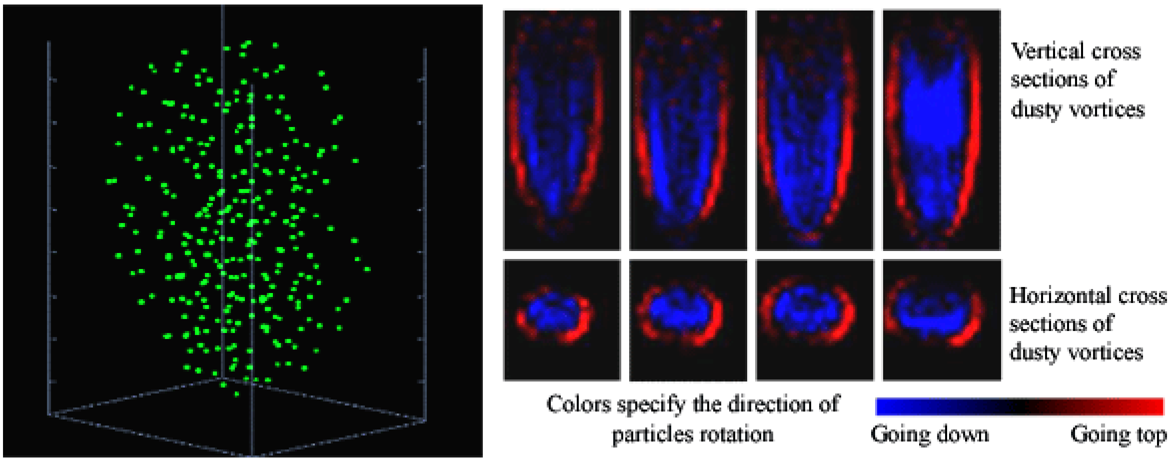

Figure 3. 3D picture of the recognized dust particle vortex and spatial distributions of the particle flows

The Rayleigh-Benard instability can arise when the fluid is confined between two horizontal plates with heat being supplied from below. In this case the density of liquid near the bottom plate is lower than the density near the upper plate and the result of this is the formation of convective motions (see Fig.4). The beginnings of the convections depend on the Rayleigh parameters:

$$\mathrm{Re} = \alpha \frac{gh^3 \Delta T}{\nu\theta}, \quad \alpha = -\frac{1}{\rho}\left(\frac{\partial \rho}{\partial T}\right)_p$$

Where α is the coefficient of thermal expansion, h – depth of a layer, g – acceleration of a gravity, ΔT – the temperature gradient, ν – kinematical viscosity and θ is the coefficient of thermal diffusion.

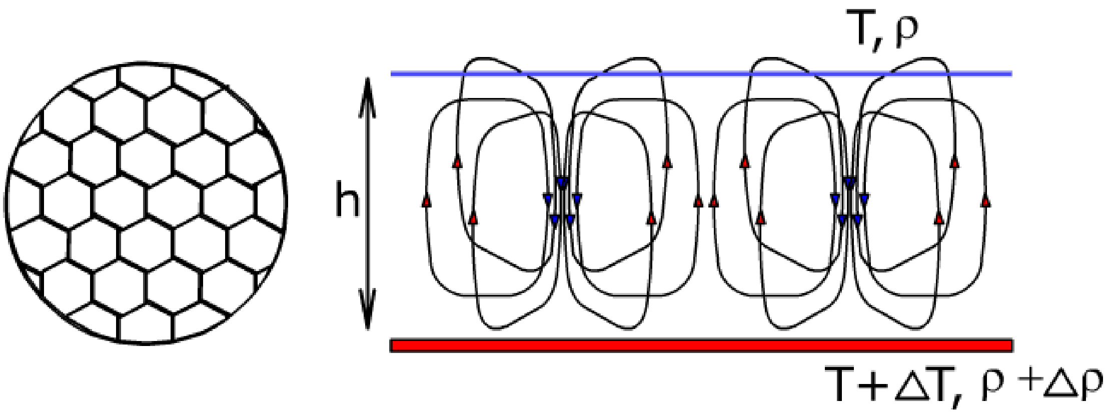

Figure 4. Schematic diagram of Rayleigh-Benard convective cells in a liquid

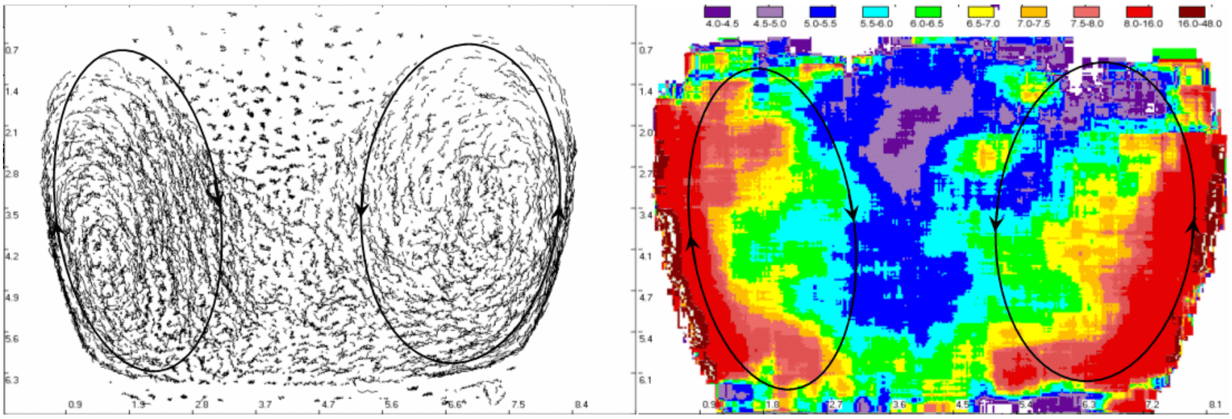

Figure 5. Dust particle tracks and kinetic temperatures of dust particles

For dust vortices in the strations of a dc discharge the values are $\alpha\Delta T \sim 1$, $\nu \sim 1$ см^2/с, $\theta \sim 10^{-2}$ см^2/с, $h \approx 0.5$ cm. Thus the critical Rayleigh number was estimated to be Re ~ 10^2. The thermal convection for a liquid with a free boundary heated from below gives Re = 657, and it may be the same for dust vortices.

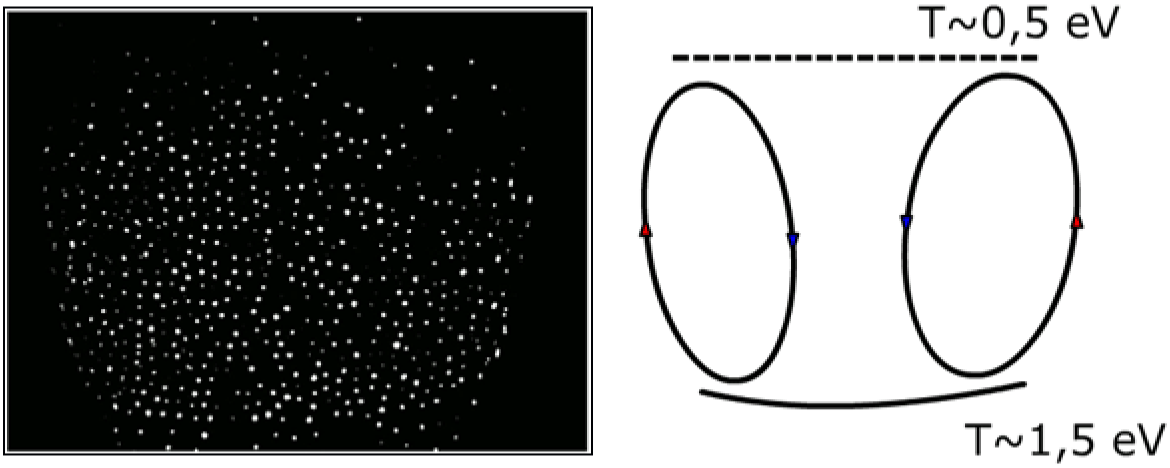

Figure 6. Video image of a vortex and schematic diagram of dc discharge dust convection

Conclusions

3D diagnostics of dust vortices in a dc discharge were carried out. The 3D visualization was based on the binocular viewing principle: observations were made simultaneously by two synchronized video cameras. Structural and dynamic characteristics were calculated for 3D dust vortex motion. It was revealed that the dc dust vortex is close to a toroid where the vertical cross section shows a counter rotating pair of vortices with dust kinetic temperature difference ΔT between the hot bottom and the cold top. A possible mechanism of the formation of dc discharge dust vortices was considered. Analysis of the Rayleigh number allowed us to propose the dust vortex as a Rayleigh-Benard convection cell with aspect ratio ~1.

1. V E Fortov, A P Nefedov, O S Vaulina, O F Petrov *et al*., J. Phys. 5, 2003, 102.

2. Vaulina O S, Samarian A A, Petrov O F, James B W and Fortov V E, 2003 New J. Phys. 5 82