Dust Particle Trapping in a Void Boundary in the Presence of Dust Flow

Y. Saitou[1], Y. Nakamura[2], T. Kamimura[3], and O. Ishihara[3]

[1] *Faculty of Engineering, Utsunomiya University, Utsunomiya 321-8585, Japan*

[2] *Faculty of Engineering, Yokohama National University, Yokohama 240-8501, Japan*

[3] *Faculty of Science and Technology, Meijo University, Nagoya 468-8502, Japan*

1. Introduction

Complex plasmas are known to have various unique properties and dust particles are easy to visualize in the system. Recently we have shown that an interaction of charged dust particle flow with an electrical obstacle placed in the flow results in bow shock formation [1]. Around the obstacle, the dust particles are excluded and a void is developed. The bow shock is formed in front of the void when $M > 1$, where M is the Mach number of the dust flow associated with dust acoustic (or lattice) wave. On the other hand, it has been found recently that a small number of dust particles are trapped in the void boundary near the confluence of the flow when $M < 1$.

In this paper, experiment and simulation on the trapping of dust particles are reported. The trapping in the void boundary, visible by the naked eyes, is a process unique to the complex plasma.

2. Experimental Setup

YCOPEX (**Y**okohama **C**omplex **P**lasma **EX**periment) device is a glass tube device of 1000 mm in length and 150 mm in inner diameter designed for investigating wide area two-dimensional complex plasmas. A schematic drawing of the YCOPEX device and its detailed description can be seen in Refs. [1, 2].

An argon plasma whose neutral gas pressure is 3.5 Pa is produced by applying rf signal (13.56 MHz, 5 W) between a parallel antenna on top of the glass tube and the grounded metal plate. A measured electron density is 5×10^{14} m^{-3}, electron temperature is 5 eV, and plasma potential is 30 V.

Dust particles in this study are Au coated silica spheres of 5 μm in diameter. The diameter is approximately monodispersed. The dust particles supplied into the plasma from the source obtain a negative charge ($\sim -4.4 \times 10^4$, e: the elementally electric charge). The charged dust particles levitate ~ 8 mm above the metal plate.

By tilting the glass tube by a jack and lowering the gate, the dust particle flow is generated. The flow velocity, v_f, is controllable by changing the tilting angle. The excited wave mode in the flow is the two-dimensional lattice mode or the three-dimensional dust acoustic mode with $C_d \approx 70$ [mm/s] [1]. Fan-shaped thin green laser lights from the radial direction illuminate the dust particles. A scattered light by the particles is recorded by a camera.

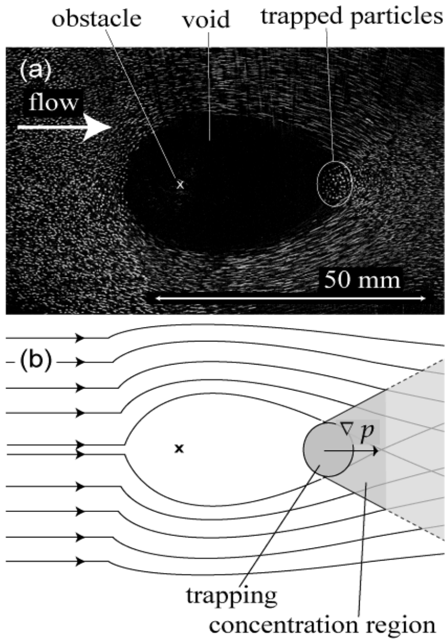

Fig. 1 (a) Typical example of the trapped particles and (b) the schematic of the trapping mechanism. Solid lines in (b) are the stream lines of the dust particles.

3. Experimental Results

The dust flow launched from the reservoir breaks into two branches when it meets a potential barrier caused by the obstacle. The branched flows meet again after passing by the potential barrier (Fig. 1 (b)).

The dust flow around the obstacle behaves differently depending on its flow Mach number M ($= v_f / C_d$) which is estimated in the upstream area to avoid the influence of the void. When $M > 1$, the flow forms the bow shock in front of the obstacle [1]. On the other hand, when $M < 1$, it is found that the dust particles are trapped in the void boundary near the confluence of the flow. Typical example of the dust flow around the void is shown in Fig. 1 (a) where $v_f = 35.3 \pm 6.2$ [mm/s] ($M \approx 0.5$). The trapped particles are seen near the confluence. The number of the trapped particles decreases with increasing v_f and becomes almost 0 when $M \gtrsim 1$ as shown in Fig. 2. It may worth noting that a wake-like structure of a triangular shape can be seen succeeding to the trapped particles [1].

4. Numerical Simulation

A molecular dynamic simulation is carried out to examine this trapping phenomenon. Basically the simulation code is constructed in the same way as Refs. [1, 3]. Detailed explanation on the simulation conditions can be seen in Ref. [1] as well.

Typical examples of the simulation are shown in Fig. 3. It is found that the particles located between the void behind the obstacle and the confluence region have almost vanishing velocity, which means these particles are trapped and settled near the confluence. The simulation supports the trapping phenomenon observed in the experiment. It should be noted that the particle whose velocity is 0 does not appear in the velocity field, Fig. 3 (b).

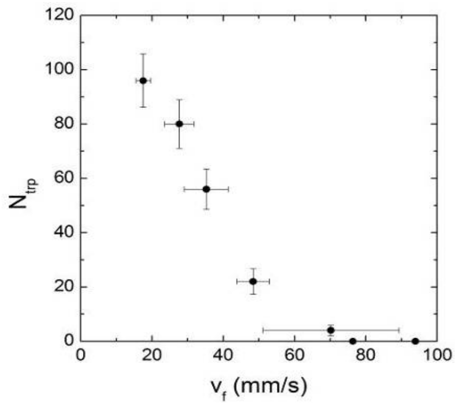

Fig. 2 The number of trapped particles versus the flow velocity.

5. Discussion

The motion of the dust particles is restricted in the two-dimensional plane where the electric force by the transient sheath and the gravitational force are balanced. Hence, the dust particles concentrate two-dimensionally in the confluence region when the branched flows meet again after passing by the potential barrier. The trapping occurs around this confluence area when $M < 1$. The mechanism of the trapping of dust particles may be understood in the following way. The confluence of the merging flows generates the higher dust pressure region than any other areas obeying the equation of states (see Fig. 1 (b)). Especially, at the void boundary near the confluence, the pressure gradient, ∇p, becomes the locally maximum. The pressure gradient thrusts some dust particles toward the void boundary layer. On the other hand, a flow passes by an object forms a shear flow and causes a wake turbulence. Generally, in the case of the uniform flow, the flow velocity behind the object is reduced as shown schematically in Fig. 4. The velocity, negative at the near wake and positive at the far wake, is known as defect velocity [4]. The distance of the boundary from the object, where the defect velocity changes from negative to positive, depends on the Mach number. The flow with smaller Mach number has a longer distance from the object. The dust particles are easy to move toward the obstacle direction once the particles encounter the negative defect flow. An encounter probability of the particle with the negative defect flow is finite even when the particle locates far from the obstacle for the case of the small Mach number.

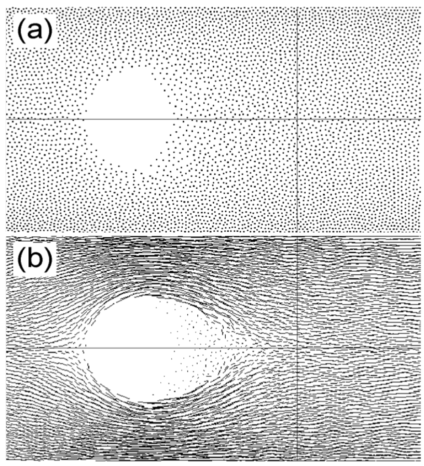

Fig. 3 Typical examples of the simulation: (a) particle position and (b) velocity distributions. The flow velocity is 1 cm/s.

At the same time, each dust particle has the negative charge with the screening length, λ_D. The inter-particle distance, which is usually larger than $5\lambda_D$ when the particles form a lattice structure [5], is compressed and shortened by the condensation at the confluence. In such a situation, it is expected that the particles approach even nearer than $5\lambda_D$. An electrostatic force is locally enhanced, particularly at the void boundary, and pushes some dust particles toward the void boundary layer. This mechanism may be similar to the one suggested for the space-limited current [6].

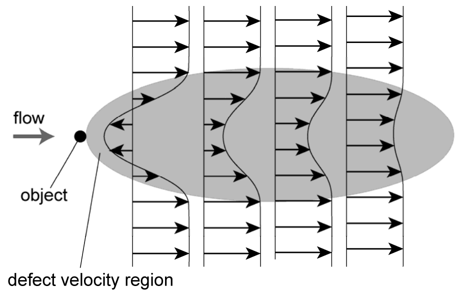

Fig. 4 Schematic of the defect velocity behind the object. Black arrows are the vectors of the flow velocities.

6. Summary

In the experiment and simulation, the dust particles are trapped in the void boundary near the confluence of the flow and the wake-like triangular structure is formed when $M < 1$. The number of the trapped particles decreases with increasing flow velocity.

The trapping is explained by the hydrodynamic mechanism based on the defect velocity due to the wake turbulence.

It is our future subject to study on the wake-like triangular structure succeeding to the trapped particles.

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