Rotation of a single vortex in dusty plasma*

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A single vortex is obtained in radio-frequency capacitive discharge in argon gas. The dust subsystem is confined in the horizontal plane with an asymmetrical saw structure placed on the lower electrode. The vortex rotates as a whole along the long side of the saw-teeth. Asymmetry of the saw structure plays an important role in the rotation of the vortex. Nonzero curl of the total force resulting from the local ion flow and the electric field in the plasma sheath could be attributed to the persistent rotation of vortex.

Keywords: dusty plasma, vortex

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1. Introduction

Dusty plasma consists of electrons, ions, neutral gas atoms, or molecules, and charged dust grains, which has attracted much attention in the fields ranging from astrophysics, the semiconductor industry to the laboratory.[1–4] The grains immersed in plasma could acquire more than thousands of elementary charges and couple strongly via Yukawa interaction. They can be visualized directly and tracked easily by a camera. Therefore, dusty plasma opens up possibilities for studying a variety of physical phenomena such as phase transition, transport, and wave at the most elementary kinetic level.[5–13]

Vortex motion is often observed in stirred liquid such as whirlpools in the wake of boats and the winds surrounding a tornado. In the presence of external forces, a vortex could rotate persistently around an axis line and has non-zero vorticity away from the core. In recent experiments, vortex motions were also observed in dusty plasma both under microgravity and on the earth.[14–16] Bi-vortices, which means a couple of vortices rotating clockwise and anticlockwise, respectively, often appears symmetrically near a dust void or a probe.[17] By reversing the effective potential of the probe with respect to the plasma potential, vortices could reverse their rotation directions. At present, the observed vortices occur at the boundary of the bulk plasma, i.e., near the sheath, where the spatial distributions of plasma parameters such as electron temperature, ion density, electric field, and grain charge are inhomogeneous. If the ion density gradient is not parallel to the electric field, the curl of the ion drag force is nonzero, which could drive the motion of vortices.[18] Vaulina *et al.* illustrated another mechanism that charge gradient together with gravity force could result in the motion of vortices.[19] Recently, the transition from multiple to single dust vortex is observed in inductively coupled RF discharge, and the vortex originates from the charge gradient of dust particles which is orthogonal to the ion drag force.[10] In a direct current glow discharge plasma, the gradient of ion density and grain charge are measured experimentally and they are attributed to the formation of the vortex.[21] To our knowledge, all those vortices occur in the form of a couple of co-rotations or in the vertical plane. The interaction between the bi-vortices and the gravity force make it difficult to understand well the dynamics of vortices in dusty plasma. Here, we report a single vortex obtained in a designed saw structure in the horizontal plane. This vortex rotates as a whole along the long side of the saw-teeth. We confirm that the asymmetry of the saw structure plays an important role in the vortex rotation.

2. Experimental setup

The experiments are performed in a vacuum chamber filled with argon as shown schematically in Fig. 1. Argon gas flows at a rate of 10 sccm and the gas pressure changes in a range of 30–100 Pa. The upper electrode is ITO glass plate and is grounded, the lower electrode is stainless steel plate which is connected to an rf power. The distance between two electrodes is 40 mm. The grains used for the experiments are macro-porous cross-linked polystyrene microspheres each with a diameter of 23 μm and mass $m_{\rm d} = 8.6 \times 10^{-13}$ kg. A resin saw structure placed on the lower electrode (see Fig. 1) is used to confine the grains to move in the horizontal plane. The internal and external diameters of the saw teeth are 10 mm and 20 mm, respectively, and the angle of the saw tooth groove is 60°. After the plasma is ignited, grains are dropped into the

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center of the saw structure. They are levitated above the lower electrode and move in the saw structure. The grains are illuminated by a flood lamp and the movements of dust grains are recorded by a camera placed on the top of the vacuum chamber. The trajectories and velocities of grains are obtained by using developed video processing program.

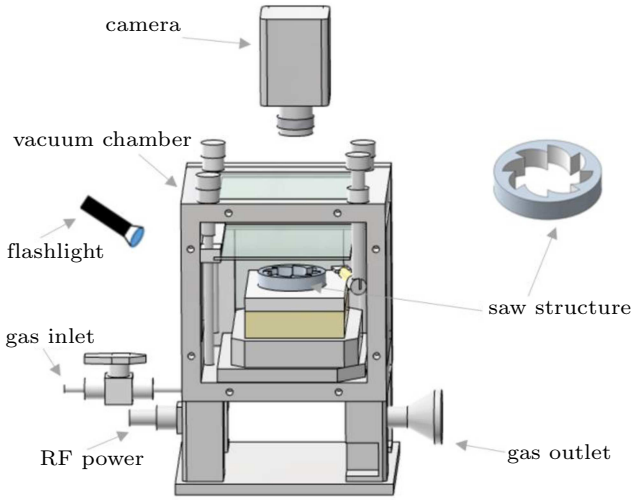


Fig. 1. (color online)Schematic diagram of the experimental setup.

3. Experimental results and analysis

Figure 2 shows the spatial distributions of dusty vortices in the horizontal plane with increasing gas pressure. When the gas pressure is low, the thickness of the sheath near the saw and the electrode is large, which provides a parabolic confinement in the horizontal plane. Grains are trapped in the center of the saw structure as shown in Fig. 2(a). With increasing the gas pressure, the sheath becomes thin. Because the potential of insulated saw is higher than that of the stainless steel plate, the thickness of the sheath above the lower electrode is larger than that near the insulated saw, which gives rise to a potential well near the insulated saw. Therefore, the grains tend to be close to the insulated saw and a void appears in the center of the saw structure as shown in Figs. 2(b)–2(d). The outer grains follow approximately the saw profile, while the inner grains follow a circle profile. When the gas pressure is high enough, the grains are trapped in the slant of the saw teeth (Fig. 2(e)).

Dusty vortices in Figs. 2(a)–2(d) always rotate clockwise as a whole as shown by the trajectories in Fig. 3. The grains couple strongly via Yukawa potential, and the coupling parameter $\Gamma = \left(Q^2/4\pi\varepsilon_0 a k_B T_d\right)$, where Q is the grain charge, a is the Wigner–Seitz radius, and $k_B T_d$ is the kinetic temperature of grains. In our experiments, the charge is estimated in terms of an empirical formula[4] $Q \sim 3.2$–6.4×10^4 e, $k_B T_d \sim 8$–12 eV, and $\Gamma \sim 360$. Due to the strong coupling, these grains rotate nearly as a whole. When the gas pressure is low, grains distribute on several shells with different radii due to the parabolic confinement as shown by the trajectories of grains in Fig. 3(a). The distances between neighboring shells are about 0.3 mm. The average speed of grains on each shell is different. Figure 4 shows the radial distribution of the average

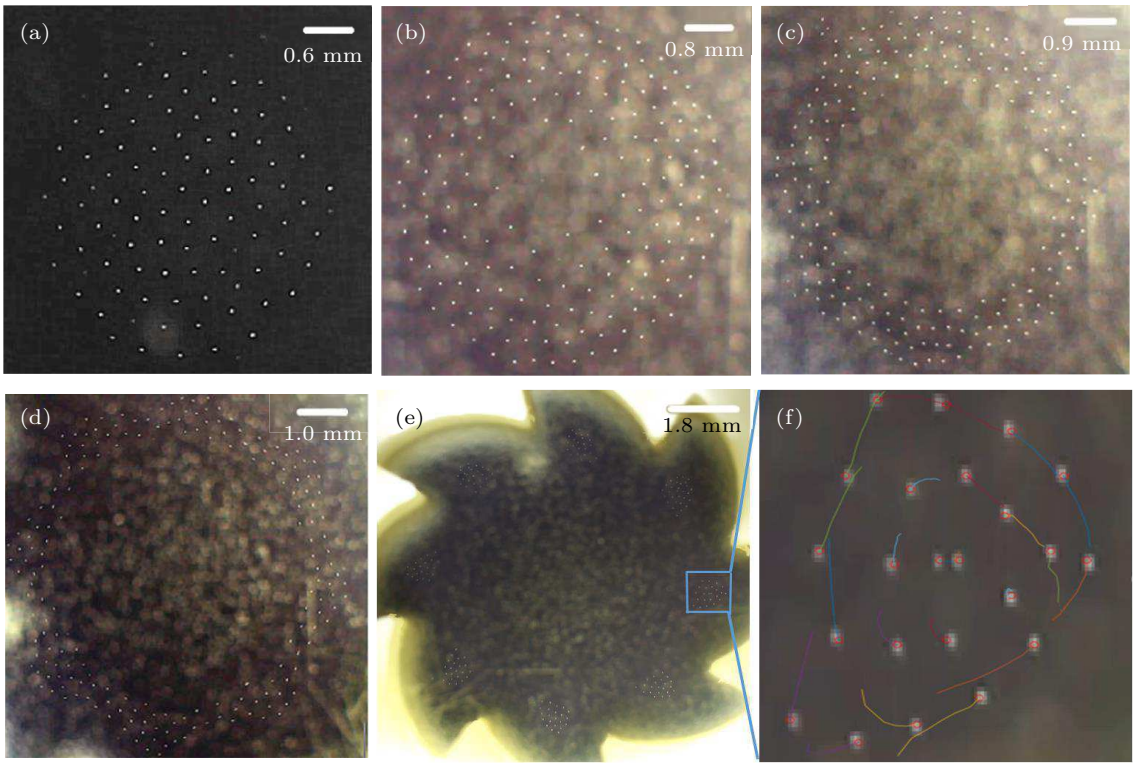


Fig. 2. (color online) Spatial distributions of dusty vortices in the horizontal plane at gas pressures of (a) 30 Pa, (b) 40 Pa, (c) 50 Pa, (d) 60 Pa, (e) 90 Pa, with rf power fixed at 15 W, and (f) trajectories of grains in a slant (e). Circles indicate the starting points of the trajectories.

speed of grains obtained at 40 Pa and 15 W. It shows that the average speed of grains increases from 1.2 mm/s near the center of the saw structure to 2.4 mm/s at the boundary of the saw structure. The average speed increases linearly with radius as indicated by the linear fitting in Fig. 4, which illustrates a whole rotation of the dusty vortex at an average angular speed of about 1 rad/s. It is different from the scenario of the double vortices observed by Bockwoldt *et al.* under microgravity conditions.[15] This is because the grains couple strongly in our experiment, and no velocity shear occurs between neighboring shells. Some grains could transit occasionally from one shell to its neighboring shell due to their higher kinetic temperature $k_{\rm B}T_{\rm d}\sim 10$ eV as indicated by the arrow in Fig. 3(b). When the gas pressure is high, the shell number decreases due to the expansion of the grains to the boundary and the appearance of dust void in the center of the saw structure as shown in Figs. 3(c) and 3(d). When the grain on the outer shell is close to the saw tip, it would be pushed to the inner shell by the electric field of sheath of the saw tip. When it leaves the saw tip, it is pushed outward by the repulsion from the neighboring grains of inner shell. Therefore, the outer shell would follow the shape of the saw teeth, while the inner shell has approximately circular shape. Individual shell becomes indistinct because the shell number near the saw tip is less than that at the slant.

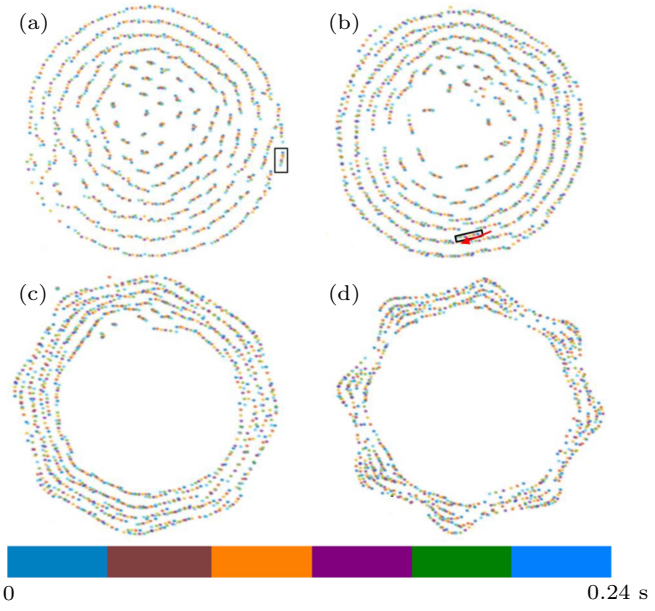


Fig. 3. (color online) Color plots of the particle trajectory at (a) 30 Pa, (b) 40 Pa, (c) 50 Pa, and (d) 60 Pa, respectively. rf power:15 W. Each trajectory of grain lasts 0.24 s, which are represented by six dots of different colors. Color bar indicates the time span.

The average angular speed of vortex increases with the gas pressure changing from 30 Pa to 60 Pa as shown in Fig. 5. When the gas pressure is low, the grains distribute in the center of the saw structure as shown in Fig. 2(a). The asymmetric action of the saw on the grains is very weak because the grains are far from the saw boundary, which leads to the slow rotation of vortex. With increasing gas pressure, the grains shells are close to the saw-teeth, and the asymmetric action of the saw becomes notable, which gives rise to fast rotation of vortex. The grains travel along the long side of the saw-teeth, i.e., following the clockwise direction. The symmetry of the confining potential near the center of saw structure is better than that near the saw-teeth. Therefore, the asymmetry of the saw-teeth of the saw structure is the key to the formation of vortex. When the gas pressure is high enough, the grains are trapped in the slant of each saw-tooth as shown in Fig. 2(e). The grains in each slant climb along the long side of the saw-teeth and return from the short side, i.e., forming clockwise vortex as indicated by the trajectories of Fig. 2(f). In each vortex the outer grains move faster than the inner grains as illustrated by the trajectories with a duration of 0.24 s. The velocity of the outer grains could reach 1 mm/s, which is smaller than that in low gas pressure case (Fig. 4). The grains at the core of the vortex exhibit random movement.

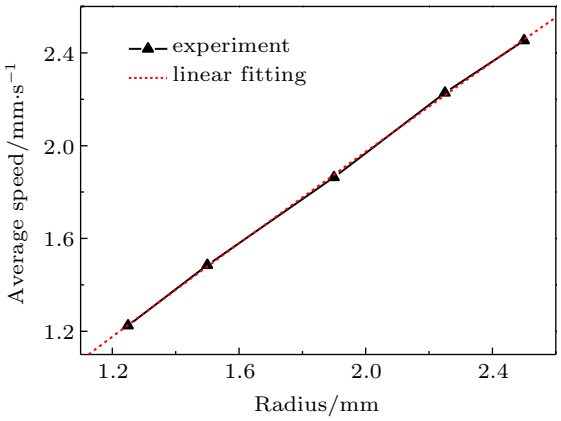


Fig. 4. Radial distribution of the average speed of grains at a gas pressure of 40 Pa and an rf power of 15 W. Dashed line represents the linear fitting.

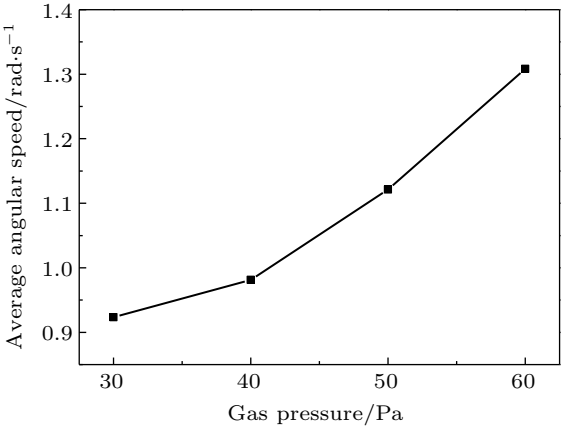


Fig. 5. Dependence of average angular speed on gas pressure at an rf power of 15 W.

Several forces act on the grains and the curl of the total forces is nonzero, which can overcome the friction from the

neutral gas and gives rise to the formation of vortex of grains. In the vertical direction, the gravitational force is balanced by the electric force from the sheath of the low electrode. We do not consider them here because the vortex performs rotation nearly in a horizontal plane. In the horizontal direction, the situation becomes complex due to the asymmetry of the saw-teeth. The asymmetrical saw plays an important role in forming the vortex. The plasma sheath would have the approximate shape of the saw-teeth. The thickness values of sheath are different at different positions of the saw structure because the thickness is related to the curvature of the saw-teeth.[22] At the tip (bottom) of the saw-teeth, the thickness of sheath is small (large). Because the thickness values of sheath at the tip and the bottom of saw-teeth are different, the gradients of plasma parameters, such as ion density, electron temperature, and grain charge, appear near the saw teeth in the horizontal plane. Local ion flow would appear near the saw-teeth due to the inhomogeneous plasma parameters. Because of the asymmetry of the saw-teeth, local ion flows from the long edge of the saw-teeth have different features (e.g., the flow directions) from that from the short edge of the saw-teeth. It would cause a net ion drag force in the tangential direction, which results in the formation of vortex. In addition, several other possibilities could also contribute to the vortex motion. First, the charge quantity deposited on grain has spatial or temporal variation across the sheath. When the charge gradient is not parallel to the electric field, the curl of the electric field and the charge gradient could be nonzero, which could drive the vortex motion of grains.[19] Second, there exists non-parallelism between the ion density gradient and the ion velocity gradient at the corner of saw. Therefore, a torque resulting from the nonconservative nature of the ion drag force gives rise to the formation of a vortex.[15] Third, if temperature gradient exists, thermal gas creep appears and convection of neutral gas could result in the grain vortices.[20] In our experiment, the effect of the temperature gradient near the saw-teeth can be negligible because the grains located far from the saw-teeth at low gas pressure can still perform rotation. Therefore, the combination of the inhomogeneous electric force and the inhomogeneous ion drag force from the long and the short edges of the saw-teeth could lead to the formation of vortex in our experiment. Due to the periodicity of the saw structure, the torque from each slant could be superimposed to drive a single vortex.

The asymmetry of the saw-teeth is a necessary condition for the formation of a vortex. If we flip the saw structure from up to down, the rotation direction of the vortex would reverse accordingly. In addition, we test a symmetrical saw structure in experiment, i.e., the two edges of one saw-tooth have the same lengths. No vortex is obtained even at the same experimental parameters as shown above. Hence, we can draw a conclusion that the asymmetry of the saw-teeth gives rise to nonzero curl of the total forces, which drives the vortex rotation.

4. Conclusions

In this work, we experimentally investigate the vortex rotation observed in an asymmetry saw structure in dusty plasma. The vortex always rotates clockwise as a whole due to the strong coupling among the grains, i.e., along the long side of the saw-teeth. With increasing gas pressure, grains tend to approach the asymmetric saw boundary, and the average angular speed increases accordingly. Nonzero curl of the inhomogeneous electric force and the inhomogeneous ion drag force from the long and the short edges of the saw-teeth could lead to the formation of a vortex in our experiment. Comparative experiments are performed and it is found that the asymmetry of the saw structure is a necessary condition for the formation of a vortex. We believe that the bi-vortices observed by other groups also originate from the asymmetry of the spatiotemporal distribution of plasma parameters.

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