Dynamic Behavior of Dust Flow with Velocity Shear in RF Plasma

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We have investigated dynamic behavior of a dust flow with velocity shear in RF plasmas. In this study, neutral drag force by the neutral gas ejected from small nozzles is used for driving directional dust flows with velocity shear. The strength of the velocity shear can be controlled over a wide range by adjusting the direction of the nozzles and the flow rate of the neutral gas. The dust particles flowing a straight channel generate many tiny vortices in the contact region between forward and backward dust flows. Complicated behaviors were observed in the dust flow when a velocity shear was enhanced by controlling the gas flow velocity.

Keywords: dusty plasma, Coulomb fluid, velocity shear flow, dust vortices, dust disordered fluctuation

1. Introduction

Property of the dust cloud can be characterized by the Coulomb coupling parameter Γ as a strongly coupled state, i.e. $\Gamma = (q_d{}^2 / 4\pi\varepsilon_0 a \kappa T_d)\exp(-a/\lambda_D)$, where q_d is dust charge, T_d is dust temperature, a is inter-particle distance and λ_D is the Debye length. It is well known that a phase transition from fluid to solid happens when $\Gamma > \Gamma_{cri} \sim 172$ in a one-component plasma (OCP) [1]. Therefore, the dust cloud behaves as a Coulomb fluid when $\Gamma < \Gamma_{cri}$. In this case, the dust cloud may change its shape and an collective motion will be generated, when the external forces, such as the electrostatic force, the ion drag force, the gravity, and so on, act on the dust fluid [2]. Ordered structure and convection of particles were observed experimentally [3]. We had also observed several characteristic behaviors of the dusty plasmas [4-6]. The external force also drives a convective motion, accompanied with velocity shear flow due to the viscosity of the Coulomb fluid [7-10]. Note that the viscosity depends both on the values of Γ and a/λ_D.

There have been many unknown subjects about physical phenomena of the Coulomb fluid which has the viscosity caused by the Coulomb collision, unlike the collision between molecules in neutral fluids. We investigate dynamic behavior of the dust flow that is considered as the Coulomb fluid in plasmas. In this study nonlinear behavior of the dust flow is clarified by observing the motion and instability of the dust flow with velocity shear.

2. Experimental Apparatus and Method

Figure 1 shows a schematic of the experimental apparatus. Argon plasma was produced using a capacitively coupled RF discharge. We used RF power of 1 - 20 W at 13.56 MHz, and Ar pressure P_{Ar} was in a range of 20 - 70 Pa. Typical plasma density is $n_e \sim 1\times10^9$ cm^{-3} and electron temperature is T_e ~2 eV. The experiment is carried out with a use of special shape of a levitation electrode plate of 1 mm in thickness, as shown in Fig. 2. The levitation plate has a hole at the center with a dumbbell shape, consisting of a straight part of 7 - 23 mm in length and 10 mm in width, combined with two circular parts of 20 mm in diameter. The straight part is used for a straight channel for counter dust streams. The dust particles of 10 μm in diameter are introduced externally into the plasma by a dust dropper and can be trapped mainly above the circular parts. Increasing the number of the particles injected, the particles are also trapped above the straight channel region.

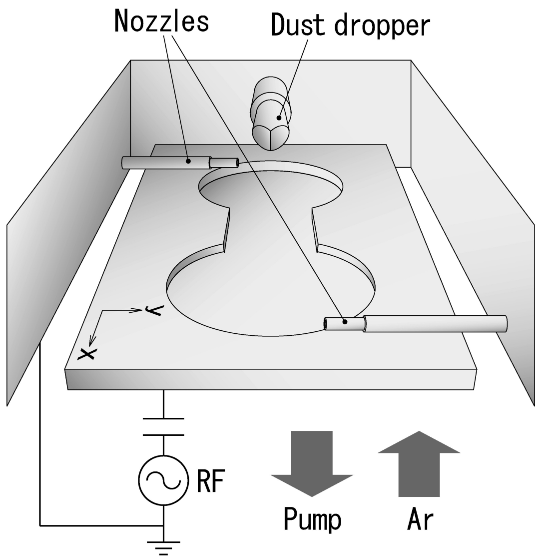

Fig. 1. Experimental apparatus.

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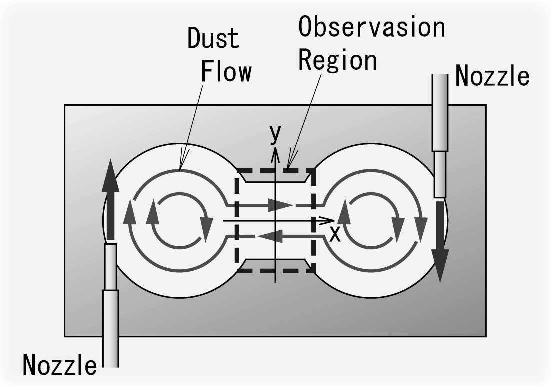

Fig. 2. Observation region of counter stream above a dumbbell-shape levitation electrode.

In this experiment, the dust particles receive a neutral drag force by the argon gas ejected from two nozzles of 0.8 mm in inner diameter. The nozzles are placed at the outer edge of the circular parts of the levitation electrode as shown in Fig. 2. Here, the coordinates x and y are defined in parallel and perpendicular directions of the dust flow in the straight channel. The gas ejected from the nozzles gives momentum locally to the dusts, which eventually drives the directional dust flow, accompanied by a counter stream consisting of forward and backward flows of the dusts in the straight channel region, contacting at the center. Hence, the velocity of the dust flow at the center of the channel ($y = 0$) is almost zero ($v_x = 0$), but the flow velocity on the upper side of channel ($y > 0$) directed forward ($v_x > 0$), while that on the lower side ($y < 0$) directed backward ($v_x < 0$). Therefore, velocity shear appears in the parallel velocity v_x of the dust flow across the channel, as schematically shown in Fig. 2. By adjusting the direction of the nozzles and the flow rate of neutral gas, the counter stream of dust flow with various strength of velocity shear can be formed above the straight channel region. The available range of the neutral gas flow rate from the nozzles is 0 – 1.0 sccm in this experiment. The dusts are illuminated from a side view window by a horizontal laser sheet of 640 nm in wavelength and their motion can be recorded from a top view window by a conventional CCD camera and a high speed CCD camera of 125 frames per second.

3. Experimental Results

The gas ejected from the nozzles gives rise to a neutral drag force locally. Then, the force acts on the dusts nearby. From a viewpoint of the experiment, such gas flow should neither give a momentum to the dusts directly nor cause a perturbation of background plasma in the straight channel region. If the plasma fluctuates by the gas flow, it may also disturb the dust flow trajectories. It is still unclear whether such gas flow from the nozzles can be sufficiently weaken for giving less effect on the particles in the straight channel region. Therefore, we first investigate the influence of the background neutral gas on both the dusts and the surrounding plasma in the counter stream region.

In the straight channel region the dusts are also confined electrically in a potential well formed between the sidewalls of the straight channel. Such electric repulsion in y direction may induce a friction force on the contact surface between the forward and backward flows by the Coulomb collisions, which gives rise to a shear viscosity in the dust stream. Here, the width of the contact region is about 4 mm, which is also determined by the thickness of the sheath in front of the sidewalls of the straight channel and the number of particles injected.

In order to evaluate the effect of the neutral gas on the dust flow, we first pay attention on a few particles coming from far outside. These particles are trapped above the RF powered electrode and can reach the region outside the dumbbell-shape levitation electrode shown in Fig. 2. The interval of these particles is much longer than the usual interparticle distance a, Therefore, they are regarded as simply floating and moving along the neutral gas streamlines without much Coulomb interactions. We can use these particles just as a measure of the neutral streamlines.

As soon as these particles approach the side edge of the straight channel region from the outsides, they are trapped electrically within the straight channel and reduce immediately their perpendicular velocity v_y, and turn their direction of motion toward the counter stream. Then, they are mixed with the particles group composing the counter stream with interparticle distance of roughly a. The change of the particle velocity v_y is shown in Fig. 3. From these results we find a background neutral gas flow that has a finite incident angle against the straight channel. The dust flow in the straight channel might be affected by such Ar gas flow.

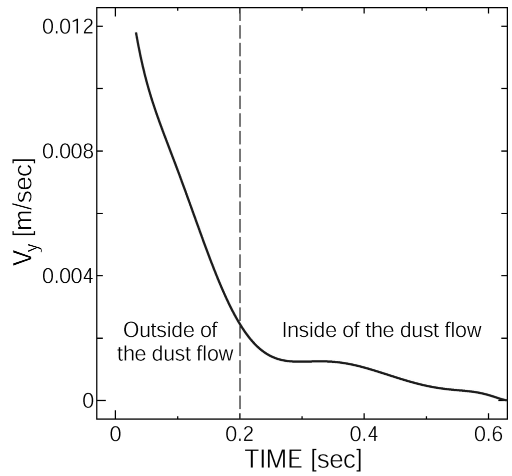

Fig. 3. Temporal variation of perpendicular velocity v_y of the dusts which enter from the outside into the counter stream. Ar flow rate is 0.5 sccm.

In order to examine a possibility of the excitation of gas turbulence in the background argon flow, we next discussed a Reynolds number R_e of the neutral argon flow in the low-pressure regime as in our experiment. If there appears such gas turbulence in the straight channel, the particle motion will be strongly affected by the disturbed gas streamlines. Taking the characteristic scale length and the velocity of Ar flow to be the width of the contact region and the dust flow velocity, respectively, R_e was calculated to be about 2×10^{-4}. R_e is very small, so the background Ar gas flow is viscous and constitutes a laminar flow, and does not contribute to an excitation of background gas turbulence accompanied with vortex formation. We actually observe no orbital fluctuation of the particles that are coming from the outside to the side edge of the straight channel, except for the central region of the straight channel.

Secondly, we evaluate the effect of neutral gas on the background plasma. We investigate perturbation of the plasma under the existence of dusts and background neutral gas flow. In order to measure the fluctuation of the plasma parameters, a small collector was placed directly under the levitation electrode and the collector current I_c was measured as a function of the collector voltage V_c. Figure 4 shows the V_c - I_c curves for the cases with and without the dust and neutral gas flow. When the dusts were introduced into the plasma, both the ion and electron saturation currents decreased a little compared with those without the dusts. This reason may be explained by a shadow effect of the dusts that act as only obstacles disturbing the electron and ion currents towards the collector. The collector current signals were also fed to an oscilloscope to analyze the plasma fluctuations, but we could not detect any meaningful change in the frequency spectrum of the signals. We concluded that the background neutral gas flow also did not give a big effect on the plasma parameters. Therefore, the perturbation of the dust fluid and the formation of the vortices were caused by the Coulomb interaction between dust particles.

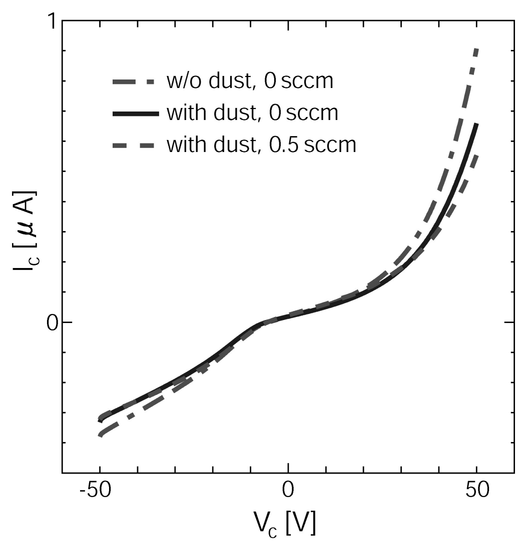

Fig. 4. Collector V_c - I_c curve with and without dusts and neutral gas flow.

The Coulomb interaction among the dusts in the contact region can be controlled by varying the neutral gas flow rate from the nozzles. Figures 5 shows the streamlines of the dust flow in the straight channel when RF power was 4 W and P_{Ar} = 40 - 60 Pa. These figures were obtained by adding 30 frames of video shot signals. Therefore, the figures show the particle trajectories during time interval of 1 second.

In the case of very slow dust flow velocity, the particles in the stream move slowly with a random motion as shown in Fig. 5(a). This is attributed to the effect of the Coulomb collisions among the particles. The particles are scattered by the other particles when their relative velocity is slow. Therefore, the particles are moving with a big fluctuation. However, with an increase in the flow velocity, such collisional interaction was reduced and a collective motion came out, and eventually structural dust flow was generated as shown in Figs. 5(c) and 5(d). Several tiny vortices were formed in the contact region between the forward and backward flows. There appeared a kind of separatrix that separated particles into two parts. One is a streaming particle, and the other is a trapped particle. Near the contact region particles motion was stagnant and their orbit was more or less fluctuated and sometimes closed.

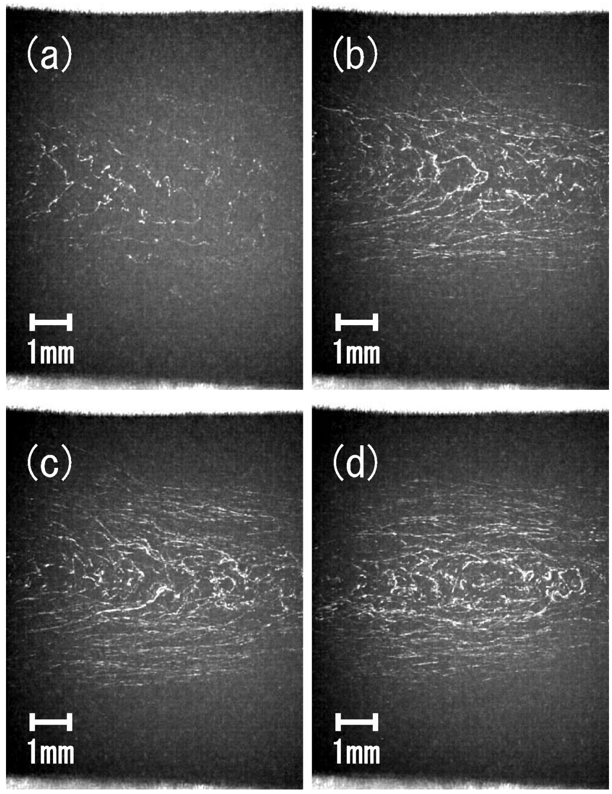

Fig. 5. Dependences of flow patterns on flow rate of Ar gas. (1) 0.1 sccm, (b) 0.2 sccm, (c) 0.3 sccm, (d) 0.4 sccm. RF power is 4 W.

On the other hand, the particles in the streaming region were rather simple. They were flowing with a less fluctuation. The scale size of the vortices was several times as large as the interparticle distance a. We can also observe trapped dust particles within the vortices. They are turning about the center of the vortices.

In our experimental configuration, it is quite easy to control the velocity shear by adjusting the gas injection from the nozzles. Under this situation we perform an experiment with a small amount of gas injection. Figure 6 shows the trajectories of the dusts in the contact region when the velocity shear is weak. Although the particle trajectories outside the contact region are almost straight lines, the trajectories in the center region are rather complicated.

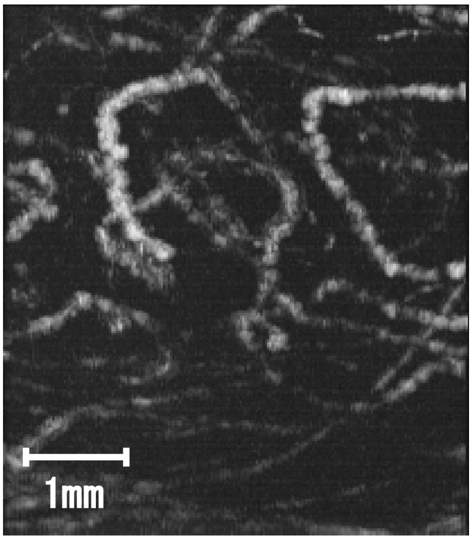

Fig. 6. Close-up trajectories of the dusts in the contact region in the case of a weak velocity shear flow.

In their boundary region, the particle orbit is quite disordered. Some particles in the forward flow were scattered into the backward flow region, then finally started flowing in the backward flow. Another particles returned to the initial flow region again after several Coulomb interactions. The momentum of the particles, flowing in the forward flow region, can be transferred to the particles in the backward flow region.

Figure 7 shows an example of temporal evolution of the particle orbit distance between two particles in the velocity phase space ($v_x - x$) with almost the same initial positions at t = 0. In the streaming region the orbit distance between both particles was almost unchanged, showing a property of laminar flow. On the other hand, in the separatrix region the orbit distance was increased with the time. The change of the orbital distance in the phase space can be used as a measure of "chaos". Here, however, a more careful analysis will be required to express quantitatively the complexity of the perturbed dust behaviors in the shear flow observed.

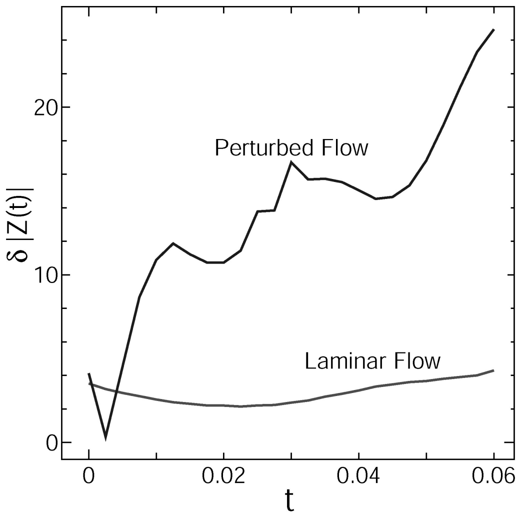

Fig. 7. Orbit distance δ in the velocity phase space ($v_x - x$) in the case of a weak velocity shear flow.

4. Conclusions

We have succeeded in the generation of a dust flow with velocity shear by the neutral drag force. We discussed the influence of the background neutral gas flow on the particle behavior in the contact region between the forward and backward particle flows. We observed a background gas flow in the observation area shown in Fig. 2. However, from an estimation of the Reynolds number, the background Ar gas constitutes a laminar flow. The neutral gas flow did not cause a direct perturbation of the background plasma. Therefore, the vortices observed in a contact region of the counter stream evolved as a result of the Coulomb interaction when the particle shear velocity is enhanced by increasing the gas flow.

The experimental configuration developed here is quite useful for investigations of the Coulomb fluid dynamics.

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