Particle classification in Taylor vortex flow with an axial flow

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Abstract. Particle classification phenomenon in Taylor vortex flow with an axial flow was investigated experimentally and numerically. The flow-visualization experiment by a laser-induced fluorescence method clearly revealed that there existed two distinct mixing regions at low Reynolds numbers. The tracer near the vortex cell boundary was rapidly transported axially owing to the bypass flow effect. On the other hand, the fluid element was confined to the vortex core region without being exchanged with the outer flow region. In order to observe particle classification phenomenon, polymethyl methacrylate (PMMA) particles suspended in the same aqueous solution of glycerol as the working fluid were fed into the top of the apparatus. Particle size was initially ranging from 10 to 80 µm. The ratio of the particle density to the fluid density was 1.04 – 1.05, which means the density difference between particle and fluid is very small. The suspended solution was withdrawn using a hypodermic needle every a certain time period at 30 mm above the bottom of apparatus. The fluid was sampled both near the outer wall and in vortex core. The particles sampled at 42 min having the size of 20 – 50 µm were mainly observed in the vortex core region. On the other hand, a large population of particles having the size of about 50 – 80 µm could be seen in the outer region of vortex. It was found that large particles located near the outer edge of vortices were quickly transported axially owing to the bypass flow effect. Numerical simulation also revealed that the loci of particles depended on the particle size.

1. Introduction
Separation and classification of materials is of great importance in industrial chemical processes. Particle classification, in particular, is one of the key technologies for the production of fine microspheres having a well-controlled particle size distribution (PSD) because the PSD affects the rheological behavior of the product and other properties of interest in applications. Recently Ookawara et al. [1] proposed a micro-separator/classifier having a curved microchannel with a rectangular cross-section. This micro-separator/classifier takes advantage of the effects of centrifugal force and secondary flow patterns called Dean vortices generated at the curved channel. According to their idea, the high centrifugal force is expected to work in favor of concentrating particles near the outer wall of the channel. Owing to the fact that the relative velocity between larger particles and the suspended medium is always higher than between smaller particles and the medium, the larger particles remain near the outer wall, while the smaller particles move along with the Dean vortices. Consequently, if the channel has an appropriate bifurcation at the outlet, the particles can be classified. They verified numerically and experimentally the effectiveness of their method.
Instead of using the Dean vortices, we focussed our attention on the flow structure of Taylor-Couette flows to develop a new method of particle classification. Secondary vortices called Taylor vortices appearing between concentric rotating cylinders have a similar structure to the Dean vortices. As compared with the micro-separator/classifier developed by Ookawara et al., the following other advantages can be expected. First, the vorticity of the secondary vortices can be controlled by the rotational speed of the inner cylinder. This provides a wider range of operational condition from particles having their size in micrometers to relatively large ones having their size in millimeters in a Taylor vortex flow type device, as opposed to in the micro separator/classifier. Second, the Taylor device can deal with larger amount of particles. Although Ookawara et al. did not clearly discuss the effect of the density difference between particle and fluid, it can be considered that the classification of particles largely depends on the density difference. Wereley and Lueptow [2] numerically investigated the motion of dilute, rigid, spherical particles in laminar Taylor-Couette flow. They found that the motion of particles with a density greater than the fluid was determined by the interplay between the centrifugal force and the drag force. Particles having certain density and size approach a limit cycle orbit. They also found that even neutrally buoyant particles did not follow fluid stream lines exactly. In chemical and/or biochemical processes, we often have to deal with particles having a very small density difference with fluid. In this case, although the effect of centrifugal force becomes small, the particle segregation due to shear-induced particle migration can be expected. Leighton and Acrivos [3] demonstrated in their experiments using a Couette device that neutrally buoyant particles might migrate across streamlines and against concentration gradients when undergoing bounded shear flow. Hence a Taylor-Couette device may have the possibility to classify particles having a very small density difference with fluid.

Furthermore, the Taylor-Couette flow has the following advantage for particle classification. There exist two distinct mixing regions, i.e. active mixing region (AMR) and isolated mixing region (IMR) in Taylor-Couette flows. Desmet et al. [4] experimentally confirmed that the tracer fluid in the outer layer of a vortex cell dispersed rapidly as compared to that in the vortex core region in the laminar Taylor vortex flow. They proposed a two-zone model consisting of the AMR and the IMR to describe mixing characteristics. Makino et al. [5] observed the IMR under laminar flow conditions in a Taylor-vortex-flow reactor from the viewpoint of chaotic mixing. Rudman [6] numerically investigated the motion of particles in the wavy vortex flow regime of Taylor-Couette flow from the viewpoint of chaotic mixing. He provided some information on axial dispersion of particles in the wavy Taylor-Couette flow. He demonstrated that particle dispersion was a strong function of wave state. If the larger particles are concentrated near the outer cylinder wall owing to the effects of the centrifugal force, the shear-induced particle migration and the secondary vortices similar to the micro-separator/classifier, they are expected to move rapidly along the bypass flow in the axial direction, while the smaller particles remain within vortex core. It can be considered that the particles are classified axially in a Taylor-Couette device.

In the present work, the particle classification phenomenon was investigated experimentally and numerically according to the above-mentioned mechanism.

2. Experimental and Numerical Simulations

The experimental apparatus with a measuring system is shown in Figure 1. The apparatus consists of an outer cylinder of plexiglass and an inner cylinder of stainless steel. The outer diameter of the inner cylinder is 50 mm and the inside diameter of the outer cylinder is 70 mm. The length and volume of the annular space are 300 mm and 550 cm³, respectively. The critical Reynolds number for the present radius ratio (η = 0.714) can be estimated to be $Re_c = 80.6$ by the linear stability theory [7]. An aqueous solution of glycerin was used as the working fluid. The density of working fluid, $\rho_f$, was 1050 – 1150 kg/m³. After the inner cylinder had reached a certain rotational speed, each experiment was performed with an adequate time for vertical vortical structures to form.
In the flow-visualization experiment, fluorescent green dye was added as a passive tracer. To induce fluorescence, the cross section of vortices was illuminated by a plane sheet of semiconductor laser light. The sequential visual data were taken by a digital video camera.

In the particle classification experiment, polymethyl methacrylate (PMMA) particles suspended in the same aqueous solution of glycerol as the working fluid were fed into the top of the apparatus at a very low rate. The axial Reynolds number ($Re_{ax}$) with regard to the flow rate of the suspended solution was 0.42. Particle size was initially ranging from 10 to 80 µm and particle density, $\rho_p$, was ranging from 1200 – 1250 kg/m³. Hence the density ratio, $\beta = \rho_p/\rho_f$ was 1.04 – 1.05, which means the density difference between the particle and the fluid was very small. The inlet concentration of particles was 0.26 wt%. The suspended solution was withdrawn using a hypodermic needle at regular intervals at 30 mm above the bottom of apparatus. The suspended solution was sampled both near the outer wall and in the vortex core. The PSD of the sampled solution was obtained by measuring size of particles with a microscope (KEYENCE, VHX-100N) on a number basis of percentage. About 200 particles were counted in the PSD measurements.

The commercial CFD code Rflow (Rflow Co., LTD) was used for the simulation of the particle classification phenomenon. This numerical code is based on the finite volume method and makes it possible to simulate particle movement by a particle tracking method. The geometry and boundary conditions for the simulation were the same as those for the experiment. In the numerical simulation, the particle density and the fluid density were set at 1200 kg/m³ and 1100 kg/m³, respectively. The density ratio was, therefore, $\beta = 1.09$. Each particle having the size of 30, 60 and 90 mm was simultaneously and continuously fed into the top of annular gap every 1 second. The fluid also flowed uniformly at a constant flow rate into the annular space in the upper end. The axial Reynolds number was set at $Re_{ax} = 0.42$, which was the same in the experiments. First, the flow field was obtained by solving the three-dimensional Navier-Stokes equations and the mass conservation for incompressible fluid. Then the particles were tracked by solving the following equation,

$$\frac{dV_p}{dt} = -\frac{3}{4d_p}C_D \rho_f \left| V - V_p \right| (V - V_p) + \rho_f \frac{DV}{Dt} + \frac{1}{2} \rho_f \left( \frac{DV}{Dt} - \frac{DV_p}{Dt} \right) + (\rho_p - \rho_f) g$$  \hspace{1cm} (1)
where \( V_p \) is the velocity of the particle, \( V \) is the velocity field of the fluid, \( d_P \) is the particle diameter and \( C_D \) is the drag coefficient. The Basset history force, which is important in the initial motion of a particle starting from rest under certain conditions, was neglected.

![Figure 2. Cross-sectional views of axial diffusion of tracer green dye. (Re = 200 and Re_{ax} = 0.42).](image)

3. Results and Discussion

Figure 2 shows cross-sectional views presenting axial diffusion process of tracer with measuring time from the injection of green dye. The Reynolds number and the axial Reynolds number were 200 and 0.42, respectively. The flow-visualization experiment by a laser-induced fluorescence method clearly revealed that there exist two distinct mixing regions at low Reynolds numbers, as shown in Figure 2. The tracer near the vortex cell boundary was rapidly transported downward in the axial direction owing to the bypass flow effect. On the other hand, the fluid element was confined to the vortex core region without being exchanged with the outer flow region. The wavy motion of the cell boundaries could be observed. Our previous work [8] revealed that the area of IMR decreases and that of AMR (bypass flow region) increases with increasing Reynolds number. The size of bypass flow region can be controlled by the rotational speed of the inner cylinder.

Figure 3 shows diagrams of PSD in the sampled solution and photographs of the particles corresponding to the PSDs at \( Re = 340 \). According to the previous result of the flow-visualization experiment, it can be considered that this flow state is also wavy vortex flow. Initially the particle size distribution is relatively homogeneous in the range from 10 to 80 \( \mu \text{m} \). The population of particles smaller than 40 \( \mu \text{m} \) is 52 \%, while that of particles larger than 40 \( \mu \text{m} \) is 48 \%. When 18 min has passed since the suspended solution was fed into the apparatus, Figure 3 b) shows that the population of particles smaller than 40 \( \mu \text{m} \) increases up to about 60 \% in the vortex core region. On the other hand, in the outer region of vortex, the diagram shows a bimodal distribution having the peaks at 30 – 40 and 60 – 70 \( \mu \text{m} \). Furthermore the population of particles larger than 50 \( \mu \text{m} \) grows to 46\% from 32 \% of the initial distribution. As shown in Figure 3 c), particles having the size of smaller than 50 \( \mu \text{m} \) are dominant in the vortex core region at 42 min after feeding the suspended solution. Their population almost reaches 70\%. These results indicate that the particles are classified by the size of 50 \( \mu \text{m} \) under the condition. This means that the Taylor-Couette flow system certainly has the property of particle classification even when the density difference is very small. One may feel that a long waiting period is necessary to see the classification as compared with the typical time scale of the Taylor-Couette flow. In this experiment, the axial Reynolds number \( (Re_{ax} = 0.42) \) is so small that it takes about 40 min for a vortex cell to move from the top to the sampling port. Furthermore, as previously described, the density difference between the particle and the fluid is very small. This means that gravity cannot play a significant role in the particle motion.
Figure 3. Particle size distribution and photographs at $Re = 500$. 

a) $t = 0$ min

b) $t = 18$ min

c) $t = 42$ min
Particle diffusion process at $Re = 125$; the black, green and blue particles are 30, 60 and 90 $\mu$m in size, respectively.

Figure 4. Particle diffusion process at $Re = 125$; the black, green and blue particles are 30, 60 and 90 $\mu$m in size, respectively.

In order to investigate particle motion in more detail, numerical simulation was conducted. Figure 4 shows particle diffusion process when particles having the size of 30, 60 and 90 $\mu$m were simultaneously fed into the top of the annular gap at $Re = 125$ and $Re_{ax} = 0.42$. This figure indicates the upper half of cylinder. In this figure, the black, green and blue particles are 30, 60 and 90 $\mu$m in size, respectively. As can be seen from Figure 4, the blue particles having the size of 90 $\mu$m are located near the outer edge of vortices and quickly move downward owing to the bypass flow. The green particles of 60 $\mu$m are located in the inner region of vortices in comparison with the blue particles and only a few particles move downward. The black particles having 30 $\mu$m in size exist in the innermost region of vortices and all particles still remain within vortex core. These results indicate

Figure 5. Time variation of PSD.
that the loci of particles depended on the particle size. Figure 5 shows time variation of PSD obtained in the upper portion (0 - 100 mm from the top) and the lower portion (200 - 300 mm from the top), respectively. In the upper portion, the population of the smallest particles (30 \( \mu m \)) increases with time and reaches to about 65 % after 18 min. On the other hand, in the time variation of PSD obtained in the lower portion, only the largest particles can be seen even after 18 min. These results imply that particles can be classified and collected by installing several outlet ports in the axial direction.

4. Conclusion
In the present work, it is confirmed experimentally and numerically that particles having various size can be classified by taking account of the vortex motion and the bypass flow near the outer edge of vortices in Taylor-Couette flow even when the density difference is very small. The mechanism of the particle classification in Taylor-Couette flow is quite similar to the Dean vortex flow observed Ookawara et al. In the present work, however, it is still unclear whether the centrifugal force or the shear-induced migration plays the more significant role in the classification, when the density difference is very small. We will examine these two effects in more detail in future work. Figure 6 shows a schematic picture of the mechanism of particle classification in Taylor-Couette flow. The centrifugal force or the shear-induced particle migration due to the rotation of inner cylinder concentrates particles near the wall of outer cylinder and the larger particles tend to be located more outside in the vortex cell. Owing to the effect of the bypass flow, the larger particles more quickly disperse in the axial direction. However, the bypass flow alone is not enough to classify the particles because both upward and downward flow exists because vortices in a pair rotate counter to each other. The axial flow plays another important role in the axial dispersion of the particles. Wereley and Lueptow [9] experimentally confirmed a strong stream of fluid winding around vortices in the axial flow direction by a PIV technique. This stream does not fill the annular gap and appear alternately displaced toward the inner and outer cylinder as shown in Figure 6. Hwang and Yang [10] also numerically obtained the same vortex characteristics as found in the experiments of Wereley and Lueptow. The winding flow potentially transports the larger particles existing in the outer region of vortex downward and prevents them from moving upward. It can be concluded that this work successfully verified the feasibility of particle classification using a Taylor-Couette-flow device.

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Figure 6. Schematic picture of classification mechanism in Taylor-Couette flow with an axial flow.
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