Experimental study on surface morphology of Taylor-vortex flow

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Abstract: *Viscous fluid that circulates between rotating double cylinders forms a Taylor-vortex flow with a structure in which multiple toroidal vortices are stacked. Taylor-vortex flow has been studied starting with theoretical and experimental studies and representing models that show non-uniqueness of flow. Specifically, in a system consisting of a stationary outer cylinder and a rotating inner cylinder, it has been confirmed that changes in the dynamic parameter, Re, and the geometric parameter aspect ratio (working fluid height / gap width of double cylinders) cause mode transition from Couette flow, Taylor-vortex flow, to wavy Taylor vortices. In the present study, we aim to elucidate the wave phenomenon of Taylor-vortex flow with free end on a free surface.In terms of the surface wave phenomenon on the free surface of the flow between rotating double cylinders, we processed the image of the free surface and measured the fluid level change to clarify the mode of development for the flow relative to the fluctuations of the mechanical parameters. Characteristics of the fluid level change with increasing Re were confirmed by classifying the results into four types. At Re = 0 to 1,400, the ridgeline cannot be confirmed, but at Re = 1,600, a ridgeline that divides the free surface into two is confirmed. As Re increased, the flow region near the inner cylinder sinks, while the flow near the outer cylinder rises. The volume of the raised portion of the fluid surface near the outer cylinder increased with Re.*

Keywords: *Taylor vortex flow, Experimental study, Free Surface.*

1. INTRODUCTION

Figure 1 shows the schematics of the Taylor-vortex flow [1]. Taylor-vortex flow has been heavily studied starting with theoretical and experimental studies and representing models that show non-uniqueness of flow. Specifically, in a system consisting of a stationary outer cylinder and a rotating inner cylinder, it has been confirmed that changes in the dynamic parameter, Re, and the geometric parameter aspect ratio (working fluid height / gap width of double cylinders) cause mode transition from Couette flow, Taylor-vortex flow, to wavy Taylor vortices. Toya et al [2] examined the critical Re at which Taylor-vortex flow transitions to wavy Taylor vortices through experiments and numerical calculations. Azuma et al [3] examined angular acceleration of the inner cylinder rotation through numerical calculations; in other words, they examined the formation process of Taylor vortices through the increase of mechanical parameters over time and showed the generation mechanism of mutation mode and secondary mode. An example of application is the elucidation of flow characteristics and optimization of the shapes inside the motor of electric vehicles.

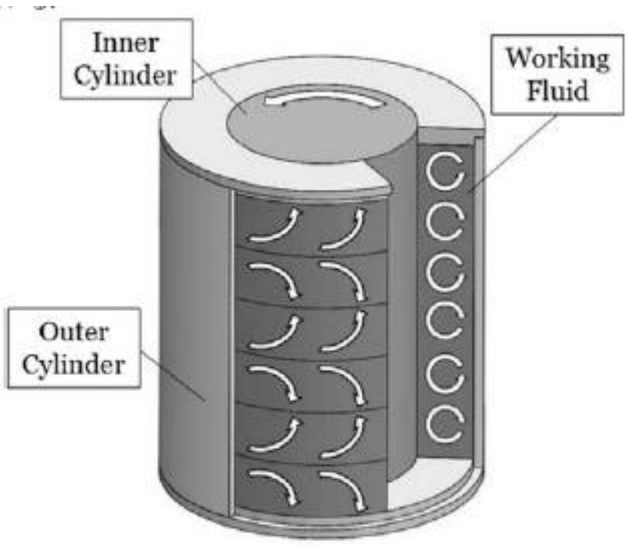

Fig -1: Taylor-vortex flow (assuming both ends are fixed)

These studies assume that both ends of the cylinder are fixed, while it has been confirmed that when one end of the cylinder is free, unlike fixed ends, Taylor-vortex flow with an odd number of cells is generated. Watanabe et al. [4] performed numerical calculations for a Taylor-vortex flow with free end and showed the flow under mutation mode generated when the inner cylinder was rapidly accelerated, and showed the bifurcation phenomenon of cell number associated with the changes of aspect ratio and Re. However, not many studies examined Taylor vortices with free end. Specifically, there is hardly any study that examined the mode of the flow of working fluid on a free surface. Nakamura et al. [5] experimented on the wave phenomenon of Taylor vortices with free end on a free surface, but their work was limited to the measurement of the fluid level change at the center of the gap between the inner and outer cylinders due to the size of their experimental apparatus, and a larger experimental apparatus is needed to elucidate the wave phenomenon across the whole free surface.

In the present study, we aim to elucidate the wave phenomenon of Taylor-vortex flow with free end on a free surface.

2. EXPERIMENTAL EQUIPMENT

Figure 2 shows the schematics of the rotating double cylinder device. The device used for the experiment consisted of a steel inner cylinder with a radius r_{in} of 200 mm and an acrylic cylinder with a radius rout of 300 mm placed coaxially. The outer cylinder was fixed onto the base using a silicone sealant. With an AC servo-motor connected through an AC timing belt, only the inner cylinder was allowed to rotate. The ratio of speed reduction between the AC servo motor and the inner cylinder was 1:64, where the number of rotations for the AC servo motor could be set at 1 rpm increments. The working fluid had free surface, and the bottom surface was fixed. The working fluid was aqueous glycerol solution with kinematic viscosity of 3.97 × 10-5 m^2/s (23°C). Since the flow on the free surface is likely to depend on the three-dimensional structure of Taylor-vortex flow, the mode of occurrence for Taylor vortices was uniquely determined. Therefore, based on the previous studies, the aspect ratio Γ was set to 3.0 to stably generate the normal three-cell mode.

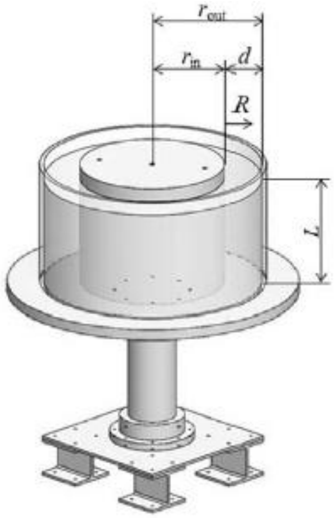

Fig -2: Schematics of the experimental equipment

We used a GoProHERO6 video camera to film free surface. A light covered with a paper was installed on the top part of the video camera to prevent reflection of light during recording.UD-500 series and data collection system NR-500 series from KEYENCE were used as an ultrasound displacement sensor to measure the fluid level change.

3. EXPERIMENTAL RESULTS

From the fluctuation data of fluid level measured with the ultrasonic displacement sensor, a graph for the average fluid level change (Y-axis) and the radial distance R of the cylinders (X-axis) is prepared to confirm the cross-sectional shape of the free surface. From the prepared graph, results are divided into four types. With Type I, fluctuation in the fluid level increases in the radial direction between R = 0.2 to 0.8. Figure 3 shows the liquid level change of each Re of Type I. At Re = 800 (Type I), the fluid level on the outer cylinder side increased by a maximum of 0.48 mm. This rise was likely caused by the centrifugal force in the radial direction caused by the rotation of the inner cylinder.

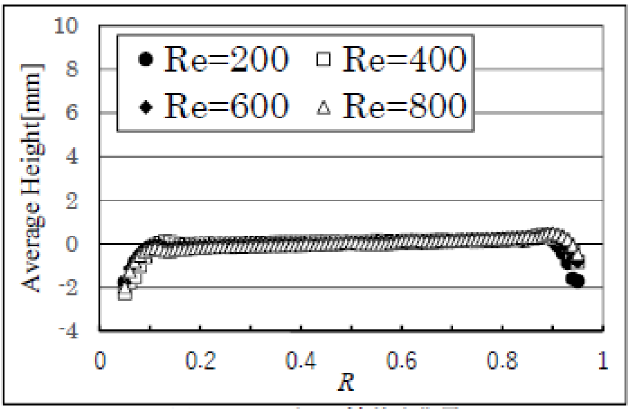

Fig -3: Fluid level change for Type I

In Type II, as Re increased, the fluid surface on the inner cylinder side dropped,while the fluid surface on the outer cylinder side rose.Figure 4 shows the fluid level change for each Type II Re. The fluid level increased rapidly between R = 0.65 and 0.80. At Re = 1,400, the fluid level rose about 0.8 mm between R = 0.71 and 0.77. The fluid level on the inner cylinder side fell about 1.2 mm, while it rose about 1.1 mm on the outer cylinder side. Similarly to Type I, as the inner cylinder rotated, centrifugal force caused the fluid level to rise.

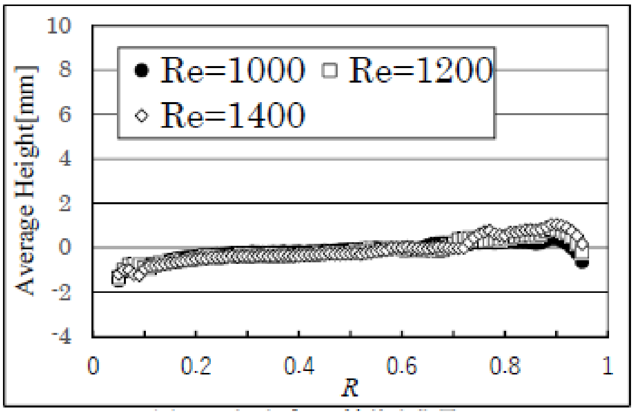

Fig -4: Fluid level change for Type II

In Type III, the fluid level on the inner cylinder side dropped and the outer cylinder side rose as Re increased in the similar manner to Type II. However, the free surface changed to a characteristic shape. Figure 5 shows fluid level change for each Type III Re. First, the fluid level dropped between R = 0.60 and 0.75, which was followed by an increase. It dropped again between R =0.75 and 0.90 and rose again. Although the fluid level increased in a similar manner to Type II,fluid surface shape was more notable. With Type III Re of 2,000, after the first drop, the fluid level rose about 1.4 mm between R = 0.66 and 0.76. After the second drop, it rose about 1.6 mm between R = 0.78 and 0.83.

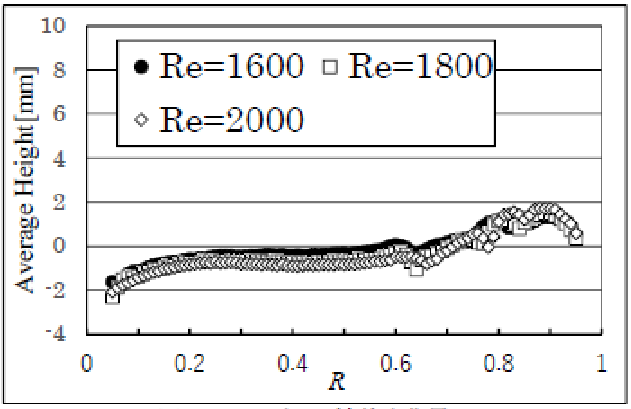

Fig -5: Fluid level change for Type III

In Type IV, the fluid level dropped between R = 0.3 and 0.6, then increased in the radial direction. Figure 6 shows the fluid level change for each Type IV Re. Differently from Type III,the fluid level decreases and increases only once.At each Type IV Re of 4,000, the fluid level dropped about 1.3 mm between R = 0.28 and 0.48, and rose about 7.8 mm between R = 0.48 and 0.85.

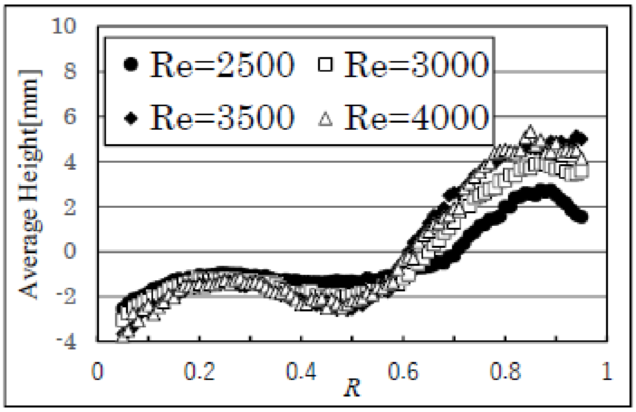

Fig -6: Fluid level change for Type IV

4. CONCLUSIONS

In terms of the surface wave phenomenon on the free surface of the flow between rotating double cylinders, we processed the image of the free surface and measured the fluid level change toclarify the mode of development for the flow relative to the fluctuations of the mechanical parameters. The main conclusions are as follows:

1. Characteristics of the fluid level change with increasing Re were confirmed by classifying the results into four types shown in Figs. 4-1 to 4-4. At Re = 0 to 1,400, the ridgeline cannot be confirmed, but at Re = 1,600, a ridgeline that divides the free surface into two is confirmed.
2. As Re increased, the flow region near the inner cylinder sinks, while the flow near the outer cylinder rises. The volume of the raised portion of the fluid surface near the outer cylinder increased with Re.

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