Stability of Anomalous Modes on Taylor-Couette vortex flow in Magnetic Fluid

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With the advance of technologies in bio-industrial field, development of a more practical device using Taylor-Couette vortex flow has been longed for. To bring this technology into active use, it needs to be downsized. And at the same time, it is necessary to secure sufficient volume for the reaction. This means that the Ekman effect will increase relatively. The Ekman effect generates various modes of Taylor-Couette vortex flow with a small aspect ratio. In the case of a practical device using this flow, fluid control is essential for controlling the reaction caused inside. Thus this study is focused on controlling Taylor-Couette vortex flow in a magnetic fluid. The Taylor-Couette vessel used in this study has a rotating inner cylinder and a stational outer cylinder. It has an aspect ratio, Γ=3 and a radius ratio, η=0.6. The axial velocity distributions are measured by a UVP model X-3 PSi. The Ultrasonic transducer has 3mm beam diameter and 8MHz basic frequency. The control of the mode transition by applying the magnetic fields has been investigated. As a result, three Anomalous modes were obtained. And their stabilities are being discussed.

Keywords: UVP, Taylor-Couette vortex flow, magnetic fluid, flow control, bioreactor

1 INTRODUCTION

Recently research and development of a bioreactor using animal and plant cells has been longed for. With the advance of technologies in medical and bio-industrial fields, it was revealed that animal and plant cells have a wide range of applications. However, animal and plant cells are adversely affected by shear stress. That is why the efficient bioreactor using Taylor-Couette vortex flow attracted a lot of attention. It is said that Taylor-Couette vortex flow has high mixing and reaction performance with little influence upon animal and plant cells. Ameer et al. [1] researched and developed a postdialyzer using Taylor-Couette vortex flow. And Haut et al. [2] examined the ability of a bioreactor using Taylor-Couette vortex flow to culture animal cells. However, when Taylor-Couette vortex flow was used for various reactions, variations in reaction efficiency appeared although bioreactors were operated at the same Reynolds numbers. Because many studies on bioreactors using Taylor-Couette vortex flow were not made from a fluid dynamical viewpoint but from a chemical and biological one, the fluid dynamical characteristics of Taylor-Couette vortex flow cannot be understood.

Taylor-Couette vortex flow is a flow between a rotating cylinder and a stational cylinder. Many studies on Taylor-Couette vortex flow have already been done, and the following sequence of flow regimes has been observed. At very low Reynolds numbers Couette flow, which is simple shear flow, appears. On increasing the Reynolds numbers Couette flow changes into Taylor-Couette vortex flow. Taylor-Couette vortex flow has some stable toroidal vortices. On increasing the Reynolds number further, the vortices oscillate. This flow mode is called Wavy vortex mode. On increasing the Reynolds number further and further, an additional wavy mode which modulates wavy vortex mode appears: this flow is called modulated wavy vortex mode. To bring a bioreactor using Taylor-Couette vortex flow into active use, it needs to be downsized. And at the same time, it is necessary to secure the enough volume for reactions. This means that the aspect ratio will be small and that the Ekman effect will increase relatively.

Taylor-Couette vortex flow with a small aspect ratio is an interesting physical phenomenon, typical of non-linear dynamics. Many researchers, for example Benjamin [3] and so on, have carried out the investigations on the mode bifurcation and the flow pattern [4]. Taylor-Couette vortex flow with a small aspect ratio bifurcates into the primary mode and the secondary mode. This bifurcation stems from the difference in initial acceleration of an inner cylinder. The primary mode will occur if an inner cylinder is accelerated gradually, and the secondary mode will occur by sudden acceleration. And these two modes bifurcate into the normal mode and the anomalous mode. The normal mode has an inward flow on both end-walls, and the anomalous mode has an outward flow at least on either end-wall or both. In the case of the aspect ratio 3, focused in this study, there are four flow modes: the normal 2cell mode (N-2cell mode), the normal 4cell mode

(N-4cell mode), the anomalous 3cell mode (A-3cell mode) and the anomalous 4cell mode (A-4cell mode).

If there is a perfect flow mode for a reaction caused in a bioreactor using Taylor-Couette vortex flow with a small aspect ratio, it is possible to improve the efficiency of reaction dramatically by maintaining the flow mode. Thus, the objective of this study is to controll Taylor-Couette vortex flow in a magnetic fluid by applying the magnetic field using a permanent magnet and to analyze the stability of the anomalous modes.

2 EXPERIMENTAL SETUP

The schematic diagram of the experimental setup is shown in Fig.1. And our Taylor-Couette vessel is shown in Fig.2. The Taylor-Couette vessel consists of two concentric cylinders and two end-walls, which are made of Plexiglas. The length of the cylinders is H = 48 mm, the outer radius of the inner cylinder is R_1 = 24 mm and the inner radius of the outer cylinder is R_2 = 40 mm. So our Taylor-Couette system has a radius ratio $\eta = R1/R2 = 0.6$ and an aspect ratio $\Gamma = H/d = 3$ ($d = R_2 - R_1$). They are positioned vertically adjacent. Only the inner cylinder is rotated by the motor. The Reynolds number Re is defined as $Re = \Omega R1d/v$ (Ω is the frequency of rotation of the inner cylinder, v is the kinematic viscosity).

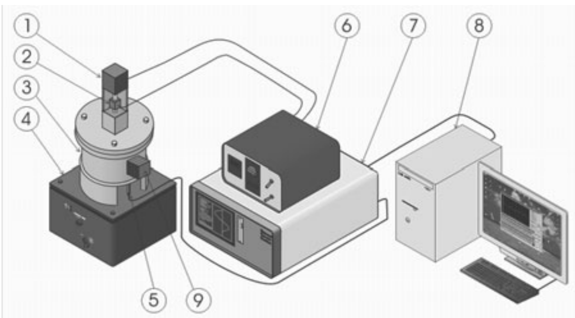

Figure 1: Experimental setup ①motor, ②encoder, ③Taylor-Couette Vessel, ④isolator, ⑤US transducer, ⑥controller, ⑦UVP monitor, ⑧PC, ⑨magnet

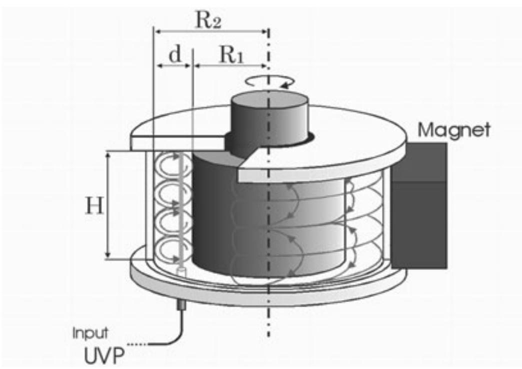

Figure 2: The Taylor-Couette vessel

The gap between the two cylinders is filled with a magnetic fluid. In this study, we used the water-based magnetic fluid of the weight concentration of 23.34wt%. The physical property of the magnetic fluid used in this study is shown in Tab.1.

The measurements were carried out with an ultrasonic velocity profiler (UVP), which can obtain a time series of instantaneous velocity profiles. Additionally UVP can obtain the velocity profiles of nebulous liquids such as a magnetic fluid. The UVP used in this work is the model X-3 PSi. The ultrasonic transducer was affixed to the outer surface of the stationary lower end-wall to measure the axial velocity distribution, as shown in Fig.2. The parameters of UVP measurement are shown in Tab.2. The ultrasound transducer was operated with a basic frequency of 8MHz and a beam diameter of 3mm. The channel distance, which is the distance between two adjacent measurement volumes, was 0.73mm. The non-uniform magnetic field was applied by attaching three permanent magnets, shown in Fig. 3, outside the stational cylinder. The locations of the ultrasonic transducer for measurements and the permanent magnet for applying magnetic filed are shown in Fig.4.

Table 1: Physical property of the water-based magnetic fluid of the weight concentration of 23.34wt% at 22℃

Kinematic viscosity	2.6 mm^2/s
Density	1.2 g/cm^3
Sound velocity	1450 m/s

Table 2: Specifications of UVP measurement

Basic frequency of ultrasound	8 MHz
Ultrasonic beam diameter	3 mm
Channel distance	0.73 mm
Number of measurement points	128
Number of profiles	1024

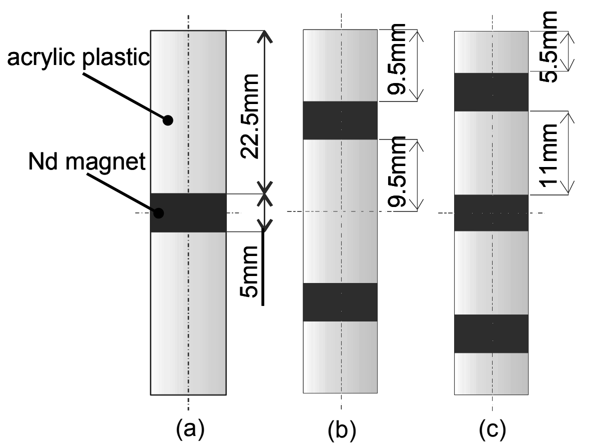

Figure 3: The permanent magnets

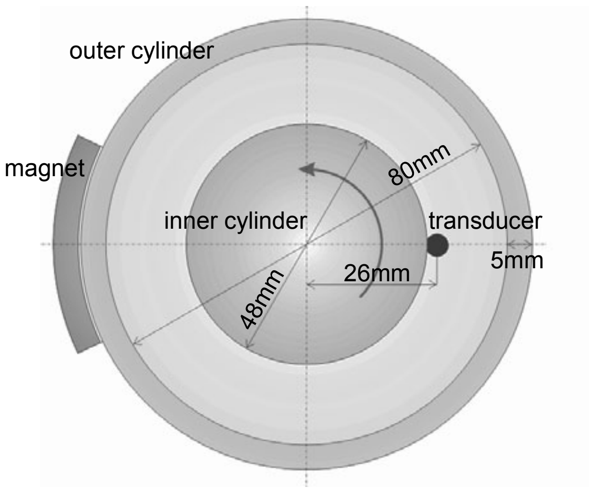

Figure 4: Top view of measuring position and applying a magnetic field position

3 EXPERIMENTAL RESULTS

3.1 Magnetic control of flow field

Figs.5-7 show the temporal-spatial velocity distributions transient change measured by a UVP when a magnetic field was applied. In these figures, the horizontal axis is time from 0 to 182 seconds and the vertical axis is the distance from the transducer and the velocity is represented by the color contour. Fig.5 (a), (b), and Fig.6 show the mode bifurcation control by applying the magnetic field from N-2cell mode to A-3cell mode, from N-2cell mode to N-4cell mode and from N-2cell mode to A-3cell mode, respectively. These mode bifurcations don't occur by changing Re. From here onwards, it is possible to control the mode bifurcation of Taylor-Couette vortex flow in a magnetic fluid by applying the magnetic field. In Fig.7, it appears as if the Anomalous vortex on the upper stationary end-wall had exchanged positions with the normal vortex on the lower stationary end-

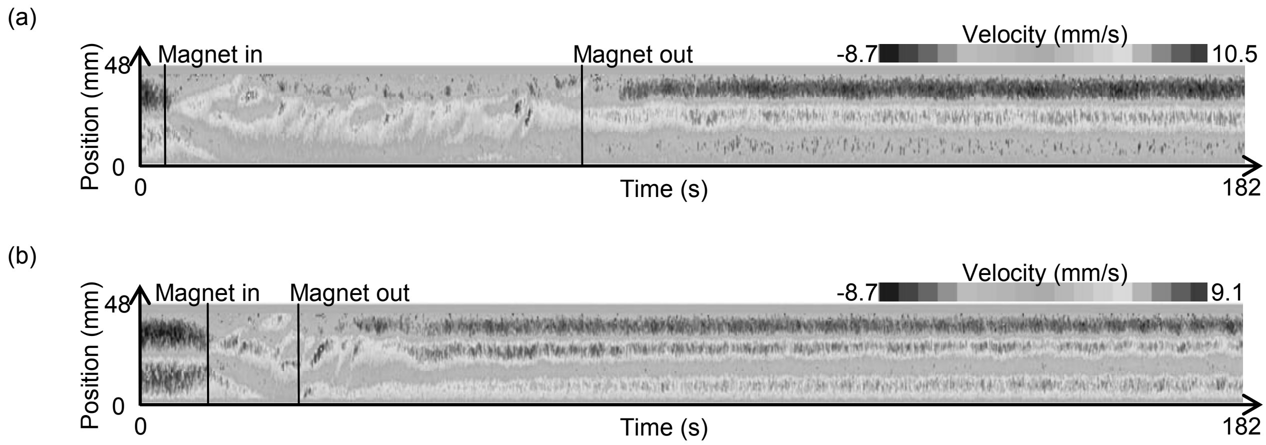

Figure 5: The temporal-spatial velocity distributions of transition by applying magnetic field with the magnet A (Re=420); (a) transition from N-2cell mode to A-3cell mode (b) transition from N-2cell mode to N-4cell mode

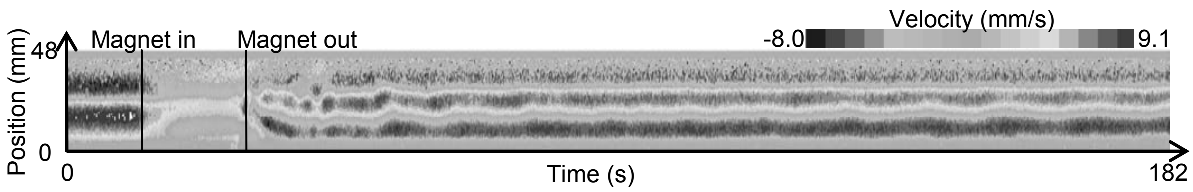

Figure 6: The temporal-spatial velocity distributions of transition from N-2cell mode to A-3cell mode by applying magnetic field with the magnet B (Re=420)

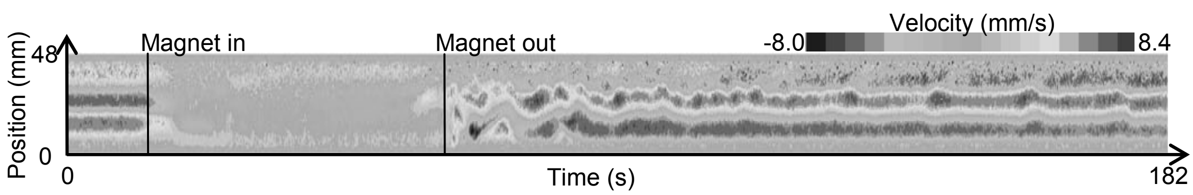

Figure 7: The temporal-spatial velocity distributions of transition from A-3cell U mode to A-3cell L mode by applying magnetic field with the magnet C (Re=420)

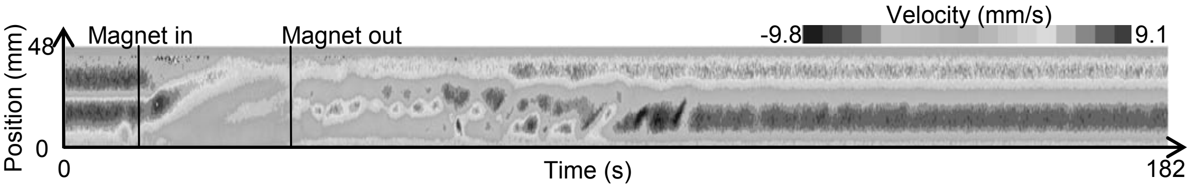

Figure 8: The temporal-spatial velocity distributions of transition from A-3cell U mode to A-3cell L mode by applying magnetic field with the magnet C (Re=420)

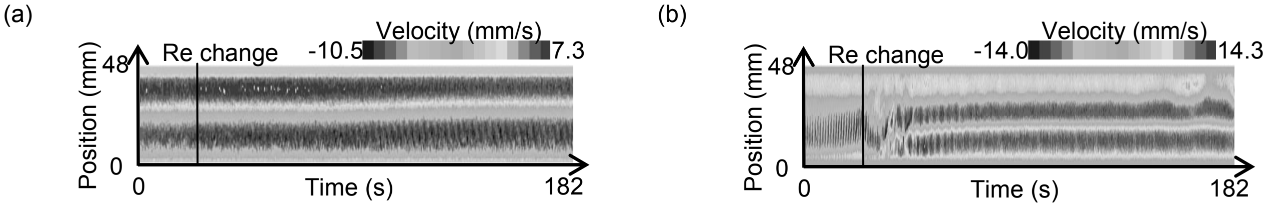

Figure 9: The temporal-spatial velocity distributions of transition on A-2cell mode by accelerating inner cylinder; (a) from A-2cell Taylor-Couette vortex flow to A-2cell Wavy vortex flow(Re=440→460) (b) from A-2cell Wavy vortex flow to A-3cell Taylor-Couette vortex flow(Re=670→700)

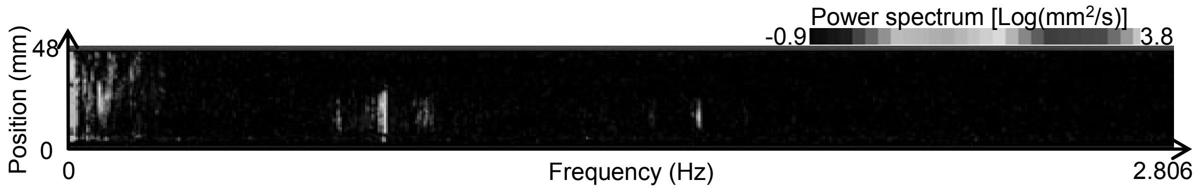

Figure 10: The result of the fast Fourier spectrum for the same data as for Fig.9 (a)

wall. Furthermore in Fig.8, Normal 2cell mode bifurcates to the opposite flow, because the color plot is inverted before and after applying the magnetic field. It shows that the cell mode has two anomalous cells, so it can be called Anomalous 2cell mode.

3.2 Anomalous 2cell mode

A-2cell mode consists of two vortices whose sizes are not the same. In this study, we refer to the larger vortex as main vortex and the smaller as sub. Fig.9 (a) and (b) show the temporal-spatial velocity distributions of the transition on A-2cell mode by changing Re from 440 to 460 and from 670 to 700, respectively. It can be observed that only the main vortex on the lower end-wall oscillated as shown in Fig.9 (a). And Fig.10 shows the result of the fast Fourier spectrum for the same data as those for Fig.9 (a). In these figures, the horizontal axis is frequency from 0 to 2.806 Hz and the vertical axis is a distance from the transducer and the power spectrum is represented by the color contour. From this result, a strong spectrum can be seen only at a lower position at nearly 0.71 Hz. This means that only the main vortex oscillated on A-2cell mode. On increasing Re further, the main vortex broke up to two vortices. Finally, the flow field settled to A-3cell mode.

4 CONCLUDING REMARKS

The controlling of Taylor-Couette vortex flow in a magnetic fluid by applying a magnetic field has been investigated using UVP. From the experimental result of applying magnetic fluid on Taylor-Couette vortex flow in a magnetic field, we found the practicability of mode bifurcation control and discovered a new cell mode, A-2cell mode. And the stability of A-2cell mode has been analyzed. Analyzing the stability of the bifurcation of A-2cell mode by changing Re is revealed.

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