Mode bifurcation control of a magnetic fluid on Taylor-Couette vortex flow with small aspect ratio

D Ito[1], H Kikura[1], M Aritomi[1] and Y Takeda[2]

[1]Research Laboratory for Nuclear Reactors, Tokyo Institute of Technology, Ohokayama, Meguro-ku, Tokyo, 152-8550, Japan
[2]Division of Mechanical Science, Hokkaido University, Sapporo, 060-0808, Japan

E-mail: ito@2phase.nr.titech.ac.jp

Abstract. The study of Taylor-Couette vortex flow with small aspect ratio is great interesting. Additionally, the importance of magnetic fluids has been increasing in the engineering applications of various fields, and this leads to increase the interests to investigate the flow of magnetic fluids, which have the reactivity to magnetic field. Then Taylor-Couette vortex flow with magnetic fluids is expected to control the flow pattern and the mode bifurcation by using magnetic field. Recently, the velocity information of various flow fields is available by using Ultrasonic Velocity Profiler (UVP). Hence, the method for investigating the flow fields in the magnetic fluids has also been available. In this study, the flow structure of a magnetic fluid in a concentric annular geometry with an aspect ratio of 3 and a radius ratio of 0.6 was investigated for an inner cylinder rotation. Axial velocity distributions of the flow field were measured using the UVP measuring technique. In the UVP measurement, an ultrasonic with basic frequency of 8MHz and beam diameter of 3mm was used. A non-uniform magnetic field was applied to the flow field using a permanent magnet located on the outside of the vessel, and the transitions of flow field with a magnet were investigated by using UVP.

1. Introduction

The magnetic fluids contain solid, magnetic, single domain particles coated with a molecular layer of a dispersant in a liquid carrier such as water or kerosene. Since the diameter of these particles lies in the size range of 5-15 nm, and due to the thermal agitation, the resulting random walk and random rotation, i.e. Brownian motion, the ferromagnetic particles remain suspended steadily. To achieve a stable dispersion in non-polar or polar solvent, the particles are coated with a single or double layers surfactant.

The importance of such magnetic fluids has been increasing in engineering application of various fields, and this leads to increase the interests to investigate the flows of the magnetic fluids, which have the reactivity to magnetic field. Conventional methods for flow investigations, such as Laser Doppler Anemometry (LDA) and Particle Image Velocimetry (PIV) cannot be applied to investigate the magnetic fluid flows, because the opaque liquid prevents the incidence of the light to the flow fields. In order to investigate the flow fields of liquids with optically non-transparent media, the Ultrasonic Velocity Profiler (UVP) has been developed [1,2]. Recently, it has been demonstrated that velocities can be measured in flowing mercury [3] and in magnetic fluids [4,5].

Taylor-Couette vortex flow with small aspect ratio, which has the effect at the end of annulus, is an interesting physical phenomenon, typical to non-linear dynamics. Many researchers have carried out the investigations on the mode bifurcation and flow pattern, applying LDA, flow visualization or other methods. Benjamin [6] studied the change in mutation of primary flow at the length of comparatively short annulus. Mullin [7] investigated the evolution of primary flow and the transition from N-cell mode to (N+2)-cell mode by flow visualization. Furthermore they found that the primary mode appears when Reynolds number is increased smoothly and the secondary mode occurs when inner cylinder is sudden rotated. In Taylor-Couette flow with small aspect ratio, the flow is also classified as primary mode and secondary modes. At aspect ratio of 3, the primary mode, Normal 2cell mode, is formed smoothly from Couette flow by a gradual increase in Reynolds number. The secondary mode, Normal 4cell mode, occurs when the Reynolds number was abruptly increased to a certain final value. The number of vortices in the secondary mode is different from one in the primary mode. The primary mode and secondary mode are distinguished into normal mode and anomalous mode. On each end wall, the flow in the normal mode has a normal cell which gives an inward flow in the region adjacent to the end wall, as shown Figure 1a. The flows of the anomalous modes have anomalous cells, which give an outward flow near the end wall, as shown Figure 1b. Anomalous modes are Anomalous 3cell mode and Anomalous 4cell mode. So four cell modes appear at aspect ratio of 3. If we use a magnetic fluid as a test liquid, it is suggested the possibility of the cell mode control by using an external magnetic field.

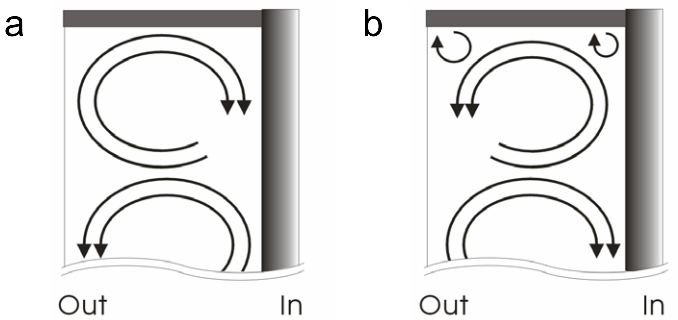

Figure 1. Flow direction near the end wall; a. normal mode, b. anomalous mode

Some experimental investigations by mean of torque characteristics for cylindrical and spherical Couette flow on magnetic fluids had also been studied [8-10]. The UVP method was applied to the time-dependent Taylor-Couette flows obtained between two concentric rotating cylinders to measure time-dependent flow dynamics of a magnetic fluid by Kikura, et al. [11]. They found that under a non-uniform magnetic field, there is an angular dependence of the flow and the maximum velocity depends on the intensity of the magnetic field and is influenced by the level of the upstream velocity.

Thus, the objective of the present paper is to measure the internal flow of a magnetic fluid on Taylor-Couette flow with fixed aspect ratio of 3 using UVP method and to discuss the influence of an applied magnetic field on the flow mode bifurcation control.

2. Experimental apparatus

The schematic of experimental apparatus is shown in Figure 2. The apparatus consists of two concentric cylinders, 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. It means that the experiment is performed at fixed aspect ratio   = $H/(R_2-R_1)$ = 3 and radius ratio   = R_1/R_2 = 0.6. They are positioned vertically and the gap between the two cylinders is filled with a magnetic fluid. The ultrasonic transducer is positioned at the bottom of vessel to measure the axial velocity distribution, as shown Figure 3. In the system with fixed outer cylinder, the fluid in the annular gap moves in a plane perpendicular to the cylinder axis for small Reynolds number which is defined as Re = $R_1(R_2-R_1)/$. Here,   is the rotation rate of the inner cylinder, and   is the kinematic viscosity of the magnetic fluid. In the present study, we used a water-based magnetic fluid weight concentration of 23.35wt% having a sound velocity of 1450m/s.

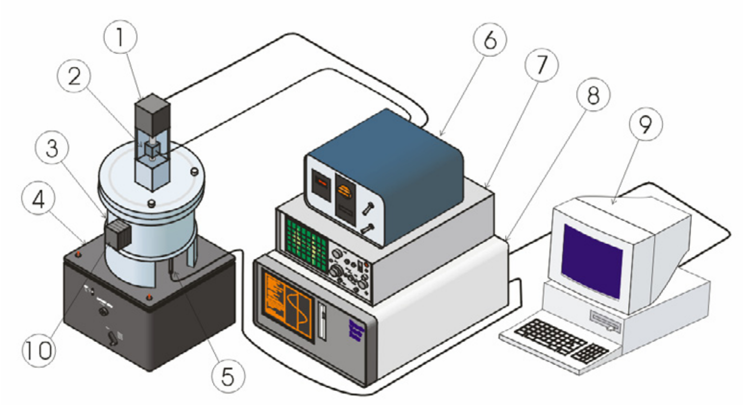

Figure 2. Experimental apparatus: (1) motor, (2) encoder, (3) Taylor-Couette Vessel, (4) isolator, (5) US transducer, (6) controller, (7) oscilloscope, (8) UVP monitor, (9) PC, (10) magnet

Table 1. 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

The UVP monitor used in this work is the Met-Flow model X-3 PSi model. The principle of the ultrasonic Doppler method is based on echography for position information and the Doppler shift relationship for velocity detection. The parameters of UVP measurement are shown Table 1. The ultrasound transducer was operated with a basic frequency of 8MHz and a beam diameter of 3mm. The channel distance, which is a distance between two adjacent measurement volumes, was 0.73mm. Using UVP method, we can obtain the successive instantaneous and mean velocity profiles and the transient change behaviors of flow field.

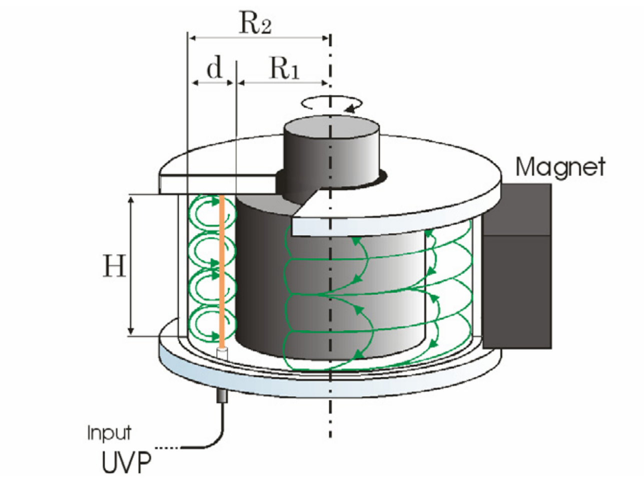

Figure 3. Test section

The non-uniform magnetic field was applied perpendicularly to the cylinder axis using two kinds of permanent magnet, whose size is 40mm×40mm×4.5mm and 10mm×10mm×20mm, positioned outside the cylinders. Typical magnetic field distribution of large magnet (B_0 = 110mT) around the cylinder is shown in Figure 4 and the locations of ultrasonic transducer for measurements are illustrated in Figure 5. The small magnet (B_0 = 170mT) was used to give the local magnetic field to the vortex. A Hall-effect Gauss meter was used to measure the vertical and horizontal magnetic inductions; hence the magnetic vector field was measured.

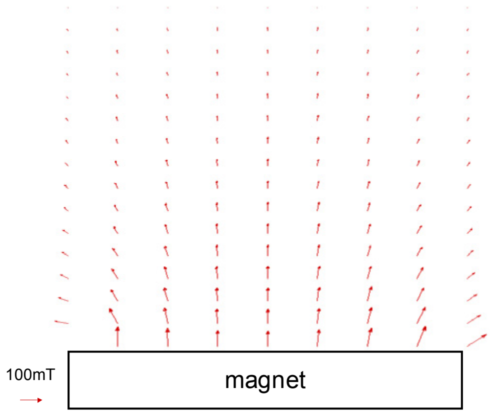

Figure 4. Measured magnetic field distribution

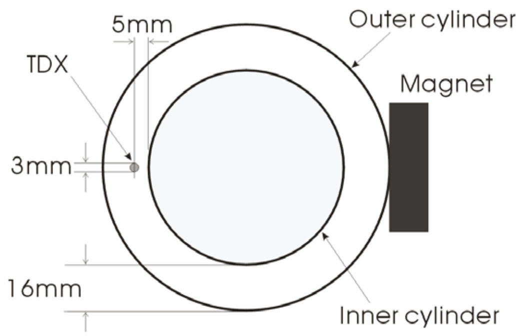

Figure 5. Top view of measuring position

3. Results and discussion

3.1. Flow field measurement of a magnetic fluid

The velocity profiles were obtained by setting up the ultrasonic transducer on the outer wall of the end plate at inner wall position, as illustrated in Figure 4. At very low Reynolds number in a rotating Taylor-Couette system, the flow is a one-dimensional circular Couette flow having the velocity profile $V = (0, V(r), 0)$. At critical Reynolds number, Couette flow becomes unstable to Taylor vortex flow (TVF), which has three-dimensional, axisymmetric counter-rotating toroidal vortices. TVF with small aspect ratio has various flow patterns. Figure 6 shows the spatio-temporal axial velocity distributions obtained from UVP measurement in different flow mode at same Reynolds number (Re = 380) without magnetic field. In Taylor-Couette vortex flow with aspect ratio of 3, the four cell modes appear when Re is near 400. Figure 6a shows Normal 2cell mode, which exists two symmetric vortices. Figure 6b shows Normal 4cell mode, which has different vortex structure between the center two cells and the end two cells. In Figure 6c, it shows Anomalous 3cell modes, which consists a pair of two vortices and an extra vortex. Figure 6d shows Anomalous 4cell mode, which has the opposite flow to Normal 4cell mode and the vortex structure like Anomalous 3cell mode.

3.2. Magnetic control of flow field

Figure 7, 8 and 9 shows the velocity fields of transient change measured by UVP when a magnetic field was applied. In these figures, the horizontal axis is time from 0 to 180 seconds and the vertical axis is a position from the transducer and the velocity levels are represented by the color contour. Figure 7a, 7b show the mode bifurcation control by applying magnetic field of the large magnet from Normal 2cell mode to Normal 4cell mode and Anomalous 3cell mode, respectively. From these results, Normal 2cell mode, which is the most stable cell mode at aspect ratio of 3, was changed to more unstable modes by a magnetic control.

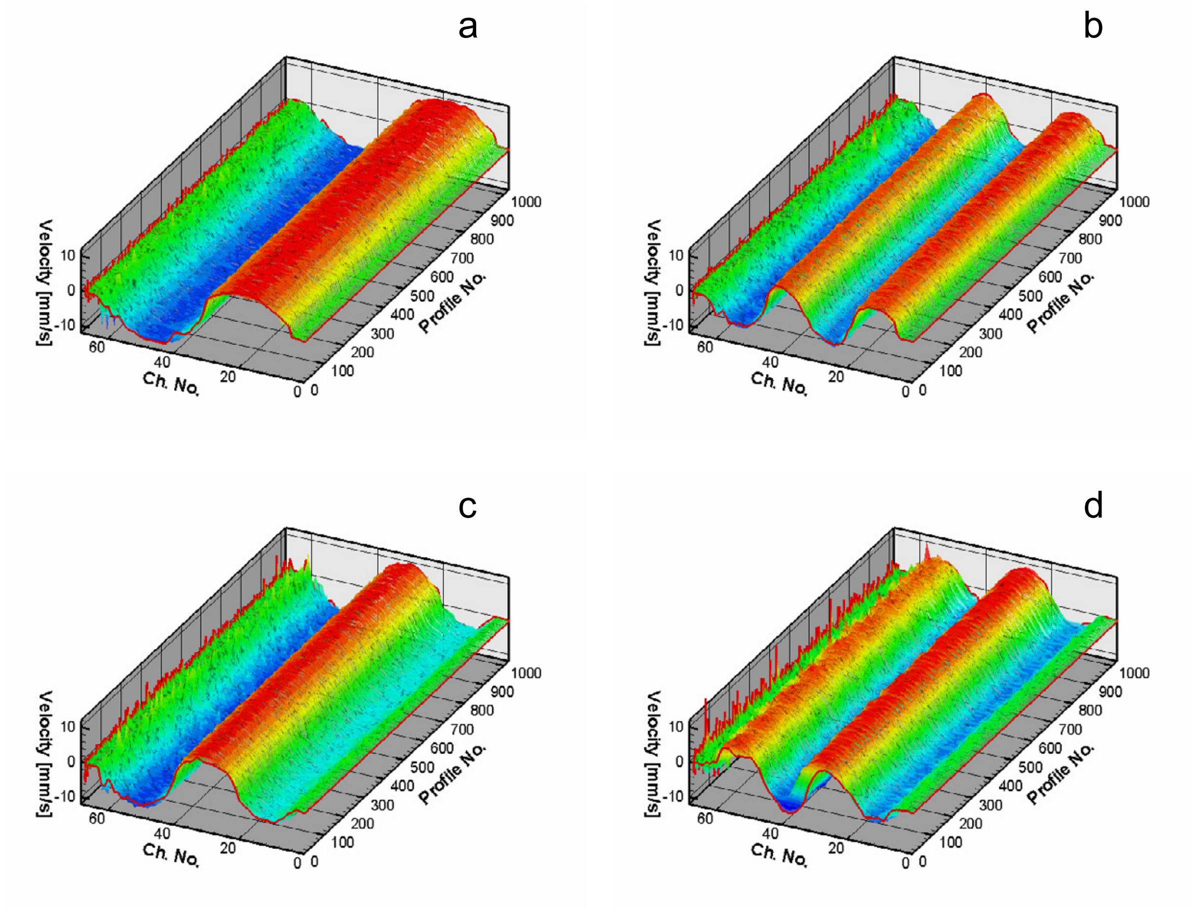

Figure 6. Spatio-temporal velocity distribution (*Re*=380, B_0=0); a. Normal 2cell mode, b. Normal 4cell mode, c. Anomalous 3cell mode, d. Anomalous 4cell mode

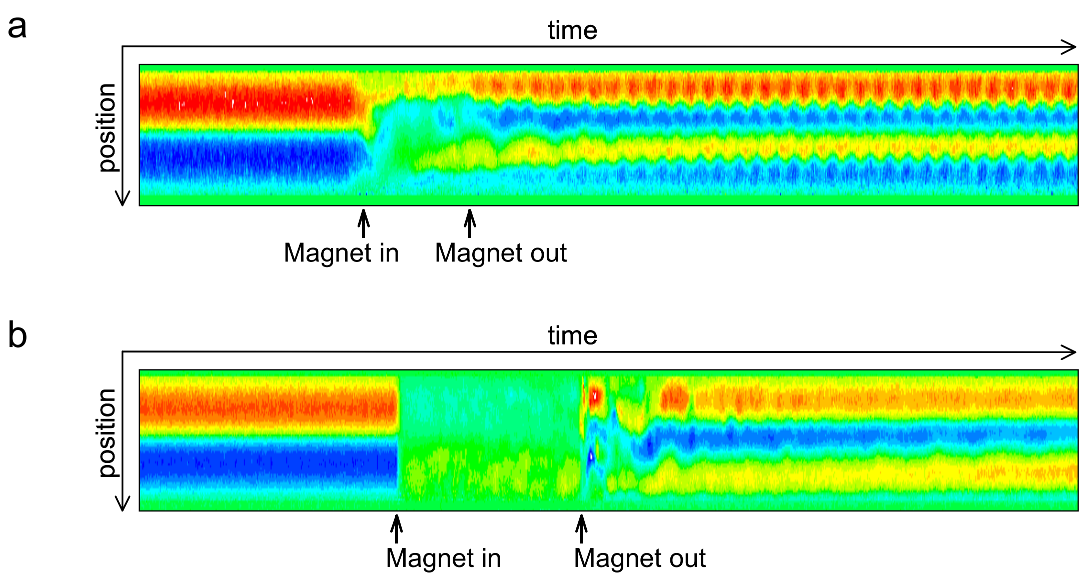

Figure 7. Velocity fields of transient change; a. from Normal 2cell mode to Normal 4cell mode (*Re*=370), b. from Normal 2cell mode to Anomalous 3cell mode (*Re*=430),

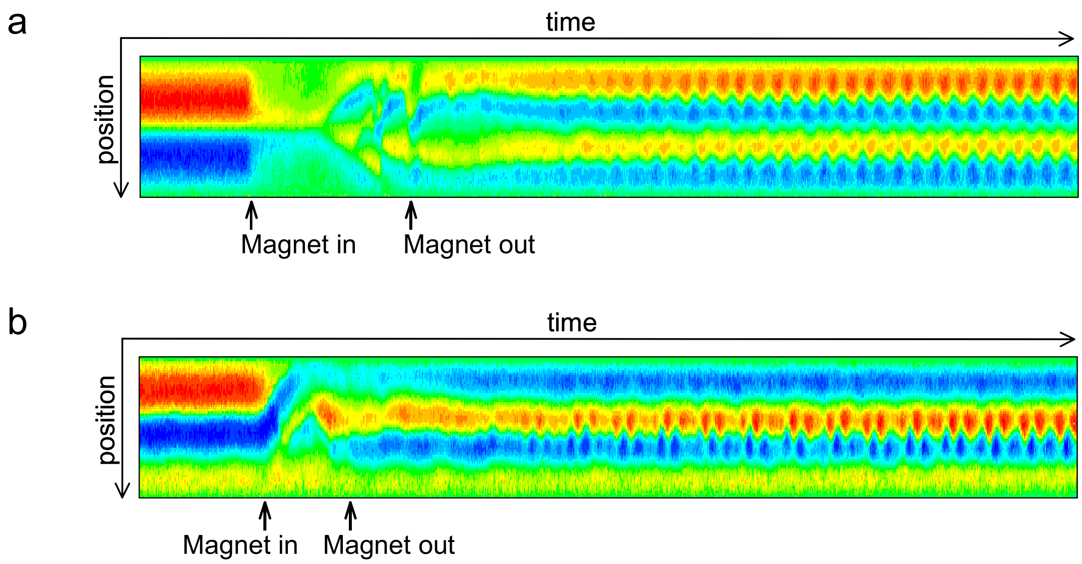

Figure 8. Velocity fields of transient change by applying local magnetic field; a. from Normal 2cell mode to Normal 4cell mode (*Re*=390), b. from Anomalous 3cell mode to Anomalous 4cell mode (*Re*=390)

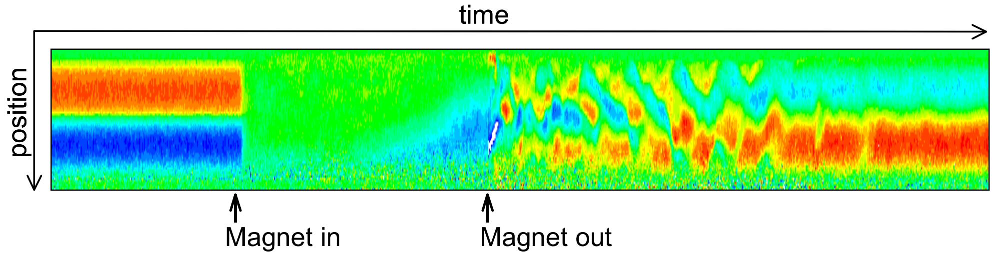

Figure 9. Velocity fields of transient change from Normal 2cell mode to Anomalous 2cell mode (*Re*=390)

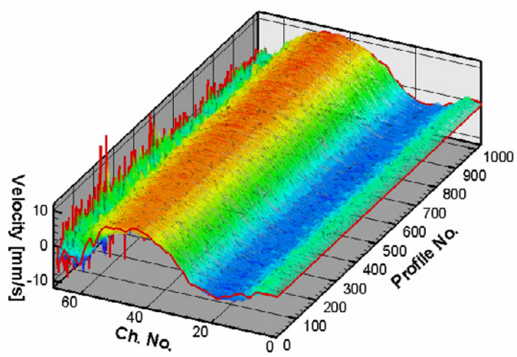

Figure 10. Anomalous 2cell mode

Figure 8a, 8b show the mode bifurcation by applying local magnetic field using the small magnet to the center of axial direction. In Figure 8a, when the magnet is applied to the middle of two vortices, additional vortices are formed between these vortices. In Figure 8b,applying the magnetic field to the middle cell of Anomalous 3cell mode, the vortex, which exists at the center, moves to the bottom of vessel and then two cells are formed there.

Furthermore in Figure 9, Normal 2cell mode bifurcates to the opposite flow by applying the magnetic field of the large magnet, because the color plot is inverted before and after applying magnetic field. It shows that the cell mode has the anomalous cells, so it can call Anomalous 2cell mode. It can understand clearly the difference of vortex structures by comparing Figure 10 with Figure 6a.

4. Concluding remarks

The Taylor-Couette vortex flow with small aspect ratio of a magnetic fluid has been investigated using the ultrasonic velocity profile (UVP) method. From the experimental results on the Taylor-Couette flow with aspect ratio of 3 in a magnetic fluid under the no external field, four types of flow modes have been understood from instantaneous velocity profiles. Influence of an applied magnetic field on the flow has been carried out and we found that the possibility of mode bifurcation control and discovery of new cell mode using magnetic field.

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