Characteristic Velocity Distribution of Rectangular Duct Flow of a Magnetic Fluid under Magnetic Field

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Velocity distribution of rectangular duct flow of a magnetic fluid was measured using Ultrasonic Velocity Profiling (UVP) method and influence of magnetic field on the velocity distribution was investigated. Velocity profile measurements have been performed in both laminar flow and turbulent flow and we paid attention to the effects of external magnetic field intensity ranging from 0 mT to 700 mT. As a result of the measurements, characteristic velocity distribution was obtained. In the case of laminar flow, when the magnetic field is applied to this magnetic fluid flow, the flow velocity at the center of the rectangular duct decreases and the velocity gradient in the near-wall region increases. On the contrary, in the case of turbulent flow, not only velocity gradient but also flow velocity near the center of the duct increases with applying magnetic field. This fact indicates that the characteristic anisotropy exist in the velocity distribution related to the magnetic field direction.

Keywords: Magnetic fluid, Rectangular duct flow, UVP, Uniform magnetic field.

1 INTRODUCTION

After development of the UVP method [1], measurement of velocity distribution in many kinds of opaque fluid could be realized. In this study, we focused on the magnetic fluid flow. Magnetic fluid is a stable colloidal dispersion of rather small surfactant-coated magnetic particles in a liquid carrier, such as water or kerosene [2]. These particles are about 10 nm in size and have magnetic single domain structure. Magnetic fluid can be treated as a Newtonian fluid under no magnetic field. However, when magnetic field is applied to magnetic fluid, several interesting flow behavior, which are not seen in a Newtonian fluid, can be observed because of its strong magnetism.

Because magnetic fluid has very unique characteristics under magnetic fluid, magnetic fluid is applied to many industrial technologies [3]. In addition, in order to better understand these characteristic properties, the internal velocity field is one of the very important information. However, in spite of the importance of the measurement of the internal velocity field, it is very difficult to measure the velocity distribution of a magnetic fluid. Because magnetic fluid is opaque and a kind of a solid-liquid two-phase flow, the optical methods such as LDV (Laser Doppler Velocimetry) or PIV (Particle Image Velocimetry), and the electrical method such as hot-wire anemometer can not apply to measure the velocity field in magnetic fluid flow. As mentioned above, the UVP method realized the measurement of the velocity field of magnetic fluid flow.

There are a few studies on the velocity distribution of a magnetic fluid flow by the UVP method. Kikura et al. [4] measured the velocity distribution of the Taylor vortex flow of a magnetic fluid and discussed the influence of non-uniform magnetic field. They reported that when the magnetic field is applied the velocity magnitude decreases, and wavelength of Taylor vortex flow also decreases with increasing magnetic field intensity. In our previous study [5], we apply the UVP method to the oscillating pipe flow of a magnetic fluid. As a result of this measurement, the Annular effect, which is the characteristic reversed flow phenomenon in the center region of the pipe in the oscillating flow of the Newtonian fluid, can be observed under no magnetic field. In contrast, when the magnetic field is applied to the oscillating pipe flow of magnetic fluid, this Annular effect disappears. Thus, these experimental studies have shown the efficiency of the UVP method for velocity profile measurement of magnetic fluid.

In our previous study [6], we investigated the forced convective heat transfer in the rectangular duct flow of a magnetic fluid in a laminar flow. The result showed the heat transfer was enhanced locally in the region in which the magnetic field existed. In order to better understand the reason of this heat transfer enhancement, the internal velocity fields should provide useful information. Therefore, in this study, we measured the velocity distribution of the rectangular duct flow of a magnetic fluid. Experiments were performed in both laminar magnetic fluid flow and turbulent magnetic fluid flow. The magnetic field intensity can be varied from 0 mT to 700 mT. On the basis of the experimental results, the influence of magnetic field on the velocity distribution was discussed.

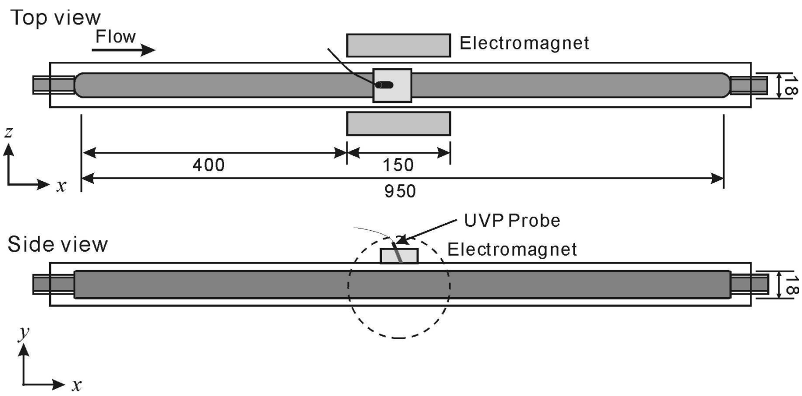

Figure 1: Detailed structure of the rectangular duct.

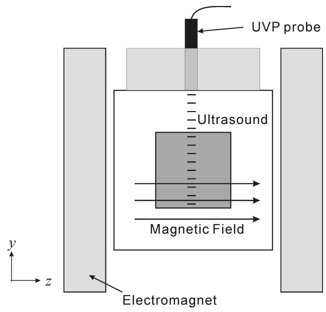

Figure 2: Cross-section of the duct.

2 EXPERIMENT

2.1 Experimental apparatus

Figures 1 and 2 showed the detailed structure of the rectangular duct and the cross-section of this duct at the center position. Experiment was performed with a closed circuit loop with this rectangular duct as a test section. This rectangular duct was made of a transparent acrylic resin, having 18 mm × 18 mm in cross-section and 950 mm in length. The hydraulic diameter D_h of this duct is 18 mm. We defined the Cartesian coordinates as shown in Figs. 1 and 2 (i.e. x: Streamwise direction, y: Direction of normal to the bottom wall, z: Spanwise direction). A thermocouple was set at the inlet of this duct. Therefore, we could measure the inlet temperature of the flow liquid T_{in}. A storage tank on the flow loop was equipped with a heater and a cooler to keep T_{in} at a constant level. An electromagnet was located at the center of the test section. This electromagnet could apply a uniform magnetic field to the magnetic fluid flow and the magnetic field could be varied from 0 mT to 700 mT. In this experiment, the Reynolds number based on the bulk mean velocity and hydraulic diameter was set to 960 (laminar magnetic fluid flow) and 2830 (turbulent magnetic fluid flow).

UVP probe was set on the center of the rectangular duct and at the position where magnetic field is applied to the magnetic fluid. Therefore, we can measure the velocity distribution in the x-y plane at the center of the duct. The UVP probe was fixed on the outer wall of the duct with an angle of 14°. The UVP monitor is XW-PSi model manufactured by Met-Flow SA. In order to obtain reflected echo signal, we added the polymethylmethacrylate particles (MBX-100 produced by Sekisui Plastics Co., Ltd.) as tracer particles. These particles have 115 μm in mean diameter.

2.2 Magnetic fluid

We used a water-based magnetic fluid named W-40 produced by Taiho Industries Co., Ltd. as the test magnetic fluid. W-40 was 40 % weight concentration of fine magnetite particles (Fe_3O_4) in water. However, because W-40 is too dense for this experiment, we diluted this magnetic fluid to 70 volume % with water as a test fluid. The density and viscosity of this test magnetic fluid were 1.301 kg/m^3 and 8.0 mPa·s, respectively.

2.3 Sound velocity in magnetic fluid

When we measure the velocity profile by UVP method, the sound velocity in the test fluid is needed for the detection of velocity profile information, such as the position from where the ultrasound is reflected and instantaneous velocity at each position. Therefore, we need to measure the sound velocity in a magnetic fluid before the velocity profile measurement by UVP method. Moreover, it is necessary to investigate the influence of magnetic field on the sound velocity in magnetic fluid.

In our previous study [7], we constructed the experimental apparatus for precise measurement of the sound velocity in a magnetic fluid under magnetic field. Details of the measurement technique can be found in Motozawa et al. [7]. Then, we measured the sound velocity in magnetic fluid and investigated the influence of magnetic field on the sound velocity in magnetic fluid. The results showed when a magnetic field is applied to a magnetic fluid, the sound velocity slightly changes with magnetic field intensity and the length of time the magnetic field is applied to magnetic fluid. Regarding magnetic fluid, the inner particles coagulate and form a chain-like cluster under a magnetic field. This change of the sound velocity in magnetic fluid seems to be caused by chain-like cluster formations. However, because the change in the sound velocity is rather small (less than 0.1 % in the case of test magnetic fluid of this study), this change does not influence UVP measurements. The sound velocity in the test magnetic fluid was c = 1429 m/s.

3 RESULTS AND DISCUSSION

3.1 Laminar flow

Figure 3 shows the velocity distribution of a rectangular duct flow of a magnetic fluid with and

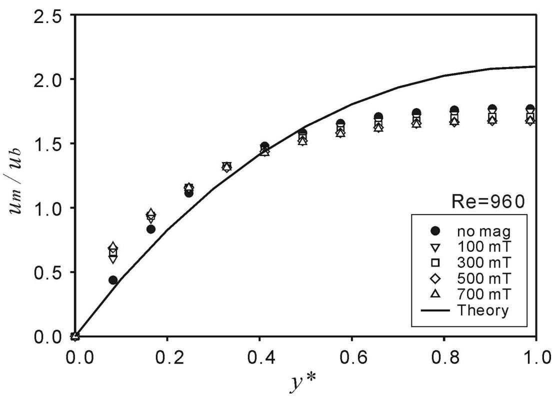

Figure 3: Influence of magnetic field on velocity distribution of laminar magnetic fluid flow (Re = 960).

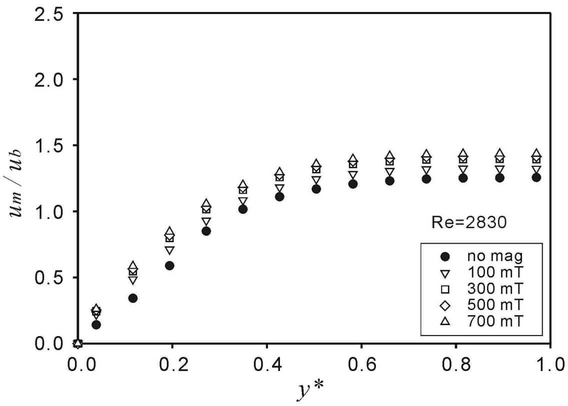

Figure 4: Influence of magnetic field on velocity distribution of turbulent magnetic fluid flow (Re = 2830).

without magnetic field at Re = 960 (Laminar flow). In this figure, the closed circle plots and solid line indicate the velocity distribution of the magnetic fluid flow under no magnetic field, and Newtonian fluid calculated by the theory, respectively. The horizontal axis is the distance from the bottom wall normalized by the half of the duct and the vertical axis is the mean velocity u_m normalized by the bulk mean velocity u_b.

Though magnetic fluid can be treated as a Newtonian fluid under no magnetic field, the configuration of the measured velocity distribution is different from that of the Newtonian fluid. This is due to a problem in the experimental system. In this experiment, we measured the velocity distribution at the developing region. Therefore, the magnetic fluid flow was not developed enough and the velocity distribution of magnetic fluid under no magnetic field was different from that of the Newtonian fluid.

On the other hand, when the magnetic field is applied to magnetic fluid, this figure indicates that the mean velocity in the center region of the duct decreases and the velocity gradient increases near the wall. The decrement of the mean velocity and increment of velocity gradient becomes larger with increasing magnetic field.

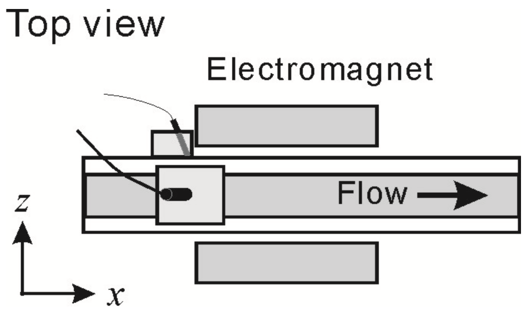

Figure 5: Measurement of velocity distribution in both x-y plane and x-z plane at entrance region of the magnetic field.

Generally, when the magnetic field is applied to magnetic fluid, the apparent viscosity increases with increasing magnetic field. Therefore, because the apparent viscosity suddenly increases in the region where the magnetic field exists, it seems that the mean velocity near the center of the duct decreases.

3.2 Turbulent flow

In contrast, Fig. 4 shows the influence of the magnetic field on the velocity distribution of the turbulent magnetic fluid flow at Re = 2430 (Turbulent flow). In the case of the turbulent flow, characteristic velocity distribution was obtained. When the magnetic field is applied to a magnetic fluid, not only the velocity gradient near the wall but also the mean velocity near the center of the duct increases with increasing magnetic field intensity. In this study, experiments carried out under a constant flow rate under magnetic field. Therefore, this fact indicates that the velocity distribution in the x-y plane is different from that in the x-z plane and characteristic anisotropy of the velocity distribution exists related to the magnetic field direction. In addition, although the result is not shown in this paper, the streamwise velocity fluctuation was greatly suppressed with increasing magnetic field intensity.

3.3 Measurement at entrance of magnetic field

It is impossible to measure the velocity distribution in the x-z plane at the same position because of the existence of the iron-core of the electromagnet as shown in Fig. 1. Hence, we try to measure the velocity distribution in the x-y plane and the x-z plane at the entrance region of the magnetic field. Fig.5 shows the position of the UVP probes for this measurement. UVP probes were set just before the iron-core of the electromagnet and ultrasound from the UVP probe should propagate the magnetic fluid flow in the region where the magnetic field exists.

Figures 6 and 7 shows the influence of the magnetic field on the velocity distribution in the x-y plane and the x-z plane respectively at Re = 2430 (Turbulent

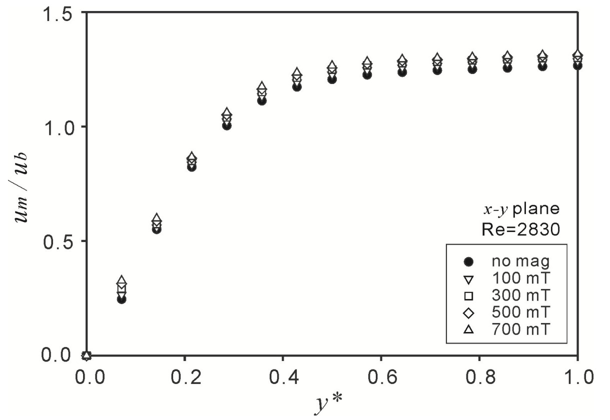

Figure 6: Influence of magnetic field on velocity distribution in x-y plane at Re = 2830 (Turbulent magnetic fluid flow).

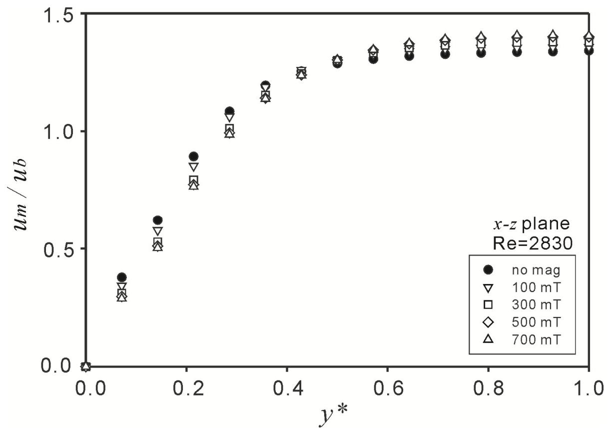

Figure 7: Influence of magnetic field on velocity distribution in x-z plane at Re = 2830 (Turbulent magnetic fluid flow).

flow). Fig. 6 indicates that although the change in the velocity distribution is smaller comparing with Fig. 4, same tendency could be observed. On the other hand, regarding the velocity distribution in the x-z plane, the mean velocity near the side wall decreases but the mean velocity near the center of the duct increases with applying magnetic field as shown in Fig. 7. Therefore, characteristic anisotropy of the velocity distribution evidently exists. It seems that this anisotropy of the velocity distribution is caused by the anisotropy of the shear stress related to the magnetic field direction.

5 CONCLUSION

Velocity distribution of the rectangular duct flow of a magnetic fluid was measured by using UVP method and the influence of the magnetic field on the velocity distribution was investigated. We performed the experiments in both laminar flow and turbulent flow of magnetic fluid.

In the case of laminar flow, when the magnetic field is applied to magnetic fluid flow, the mean velocity at the center of the duct decreases with increasing magnetic field intensity and velocity gradient slightly increases near the wall.

On the contrary, in the case of turbulent flow, when the magnetic field is applied to magnetic fluid, the mean velocity near the center of the duct slightly increases with increasing magnetic field intensity. This fact indicates that characteristic anisotropy exists in the velocity distribution related with the magnetic field direction. We confirmed this anisotropy experimentally by the measurement at the entrance region of the magnetic field.

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