INFLUENCE OF CHAIN-LIKE CLUSTERS ON OSCILLATING PIPE FLOW OF A MAGNETIC FLUID

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ABSTRACT

The Ultrasonic Velocity Profile (UVP) method is used to sense velocity information using ultrasonic waves, and, as such, is very suitable for measuring the velocity profile of opaque fluids. In this experiment, the UVP method is used to investigate oscillating pipe flow of a magnetic fluid subject to a magnetic fluid. The test liquid is a diluted water-based magnetic fluid and the magnetic field is applied by two permanent magnets. When the magnetic field is applied for some period before measurement, interesting velocity profiles are obtained and are suggested to be caused by the growth of chain-like clusters in the magnetic fluid. The influence of the amount of time of pre-applying the magnetic field and magnetic field intensity on flow behaviors are discussed. The apparent flow rate is introduced to aid in evaluating the correlation between the velocity profile and the growth of chain-like clusters. It is found that the rate of change of the apparent flow rate increases with both magnetic field the pre-application time and magnetic field intensity.

Keywords: Magnetic Fluid, Oscillating Pipe Flow, UVP, Clusters

INTRODUCTION

A magnetic fluid is a stable colloidal suspension of uniformly dispersed ferromagnetic particles in solvents such as water and kerosene. The ferromagnetic particles remain suspended because of their Brownian motion. When a magnetic field is applied to a magnetic fluid, several interesting phenomena, which do not occur in a Newtonian fluid, are observed because of the combination of strong magnetism and liquidity. Several unusual flow behaviors of a magnetic fluid have been observed and they are considered to be caused by the formation of chain-like clusters. To date there have been few experimental studies directed to clarifying the influence of these clusters on magnetic fluid flow behavior. In order to use magnetic fluids in fluid mechanical systems, for example as a magnetic fluid damper, a magnetic fluid actuator, etc., a more-detailed measurement of internal velocity profiles is necessary. It is expected that further applications will be developed by further examining these phenomena in a magnetic fluid.

The Ultrasonic Velocity Profile (UVP) method, which was been developed by Takeda[1], is a method of measuring a velocity profile on a line with respect to the velocity component along an ultrasonic beam. This technique has two main advantages in comparison with ordinal methods like LDV or PIV. First, it can be applied to opaque fluids such as liquid metals, chocolate in food processing, and the like, and second, flow mapping is practical because a line measurement is used. Takeda has studied a mercury flow[2] and has developed this method systematically[3]. Kikura, et al.[4] measured velocity profile of the Taylor vortex flow of a magnetic fluid using the UVP method. Sawada, et al.[5] examined horizontal velocity profiles of a magnetic fluid in a rectangular container which was laterally vibrated. These experimental studies have shown the efficiency of the UVP method for velocity profile measurement of opaque fluids, including magnetic fluid.

In the present paper, we examine the characteristics of the velocity profile of oscillating pipe flow of a magnetic fluid subject to a magnetic field. In particular, the effect of chain-like cluster formation in a magnetic fluid on the velocity profile is experimentally investigated using the UVP method.

EXPERIMENT

Figure 1 shows the experimental apparatus. The test section is an acrylic pipe having inner diameter 30 mm, outer diameter 40 mm and length 3000 mm. One end of the pipe is connected to a tank (300 mm × 300 mm × 300 mm), which is at 540 mm height from the center of the pipe. The water pressure is controlled to fluctuate less than 1 % . The other end of the pipe is provided with a piston which is driven by a crank system to cause oscillating flow. The piston frequency is controlled by an inverter. A water-based magnetic fluid W-40 is used as a test liquid. The ratio of the volume of the magnetic fluid to water is 7 : 3. The kinematic viscosity is $\nu = 4.35$ mm^2/s and the sound velocity in the magnetic fluid is c = 1420 m/s at 20 °C.

The UVP monitor is a model XW-PSi manufactured by Met-Flow SA. The basic ulutrasound frequency is 4MHz. In order to obtain an echo, porous SiO_2 particles with a mean diamiter of 0.9 μm (MSF-10M, Liquidgas Co., Ltd.) were added as reflectors. A transducer is fixed on the outer wall of the pipe at an angle of 14° and a measurement line from the transducer is parallel to two magnets (described in Fig.2). The diameter of the transducer is 5 mm, and the measuring volume has a thin-disc shape, ϕ 5 mm × 0.71 mm.

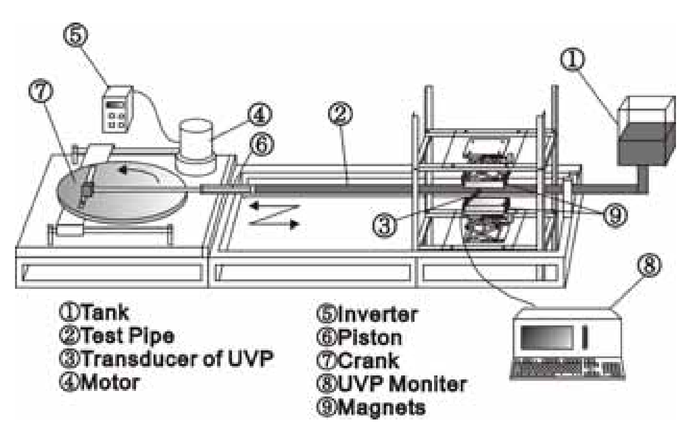


Fig.1 Experimental apparatus

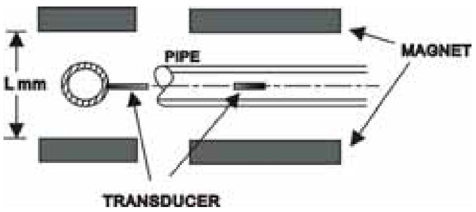


Fig.2 Close-up of permanent magnets

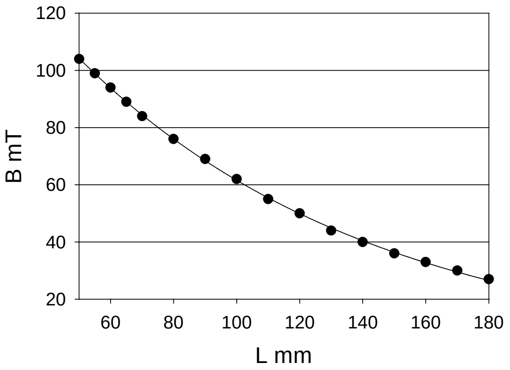


Fig.3 Magnetic flux density vs. interval between magnets

Two permanent magnets (150 mm × 100 mm × 25 mm) are placed on opposite sides of the pipe as shown in Fig. 2. The magnetic field intensity in the pipe can be controlled by the interval between the two magnets. The relation between magnetic flux density and interval L of the magnets is shown in Fig. 3. Here B is the magnitic flux density at the center of the pipe.

The piston frequency is kept at 0.053 Hz and Wormersley number $W = 4.2$ which is defined by

$$W = R\sqrt{\frac{\omega}{\nu}} \tag{1}$$

where R is radius of the pipe and ω is angelar velocity of the piston. The Wormersley number is an important dimensionless parameter for an oscillating flow and indicates the ratio of unsteady inertia and viscosity forces.

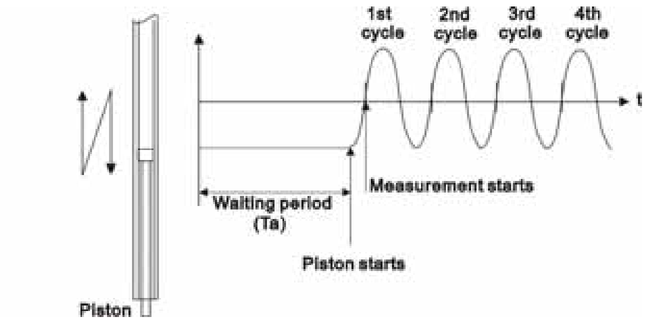


Fig.4 Measurement time chart

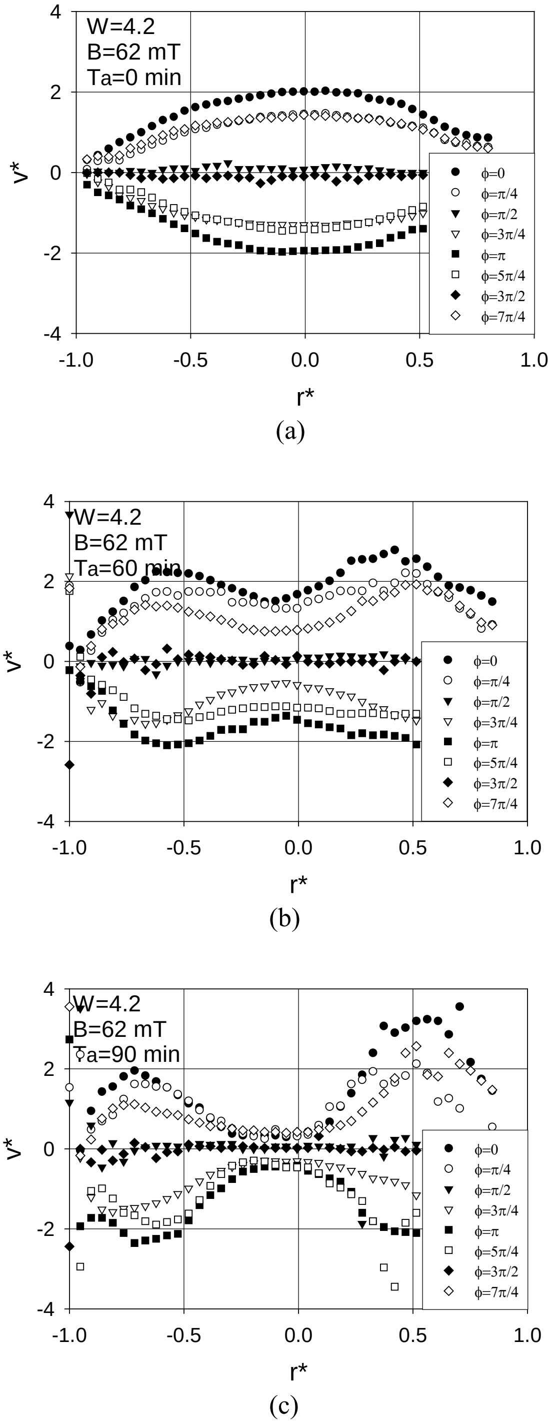
RESULTS AND DISCUSSION

In the experiments, a magnetic field is applied prior to the measurement of velocity profiles as shown in Fig. 4. Since the magnetic field is applied parallel to the pipe for *Ta* minutes before measurement begins, chain-like clusters have an opportunity to form in the direction of the magnetic field lines. After *Ta* minutes an oscillating flow is generated by the piston, and changes in velocity profiles are observed. The observed changes were quite remarkable and, can not be explained by an increase of the apparent viscosity owing to the magnetic field.

Figure 5 shows velocity profiles for different times of pre-applying the magnetic field: $Ta = 0$ min, 45 min, 90 min at the same magnetic flux density $B = 62$ mT. Here $v*$ and $r*$ are defined by

$$v^* = \frac{v}{r_k\omega}, \qquad r^* = \frac{r}{R} \tag{2}$$

where r_k is the radius of the crank and $r_k = 100$ mm. ϕ corresponds to the phase difference from the middle point of top and bottom dead points. $r^* = -1$ indicates the side wall where the transducer is fixed and $r^* = 1$ indicates the opposite side wall. Figure 6 shows changes of the velocity profiles for various *Ta* at each phase. From Figs. 5 and 6, it appears that velocities at each phase approach zero near the center of the pipe with an increase of *Ta*. We also found that after several cycles, the singular velocity profiles shown in Fig. 5 (b)-(c) become the ordinary velocity profile (of Fig .5 (a)). Figure 7 shows the process of returning to a stable velocity profile for $B = 62$ mT, $Ta = 180$ min and $\phi = \pi$. From these figures, it is suggested that the size of the chain-like clusters grows gradually larger near the pipe wall and spreads in a cross-section of the pipe. This process is illustrated in Fig. 8. If chain-like clusters grow toward the center area of the pipe, the magnetic fluid may be prevented from flowing by the chain-like clusters. These chain-like clusters may then collapse gradually after the beginning of the oscillating flow.



(a)

(b)

(c)

Fig.5 Velocity profiles with pre-applied magnetic field

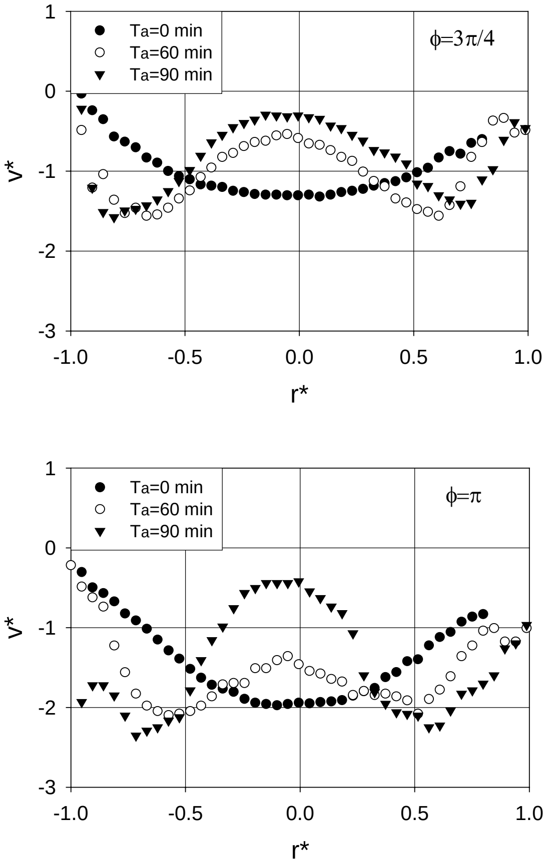


Fig.6 Velocity profiles at two phases

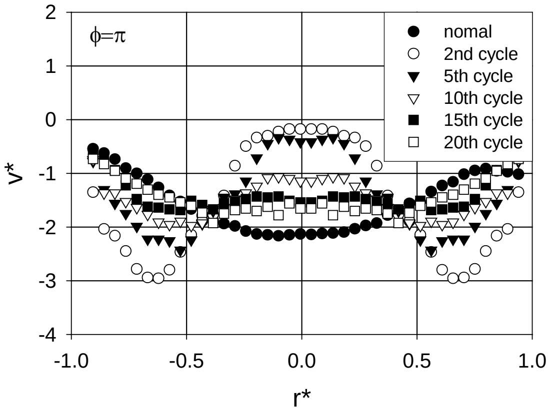


Fig.7 Process of returning to stable velocity profile (W = 4.2, B = 62 mT, Ta = 180 min)

In order to examine the influence of the growth of chain-like clusters on the change of velocity profiles, we introduce the chage rate of the apparent flow rate (ΔQ) as follows:

$$Q_{\phi}^{*} = 2\int_{0}^{1} \left| v_{\phi}^{*} \right| dr^{*} \tag{3}$$

$$Q^{*} = (Q_{0}^{*} + Q_{\pi/4}^{*} + Q_{3\pi/4}^{*} + Q_{\pi}^{*} + Q_{5\pi/4}^{*} + Q_{7\pi/4}^{*}) \tag{4}$$

$$\Delta Q^{*} = (Q^{*}_{B\,\mathrm{mT},\,Ta\,\mathrm{min}} - Q^{*}_{0\,\mathrm{mT},\,0\,\mathrm{min}}) / Q^{*}_{0\,\mathrm{mT},\,0\,\mathrm{min}} \tag{5}$$

Here Q_{ϕ}^{*} is an apparent flow rate at each phase, which is obtained by integrating the absolute velocity along the measuring line, i.e. the horizontal center line in Fig. 8. Q^{*} is the sum of apparent flow rates. When the magnetic field is applied, Q^{*} becomes larger in accordance with the growth of chain-like clusters. ΔQ^{*} is the change rate of Q^{*} when a magnetic field is pre-applied.

Figures 9 and 10 show the relationsip between ΔQ^{*} and Ta, and ΔQ^{*} and B, respectively. From Fig. 9, it can be seen that when Ta increases, ΔQ^{*} also increases in a linear fashion. Further, ΔQ^{*} is larger under strong magnetic fields than under

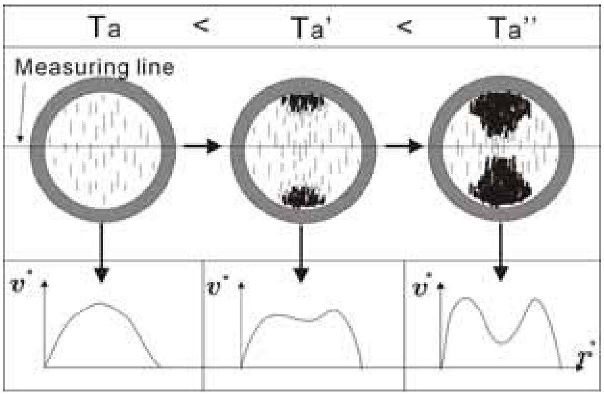


Fig. 8 Growth of the chain-like clusters

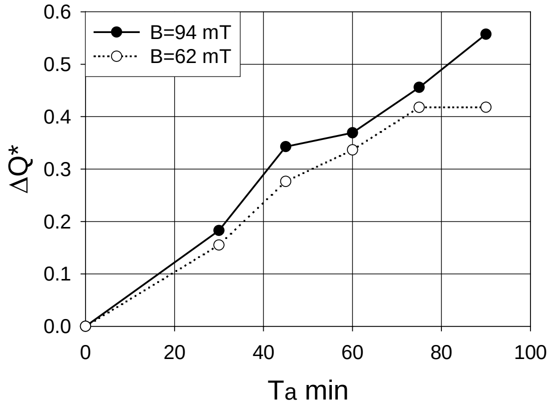


Fig. 9 Increase in change rate of the apparent flow rate with *Ta*

weak magnetic fields. From Fig. 10, it can be seen that, when the magnetic field intensity increases, *ΔQ** has a tends to grow larger. Further, *ΔQ** is larger for longer *Ta*. It is suggested that an increase of *ΔQ** has some correlation with the growth of the chain-like clusters, and the growth of the chain-like clusters depends on the amount of the times of pre-applying the magnetic field and the magnetic field intensity.

CONCLUDING REMARKS

Magnetic fluids show more complicated behaviors than ordinary fluids because of the formation of chain-like clusters when the magnetic fluid is subject to a magnetic field. We observed a unique phenomenon of the velocity profile of an oscillating pipe flow subject to pre-application of a magnetic field that might be caused by the chain-like clusters. This lead to a study of the growth of the chain-like clusters by using the velocity profile measured by the UVP method. As a results, we observed that individual velocity profiles had some correlation with the amount of time the magnetic field was pre-applied before taking measurements. These individual velocity profiles appeared to be dependent on the magnetic field intensity as well as the amount of time pre-applying the magnetic field. The apparent flow rate was introduced to evaluate a correlation between changes in the velocity profile and the growth of chain-like clusters. It was clarified that the rate of change of the apparent flow rate increases with increases in the amount of time pre-applying the magnetic field and with the magnetic field intensity.

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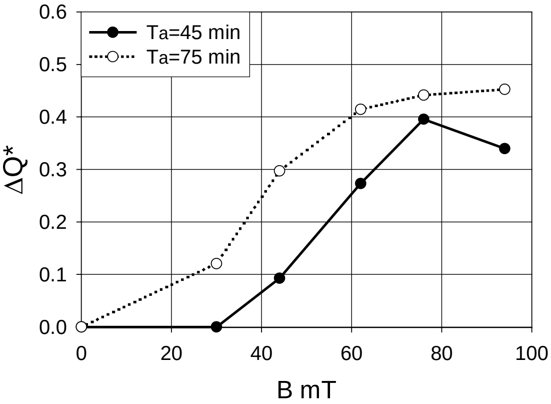

Fig. 10 Increase in change rate of the apparent flow rate with *B*

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