Dynamic Response of Magneto-Rheological Fluid Channel Flow with Fluid-Wall Interactions

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Abstract. The objective of this study is to provide the fundamental data for the novel application of MR fluid plugging (MRF plugging) to a medical or safety devices for flow control. Experimental evaluation on dynamic response of MRF plugging in pressure mode was conducted to clarify the effect of piston velocity, magnetic flux intensity and wall surface roughness to its plugging performance. MRF plugging performance has been discussed through the evaluation of the endurance pressure of MRF plugging and flow rate. It is shown that the endurance pressure of MRF plugging is increased by the piston velocity, the magnetic flux intensity, and the adoption of wall surface structure. Furthermore, the endurance pressure is decreased for the circular and elastic tube, assuming a biological tube.

1. Introduction
MR fluid plugging (MRF plugging) performance by MRF column is recently expected to be one of the most promising applications to medical or safety devices, such as blood flow control, steam shut-down valve or fuel supply [1,2]. Researches of MR fluid have been actively conducted on the evaluation of rheological properties and its industrial applications, due to its attractive characteristics of controllable yield stress and significant viscous force under even small applied magnetic field. Furthermore, the evaluation of flow control ability has been actively investigated in these days, considering the channel permeability or wall configurations [3-6].

In this study, the effect of surface roughness on rheological properties of MR fluid was experimentally clarified. Then, dynamic response of MRF plugging in pressure mode with fluid-wall interactions was investigated, considering the effects of magnetic flux intensity, piston velocity, the channel configurations, its surface structure and tube elasticity. The final objective of this study is to provide the fundamental data for the novel application of MR plugging performance to a medical or safety devices for flow control.

2. Experimental Procedure and Evaluation
In this study, MRF-132DG manufactured by LORD Corporation is used as a test sample.

(1) MR fluid is filled inside the piston cylinder and horizontal flow channel shown in Fig.1. A MR channel is made of acrylics with rectangular cross section of 10 mm × 10 mm. After forming MR fluid column in a channel by applying magnetic field with electromagnet,
piston is driven at the constant head velocity controlled by a stepping motor to produce the pressure flow mode against the MRF plugging.

(2) Pressures inside the channel are measured by transducer piezoresistive pressure sensors.

(3) Exit of flow channel is opened to atmospheric pressure. The mass of exhaust MR fluid is measured by electrical scale for the evaluation of flow rate.

(4) The same procedures are taken for the different channels: the rectangular channel with the wall surface structure (distorted lattice 1 mm-depth-groove pattern at the magnetic pole side of the internal wall), a semi-rigid circular tube ($d_i = 12$ mm, Young’s modulus of 6.7 kPa), an elastic circular tube ($d_i = 12$ mm, Young’s modulus of 2.5 kPa).

3. Results and Discussion

3.1. Effect of surface roughness on rheological properties in rotating shear mode

Figure 2 shows shear stress measured by cone-plate rheometer with smooth cone ($R_z = 0.5$) and the rough cone ($R_z = 4.5$) in rotating shear mode at various magnetic field intensities. The static yield stress is higher for the rough cone especially under effective magnetic field intensity larger than 2.64 kA/m due to an anchoring effect even in rotating shear mode.

3.2. Effect of piston speed on MRF plugging performance in pressure mode

Figure 3 shows the time evolutions of channel pressures $p_{MR}$, piston displacement $d_{piston}$ and the exhausted flow rate $Q_{out}$ at various piston head speeds under the applied magnetic flux density of 800 G. Piston starts at $t = 0$, after 3 minutes in resting state under a magnetic field for MR column formation. $p_u$, $p_{d1}$, and $p_{d2}$ represent pressures at upstream and downstream of MR column, respectively, as shown in Fig.1. For the references, Fig.3(a) also includes $p_u$ without magnetic field. Under magnetic field, $p_u$ increases without the exhausted flow rate as the piston moves. This shows the MR fluid column ‘plugs’ the flow. To evaluate its plugging performance, its endurance pressure $P_{plug}$ is defined as $p_u$ at the moment that MR fluid starts to flow detected by $Q_{out}$. With increasing piston head velocity, which corresponds to the given work per unit volume of the MR fluid column, the endurance pressure and flow rate increase. Furthermore, their time gradients also get steeper and steeper. This difference in the time gradient shows the time evolution of MRF plugging breakdown behavior. The increase in $P_{plug}$ is due to the robust resistance of cluster and a higher local concentration of magnetic particles at the upstream of MRF column with increasing piston speed.
3.3. Effect of wall roughness on MR fluid plugging performance in pressure mode

Figure 4 shows time evolutions of internal pressure, piston displacement and exhausted MR flow rate for smooth and rough surface channels under $B = 1200$ G. The increase of endurance pressure with the increase in applied magnetic field well corresponds to the increase of static yield stress in its rheological property[7]. Comparing with two endurance pressures in Fig.4, $p_{plug}$ for the rough surface channel is 1.5 times larger than that for the smooth one, although there is not much difference in the case of $B = 0$ G. The effect of wall roughness on the endurance pressure is clearly shown in Fig.5. Furthermore, the higher magnetic flux density, the more remarkable effect of surface roughness appears. Referring to the discontinuous pressure response and fluctuating flow rate behavior for the rough surface channel, the MR column seems to resist robustly and yield complexly. These can be due to a strong anchoring between clusters’ roots and wall roughness structure. The mechanics of this phenomenon in micro scale and macro scale will be further investigated in the future research.

3.4. Effects of cross section configurations and tube elasticity on MR fluid plugging in pressure mode

Figure 6 shows time evolutions of pressure and flow rate for semi-rigid and elastic circular tube. $p_u$ repeats increasing and decreasing, and $Q_{out}$ goes on-and-off intermittently for high elastic tube with the presence of air bubble content. In this case, $p_{plug}$ is defined as the average of local maximum $p_u$ for endurance pressure evaluation. By evaluating $p_{plug}$ in Fig. 7, it is shown that...
4. Conclusions
The effects of surface roughness on rheological properties and the effect of wall surface structure, channel cross section, and tube elasticity on the dynamic response of MRF plugging in pressure mode are made clear through the experiment analysis as the first step. The obtained results are summarized as follows:

(1) Static yield stress increases for cone with roughness in rotating shear mode.

(2) The endurance pressure of MRF plugging is increased by applied magnetic field intensity, piston velocity and the wall roughness.

(3) The endurance pressure of MRF plugging is decreased by the circular and elastic tube.

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6. References
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**Figure 6.** Time evolutions of internal pressure, piston displacement, and flow rate, in case of semi-rigid and elastic circular tube.

**Figure 7.** Effects of cross section configurations and tube elasticity on MRF endurance pressure.

...the endurance pressure decreases because of circular cross section and high elasticity, assuming a biological tube. The robust cluster region decreases for circular cross section, which leads to the decrease in endurance pressure. Furthermore, the endurance pressure can be decreased for high elasticity tube with its deformation during the cluster formation.