A Study on Flow Characteristics of ERF Between Two Parallel-Plate by Using PIV

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평형평판 간극사이에서 PIV를 이용한 ER유체의 유동특성에 관한연구

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Abstract

An experimental investigation was performed to study the characteristics of ER(Electro-Rheological) fluid flow in a horizontal rectangular tube with or without D.C voltage. To determine some characteristics of the ER flow, 2D PIV(Particle Image Velocimetry) technique is employed for velocity measurement. This research found the mean velocity distribution with 0kV/mm, 1.0kV/mm and 1.5kV/mm for Re = 0, 0.62, 1.29 and 2.26. When the strength of the electric field increased, the cluster of ERF are clearly strong along the test tube and the flow rate decreased. In this study, the rheology of ER fluid stagnating or flowing through a dispersion meter will be investigated by PIV method. And then the ER effect, which appears at the ER valves and their appliance will be visualized.

Key Words : Electro-Rheological Fluids, Cluster, Particle Image Velocimetry(PIV), ER Valve, Electric Field, Rectangular Tube, Rheology

1. Introduction

Recently, many studies have investigated the behavior of the ER fluid. It which depends on the rheology closely related to the intensity of the electric field. It can be applied to the robotic area because the response period is within several tens of msec. Therefore, addition to the studies[1~4] on the applications of ER fluid to new areas, the fundamental studies that confirm the mechanism related to the ER fluid flow characteristics have become important. But only few studies have investigated ER fluid flow conditions. It is very important to investigate the ER fluid flow conditions to improve the performances of the equipment and system that use ER fluid.

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One study on the flow conditions of the ER fluid, Wang, etc.[5] explained the flow characteristics of ER fluid with numerical analysis method. Tsukiji[6] calculated using fundamental equations, which assume that ER fluid behaves like a Bingham fluid. Park Myung Gwan, etc.[7] performed flow visualization experiments for ER fluid in the narrow space between electrodes. Jang Sung Cheol, etc.[8~10] carried out a fundamental study and visualization experiment ofthe ER fluid through a dispersion meter, and then a performance test using application apparatus such as ER valves and so on.

As mentioned above, the studies on flow visualization the cluster formation of ER fluid between short electrodes (10mm) and narrow clearances(1mm). But, because long electrodes of ER valves and similar equipment produce the ER effect and the ER particle sizes between electrodes are different, experimental investigation on the mechanism of electrical rheology is very important.

In this study, the rheology of ER fluid stagnating or flowing through a dispersion meter will be investigated by PIV method. And then the ER effect, which appears at the ER valves and their appliance will be visualized.

2. Flow characteristics of ER fluid

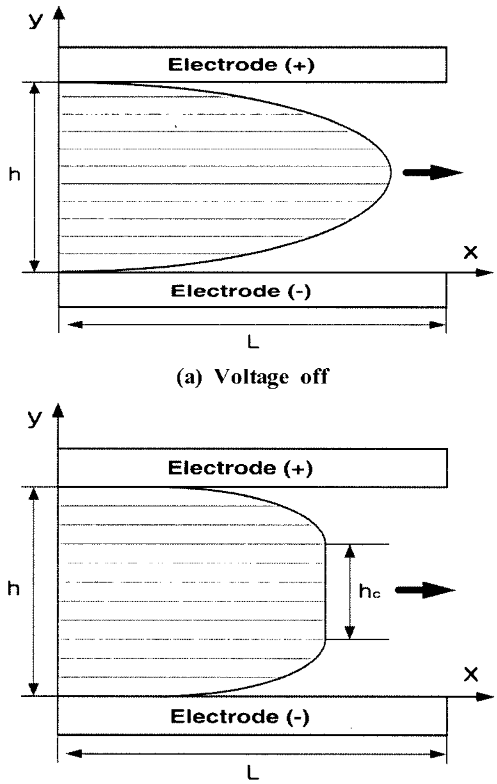
When the inertia force arisen from the fluid movement is applied to the ER fluid being charged by an electric field, there is a resistance force to ER fluid. When the coherent force of the ER fluid particles in the electric field is smaller than the inertia force due to ER fluid movement, ER fluid, starts to flow, and complicated changes near the flow initiation point. Although these phenomena there is no precise presentation cannot be precisely explained, generally they depend on the size, shape, and temperature of the ER fluid particles,; the type of insulation oil,; and the intensity of the electric field. The cluster shape depends on the change in flow velocity and the intensity of the electric field so that the shear force may be changed. If the form processes and behaviors of the cluster are investigated and can evaluated against the flow velocity and electric field intensity changes, the information can be utilized as the basic data of ER fluid.

Even though in case of no electric field ER fluid is acted as Newtonian fluid, but if formed the ER fluid particles form the clusters and show us the characteristics of Bingham fluid, which make a yield shear stresses increased. If ER fluid is regarded as Bingham fluid, the relationship between the shear stress and shear velocity ratio of ER fluid can be expressed as follows[3].

$$\tau = \tau_y(E) + \mu \frac{du}{dy} = \alpha E^{\beta} + \mu \frac{du}{dy} \qquad (1)$$

where $\tau_y(E)$ means the yield shear force under an electric field; μ is the fluid viscosity; $\frac{du}{dy}$ is the shear velocity ratio; E is the intensity of electric field; α, β are experimental values that depend on the weight fraction ratio, the viscosity of the insulation oil and so on.

Fig. 1 (a) and (b) show the flow characteristics with and without the electric field. With the electric field, the



(a) Voltage off

(b) Voltage on

Fig. 1 Flow of ER fluids in test tube

pressure drop is affected by the viscosity of the ER fluid and proportional to the flux between the test tubes. Therefore, the pressure drop can be defined by the as following equation.

$$\triangle P_{\mu} = \frac{12\mu LQ}{bh^3} \tag{2}$$

where b is the test tube width; h is the gap between the test tubes; L is the electrode length in the test tube; Q is the flux with no electric field. With no electric field, the ER fluid in the test tube has only viscosity, and therefore flow velocity at the electrodes is zero, and at the other zones a quadratic velocity profile shown in Fig. 1 (a). But with electric field, the pressure drop will be increased by the yield shear stress $\tau_y(E)$ of the ER fluid. Like Fig. 1 (b), it can be regarded as a plug movement of gap h_c between electrodes, and hence there will be additional pressure drop $\triangle P_{ER}$ due to $\tau_y(E)$. This additional pressure drop can be expressed as follows.

$$\triangle P_{ER} = \frac{2L\tau_y(E)}{h} \tag{3}$$

Here, Q_{ER} means the flux betweenthe test tube electrodes when the electric field is formed. Although the electric field is formed. Although the electric field is formed, if $\triangle P$ is less than $\triangle P_{ER}$, there is no flux. But, when the overall pressure drop $\triangle P$ is larger than the cluster resistance force, flux exists. Therefore, the overall pressure drop($\triangle P$) between the test tube electrodes can be defined as the sum of pressure drop due to the viscosity of the ER fluid and the yield shear stress change according to the electric field as follows.

3. Test Equipment and Method

Fig. 2 shows us a layout of the PIV system and test equipment, which were used to visualize the flow characteristics of ER fluid mixed with silicone oil and starch particles. They were designed and manufactured to be used for observing the ER fluid in the state of stagnation or flow. ER fluid was stored in a tank, and to prevent it from precipitating and maintain it with uniform compositions, the fluid was agitated with a agitator. ER fluid was designed

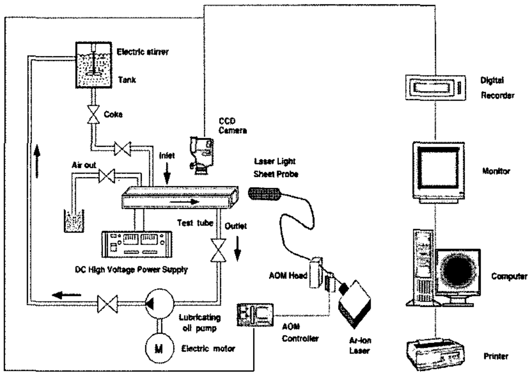


Fig. 2 Experimental apparatus and PIV system

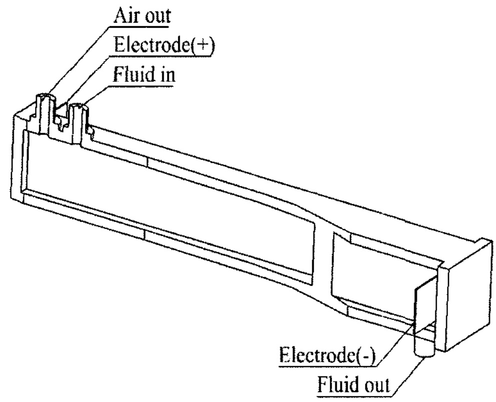


Fig. 3 Geometry or the test tube

to flow from the tank to the test tube by potential energy. Flux was controlled by the valve, which was installed upstream and downstream of the test tube. The ER fluid in test was the ER oil in the dispersion meter, which consisted of silicon oil of S company(ShinEtsu Silicone Korea Co.) and starch particles(180μm). The test tube was inclined at an angle of 15 degrees to prevent particles from precipitating. In this test, to build up a fully developed flow field in the X-direction, flow field length was placed as X/b=60, and the entrance was designed to minimize an entrance effect. CCD cameras were installed upstream and at the exit tube. The ER fluid flow could be visualized. The software used in this study was Thinks, which was developed by T Company. The Reynold number was calculated by the average flow speed in the test tube using ER fluid particles speed, the length of test tube, and the dynamic viscosity of the ER fluid.

Fig. 3 show the shape of test tube that was used for visualization of the flow characteristics of the ER fluid. The flow route consisted of a 13mm gap made by 2 electrodes, 240mm in length 25mm in width. To prevent fluid from vaporizing along the route of the test tube, an air vent was installed at the entrance. And the diameter of entrance and exit was 7mm. Mean while, was made of transparent acryl so that the flow inside the tube could be observed a CCD camera and visual angle. The electrodes were made of copper foil(0.1mm), and installed on the left and right of tube route. And then, to prevent risk of electric shock from high voltage, the joint area between the test tube base and each components was made of nylon synthetic resin insulator.

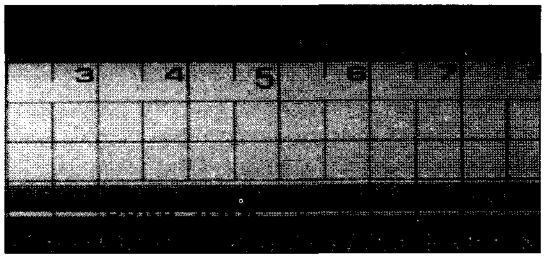
4. Experiment Result and Investigation

4.1 Characteristics of stagnant ER fluid

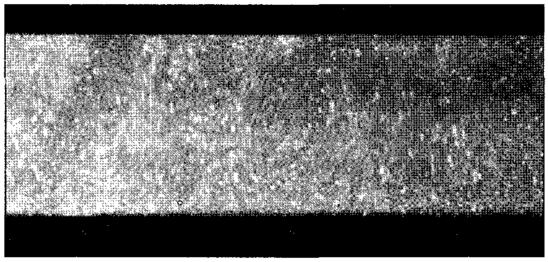
Fig. 4~Fig. 5 are the results of PIV measurement at 1.5kV/mm of electric field, when the exit valve was closed and there was no flow rate(Re=0).

Fig. 4 (a) is the image before the formation of the electric field. It shows that the ER fluid is uniformly distributed between (+) and (-) electrodes. Fig. 4 (b) shows the same state as Fig. 4 (a) but with the formation of the electric field. Both figures show that ER particles shifted to (+) and (-) electrodes and rotated instead of forming a linear cluster. Fig. 4 (c) shows the velocity vectors of the ER particle shift. Large shifts occurred at 3.75, 4.2, and 5.7 of the X-direction and 0.4~0.8 of the Y-direction. This is thought that big ER particles are at 3.75, 4.2, and 5.7 of X-direction and 0.4~0.8 of Y-direction. In this state, with the formation of the electric field, bigger ER particles have bigger ER effects and shift toward (+) and (-) electrodes, and the smaller, stagnated may shift minutely because bigger ones push their ways through the smaller ones. After positive and negative charges of ER particles were uniformly distributed and reached equilibrium, and if the electric charge formed, the electric charges rotated toward the electrode having the opposite pole, having momentum and velocity vectors.

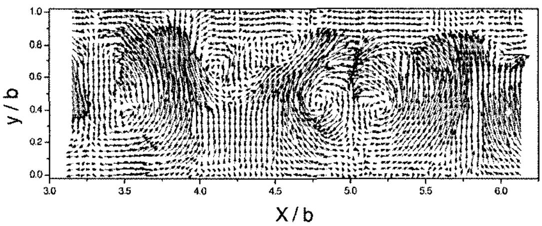
Fig. 5 (a) indicates the pressure distribution of ER particles



(a)Visualized image (E=0kV/mm)



(b) Visualized image (E=0.8kV/mm)



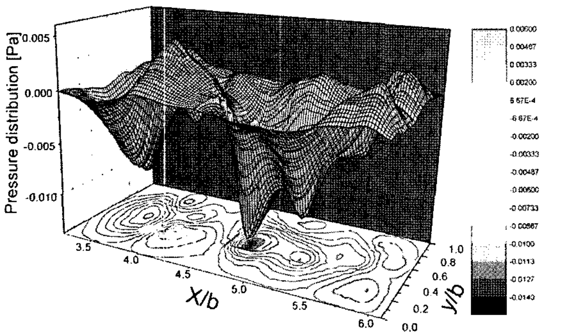
(c) Mean velocity vectors distributions

Fig. 4 Distributions of ER particles alongt the test tube for Re=0 with D.C 1.5kV/mm

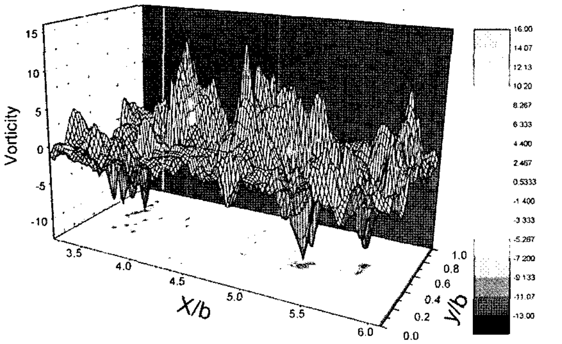
in the state of Fig. 4 (c), and Fig. 5 (b) the voltex flow distributions. Fig. 4 (c) shows that at 3.75, 4.2, and 5.7 in the X-direction, the speed distribution of the ER particles is high and the pressure is low. The pressure may have decreased in the high-speed zone, and increased at the low-speed zone.

4.2 Flow Characteristics of ER fluid

Fig. 6 shows the flow of ER particles as measured by the PIV method without the formation of the electric field. These vectors show a typical laminar flow, as in Fig. 1 (a). also show the maximum velocity at the center of tube and minimum velocity near both walls. The ER fluid flow with an electric field 0.5kV/mm, is shown in Fig. 7. Fig.



(a) Pressure distribution



(b) Vorticity distribution

Fig. 5 Pressure and vorticity distributions along the test tube for Re=0 with D.C 1.5kV/mm

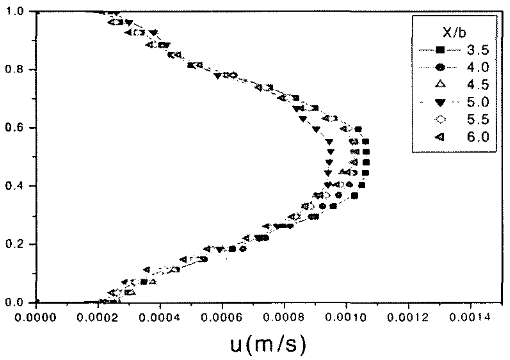


Fig. 6 Velocity distributions along the test tube for Re=2.267 without D.C voltage

7 shows no cluster at the forward section of the test tube, but minute clusters at the back section. When the velocity of ER fluid increase, the inertia force becomes bigger than the electric force; Therefore, the clusters are thought

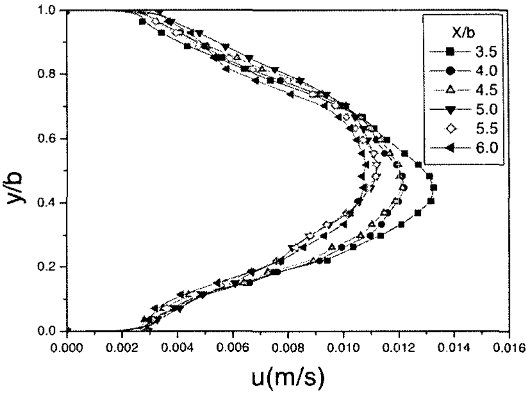


Fig. 7 Velocity distributions along the test tube for Re=2.077 with D.C 0.5kV/mm

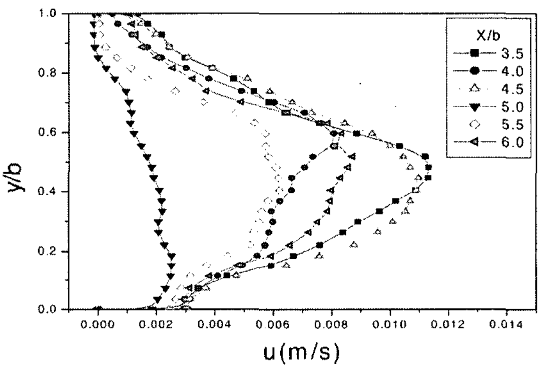


Fig. 8 Velocity distributions along the test tube for Re=1.29 with D.C 1.0kV/mm

to be broken. Fig. 7 show that under the same effects, the and local velocity of ER fluid are not influenced greatly by an electric field. for Re=2.07 along the test tube with D.C 0.5kV/mm.

The ER fluid flow an electric field of 1.0kV/mm,is shown in Fig. 8. The coherence of the particles increased, and many clusters, which have a band shape, build up near both electrodes. These clusters change the velocity distribution of the ER fluid, and therefore, the pressure drops at the entrance and exit of the tube. The band type clusters that built up inside flow route cannot maintain their shapes after the build up but repeat their nullification and creation processes in short cycles. Because of cluster effects due to the electric field, the velocity distribution of the ER fluid increase when ER fluid approaches the lower part.

The change in the flow rate of the ER fluid under an electric field of 1.5kV/mm is shown in Fig. 9, as observed by PIV. At low flow velocity, the clusters build up from near the electrodes toward the tube center. With increasing flow speed the clusters at the tube center appear to break down. This breakdown is thought to be due to the inertia force, that is generated when the velocity increase is greater than the electric force among the starch particles, formed by ER effects. But near the electrodes, the viscosity effects of the ER fluid and the electric forces for the starch particle cluster are expected be greater than the inertia forces such that the clusters may be broken down and their particles may be arranged toward the electrodes. The clusters, adhering to the electrodes become thicker and longer according to the intensity of the electric field. The clusters of the ER fluid, formed under flowing and coherence of clusters are resistant to fluid flows, and therefore, the fluid flows upstream at the upper part of the test tube after X/b=4.0.

ER fluid velocity is zero at electrodes, and has a quadratic velocity profile at the other zone. Because of the clusters formed in these ways, the flow rate changes or the pressure of the ER fluid drops at the entrance and exit of the tube. ER fluid flowing along the test tube route changes the volume of the cluster, which is built up at (+) and (-)

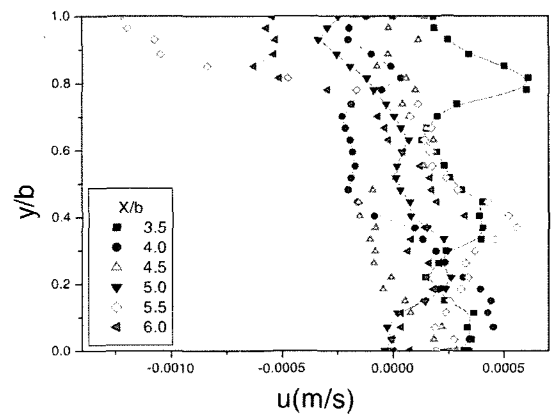


Fig. 9 Velocity distributions along the test tube for Re=0.62 with D.C 1.5kV/mm

electrodes, according to the intensity of electric field. And it can be confirmed that a plug flow zone builds up at the center of the flow route. The results show that the electric fields increase the cluster formation increase, the flow rate decrease, and Reynolds number decreases.

5. Conclusion

In this study, flow visualization experiments of ER fluid were performed; the dislocations of particles were measured through image input device, and; velocity distributions were obtained; The conclusions are as follows.

(1) If an electric field is formed around a stagnant ER fluid, bigger ER particles produce more ER effects and shift toward (+) and (-) electrodes. The smaller stagnant particles are may shift minutely because the bigger ones push their ways through the smaller ones, and pressure and then, the voltex flow distributions appear. After positive and negative charges of ER particles are uniformly distributed and they reach equilibrium, and if electric field is formed, electric charges rotate toward the electrode having the opposite pole and build up momentum and have velocity vectors.

(2) ER fluid flowing along the test tube route change the volume of cluster, which is built up at (+) and (-) electrodes, according to the intensity of the electric field. And a plug flow zone builds up at the center of the flow route.

(3) The relationship between the Reynolds number and electric field shows the increasing electric field, more cluster formation, decreasing flow rate, and decreasing Reynolds number.

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