International Journal of Fluid Power 6 (2005) No. 3 pp. 25-31

THE RESPONSE PERFORMANCE OF ELECTRORHEOLOGICAL FLUIDS IN A CONTROL FLOW FIELD

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Abstract

The accurate description of the flow behaviour is a key link for the practical application of electrorheological (ER) fluids in fluid control technology. This paper is concerned with an experimental determination of the response performance of ER fluids. A power source control system for ER fluids has been designed to obtain the flow information of the ER fluids in the practical application. The dynamic response of ER fluids in control flow field was experimentally measured. The experimental results show that the response characteristics of ER fluids in control flow field differ from that in rotary shearing flow field. Besides the ER effect, there is a concomitant-effect of ER response called “capture effect”.

Keywords: electrorheological (ER) fluids, suspensions, control flow field, ER response, capture effect

1 Introduction

Electrorheological (ER) fluids are a kind of smart material, the rheological properties of which could be rapidly and reversibly changed under an external electric field. Because of their fast response and low power requirement, ER fluids provide the possibility of rapid-response by coupling mechanical devices to electronic control (Wang et al, 2001), and many potential industrial applications by ER technology have been proposed. One of the most popular applications of ER fluids is fluid control (Agrawal et al, 2001, Wei et al, 2004) because the ER fluid control units are characterized by a simple construction without moving parts and high response rate caused by the short reaction time of the ER fluids (Lindler and Wereley, 2000). Within the field of fluid control, ER fluids present a flow mode. The Bingham plastic model has been widely used to describe ER fluid behavior in the flow mode (Brooks, 1992, Peel and Bullough, 1994). However, this model conflicted with measured values sometimes (Wolff and Fees, 1998, Lindler and Wereley, 2003, Wereley *et al*, 2004). In order to explain this difference, Wolff and Fees (1998) thought the Bingham model could not describe the geometry-independent substance characteristics, and it was only approximated for specific geometrical configurations. They put forward a simple model, which was based on the assumption that the pressure difference consisted of a Newtonian fluid through an annular gap with a laminar flow (Δp_o) and the ER fluids pressure difference (Δp_e). Wereley et al (2004) owed this to the result of leakage effect, defined as a second path of Newtonian flow in addition to the Bingham plastic flow through an ER valve. Since the rheological models proved to be very complex, it is necessary to further investigate the behaviour of ER fluids in the flow mode.

In this paper, the response performances of ER fluids in a control flow field are presented. For the experimental study, a power source control system for ER fluids has been designed. A new effect called “capture effect” was found and its mechanism is explained.

2 The General Description of ER Effect in the Flow Field

The ER response means an instantaneous change in the microstructure of the ER fluids under the application of an electric field. For the macro-behavior, this results in an instantaneous change of apparent viscosity

This manuscript was received on 13 October 2004 and was accepted after revision for publication on 15 September 2005

or yield stress of the ER fluids. At present, the electrostatic polarization model and the interface polarization model are usually used to account for this physical phenomenon. The latter is also called the Maxwell-Wanger model. Both models emphasize that the essence of the ER effect or the polar force is a result of the dielectric mismatch of two components in the ER suspension. The polar force is proportional to $12\pi\varepsilon_c\varepsilon_0 a^2(\beta E)^2$ (Gast and Zukocki, 1989, Zukocki, 1993), in which ε_c is the relative dielectric constant of the continuous liquid phase, ε_o is the dielectric constant, β is the relative polarization coefficient of particle, a is the diameter of particle, and E is the electric field strength.

Assuming a flow field inside a gap between two parallel plates, when the electric field strength $E = 0$, the flow of the ER fluids resembles that of a Newtonian fluid and the pressure drop is constant unless the flow rate is changed. When $E \neq 0$, electro-sensitive particles in the suspension overcome viscous resistance (Stokes force) in flow direction and form a chain-like configuration along the direction of the electric field. The chains adsorbing on positive and negative electrodes cause a damping force to resist flow. Then, the pressure drop Δp is changed. This phenomenon is the ER response upon the application of an electric field, which can change the pressure drop instantaneously.

$E \neq 0$ is a prerequisite for the ER effect to occur, but the ER effect is not predominant enough when the viscous resistance is much greater than the electric field force. Marshall et al (1989) put forward a Mason number M_n to distinguish whether the ER effect is predominant enough or not.

$$M_n = \frac{\mu\dot{\gamma}}{2\varepsilon_0\varepsilon_c\beta^2 E^2} \tag{1}$$

where μ is the dynamic viscosity of ER Fluids and $\dot{\gamma}$ the shearing rate.

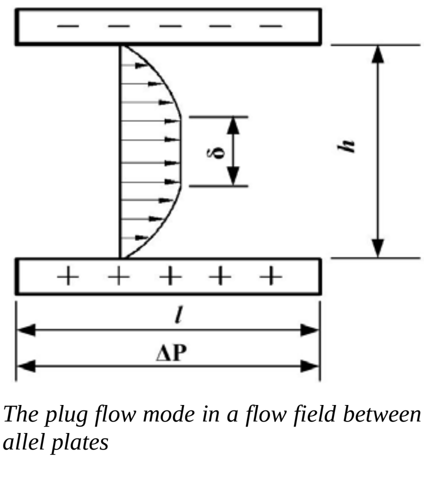


Fig. 1: *The plug flow mode in a flow field between the parallel plates*

If $M_n << 1$, the characteristics of fluid transmission in a flow field depend on the electric field force, otherwise on the Stokes force.

The Mason number M_n consolidates the influence of the main parameters $(\dot{\gamma}, \beta, E)$ in one expression and explains also that the stability of chain configuration depends on the polar force and the viscous resistance. Dassanayake et al (2004) considered the effect of flow-modified permittivity (FMP) on ER fluids using the Mason number and found that an FMP-induced misalignment between the particle dipole moments played a crucial role in producing ER effects. However, they did not offer more information about ER response in the flow field.

In flow mode of operation, the plug flow mode, which is shown in Fig. 1, is usually used to describe the behivour of the ER fluids (Ugaz et al, 1994, Wereley et al 2004). In the plug flow mode, ER fluids experience pre-yield behaviour in the plug zone of thickness δ, and yields outside. Assuming, (a) the medium in flow field is continuous and uncompressible, (b) the electric field satiates $\nabla \times E = 0$ and $\nabla \cdot E = 0$, (c) the height of the flow field is far less its width ($h << w$), the flow field in a parallel plate ER valve can be considered to be of one dimension. If the medium is a Bingham plastic fluid upon the application of an electric field, the expression of pressure difference of the ER fluids can be obtained (Zhu, 2001) as

$$\Delta p_{er} = \frac{2l}{\delta}\tau_d \tag{2}$$

where Δp_{er} is the pressure difference of the ER valve, l is the length of the flow field, δ is the plug thickness in the flow field, and τ_d is the dynamic yield stress of the ER fluids.

If τ_d is known and the viscous damping is not influenced by the electric field when the plug thickness $\delta = 0.1h$, the response range of the electric field or pressure drop Δp in an ER valve can be calculated. It is obvious that this expression has a high relevance to engineering applications because τ_d and Δp_{er} include all parameters: the contribution of the ER effect, the intensity of the fluid power control, and the design parameters l and h of the ER power unit. This expression is a common description for the ER effect. It is based on the assumption of electrostatic polarization and the approximation by a Bingham plastic fluid, and also on the static observation on a rotary shearing flow field. However, the control flow field or electric field in fluid power transmission is different from a rotary shearing flow field in an ER device. The results show that there is not only a velocity gradient field but also a pressure gradient field and its attribute is changing ceaselessly while the ER fluids are flowing through the control flow field. The ER fluids are a Bingham plastic fluid in the control flow field and a Newton fluid out of the control flow field. As the boundary conditions have been changed, it is necessary to re-observe and re-research the ER response in a fluid power transmission.

3 Experimental Equipment and Description of ER Fluids

A power source control system for ER fluids has been designed to obtain the flow information in a practical application. Figure 2 shows the experimental configuration in principle. The power source control system is mainly made up of a tank (mixed and sealed), a restrictor (model number LF-B10C), a signal generator, the measure element, and the control element. The function of the restrictor is to regulate the entry initial pressures of the measure elements, and to raise the working stability of the system at the same time. The measure elements include the pressure sensor (model number ZQ-Y1), the universal electric bridge (model number PM6303), and the oscillograph (model number TEK-2456A). Two kinds of typical control elements of ER fluids are used as the control element: a parallel plates structure and an annular structure element. Their configurations are shown in Fig. 3. The dimensions of the parallel plates structure are: electrode width w = 65mm, electrode separation gap h = 1mm, electrode length l = 61mm. And the annular structure is: mean annular diameter D = 20mm, electrode separation gap h = 1mm, electrode length l = 61mm.

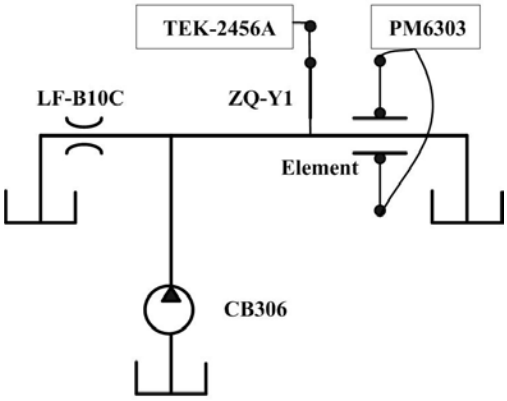


Fig. 2: *Configuration of the experimental set-up*

(a) The parallel plates structure

(b) The annular structure

Fig. 3: *Photograph of ER control elements*

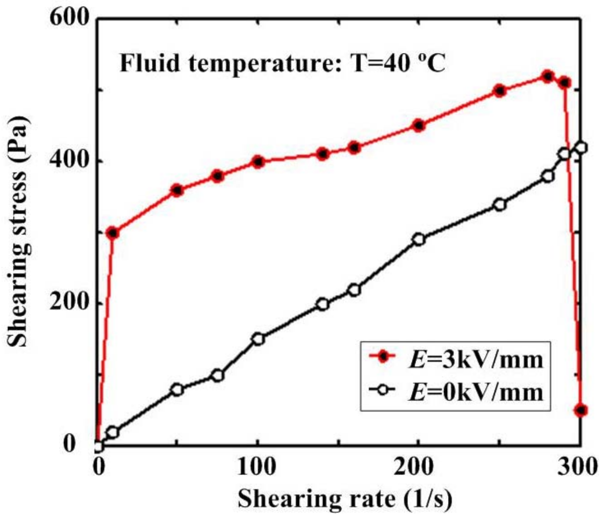


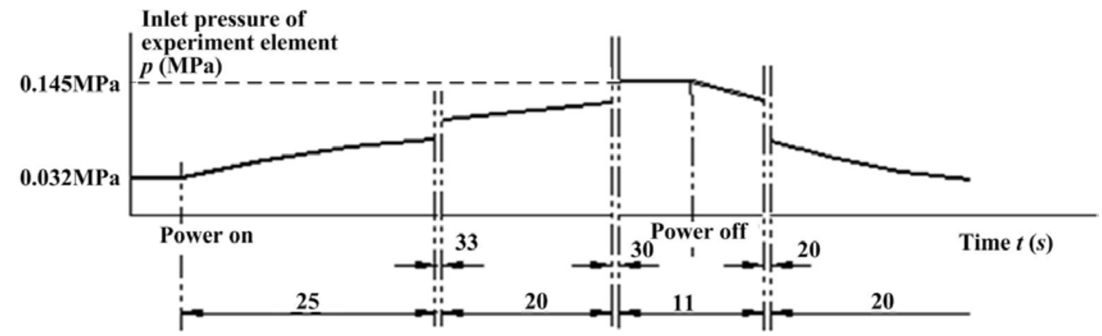
Fig. 4: *Characteristic curve of ER fluids*

The working medium is the ER suspension. The continuous medium phase is methyl silicon oil (made by Hangzhou Jinjiang Chemical Plant) and its viscosity η = 1000 cP, the relative dielectric constant ε_c = 2.0, and the density ρ = 0.68 g/cm^3. The dispersed particle is silica gel GF254 (made by Qingdao Marine Chemical Plant) with a relative dielectric constant ε_p = 4.7 (Measured after 48 hours in the air when uncovered), the diameter of the particle d = 10-40 µm (primitive), and its density ρ = 0.75-0.80 g/cm^3 (piled up). The mix equipment is a colloid mill JTM50 D/D1 (Volume fraction Φ = 0.25). The rheological characteristic of the ER suspension measured with HAAKE Rheometer (model number CV20) is shown in Fig. 4.

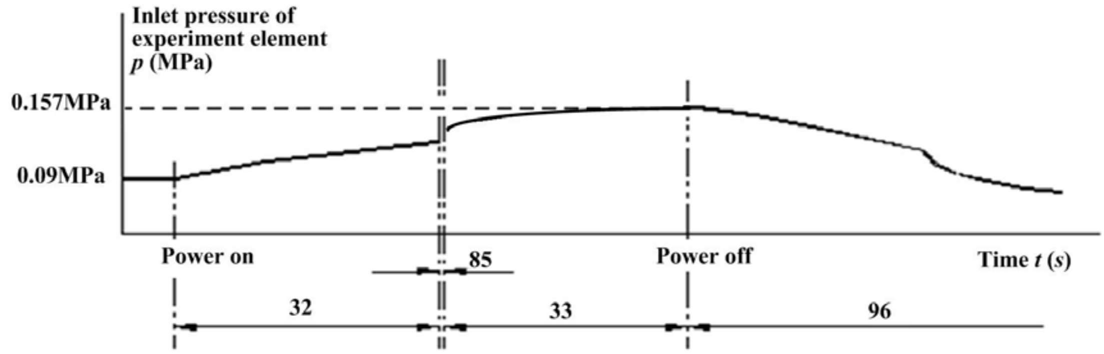
4 The Capture-Effect of the ER Response in a Control Flow Field

When the ER fluids are flowing through a control flow field or a control unit and an electric field is applied, its configuration will be instantaneously changed because of the action of the orthogonal electric field force and the Stokes force. In general, the configuration is a quantity of quasi-stable chains composed of particles. These chains create and break up repeatedly, resulting in an apparent change of flow damping.

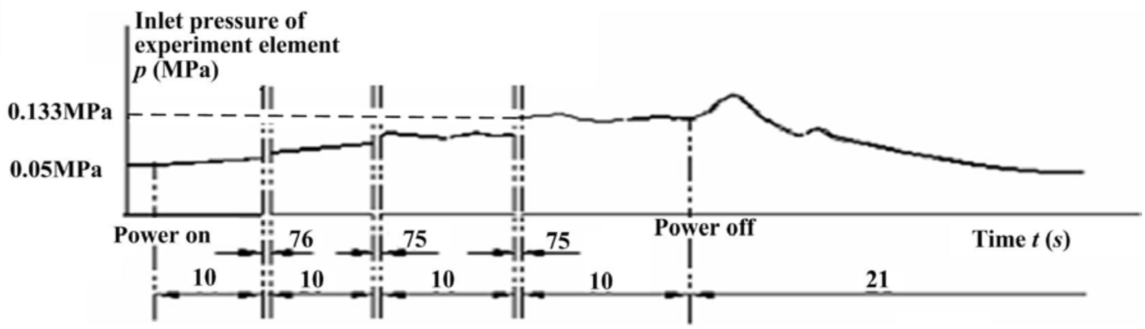
There is a new phenomenon in the experiment. The strength of the chain configuration is increased instantaneously when the field strength is raised by an increment ΔE, resulting in an increment $\Delta p_{\Delta E}$ for the pressure drop Δp. $\Delta p_{\Delta E}$ is not constant but increases slowly with time. This phenomenon occurs because the chain-network in the control flow field captures electro-sensitive particles when the ER fluids flow through the field. The volume fraction φ, the mean density ρ, the stack form of particles N, and even the electric characteristic of the medium in the field are all changed accordingly, and the strength of the chain-network configuration tends to increase. Special attention should be given to this phenomenon, which is different from a rotary shearing flow field in a rotary viscosity-meter.



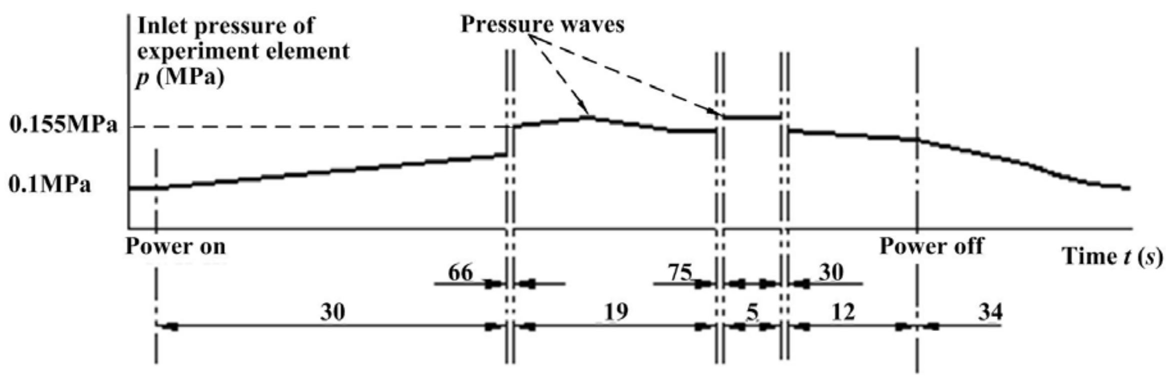
(a) *Annular structure element (step signal: ΔE=3280kV⊙m^{-1};*
electric current: 9μA; flow ate: 150ml/150s; oil temperature at outlet: 16 ^{0}C)



(b) *Annular structure element (step signal: ΔE=3280kV⊙m^{-1};*
electric current: 9μA; flow rate: 150ml/150s; oil temperature at outlet: 19 ^{0}C)



(c) *Annular structure element (step signal: ΔE=2500kV⊙m^{-1};*
electric current: 9μA; flow rate: 305ml/150s; oil temperature at outlet: 24.5 ^{0}C)



(d) *Parallel-plates structure element (step signal: ΔE=2500kV⊙m^{-1};*
electric current: 33μA; flow rate: 420 ml/174 s; oil temperature at outlet: 30 ^{0}C).

Fig. 5: *Dynamic measure result of the ER effect in a control flow field*

Figure 5 shows this phenomenon. In Fig. 5(a), the initial pressure is 0.032 MPa. The risen rate of pressure (increment of pressure vs. time) is 5.553 MPa/s continuing 14 s from the time of power on, and arriving at a stable pressure 0.145 MPa after 108 s. The curve is smooth as a whole and approximated by a straight line with a rising rate of 2.895 MPa/s. In Fig. 5(b), the initial pressure is 0.09 MPa. The rising rate of pressure is 5.946 MPa/s continuing 10 s from the time of power on, and arriving at a stable pressure 0.157 MPa after 150 s. The curve is smooth and unfluctuating. In Fig. 5(c), the initial pressure is 0.05 MPa. The rising rate is 2.386 MPa/s from the time of power on, and arriving at a stable pressure 0.133 MPa after 256 s. After that, there is suddenly a pressure wave, $p_{\max} = 0.143$ MPa, $p_{\min} = 0.13$ MPa. In Fig. 5(d), the initial pressure is 0.1 MPa. The rising rate of pressure is 3.576 MPa/s continuing 14 s from the time of power on, and arriving at a stable pressure 0.155 MPa after 96 s. Fig. 5(d) also shows there are two big pressure waves between 96 s and the time of power off, in which $p_{\max} = 0.165$ MPa and $p_{\min} = 0.148$ MPa.

This phenomenon is defined as the concomitant-effect of the ER effect or “capture effect” in a control flow field, which depresses control precision. The number of electro-sensitive particles flowing through the flow field is $\varphi{\cdot}v{\cdot}A$ per unit time at zero electric field, and there is a quasi-stable chain-network at non-zero electric field. It is the chain-network that makes the number of electro-sensitive particles change or increase, so that the volume fraction φ of the ER fluids in a flow field is also changed. Assuming the volume fraction φ of the ER fluids is $\varphi(t)$ at the time t, after the electric field strength gets an increment ΔE at the same moment, the volume fraction φ of the ER fluids at the time $(t+\Delta t)$ is

$$\varphi(t + \Delta t) = \varphi(t) + \Delta\varphi \tag{3}$$

The mean density ρ of the ER fluids is also changed

$$\rho\left(t+\Delta t\right) = \varphi\left(t+\Delta t\right)\rho_{\mathrm{p}} + \left[1-\varphi\left(t+\Delta t\right)\right]\rho_{\mathrm{c}} \tag{4}$$

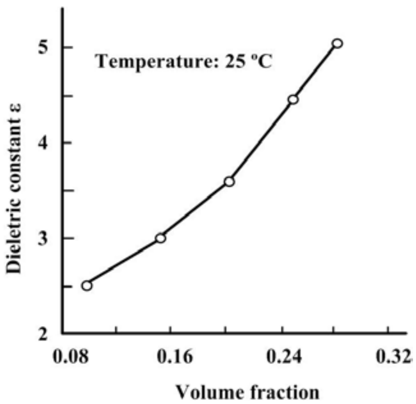
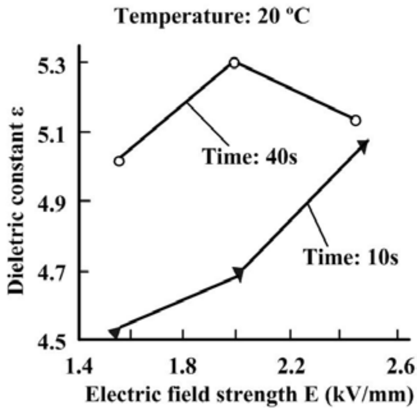
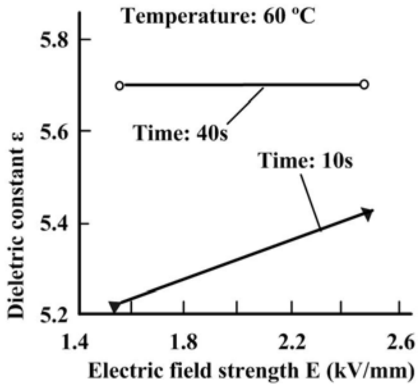


Fig. 6: *The relationship of φ – ε in a zero electric field*

The variation of φ and ρ cause the relative dielectric constant ε of the medium in the control flow field to change. Then the electric field force would change, so the strength of the chain-network configuration tends to rise with time. In an engineering system, this tendency makes the differential pressure of the ER unit contain another increment Δp_{cap} besides the increment $\Delta p_{\Delta\mathrm{E}}$ caused by an increment of electric field strength ΔE. The Δp_{cap} increases slowly with time and is not an instantaneous ER response at the time t.



(a) Fluid temperature T=20 ^{0}C



(b) Fluid temperature T=60 ^{0}C

Fig. 7: *The relationship of t –ε for different electric field strength*

These experiments provide a further confirmation of the “capture effect”. Figure 6 is an experimental curve of the volume fraction φ vs. the relative dielectric constant ε of the ER fluids at a normal temperature (25 ^{0}C). Figure 7 shows the relationship between the relative dielectric constant and the electric field strength for some different times in a control flow field. From the above figures, we can conclude:

1. Upon the application of a constant electric field, the change of the dielectric constant, to which the change of volume fraction φ contributes, is the main cause for the “capture effect” during the first 40 s. After 40 s, the change of the volume fraction φ is the main cause for the “capture effect”. The contribution of the dielectric constant decreases until the volume fraction φ of the medium reaches a saturation state at a certain temperature.
2. At a higher temperature (as 60 °C), the change range of the dielectric constant during 10 s or 40 s is smaller than at a lower one (as 20 °C) (as shown in Fig. 7(b)). It indicates that the contribution of the dielectric constant changing reaches its saturation in shorter time.

3. The “capture effect” causes a density change and a reorganization of the particles which has influence on the fluid power transmission in the flow field. The changing quantity of particles has also an effect on ε (Coelho, 1979).

According to the above experimental and theoretical results, a time t_{cap} exists, in which the volume fraction φ reaches a saturation state. It depends on the electrical field and the temperature. On the assumption that the saturated volume fraction φ_s is directly proportional to time t and to the viscosity μ at zero electric field, but inversely proportional to the stack density of particles ρ_p, an expression of the continuing time of “capture effect” t_{cap} can be written as:

$$t_{cap} = \varphi_s (K \cdot \mu \cdot \rho_p^{-1})^{-1} \tag{5}$$

where K is a factor representing the contributions of other parameters.

The experiments have shown that the “capture effect” will be weakened and the continuing time t_{cap} is decreased when the temperature is increased.

5 Conclusions

It is the essence of the ER effect that an instantaneous change in microstructure (a chain configuration of particles) of ER suspensions occurs upon the application of an electric field. In a control flow field, in which the directions of both medium flow and electric field force are orthogonal to each other, the ER effect causes an instantaneous change of flow resistance. The experimental results of this paper confirm that the ER fluid power transmission is directly controlled by the electric field, but have shown that there is a concomitant-effect called “capture effect” causing an additional increase in the flow resistance. The differential pressure of the control flow field goes up slowly because the electro-sensitive particles from the upriver are captured by the chain-network. The characteristic of “capture effect” is a slow increase of the pressure differential as the electro-sensitive particles storing up in a control flow field. The “capture effect” is a known phenomenon in controlling the ER fluids.

Nomenclature

a	Diameter of particle	[m]
E	Electric field strength,	[$V \cdot m^{-1}$]
h	Height of the flow field	[m]
w	Width of the flow field	[m]
l	Length of the flow field	[m]
K	Factor of continuing time of “capture effect”	[$s^2 \cdot m^{-2}$]
Δp	Pressure difference of valve	[Pa]
Δp_{er}	Pressure difference of ER fluids	[Pa]
$\Delta p_{\Delta E}$	Increment caused by a increment of electric field strength ΔE	[Pa]
Δp_{cap}	Increment of differential pressure caused by “capture effect”	[Pa]
t_{cap}	Continuing time of “capture effect”	[s]
β	Relative polarization coefficient of particle	
$\dot{\gamma}$	Shearing rate	[s^{-1}]
δ	Plug thickness, m	[m]
ε_c	Relative dielectric constant of continuous component	
ε	Relative dielectric constant of ER fluids	
ε_o	Vacuum dielectric constant	[$F \cdot m^{-1}$]
ε_p	Relative dielectric constant of particles	
μ	Dynamic viscosity of ER fluids in electric field	[Pa·s]
v	Mean flow velocity in a flow field	[$m \cdot s^{-1}$]
ρ	Mean density of ER fluids	[$kg \cdot m^{-3}$]
ρ_p	Density of particle	[$kg \cdot m^{-3}$]
ρ_c	Density of continuous component	[$kg \cdot m^{-3}$]
τ_d	Dynamic yield stress	[$N \cdot m^{-2}$]
φ	Volume fraction	
φ_s	Saturated volume fraction	

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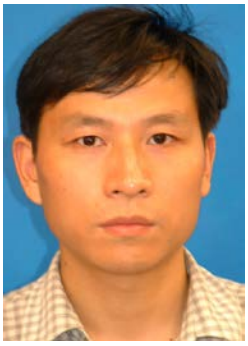

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