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Research Article

Visualization Experiment on Electrorheological Fluid in Dynamic Coupling Field

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Due to lack of visualization experiment on the mechanism of electrorheological effect in dynamic field, a visualization experimental system is designed and successfully made. Through this experiment, the submicroscopic dynamic structural changes of electrorheological (ER) fluids in the coupling field composed by external electric field and flow field are observed. The experimental results indicate that the rheological behaviors of ER fluids are mainly influenced by the polarization forces and the hydrodynamic forces in the dynamic coupling field. And the experiment shows that the yield fracture of chain structures determined the yield strength of ER fluids firstly occurring near the plate electrodes, which expresses the microflow characteristic of velocity slip. Meanwhile, the capture effect has been verified in this experiment.

1. Introduction

Electrorheological (ER) fluid is a type of new intelligent material whose rheological properties can be regulated by applied electric field [1–6]. However, there are still no mature products relevant to ER materials on the market after decades of research. The reason mainly lies in the insufficient investigations on various mechanical properties of ER fluids and their mechanism in external electric field. In particular, researchers are unable to grasp the dynamic coupling relation between mechanical properties and submicroscopic structure with multifield coupling effect (flow field, electric field, etc.) in all directions [7, 8]. It may accurately elaborate the mechanism of ER effect when the dynamics behavior of ER fluids is studied in the coupling effect composed by the polarization force and chain structures.

Since dielectric particles in ER fluids are mesoscopic and their structural evolution in electric field is quite complicated, it is rather inconvenient for researchers conducting experiments to observe the whole structural evolution process. Therefore, domestic and foreign scholars have mainly adopted numerical simulation to investigate the inner mechanism of ER effect. And lots of rewarding achievements have been made. By using the principle of minimum potential energy, Tao and Jiang [9] calculated that the three-dimensional stable structure of dielectric particles is a body-centered cubic structure when the ER fluids are under the effect of external electric field. And this structure has been verified and simulated in computer. Cao et al. [10] analyzed the three-dimensional structural evolution of ER fluids and their mechanical properties in shearing field and found that the shearing stress value of ER fluids would be fluctuating in electric field when it has reached a certain marginal value. Kadaksham et al. [11] researched on the dynamic behaviors of ER fluids with coupling effect composed by nonuniform electric field and flow field and found that, in a given nonuniform electric field, when the pressure gradient is less than the marginal value, it is conducive for particles to aggregate together. Zhao et al. [12, 13] investigated the flow properties of ER fluids in Poiseuille flow field by computer simulation. And they found that when the pressure gradient reached the marginal value, dielectric particles failed to form chain structure. And then Zhu et al. [14] made further simulation study on dynamic coupling relationship (structure-force) between the mechanical properties of ER fluids and their submicroscopic structures in Poiseuille flow field. Through

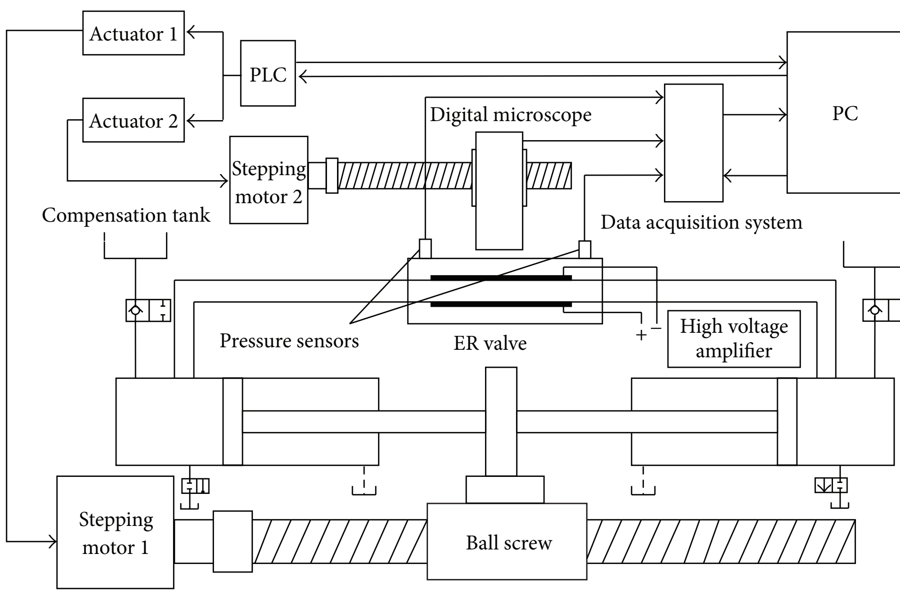


Figure 1: Schematic diagram of the experimental apparatus.

dynamic simulation using a multipolar model, Limsimarat and Techaumnat [15] explored the relationship between the chaining speed of ER particles and the lengths of chains. And they found that the chaining speed of ER fluids in the effect of multiple dipole was faster than that of single dipole and the length of chain is longer as well. By modeling and simulating, Au et al. [16] researched on rheological properties of ER fluids in Couette flow field and analyzed the influence of shearing rate on the submicroscopic structure. Průša and Rajagopal [17] simulated dynamic behaviors of ER fluids in eccentric rotating cylinders by three-dimensional constitutive model.

Although a part of problems of research can be solved by simulation, there are still many differences between the actual physical form of ER fluids and their dynamic behaviors. What is more, some disturbances in engineering applications are ignored. Therefore, some researchers (Rhee, Nam, and Kontopoulou et al. [18–26]) conducted a series of visual experiments and made some achievements. However, the visual experiments work only centered on observing the evolution process in which submicroscopic structures of ER fluids in a fixed area are changing with time. But the motion law and the structural evolution of some dielectric particles or micelles in a certain part changing with time failed to be investigated. In addition, observing the structural evolution of ER fluids and testing their mechanical properties were normally separated from each other. No apparatus were available to observe the structural evolution of ER fluids and test their mechanical properties synchronously. Therefore, the dynamics information of ER fluids covering cannot be grasped in all directions, which thereby prevented people from deepening their understanding of the mechanism of ER effect. Due to the above reasons, a visualization experimental system was designed and successfully made. By virtue of this apparatus, a visual experiment has been conducted in order to investigate the dynamic behaviors of dielectric particles under the coupling effect of multifield (external electric field, flow field, etc.), the structural evolution of whole system, the flow behavior, and yielding state after forming chain structures. The experimental results provide realistic basis for perfecting the dynamics modeling of ER fluids and studying further on the mechanism of ER effect.

2. Experimental Setup and Material

According to the requirements of experimental parameters and functions, combining the machine design with signal testing and processing, an experimental scheme shown in Figure 1 is drafted [27].

The whole setup is composed of power source, transmission mechanism, hydraulic system, control system, and acquisition system. Its basic principle of operation is as follows: driven by stepping motor 1, ball screw gets rotated, thus turning rotary motion into linear motion. After that, through the piston rod of motion which is driven by the baffle of feed screw with nut set, the pressure flow is formed in the electrorheological valve. Control valve is composed of insulated seat, two pieces of transparent glass, and the plate electrode. And it is equipped with a digital microscope (AM413ZT) on its upper end. The microscope can make horizontal motion driven by the screw connected with stepping motor 2, thereby observing the submicroscopic structure evolution of dielectric particles both fixedly or movably. In order to measure the pressure drop of control field, the control valve is equipped with two pressure sensors. The adjusting of flow is done by PC controlling the motion speed of piston rod. The data acquisition device is connected with PC. Compensation tank is an ultrasonic cleaning tank with a valve, by which the ER fluids can be mixed and heated. The dimensions of the ER fluid control valve are as follows: electrode width $w = 65$ mm, electrode separation gap $h = 1$ mm, and electrode length $l = 61$ mm.

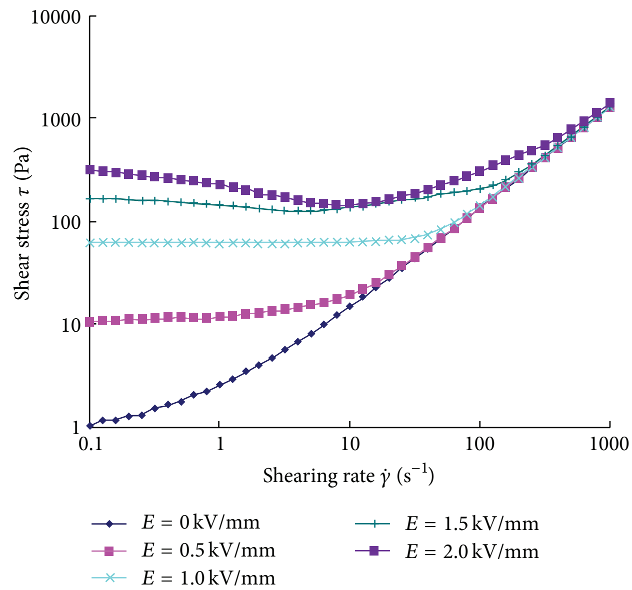


FIGURE 2: Characteristic curve of ER fluids.

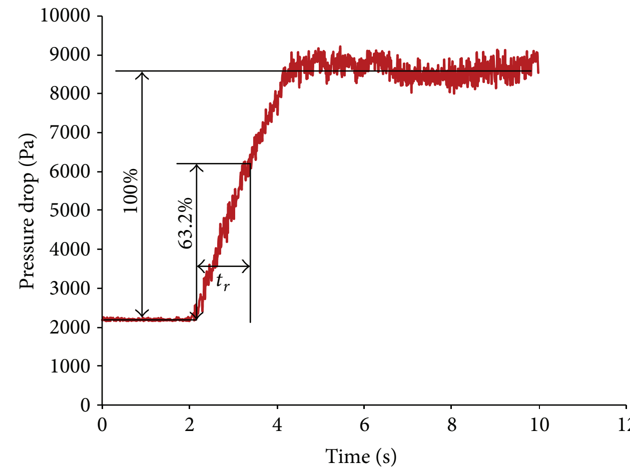


FIGURE 3: The temporal pressure behavior of the ER fluids (E = 1.0 kV/mm, v = 2 cm/s).

Dimethyl silicone oil and anion exchange resin particles are, respectively, selected as basic medium fluid and dielectric particles in the experiment. The continuous medium phase is dimethyl silicone oil and its viscosity is as η = 100 mPa·s, the relative dielectric constant is as ε_c = 2.0, and the density is as ρ = 0.96 g/cm^3. The dielectric particles are anion exchange resin particles with a relative dielectric constant as ε_p = 4.8, the diameter of the particle as d = 0.0425~0.0650 mm, and its density as ρ = 1.12~1.20 g/cm^3. According to the experimental requirements, a sample of ER fluids (volume fraction φ = 0.15) is successfully made, and its parameter of the mechanical property measured with the rheometer (model number MCR301) is shown in Figure 2. All the experiments are conducted at room temperature (about 25°C).

3. Visualization Experiment and Discussions

3.1. The Submicroscopic Structure Evolution of ER Fluids and Its Macromechanical Properties in Dynamic Field. The intensity of stepwise electric fields is as E = 1.0 kV/mm and the flow velocity in control flow field is as v = 2 cm/s; the transient pressure response of ER fluids is shown in Figure 3.

The submicrostructure evolution of ER fluids in control flow field is shown in Figure 4 (photos are taken by overlooking). When T = 2 s, the high voltage power supplier is switched on and the digital microscope starts to shoot simultaneously, adjacent particles agglomerated together immediately. Along the electric field and starting from the electrode plates, those particles stretched into the center area and formed into short chains. At this moment, basic medium fluid flowed through the tiny gaps between particles (which can be considered as porous media flow), and the pressure drop of controlling field kept increasing; as chains composed by particles are becoming longer and thicker, the connection between particles is becoming closer, and its damping against basic medium fluid is gradually reinforcing. And then, the pressure drop of ER fluids reached a peak value after chain structures tended to be stable; when the chain has reached a certain length and strength, because the area that collided by the fluid becomes larger, it deformed along the direction of fluid flowing and then gradually turned into a plunger-shaped chain. The deformation of chains is more obvious at the center area in which the flow rate is greater. The chain structures that are not very stable suffered from yield fracture when they deformed into saturation. And then the interrupted chains would rapidly form new chains after combining with dispersed particles. Chain structures are constantly reconstructed after being interrupted over and over again, thus making the pressure drop fluctuate around the marginal value. As shown in Figure 3, the pressure drop of ER fluids is about 6.7 kPa which is slightly less than the theoretical value [28]. The reason probably lies in precipitation, environment, and so forth.

3.2. Boundary Slip in Dynamic Field. In the experiment, it is noted that the scales of characterizing the time-space domain of ER effect are very small (time is in milliseconds and space is generally millimeter). Hence, the response of ER fluids in dynamic field can be approximately counted as microscale flow. According to the theory of microscale flow, the boundary slip effect plays a dominant role in the flow. Figure 5 shows the boundary slip of ER fluids in dynamic field [29, 30]. As can be seen clearly from Figures 5(a)–5(d), at first, chain structure bent and deformed; after the deformation was unable to continue, the chain structure would suffer from yield fracture near the plate. However, the whole chain structure, without being scattered, slipped along the boundary by following the direction of flowing.

The above experimental phenomena show that, in the dynamic coupling effect composed by flow field and external electric field, the yield strength of ER fluids is mainly determined by the bonding strength of the chain structure and the electrode plates or the particles near electrode plates.

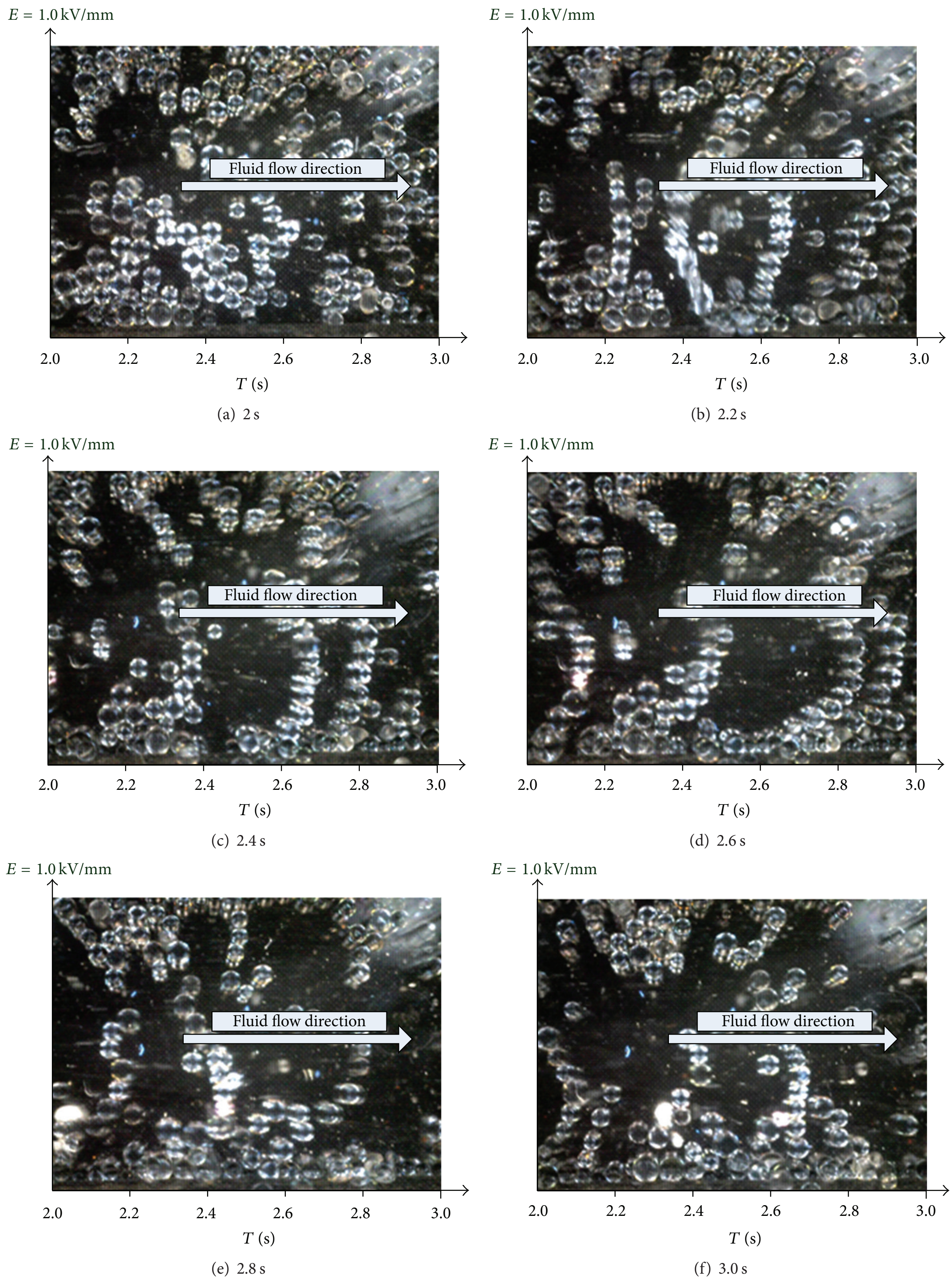
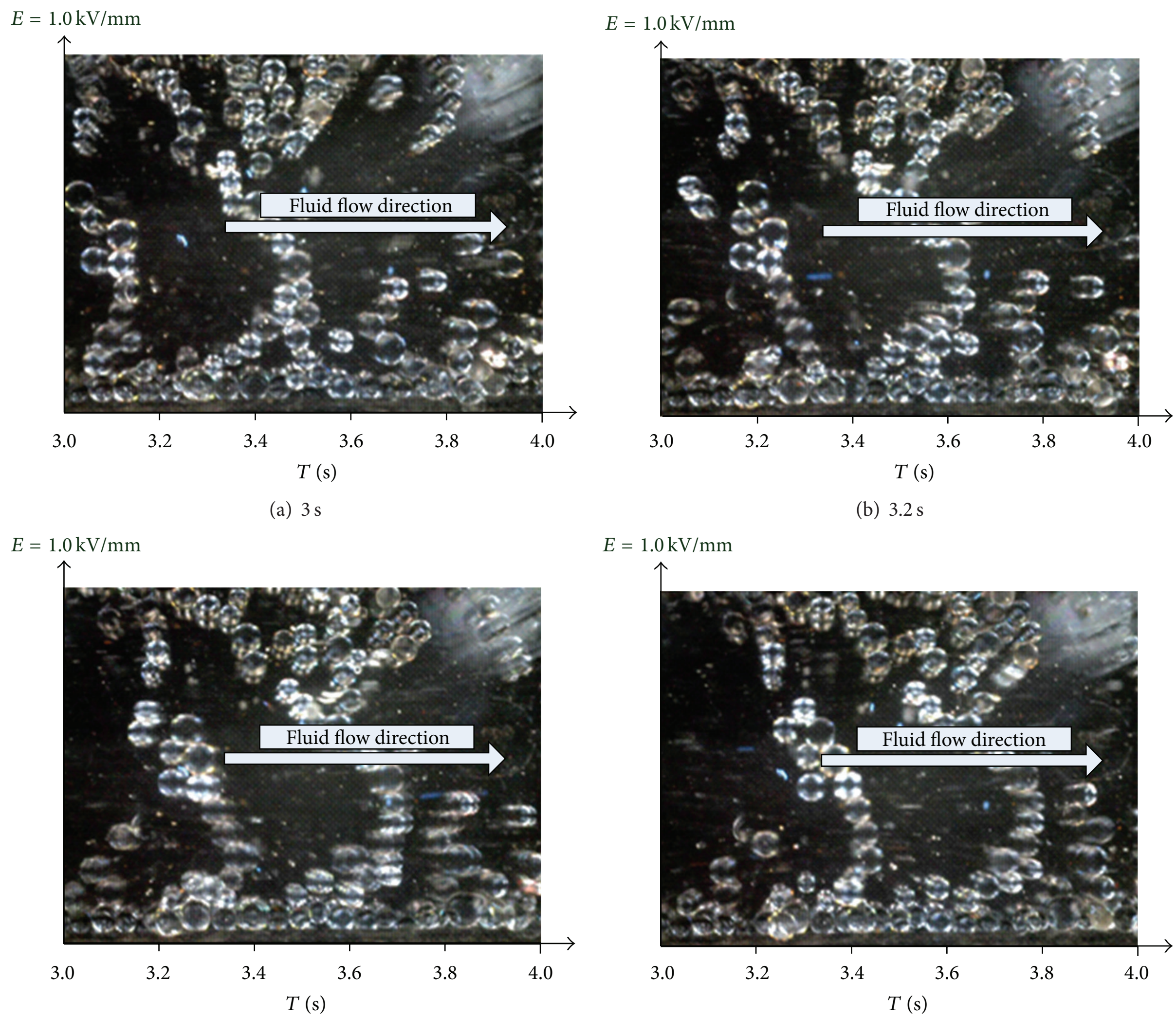


FIGURE 4: Structure evolution processes of the ER particles ($E = 1.0\,\mathrm{kV/mm}$, $v = 2\,\mathrm{cm/s}$).



(a) 3 s (b) 3.2 s (c) 3.4 s (d) 3.6 s

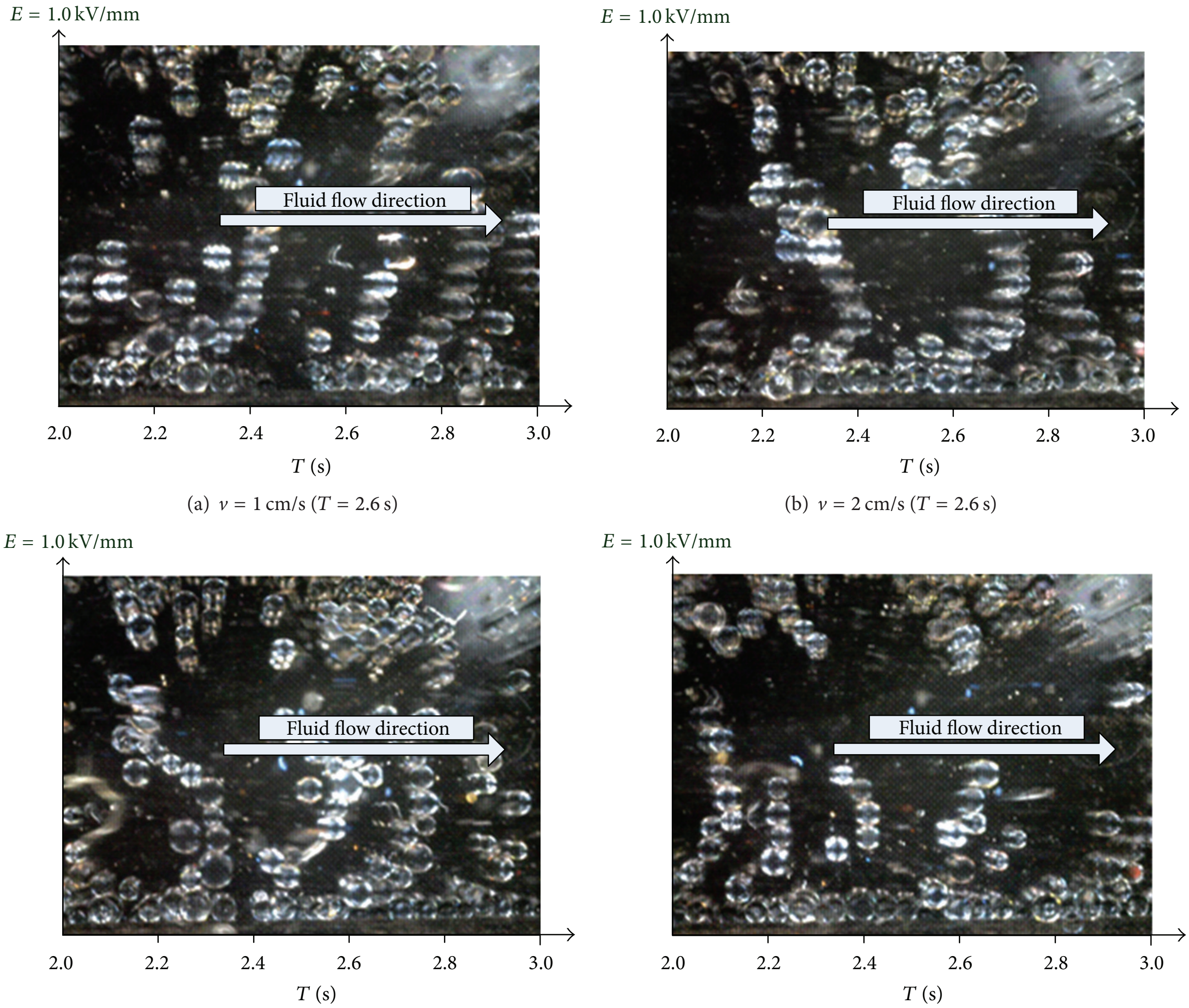
Figure 5: Boundary slip of ER fluids in dynamic field.

If the intensity between plates and chains is increased, the yield strength of ER fluids can also be raised.

3.3. The Capture Effect in Dynamic Field. Studying the submicroscopic dynamic structure of ER fluids in visualization, it is found that when ER fluids flowed through the coupling field, dielectric particles from the upstream were captured by the chain-network structure in the downstream and then formed into new chain or column structures which are more stable than the former one. The capture effect will cause dynamic changes of the whole structure and the change of macroscopic mechanical properties [31, 32].

As can be shown in Figures 4(c)-4(d), after suffering from yield fracture, the chain structure flowed to the downstream along the plates. However, the chain structure in the downstream which is more stable would capture dielectric particles flowing from the upstream to form larger chain structure. In addition, Figures 4(e)-4(f) show that some thin and short chains would be scattered by the fluid. However, the particles near the plates would rapidly reconstruct and form into new short chains, and, by capturing the dispersed particles or some unstable chains flowing from the upstream, new chain structures formed.

3.4. The Influence of Pressure Gradient on ER Effect in Dynamic Field. Figure 6 shows the rheological structure of ER fluids in dynamic coupling field with the same electric field strengths and different pressure gradient. From the figure, it can be seen that, with the increasing pressure gradient, the chain structures are becoming looser and looser. In particular in the middle of the flow channel whose flow velocity is relatively high, it is almost impossible for particles to agglomerate so as not to be completely scattered. Besides, by observing the number of particles adhering to boundary area it can be known that, within a certain range of flow rates, the faster the flow velocity of ER fluids is, the more the particles moving to the plate and agglomerating near the plate will be, so some particles stay in the flow channel without flowing out (Figures 6(a), 6(b), and 6(c)); when the flow velocity reaches a certain



(a) $v = 1$ cm/s ($T = 2.6$ s) (b) $v = 2$ cm/s ($T = 2.6$ s) (c) $v = 4$ cm/s ($T = 2.6$ s) (d) $v = 6$ cm/s ($T = 2.6$ s)

Figure 6: Structural evolution of the ER fluids at different pressure gradient ($E = 1.0$ kV/mm).

value, the particles of the boundary region can hardly adhere (Figure 6(d)).

The above experimental phenomenon shows that, in the dynamic response of ER fluids, evolution of structures is mainly influenced by polarization force and hydrodynamic forces. When flow velocity is relatively low, the polarization force is greater than the hydrodynamic force, so dielectric particles can form into chain structures. Besides, when the flow velocity reaches a certain value that the polarization forces are less than hydrodynamic forces, dielectric particles fail to form into chain structures. Therefore, when the dynamics model of multifield coupling is established, the impact of the fluid flow should be taken into full consideration.

Through pasting an insulating film on the surface where electrode plate (brass) touched ER fluids, ER fluids will not suffer from breakdown which will cause the great dissipation of energy. And this approach greatly improves the test environment. However, it still needs further systematic study to find out whether the technique of pasting an insulating film is conducive to the development of the electrorheological technology for engineering applications.

4. Conclusions

The dynamic behaviors of electrorheological (ER) fluids in dynamic coupling field were investigated experimentally by the visual apparatus. The experimental results show that, in the process of dynamics coupling (structure-force), the submicroscopic structure changes of ER fluids are mainly influenced by the polarization forces (the electric field-induced particle interaction forces) and the hydrodynamic forces. When the flow velocity is relatively low, polarization force is greater than hydrodynamic force, so dielectric particles can effectively form into chain structures. Besides, when the flow velocity reaches a certain value that polarization force is less than hydrodynamic force, dielectric particles fail to form into the chains. The yield fracture of particle chains firstly occurs near the electrode plates, and the strength of this region determines the yield strength of ER fluids. The chain structures in the downstream can capture slipping chains or dispersed particles flowing from the upstream to form more stable columnar structures.

Competing Interests

The authors declare that there are no competing interests regarding the publication of this paper.

Acknowledgments

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