Experimental investigation for the time-dependent effect in electrorheological fluids under time-regulated high pulse electric field

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A new time-regulated high-voltage power supply is designed to investigate the dynamic process of the particle–particle interaction in electrorheological (ER) fluids. Its shortest acting time on the particle is less than 200 ns and the field strength can be adjusted linearly from 0 to 15 kV. At a field strength of 1.2 kV/mm, it is found that the initial response time of the glass microsphere is 18 ms and the respective chain and column formation times are measured to be about 125 and 900 ms. During particle aggregation, a sensitive shear stress device is applied to test the time dependence of ER effect and the results indicate that there exist three different stages of increasing effect. In addition, it is found that the aggregation of the microspheres becomes faster and the interaction among particles is much stronger under higher field strength. © *1998 American Institute of Physics.* [S0034-6748(98)03810-6]

I. INTRODUCTION

An electrorheological (ER) fluid is a colloid which consists of fine particles suspended in an insulating oil. The effective viscosity of ER fluid increases dramatically when an external electric field is applied. These phenomena occur rapidly and reversibly. In the past decade, much theoretical and experimental work has been accomplished on electrorheological fluid (ER) due to its potential industrial applications.[1–7] It is thought that the change of viscosity of ER fluids is caused by the dipole–dipole interaction induced by an external field on the particles.

According to the conventional expression of dipole–dipole approximation, the force between the dipoles induced by an external electric field can be given by

$$F=\frac{6p^2}{4\pi\epsilon_0\epsilon_f d^4}.$$

Here, $p=4\pi\epsilon_0 a^3\epsilon_f\beta E$ represents the dipole moment. E is an external filed applied on the system, which can be thought as a dc field during acting period in the experiment. $\beta=(\epsilon_p-\epsilon_f)/(\epsilon_p+2\epsilon_f)$ expresses the mismatch factor of the permittivity between solid and liquid phase, where the subscripts p and f indicate the particle and fluid, respectively. The particles aggregate if the force F between neighboring particles surpasses a certain value. This aggregation phenomenon has been observed by means of test methods.[8–10] However, no direct observations for the dynamic process of particle aggregation and the formations of chain and column were made, including that for the time dependence of the ER effect.

In this work, a newly designed time-regulated high-voltage power supply and a sensitive ER effect device are introduced to investigate the time dependencies of the particle aggregation and corresponding ER effect induced by the interaction among the aggregated particles. The results show that, under fixed electric field strength, the suspended glass microspheres in the silicon oil will aggregate only when the time of the electric field acting on the particles reaches a certain threshold value. The aggregated particles form chains and columns sequentially if the acting time on the particles is further increased. During particle aggregation, the ER effect induced by the interactions among the particles increases through three separate stages. In addition, it is observed that the aggregation of the particles becomes faster and the interaction among particles is much stronger under higher field strength.

II. EXPERIMENTS AND RESULTS

A. Time-dependent effect of particle aggregation

In order to study the time dependence of the particle aggregation and corresponding ER effect, a special high-power supply was designed for our experiment which is shown in Fig. 1(a).[11] It consists of five parts: (1) function generator (HP PM5238), (2) low-voltage dc power supply, (3) high-voltage dc power supply (0–15 kV), (4) trigger signal source, and (5) high-voltage switch HVS (HTS 150-PGSM, BEHLKE ELECTRONIC GmbH). As can be seen from circuit diagram in Fig. 1(a), the trigger signal produced by the IC2 is used to trigger the function generator PM5138. Its period T is varied continually through V_{R1} and C^*. To control the time-on width t_w of the trigger signal outputted from the function generator, one burst wave number of PM5138 should be chosen, thus the time-on pulse t_w, which is defined as acting time on the particle can be adjusted easily. The output wave from the PM5138 can be seen in the left upper side of Fig. 1(a), where T and t_w of pulse *Tr*, which is used to trigger the HV switch, are controlled by the IC2 and PM5138, respectively. The magnitude of the high-voltage pulse is controlled linearly by a high dc power supply, which ranges from 0 to 15 kV, see Fig. 1(b). With this configuration, the requirement of an acting time t_w less than 200 ns is satisfied. The difference between the high-voltage pulse gen-

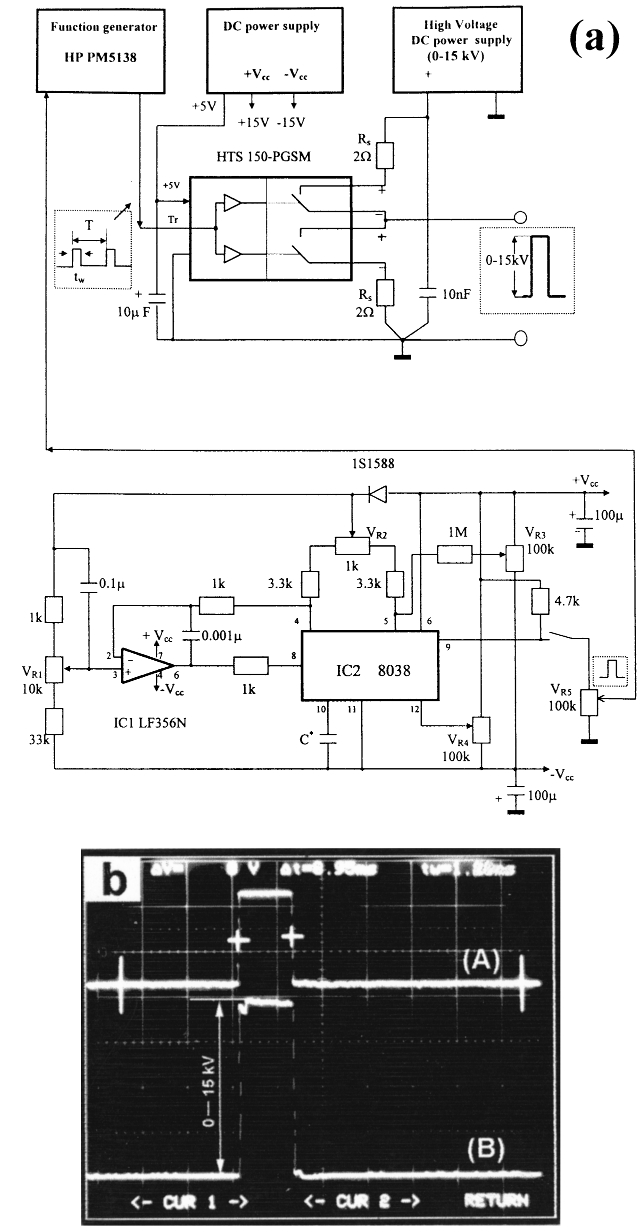

FIG. 1. Schematic of the electronic system.

erators that are available commercially (such as Cober Electronics, 605 P or DEI, GRX-6.0K) and ours is that the periods of time-on and -off of ours can be adjusted individually, which is particularly useful to monitor the particle aggregation within an individual pulse-on period.

The experimental cell used to contain ER fluid is formed by mounting two parallel electrodes onto a glass slide, on which a drop of well-mixed glass/oil ER fluid is dispersed. An optical microscope with video recorder is employed to monitor the dynamic process of particle aggregation as the electric field is applied to the sample. The volume fraction of the sample is about 0.05–0.06. During the experiment, the high-voltage pulse width t_w is altered to examine the particle behavior. Data are collected under a pulse $V_{p\text{-}p}$ of 1.2 kV/mm.

Figure 2 illustrates the aggregation process of the glass microspheres under an external electric pulse of $V_{p\text{-}p}$ $=1.2$ kV/mm. To measure the minimum acting time t_w needed to generate relative motion between two neighboring particles, t_w was increased gradually starting from 200 ns while the movement of the particles was monitored. Since the size of the microspheres used is 47 μm, the Brownian motion could be ignored. It was found that no obvious particle movement could be detected until t_w was increased to 16 ms. It can be seen from Fig. 2 that at $t_w=0$, all particles were dispersed randomly in the oil. When t_w reached 51 ms some short chains could be clearly identified as shown in Fig. 2(b). As t_w increased, the chain length increased and finally stretched across two electrodes; see Fig. 2(c). The time needed for the chain formation ranged between 100 and 130 ms. Figure 2(d) shows the final column state for t_w $=840$ ms, where individual columns could be observed. For $t_w>840$ ms, then all columns were in stabilization and no change observed for higher t_w. We have also tested the interaction under different field strength and found that the higher the field strengths, the faster the particle aggregation and the higher the particle interaction.

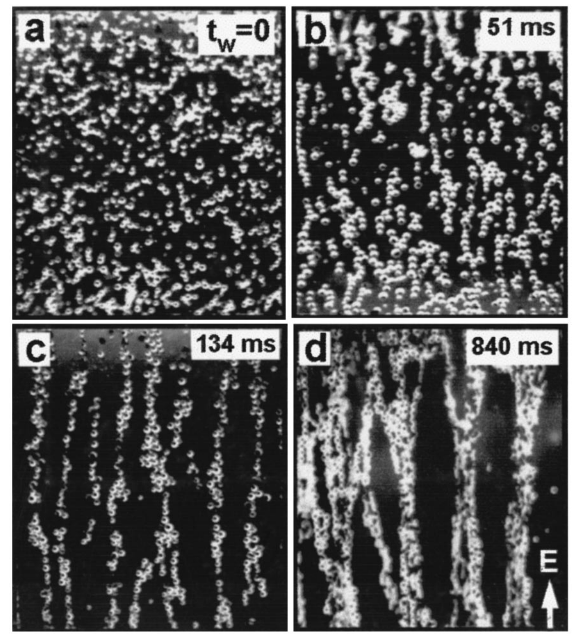

FIG. 2. Structure changes at different t_w. Here V_{p-p} is fixed at 1.2 kV/mm.

B. Time dependence of ER effect

Figure 3 shows the schematic of a sensitive ER effect device designed for testing weak interaction among glass microspheres suspended in oil. The ER effect is measured by using a parallel plates torsion system with a pules electric field applied across the ER fluid sandwiched between the two parallel plates. The lower plate is mounted to a computer-controlled motor whose rotating speed is fixed at 0.001 rpm. The upper plate is held by a stainless wire on which a mirror is fixed. Without field, the reflected laser spot on the reading device is at the left zero position (see upper left of Fig. 3) and corresponds to the lower plate rotating very slowly and dragging the top plate. When an electric field is applied, the viscosity of ER fluids increases and results in the displace-

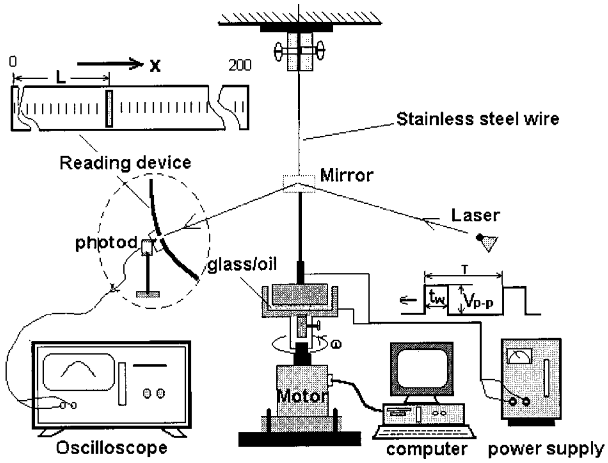

FIG. 3. Setup for ER effect measurement. The motor speed is 0.001 rpm.

ment of the spot on the reading device from its original position towards the x direction, thus the reading on the screen can be read out until slipping occurred between the two plates.

Figure 4 shows the time dependence of ER effect at fixed field strength, which was done by moving the laser spot on the reading device near to the photod ($L=1-2$ scales in distance) at $t_w=0$ and then detecting the signal emitted from the photod as t_w increased, starting from 200 ns. Any interaction among the particles would result in a viscosity increase in the ER fluid and hence a displacement of the laser spot on the reading device. The sensitivity of this setup can be easily controlled by adjusting the distance between the mirror and reading device. When t_w was at 2.5 ms, the output signal was as shown in Fig. 4(a). The test presented here was so sensitive that even very weak interaction among the particles could be detected. For increases in t_w, the laser spot moved faster and faster; therefore, the magnitudes of signal s emitted from the photod were smaller and smaller, as seen Figs. 4(b)–4(d). The minimal time for the ER effect was shorter than 2.5 ms.

Further results from two experiments corresponding to particles of two different sizes are given as Fig. 5. We note that the response time of the ER effect changes with particle

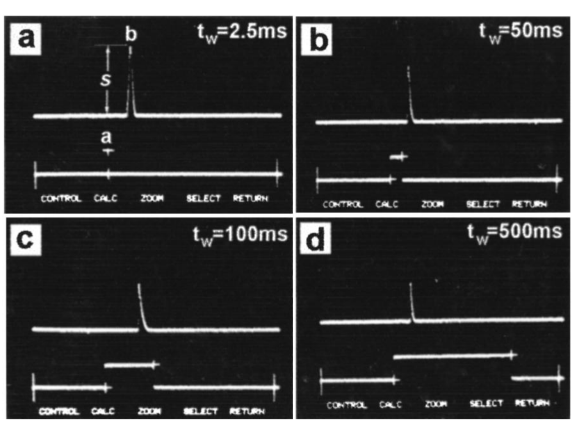

FIG. 4. Time dependence of ER effect tested with 1.5 μm sample. Here the field strength V_{p-p} is 1.2 kV/mm. s presents the signal amplitude outputted form photod.

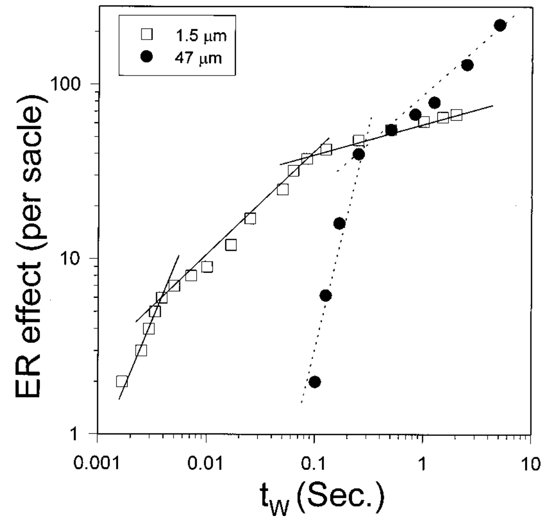

FIG. 5. Time dependencies of ER effect tested with 1.5 and 47 μm samples, respectively.

size. That is, the smaller the particle size, the shorter the response time of the ER effect. Under the same experimental conditions, the initial ER effect response time (i.e., when the spot first moves) was less than 2 ms for an ER fluid consisting of 1.5 μm particles, while the ER fluid consisting of 47 μm particles was nearly to 100 ms. The reason for this may be particle sedimentation—almost all particles sediment to the bottom of the lower plate before the electric field is applied. When the field was applied, the particles suspended themselves before interaction occurred among them. Intuitively, then, the bigger the particle size the longer response time for the ER effect. A more interesting phenomenon, which can be identified from Fig. 5, is that there exists three

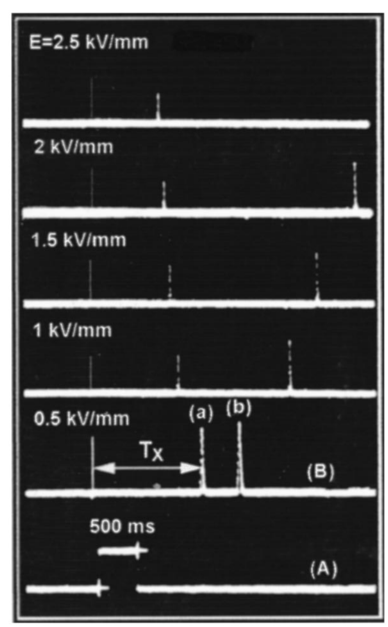

FIG. 6. Field dependence of ER effect taken from an oscillosynchroscope; T_x is the time that the laser spot on the reading device moves from zero to photod; signals (A) and (B) are HV pulse and output from photod; (a) and (b) are the signals going and going back through photod.

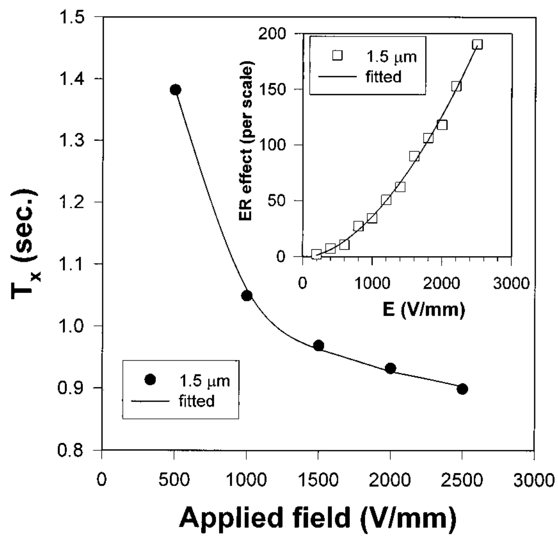

FIG. 7. Field dependence of ER effect at fixed t_w.

different stages of increasing ER effect. A rapid increase of the ER effect can be seen in first stage.

For the case of 1.5 μm sample, where $t_w = 500$ ms, the dependence of the ER effect on the magnitude of the pulse field is determined as shown in Fig. 6. The test is performed by increasing the field strength $V_{p\text{-}p}$ from 500 to 2500 V/mm while measuring the variations of T_x, which is defined as the time needed for the laser spot to move from zero to the photod ($L=20$ scales in distance). It can be seen that T_x decreases as field strength is increased, which means that the higher the field strength the stronger the ER effect. The data are plotted in Fig. 7. By curve fitting, a power-law dependence is found between T_x and field strength E: $T_x \sim E^m$ with the exponent m approximately equals to -1.37. Finally, for the same t_w, the field dependence of ER effect (by counting scale numbers which the laser spot moved) has also been measured and the results can be seen in the inset of Fig. 7, where the relationship between ER effect τ and field strength E is satisfied, with $\tau \sim E^{1.81}$ in our test.

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