In situ time response measurement of the microspheres dispersed in electrorheological fluids

Weijia Wen, D. W. Zheng, and K. N. Tu
Department of Materials Science and Engineering, University of California at Los Angeles, Los Angeles, California 90095-1595
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The aggregations of different kinds of microspheres suspended in electrorheological fluids have been observed *in situ* upon application of time-regulated electric field. It is found that both the initial response time and the chain's formation time depend on the conductivity of the microspheres. Water free, watered, and metal-coated glass microspheres together with $SrTiO_3$ and Cu microspheres were studied. Among them, the water-free glass particle shows the longest initial response (chain formation) time of 16.7 ms (117.6 ms) under an electric pulse strength V_{p-p} of 2.6 kV, while the metal-coated microsphere has the shortest initial response (chain formation) time of 0.5 ms (25.4 ms). The overall trend is that the higher the microsphere's conductivity, the shorter the response time and the stronger the particles' interaction under the same external electric field. Moreover, it is found that the aggregation of the microspheres becomes faster if the applied field strength is increased. [S1063-651X(98)11904-9]

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In the past decade many theoretical and experimental works have been performed on electrorheological fluid (ER) due to its potential industrial applications. The ER fluid consists of dielectric particles immersed in an insulating liquid. Its unique property is a large increase in the viscosity upon application of an external electric field and returns to its original state when the electric field is removed. The change of viscosity of ER fluids is thought to be caused by the dipole-dipole interaction induced by external field on the particles [1–5]. A large number of material particles show ER activities in addition to dielectric particles: metal particles as well as dielectric particle coated with metal layer [6,7]. Recent experiments show that the aggregation pattern formed by these particles can be totally different depending on their surface conductivity. The effect of conductivity on the ER activity has been put forth in earlier theoretical work [8–11].

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

$$F=\frac{6p^2}{4\pi\varepsilon_0\varepsilon_f d^4}, \tag{1}$$

where $p=4\pi\varepsilon_0 a^3\varepsilon_f\beta E$ represents the dipole moment. E is an external field applied on the system that can be thought of as a dc field acting during a period in the experiment $\beta=(\varepsilon_p-\varepsilon_f)/(\varepsilon_p+2\varepsilon_f)$ expresses the mismatch factor of permittivity between solid and liquid phases, where the subscripts p and f indicate the particle and fluid, respectively. The particles would aggregate if the force F between neighboring particles surpasses a certain value that has been observed in many experiments as the electric field is increased. Though there are some primitive attempts to measure the initial and chain formation response times [12], which is very important for the application of ER fluids in damping devices, no accurate measurements of these parameters have been carried out.

In this paper we present experimental data that show that, under a fixed time-regulated electric field, the suspended particles in silicon oil will aggregate only when the time of the electric field acting on the particles surpasses a certain threshold value. Below the threshold value they will suspend randomly in the liquid. We found that the particle aggregation time and the distance a particle moves within each pulse period depend not only on the strength and acting time of the external electric field but also on the particle conductivity. Our experiments show that, under the same external electric field strength and acting time, the interaction force among the water-free glass microspheres is the weakest, while that of metal-coated microspheres is the strongest. In addition, the interaction force increases drastically when a little amount of water is added to the glass particles.

Our experimental cell is formed by two parallel electrodes mounted on a glass slide a drop of well-mixed ER fluid is dispersed. An optical microscope with a video recorder is used to monitor the whole process of particle aggregation as the electric field is applied to the sample. In order to observe the dynamic process of particle aggregation, a special high-power supply was designed for our experiment, which is shown in Fig. 1. It consists of two function generators. One is used as a standard frequency reference and the other (Hewlett-Packard model No. PM5138) is used as a transistor-transistor logic (TTL) trigger that is connected to an input trigger terminal of the high-voltage switch (HVS)

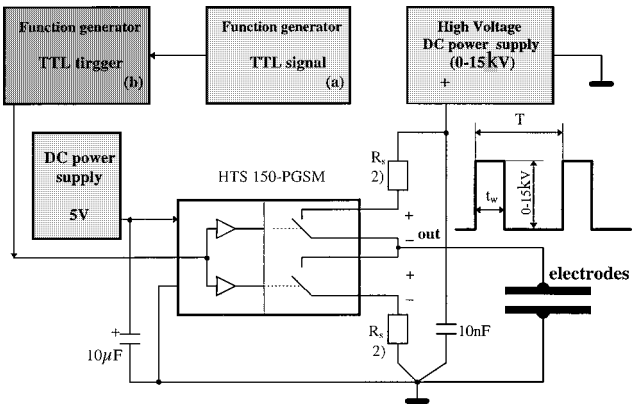

FIG. 1. Schematic diagram of the electronic system used in this study.

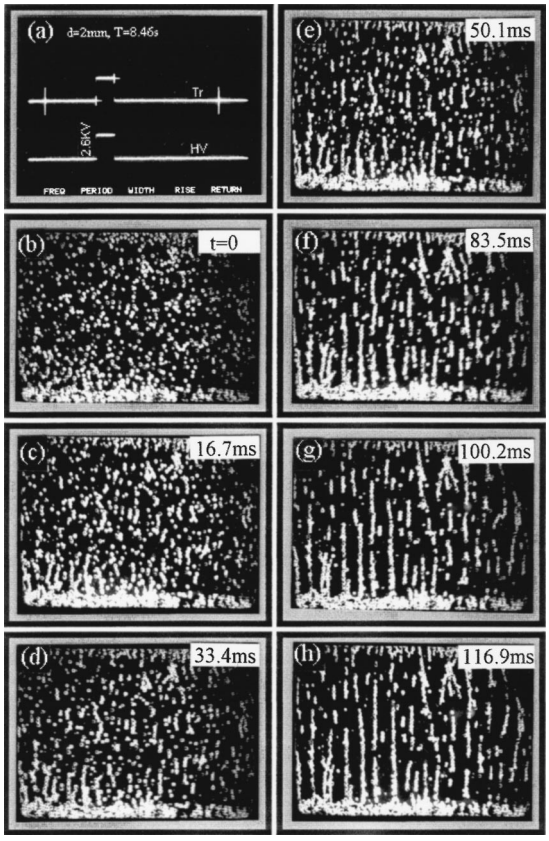

FIG. 2. Optical microscope image of the particle pattern formed at different high-voltage width values (t_w) in the case of (a) a water-free glass microsphere pattern of the applied signal on the oscilloscope for (b) $t_w = 0$ ms, (c) $t_w = 16.7$ ms, (d) $t_w = 33.4$ ms, (e) $t_w = 50.1$ ms, (f) $t_w = 83.5$ ms, (g) $t_w = 100.2$ ms, and (h) $t_w = 116.9$ ms. The volume fraction of ER fluids used here is 0.05.

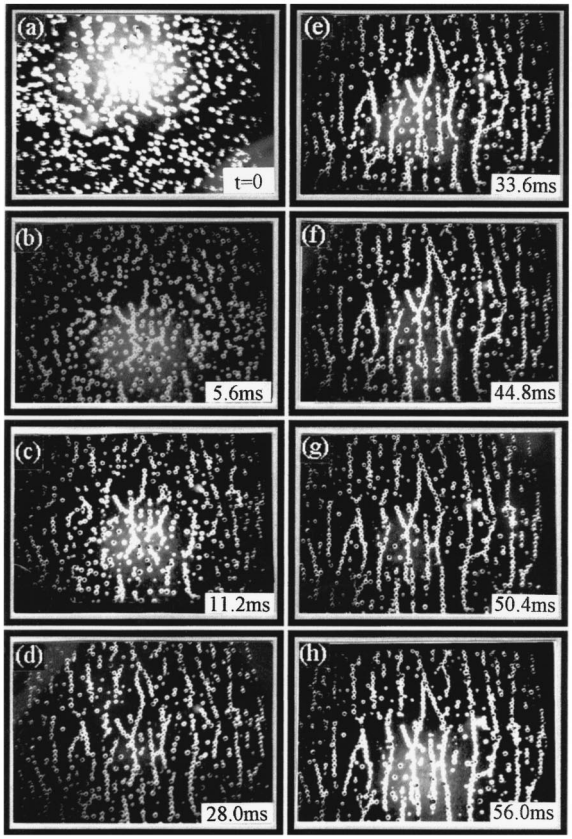

FIG. 3. Optical microscope image of the particle pattern formed at different high-voltage pulse-width values (t_w) in the case of a water-evaporated glass microsphere.

(HTS 150-PGSM, Behlke Electronic GmbH). In the figure t_w and T represent the field acting time and repetitive time, respectively. The shortest acting time of high strength field on the particles can be less than 200 ns. Both the input trigger signal and output high-voltage pulse can be easily controlled through adjusting the standard frequency and the number of burst waves of two function generators. The output field amplitude is controlled by a high dc power supply so that a satisfying linear increment of field strength could be easily achieved. The actual electric-field application time was measured by adding up the accumulative power on time within each pulse and experimentally we observed that the response time data were irrelevant to whether we had a long power-on time within one pulse or several pulses with equivalent accumulative power-on time. To characterize the system's dynamic behavior, we have defined two parameters: One is the initial response time, which is defined as whenever we can identify the relative motion between two neighboring particles under the external electric field; the other is the chain formation time, which is defined as whenever we start to see a complete path formed by the particles from one electrode to the other.

To compare the effect of conductivity on the initial and chain formation response times, various particles were tested in our experiment, including a glass microsphere, a watered glass microsphere, and a glass microsphere coated with a Ni layer by electroless plating, a high dielectric constant microsphere $SrTiO_3$, and a metal Cu microsphere. All particles used have a diameter of 35 ± 5 μm. A repetitive high-voltage electric pulse was applied with a fixed period of $T = 8.46$ s. This pulse repetition time allowed our video system to record the particle movement in response to individual external electric pulses. The high-voltage pulse width t_w was altered

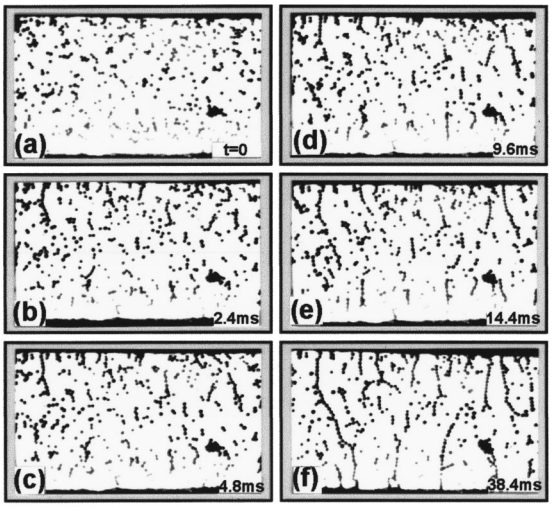

FIG. 4. Optical microscope image of the particle pattern formed at different high-voltage pulse-width values in the case of a Ni-coated glass microsphere.

TABLE I. Measured results of the average initial interaction time (t_i) and the chain formation times (t_c) carried out with various microspheres under different fields V_{p-p} of 1.2 and 2.6 kV, respectively. The volume fraction is 0.05.

Materials		Water-free glass microsphere	Watered microsphere	Metal coated	$SrTiO_3$ microsphere	Copper microsphere
Applied field	Time (ms)					
$V_{p-p}=1.2$ kV	t_i	28.2	11.6	0.7	24.8	1.1
	t_c	202.5	96.5	48.5	167.7	62.6
$V_{p-p}=2.6$ kV	t_i	16.7	5.6	0.5	13.4	0.8
	t_c	117.6	55.7	25.4	98.5	39.5

to examine the particle behavior. Data were collected under a V_{p-p} of 2.6 and 1.2 kV, respectively. It should be pointed out that, to ensure clear observation, all samples used were diluted to a low-volume fraction less than 0.05 of the solid phase.

Figure 2 illustrates the aggregation process of water-free glass microspheres under an external electric field pulse with a V_{p-p} of 2.6 kV. Figure 2(a) depicts the pulse applied to the samples. 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 was 35 μm, all Brownian motion could be ignored. In addition, at the same t_w, the interaction among the particles would be stronger as represented by a faster aggregation of the particles if the external electric-field amplitude was increased. A series of pictures of the whole process of particle aggregation is shown in Figs. 2(b)–2(h). At $t_w=0$, all the particles are dispersed randomly in the oil; see Fig. 2(b). At $t_w=16.7$ ms, some short chains can be observed clearly; see Fig. 2(c). As t_w is increased further, the length of chain increases; see Figs. 2(d)–2(g). The final state is Fig. 2(h), where all particles sticks to the chains and the system is stabilized.

It has been hypothesized that any addition of water to the dielectric particles would change their surface dielectric constant and conductivity and would increase the interaction force among them. However, the direct observation of the interaction between individual microspheres remains unexplored. In our study, we use the same kind of glass microsphere as mentioned in the previous experiment except that they were moistened by water evaporation before being mixed with silicon oil. Figure 3 shows the aggregation of the watered microsphere at different t_w values. We note that the initial response time is 5.6 ms, which is much shorter than that of water-free particles, and the chain formation time is about 56 ms.

Figure 4 shows the case of glass microspheres coated with a Ni thin film. It is found that the metal-coated microsphere has the fastest initial response time and chain formation time, measured to be 0.5 and 25.4 ms, respectively. The interaction is so strong that even when the electric-field strength is lowered and the acting time is shortened, it can be seen clearly.

We have also studied the aggregation of water-free $SrTiO_3$ microspheres and found that the initial and chain formation response times are about 13.4 and 98.5 ms, which are almost the same as those of water-free glass particles. However, a faster response would occur if a small amount of water was added to such particles. This indicates that the interaction between particles depends not only on the dielectric constant but also the surface conductivity. Finally, Cu microspheres were investigated and the results indicate that its response time is close to Ni-coated glass microspheres. However, a slower aggregation was detected than that of Ni-coated glass particles due to the mass difference. In addition, the patterns formed by metal particles are different and they tend to be fractal-like patterns rather than straight chains. Finally, the initial (t_i) and chain formation (t_c) times for different materials under a field of $V_{p-p}=1.2$ and 2.6 kV are shown in Table I, where it is shown that the metal-coated particles have the shortest response time. This suggests that this kind of material is suitable for fast-response devices such as high-frequency dampers.

In summary, the particles interaction in silicon oil and their response time under the external electric field have been investigated in this paper. It is found that microspheres with conductive metal coating exhibit the strongest interaction as represented by the fastest chain formation time, while that of the waster-free glass microspheres is the weakest. This suggests that the effect of conductivity is much larger than that of the dielectric constant on the particle response time and particle interaction in ER fluid.

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