Single-phase electrorheological effect in microgravity†

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We report the first observation of an electrorheological (ER) effect in a single phase ER suspension, comprising mono-dispersed dielectric particles, from a microgravity experiment. In microgravity, the particles can form stable single phase suspension without a suspending liquid, which is usually necessary for the conventional ER fluid. The size of the column structures formed by the particles exceeds the maximum column width usually observed in the two-phase ER fluids. Numerically evaluating the variation of the electric energy density with respect to the strain yields a good account of the measured data, especially in the low field region.

Electrorheological (ER) fluids1–13 are made by dispersing micron/nano-size dielectric particles in the low-viscosity non-conducting liquid (e.g.: silicone oil). An externally applied electric field can induce interactions among the polarized particles due to the dielectric constant mismatch between the solid and liquid phases, thereby giving rise to the increased viscosity of the ER fluids.1,5,6 The rheological variation is reversible and the response time can be as short as a few milliseconds. ER fluids can serve as an electrical–mechanical interface. When coupled with sensors to trigger the electric field, ER fluids can turn many mechanical devices into active elements capable of responding to environmental variables.14–18 Meanwhile, fluid logic functions have been realized by introducing the recently discovered giant electrorheological (GER) fluids2,11 into microfluidic chips.19 Hence, ER fluids are usually denoted as “smart” fluids.

ER fluids are typically two-phase colloidal systems. The liquid phase is generally needed, partially for preventing the sedimentation of the dielectric particles in the gravity environment. Therefore, most of the theoretical and experimental efforts were endeavored to study the mechanisms and applications of the two-phase ER fluids, while very little work concerns the ER behaviors of single-phase ER fluids without the dispersing liquid.8 The density and zero field viscosity of such single-phase ER fluids may be extremely low, and their response to the applied field may be even faster, both due to the absence of the liquid phase (and hence the viscous drag). Potential applications of single-phase ER fluids may be found in the outer-space stations with micro-gravity environment, serving as a tunable friction-generating material.

In this work, we report the first observation of ER effect for a single phase ER suspension, comprising mono-dispersed glass beads (100 μm in diameter, G8893, Sigma), from a drop-tube microgravity experiment. A highly sensitive setup for measuring the ER effect was specially designed for this experiment, including a lab-made electro-rheometer for single-phase ER fluids, an imaging system, and accessorisal system for control and data recording purposes. Our results show that in the microgravity environment, the glass beads can form stable single-phase suspension without the suspending liquid phase. Such suspensions are capable of producing ER effect under an applied electric field, that is explainable on the basis of the induced polarization mechanism.1,5,6 The size of the structures formed by the glass particles is observed to exceed the maximum column width usually observed in the two-phase ER fluids, implying a different kinetics. The lack of a liquid background (typically with a dielectric constant around 2, the value adopted from silicone oil) can further enhance the dielectric constant mismatch, and hence the ER effect. The finite element method (FEM) is used to evaluate numerically the shear stress as a function of the applied field, and the results are in good agreement with the measured data, especially in the low field region. The adopted experimental method can successfully rule out possible contributions to the observed ER effect arising from the dispersing liquid. Therefore, it may be employed to investigate interactions induced by the liquid phase in some more complex colloidal systems, including the GER fluids.

A drop tube or drop tower is the most convenient ground-based facility for microgravity experiments. Our measurements were conducted at the Micro-Gravity Laboratory of Japan (MGLAB, Japan), where a high quality microgravity experiment environment (10⁻⁴ G level) is offered. The vacuum drop tube (≤13.3 Pa) consists of a ~100 m free drop zone and a 50 m braking zone. Duration of microgravity is approximately 4.5 s. More details on MGLAB, Japan, can be found at http://www.mglab.co.jp/.

A highly sensitive automatically operated linear shear type electro-rheometer was specially designed and implemented for the microgravity experiment, as shown in Fig. 1. The gap between two parallel electrodes is 1 mm, and the dimension of the two parallel electrodes is...
95.8 mm × 95.8 mm. The speed of the shearing electrode is set to be 5 mm min⁻¹, corresponding to a strain rate of ~0.08 radian s⁻¹. An integrated imaging system served to capture the images and record the relevant data. All the components were carefully optimized to avoid being affected by the harsh experimental conditions, such as the large acceleration and the interfering noise from the surrounding electronics.

System error introduced by friction has been calibrated out. Technical details of our microgravity electro-rheometer can be found in the ESI†.

Mono-dispersed glass beads (100 μm in diameter, G8893, Sigma) were selected for testing single-phase ER behavior in microgravity. To demonstrate the possible effect of microgravity on the ER behaviors, no surface coating of the particles has been performed so that comparison may be made between the measurements and the simple calculation of the DER theory. A total four productive drops were performed, after an initial testing drop. The electric field was applied by using a 1 Hz rectangular voltage signal with a duty cycle of 0.5. The magnitude of the field ranges from 400 V mm⁻¹ to 700 V mm⁻¹, starting with 400 V mm⁻¹ in the first drop and increasing by a 100 V mm⁻¹ step in each subsequent drop. For the productive drops, the load of the glass beads is fixed at 9 g, corresponding to a volume fraction of 36%. The sample is stirred at the beginning of each microgravity period with the purpose of ensuring uniform distribution. It is noticed that in a similar lab-made high voltage system, strong evidence has been recently found for the production of hydrated electrons by the field-directed injection of electrons from metallic electrodes into the surface condensed water films on the silica particles.⁸

Fig. 2 shows the snapshots of the sample taken at 0 s, 1 s, 2 s, and 3 s during the microgravity period of one drop, with an applied electric field of 700 V mm⁻¹. White dashed lines separate the region in which the glass beads were well stirred (the lower right part of the vessel) before the field was turned on, while in the upper left part, the glass beads remained in a state of high filling ratio (apparently not affected by the initial stirring) so that no field induced configuration evolution can be observed. Below we focus our attention on the lower right part of the vessel in Fig. 2. Formation of column-like structures started as soon as the first pulse was applied (top-views shown in Fig. 2b). At the end of the third pulse, several well-developed columns can be clearly observed, as shown in Fig. 2d. It is worth mentioning that in the conventional two-phase ER fluids the maximum column width usually observed is ~7 to 8 particle diameters. In the present case the observed column widths are much larger (as circled in Fig. 2d in yellow). Furthermore, complex connected lateral network configurations are also observed (as circled in Fig. 2d in red). This phenomenon may imply that the kinetics of the structure formation in the single-phase ER fluids in microgravity could be different from that for the two-phase ER fluids, probability due to the absence of dispersing liquid, and hence the viscous drag.

Fig. 3 shows the measured shear stress as a function of the magnitude of the applied electric field, with insets (a) and (b) showing the measured force as a function of time, at 600 V mm⁻¹, for samples

![Fig. 1](image1.png)  
**Fig. 1** (a) Schematics of the electro-rheometer for the microgravity experiment with (1) upper electrode, (2) bottom electrode (ITO glass), (3) sample vessel, (4) motor, (5) force sensor, (6) suspending stage, (7) CCD, (8) optical lens for imaging system, (9) illuminating system. (b) Schematics of the measurement. (c) Equipment arrangement inside the drop capsule.

![Fig. 2](image2.png)  
**Fig. 2** Top-view images of the sample taken at (a) 0 s, (b) 1 s, (c) 2 s, and (d) 3 s of the microgravity drop period, with an applied field of 700 V mm⁻¹, showing the structure formation (indicated by the light-colored areas) driven by the electric field. Particles are seen to be initially well distributed in the region below the dash line. In (d) the column and network structures are highlighted by yellow and red circles, respectively.

![Fig. 3](image3.png)  
**Fig. 3** Measured shear stress as a function of the electric field. The recorded force signal as a function of time at 600 V mm⁻¹ for the 60% and 36% (volume fraction) samples are shown in the insets (a) and (b), respectively. The applied voltage pattern is plotted on the same graph.
with a high concentration (60%, for the testing drop) and low concentration (36%, the productive drops), respectively. The applied voltage pattern is plotted on the same graph. The shear stress increases immediately with ‘‘pulse on’’ and decays with ‘‘pulse off.’’ Such correlation confirms the ER effect of our single phase samples to arise from the applied electric field. However, from the limited data points, the quadratic dependence of the shear stress on the electric field as for typical DER fluids cannot be verified. It is instructive to compare the magnitude of the measured shear stress with that predicted by the DER model.6

To do this, the finite element method (FEM) approach was adopted to numerically calculate the system’s electric free energy density as a function of the strain, with the shear stress evaluated by direct differentiation. In the FEM simulations, it was assumed that the particles can form large columns under an electric field. The structure of the glass spheres within the column is taken to be the body-center tetragonal (BCT), which is the ground state of DER fluids according to our previous results.6 Radius and volume fraction of the glass spheres are set to be the same as in the experiment. Note that the background dielectric constant is set to be 1. The strain is imposed by tilting the angle between the columns and the applied electric field in the simulations. The shear stress is obtained from the variation of the calculated electric free energy density with respect to the strain. For different electric field magnitudes, values of shear stress at a fixed strain of 18.5° (corresponding to that between 3 s and 4 s in the experiment.) were taken from the simulations for comparison with the experiment data. It is found that the FEM results are in good agreement with the measurements for the low field cases, e.g., for 400 V mm⁻¹ and 500 V mm⁻¹, the calculated shear stress is around 16.4 Pa and 25.6 Pa, respectively. However, in the higher field region, the measured shear stress is suppressed, and the calculation overestimates the stress by a factor by 25% at 600 V mm⁻¹ and 74% at 700 V mm⁻¹.

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Notes and references