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Sedimentation behaviour in electrorheological fluids based on suspensions of zeolite particles in silicone oil

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ABSTRACT

Sedimentation is a known and expected shortcoming of electrorheological fluids (ERFs) due to the inherent difference in the constituent densities. The long-term sedimentation causes loss of the electrorheological phenomenon and the exploitable electromechanical and viscoelastic properties despite the presence of the stimulating electric field. In this work, we report the effect of temperature and surfactant concentration on the stability of ERFs prepared from zeolite particles and silicone oil with primary focus on the sedimentation of the particles in the ERF. As the temperature stability of the ERFs is fundamentally important, we have studied three different ERF suspensions composed of different zeolite particles, in silicone oil. These ERFs have been comparatively evaluated for their sedimentation over time, across a wide range of temperatures (−40 °C to +60 °C). The influence of surfactant concentration on the colloidal stability of the ERFs has also been investigated. A novel method of acoustic stirring (kHz range) on the homogenisation of the ERFs has been proposed and its effect on the sedimentation process evaluated. These results are useful for assessment of alternative suspension methods for specific applications.

1. Introduction

Electrorheological fluids (ERFs) are special type of suspensions of particles in an insulating liquid medium with low dielectric constant and viscosity, which exhibit controllable fluidity under the influence of an applied electric field. They contain semiconducting or polarisable particles as electro-responsive constituents, which align in the direction of the applied electric field to generate a solid-like phase in the suspension. ERFs have received intensive research interest during the last decade, mainly due to their very interesting electromechanical properties and functionalities. When polarised by the electric field, the conductive particles dispersed into the non-conductive medium fibrillate and form long chains modifying the viscosity of the material. Viscoelastic behaviour is stimulated by fields above a few hundred kilovolts per mm. Extreme field conditions cause the ERF to change its state from liquid to solid – a reversible behaviour, upon removal of the field. This so called (positive) electrorheological phenomenon (ERP) has long been observed [1,2] and the preparation of suspensions that exhibit a strong and exploitable ERP has also been reported [3–7]. This has resulted in renewed research interest in ERFs, mainly motivated by their applications in the area of automotive industry (clutches, brakes, absorbers, bumpers, etc.). To this effect, various studies have been carried out on the rheology and stability of ERFs [8–16].

Modern ERF suspensions consist of zeolite or lead titanate particles dispersed in silicone oils. From an electrical point of view, ERFs are required to possess a high electrical resistance so as not to conduct current under electric field, in order to avoid heating. Critical for applications is the range of temperature within which the ERP is obtained. Automotive industry, for example, requires steady mechanical properties in a range of −15 to +120 °C. Another critical requirement, which was detected quite early by Winslow [1], is to reduce the amount of water or other similar substances absorbed by the particles, which can increase electric conductivity, heating and corrosion. These effects in turn, result in an ERF of reduced strength. On the other hand, extensive drying for the elimination of water also reduces the strength of the ERF. A controllable dehumidification process is seen to be the optimum. The first successful suspensions in this aspect were patented in the late 1980s. Today, intense research efforts are focused on this aspect. The importance of stable electromechanical properties over time has prompted researchers to investigate materials and suspensions that are non-abrasive, non-corrosive and resistive to sedimentation and electrophoresis [2,6].

There are many important characteristics of ERFs, including high yield stress under electric field, rapid response and dispersion stability that must be met in the required applications. The stabil-

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ity of ERFs towards sedimentation is an important criteria for their long-term use and performance. In order to improve dispersion stability several methods, such as matching the density between the two phases, stabilising particles by surfactant addition, and using high-viscosity liquids and/or small particles have been proposed [17–23]. Li and co-workers have prepared suspensions exhibiting the giant electrorheological (GER) effect comprising multiwall carbon nanotubes (MWCNTs) composite particles dispersed in silicone oil [24]. The nanoparticles–nanotubes composites were obtained by a modified co-precipitation method with MWCNTs and urea-coated barium titanyl-oxylate nanoparticles as the components. The study showed that the stabilised suspensions with the composite particles dispersed in silicone oil could be stored for several months without any noticeable sedimentation and without affecting their yield stress characteristics [24].

The stability of electrorheological (ER) fluids towards sedimentation is an important criterion for their suitability in a variety of fields, particularly for long-term applications. This work reports on the study of the effect of temperature, stirring and surfactant concentration on the dispersion stability of zeolite particles in silicone oil. A new method using kHz range acoustic vibrations to increase the stability of ERF suspensions is also reported.

2. Experimental

2.1. Materials

Zeolites or molecular sieves are crystalline metal aluminosilicates having a three-dimensional interconnecting network of silica and alumina tetrahedra. In this study, three different types of zeolites (organophilic, 5A and 13X) were employed for the preparation of ERFs suspensions. The organophilic zeolites (high silica zeolites) are similar to Type A and Type X zeolites, except that they have a significantly higher proportion of SiO_2 to AlO_2 in their molecular structure. With the reduced amount of AlO_2 and corresponding reduction in the cation density, the high silica zeolites are hydrophobic and organophilic adsorbents. Also, they are stable at low pH values and can sustain high temperatures up to 700 °C. For the first part of the study only 5A type zeolite was used, however all three types were employed in the second part related to the effect of a range of temperatures on the dispersion stabilities of ERFs. The liquid medium used in the preparation of all ERFs was silicone oil (polydimethylsiloxane) which has viscosity of 10 cSt and a density of 0.93 g/ml at 25 °C. Span 40, sorbitan monopalmitate, was used as the non-ionic surfactant. All the materials used in this study were purchased from Sigma Aldrich and were used as-received.

2.2. Preparation of ERFs

The following general procedure was adopted for the preparation of the ERFs. The zeolites were first dried at 200 °C for 2 h and allowed to cool to the ambient temperature in a desiccator. The ER fluids were then prepared by dispersing the dry zeolite particles in silicone oil by stirring the mixture using a mechanical stirrer (Fig. 1). The suspensions were further heated in a microwave for 1 min at 500 W power. All the ERF samples were prepared using the same stirring rate. The concentration of the zeolite particles was adjusted for each sample between 30 and 50 w/v% as required. The non-ionic surfactant used in the current study was Span 40 with a density of 0.97 g cm^{-3} and molecular weight 402 g/mol. The surfactant concentration was adjusted between 1 and 5 wt.% as desired. The morphologies of the particle dispersions were determined using an optical microscope and a scanning electron microscope (Hitachi S3400).

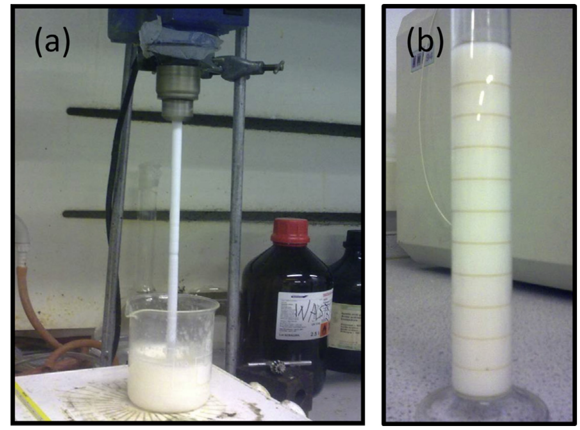

Fig. 1. (a) Preparation of ERF using mechanical stirring and (b) resulting ERF suspension.

Table 1
Properties of zeolites used for ERF Preparation.

ER fluid code	Zeolite type	Particle size (μm)	Pore diameter (Å)	Bulk density (lb/cu ft)	Moisture (%)
ERF1	Organophilic	3–5	3	32	<2
ERF2	5A	3–5	5	30	<2
ERF3	13X	3–5	10	30	<2

2.3. Determination of dispersion stability

The sedimentation propensity of the ERF at the ambient temperature was determined by filling 100 ml graduated glass cylinders with the ERF to the mark and then allowing the particles to settle over a period of up to 100 h. For this, different suspensions of 30, 40 and 50 w/v% were prepared as per the procedure given above. The volume or height of the settled particles as a function of time was then determined. For the ambient temperature (23 °C) study ERF2 (see Table 1) was used, which was a suspension of zeolite 5A in silicone oil. In order to study the effect of temperature a modified procedure was adopted. For each one of the three suspensions, a 100 ml volume was prepared following the procedure described above. The solids content of the ERFs were 40 w/v%. The ERFs are stirred to obtain homogeneous suspensions just before the experiment. Three 10 ml-volume graduated glass cylinders were filled with each suspension and then placed in a temperature controlled chamber. The different temperature values used were −40 °C, −10 °C, 0 °C, 30 °C, 40 °C and 60 °C. The chamber was pre-heated/pre-cooled at the required temperature before inserting the graduated glass cylinders containing the ERF samples. When a specific temperature value was obtained and stabilised in the chamber, the three 10 ml graduated glass cylinders were placed in the chamber simultaneously. The separation level between the suspension (lower part) and the pure liquid (upper part) was monitored by a photographic camera, through the transparent chamber door. The relevant levels were then translated into sedimentation volume in cm^3. Results were plotted over time for each one of the six following temperatures [−40 °C, −10 °C, 0 °C, 30 °C, 40 °C, 60 °C], respectively.

3. Results and discussion

3.1. Effect of zeolite concentration

The effect of zeolite concentration (30–50 w/v%) on the sedimentation behaviour of the electrorheological fluid (ERF2) at ambi-