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Behavior of carbon cone particle dispersions in electric and magnetic fields

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ABSTRACT

The behavior of carbon cone (CC) particle dispersions in electric and magnetic fields is presented. The behavior of CC dispersions in an ac electric field was studied by the use of electrorheological (ER) measurements. Low ac electric fields were sufficient for fibrilar structures to form. However the structures formed were relatively weak as determined by ER measurements and this was attributed to the high conductivity of the particles. This is also consistent with the low relaxation frequency found by impedance spectroscopy. The behavior of a dispersion of CC added ferrofluid was studied using magnetorheological measurements. The relative increase in viscosity was found to be around 1.2–1.5 for low magnetic fields and low shear rates. This was attributed to purely hydrodynamic effects caused by CC particle–particle interactions.

1. Introduction

In some particle suspensions subjected to an electric or magnetic field, the particles form fibrilar structures which may change the properties of the suspension from liquid-like to solid-like. These kinds of suspensions are called electrorheological (ER) and magnetorheological (MR) fluids and they are used in a wide range of applications [1,2]. By measuring the rheological properties of these fluids the strength or rigidity of the fibrilar structures may be studied. The solid phase of such suspensions may be composed of various materials such as silicate ceramics, conductive organics and polymers. Numerous articles also report the use of carbonaceous particles of various kinds [3–8]. Some of these suspensions function as ER fluids. In other cases it is the resulting fibrilar structures that are interesting as they may be used for conductive paths in composites [4,7]. In this work a unique material called carbon cone material is used as the solid phase of various suspensions. Little experimental work has been done regarding this material, hence the basic physical properties are mostly unknown. The material is produced in an industrial scale process named Kværner Carbon Black & Hydrogen process [9]. Particles with conical and disk shape result from the process. The large scale process greatly reduces the material cost making the investigation of this materials interesting for possible future applications. Compared to carbon black, also produced in industrial scale processes, the carbon cone material contain particles with semicrystalline structure. In addition the conical particles represent perfect structures with a closed tip, creating unique electronic properties in the tip area [10]. At the present, pure samples representing only one geometry does not exist and finding an efficient purification process has proven difficult. Hence this study investigates the behavior of the mixed carbon particles in a dispersion in an electric and magnetic field. The influence of the particle concentration and the electric/magnetic field on the apparent viscosity is investigated. The ER effect is discussed with regard to the particle conductivity and the relaxation frequency of the dispersion. Possible applications are also discussed.

2. Experimental

2.1. Materials

The carbon cone (CC) particles provided by n-Tec AS [11], were used as the dispersant phase in both ER and MR fluids. The particles were used as produced. The particles have various geometries consisting of approximately 20% cones, 70% disks and 10% amorphous carbon. The size distribution typically varies from a few hundred nanometers for the amorphous carbon to about 5 μm for the largest disks, with most of the particles having dimensions of 1–3 μm, as determined by SEM analysis, Fig. 1.

For electrorheological studies the dispersive phase used was polydimethylsiloxane (silicon oil) (Dow Corning, density $\rho =$

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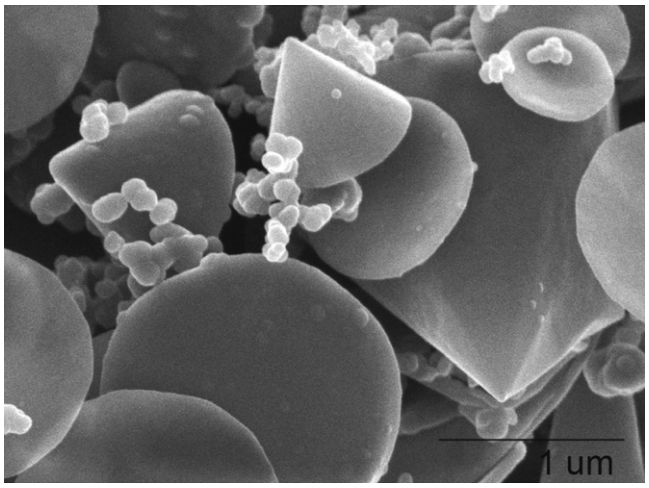

Fig. 1. The dispersant phase consisting of carbon cones, disks and amorphous carbon particles.

0.976 g/ml, viscosity $\eta = 100$ mPa s at 25 °C, dc conductivity $\Sigma_s \sim 10^{-12}$ S/m [12], permittivity $\varepsilon_s = 2.8$). The ER samples studied were prepared by mixing the carbon particles with the silicon oil. Four samples were prepared with concentrations 0.2, 0.5, 1.1 and 2.5 wt%. After mixing of the particles with the fluid, using ultrasonication (20 min at 30 W), the CC particles were well dispersed in the silicon oil. The dispersions were stable for days depending on the volume fraction.

For producing a magnetorheological fluid we used ferrofluid (FF) EMG901 from FerroTec with bulk viscosity 10 mPa s at 27 °C, density 1.53 g/cm^3 at 25 °C, and saturation magnetization 60 mT [13]. The carrier liquid of this FF is a synthetic isoparaffinic solvent with an anionic surfactant (oleic acid). The magnetite particles (Fe_3O_4) are predominantly spherical with diameter 10 nm with log-normal distribution. The MR sample was prepared mixing 1.5 wt% CC with the ferrofluid using vigorous shaking and then sonicating for 1 h. The dispersion was stable for a couple of hours.

2.2. Electrorheological measurements

ER properties of the samples were measured at 25 ° C using a rotation type rheometer (Physica MCR 300) with an ER cell with concentric cylinder geometry. The gap between the cylinder and the cup was 1.13 mm. A high voltage ac generator with a fixed frequency of 50 Hz was used to create the electric field perpendicular to the flow direction. The fields used were 100, 200 and 300 V/mm. The voltage was controlled manually, which introduces an uncertainty of approximately ±10 V/mm in the electric field. Due to friction from the electrodes on the rotating cylinder, all data were corrected accordingly by subtracting the values recorded for the empty cell.

All samples where dehydrated at 100 ° C for 20 h. Prior to each ER measurements all samples where sonicated for 20 min. A pre-shear experiment was carried out to measure the rheological properties at zero field. Then ac electric field was applied for 3 min, to allow structure buildup, before the next measurement. Flow curves were obtained with the shear rate starting at 1×10^{-3} Hz and increasing in a ramp logarithmic manner to 1×10^3 Hz. As previous work showed that chains formed by carbon cone particles do not dissolve after the electric field is turned off [8], the samples were sonicated between each measurement to assure similar conditions for all measurements.

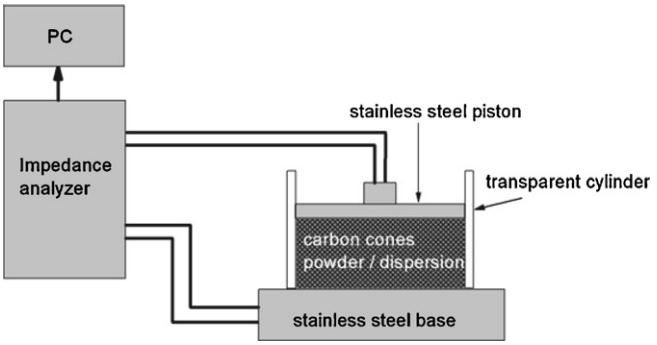

Fig. 2. The experimental set-up for impedance measurements, using a cell with two-electrode configuration.

2.3. Magnetorheological measurement

For magnetorheological measurements the same rheometer as described in Section 2.3 was used with a MR cell using a parallel plate geometry. This setup gives average higher radial shear than a cone/plate geometry. The experiments were run at a constant temperature of 20 ° C and with 0.20 mm between the plates. The shear rates used were between 20 and 1×10^3 Hz. The magnetic fields varied between $B = 0$–1085 mT.

2.4. Conductivity measurements

To measure the dc electrical conductivity of the dry carbon cone powder a two-electrode configuration was used. The measurement cell (shown in Fig. 2) consisted of a cylindrical tube placed on a stainless steel support plate which served as one of the electrodes. A stainless steel piston with diameter equal to the inner diameter of the cylinder was used as the second electrode ($A = 28.3$ cm^2). Carbon cone powder was poured into the cylinder, the cylindrical electrode was placed carefully on top and the height of the resulting powder column, typically ~ 2 cm, was measured manually. This was repeated for pressures varying from 0.87 to 9.98 kPa using additional weights. A dc voltage between 0.5 and 3.0 V was applied to the circuit and the resulting current through the circuit was recorded by a multimeter (HP 3478A) connected to a PC via a GPIB connection. For as-produced carbon cone particles the dc conductivity was found to be amplitude dependent as seen in Fig. 3. This might be due to a contact potential between the carbon particles. As expected

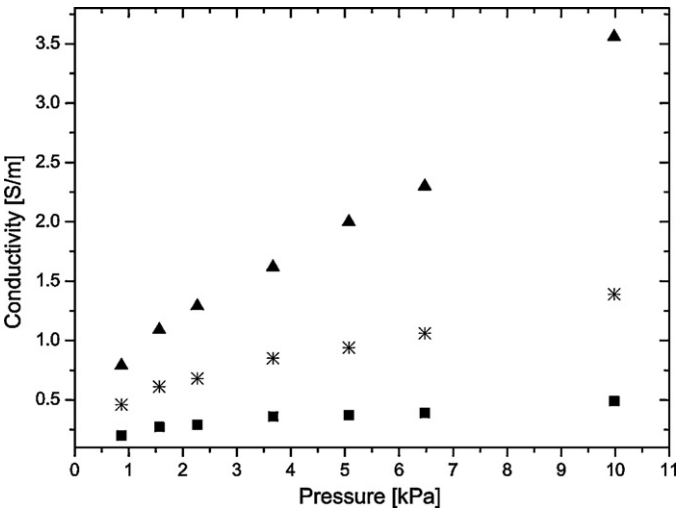

Fig. 3. DC conductivity of dry CC powder at various voltages as a function of packing pressure. Amplitudes used were; 1 V (square) 2 V (star) and 3 V (triangle).