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Electrical characterization of the solid phase (particles) of electrorheological fluids

Q Guegan and J-N Foulc
Grenoble Electrical Engineering Laboratory, UMR 5269, CNRS and University of Grenoble, BP 166, 38042 Grenoble Cedex 9, France

E-mail: jean-numa.foulc@grenoble.cnrs.fr

Abstract. Electrorheological (ER) fluids are suspensions of fine particles dispersed in a dielectric liquid. To understand and model the ER phenomenon, it is necessary to take into account the dielectric properties (conductivity and permittivity) of the solid and liquid phases. For the experimental investigation, the main difficulty is to measure the conductivity and the permittivity of the micro-sized (or nano-sized) particles. In this paper, we propose a method based on the arrangement of the particles in columns between electrodes under high applied field. The measurement on a cellulose/silicone oil suspension of the resistive and capacitive parts of the dc and ac time-varying currents allows us to obtain an apparent conductivity and permittivity of the cellulose particles. Finally, we discuss on the interest of the proposed characterization method from the specific conduction properties of the ER fluids.

1. Introduction

Electrorheological (ER) fluids are suspensions of fine particles dispersed in a dielectric liquid [1]. Upon application of an electric field, the solid phase (particles) fibrillates along the field lines between the electrodes. Thus, the rheological properties of the suspension are drastically modified (strongly dependence of the viscosity of the suspension on the applied field strength).

All the models proposed to describe the ER effect take into account the dielectric properties of the host liquid and the suspended particles [2,3]. There are several methods to evaluate the electrical parameters of randomly dispersed particles in a liquid medium [4]. Here we propose an alternative approach, better suited to the electrorheology, based on the characterization of the fibrillated suspension under high electric field to obtain the dielectric properties of the particles. The measurement of the electrical current under dc and ac voltages allows us to calculate the resistive and capacitive parts of the fibrillated ER fluid and then to deduce the conductivity and the permittivity of the particles.

2. Principle

For the calculation of the conductivity and the permittivity of the powder (fine particles), we assume that the ER fluid subjected to a high electric field is composed of a pure liquid phase (silicone oil) and a solid-like phase (thick cellulose column). Figure 1 describes the system. Thus, we estimate the section areas of the cellulose solid part S_S and of the liquid part S_L as $S_S = S_T\,\Phi$ and $S_L = S_T\,(1\text{-}\Phi)$ with $S_T = S_S + S_L$. Φ denotes the volume fraction of the particles and S_T the electrode surface. The thickness e is the same for the solid and the liquid parts. Then each of the two parts of the ER fluid can be represented by a resistance and a capacitance in parallel.

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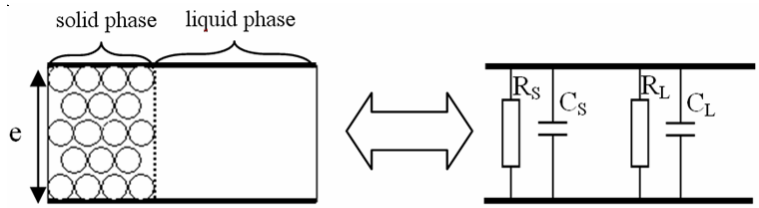

Figure 1. Sketch of the modelled arrangement of the ER fluid in two parts under high field and corresponding electrical circuit.

2.1. Conductivity

When the particles are fibrillated under dc voltage, the equivalent electrical model (Fig. 1) leads to the following expression:

$$\frac{1}{R_T} = \frac{1}{R_S} + \frac{1}{R_L} = \frac{\sigma_S \cdot S_S}{e} + \frac{\sigma_L \cdot S_L}{e} = \frac{I}{U} \tag{1}$$

where σ_S, S_S, σ_L and S_L are the conductivity and the section area of the solid and the liquid parts respectively. I is the measured current, U is the applied voltage and R_T is the total resistance of the ER fluid.

From Eq. 1, we can deduce the conductivity of the particles:

$$\sigma_S = \frac{j/E - \sigma_L \cdot (1-\Phi)}{\Phi} \tag{2}$$

If the conductivity of the liquid and the volume fraction of the solid phase are known, the measurement of the global current density $j = I / S_T$ for a given electric field strength E leads us to obtain the conductivity of the cellulose.

2.2. Permittivity

Under ac voltage and in capacitive regime ($I \propto f$), we can write (Fig. 1):

$$C_T = C_S + C_L = \frac{\varepsilon_S \cdot S_S}{e} + \frac{\varepsilon_S \cdot S_S}{e} = \frac{I}{U \cdot \omega} \tag{3}$$

where C_T is the total capacitance, ε_S and ε_L are the permittivities of the solid and the liquid parts respectively and $\omega = 2\pi f$ (f is the frequency). Thus, we obtain:

$$\varepsilon_S = \frac{\frac{j}{E \cdot \omega} - \varepsilon_L \cdot (1-\Phi)}{\Phi} \tag{4}$$

3. Experimental set-up

The measurement cell is shown in figure 2. The ER fluids consisted of a suspension of cellulose microcrystalline powder (Avicel, by Merck), with a typical size of 30 µm, relative humidity of 5.2% and bulk density of 1.4 g/cm^3, dispersed in silicone oil (Rhodia H47V20), with $\sigma_L \cong 10^{-13}$ S/m and relative permittivity $\varepsilon_L \cong 2.7$. Several samples of ER fluid with different values of particle concentration (in g/ml) were prepared and characterized (m grams of solid particles dispersed in 20 ml of silicone oil).

To apply the dc or ac high voltage in the cell, we used a generator function (*Hameg HM8030*) and a high voltage amplifier (*Trek 5/80*). The current was monitored with a home made pico-ampermeter with an analog output. All measurements were performed at room temperature.

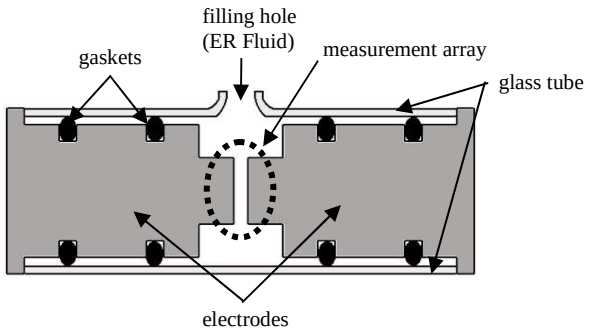

Figure 2. Schematic of the measurement cell.

4. Results and discussion

The *j-E* and *j-f* characteristics are show in figure 3. We find a $j\text{-}E^{3/2}$ law (Fig. 3a) as indicated by the conduction model [3]. It may be noted in figure 3b that the capacitive regime occurs for $f > 80$ Hz. Therefore, to calculate the particle permittivity we used the data obtained at $f = 100$ Hz. Figures 4a and 4b show that the calculated values of the conductivity and the permittivity of the cellulose are weakly dependents on the concentration (except for the high concentration). We also see in figure 5a that the conductivity of the cellulose increases with the electric field ($\sigma_S \propto E^{1/2}$). Figure 5b shows that the permittivity of the cellulose decreases when the frequency increases. We expect that for larger frequencies (in the full capacitive regime) the permittivity tends to a constant value.

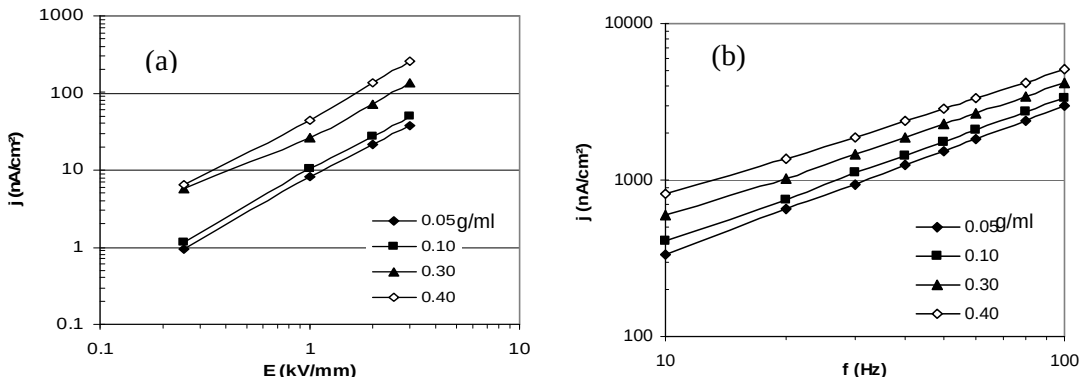

Figure 3. (a) Current density vs electric field in dc voltage and (b) current density vs frequency in ac voltage ($E = 2$ kV/mm) for different particle concentrations.

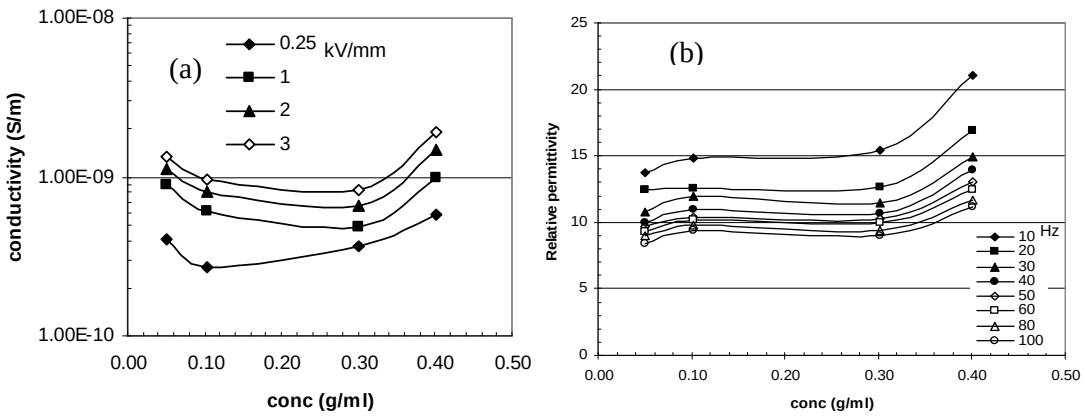

Figure 4. (a) Cellulose conductivity vs particle concentration and (b) cellulose relative permittivity vs particle concentration ($E = 2$ kV/mm), for different frequencies.

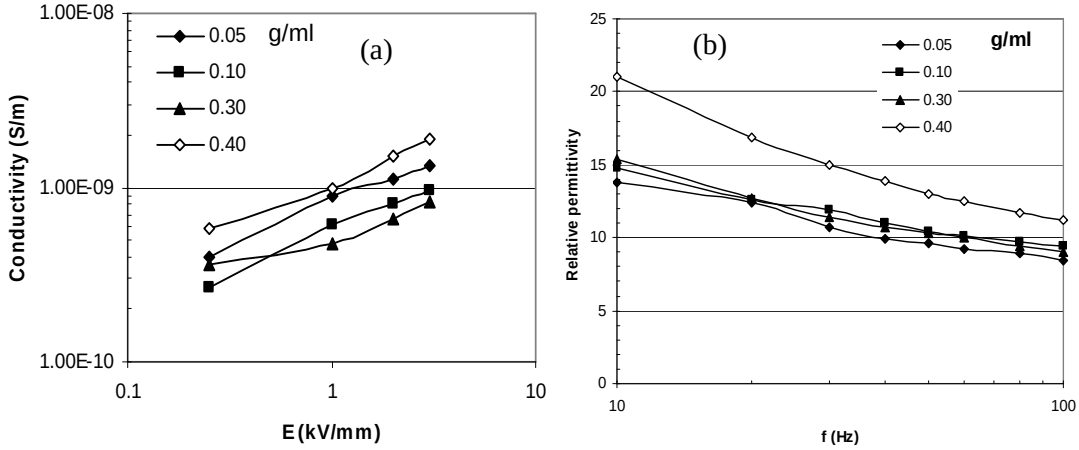

Figure 5. (a) Cellulose conductivity vs electric field and (b) cellulose relative permittivity vs frequency (E = 2 kV/mm), for different particle concentration

The conductivity and the permittivity of the cellulose powder greatly depend on its water content. In our case we obtain $\sigma_S \approx 10^{-9}$ S/m and $\varepsilon_{S\,rel} \approx 9$ which is rather consistent with the expected values [5].

In previous works [3,6] we have shown that in dc condition, the conduction properties of the solid and liquid components of the ER fluids determine both the current density and the yield stress of the fluids. More precisely, in the case of two particles (conductivity σ_S) in contact, immersed in dielectric liquid (conductivity $\sigma_L < \sigma_S$) and subjected to an electric field, the conduction model highlight the existence of an electrical contact zone of radius δ through which the current escapes from the particle and crosses the liquid. The conductance C_S of the electrical contact zone is given by $C_S = 2\,\sigma_S\delta$ with $\delta = f(\sigma_S/\sigma_L)$ and the current flowing the particle chain is $I = C_S U$ (U is a particle-particle voltage). Therefore the current flowing the ER fluids (which is essentially the current flowing the particle chains because $\sigma_S >> \sigma_L$) depends on both the particles and liquid conductivities. Regarding the characterization specificities of the particles used in ER fluids one can deduce the following remarks:

i) for very small particle sizes (< µm) the measurement of the conductivity and the permittivity appears to be very difficult in practice (choice and availability of a specific measurement set-up)

ii) an alternative method to obtain the dielectric properties of the particles is that we propose in this paper: fibrillation under dc voltage (with a large dc and a weak ac signals) of the particles immersed in dielectric liquid, measure of the dc and ac values of the current and then calculate the apparent conductivity and permittivity of the particles for a given field strength and volume fraction.

5. Conclusion

In this paper we proposed a method to obtain the dielectric properties of the particles used in ER fluids. We noted that the electrical characterization of a fine isolated particle is difficult but not essential to determine the efficiency of this material. Our method is based to the characterization of a fibrillated particles immersed in insulating liquid to deduce the apparent conductivity and permittivity of the particles. The results obtained on cellulose powder/silicone oil suspensions are promising and many others ER materials in particular the nanosuspensions need to be tested and a specific measurement procedure detailed before to validate the method.

6. References

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