Characterization and effectiveness of ER fluids: an attempt to unify methods and criteria

Quentin Quegan, Jean-Numa Foulc

Characterization and effectiveness of ER fluids: an attempt to unify methods and criteria

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. This paper concerns a proposal to define a way to evaluate the effectiveness of ER fluids. After recalling the basic parameters of the ER fluids: static yield stress τ_y, current density *j*, and zero-field viscosity η_0, we determine for a lot of ER suspensions the experimental values of two corresponding parameters $E_1 = \tau_y / j$ and $E_2 = \tau_y / \eta_0$, and thereafter of a global effectiveness parameter $E_n = E_1E_2$. We also compare the results obtained in the different cases of micrometer-sized and nanometer-sized particles-based ER fluids.

1. Introduction

The fundamental property of the ER fluids [1] is their capacity to change reversibly from a natural liquid state to a solid-like state in the presence of an electric field *E*. In its liquid state (E = 0) they should have low viscosity in order to limit the viscous losses when the fluid flows. In the solid state ($E \neq 0$) it must withstand a strong yield stress to be able to transmit large mechanical forces. In addition, to increase the energy efficiency, it is necessary to reduce the consumption of electric current passing through the fluid. Finally, taking into account that the practical electrical field ranges from 3 to 5 kV/mm (electric field strength can be regarded as a nearly constant value) it can be considered that the main features of ER fluids are: i) the static yield stress and the current density, and ii) the zero-field viscosity. Since the discovery of the electrorheological (ER) effect more than fifty years, significant advances including the synthesis of new efficient ER fluids have emerged. The first important step forward led to replace the water-activated particles by the intrinsic conductivity particles [2,3]. This has provided more thermally stable fluids. The second significant development has emerged more recently. The use of nanometer-sized particles (having specific physical properties) has significantly increased the value of the static yield stress of the ER fluids under electric field. An increase in excess of 20 times or more of the yield stress appears in this case. This is known as the giant ER effect [4].

2. Characterization and effectiveness of ER fluids

2.1. Experimental procedure

The steady rheological response of ER fluids is usually modelled by the following equation:

$$\tau(E, \dot{\gamma}) = \tau_y (E) + \eta_p \dot{\gamma} = \eta_{app} \cdot \dot{\gamma} \qquad (1)$$

where the measured values are: the shear stress τ, the shear rate $\dot{\gamma}$, the electric field E and the calculated parameters are: the (static or dynamic) yield stress τ_y, the plastic viscosity η_p and the apparent viscosity η_{app}.
Unfortunately, the different parameters defined in Eq. (1) are more or less dependent on the experimental conditions. So, if we want to properly compare the electrical and rheological responses of ER fluids it is necessary to apply at the characterization stage a well established experimental procedure. The temperature of the ER fluids is an important parameter influencing the responses of the fluids (for the yield stress and current density particularly). Other specific experimental conditions are: application way of the electric field and mechanical stress to the fluid prior to the measurements, order, duration and magnitude of the application of the field and the shear rate (or shear stess) during experiment, type of experimental set-up (shear or squeeze flow), geometry of measurement cell (parallel plates, concentric cylinders …).
Thus it seems like a necessity to clearly specify the whole experimental conditions for the electrorheological measurements (ERM) and better still to define standards of ERM. In this case one may expect to compare more effectively the performances of the ER fluids.

2.2. Proposal of an effectiveness ER parameter E_n
Previous studies have highlighted a strong correlation between the yield stress and the electric current density for an ER fluid at rest or in solid-like state. This result is based on the theory (the conduction model) and the experience [5,6]. Furthermore it may also be noted that the recent nanoparticles-based ER fluids shows most of the time a relatively high value of the zero-field viscosity.

These remarks lead us to propose:

i) a first efficiency parameter E_1 in connection with the static yield stress τ_y and the corresponding current density *j*, at a given electric field strength:

$$E_1 = \tau_y / j \tag{2}$$

ii) a second efficiency parameter E_2 including the static yield stress and the zero-field viscosity η_0:

$$E_2 = \tau_y / \eta_0 \tag{3}$$

iii) an ER fluids effectiveness parameter E_n:

$$E_n = E_1 E_2 \tag{4}$$

For the micrometer-sized-based ER fluids the zero-field viscosity is still quite limited (typical values: $\eta_0 < 0.2$ Pa·s for a volume fraction $\phi \sim 25$ %) whereas for the nanometer-sized-based fluids the zero-field viscosity is widely greater ($\eta_0 > 2$ Pa·s). In some cases, for the latter ER fluids, a gel of the suspension at rest appears due to the strong interaction between nanoparticles. In this situation, one can used, a zero-field viscosity for a very low value of shear rate (for example $\dot{\gamma} = 1$ s^{-1}).

3. Some experimental results and discussion
We have gathered below some experimental data from the literature and from our previous works. We note that the data used (see legends of Figs. 1 and 2) correspond to a large variety of ER fluids (size and formulation of the dispersed phase, various host insulating liquid and volume fraction of the solid phase …). We note in figure 1, for E ranging from 3 to 5 kV/mm, a widely dispersion of the values of the static yield stress τ_y and current density *j* (τ_y and *j* varie over three order of magnitude) whereas a much closer values for the ratio τ_y / j (one order of magnitude). These results confirm the correlation between the static yield stress and the current density for ER fluids subjected to a dc electric field both for the micrometer-sized and the nanometer-sized ER suspensions.

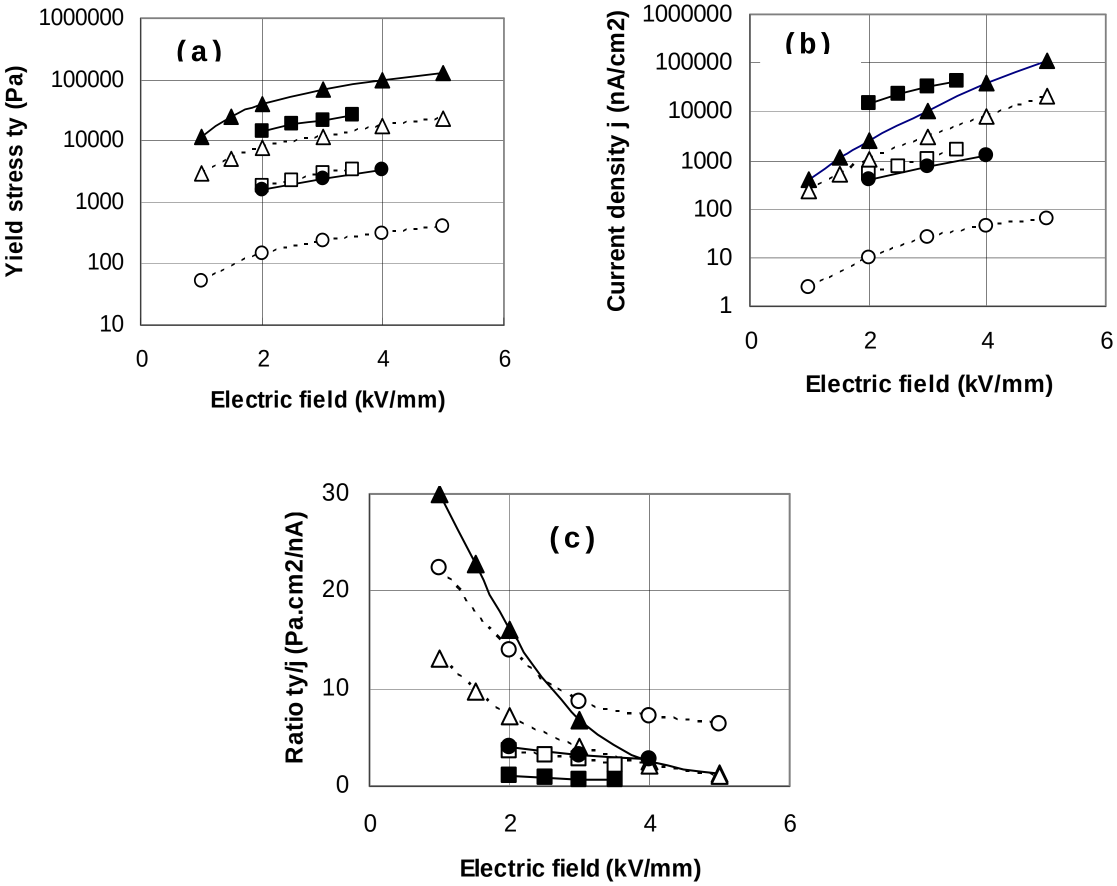

Figure 1. (a) Static yield stress τ_y, (b) current density j and (c) ratio τ_y / j vs applied electric field for various ER fluids. Symbols: nanometer-sized particle-based ERF, ▲△ [4], ■□ [7], ● Q. Quegan *et al.* unpublished, micrometer particles-based ERF, ○ [8].

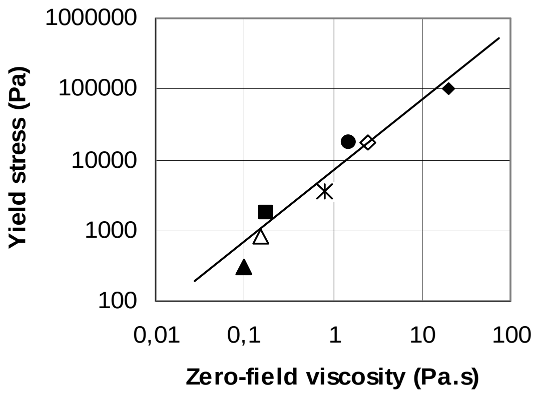

Figure 2. Static yield stress at E = 4 kV/mm vs zero-field viscosity for various ER fluids. Symbols: nanometer particles-based ERF, ◆◇ [9], ● [10], ✳ [11], ▲ Q.Guegan *et al.* unpublished, micrometer particles-based ERF ■ [12], △ [7]. Dots: experimental points. Solid line: linear fit.

Figure 2 shows the variation of the static yield stress τ_y as a function of the zero-field viscosity η_0 for a constant field strength E. A rather surprising result appears: all the data seem to follow a master straight line with a linear law (τ_y = k η_0) meaning that E_2 can be roughly considered as a constant value k (Eq. 3). Here we find for E = 4 kV/mm, E_2 = k ≅ 0.6 x10^4 s^{-1}. Noting that above E = 2 kV/mm the static yield stress of the ER fluids varies almost linearly with the applied field, we can consider in the first approximation that k is proportional to E: k = k'E with k' ≅ 0.15x10^4 (s kV/mm)$^{-1}$. Obviously, the experimental data used is not enough to justify a universal law for the dependence of the static yield stress on the zero-field viscosity for the ER fluids but this should be deepened in future work. Taking into account a constant value for E_2 (E_2 = k) for a given electric field strength we then obtain for the effectiveness parameter: E_n = k E_1.

If further experiments confirm that the zero-field viscosity is more or less proportional to the static yield stress (for a same field), this will imply that the ideal ER fluid concept (i.e. a strong yield stress and a low zero-field viscosity) is illusory. This situation is probably the consequence of the dispersion forces (van der Waals) between manometer-sized particles in "contact" and more generally to the importance of the dielectric interfacial properties at the nanometric scales [13]. However future progress on material science should lead to provide a better stabilization of the ER nanosuspensions and to obtain a satisfactory stress/viscosity compromise.

4. Conclusion

In this paper we proposed a global parameter E_n intended to compare the effectiveness of the ER fluids. Firstly, we have noted the importance to well define experimental conditions for the relevance of this comparison. Then, we have defined two basic efficiency parameters. The first one E_1 specifies the correlation between the ER effect (static yield stress) and the conduction properties of the suspension (current density). The second parameter E_2 shows other correlation based on the rheological responses of the fluid, under electric field (static yield stress) and without field (zero-field viscosity). It would appear that the zero-field viscosity rises with the static yield stress. This behaviour seems to exist for a large variety of ER fluids (among others, for the micrometer-sized and the nanometer-sized particles-based fluids) and may be explained by the size effect of the dispersed phase of the suspensions. Finally, an effectiveness ER parameter E_n is proposed taking into account the main chatacteristics of the ER fluids: static yield stress and current density at a given field strength, zero-field viscosity, and temperature (in this regard E = 4 kV/mm and T = 25 °C may be considered as a typical standard values).

References

[1] Gast A P and Zukoski C F 1989 *Adv. Coll. Int. Sci*. **30** 153
[2] Filisko F E and Radzilowski L H 1990 *J. Rheol*. **34** 539
[3] Block H Kelly J P Qin A and Watson T 1990 *Langmuir* **6** 6
[4] Wen W Huang X Yang S Lu K and Sheng P 2003 *Nature Materials* **2** 727
[5] Atten P Foulc J N and Felici N 1994 *Int. J. Mod. Phys. B* **8** 2731
[6] Wu C W and Conrad H 1996 *J. Phys. D: Appl. Phys*. **29** 3147
[7] Wu Q Zhao B Y Fang C and Hu K A 2005 *Eur. Phys. J. E* **17** 63
[8] Foulc J N and Atten P 1994 in *Proc. Int. Conf. on ER fluids* Tao R and Roy G D ed. World Scientific 358
[9] Wen W Huang X and Sheng P 2004 *Appl. Phys. Lett*. **85** 299
[10] Yin J and Zhao X 2005 *Int. J. Modern Phys. B* **19** 1071
[11] Wang X Shen R Wen W and Lu K 2005 *Int. J. Modern Phys. B* **19** 1110
[12] Ishino Y Maruyama T Ohsaki T Endo S Saito T and Goshima N 1995 in *Progress in electrorheology* Havelka K O and Filisko F E ed. Plenum 137
[13] Lewis T J 2004 *IEEE Trans. DEI* **11** 739