Non-linear behavior of Ferrofluids and Magnetorheological fluids subjected to extensional flow in a magnetic field

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Experiments under controlled shear and elongational flows[1] are typically performed in Rheology in order to measure material functions of non-Newtonian fluids and, subsequently, to fit to an appropriate constitutive equation. In the particular case of magnetic colloids (ferrofluids -FF- and/or magnetorheological fluids -MRF-), many rotational rheometers have been conveniently modified with fixtures to apply external magnetic fields to the sample undergoing shear deformation, either using magnetic circuits or solenoids. However, to our best knowledge, measurements of rheological material functions in uniaxial extension of FF and MRF have not been carried out, at least for low viscosity solutions.

We have developed a technique (patent pending) that, in general terms, allows the application of an external homogeneous magnetic field (AC or DC, constant or tuneable, and aligned or perpendicular to the flow direction) to the uniaxial extension flow kinematics undergone by a fluid sample in the commercial version of the Capillary Breakup Extensional Rheometer[2] (Haake™ CaBER1™, Thermo Scientific). The same principle can be also adapted to FiSER-type rheometers[3] with relative ease.

Using such feature, we present data from measurements of commercial ferrofluids and magnetorheological fluids, obtained on the commercial CaBER 1 rheometer. Fig.1 plots the filament thinning with time for different ferrofluids (FF40, FF200 and FF500) having the same magnetization (M) versus field strength (H) hysteresis curve but with different shear viscosities, measured under three different configurations: (1) absence of magnetic field, (2) under the influence of a fixed DC external magnetic field by means of rod-like permanent magnets (Neodymium N42, 8mm diameter and 30mm length) perpendicular to the extensional flow and (3) under the influence of a fixed DC external magnetic field by means of rod-like permanent magnets (Neodymium N40, 8mm diameter and 77.5mm length) parallel to the extensional flow. All fluids exhibited a Newtonian-like behavior when no magnetic field was applied, i.e. the filament decreased linearly in time. Thus, the filament thinning process is determined by the balance between viscous and capillary forces. The capillary forces are determined by the Laplace pressure, which for curved filament shape is given by $\Delta P = \sigma(\frac{1}{R_1} + \frac{1}{R_2})$, with σ representing the surface tension of the fluid, R_1 the filament radius and R_2 the radius of curvature. Nevertheless, the time evolution of the filament thinning became non-linear under the effect of a magnetic field, due to the particle-particle interaction forces generated by the magnetic field. As expected, the shape of the curve depends on the demagnetization factor of the ferrofluid sample under deformation. Thus, when the field is aligned with the flow direction the breaking time is longer, as the interparticle forces are also aligned with the direction of flow. Moreover, the larger the viscosity of the ferrofluid the larger the breaking time will be. According to Niedzwiedz et al.[4], the profile of the filament thinning observed in Fig. 1, under the effect of a magnetic field, corresponds to a yield stress material.

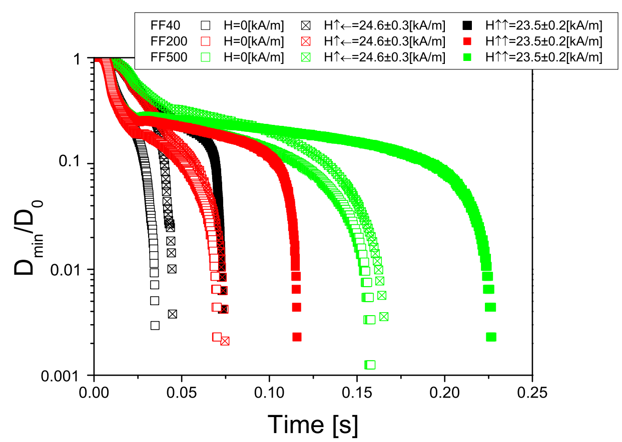

FIG. 1. Filament thinning evolution with time for different ferrofluids (FF40, FF200 and FF500) measured in the CaBER device with no magnetic field supplied (empty symbols) and under the influence of a constant external magnetic field perpendicular (crossed symbols) and parallel (filled symbols) to the extensional flow at 25±1°C.

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