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Weak periodic excitation of a magnetic fluid capillary flow

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Abstract

Recently it has been predicted and shown experimentally that the viscosity of a magnetic fluid flowing through a capillary pipe (Hagen–Poiseuille flow) can be reduced under the influence of an alternating, linearly polarized magnetic field. We compare experimental results with the analytical formula for small alternating magnetic fields. © 1999 Elsevier Science B.V. All rights reserved.

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1. Introduction

The increase of the viscosity of a magnetic fluid due to a DC–magnetic field has been known since the early measurements of McTague in 1969 [1]. A theoretical treatment for dilute dispersions, taking into account for the Brownian rotational motion with their relaxation time τ_B was first presented by Shliomis [2,3]. For the reduced viscosity η_r he obtained

$$\eta_r = \frac{\Delta\eta}{\eta} = \frac{3}{2}\phi_h \frac{\xi L^2}{\xi - L}\sin^2\beta\,, \tag{1}$$

where ϕ_h denotes the volume fraction of the hydrodynamic effective volume of the particles. The Langevin parameter $\xi = mH/kT$ is the ratio between the energy of a particle with magnetic moment m in a magnetic field H and its thermal energy kT. The Langevin function L is given by $L(\xi) = \coth(\xi) - 1/\xi$. The angle between the direction of the field H and the local angular velocity of the particle is measured by β.

Later, in 1994, Shliomis and Morozov [4] predicted a negative viscosity contribution ($\Delta\eta < 0$) for a flow with vorticity due to an alternating magnetic field, which has recently been detected [5]. For the case of a sinusoidal alternating magnetic field with small amplitude, i.e. $\xi \ll 1$, Shliomis and Morozov obtain

$$\eta_r(\omega\tau_B, \xi_0) = \frac{1}{4}\phi_h \xi^2 \frac{1 - \omega^2\tau_B^2}{(1 + \omega^2\tau_B^2)^2}\,, \tag{2}$$

where ω denotes the frequency of the exciting magnetic field.

In the following, we present experimental results in order to compare them quantitatively with the above formula.

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2. Experimental

We have used a continuous flow of magnetic fluid passing two capillaries in series. The first one is mounted in a solenoid, the second one acts as reference. The influence of the magnetic field on the viscosity of the fluid is measured via the pressure differences over the capillaries with and without the field. Using the Hagen–Poiseuille formula for the mass flow rate in each capillary one obtains the reduced viscosity. A full description of the experimental setup is given in Ref. [6].

For the experiments we have selected a water-based dispersion of magnetite (Fe_3O_4) particles, namely EMG 705 available from Ferrofluidics Corp. Its properties at room temperature ($T = 295$ K) are: density $\rho = 1190\ \mathrm{kg\,m^{-3}}$, surface tension $\sigma = 4.75\times10^{-2}\ \mathrm{kg\,s^{-2}}$, initial magnetic permeability $\mu = 1.56$, magnetic saturation $M_S = 0.02$ T, and dynamic viscosity $\eta = 6\times10^{-3}\ \mathrm{N\,s\,m^{-2}}$. The anisotropy constant of magnetite is given to be $K = 8\times10^4\ \mathrm{J\,m^{-3}}$ [7], and the domain magnetisation is expected to be $M_d = 0.56$ T [7]. The fluid was diluted with water with a ratio of about 1 : 3.

3. Results and discussion

For 16 different values of the driving frequency the reduced viscosity η_r has been measured as a function of the amplitude of the alternating magnetic field. Fig. 1 gives four representative curves. Each point has been obtained by averaging ten independent measurements of the reduced viscosity. The curves for 250 and 2003 Hz show a monotonous increase. For higher frequencies we clearly observe a negative viscosity contribution, which becomes more prominent with increasing values of the driving frequency. For 22321 Hz we observe a maximal reduction of the magnetoviscosity of about 0.001. The solid lines stem from a fit according to the model for arbitrary strength of magnetic excitation, as proposed in Ref. [5]. For a quantitative comparison of this model with measured data see Ref. [6].

In order to simplify the comparison of our results at weak excitation with Eq. (2) we define the viscous

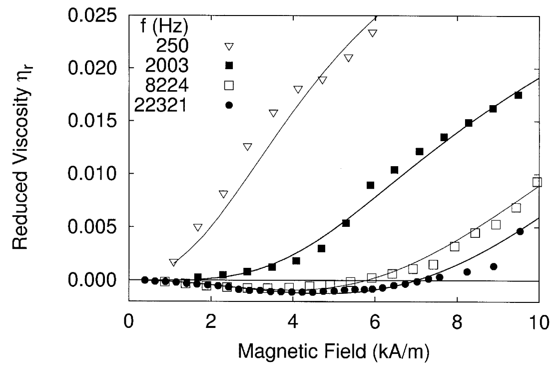

Fig. 1. Reduced viscosity as a function of the magnetic field for four representative frequencies.

susceptibility

$$\chi_v \equiv \frac{\eta_r}{H^2} \tag{3}$$

of a magnetic fluid. From Eq. (2) we then obtain

$$\chi_v = \frac{\eta_r}{H^2} = \frac{1}{4}\phi\left(\frac{m}{kT}\right)^2 \frac{1-\omega^2\tau_B^2}{(1+\omega^2\tau_B^2)^2}, \tag{4}$$

for the viscous susceptibility of a magnetic fluid as function of the driving frequency.

In Fig. 2 the viscous susceptibility of the investigated magnetic fluid is plotted as a function of the frequency of the magnetic field. The experimental values for χ_v are marked by squares and have been obtained from fits of the consecutive sets of experimental data to Eq. (3). For these fits the range of the magnetic field up to 1.8 kA/m was chosen. In this range a parabolic dependence of the reduced viscosity with the field strength can be observed for all frequencies. The thin solid line (a) in Fig. 2 gives the fit of Eq. (4) to the data. For the Brownian relaxation time we obtain a value of $\tau_B = 1.3\times10^{-4}$ s. The second parameter extracted from the fit is the product $\frac{1}{4}\phi(m/kT)^2 = 8.2\times10^{-10}\ \mathrm{m^2\,A^{-2}}$. It is obvious, that there exists only a qualitative agreement between the fit and the values of the viscous susceptibility.

The thick line (b) stems from a fit of Eq. (3) to our data using the frequency–dependent Brownian relaxation time as observed in Ref. [6]. The phenomenological frequency dependence found there

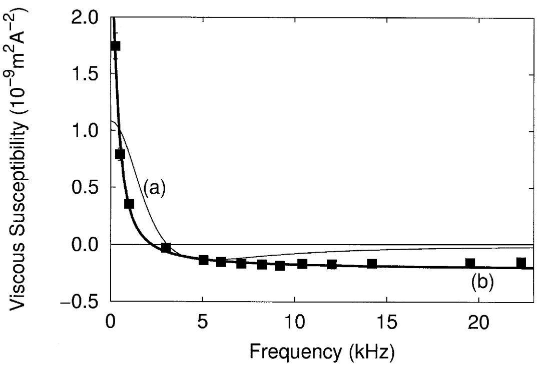

Fig. 2. Viscous susceptibility χ_v of the investigated magnetic fluid versus the driving frequency. The squares mark χ_v determined from the different experimental runs. The thin line (a) shows the fit to Eq. (4). The thick line (b) displays the fit to Eq. (6).

reads

$$\tau_B(f) = \frac{1}{\dfrac{1}{\tau_{B,0}} + \gamma f}, \tag{5}$$

where $\tau_{B,0}$ denotes the Brownian relaxation time in the limit of zero frequency and γ a fitting parameter. Inserting Eq. (5) into Eq. (4) one obtains

$$\chi_v = \frac{\eta_r}{H^2} = \frac{1}{4}\phi\left(\frac{m}{kT}\right)^2 \frac{1-(\omega/((1/\tau_{B,0})+\gamma f))^2}{[1+(\omega/((1/\tau_{B,0})+\gamma f))^2]^2}. \tag{6}$$

By fitting the experimental data to Eq. (6) we extract the Brownian relaxation time in the limit of zero frequency to be $\tau_{B,0} = 3.9\times10^{-4}$ s and $\gamma = 5.1$. For the product $\frac{1}{4}\phi(m/kT)^2$ we obtain $= 2.7\times10^{-9}$ m^{2}A^{-2}. This extended formula describes the experimental data surprisingly well.

The value for the Brownian relaxation time $\tau_{B,0}$ in the limit of zero driving frequency is close to the value $\tau_{B,0} = 3.7\times10^{-4}$ s found in Ref. [6], where measurements were made on the same material but without dilution and with a different theoretical model i.e. for arbitrary field strength.

The successful fit with the extended formula is a further indication for the practical relevance of the phenomenological ansatz (5). Whether this frequency variation is due to a frequency-dependent thickness of the surfactant layer, aggregation of the particles, the distribution in particle size or the influence of the Néel relaxation we do not know. None of these features have been included in the theory given in Ref. [4].

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