Journal of Magnetism and Magnetic Materials 252 (2002) 250–252

journal of magnetism and magnetic materials

www.elsevier.com/locate/jmmm

Investigation of the Weissenberg effect in ferrofluids under microgravity conditions

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Abstract

We have investigated the appearance of normal stress forces in kerosene-based ferrofluids by observation of the rise of a free fluid surface at a rotating rod. The balance between centrifugal and normal stress forces inside the sheared ferrofluid — causing the so-called Weissenberg effect — is controlled by an applied magnetic field by means of changes in the fluid microstructures. The observed rise of the ferrofluid surface depends on field strength, shear rate, and amount of chain building bigger particles. The experiment had to be carried out under conditions of reduced gravity during parabolic flights.

Keywords: Weissenberg effect; Magnetic fluid; Ferrofluid; Viscoelastic properties; Rod climbing; Particle aggregates

1. Introduction

Kerosene-based magnetic colloids with magnetic particles made from magnetite have been treated for a long time as ideal ferrofluids, where the magnetic particles do not interact with each other. In real ferrofluids, aggregates of magnetic particles occur under the influence of an applied magnetic field, which has been observed in water-based ferrofluids [1]. Rheological investigations on the magnetoviscous effect in kerosine-based ferrofluids [2,3] show non-Newtonian effects, which can be explained by dipole–dipole interaction energy between particles strong enough to form chains of particles in the presence of magnetic fields. But the dipole–dipole interaction energy of the frequent magnetite particles with the average size of 10 nm is too weak to form agglomerates. So the important question is, whether the small number of large particles is sufficient to lead to the observed effects.

Satoh et al. have shown, in simulations of forming and destruction of chains in shear flow [4], that large particles in principle could lead to such effects.

The formation of chains of magnetic particles in ferrofluids possibly do not only influence the magnetoviscous effect, but also generate field-induced viscoelastic effects. This can be also found in magnetorheological fluids. These suspensions contain micronsized magnetic particles which strongly interact. Therefore, drastic changes from viscous to viscoelastic behaviour can be induced by magnetic fields [5]. The problem of these kind of fluids is their reduced stability caused by sedimentation due to their size. A viscoelastic liquid based on nanosized magnetic particles would be a promising development because of its long-term stability.

2. Weissenberg effect

To get an idea about the possible viscoelastic behaviour of ferrofluids, we searched for the appearance of normal stress effects in these fluids which were predicted by Zubarev [6] under the assumption of the presence of chain-like structures.

One of the most famous viscoelastic effects and a simple instrumentation to prove the existence of elastic properties in ferrofluids is the so-called Weissenberg

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PII: S0304-8853(02)00678-9

effect, i.e. a rise of the free surface of a viscoelastic fluid at a rotating rod of radius r_0 and angular velocity ω_0 due to normal stress forces. Eq. (1) expresses the shape of the free surface determined by the balance between normal stress and centrifugal forces when surface tension is neglected [7]:

$$h(r) = \frac{r_0^2 4\pi\omega_0^2}{g}\left[-\frac{1}{2} + \frac{v_{10} + 4v_{20}}{\rho r^2}\right]\left(\frac{r_0}{r}\right)^2. \quad (1)$$

Here, v_{10} and v_{20} are the coefficients of both normal stress differences in the limit of small shear-rates, ρ the density of the ferrofluid, g the gravitational acceleration and $h(r)$ is the height of the surface at distance r from the centre of the rod.

The rod climbing in a viscoelastic fluid at $r = r_0$ is observed when the rod diameter does not exceed a critical radius $r_c = \sqrt{2(v_{10} + 4v_{20})/\rho}$. Above this critical value, the influence of the centrifugal forces dominates and the surface elevation will be negative. A theory which take into account the effect of the surface tension on the Weissenberg effect is given by Joseph et al. [8].

For magnetic fluids the height $h(r)$ of the surface at the rod depends not only on the diameter of the rod like in usual viscoelastic fluids, but also on the length and amount of the particle chains inside the fluid, which are influenced by the strength of the applied magnetic field, the concentration of bigger magnetic particles in the fluid, and the shear rate [9]. So the shape of the ferrofluid near the rod should be varied if there is a shift of balance of the forces by changing the state of particles chains inside the fluid through the magnetic field at a given small rod diameter. In addition, the shear rate has influences on the formation, amount, and maximum length of the chains at a given magnetic field.

In kerosene-based ferrofluids the amount of bigger "units" (single particles and primary agglomerates), which are able to form chains in the presence of a magnetic field, is too low to create an observable Weissenberg effect under normal terrestrial conditions against the dominant hydrodynamical pressure. Because of the amplification effect of the $1/g$ dependence of the surface height h (see Eq. (1)), we performed parabolic flight experiments to be able to observe measurable changes in the fluid surface height under microgravity conditions [10]. One has to take into account that for $g \to 0$ the surface tension cannot be neglected and we get a finite surface elevation at microgravity. Delgado found that the free surface takes an ellipsoid-like shape for normal viscoelastic fluids in microgravity conditions. The shape is caused only by the balance between surface tension and centrifugal forces [11]. For weak viscoelastic fluids like kerosene-based ferrofluids, the normal stresses are dominant enough to shape the free surface as in Eq. (1) predicted under reduced gravity [12].

3. Experiment

In the first parabolic flight campaigns, we investigated the dependence of the Weissenberg effect in ferrofluids on the strength of the applied magnetic field, volume concentration, and shear rate. Fig. 1 shows the rise of the free surface at the rod $h(r_0)$ as a function of the applied homogenous magnetic field parallel to the surface. The investigated ferrofluid is the APG 513A from Ferrofluidics based on diester with a mean diameter of the magnetite particles of about 10 nm and a volume fraction of 7.2%. The Weissenberg effect has been investigated for a constant rod diameter of 5 mm and at different shear rates. The strength of the elastic forces rise with the field strength as expected and one can see a weak dependence of the shear rates, at lower shear rate the effect is stronger for constant field as for the higher shear rates.

The influence of the amount of bigger "units" which seem to be responsible for the appearance of elastic properties in ferrofluid had been investigated in the last two campaigns. This was possible due to special samples of ferrofluid originated from the same production process — they own the same fluid properties and volume concentration, but differ in their amount of big particles from each other [13]. Fig. 2 shows the surface height of two of these five samples as a function of the field strength at constant shear-rate (fluid F2 has less big particles than fluid F4). As expected, the surface rises for both fluids with the field strength, but the increase for fluid F2 is weaker. This behaviour points to less particle-chains inside fluid F2 compared with fluid F4 at the same field. The difference between these two curves is an indication for the dependence of chain formation on the amount of bigger "units" in ferrofluids.

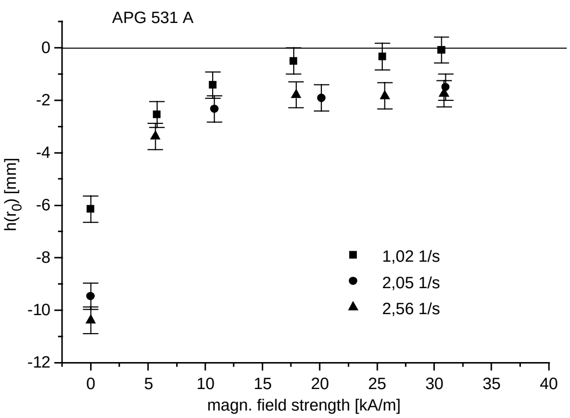

Fig. 1. Weissenberg effect for APG 513A (Ferrofluidics) under reduced gravity condition.

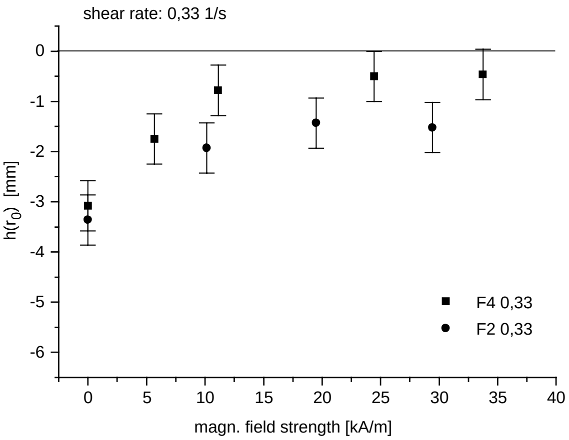

Fig. 2. Dependence of the Weissenberg effect on the quantity of bigger particles. Fluid F2 has got less amount of these particles than fluid F4.

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