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Measurement of the torque on diluted ferrofluid samples in rotating magnetic fields

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ABSTRACT

We study magnetic suspensions with different concentrations of ferromagnetic nanoparticles in a spherical container under the action of a rotating magnetic field. Experimental data on the concentration dependence of the rotational effect, viz. the torque exerted by the magnetic field, are presented. We explain the observed torque characteristics using a model that takes into account field-driven aggregation of the magnetic nanoparticles in stationary or slowly rotating fields. At sufficiently high rotation rates, the rotating magnetic field obviously destroys these aggregates, which results in a decreasing torque with increasing rotation frequency of the field.

1. Introduction

The dynamics of the rotational motion of complex liquids under the action of external magnetic fields traditionally attracts the attention of researchers for several reasons. Among those are potential applications in magneto-mechanical and magneto-optical devices, and fundamental insights in structures of such fluids and internal dynamic mechanisms. The phenomenon that nanostructured magnetic fluids follow a rotating magnetic field is known as rotational effect [1]. There are numerous studies in literature devoted to magnetic fluids exposed to external rotating or oscillating magnetic fields [2–31]. Previous experiments have mainly been focused on the detection and quantitative evaluation of 'negative viscosity' effects [4], where the rotation of ferromagnetic particles interacts with the vorticity of flow fields and consequently reduces the effective viscosity, e.g. in pipe flow.

Studies of ferrofluids in rotating magnetic fields have a long history [2]. Experiments to determine the flow or torques have been performed in several geometries, e.g. in spindles or cylindrical samples [7–13,33], in spherical containers [14,15] and in free drops[16,17]. There is still a controversy about the interpretation of several of these experiments, see e.g. Refs. [18,19]. A considerable number of theoretical studies concerning ferrofluid flow of rotating containers in static magnetic fields or of ferrofluid samples in rotating magnetic fields has been published (e.g. [20–29]). The coupling of the rotating field torque and the flow vorticity can be applied, for example, to pump ferrofluids [30]. A status report of earlier work can be found, e.g. in Ref. [31]. The model that describes the ferrofluid flow under the action of an external rotating electromagnetic field has been developed as early as 1967, when Moskowitz and Rosensweig interpreted experiments in a cylindrical container geometry [2].

In our article, we present results on the dependence of the rotational effect on the concentration of the magnetic particles in the suspensions and on the viscosity of the carrier fluid. The complex characteristics require a comprehensive discussion, and reveal structural details of the suspensions.

2. Experiment

We carried out the study using a commercial magnetic fluid from *Ferrotec Corporation* (Japan). The carrier liquid is synthetic hydrocarbon oil and the magnetic phase is magnetite Fe_3O_4. The physical characteristics of the non-diluted sample are shown in Table 1. We diluted this magnetic fluids with *durasyn* (density 830 kg/m^3, viscosity 46 mPa s). The following sets of diluted APG 2135/durasyn samples were prepared: 50%, 60%, 70%, 80%, 90%, 100% (vol). The concentrations refer to the APG 2135 content.

The experimental magnetization curves for non-diluted APG 2135 and for APG 2135 diluted up to 60% are shown in Fig. 1. In relative units these dependences are equal, so we can conclude that samples under study are chemically stable. We note that there is a slight difference between both characteristics when they are scaled by their maximum magnetizations, the susceptibility of the undiluted sample is slightly stronger than expected from the ratio of ferroparticle concentrations.

Fig. 2 shows the sketch and block diagram of the experimental setup for studying the behavior of the sphere filled with magnetic fluid in a rotating or oscillating magnetic field [32]. The sample is suspended

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Table 1
Parameters of APG2135.

Thermal conductivity [mW/K m]	150
Thermal expansion coefficient [K^{-1}]	$7.5{\cdot}10^{-4}$
Saturation magnetization [mT]	22
Viscosity [mPa s]	1500
Density [kg/m^3]	1070

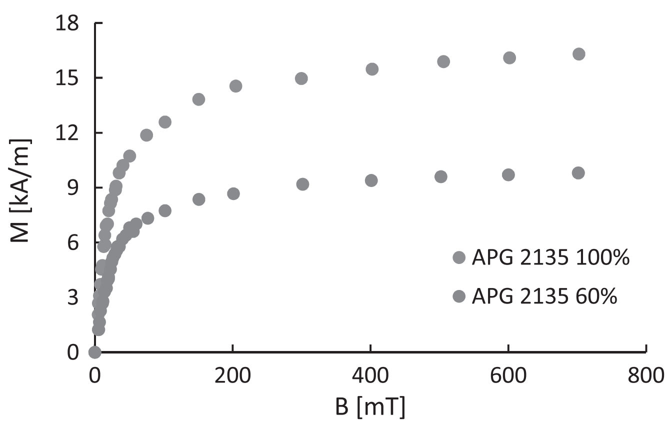

Fig. 1. Magnetization curves for the diluted and non-diluted samples, the curves exhibit identical characteristics except for a scaling factor of 0.6 that reflects the different concentrations of nanoparticles.

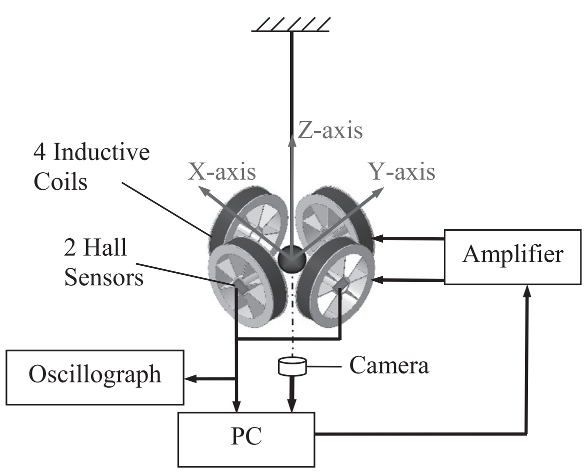

Fig. 2. Sketch of the experimental setup.

on a glass fiber of about 0.5 m length. Two pairs of (nearly) Helmholtz coils of 6 cm diameter provide a rotating magnetic field, a function generator and two-channel amplifier provide the 90° phase-shifted sine currents for these coils, and Hall probes together with an oscillograph serve as monitors for the magnetic field.

The distortion of the glass fiber with the sample is recorded with a camera, and from the distortion we determine the torque on the sample. In order to dampen oscillations of the container when magnetic field parameters are changed rapidly, the container can be slightly immersed in a shallow water layer on a dish below. The restoring moment of the glass fiber is determined from small amplitude oscillation frequencies of the suspended sample container and its known moment of inertia. Typical pendulum frequencies are below 0.1 Hz, i.e. the setup averages torques over several seconds, much longer than the magnetic field cycle, we record time averaged torques. In the stationary state, after some transients, when the sample magnetization follows the field synchronously with constant phase lag, that the torque is expected to be constant and no information is lost.

The measurement principle is as follows: the rotating field produces a torque on the ferroparticles. These start to rotate and transfer the torque to the fluid carrier, which in turn develops a vortex flow inside the container. Shear stresses transfer the frictional torque to the container walls, so that the container starts to rotate with the fluid. Thereby one can assume no-slip conditions of the fluid velocity at the container walls. Finally, the viscous torque of the fluid on the container is balanced by the back-driving torque of the glass fiber. When all torques are balanced, the fluid rotates stationary in the container, and the twist of the glass fiber is an exact measure of the torque exerted by the magnetic field on the ferrofluid, irrespective of the type of relaxation of the magnetization (Brownian or Néel).

For each sample, we measure the torque density (torque per volume) [32] in dependence on the magnetic field strength and frequency. The rotation frequency range was varied between 2 Hz and 350 Hz, and the magnetic field was varied up to 3 mT.

3. Results

Fig. 3 presents the measured dependence of the torque density on the magnetic field frequency. The characteristics are non-monotonous and depend significantly on the concentration of magnetic nanoparticles. A general tendency is the shift of the maximum torque in the direction of lower frequencies in the higher concentration samples (Fig. 4).

4. Discussion

If the magnetic fluid had a structure independent of the applied magnetic field, the torque would be proportional to the magnetic particle concentrations, and it would continuously increase with increasing rotation rate of the field at constant field strength. The reason for the latter is the increasing phase lag between magnetization and field with increasing frequency. This condition is in fact fulfilled only for well-diluted samples. The highly concentrated samples show this trend only at very low rotation rates. The subsequent drop of the torque with increasing rotation frequency indicates a structural change in the ferrofluid. Another indication is the slope of the torque versus frequency curves for different concentrations. If the ferrofluid particles would contribute independently to the torque, this slope should increase linearly with concentration. In fact, higher concentrated samples show stronger torques than expected. A natural explanation is some structural change from a suspension of aggregates at low frequencies/high concentrations to suspensions of individual nanoparticles at higher rates and/or lower concentrations.

Tsebers [34,35] considered a magnetic fluid as an ideal multi-component gas and investigated associations of particles and their possible agglomeration in chains in the magnetic field. He showed that with increasing concentration of the solid phase, the average number of particles in aggregates increases. Other authors provided evidence that the aggregates start with small formations from larger particles that exist even in absence of a magnetic field. In magnetic fields, interac-

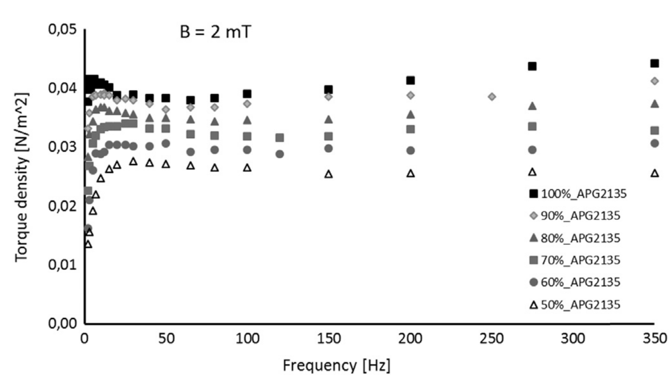

Fig. 3. Experimental torque densities versus rotation frequency at a magnetic field of 2 mT.