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The use of magnetic small angle neutron scattering for the detection of flow profiles in magnetic fluids

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Abstract

We have investigated the possibility of using magnetic small angle neutron scattering (MSANS) to detect the flow pattern of flow in concentrated magnetic fluids. It has been shown that the anisotropy of the scattering pattern can be determined with appropriate accuracy allowing to identify changes of the anisotropy induced by different flow states. These changes can be used as a measure for flow characteristics in the fluids. In this paper we present the general idea and an experimental demonstration of the concept using a simple convective flow pattern. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: Small angle neutron scattering; Magnetic fluids; Flow detection

1. Introduction

Investigations of flow in magnetic fluids require special flow diagnostic since ferrofluids of reasonable concentration of the magnetic component cannot be investigated with normal optical measuring methods due to their optical opaqueness [1]. For many fields of hydrodynamic research in concentrated ferrofluids special methods for flow detection have been developed. E.g. thermal flow can be detected by Schlieren techniques [2] or direct temperature measurement [3], while isothermal flow at high flow velocities can be observed by ultrasound Doppler technique. Unfortunately such alternatives are presently not available for isothermal flows with low flow velocities. Such flows are important, e.g. in the investigation of diffusion induced convection [4,5] or in rheological measurements. Thermal anemometry with determination of temperature changes in the order of mK corresponding to flow velocities in the range of a few mm/s like it was used in [5] cannot be extended to detection of flow profiles with appropriate spatial resolution due to technical reasons. In the following we will present an approach, using the velocity dependent change of anisotropy of the scattering pattern of a ferrofluid in MSANS measurements as a tool for flow detection in the fluid.

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2. Experimental concept and setup

The idea for this method of flow detection is based on the fact that mechanical and magnetic torques are counteracting on the magnetic particles in a magnetic fluid subjected to a shear flow in the presence of a homogeneous magnetic field. At a given magnetic field strength and velocity of flow, mechanical and magnetic torque will balance in a way that a mean magnetization lower than the equilibrium value in the fluid at rest will appear. The difference increases with increasing velocity of the flow, so the relative changes in the magnetization of the fluid can be used as a measure for the flow velocity, provided that a non-disturbing method for a position sensitive detection of small changes in magnetization in the fluid is available.

The anisotropy of the scattering pattern obtained by MSANS can be used as a precise measure for the magnetization of a ferrofluid in a flow cell with reasonable spatial resolution. As it is well known, the scattering intensity for unpolarized neutrons is maximal for the scattering vector q vertical to the magnetization M of the sample and 0 for parallel alignment. The absolute value of the intensity for $q \perp M$ is proportional to the magnetization. Since the anisotropic part of the scattering from a magnetized magnetic fluid results only from scattering of the magnetic particles, the anisotropy itself can be directly used as a measure for the magnetization in the sample volume exposed to the neutron beam. For a two-dimensional pixel detector the anisotropy is defined by

$$A = \frac{\sum_{mn} I_{mn} \cos(2\varphi_{mn})}{\sum_{mn} I_{mn}}. \quad (1)$$

as it was already used in Ref. [6]. Here I_{mn} denotes the intensity measured in a certain pixel (mn) in row m and column n while φ_{mn} measures the angle between the direction of the magnetic field and the direction from the center of the detector to pixel (mn). Since A is proportional to M the measure of A can be used to detect differences in flow velocity in the fluid.

To have a well known accurately adjusted flow, we have used a thermally induced buoyancy flow as a test for the applicability and potential of the method described above. The magnetic fluid was enclosed in a rectangular box heated from the bottom and cooled at the top as shown in Fig. 1. The length of the box was 8 cm, its height 2 cm and the depth in the direction of the beam 6 mm allowing the appearance of 4 counterrotating flow vortices with 2 cm diameter. The walls of the chamber in the direction of the neutron beam have been made from quartz to eliminate disturbing scattering from the beam windows. The fluid has been under the influence of a homogeneous magnetic field in the direction of the temperature gradient providing a magnetization perpendicular to the neutron beam.

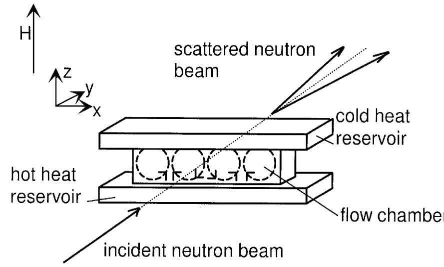

Fig. 1. Sketch of the experimental setup used for the test experiments on flow detection by MSANS.

For the neutron scattering experiments we have used the SANS-facility D11 at the high flux reactor of ILL in Grenoble. The instrument is equipped with a two-dimensional $64 \times 64\ \text{cm}^2$ neutron detector having 64×64 pixel. This detector has been placed 10 m from the sample to provide a range for the momentum transfer up to $Q_{\max} = 3.3 \times 10^{-2}\ \text{Å}^{-1}$ with a resolution of $\Delta Q = 1 \times 10^{-3}\ \text{Å}^{-1}$. For all experiments described later on we have used a wavelength of 6 Å.

The magnetic fluid, produced by TU Timisoara, contained magnetite particles with a mean diameter of about 10 nm in deuterated benzene. In the first test we compared a fluid with deuterated carrier liquid and conventional surfactant with a fully deuterated fluid having deuterated carrier liquid as well as deuterated surfactant. It could be found that the scattering intensity rose by a factor 3 for the fully deuterated liquid while the signal/noise relation was strongly improved due to the reduction of incoherent scattering by hydrogen. Since this improvement reduced the necessary scattering times reasonably, only the fully deuterated liquid was used in the experiments.

3. Experimental results and discussion

With the experimental setup described above we have carried out a series of experiments to prove the potential of the described MSANS method for the detection of flow profiles in magnetic fluids and to demonstrate its applicability with the discussed example of a thermally driven flow. Fig. 2 shows typical scattering patterns for $H = 0$ and 12 kA/m showing clearly the anisotropy of the scattering pattern due to magnetic scattering.

We have taken eight scattering patterns along the x-direction (see Fig. 1) using a spatial resolution of 5 mm and a diameter of the neutron beam of 5 mm too. The starting point of the scan through the flow pattern was chosen 20 mm from one end of the cell to be able to obtain information from the central 40 mm of the cell. In this way we excluded possible boundary effects on the flow profile. At each position the scattering pattern was taken in a measuring time of about 5 h to obtain optimum statistics. For the whole time of measurement the fluid was under the influence of a temperature gradient of $\Delta T = 8$ K driving the thermal convection flow and a magnetic field in the z-direction with a strength of $H = 12$ kA/m.

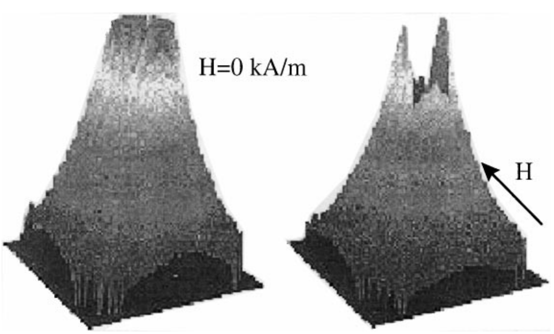

Fig. 2. The measured scattering pattern for $H = 0$ and 12 kA/m. The axis spanning the base plane corresponds to the positions of the detector cells while the height of depicted surface corresponds to the count rate obtained in the corresponding cell.

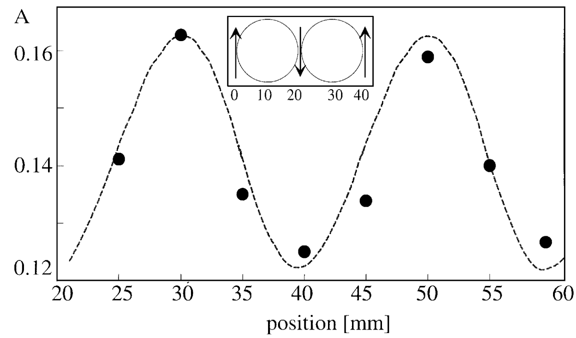

Fig. 3. The anisotropy A of the scattering pattern corrected by effects due to temperature differences as a function of the position in the x-direction. The position is counted from one edge of the cell. The inset shows the corresponding flow pattern. The dashed line is a guide to the eye.

From the measured patterns we have calculated the anisotropy using Eq. (1). The obtained anisotropies have been corrected by the temperature dependent changes of magnetization induced by temperature differences resulting from the convective flow. In this way the change of anisotropy due to changes in the flow velocity could be extracted. The spatial distribution of the temperature in the fluid cell was determined by reference experiments using a suspension of thermosensitive liquid crystals in an oil with thermal properties matching those of the ferrofluid.

In this way we obtained a profile of the anisotropy A as a function of the position in the x-direction as shown in Fig. 3. As it is seen from the figure, the anisotropy pattern corresponds well with the flow profile.

Thus we can finally conclude that the determination of the anisotropy of the scattering pattern obtained from MSANS measurements can be used as a noninvasive tool for the investigation of flow profiles in concentrated magnetic liquids. From the long measuring times needed in our experiments one can see that such a kind of experiment requires a high flux neutron source like the reactor at ILL in Grenoble, and that it is definitely necessary to use fully deuterated magnetic liquids and optimized fluid cells to avoid unnecessary reduction of the scattering intensity.

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