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LETTER TO THE EDITOR

Cavity field measurements in magnetic fluids

P R Bissell, R W Chantrell and P A Bates
Division of Physics and Astronomy, Preston Polytechnic, Preston, Lancs. PR1 2TQ, UK

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Abstract. Measurements are presented of the field within a cavity in a magnetic fluid. It is shown that a device for measuring the saturation magnetisation of a magnetic fluid based on such measurements is possible. Further investigation is shown to be necessary, however, in order to develop an instrument capable of measuring the full magnetisation curve.

Magnetic fluids are highly stable colloidal dispersions of ferro- or ferri-magnetic particles in a non-magnetic carrier fluid. Particle aggregation and instability is controlled using small particle sizes and particle coatings of long-chain surfactant molecules. In most systems, particle relaxation times are short so that the fluid behaves as a paramagnet exhibiting no hysteresis but with a magnetic moment about 1000 times greater than that of a paramagnetic gas.

Magnetic fluids have great commercial potential and are already being used in high speed rotary vacuum seals, dust seals for magnetic disc drive units, crystal-pulling furnaces and high quality loudspeakers where the fluid is positioned by a magnetic field but provides its normal fluid properties.

Characterisation of these fluids in terms of their magnetisation curves is essential in determining their application potential and this is normally achieved using a vibrating sample magnetometer. We have investigated the feasibility of developing a new form of magnetometer for this purpose based on cavity field measurements. In this letter, we present some of our initial measurements on magnetic fluids and compare the results with magnetisation curves obtained using a vibrating sample magnetometer.

The magnetic field in a cavity within the bulk of a magnetised material can be evaluated by summing the field contributions from all elements of the fluid outside the cavity. If, however, the fluid is uniformly magnetised and the container and cavity shapes approximate to ellipsoids of revolution, the summation reduces to the simple relation

$$H_T = H_0 + H_L - H_s$$

(for a proof of this result for the analogous situation of a dielectric material in an electric field see Kittel (1971)). H_T is the total field and H_0 the externally applied field. H_L is the field due to the (fictitious) 'free poles' on the inside of the cavity. This is the Lorentz field which acts in the same sense as H_0. H_s acts in the opposite direction to H_0 and is the demagnetising field due to the 'free poles' on the surface of the sample container.

The values of H_L and H_s are directly proportional to the magnetisation of the fluid, with the constants of proportionality dependent upon the shapes of the cavity and

container respectively. Thus, if we define the internal field H_I as

$$H_I = H_T - H_0$$

then

$$H_I = M(N_L - N_s)$$

where N_L and N_s are the demagnetisation factors of the cavity and sample respectively and M is the fluid magnetisation measured in gauss.

The cavity field H_T and the applied field H_0 were measured using two Hall probes shown diagrammatically in figure 1. Probe A was mounted in a flat sided cavity of cross-section 1 mm × 5 mm placed at the centre of a cylindrical glass container 10 mm in diameter and 150 mm long. Probe B was mounted 25 mm away outside the container. Both probes were normal to the applied field and placed symmetrically between the 100 mm diameter flat pole pieces of the electromagnet which generated the magnetic

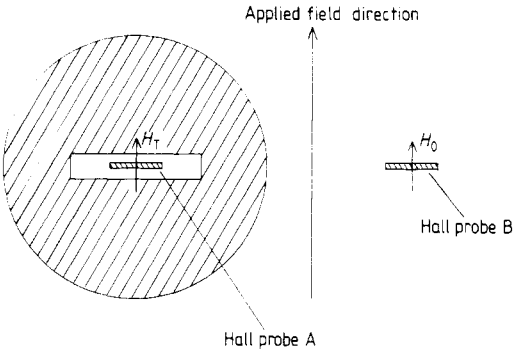

Figure 1. Schematic diagram (not to scale) of a cross-section through the sample showing the Hall probe arrangement for measuring the cavity field H_T and the applied field H_0.

field. The Hall voltages were amplified to give signals S_A and S_B which were numerically equal to the measured field in gauss. Digital displays of $(S_A - S_B)$ and S_B could be read directly as H_I and H_0. In the absence of a magnetic fluid specimen, the value of H_I is expected to be zero in any applied field. Under such conditions it was found, however, that because of the nonlinear Hall probe characteristics, a zero display could only be achieved at two field settings. By adjusting the Hall currents and the Hall voltage offsets, H_I was made zero in zero field and in the maximum field achievable with the electromagnet (11.5 kOe). Careful resistance loading of the probes reduced the zero offset to less than 50 gauss for all intermediate field settings. Provided the probes were not moved relative to the applied field, it was found that the field dependence of the zero offset was reproducible and could be subtracted from the cavity field measurements to give a corrected value for H_I.

When a magnetic fluid was placed in the glass sample container, corrected values for H_I were recorded as a function of H_0. Typical results are shown in figure 2 for two magnetic fluids A and B. These samples were commericially manufactured kerosene based ferrofluids (Ferrofluidics Corporation, 40 Simon St, Nashua, NH 03061, USA) with nominal saturation magnetisations of 600 G and 400 G respectively. Figure 2 also shows the magnetisation curves obtained using a vibrating sample magnetometer. Com-

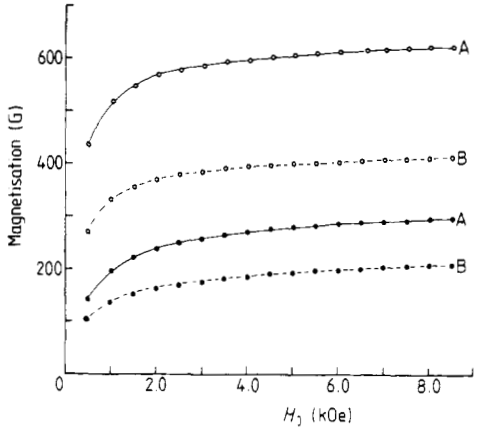

Figure 2. Magnetisation M and the cavity internal field H_1 as a function of the applied field H_0: ○, measurements of M made with a vibrating sample magnetometer; ●, measurements of H_1. The curves are for two commercial magnetic fluids A and B.

parisons of the curves shows that they have a similar shape but with values of H_1 depressed below the value of the magnetisation, as expected. At low field values, H_1/M is not constant and appears to depend on factors additional to the geometric demagnetisation factor. This may be due to fringe effects at the edge of the magnetic field or non-uniformity in the width of the cavity, but requires further investigation.

In the high field limit, M varies with H_0 according to

$$M = M_s(1 - a/H_0)$$

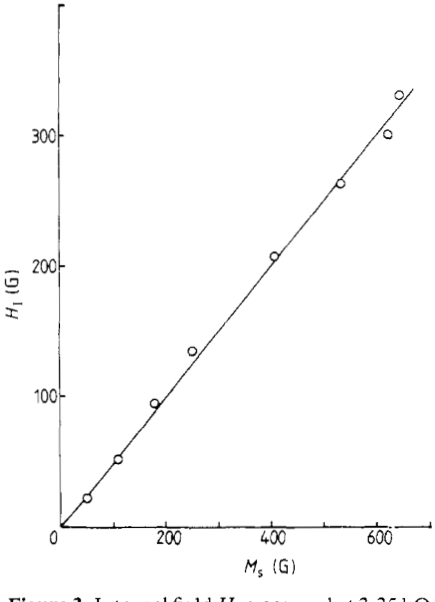

Figure 3. Internal field H_1 measured at 3.35 kOe for a number of magnetic fluids and plotted against the saturation magnetisation M_s. The fluids contain various particle types of different sizes and in different carrier fluids.

for a magnetic fluid, where a is a constant dependent on the size distribution parameters of the magnetic fluid (Chantrell *et al* 1978). Hence, the variation of H_I with $1/H_0$ should be linear and extrapolate to

$$H_{Is} = (N_L - N_s)M_s$$

where M_s is the saturation magnetisation of the fluid. From measured values of H_{Is} and M_s for each of the fluids, we obtain a value of $(N_L - N_s)$ of $0.5 \pm 6\%$ which is consistent with the sample geometry used.

We have also measured H_I in a fixed field strength of $H_0 = 3.35$ kOe for a number of different fluids with different particle sizes, types and carrier fluids. This value of H_0 is sufficient to magnetise a magnetic fluid to within a few per cent of its saturation value. Thus, we expect a linear variation of H_I with M_s. The results are shown in figure 3 and confirm this prediction. As a result of this linearity, it is clear that a simple magnetometer based on the cavity field principle is possible for saturation measurements. Saturation magnetisation is a very important parameter in the characterisation and quality control of commercially produced magnetic fluids and such a magnetometer would be of benefit to its speedy measurement. We are at present working on the development of a cavity field magnetometer for this purpose.

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