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THE ANISOTROPY CONSTANT OF MAGNETIC PARTICLES IN THE GLYCERINE FERROFLUID[1]

КОНСТАНТЫ АНИЗОТРОПИИ МАГНИТНЫХ ЧАСТИЦ В ГЛИЦЕРИНОВЫХ ФЕРРОЖИДКОСТЯХ

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Magnetic fluids, often called ferrofluids, are defined as a colloidal suspension of single domain particles (Co, Fe_3O_4, Fe) with a diameter between 5—20 nm. The liquid carriers are water, glycerine, oil and others. The magnetic properties are best described as superparamagnetic and the classical theory of Langevin paramagnetism, modified to include a particle size distribution can be used. The mode of magnetization may, therefore, be complex arising either through the physical rotation of the particle (Brownian motion) or a rotation of the magnetization within an essentially static particle (Neél rotation) [1]. On the application of the magnetic field to the fluid in the liquid phase, the magnetic moments may achieve thermal equilibrium through the Brownian and the Neél relaxations. In the solid phase (when the liquid carrier is frozen) the Brownian motion is prevented and the thermal equilibrium can only be achieved through the Neél relaxation process. The rotation of the magnetization vector (the Neél process) within the particle is hindered by the energy barrier. When the magnetic fluid is cooled down to the temperature at which the solvent is frozen, it still exhibits a superparamagnetic behaviour. This means that the magnetic moments are oscillating thermally in fixed particles. At low temperatures when the energy barrier to the rotation for the uniaxial particle $KV > k_B T$ (K is the anisotropy constant of the particle which may be due to crystalline anisotropy and/or particle shape), the particles are said to be blocked and remanence and coercivity are observed. At high temperature when $KV < k_B T$, the fluid may be superparamgnetic (V is the volume of the particle).

The transition between remanence and superparamagnetic behaviour depends on the particle size. This condition is given by the equation [2]

$$V_0 = 25 k_B T / K. \tag{1}$$

The particles with $V > V_0$ are blocked and the particles with $V < V_0$ are free. Using the above mentioned discussion we can write for the magnetization as a function of a magnetic field at room temperature (liquid phase)

$$I(H) = I_s \int_0^\infty L(ax) f(x)\,\mathrm{d}x, \tag{2}$$

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where $L(y) = \coth(y) - 1/y$ is the Langevin function, $a = \pi I'_s D_v^3 H/6k_B T$, I'_s is the saturation magnetization of bulk material, $x = D/D_v$ is the reduced diameter (D_v is the median diameter of particles) and $f(x)$ is the particle size distribution function. In the solid phase we can write the following equation:

$$I(H) = I_s \int_0^{x_0} L(ax) f(x)\,\mathrm{d}x, \tag{3}$$

where x_0 is defined from eq. (1) as

$$x_0^3 = 150\,k_B T/\pi K D_v^3. \tag{4}$$

The particles with $x > x_0$ have the remanence behaviour, thus we can write

$$I_R = (n\pi D_v^3 I'_s/6) \int_{x_0}^{\infty} x^3 f(x)\,\mathrm{d}x, \tag{5}$$

where n is the density of the magnetic particles.

For experimental measurements we have used the glycerine based ferrofluid with the Fe_3O_4 particles. The magnetization of a ferrofluid in an applied magnetic field was obtained on a ballistic galvanometer when a capsule of a cylindrical sample of the ferrofluid (15 mm long × 2 mm diameter) was rapidly removed from a search coil placed in a field H. The deflection is directly proportional to the fluid magnetization.

Calibration was against a standard pure nickel sample of an equal shape and volume as the ferrofluid.

Figure 1 shows the magnetization curve for a glycerine based fluid containing Fe_3O_4 particles at room temperature. The curve shows the characteristic superparamagnetic behaviour and there is no remanence. Using the Chantrell et al. technique [3] we have calculated the parameters of the log-normal particle size distribution function: $D_v = 15.25$ nm and $\sigma = 0.567$ respectively. Using these parameters we have calculated the theoretical fit of the magnetization (full line in fig. 1).

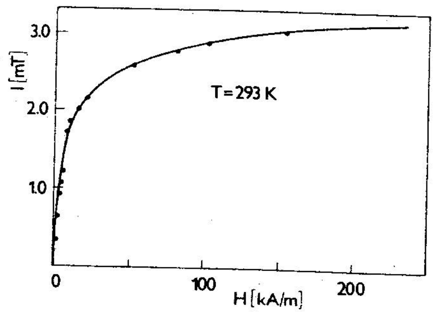

Fig. 1. Room temperature magnetization curve of a glycerine based ferrofluid. The full line is the theoretical line using the superparamagnetic theory.

Figure 2 shows the magnetization curves at liquid nitrogen temperature in two situations:

i. the ferrofluid was cooled to liquid nitrogen temperature in a zero field (full symbols). Here the superparamagnetic behaviour is evident.

ii. the ferrofluid was cooled to liquid nitrogen temperature in the field 10^5 A/m (empty symbols); here the remanence behaviour is evident.

The saturation magnetization of the ferroflud is $I_s = 3.38$ mT, the concentration of the magnetic particles in unit volume is $n = 1.28 \times 10^{22}\,\mathrm{m}^{-3}$ and the remanence magnetization is $I_R = 1.35$ mT.

From the value of I_R and eq. (5) we have determined $x_0 = 0.86$, which gives the effective anisotropy constant of the Fe_3O_4 particles $K = 2.25 \times 10^4\,\mathrm{Jm}^{-3}$. This calculation is performed assuming the material to have uniaxial anisotropy. The calculated value is in good agreement with the effective anisotropy constant $K = 3.1 \times 10^4\,\mathrm{Jm}^{-3}$ determined from ac susceptibility measurements [4].

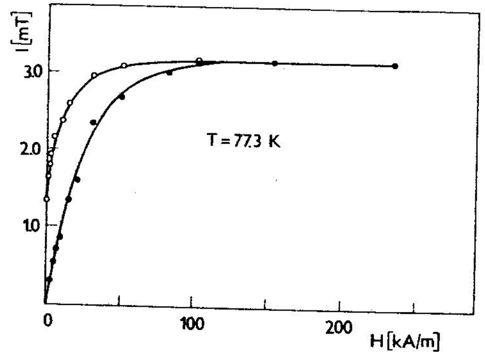

Fig. 2. Liquid nitrogen temperature magnetization curves. ● — the ferrofluid cooled in a zero field; ○ — the ferrofluid cooled in the field $H = 10^5$ A/m. Full lines are theoretical fits using eqs. (3) and (5).

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