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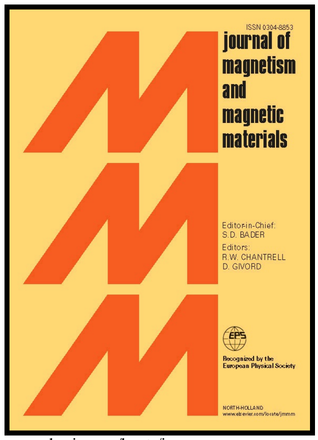

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The effect of polydispersity on the magnetostatic properties of concentrated ferrofluids

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Abstract

A statistical model of highly concentrated polydisperse ferrocolloids is proposed. The study approach is based on the second-order modified mean-field theory (MMF2) [A.O. Ivanov, O.B. Kuznetsova, Phys. Rev. E 64 (2001) 41405]. To increase the accuracy of the analytical expression of the magnetization we calculate the contribution of the dipole-dipole interaction energy up to the 2nd order in the pair distribution function for ferroparticles system. The obtained expression of magnetization corresponds the theoretical expression of initial magnetic susceptibility proposed by the new polydisperse theory [A.O. Ivanov, E.A. Elfimova, J. Magn. Magn. Matter. 374 (2015) 327] exactly. In conjunction it can be applied for magnetogranulometric analysis of polydisperse concentrated ferrofluids.

Keywords: ferrofluids, polydispersity, magnetization, static initial magnetic susceptibility, magnetogranulometric analysis

1. Introduction

Ferrofluids are the stable colloidal systems of ferro- or ferrimagnetic nanoparticles, which are suspended in a liquid carrier. Ferrofluid interacts with the external magnetic field and at the same time has the liquid state. Such a unique combination of properties proves its active application in modern technologies and medicine [1, 2, 3, 4]. Therefore, it is important to study the theoretical behavior of ferrofluid primarily in the presence of a magnetic field. The main difficulty in the description of magnetostatic properties of ferrofluid is taking into account of the long-range dipole-dipole interparticle interactions, which are essential to the system's behavior. Moreover, the polydispersity is an inherent characteristic of real ferrofluids, and it can significantly affects the properties of these systems [5].

In theoretical studies the ferrofluids are commonly modeled by the fluid of hard spherical dipolar particles (DHS) of diameter x covered by the surfactant layer with the thickness l; the outer diameter of the particles is $d = x + 2l$. The magnetic moment of each ferroparticle m is proportional to the product of the saturation magnetization of the magnetic material M_0 and the volume of its magnetic core $m = M_0 \pi x^3/6$. According to single-particle model [6], the magnetization of ferrocolloids obeys classical Langevin law, and the initial susceptibility χ_L is proportional to the concentration n and mean square of magnetic moments of particles $\langle m^2 \rangle$ and inversely proportional to the temperature T:

$$M_L(\alpha) = n\langle m(x)L(\alpha(x))\rangle_x, \quad L(\alpha) = \coth\alpha - \frac{1}{\alpha}, \tag{1}$$

$$\chi_L = \frac{n\langle m(x)^2\rangle_x}{3kT}, \quad \langle ... \rangle_x = \int_0^\infty ... \, f(x)dx, \tag{2}$$

where $\alpha(x) = m(x)H/kT$ is Langevin parameter for an external uniform magnetic field H. In this case interparticle interactions are neglected and ferrocolloids are considered as ideal paramagnetic gas of magnetic ferroparticles suspended in a liquid matrix. The attempts to account for interparticle interactions were made in later theories namely the effective field model in Weiss form [7], mean-spherical approximation [8, 9], different variants of thermodynamic perturbation theory [10, 11, 12, 13]. These studies conclude that magnetodipole interparticle interactions increase magnetic characteristics of ferrocolloids compared to those for noninteracting particles and that the initial magnetic susceptibility increases with the concentration of ferrophase more rapidly than it is predicted by the linear Langevin law. One can note a good agreement of these models with experimental magnetization curves and both temperature and concentration dependencies of the initial susceptibility of ferrofluids with the low and moderate content of magnetic phase (10-12%). However, for more concentrated systems (15-18%), significant discrepancies between theoretical dependencies and experimental results [9, 14, 15] are observed, first of all, in the temperature behavior of magnetic susceptibility. The approach of the second-order modified mean field theory (MMF2) [16] allows to obtain analytical expressions for magnetization and initial magnetic susceptibility, which can successfully describe these concentrated systems:

$$M(H) = n\int_0^\infty m(y) f(y) L\left[\frac{m(y)H_e}{kT}\right]dy, \tag{3}$$

$$H_e = H + \frac{4\pi}{3}M_L(H) + \frac{(4\pi)^2}{144}M_L(H)\frac{dM_L(H)}{dH},$$
$$\chi = \chi_L\left[1 + \frac{4\pi\chi_L}{3} + \frac{(4\pi\chi_L)^2}{144}\right]. \tag{4}$$

In the first half of 2000s Perm laboratory synthesized the sample of very dense ferrofluids with the magnetic phase vol-

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