Available online at www.sciencedirect.com
SCIENCE DIRECT®

Journal of Magnetism and Magnetic Materials 258–259 (2003) 436–438

Journal of magnetism and magnetic materials

www.elsevier.com/locate/jmmm

Influence of double electrical layers on the diffusion of magnetic particles in the ionic magnetic fluids

V.V. Gogosov, G.A. Shaposhnikova*

Institute of Mechanics, Moscow University, Michurinkii Pr. 1, 119192 Moscow, Russia

Abstract

The presence of the force F_{dl}, acting on the particles with double electrical layers in the ionic magnetic fluids during nonuniform particle distribution in the space, is discussed. This force is analogous to force F_{B}, caused by Brown motion of the "gas" of the particles. Introducing relation $\lambda = F_{\mathrm{dl}}/F_{\mathrm{B}}$, it is possible to find corrections to the diffusion coefficients. The dependence of value λ from the parameters of magnetic fluid is investigated. It is shown that this correction can be essential for the highly concentrated magnetic fluids.

Keywords: Ionic magnetic fluids; Double electrical layers; Diffusion coefficient

1. Introduction

It is known that around the magnetic particles, dispersed in the ionic magnetic fluids, the double electrical layers appear. The presence of these layers ensures the stability of magnetic fluids. Double layers are formed as a result of selective absorption of the ions of one sign on the particles surface, the ions of the opposite sign surround the particle by the diffusion layer. The thickness of this layer is approximately equal to Debye's radius and depends on the concentration of ions in the liquid (its conductivity) and the temperature.

The presence of double layers has an effect on the rheology of magnetic liquids, and also on the motion of magnetic particles relative to the dispersive liquid [1]. During the rapprochement of the magnetic particles up to distances smaller than the Debye's radius, double layers intersect. This leads to the repulsion of the magnetic particles from each other, on the particles acts the force, which is called the disjoining pressure [2]. Formula for the repulsive force between two particles, when the sizes of the particles are much more than the thickness of the double layer, and distance between the particles was obtained in Ref. [3]. For the spherical particles in the case of small potentials ($e\varphi_0/kT \ll 1$), this formula takes the form

$$F = \frac{\varepsilon}{4} a_{\mathrm{d}} \varphi_0^2 \left[1 - \mathrm{th}\left(\frac{h_{\mathrm{d}}}{2}\right)\right], \quad a_{\mathrm{d}} = \frac{a}{r_{\mathrm{D}}}, \quad h_{\mathrm{d}} = \frac{h}{r_{\mathrm{D}}},$$
$$r_{\mathrm{D}} = \sqrt{\frac{\varepsilon kT}{8\pi e^2 n_0}}. \tag{1}$$

Here a is the radius of particle, h is the distance between the nearest points of the particles surface, n_0 is ions concentration in the magnetic fluids, k is the Boltzmann constant, T is the temperature, ε is the dielectric permeability of the liquid, in which the magnetic particles are dispersed, e is the ions charge and φ_0 is the potential of the particle. When the distance between the particles is more or approximately equal to the radius of the particle, and the inequality

$$\exp(-h_{\mathrm{d}}) \ll 1 + \frac{h}{a}, \tag{2}$$

is fulfilled, it is possible to use the formula obtained in Ref. [4]. For the spherical particles in the case of small potentials ($e\varphi_0/kT \ll 1$) this formula takes the form

$$F = \frac{\varepsilon a_{\mathrm{d}} \varphi_0^2 (1 + h_{\mathrm{d}} + 2a_{\mathrm{d}})}{(h_{\mathrm{d}} + 2a_{\mathrm{d}})^2} \exp(-h_{\mathrm{d}}). \tag{3}$$

*Corresponding author. Fax: +7-095-9390165.
E-mail address: gshap@imec.msu.ru (G.A. Shaposhnikova).

0304-8853/03/$ - see front matter © 2002 Elsevier Science B.V. All rights reserved.
PII: S0304-8853(02)01087-9

Inequality (2) means that the disturbances introduced by a particle in the distribution of electric potential, damp at the distances approximately equal to h. Let us note that with $h \gg a$ inequality (2) is always fulfilled, independent of the value of Debye's radius.

During a nonuniform distribution of the particles in the space on the single chosen particle the force, caused by the asymmetrical action on it of other particles, will act. From that side, where the particles are distributed nearer to the chosen particle, the disjoining pressure will be more and resulting force will arise, directed to the side, opposite to the direction of the concentrations gradient of the particles [5]. In this work similar force acting on the particles in the ionic magnetic fluids is considered.

2. Model

Let us assume that in the magnetic fluid all particles identical, i.e., have one and the same radius and the same electrical potential and for all particles inequality (2) is fulfilled. The force, F_p, which acts on the chosen particle from the side of the particles will be on the whole determined by the interaction of the chosen particle with the two adjacent ones, situated on the straight line, directed along the concentrations gradient. Let us examine three particles, situated along this straight line, so that distances from the chosen particle to the adjacent particles are equal h_1 and h_2. For calculation of the force F_p of the interaction of the chosen particle with the adjacent we will use formula (3). Assuming, $h_1 = h$, $h_2 = h + \Delta h$, $\Delta h \ll h$ we will obtain

$$F_p = \frac{\varepsilon a_d \varphi_0^2 (1 + (1 + h_d + 2a_d)^2)}{(h_d + 2a_d)^2} \exp(-h_d)\Delta h. \tag{4}$$

Let h is equal to average distance between the particles, . Let us assume also that ∇n_p changes weakly at the distances are approximately equal to h. Then, expanding h and n_p into Taylor series, we obtain

$$\Delta h = \frac{\partial h}{\partial n_p}\Delta n_p = \frac{\partial h}{\partial n_p}(h + 2a)|\nabla n_p| = -\frac{1}{3} n_p^{-1/3}(h + 2a)|\nabla n_p|. \tag{5}$$

Substituting Eq. (5) in Eq. (4), we have

$$F_p = -\frac{\varepsilon a a_d \varphi_0^2}{3 n_p}\left[n_p^{1/3} r_d + \frac{(n_p^{1/3} r_d + 1)^2}{n_p^{1/3} r_d}\right] \times \exp\left(2a_d - \frac{1}{n_p^{1/3} r_d}\right)\nabla n_p. \tag{6}$$

The force F_{dl}, which acts on the particles per unit of volume of the magnetic fluid, is equal to (of course, the given conclusion it can pretend to the estimation of the force only approximately)

$$F_{dl} = n_p F_p = -\frac{\varepsilon a a_d \varphi_0^2}{3}\left[n_p^{1/3} r_d + \frac{(n_p^{1/3} r_d + 1)^2}{n_p^{1/3} r_d}\right] \times \exp\left(2a_d - \frac{1}{n_p^{1/3} r_d}\right)\nabla n_p. \tag{7}$$

This force is analogous to the force caused by the Brown motion of "gas" of the particles, it is proportional to the concentration gradient of magnetic particles and causes the motion of these particles because of a nonuniform distribution of particles in the space. Let us introduce the relation

$$\lambda = \frac{F_{dl}}{F_p} = \frac{\varepsilon a a_d \varphi_0^2}{3kT}\left[n_p^{1/3} r_d + \frac{(n_p^{1/3} r_d + 1)^2}{n_p^{1/3} r_d}\right] \times \exp\left(2a_d - \frac{1}{n_p^{1/3} r_d}\right). \tag{8}$$

This relation can be considered as correction to the diffusion coefficient. Let us introduce the effective diffusion coefficient

$$D_{eff} = D(1 + \lambda) = \frac{kT}{6\pi\mu a_h}(1 + \lambda). \tag{9}$$

Here μ is the dynamic viscosity of the carrying liquid, a_h hydrodynamic radius of the magnetic particle.

The value λ at the given temperature and the potential of the particles depends on three parameters: the number of magnetic particles per unit of volume of magnetic fluid n_p or volume concentration, $\Gamma = 4\pi a^3 n_p/3$, radius of Debye (ions concentration n_0 in the carrying liquid or its conductivity) and radius of magnetic particles a. With an increase of n_p and a the relation λ grows. Dependence of λ on Debye's radius (ions concentration n_0) is nonmonotonic. With the decrease of Debye's radius (increase in ions concentration n_0) to a certain value equal r_D^* the force F_{dl} and, therefore, relation λ grow

$$r_D^* = \frac{n_p^{-1/3} - 2a}{2n_p^{1/3}(a + \sqrt{a n_p^{-1/3} - a^2})}.$$

With further decrease of the radius of Debye (increase in ions concentration n_0) the force F_{dl} and relation λ diminish, since the region of the overlapping of the double electrical layers decreases. At those values of Debye's radii, when the double layers can be considered not intersecting, the force F_{dl} and relation λ is in effect equal to zero. Evaluations according to the given formulas show that the correction to the diffusion coefficient λ for the liquids usually not aggregated, $\Gamma \approx 0.02, a \approx 10^{-6}$ cm, does not exceed 0.1. For the highly concentrated magnetic fluids, $\Gamma \approx 0.1, a \approx 10^{-6}$ cm, the parameter λ is approximately equal to 0.2. For the aggregated magnetic fluids, $\Gamma \approx 0.02, a \approx 10^{-5}$ cm, the correction to the diffusion coefficient λ can be approximately equal to one, i.e., the presence of double electrical layers can increase the diffusion coefficient twice. For the highly concentrated aggregated magnetic fluids, $\Gamma \approx 0.1, a \approx 10^{-5}$ cm, the force $F_{\rm dl}$ can exceed the force caused by Brown motion of the particles. In the calculations it was assumed that $\varepsilon = 2, \varphi_0 = 30\,\rm mV$.

Analogously, the presence of the gradient of the temperature in the magnetic fluids causes the asymmetry action from the side of the surrounding particles to the chosen particle, caused by the presence of double electrical layers. As a result, the force proportional to the gradient of the temperature acts on the particles. The presence of this force can be approximately taken into account in the form of correction to the coefficient of the thermal diffusion .

3. Conclusion

For the aggregated magnetic fluids the presence of double electric layers on magnetic particles can increase the value of diffusion coefficients essential.

References

[1] K.I. Morozov, J. Magn. Magn. Mater. 201 (1999) 248.
[2] B.V. Deryagin, M. Kusakov, Izv. Akad. Nauk SSSR, Chem. Ser. 5 (1937) 1119.
[3] B.V. Deryagin, Izvestiya Akademii Nauk SSSR, Chem. Ser. 5 (1937) 1153.
[4] G.M. Bell, S. Levine, L.N. McCarthey, J. Coll, Interface Sci. 33 (1970) 335.
[5] O.N. Bondarenko, V.V. Gogosov, G.A. Shaposhnikova, Fluid Dynamics (Izv. Akad. Nauk SSSR, Mekh. Zhidk. Gaza) 5 (1984) 98.