MAGNETOHYDRODYNAMICS Vol. 54 (2018), No. 1-2, pp. 5–10
DOI: 10.22364/mhd.54.1-2.1

MAGNETO-OPTIC EFFECT IN WATER-BASED MAGNETIC EMULSIONS

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Extinction and scattering of light by aqueous magnetic emulsions with different concentrations of magnetic fluid were studied. Particles size distribution in magnetic emulsions by dynamic light scattering was measured. Peculiarities of light extinction under the action of a magnetic field are discussed.

Introduction. Emulsions are mixtures of two or more immiscible fluids stabilized by interfacial adsorption of surfactants. A stable (oil-in-water type) magnetic emulsion was produced by the emulsification of a magnetic fluid in an aqueous solution of surfactants having an appropriate hydrophilic-lipophilic balance [1–3]. The properties of the emulsions with magnetic fluid droplets dispersed in water have been studied in several works [4, 5]. A magnetic emulsion subjected to a magnetic field exhibits a complicated structural behaviour: droplets can deform, elongating along the vector of the magnetic field strength, and aggregate to form various structures [6, 7]. These processes affect the magnetic, rheological and optical properties of magnetic emulsions [8–10]. In magnetic emulsions, the field-induced drop deformation and structural transitions are investigated by measuring the diffraction patterns [11, 12] and transmitted light intensity [13]. Magnetic emulsions are used for imaging internal defects in materials [14] and for novel tunable optical filters [15]. In this paper, we present the results of a kinetic investigation of the scattering and extinction of light in magnetic emulsions.

1. Experimental. Peculiarities of the optical effects of extinction and scattering of light in magnetic emulsions with magnetic fluid droplets dispersed in water were investigated. Samples of the magnetic emulsions were prepared using kerosene-based magnetic fluids produced by the Scientific Institute of Gas Processing (Russia). To produce a sample, a magnetic fluid was stirred in water using ultrasound with the addition of a surfactant, and the largest drops were subject to a non-uniform magnetic field. The volume concentration of the magnetic drops in the samples was $0.2-2\%$. A light scattering measurement was made using a Photocor-Complex spectrometer of static and dynamic light scattering. To study the variation of light extinction in a magnetic emulsion under the action of a magnetic field, a transparent glass cell with a sample was placed in the zone exposed to a uniform field induced by Helmholtz coils. A pulsed magnetic field was created by a pulse generator. The light of a helium-neon laser with a wavelength of 633 nm passed through the cell with an emulsion sample and was detected by a photomultiplier.

The size of the magnetic drops was determined by applying the dynamic light scattering method considering the measurements of the translational Brownian diffusion coefficient. The dependence of the scattered light intensity on the scattering angle was studied by the method of static light scattering. In Fig. 1, the scattering indicatrices for emulsions with different concentrations of magnetic drops are shown. In the samples studied, the light scattering at small angles predominates, indicating that the particle size in the emulsion is comparable to or greater than the wavelength (650 nm).

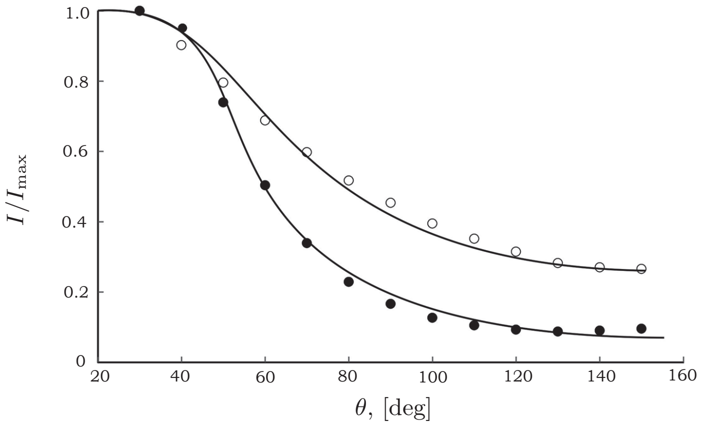

Fig. 1. Indicatrix of light scattering in two samples of magnetic emulsions.

The particle size distributions of magnetic emulsion droplets were calculated from the data of dynamic light scattering. It was assumed in the calculations that the application of the dynamic light scattering method for strongly opalescent systems is limited only by the scattering angles exceeding 90 degrees, in which the multiply scattered light is minimal. The classical definition of the size r of a solid particle from the dynamic light scattering data employs the Einstein–Stokes equation [16]:

$$D_{\mathrm{t}} = \frac{kT}{6\pi\eta r} \tag{1}$$

The emulsion droplets are not solid and, in this case, the diffusion coefficient should be calculated using the Rybczynski–Hadamard formula [17]:

$$D_{\mathrm{t}} = \frac{kT}{2\pi r\eta_{\mathrm{m}}\dfrac{2\,\eta_{\mathrm{m}} + 3\eta_{\mathrm{d}}}{\eta_{\mathrm{m}} + \eta_{\mathrm{d}}}}, \tag{2}$$

where η_{d} and η_{m} denote the magnetic fluid droplets and the water viscosities, respectively. When $\eta_{\mathrm{d}} \gg \eta_{\mathrm{m}}$, Eq. (2) becomes the classical Einstein–Stokes Eq. (1).

Fig. 2 shows the magnetic droplets size distribution obtained from the light scattering data at an angle of 140 degrees. The analysis of the distribution in the sample showed the presence of two fractions of droplets with average sizes of 110 nm and 750 nm with scatterings in sizes of 80 – 150 nm and 500 – 1000 nm, respectively.

Variations of the optical density in magnetic emulsions under the influence of a magnetic field are illustrated in Figs. 3 – 5.

2. Results and discussion. The effect of the light extinction variation in a dispersed system in an external field is usually estimated from the relative variation in optical density [18]:

$$\delta D = \frac{D_H - D_0}{D_0} = \frac{1}{D_0} \cdot \log \frac{I_0}{I_H}, \tag{3}$$

where D_H, I_H and D_0, I_0 are, respectively, the optical densities and intensities of light under the action of the magnetic field and in the field absence.

When the magnetic field is switched on, the optical density of the system decreases (the emulsion becomes more transparent, the parameter of the magneto-optical effect is negative $\delta D < 0$). It was found that when the magnetic field was

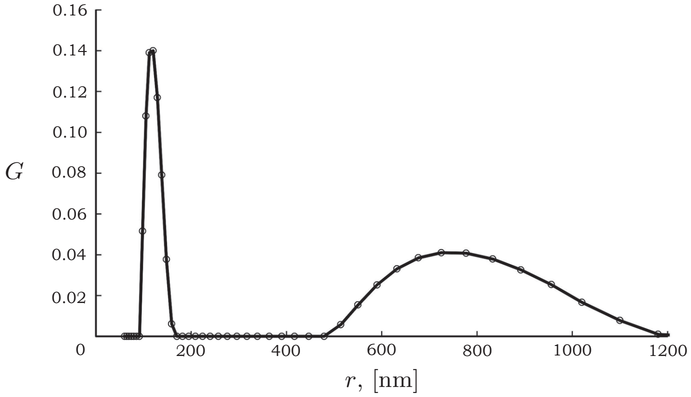

Fig. 2. Particles size distribution in magnetic emulsion.

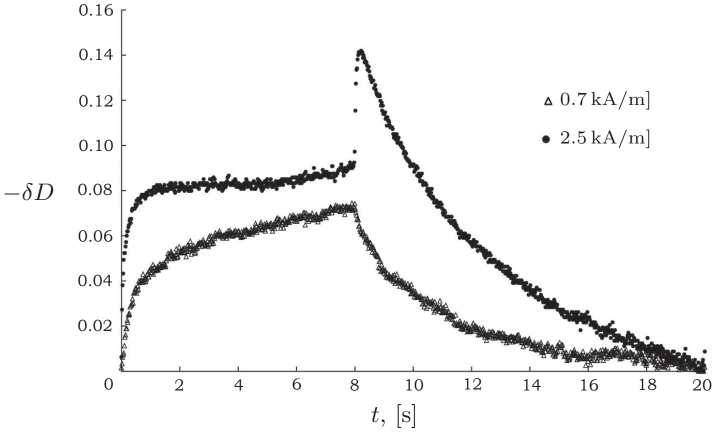

Fig. 3. Optical density variation under the action of a pulsed magnetic field.

switched off ($H > 1.5\,\mathrm{kA/m}$), the relaxation had an unusual character for the magneto-optical effects (it increased with field switching on, the stationary phase and relaxation after switching the off – see Fig. 3). During $0.1-0.3$ seconds after the field was switched off, the optical density of the system decreased sharply, significantly exceeding the magnitude of the effect in the field, and then decreased according to a law similar to exponential to a value of D_0. The effect becomes more distinct when the amplitude of the field pulse increases. A characteristic feature of the effect is the presence of hysteresis even under relatively small magnetic fields (Fig. 4).

In addition, in sufficiently strong fields ($H > 3\,\mathrm{kA/m}$), the optical density decreased first after the field was switched on, and then again it increased to practically that value characteristic to the absence of the field. The value of δD in the stationary zone before the field variation varied nonlinearly with the field and had a maximum at $1.8-2\,\mathrm{kA/m}$.

The relaxation time of the effect was $3-4$ seconds (Fig. 5). According to [6], the relaxation of the electro- or magneto-optical effect is described by the expression:

$$\delta D(t) = \delta D_{\max}\,\mathrm{e}^{-t/\tau}, \tag{4}$$

where τ is the relaxation time of the effect. In the case of orientational optical effects (birefringence, dichroism), the relaxation time is determined by the rota-

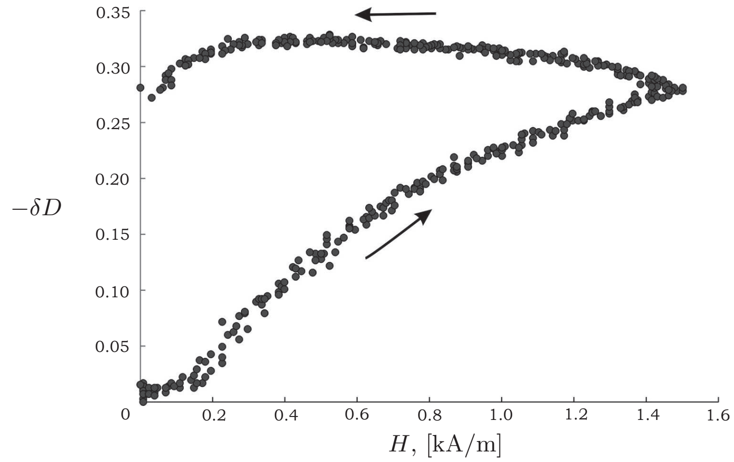

Fig. 4. Hysteresis of the magneto-optical effect in magnetic emulsion.

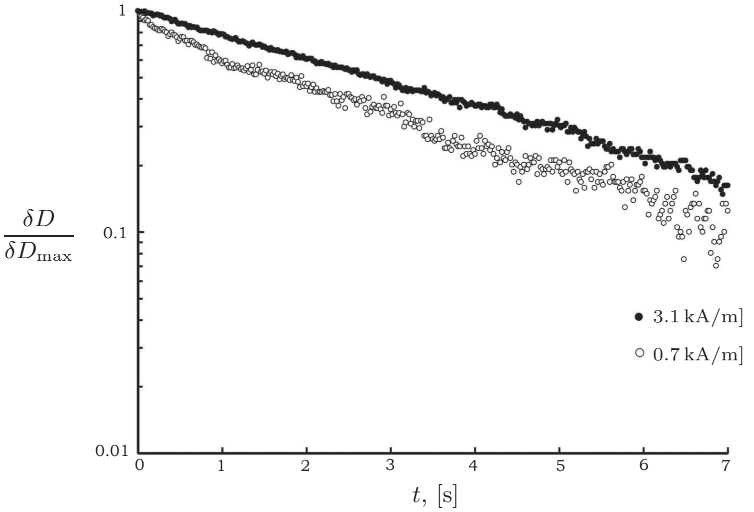

Fig. 5. Relaxation curves of the magneto-optical effect in magnetic emulsion upon switching off magnetic field pulses.

tional Brownian diffusion coefficient. In aqueous magnetic emulsions, the magneto-optical effect is apparently not orientational, and the relaxation after the field is switched off can be determined by the translational diffusion of individual droplets. Upon switching the field off, the resulting chain aggregates of the emulsion micro-droplets were destroyed by the action of Brownian diffusion. The relaxation time, in this case, can be estimated from the formula:

$$\tau \approx \frac{L^2}{D_\tau}, \tag{5}$$

with L being the average distance between the microdroplet chain aggregates. The estimation of this time using the data on microscopic observations gives values of the order of $5-10$ sec, which agrees well with the experimental data, taking into account that the largest and, respectively, the slowest drops are clearly visible in the microscope.

3. Conclusions. In the aqueous magnetic emulsion, two fractions of droplets with average sizes of 100 and 500 nm were detected by optical methods. The investigated samples are dominated by forward scattering due to the largest drops. The effect of the optical density variation in a longitudinal field can be characterized by the formation and transformation of complex aggregate structures consisting of the magnetic emulsion droplets.

Acknowledgements. This work was supported by the Russian Foundation for Basic Researches (project No.18-03-00279).

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Received 27.12.2017