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REVIEWS

THERMAL AND PHYSICAL PROPERTIES OF MAGNETIC FLUIDS

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The basic physical properties of dilute magnetic colloidal solutions (a new class of fluids, in which the interaction of the dispersed phase with an external magnetic field is a source of an additional inertial force) were considered in the review [1]. As a result of this interaction, it appears to be possible to enhance the transport of heat in a magnetic fluid by means of a stationary nonuniform magnetic field, which induces thermomagnetic convection in a nonisothermal fluid. In the time since the appearance of this review, extensive experimental data has become available on the thermal and physical properties of concentrated magnetic fluids (volume concentration of the dispersed phase in the interval $0.1 \le \varphi \le 0.20$). In addition, new mechanisms enhancing heat transport in concentrated magnetic fluids have been identified. One of them is connected with the microscopic mixing of a fluid with rotation induced by means of solid colloidal particles and aggregates [2]. Rotation can also cause macroscopic motion, which affects the transport of heat in a nonisothermal fluid [3].

It is of interest to summarize the experimental results obtained in the last few years on the thermal and physical properties of magnetic fluids for a wide interval of concentrations of the dispersed phase.

The thermal regime of the most common device using magnetic fluids (magnetic-fluid seals) depends mainly on viscous dissipation inside the working gap [4]. Therefore, we also consider in the present review internal friction in magnetic fluids for strong shear deformations in the presence of a magnetic field.

The technology for obtaining magnetic fluids whose dispersed phase is single-domain magnetite (Fe_3O_4) particles is the most developed. The mass per unit volume of fluid is composed of the masses of three components:

$$\rho_{mf} = \rho_0 \varphi_0 + \rho_M \varphi + \rho_{SAM}[1 - (\varphi_0 + \varphi)]. \tag{1}$$

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From this relation one can obtain an equation for the volume concentration of Fe_3O_4 in terms of density measurements. The equation is simple when the densities of the fluid components (the solvent and the surface-active material (SAM)) are approximately equal:

$$\varphi = \frac{\rho_{mf} - \rho_{SAM}}{\rho_M - \rho_{SAM}}. \tag{2}$$

Since the ratio of the densities of magnetite and the surface-active material (oleic acid) is typically $\rho_M/\rho_{SAM} \approx 5\ \ 5$, from (2) we have $\rho_{mf} \sim 1.5\rho_{SAM}$ for concentrated fluids.

The single-domain magnetite particles suspended in the fluid phase impart magnetic properties to the fluid as a whole. Obviously the saturation magnetization M_0 of the magnetic fluid will be proportional to the concentration of the dispersed phase: $M_0 = \varphi_M M_s$. Here φ_M is the volume concentration of magnetic material; M_s is the magnetization of a domain. The magnetization curve of a magnetic fluid has a hysteresis-free form [6, 7] characteristic of paramagnets, whose magnetostatic properties are described by the Langevin formula:

$$M = M_0\left(\operatorname{cth}\frac{\mu_0 m_{ef} H}{kT} - \frac{kT}{\mu_0 m_{ef} H}\right), \tag{3}$$

where $M_0 = nm = \varphi_M M_s$; $m_{ef} = (\pi/6)M_s\bar{d}^3$.

It is evident from (3) that in thermodynamic equilibrium the static magnetization of the fluid is uniquely determined by the number of particles n per unit volume and by the thermodynamic parameters H and T. This dependence describes the equilibrium magnetization: $\mathbf{M}\uparrow\uparrow\mathbf{H}$. When a magnetic fluid flows in the presence of a stationary magnetic field (or if it is acted upon by a nonstationary field) a nonequilibrium component of the magnetization is induced by the coupling beween the rotation of particles in the flow and the rotation of their magnetic moments. The degree to which the magnetic moment is "frozen" in the particle is characterized by the parameter $\zeta = K_a V_M/2kT$. Here V_M is the "magnetic" volume of the particle. For colloidal particles of magnetite $\zeta = 0.3$–3, and in a dilute fluid ($\varphi < 0.03$) one can normally neglect the effect of the motion of the fluid on its magnetic properties 8 .

In concentrated fluids a spatial structure of magnetite particles can exist. When this structure is destroyed by the flow of the fluid, the magnetic susceptibility can change. Measurement of the initial magnetic susceptibility of fluids with transformer oil (MMt-95) as the solvent showed that the static susceptibility falls by about 15% when a cylindrical shear flow with $\dot{\gamma} = 28\ \sec^{-1}$ is created inside the magnetometer [9]. Therefore, the use of the static magnetization in hydrodynamic calculations involving weak shear flow is applicable only up to moderate concentrations of magnetite ($\varphi < 0.10$).

The decrease of the magnetization of a magnetic fluid with increasing temperature can lead to thermomagnetic convection. In many ways the onset of thermomagnetic convection resembles the loss of convective stabilityof an incompressible fluid resulting from the dependence of its density on temperature [10]. Experiments in the temperature interval T = (298–361)°K showed an approximately linear dependence of the saturation magnetization of highly concentrated, kerosene-based fluids ($\varphi = 0.28$) on temperature [11]:

$$M_0 = M_0^{298} - \tilde{\mathcal{K}}(T - 298), \tag*{4)}$$

where $\tilde{\mathcal{K}} \approx 0{,}15$ kA/(m·K) is the generalized pyromagnetic coefficient, which satisfies the relation $\tilde{\mathcal{K}} = \beta_{mf} M_0$ to within ±15% in this temperature interval.

Hence, far from the Curie point and in a strong magnetic field, the temperature dependence of the saturation magnetization is determined by the thermal expansion of the magnetic fluid.

The coefficient of thermal expansion of a magnetic fluid is found from the mixing rule:

$$\beta_{mf} = \beta_{SAM} + \varphi_0(\beta_0 - \beta_{SAM}) + \varphi(\beta_M - \beta_{SAM}), \tag{5}$$

where β_0, β_{SAM}, and β_M are the coefficients of thermal expansion of the solvent, the surface-active material, and the solid phase.

Measurements of the temperature dependence of the density of dilute, kerosene-based magnetic fluids ($\varphi \approx 0.03$) 12 show that in the interval T = (288–373)°K the density of the fluid decreases linearly with increasing temperature. A least-squares fit of the experimental data gives the quantity $\beta_{mf} \approx 0.75 \cdot 10^{-3}\ {}^\circ K^{-1}$, whereas $\beta_0 \approx 0.84 \cdot 10^{-3}\ {}^\circ K^{-1}$ for kerosene 13 . Obviously this difference will increase as the concentration of the dispersed phase increases.

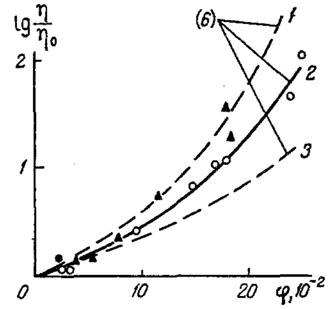

Fig. 1. Dependence (6) of the relative viscosity of a magnetic fluid (hydrocarbon solvent) on the volume concentration of magnetite for H = 0: 1) p = 3; 2) p = 2.5; 3) p = 2.

The energy dissipated when a magnetic fluid is pumped around a heat exchange cycle depends on the viscosity of the fluid. The internal friction generated when a magnetic fluid flows is larger than that of an ordinary fluid because of the presence of the solid particles, the effect of the external field on the motion of the particles, and magnetic dipole interaction between them. In the case when the latter interaction is insignificant and when H = 0, the internal friction should be describable by the well-known relations for the viscosity of a suspension.

In Fig. 1 the logarithm of the ratio of the experimental values of the viscosity of a magnetic fluid to the viscosity of the solvent is plotted for shear deformation rates in the interval $\dot{\gamma}$ = (730-1300) sec^{-1} [14]. The experimental data was approximated by the equation of 15 for the viscosity of concentrated suspensions with noninteracting particles

$$\ln\frac{\eta}{\eta_0}=\frac{2{,}5\varphi+2{,}7\varphi^2}{1-0{,}609\varphi}. \tag{6}$$

For small concentrations $\varphi \ll 1$ this reduces to the Einstein formula

$$\eta=\eta_0(1+2{,}5\varphi). \tag{7}$$

In magnetic fluids the viscosity depends on the hydrodynamic concentration of the dispersed phase $\varphi_h = p\varphi$, which is calculated taking into account the thickness of the adsorbed shell of surface-active material covering each particle: $d_h = d + 2\delta$. Here it is assumed that p is a coefficient which does not depend on concentration. The curves in Fig. 1 are constructed from the relation (6) for three different values of p. It is clear that the experimental points are closely approximated for moderate and high concentrations by the equation (6) with p = 2.5-3. Since $p = (d_h/d)^3$, we then have d_h/d = 1.357 to 1.442. For a mean particle size of $\bar{d}$ = 10 nm, we obtain a thickness of the adsorbed layer of $\delta = (d_h - \bar{d})/2$ = (1.8-2.2) nm. This is of the same order as the length of an oleic acid molecule. This fact suggests that dipole interactions between the particles are unimportant in determining the internal friction, in the absence of an external field. We note that the effective viscosity of a magnetic fluid for a moderate concentration of solid particles increases by a factor of 5-8 because of the presence of the dispersed phase.

Capillary viscometry data for the dependence of the effective viscosity of a magnetic fluid on the concentration of dispersed magnetite at H = 0 is described very well by (6), generalized to the case of a high concentration of solid spherical particles [16]:

$$\eta^{(0)}/\eta_0=(1-\varphi_h)^{-2{,}5}. \tag{8}$$

A particle rotating in a shear flow is braked by the external magnetic field if its magnetic moment $\mathbf{m}$ is fixed to the particle. The interaction of the solid particles and the solvent in this case is characterized by the coefficient of rotational viscosity, which reaches its limiting value for "frozen" moments ($\zeta \gg 1$) in large magnetic fields [17]:

$$\eta_r^{(\infty)}=1{,}5\varphi_h\eta_0. \tag{9}$$

With the help of (8) and (9), we obtain the following result for the relative contribution of rotational viscosity in the linear approximation in φ_h:

$$\frac{\eta^{(\infty)}}{\eta^{(0)}} = \frac{\eta^{(0)} + \eta_r^{(\infty)}}{\eta^{(0)}} \approx 1 + 1{,}5\,\varphi_h. \tag{10}$$

The dependence (10) does not take into account dipole interactions between the particles. The experimental data of [12] is consistent with (10) only up to $\varphi \simeq 0.04$. Therefore, one can introduce the following relation for the effective viscosity of a dilute fluid in a strong field:

$$\eta^{(\infty)} = \eta^{(0)}(1 + 1{,}5\,\varphi_h). \tag{11}$$

As the concentration of the dispersed phase in the magnetic fluid increases, the contribution of dipole interactions between the particles to the effective viscosity increases (if the fluid is in an external field). By plotting the flow curves of magnetic fluids with $\varphi > 0.15$ in logarithmic coordinates, one can show that they are described very well by the power law $\tau = k\dot{\gamma}^n$. The value of the power n, which characterizes the deviation from the Newtonian flow law, is $n \simeq 0.8$ for a field $H = 84$ kA/m.

In earlier hydrodynamic calculations the temperature dependence of the viscosity of the solvent was used. Historically, this approach was connected with the first (and simplest) physical model of a magnetic fluid, which described the flow of a homogeneous magnetic fluid with a viscosity that was independent of the magnetic field [18]. But there are two significant facts for a magnetic fluid. First, a certain quantity of surface-active material is dissolved in the solvent, and this material "distorts" the transport properties of the solvent. Therefore, in equations (6)-(9) η_0 should be replaced by the dynamical viscosity of the fluid phase containing the surface-active material. Secondly, the viscosity of a magnetic fluid is really an effective quantity dependent on several dissipative mechanisms which are absent in a homogeneous fluid. The contribution of these mechanisms to the internal friction can also be temperature dependent. The experiments of [19] demonstrated the difference between the temperature dependence of the effective viscosity of a hydrocarbon-based magnetic fluid and that of the solvent. The data agree qualitatively with measurements of the effective viscosity of water-based magnetic fluids [20], which were done for two concentrations of Fe_3O_4 particles. In the absence of a magnetic field the temperature dependence of the viscosity of a dilute fluid is determined by the temperature dependence of the viscosities of the solvent and surface-active material.

For magnetic fluids with kerosene MK-24 as the solvent, the effective viscosity in the temperature interval T = (233-303)°K and for the shear rate $\dot{\gamma} = 1312$ sec^{-1} satisfies the Andrade formula:

$$\eta_{ef} = B \exp(E/RT), \tag{12}$$

where $E = 15.8 \cdot 10^3$ J/mole, $B = 5.9 \cdot 10^{-3}$ mPa•sec, and $R = 8.31$ J/(mole•°K). In this interval the temperature dependence of the solvent can be described by (12) with $E = 15.2 \cdot 10^3$ J/mole, $B = 2.7 \cdot 10^{-6}$ mPa•sec [13]. In analyzing this result it should be noted that over practically the entire temperature interval considered here the surface-active material (oleic acid) was in the solid state.

The flow of a dilute fluid in a magnetic field is also accompanied by dissipation of energy because of rotational viscosity, which reaches a limiting value in strong fields ($H \sim 10^5$ A/m). In this case the magnetic moments of the particles are aligned along the field and if the magnetic moments are "frozen" in the particles, the magnetic moments rotate with respect to the solvent with the angular velocity $\mathbf{\Omega} = 1/2 \operatorname{rot} \mathbf{v}$. The velocity of the flow near a given particle varies from zero at the surface of the particle to $\mathbf{v}$ at distances exceeding the thickness of the adsorbed layer. The viscous frictional torque $6\eta_0 V_h \Omega$ acting on a particle leads to a deformation of the adsorbed layer [21]. Therefore, the temperature dependence of the effective viscosity of a magnetic fluid moving in a magnetic field resembles the corresponding dependence for the surface-active material more than when the flow is in the absence of the field.

For a certain value of $\mathbf{\Omega}$ the viscous torque will exceed the orienting effect of the field and the particle begins to rotate with a velocity characteristic of a hydrodynamic vortex. In this case the rotational viscosity vanishes. This effect was detected experimentally for magnetite magnetic fluids in a coaxial-cylindrical viscometer in the interval $\dot{\gamma} = (10^4$-

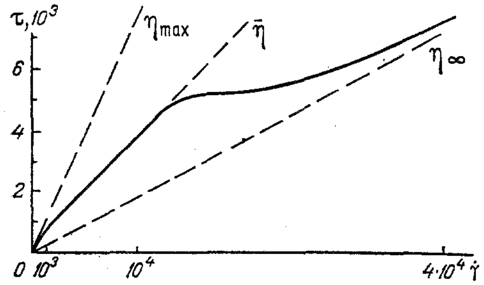

Fig. 2. Typical flow curve of a concentrated magnetic fluid in a magnetic field. τ, Pa; $\dot{\gamma}$, sec^{-1}.

$5\cdot10^4$) sec^{-1} in a radial magnetic field ($H \sim 10^6$ A/m) 22 . At these shear deformation rates the effective viscosity in the magnetic field appraoches the viscosity of a magnetic fluid in the absence of the field, because the magnetic mechanisms of energy dissipation can be neglected. The curve of the temperature dependence of the effective viscosity of a magnetic fluid (for $\dot{\gamma} \sim 10^5$ sec^{-1}) lies between the corresponding curves for the solvent and for the surface-active material.

Analysis of the experimental data obtained for different regions of the shear deformation rate lead to the curve shown in Fig. 2 23 for a concentrated magnetic fluid ($\varphi \sim 0.20$) in a strong ($H \sim 10^6$ A/m) magnetic field normal to the shear plane.

Another transport property characterizing the heat carrier is heat conduction. No effect of a magnetic field on the thermal conductivity of magnetic fluids in fields up to H = 200 kA/m was observed in [24-26]. One of the first formulas for the thermal conductivity of colloidal solutions was obtained in [27] and was based on the same method used to calculate the electric field in a two-phase system:

$$\lambda = \lambda_0 \frac{2\lambda_0 + \lambda_M - 2\varphi(\lambda_0 - \lambda_M)}{2\lambda_0 + \lambda_M + \varphi(\lambda_0 - \lambda_M)}. \tag{13}$$

Figure 3 shows the experimental values of the thermal conductivity of hydrocarbon-based magnetic fluids with different concentrations of magnetite at room temperature. They are consistent with (13) only up to $\varphi \sim 0.10$. Extrapolating the experimental curve onto the abscissa, the value $\lambda_0 = 0.120$ W/(m•°K) is obtained, which corresponds approximately to a 5% content of oleic acid in the solvent. Hence one can assume that the fluid phase is a 5% solution of oleic acid in the solvent, and in (6) through (9) the quantity η_0 should be replaced by the dynamical viscosity of the fluid phase. The surface-active material existing in the magnetic fluid in the free state lowers the surface tension. In addition, the surface active material covers the solid surface (exposed to the magnetic fluid) with a hydrophobic film, which protects the surface from corrosion.

From Fig. 3 it is evident that in the region of magnetite concentration $\varphi > 0.10$, the measured values of the thermal conductivity deviate systematically from the dependence (13). The thermal conductivity of concentrated magnetic fluids ($\varphi \sim 0.20$) satisfies the relation

$$\lg \lambda = (1 - \varphi) \lg \lambda_0 + \varphi \lg \lambda_M, \tag{14}$$

which was obtained for a binary system with a disordered arrangement of the components [28].

A fit of the existing experimental data for hydrocarbon-based magnetic fluids in the interval $0.004 \leq \varphi \leq 0.20$ by the polynomial expression

$$\lambda = a_0 + a_1\varphi + a_2\varphi^2 \tag{15}$$

gives $a_0 = 0.1267$; $a_1 = -0.0559$; $a_2 = 3.455$. The mean square deviation of the experimental points from this function is about 3%, while the maximum deviation does not exceed 6%.

The temperature dependence of the thermal conductivity of a magnetic fluid is determined by the concentration of the dispersed phase, and the temperature dependence of the thermal conductivity of this phase is different from that of the fluid phase. Analysis of the available experimental data shows that in magnetic fluids one observes a linear decrease of the

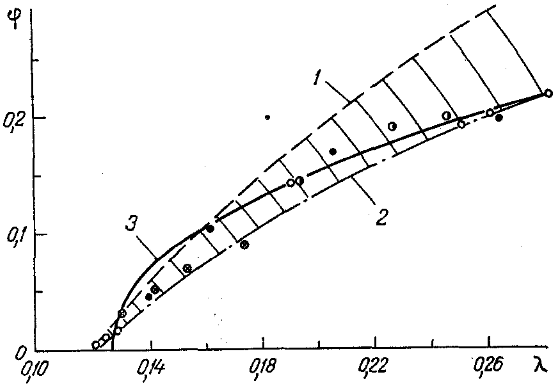

Fig. 3. Concentration dependence of the thermal conductivity of hydrocarbon-based magnetic fluids: 1) calculated using (13); 2) calculated using (14); 3) the approximation (15). λ, W/(m• °K).

effective thermal conductivity with increasing temperature. Hence, because of the difference between the temperature dependences of the thermal conductivities of the fluid and solid phases, the excess of the thermal conductivity of the magnetic fluid over that of its solvent gradually decreases with increasing temperature: from 30% at room temperature to 17% at T = 363°K [29].

A general expression for the thermal conductivity of magnetic fluids in the temperature interval considered here is

$$\lambda = K_1(\varphi)\,\lambda_0^{293}\,[1 - K_2'(\varphi)\,A_0\,(T - 293)], \tag{16}$$

in which the functions K (φ) and $K_2(\varphi)$ are greater than unity for $\varphi > 0$; A_0 is the temperature coefficient of the thermal conductivity of the fluid phase.

An important caloric property is the heat capacity and its dependence on temperature. The experiments of [30] have shown that one can use the mixing rule to calculate the heat capacity of a magnetic fluid in the interval T = (320-370)°K. The temperature dependence of the heat capacity of a highly concentrated magnetic fluid with transformer oil as solvent ($\varphi = 0.26$) can be approximated by a linear function with a correlation coefficient of 0.997:

$$c_p = 1{,}088 + 0{,}227\cdot 10^{-2}\,(T - 273)\ \text{kJ/(kg}\cdot{}^\circ\text{K)}.$$

A least squares fit to the data on the heat capacity of the solvent (transformer oil) gives

$$c_p^0 = 1{,}921 + 0{,}267\cdot 10^{-2}\,(T - 273)\ \text{kJ/(kg}\cdot{}^\circ\text{K)}$$

The fact that the heat capacity of a highly concentrated fluid is lower than that of its solvent is due to the high content of dispersed magnetite, for which c_p = (0.654-0.712) kJ/(kg• °K) [31] for the temperatures considered here. The deviation between the heat capacities calculated from the mixing rule (using mass fractions) and the measured values is less than 1.8% (Fig. 4).

The available measurements show that one can use the following relation to compute the specific heat of a concentrated magnetic fluid ($\varphi \sim 0.20$):

$$c_p = 0{,}425 + 0{,}135\cdot 10^{-2}\,(T - 273) + 0{,}345\,c_p^0\ \ \text{kJ/(kg}\cdot{}^\circ\text{K)}. \tag{17}$$

Surface tension of the fluid has a significant effect on heat exchange processes during boiling. Heat exchange in a boiling magnetic fluid in an external magnetic field was studied in [32-34]. Table 1 gives the physical properties of magnetic fluids based on various solvents at T = 298°K 35 , including the surface tension σ.

For comparison, the surface tensions of kerosene and water at T = 293°K [13] are:

$$\sigma_k = 0{,}0268\ \text{N/m},\quad \sigma_w = 0{,}0727\,\text{N/m}.$$

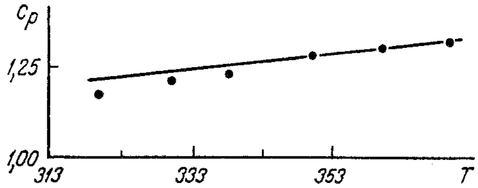

Fig. 4. Temperature dependence of the specific heat of a magnetic fluid with transformer oil as solvent ($\varphi = 0.21$). Curve: calculation; points: experiment. c_p, kJ/(kg•°K); T, °K.

TABLE 1. Physical Properties of Magnetic Fluids

Solvent	Saturation magnetization M_0, kA/m	Density $\rho \cdot 10^{-3}$, kg/m³	Viscosity* η, N•sec/m²	Solidifying point,† °K	Boiling point,‡ °K	Surface tension σ, N/m	Thermal conductivity λ, W/(m•°K)	Heat capacity per unit volume $c \cdot 10^{-6}$ kJ/(m³•°K)	Thermal expansion coefficient** $\beta_{mf} \cdot 10^{-4}$, °K⁻¹
Ethylhexonic ether of azeloic acid	15,90	1,185	0,075	236	422	—	—	—	—
Hydrocarbon	15,90	1,05	0,003	278	350	0,028	0,15	1,715	9,0
	31,80	1,25	0,006	281	350	0,028	0,15	1,840	8,6
Fluroalkyl polyether	7,96	2,05	2,500	239	456	0,018	0,20	1,966	10,6
Ether of silicic acid	15,90	1,15	0,014	217	422	0,026	0,31	3,724	8,1
	31,80	1,30	0,033	217	422	0,026	0,31	3,724	8,1
	47,70	1,40	0,035	217	422	0,021	0,31	3,724	8,1
Water	15,90	1,18	0,007	273††	299‡‡	0,026	1,40	4,184	5,2
	31,80	1,38	0,010	273††	299‡‡	0,026	1,40	4,184	5,0
Polyphenyl ether	7,96	2,05	7,500	283	533	—	—	—	—

*Measured in the absence of a magnetic field for $\dot{\gamma} > 10$ sec⁻¹.
†Corresponds to the value $\eta = 100$ N•sec/m².
‡At pressure 133 Pa.
**Average values in the interval 298-367°K.
††Freezing point.
‡‡At pressure 3.2 kPa.

In the absence of a magnetic field, the difference between the surface tensions of kerosene-based magnetic fluids ($0.03 \leq \varphi \leq 0.20$) and the surface tension of the solvent is within the scatter of the experimental data obtained by different methods [36].

In [37] a theory was developed for the dependence of the surface tension of a magnetic fluid on the component of the magnetic field normal to the free surface. The correction to the surface tension of the liquid phase comes from the interaction of the magnetic particles with the molecules of the liquid phase (in the absence of the external field) and from dipole interaction between the magnetic particles (in the presence of the field).

The experiments conducted in [38] on the instability of the surface between a magnetic and nonmagnetic fluid do not clarify the effect of a uniform magnetic field tangent to the surface on the surface tension.

A detailed study of the effect of a nonuniform magnetic field on the wetting of a solid (glass) surface by a magnetic fluid was carried out in [39]. Two colloidal solutions were used in the experiments: 1) ferromagnetic iron lignosulfonate particles in water and 2) magnetite particles in an aqueous solution of lauric acid.

Most of the runs were done on the first sample, which had the following characteristics: dynamical viscosity at room temperature $\eta = 35 \cdot 10^{-3}$ N•sec/m²; saturation magnetization $M_0 = 12$ kA/m; surface tension for the liquid–air boundary in the absence of a magnetic field (measured using the liquid drop method) $\sigma = (0.0638 \pm 0.0038)$ N/m.

The authors answered in the affirmative two questions posed by them as the purpose of the study: 1) does a magnetic field affect the wetting of a solid surface by a magnetic field; 2) is it possible to control, with the help of a magnetic field, the basic characteristics on the line of contact of the three phases.

Unlike the case of nonmagnetic fluids, where the wetting angle increases when the liquid-gas surface is placed on an earlier wetted surface, in a magnetic fluid in a field the wetting angle decreases.

There are other interesting effects which may be important in practice, such as the fact that the magnetic force causes a spreading of magnetic fluid drops along a solid surface which is not wetted by the fluid in the absence of the magnetic field.

It should be noted, however, that the available experimental data are still insufficient to calculate quantitatively the dependence of the surface tension of a magnetic fluid on the strength of the applied magnetic field.

At high temperatures an irreversible physical-chemical change in the heat carrier can occur. The thermal instability of a magnetic fluid is due primarily to the desorption of the adsorbed layer from the surfaces of the particles. It was initially suggested [40] that the coupling between the adsorbed layer and the particles could be increased with the help of polymerization. However, study of the thermal stability of magnetic fluids in which the surface-active material is oleic acid has shown that polymerization of the oleic acid by means of prolonged heating also causes coagulation of the dispersed phase [41]. Upon heating up to a temperature T = 423°K in open vials, only the kerosene-based magnetic fluids remained stable [42]. For experiments in closed vials, coagulation of the magnetic fluids set in after the samples were allowed to stand at a temperature of T = 588°K over a period of 24 h. It should be noted that these data were obtained for fluids prepared by prolonged dispersion of mixtures of powdered magnetic material, the solvent, and the surface active material in a ball mill back in the late 1960s. Better methods of producing magnetic fluids have since been developed, such as condensation of highly dispersed magnetite particles when divalent and triavelent iron salt solutions react with excess alkali, obtaining magnetic paste. It is dispersed in the solvent by prolonged heating and mixing [5]. Magnetic fluids in different solvents obtained by this method remain stable when subjected to prolonged heating up to 373°K and higher.

NOTATION

φ, volume concentration of the dispersed phase; ρ, density; M, magnetization; m, magnetic moment of a solid particle; d, diameter of a particle; H, magnetic field strength; T, temperature; K_a, crystallographic anisotropy constant; k, Boltzmann constant; V, volume of a particle; γ, shear deformation rate; β, coefficient of thermal expansion; η, dynamical coefficient of viscosity; τ, tangential stress; $\mathbf{v}$, velocity; λ, thermal conductivity; c_p, specific heat; σ, surface tension.

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