THERMAL CONDUCTIVITY OF MAGNETORHEOLOGICAL SUSPENSIONS IN THE PRESENCE OF SHEAR FLOW

S. A. Demchuk, É. A. Zal'tsgendler,
V. I. Kordonskii, I. V. Prokhorov,
and B. M. Khusid

UDC 532.135:537.84:536.22

The structure and physical properties of magnetorheological suspensions (MRS) in shear flows is studied in [1, 2]. A microscopic model was proposed to describe the dynamic structure of the MRS. According to the model, the suspension is a system of axisymmetrical elongated aggregates made up of the particles of the dispersed phase, oriented at some angle to the direction of the flow, forming under the action of the magnetic field. For simplicity, these aggregates are assumed to be axisymmetrical ellipsoids. The lengths of the semiaxes of the ellipsoid are determined by the ratio of the magnetic and hydrodynamic forces acting on an aggregate. The model is confirmed by the satisfactory agreement with experimental data for the magnetic susceptibility and the effective viscosity of the suspension. In this paper, this model is used to determine the effective coefficient of thermal conductivity of the MRS. The thermal conductivity tensor is calculated by the self-consistent field method (Lorenz–Lorentz) analogously to the calculation of the magnetization in [1, 2].

The thermal conductivity of a suspension of uniformly distributed and randomly oriented anisodiametric particles was calculated in a similar manner in [3, 4]. The temperature fields in the particle and in the dispersed medium, owing to the effective temperature gradient Ω,

Translated from Magnitnaya Gidrodinamika, No. 1, pp. 14–18, January–March, 1985. Original article submitted August 7, 1984.

 0024-998X/85/2101-0010$09.50

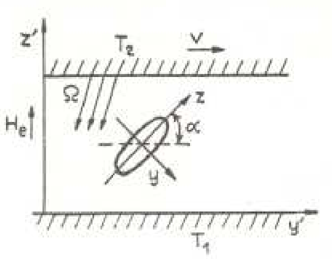

Fig. 1

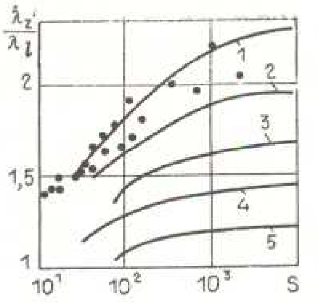

Fig. 2

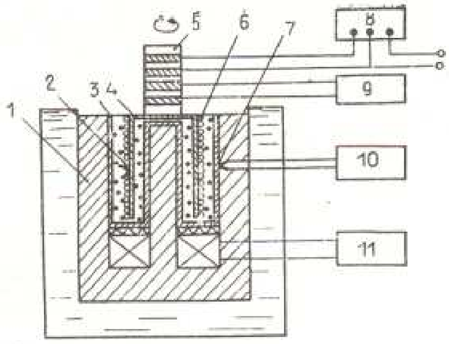

Fig. 3

Fig. 1. Working diagram for a nonisothermal Couette flow.

Fig. 2. Dependence of the relative coefficient of thermal conductivity on the complex S: φ : 1) 0.1; 2) 0.08; 3) 0.06; 4) 0.04; 5) 0.02. The experimental data (dots) were obtained for a suspension of carbonyl iron (φ = 0.1).

Fig. 3. Diagram of the experimental apparatus: 1) electromagnetic; 2, 7) thermistors; 3) stationary cylinder; 4) rotating cylinder; 5) current output; 6) heater; 8) power meter; 9, 10) recording devices; 11) dc current source.

far from the particle are examined. The working scheme for the nonisothermal Couette flow is shown in Fig. 1, where T_2 and T_1 are the wall temperatures and v is the velocity of the wall. After the temperature fields are found, the average value of the heat flux and of the temperature gradient in the suspension are calculated:

$$\mathbf{q}=-\langle\lambda_a\nabla T_a\rangle-\langle\lambda_l\nabla T_l\rangle; \tag{1}$$

$$\nabla T=\langle\nabla T_a\rangle+\langle\nabla T_l\rangle. \tag{2}$$

Here λ_a and λ_l are the thermal conductivity of the particle and of the liquid, and T_a and T_l are the temperature fields in the particle and in the liquid. The averaging in (1) and (2) extends over the volume of the suspension.

The elimination of the effective temperature gradient $\mathbf{\Omega}$ from relations (1) and (2) leads to relations between the thermal flux $\mathbf{q}$ and temperature gradient ∇T vectors, i.e., to formulas for the thermal conductivity tensor of the suspension. In this approach the mutual effect of the temperature fields of the particles is taken into account in the dipole approximation.

The components of the thermal conductivity tensor along the magnetic field are determined in the form (Fig. 1)

$$\lambda_{z'}=-q_{z'}/T_{z'}. \tag{3}$$

In the coordinate system tied to the ellipsoid, for the components of the heat flux g_i (i = 1, 2, 3) we have (see the corresponding relation for the induction and electric current intensity in [5]):

$$q_i=-\lambda_l\Omega_i\left(1+\frac{\lambda_a+\lambda_l}{\lambda_a n_i}\frac{2\varphi_a}{3}\right), \tag{4}$$

where Ω_i are the components of the vector of the effective thermal field, n_i are the coefficients of depolarization, and φ_a is the volume particle density.

The formulas for the depolarization coefficients of an axisymmetrical ellipsoid are presented, for example, in [5]. The expression for the temperature gradient in the suspension is written analogously:

$$\nabla T_i=\Omega_i\left(1-\frac{\lambda_a-\lambda_l}{\lambda_a n_i}\frac{\varphi_a}{3}\right). \tag{5}$$

Eliminating the components Ω_i and using the fact that $\nabla T_{z'} = (T_2 - T_1)/h$ (h is the width of the gap), we obtain

$$\Omega_y=-\frac{T_2-T_1}{h}\cos\alpha\Big/\left[1-\frac{(\lambda_a-\lambda_l)\varphi_a}{3\lambda_a n_y}\right]; \tag{6}$$

$$\Omega_z = \frac{T_2 - T_1}{h} \sin\alpha \Big/ \left[1 - \frac{(\lambda_a - \lambda_l)\varphi_a}{3\lambda_a n_z} \right]. \tag{7}$$

Using the formulas (4), (6), and (7), we find the dependence of the coefficient of thermal conductivity along the field on the parameters of the MRS structure:

$$\frac{\lambda_{z'}}{\lambda_l} = \frac{A_1}{A_3} \sin^2\alpha + \frac{A_2}{A_4} \cos^2\alpha. \tag{8}$$

Here

$$A_1 = 1 + \frac{\lambda_a}{\lambda_l + (\lambda_a - \lambda_l) n_z} \frac{2\varphi_a}{3}, \quad A_2 = 1 + \frac{\lambda_a}{\lambda l + (\lambda_a - \lambda l) n_y} \frac{2\varphi_a}{3},$$

$$A_3 = 1 - \frac{\lambda_a}{\lambda_l + (\lambda_a - \lambda_l) n_z} \frac{\varphi_a}{3}, \quad A_4 = 1 - \frac{\lambda_a}{\lambda_l + (\lambda_a - \lambda_l) n_y} \frac{\varphi_a}{3}.$$

It is evident from the formula (8) that the value of the coefficient of thermal conductivity is determined by two parameters: the ratio of the ellipsoid axes r_e and the orientation angle of the ellipsoid α.

The dependences of these quantities on the magnetic-field intensity H_e and the shear velocity $\dot{\gamma}$ are given in [1, 2] in the form of functions of the complex

$$S = \frac{\mu_0 \varkappa_a H_e^2}{\eta_0 \dot{\gamma}}$$

where η_0 is the viscosity of the dispersed medium, $\varkappa_a$ is the magnetic susceptibility of the aggregate, μ_0 is the magnetic permeability of the vacuum, and H_e is the intensity of the magnetic field. The value of the coefficient of thermal conductivity of an aggregate λ_a was calculated from the data obtained by measuring the coefficient of thermal conductivity of a MRS at rest by a nonstationary method [6]. In this case, the aggregates were oriented along the field and $r_e \to \infty$. Then (8) transforms into the well-known relation for the suspension of oriented cylinders:

$$\frac{\lambda_{z'}}{\lambda_l} = \frac{1 + 2\lambda_a\varphi_a/3\lambda_l}{1 - \lambda_a\varphi_a/3\lambda_l}. \tag{9}$$

The values of λ_a obtained with different concentrations differed insignificantly and were equal to 0.7 W/(m·deg). The degree of filling of the aggregate was assumed to be equal to 0.5 [1, 2]. The results of the numerical calculations of the coefficients of thermal conductivity of a moving MRS with different concentration are presented in Fig. 2. As S is increased, the anisodiametric nature of the aggregates increases and the angle between their long semiaxis and the direction of the field decreases. As a result, the thermal conductivity increases monotonically, asymptotically approaching a constant coinciding with the value of the thermal conductivity of the suspension of cylinders oriented at a limiting angle relative to the field (the value of the limiting angle is given in [1, 2]).

An experiment on determining the coefficient of thermal conductivity of MRS under the conditions of a shear flow was performed using an apparatus whose principle part was a standard Reotest-2 viscosimeter. The temperature of the stationary wall (outer measuring cylinder) was maintained constant by temperature regulation and a constant thermal flux flowed onto the inner rotating cylinder (bell-type rotor). In order to provide the conditions for propagation of a heat flux across the gap only, the standard metallic rotor in the viscosimeter was replaced by an analogous ebonite rotor, which had a low coefficient of thermal conductivity (λ = 0.16).

A diagram of the apparatus used is presented in Fig. 3. The setup consisted of a stationary 3 and rotating 4 cylinders, placed in a radial magnetic field produced by an electromagnet 1. The outer surface of the electromagnet is thermally stabilized.

The temperature of the rotating and stationary cylinders is measured by the thermisters 2 and 7, caulked flush against the surface of the cylinders, and the thermistor 2 is connected to the recording device 9 by means of the current output unit 5. The heater 6 is placed on the rotating cylinder 4 and is connected to the current source through the current output device. The power dissipated at the heater is maintained constant in each experiment and is measured by the power meter 8. The temperature of the stationary cylinder is measured by the recording device 10, and the required magnetic-field intensity is set by the dc current source 11.

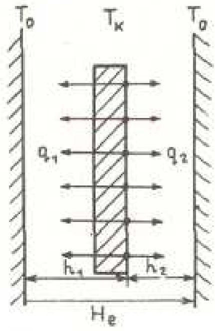

Fig. 4

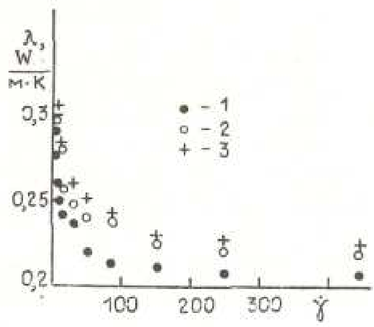

Fig. 5

Fig. 4. Working diagram of the experiment.

Fig. 5. Effect of the shear flow on the thermal conductivity of MRS based on carbonyl iron (φ = 0.1). H: 1) 5; 2) 12; 3) 20 kA/m.

A working diagram of the experiment is shown in Fig. 4, where T_0 is the temperature of the outer cylinder, T_k is the temperature at the surface of the heater, h_1 and h_2 are the gaps between the heater and the inner surfaces of the stationary cylinder, and q_1 and q_2 are the thermal fluxes. The rotating cylinder 4, on whose surface the heater winding is wound, consists of a material whose thermal conductivity is close to that of the MRS under study. The thickness of the cylinder walls is small and equals to 10% of the gap width between the cylinders. In this case, the temperature profile in the gap may be assumed to be linear. Taking into account the smallness of the gap and its relatively long length and ignoring convection, we can write the relation

$$q_1=\lambda_l \frac{T_k-T_0}{h_1} S, \quad q_2=\lambda_l \cdot\frac{T_k-T_0}{h_2} S.$$

Then the heat balance in the stationary state is written in the form

$$q_1+q_2=\lambda_l S(T_k-T_0)\left(\frac{1}{h_1}+\frac{1}{h_2}\right)=W, \tag{10}$$

where λ_l is the thermal conductivity of the liquid studied, S is the lateral surface of the rotor, and W is the power fed to the heater.

The working formula for determining the coefficient of thermal conductivity has the form

$$\lambda=\frac{Wh}{S\Delta T}, \tag{11}$$

where $h = h_1h_2/(h_1 + h_2)$ and ΔT is the temperature drop at the walls of the cylinders.

The experiments, performed on a series of control liquids with different viscosities (glycerine, water, mineral oil), showed that the measurement error obtained with the use of this technique under conditions when both cylinders do not rotate is equal to 5%. When the inner cylinder rotates, in the range of shear velocities 1-146 sec^{-1} the measurement error increases and is equal to 7-8%, and for shear velocities of 246 and 444 sec^{-1} it increases up to 10%. The results of the measurements of the thermal conductivity of the MRS at rest under the action of an external magnetic field were compared with the data obtained on the setup which implements the nonstationary measurement method [6]. The results obtained with the two methods are in good agreement.

Figure 5 shows the data from measurements of the coefficient of thermal conductivity of MRS in magnetic fields of different intensity in the presence of a shear flow.

In the general case, the thermal conductivity of the MRS is an effective quantity, i.e., it depends on the experimental conditions. It is evident from Fig. 5 that the coefficient of thermal conductivity of the MRS decreases with the shear velocity and increases with the magnetic-field intensity.

The experimental results in a wide range of shear velocities for different magnetic-field intensities were compared with the computational results (see Fig. 2). The good agreement between the experimental data and the theoretical results indicates that the model of the dynamic structure of the MRS can be used to calculate heat-transfer processes in such systems.

LITERATURE CITED

1. Z. P. Shul'man, V. I. Kordonskii, É. A. Zal'tsgendler, I. V. Prokhorov, B. M. Khusid, and S. A. Demchuk, "Structure, magnetic and rheological characteristics of ferrosuspensions (experiment)," Magn. Gidrodin., No. 3, 3-10 (1984).
2. Z. P. Shul'man, V. I. Kordonskii, É. A. Zal'tsgendler, I. V. Prokhorov, B. M. Khusid, and S. A. Demchuk, "Dynamic and physical properties of ferrosuspensions with a structure which can be changed by an external magnetic field," Magn. Gidrodin., No. 4, 30-38 (1984).
3. E. P. Bel'skaya, V. M. Postnikov, B. M. Khusid, V. V. Mel'nichenko, and L. N. Novichenok "Thermal conductivity of filled polymer compositions," Inzh.-Fiz. Zh., 41, No. 3, 483-490 (1981).
4. Z. P. Shulman, L. N. Novichyonok, E. P. Belskaya, B. M. Khusid, and V. V. Melnichenko, "Thermal conductivity of metal-filled systems," Int. J. Heat Mass Transfer, 25, No. 5, 643-651 (1982).
5. L. D. Landau and E. M. Lifshitz, Electrodynamics of Continuous Media, Pergamon Press (1960).
6. S. A. Demchuk, V. I. Kordonskii, V. E. Ivanov, and I. V. Prokhorov, "Method for measuring the thermal conductivity of liquids in a magnetic field," in: Electrorheology: Research and Applications [in Russian], Institute of Heat and Mass Transfer, Academy of Sciences of the Belorussian SSR, Minsk (1981), pp. 123-132.