CHARACTERISTICS OF HEAT TRANSFER IN MAGNETORHEOLOGICAL SYSTEMS

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The influence of a constant and an alternating magnetic field on the heat-transfer process in a cylindrical layer is investigated experimentally in connection with magnetorheological systems with shear flow.

Magnetorheological systems (MRS) comprise ferromagnetic suspensions with a characteristic structure formed by magnetization and interaction of the ferromagnetic particles with an external magnetic field. The mechanical behavior of such fluid systems is determined largely by the shear strength of the structure. The latter property depends on such factors as the strength and orientation of the magnetic field, the particle sizes, the magnetic characteristics and concentration, the properties of the dispersion medium, the temperature, etc., [1].

We have previously demonstrated the highly specific and substantial influence of a magnetic field on the thermophysical characteristics of MRS [2]. We found that in stationary magnetorheological compositions, along with intensification of the conductive heat-transfer process in the direction of the magnetic field, there is a reduction in the effective thermal conductivity in the perpendicular direction. Thus, for the MRS containing 50 wt. % electrolytic nickel powder in AMG-10 hydraulic fluid thickened with 8% aluminum stearate the coefficient $\lambda_e^{\parallel}/\lambda_0$ of induced anisotropy of the thermal conductivity attains a value of 1.7, whereas for the analogous 10% MRS of carbonyl iron it has a value of 1.2. The nature of the influence of variously oriented magnetic fields on $\lambda_e^{\parallel}$ and $\lambda_e^{\perp}$ for different MRS is illustrated by the curves in Fig. 1a. Disregarding the physical mechanism of heat transfer in the given microheterogeneous systems, the evident exponential growth of the thermal conductivity with the magnetic field is clearly attributable to preferential strengthening of the contacts between elements of the structure in the direction of the field due to the increase in the energy of anisotropic particle interaction [3]. The validity of this hypothesis is illustrated by Fig. 1b. Here the data obtained in [2] for a magnetic field parallel to the heat-flux direction are given as a function of the specific energy of interaction: $V_{sp} \simeq l^2/\varphi$ [3]. The satisfactory generalization of the experimental data by curve 1 leads to the empirical relation

$$\lambda_e^{\parallel}/\lambda_0 = V_{sp}^{0.1},$$

which is suitable for approximate calculations of the thermal conductivities $\lambda_e^{\parallel}$ in the investigated ranges of the parameters. Preferential reduction of the thermal resistance in the direction of the magnetic field, in turn, decreases the heat-transfer rate in the perpendicular direction. The thermal conductivities $\lambda_e^{\perp}$ can be determined from the expression [4]

$$\frac{1}{\lambda_0} = \frac{1}{3}\left(\frac{1}{\lambda_e^{\parallel}} + \frac{2}{\lambda_e^{\perp}}\right).$$

The coefficients $\lambda_e^{\perp}$ thus calculated differ at most by 4% from the experimental.

We note that the above-mentioned characteristics of conductive heat transfer in MRS refer to the case of a stationary plane layer with unbroken structural elements oriented in the direction of the magnetic force lines.

In practice, however, particularly in heat-exchanging equipment, magnetorheological systems experience strong shear flow. In the given instance, despite particle interaction, an ordered structure is generally absent.

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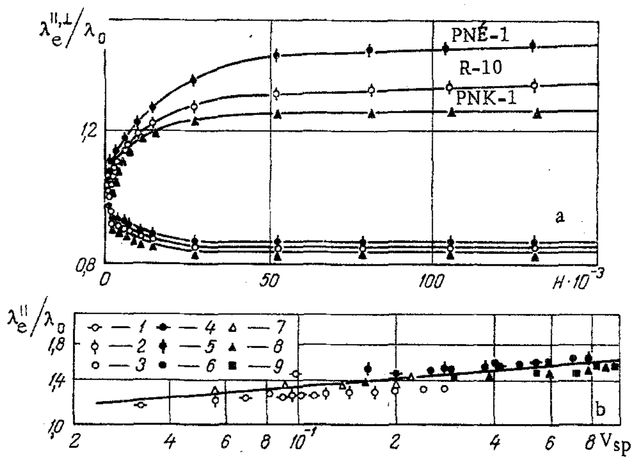

Fig. 1. Relative thermal conductivity of MRS versus a) constant magnetic-field strength $H \cdot 10^{-3}$, A/m (1 vol. %); b) specific energy of interaction of ferromagnetic particles V_{sp}, J/m^3. 1) 1.2% R-10; 2) 4.3% R-10; 3) 9.5% R-10; 4) 1.0% PNÉ-1; 5) 3.9% PNÉ-1; 6) 8.6% PNÉ-1; 7) 1.0% PNK-1; 8) 4.3% PNK-1; 9) 9.5% PNK-1.

We have attempted to perform an experiment under conditions such that the heat transfer associated with shear flow is determined solely by thermal conduction. This situation makes it possible to compare earlier data on the thermal conductivity of a stationary MRS layer with measurements in systems having a structure that is subjected to continuous breakup by shear flow. The most appropriate hydrodynamic situation for the given experiment is Couette flow created, for example, in the annular space between rotating coaxial cylinders.

For sufficiently slow flow, such that dissipation of mechanical energy is negligible, the heat-transfer coefficient in the space between a rotating inner cylinder and a stationary outer cylinder does not depend on the speed of rotation, and the dimensionless heat-transfer coefficient is [5]

$$N_s = 2g_1 s/(T_1 - T_2)\lambda = 2. \tag{1}$$

We created flow of this type in the space between the two coaxial cylinders of a specially modified Reotest-2 rotation viscosimeter. An electric heater of constantan wire 0.3 mm in diameter was fitted to the surface of the rotating inner ebonite cylinder. A layer of copper foil 0.1 mm thick was wrapped around the heater, making the outside diameter of the rotor a total of 21 mm. A copper–constantan thermocouple 0.1 mm in diameter was caulked onto the surface of the copper foil. Current collectors were mounted in the upper part of the rotor to supply the heater and take off the thermocouple output signal. Current was supplied to the heater through an autotransformer from the ac line; the power in the heater circuit was measured with an F-585 electronic wattmeter. The thermocouple emf on the inner and outer cylinders of the viscosimeter was recorded with VK-2-20 digital voltammeters having a maximum 1-μV error. The stationary outer cylinder on the viscosimeter was thermostatically regulated with distilled water from a U-10 thermostat with maximum 0.1°C fluctuation.

We used R-10 carbonyl iron and PNÉ-1 electrolytic nickel MRS (10, 30, and 50 wt.%) in AMG-10 hydraulic fluid thickened with 8% aluminum stearate to invest the system with stability. The working cell could be placed in longitudinally and transversely oriented constant magnetic fields relative to the direction of heat flow and in a transverse alternating field. In the latter case the solenoid winding was connected through an autotransformer directly to the ac line ($f = 50$ Hz).

We first conducted calibration experiments to test the realizability of the necessary heat-transfer conditions. The standard liquids were glycerin, Vaseline oil, and silicon oil, as well as AMG-10 hydraulic fluid thickened with aluminum stearate. At all rotor speeds the temperature was measured after the system had settled into the steady state and the magnetic field had been applied. The results of the calibration tests exhibit good agreement with relation (1), justifying the assumption that thermal conduction is the main factor governing the heat-transfer process in the experimental cell under the investigated weak shear-flow conditions ($\gamma = 0$ to 16.2 sec^{-1}).

In the next series of tests it was assumed that heat transfer in the cell was realized solely by thermal conduction. The value of the effective thermal conductivity for each shearing rate was determined from expression (1). The values thus obtained for the thermal conductivities were compared with the corresponding data obtained earlier for a plane MRS layer with an unbroken structure [2].

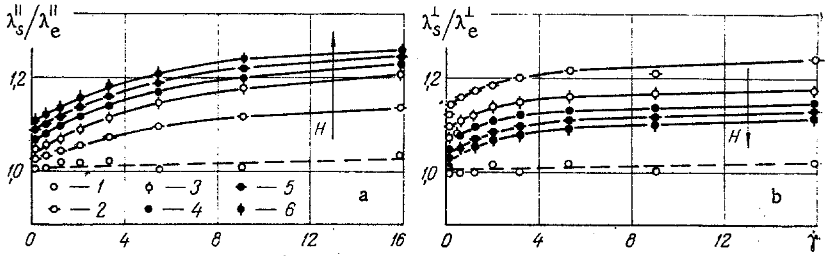

Fig. 2. Relative thermal conductivity of PNÉ-1 MRS (1 vol. %) versus shearing rate $\dot{\gamma}$, sec^{-1}: a) constant longitudinal magnetic field [1) H=33.6 kA/m; 2) 40.8; 3) 44; 4) 47.2; 5) 49.6; 6) 52]; b) constant transverse magnetic field [1) H=26 kA/m; 2) 52; 3) 78; 4) 59.4; 5) 130; 6) 156]; dashed durve) H=0.

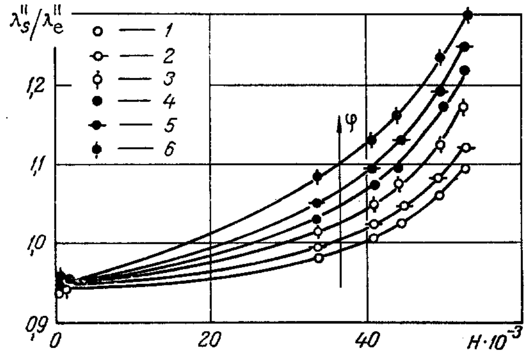

Fig. 3. Influence of concentration factor on relative thermal conductivity in a longitudinal constant magnetic field. For R-10 MRS: 1) φ=1.2%; 2) 4.3%; 3) 9.5%. For PNÉ-1 MRS: 4) φ=1.0%; 5) 3.9%; 6) 8.6%.

The influence of the shearing rate on the thermal conductivity of the systems is significant even in the case of MRS without the application of a magnetic field. The results of these tests are given in Fig. 2a and b, where they evince a certain tendency of the thermal conductivity to increase with the shearing rate.

The pattern changes considerably with the application of a magnetic field to the system. The data in Fig. 2a illustrate the nature of the dependence of λ_s/λ_{s0} on the transverse velocity gradient in the system in a longitudinal field of variable strength. With an increase in the shearing rate, the thermal conductivity increases quite appreciably. The effect is intensified with an increase in the magnetic field. The dependence of the thermal conductivity on the shearing rate exhibits qualitatively the same behavior for an MRS in a transverse field (Fig. 2b). Now an increase in the field decreases the heat transfer in the cell, a result that is fully explained by allowing for the thermal-conductivity anisotropy factor in the MRS.

The heat transfer in an MRS depends not only on the magnetic field and shearing rate, but also on the concentration of the dispersed phase. The extent to which the coefficient λ_s increases with the concentration is evident from the data in Fig. 3.

The results of experiments on the influence of the shearing rate on the thermal conductivity of MRS with different types and concentrations of the dispersed phase over a wide range of longitudinal-magnetic-field strengths can be reduced to a single empirical relation with the specific energy of interaction as the reduction parameter (Fig. 4). The product here represents the rate of energy dissipation per unit volume of MRS [3].

Thus, the experiments described above disclose an appreciable increase of the thermal conductivity with breakup of the MRS structure by shear flow. This fact must be taken into account when analyzing heat-transfer processes in MRS.

The mechanism of the observed phenomenon admits the following tentative explanation. The thermal conductivity of heterogeneous systems such as concentrated magnetorheological suspensions depends largely on the specific state of interparticle contact.

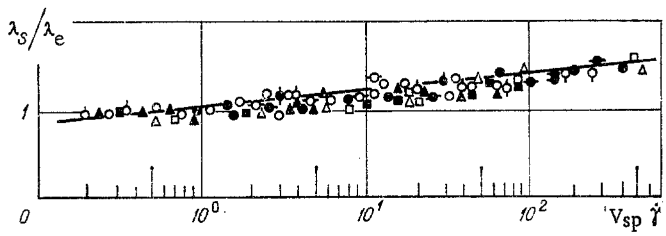

Fig. 4. Relative thermal conductivity of the MRS R-10 and PNÉ-1 versus rate of dissipation of specific energy of interaction $V_{sp}\dot{\gamma}$, J/m³·sec.

Under the action of a magnetic field, stationary suspensions form a structure composed of aggregates elongated in the field direction. The increase in the energy of particle interaction and its endowment with anisotropy by the external field cause an intensification of heat transfer through the aggregate in the direction of the field, whereas the thermal conductivity of the entire system is clearly limited by the total thermal resistance of the contact zones between aggregates. The forces arising in the aggregates in shear flow induce their breakup prior to equilibrium. The number of parallel bonds increases, and at each instant in the shear flow of the MRS there is a total contact area whose thermal resistance is lower than the resistance of the stationary layer. As before, preferential heat transfer takes place in the field direction. Given an identical velocity gradient, aggregates oriented across the flow break up more intensely than aggregates oriented parallel to the flow by the magnetic field. Accordingly, the increment of the effective viscosity is much greater in the former case.

We note in conclusion that the nature of the dependences of the thermal conductivity on the shearing rate, as determined experimentally and interpreted as a cascaded process of aggregate "refinement," is qualitatively similar to the flow curves for magnetorheological systems [1].

NOTATION

$\lambda_e^{\parallel}$, effective thermal conductivity of stationary MRS layer for parallel orientation of temperature and magnetic fields, W/m·°C; $\lambda_e^{\perp}$, effective thermal conductivity of stationary MRS layer for perpendicular orientation of temperature and magnetic fields, W/m·°C; λ_s, effective thermal conductivity of cylindrical MRS layer with shear flow, W/m·°C; λ_{s0}, effective thermal conductivity of cylindrical MRS layer for $\dot{\gamma}=0$, W/m·°C; λ_0, effective thermal conductivity of MRS layer for H = 0, W/m·°C; $\dot{\gamma}$, uniaxial shearing rate, sec^{-1}; φ, volume concentration of dispersed phase, %; I, magnetization of MRS, T; $V_{sp} \simeq I^2/\varphi$, specific energy of interaction of MRS, J/m³; N_s, dimensionless heat-transfer coefficient; q_1, heat-flux density, W/m²; s, thickness of investigated MRS layer, m.

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