NOTATION

$\bar{t} = t_c + {}^1/_2\vartheta$; c_c, heat capacity of copper rod; h, $\bar{F}$, thickness and mean cross section of liquid layer; b, heating rate; ϑ^0, correction to indication of thermocouples measuring temperature differential across layer; $\Delta\sigma_c$, $\Delta\sigma_f$, and $\Delta\sigma_\vartheta$, corrections for heat capacity, curvature, and nonlinearity; $\Delta\lambda$, correction for heat transfer from block to rod through "parasitic" channels; k(t), thermal conductivity of air gap; c_a, heat capacity of ampule; γ, density of liquid.

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INVESTIGATION OF THE EFFECT OF A MAGNETIC FIELD ON THE THERMOPHYSICAL CHARACTERISTICS OF FERROMAGNETIC SUSPENSIONS

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The effect of a constant magnetic field on the heat-transfer process in ferromagnetic suspensions has been experimentally investigated. The effective thermal conductivity of ferromagnetic suspensions is shown to be anisotropic in character.

Attempts to intensify technological processes and control transfer processes in fluid systems have recently led to the development of fluids sensitive to magnetic fields. These include ferrosuspensions whose rheological properties are a certain function of the external magnetic field. However, although we already know a good deal about the magnetorheological characteristics of ferrosuspensions [1-2], information about the effect of a magnetic field on their thermophysical characteristics is still very scarce [3].

We have investigated the effect on the thermophysical characteristics (thermal conductivity, thermal diffusivity, specific heat) of ferrosuspensions by varying the type and concentration of the disperse phase, the strength of the magnetic field, and the orientation of the field relative to the direction of the temperature gradient.

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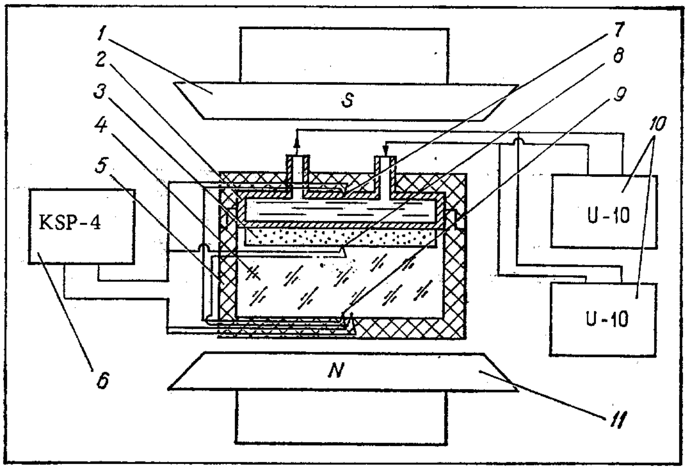

Fig. 1. Diagram of experimental setup: 1,11) electromagnet poles; 2) thermostating vessel; 3) investigated layer of ferrosuspension; 4) substrate—standard; 5) thermal insulation; 6) potentiometer; 7,8,9) thermocouple junctions; 10) thermostat.

TABLE 1. Physical Properties of Ferromagnetic Powders

Disperse phase	ρ, g/cm^3	λ, W/(m·deg)	I_{res}, T	$\bar{d}$, μ
Carbonyl iron	7,9	61,0	0,17	3,5
Iron γ oxide	5,2	—	0,19	1,0
Nickel	8,9	58,6	0,05	20,0
Carbonyl nickel	8,9	58,6	0,05	1,0

The principal thermophysical characteristics were determined experimentally by means of the nonstationary plane-layer method described in [4], which is based on the solution of the heat-conduction problem with boundary conditions of the first and fourth kinds. The essence of this method is as follows: The starting system consists of two bodies (bounded and semibounded) with different thermophysical characteristics. At the initial instant of time the free surface of the bounded body is instantaneously heated to a given temperature, which is kept constant throughout the experiment, and the temperature change at the junction is determined. This method has the following advantages: a) the experiment is relatively easy to set up; b) the plane-layer geometry makes it possible to investigate the anisotropy of the thermophysical properties; c) each experiment takes only a short time; d) the calculations are simple; e) all the thermophysical characteristics can be obtained from a single experiment. The experimental setup comprised a measuring chamber, a recording potentiometer, and a thermostating system (Fig. 1). The design and dimensions of the working chamber were adapted to the requirements of a thermophysical experiment and the parameters of the electromagnet pole gap. As the isothermal heat source we used distilled water at a given temperature circulating through the top of the measuring chamber and separated from the test suspension by a thin copper wall. As heat pulse sensors we used two differential copper—Constantan thermocouples (0.1 diameter), whose readings were recorded on the chart of a KSP-4 potentiometer.

The layer of ferrosuspension was 1 mm thick, and the temperature drop during the experiment reached 5°C. To protect the measuring apparatus from external influences the working chamber and the leads were screened. The chamber was watertight, so that it could be oriented in any direction relative to the direction of the magnetic field.

A constant uniform magnetic field was created by a dc electromagnet with pole pieces measuring 850 × 200 mm and a maximum pole gap of 240 mm. The maximum field strength in the gap was $12 \cdot 10^5$ A/m.

We investigated ferromagnetic suspensions based on transformer oil and AMG-10 hydraulic fluid with the following types of disperse phase: carbonyl iron, iron γ oxide, nickel, and

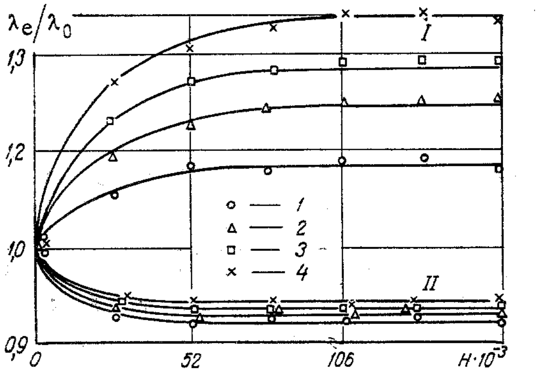

Fig. 2. Effective thermal conductivity $\lambda_e^{\parallel,\perp}$ of ferrosuspensions of the same mass concentration (20%) as a function of magnetic field strength H, A/m: I) temperature and magnetic fields parallel; II) temperature and magnetic fields mutually perpendicular; 1) iron γ oxide; 2) carbonyl iron; 3) carbonyl nickel; 4) electrolytic nickel.

carbonyl nickel. The principal characteristics of the disperse-phase particles, which differed with respect to size, shape, and magnetic properties, are indicated in the table.

Thermophysical measurements were made both with the temperature gradient coinciding with the direction of the field lines and with the temperature gradient and the field lines at right angles.

It was found that in a constant magnetic field the ferromagnetic suspensions were characterized by anisotropy of the thermal-conduction property. When the heat flux and the field lines coincided, the heat transfer was intensified, whereas when they were at right angles thermal conduction deteriorated. The dependence of $\lambda_e{}^{\perp,\parallel}/\lambda_0$ on the magnetic field strength has been plotted in Fig. 2 for a number of suspensions with the same mass concentration (20%). It should be noted that, other things being equal, the nickel suspensions give the greatest interest in $\lambda_e{}^{\parallel}$. This increase amounted to 70%, being somewhat less (30-50%) for the other suspensions.

For all the suspensions investigated, the decrease in $\lambda_e{}^{\perp}$ did not exceed 15-20% of the value λ_0 at $H = 0$ and depended only slightly on field strength and concentration. This may be because in this case the distance between metal particles increases and the number of metal particles per unit length is less than in the longitudinal direction. Accordingly, the electron component in the transverse direction is less than that in the longitudinal direction.

As regards the effect of a magnetic field on the thermal diffusivity and specific heat, it should be noted that the variation of a_e is similar to the variation of λ_e. The specific heat of the ferrosuspension is not affected by the action of the field.

It is clear from the behavior of λ_e that at a certain field strength H_{cr} the magnetic field ceases to affect the thermal conductivity of the suspension. Saturation ensues. This is evidently a sign of the completion of structure formation in the investigated layer. The value of the critical field strength depends on the nature, dispersity, and concentration of the ferromagnetic powder. Thus, for example, for carbonyl iron suspensions (Fig. 2), $H_{cr} = 80\cdot 10^3$ A/m, whereas for nickel suspensions, $H_{cr} = 160\cdot 10^3$ A/m. This means that the greater the particle size, the stronger the magnetic field required to complete structure formation in the investigated layer.

An analysis of the results obtained shows that the process of intensification of heat transfer is qualitatively the same for all the suspensions investigated. In the absence of a magnetic field the ferrosuspension resembles ordinary heterogeneous systems with oil as the medium and a ferromagnetic powder as the disperse phase. Such systems are described by a simple physical model based on the electrothermal analogy. When $\lambda_p \gg \lambda_c$ and the volume concentration is not greater than 0.4, the effective thermal conductivity of a heterogeneous system is given by the expression [6].

$$\lambda_e = \lambda_c \frac{1+2g}{1-g}\ . \tag{1}$$

Clearly, λ_e does not depend on the λ_p of the disperse phase, whereas in our case the thermal conductivity of the investigated layer in the presence of a magnetic field is closely related to structure formation which, in its turn, depends on the nature, dispersity, and volume concentration of the ferromagnetic powder. Hence, Eq. (1) is not applicable in this case.

Having quantitatively and qualitatively evaluated the experimental data, we may conclude that under the influence of an external magnetic field the effective thermal conductivity of a ferromagnet suspension varies according to an exponential law:

$$\lambda_e = \lambda_0 + (\lambda^* - \lambda_0)[1 - \exp(-BH)], \tag{2}$$

where B is a coefficient determined by the magnetic properties of the suspension and numerically equal to the slope of log λ_e relative to the H axis.

We have attempted to establish the nature of the heat-transfer mechanism in ferromagnetic suspensions. As is known [5], the thermal resistance R_T of disperse systems depends on the size, shape, nature, and surface purity of the particles of the disperse phase. Moreover, when ferromagnetic suspensions are exposed to a magnetic field it may be assumed that R_T also depends on the contact density, which is determined by the magnetic properties of the ferromagnetic particles. Thus, in our case the nickel powder had the largest particles (about 20 μ), i.e., the largest uncompensated magnetic moment, which ensured closer contact under the influence of the magnetic field and considerably reduced R_T. Moreover, an increase in particle size is accompanied by a decrease in the number of contact resistances in the thermal bridges formed by the forces of magnetic interaction, which also reduces the thermal resistance of the system as a whole.

In general, it may be assumed that the heat-transfer mechanism in a ferromagnetic suspension comprises two components: electron and phonon. In the metal particles of the ferromagnetic powder heat transfer is effectuated by the motion of electrons [7] and in the continuous phase, by phonon transport. The contributions of these two components depend on the general state of the system and, in particular, the presence or absence of an external magnetic field.

In the presence of a magnetic field the ferromagnetic particles are oriented along the field lines and thus form a thermally anisotropic structure whose thermal conductivity acquires a tensor character. The interaction developing between the particles draws them closer together, which considerably improves the heat transfer. This intensification of the heat-transfer process may be analogous to the increase in electrical conductivity in highly concentrated disperse systems, which is said to be determined by the thermal emission of electrons across the gaps between filler particles [8].

NOTATION

ρ, density; λ, thermal conductivity; $\lambda_e^{\parallel}$, effective thermal conductivity of layer with magnetic field and heat flux parallel; $\lambda_e^{\perp}$, effective thermal conductivity with magnetic field and heat flux mutually perpendicular; λ_c, thermal conductivity of continuous phase; λ_p, thermal conductivity of metal particles; a_e, effective thermal diffusivity; I, magnetization; $\bar{d}$, mean ferromagnetic particle diameter; R_T, thermal resistance; H, magnetic field strength; g, ferromagnetic volume concentration $\lambda^* = \begin{cases} \lambda_{max} \text{ for } H\uparrow\uparrow q, \\ \lambda_{min} \text{ for } H\uparrow\uparrow q. \end{cases}$

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