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THE MECHANISM OF HEAT TRANSFER IN MAGNETORHEOLOGICAL SYSTEMS

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Abstract—The paper describes the procedure and results of investigation of heat transfer in ferromagnetic suspensions with an unstable structure specified by magnetization and magnetodipole interaction of particles of a disperse phase. An anisotropic character of heat conduction is revealed that manifests itself as enhancement of heat transfer in the direction of the field and decrease of heat conduction in the perpendicular direction. A marked increase in the heat-transfer rate in magnetorheological systems is shown to occur due to the breakdown of structure by shear flow. An interpretation of the mechanism of the observed phenomena is proposed.

NOMENCLATURE

H, magnetic field intensity [A/m];
$\dot{\gamma}$, coaxial shear rate [s^{-1}];
R_T, thermal resistance [m·deg/W];
λ_0, effective thermal conductivity at $H = 0$ [W/m·deg];
$\lambda_{eff}^{\parallel}$, effective thermal conductivity in a fixed layer with codirectional temperature and magnetic fields [W/m·deg];
$\lambda_{eff}^{\perp}$, effective thermal conductivity in a fixed layer with mutually perpendicular temperature and magnetic fields [W/m·deg];
λ_s, effective thermal conductivity for shear flow [W/m·deg];
λ_{s0}, effective thermal conductivity of a cylindrical layer at $\dot{\gamma} = 0$ [W/m·deg];
I, magnetization [T];
ϕ, volumetric concentration of a disperse phase [%];
U_{sp}, specific energy of interaction [J/m^3];
N, dimensionless heat-transfer coefficient;
q, heat flux density [W/m^2];
S, test layer thickness [m].

1. INTRODUCTION

THE MAGNETORHEOLOGICAL systems are recognized as ferromagnetic suspensions with an unstable structure formed as a result of magnetization and interaction of ferromagnetic particles in an external magnetic field. This important property distinguishes them from the colloidal ferrofluids [1] in which structure formation does not take place in the external field and, therefore, the rheological effect is not markedly pronounced.

Thus, the mechanical behaviour of the magnetorheological fluid systems is much accounted for by the fact that they contain structures whose elasticity and shear strength are specified by the magnitude and orientation of the magnetic field, size of particles, their magnetic characteristics and concentration, disperse medium properties, temperature, etc.

Though there are works concerned with investigation of magnetorheological characteristics of these systems [2, 3], however, the effect of the magnetic field on heat transfer in magnetorheological systems has been almost not explored to date.

The present paper reports the experimental results on thermophysical characteristics of magnetorheological systems and heat-transfer characteristics for shear flow in the system of coaxial cylinders. The type and concentration of the dispersed phase of ferrosuspensions, the magnetic field intensity, its orientation with respect to a temperature gradient have been varied.

2. EXPERIMENT

2.1. *Fixed layer*

The thermophysical characteristics of fixed magnetorheological systems have been determined with the aid of the unsteady-state plane-layer technique [4]. The advantages of this method are as follows: (a) a comparatively simple experimental set-up; (b) the plane layer geometry distinctly reveals anisotropy of the thermophysical properties; (c) a short duration of a single experiment; (d) simple prediction formulae; (e) all thermophysical characteristics can be obtained from a single experiment.

A schematic diagram of the experimental apparatus is shown in Fig. 1. The design and dimensions of the working cell met the requirements of the thermophysical experiment and geometry of the interpolar gap of an electromagnet. Isothermal conditions of the experiments were ensured by circulation of distilled water, at a prescribed temperature, via the measuring cell cap. Two differential copper–constantan 0.1 mm dia thermocouples were used as heat pulse sensors.

The test magnetorheological suspension layer was 0.001 m thick. A temperature drop in the experiment did not exceed 5°. The cell tightness allowed it any position relative to the magnetic field direction. A uniform magnetic field was induced by the DC electromagnet with the 0.85 × 0.2 m pole shoes, with

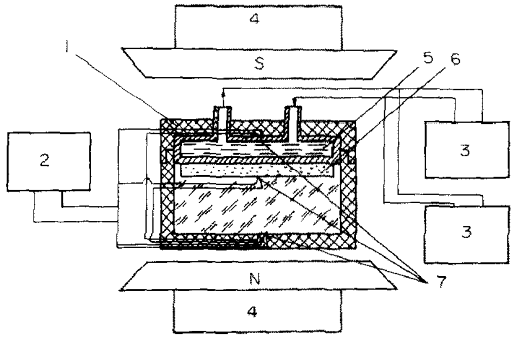


FIG. 1. A schematic of the experimental set-up for investigation of the constant magnetic field effect on heat transfer in a fixed plane layer of ferrosuspensions: (1) measuring cell; (2) electronic potentiometer; (3) thermostating arrangement; (4) electromagnet poles; (5) cooling bath; (6) test ferrosuspension layer; (7) thermocouple junctions.

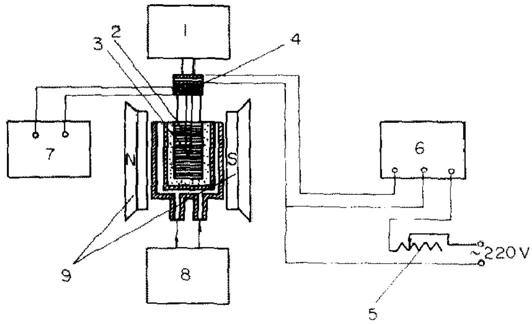


FIG. 2. A schematic of the experimental set-up for investigation of the magnetic field effect on heat transfer involving shear flow of ferrosuspensions: (1) viscometer "Rheotest-2"; (2) rotating inner cylinder with heater; (3) working thermocouple junction; (4) current collectors; (5) autotransformer; (6) electronic wattmeter; (7) digital voltmeter; (8) thermostat; (9) electromagnet poles.

the maximum distance between the poles being 0.24m. The magnetic field intensity in the gap amounted to 200×10^3 A/m.

Thermophysical measurements were made both at the same direction of the temperature gradient and the force lines of the magnetic field, and when they were normal to each other.

Investigation was made of ferromagnetic suspensions of the carbonyl iron P-10, iron gamma-oxide T-6, electrolyte nickel PNE-1 and carbonyl nickel PNK-1 in the transformer oil and hydraulic fluid AMG-10. The size, shape of particles and their magnetorheological characteristics were examined in separate experiments.

2.2. *Moving layer*

In a number of cases, in heat exchangers and water power plants particularly, the magnetorheological systems develop an intense shear flow. Then the interaction of particles becomes insufficient for forming an ordered structure.

In our experiments, the conditions have been realized when shear flow heat transfer is controlled only by the effective thermal conductivity. This allowed the comparison of the earlier obtained results on thermal conductivity of a fixed ferrosuspension layer with the measurements of the systems whose structure is being continuously broken down by shear flow. In the present experiment, the Couette flow in an annular gap between the rotating coaxial cylinders has been the most preferable.

With sufficiently slow flow, when the mechanical energy dissipation is negligible, the dimensionless heat-transfer coefficient in the gap between the inner, rotating, and the outer, fixed, cylinders does not depend on the rotation speed of the inner cylinder [5], i.e.

$$N = \frac{2qS}{(T_1 - T_2)\lambda} \simeq 2. \qquad (1)$$

In the experiments, a modified rotational viscometer "Rheotest-2" was used. The standard inner

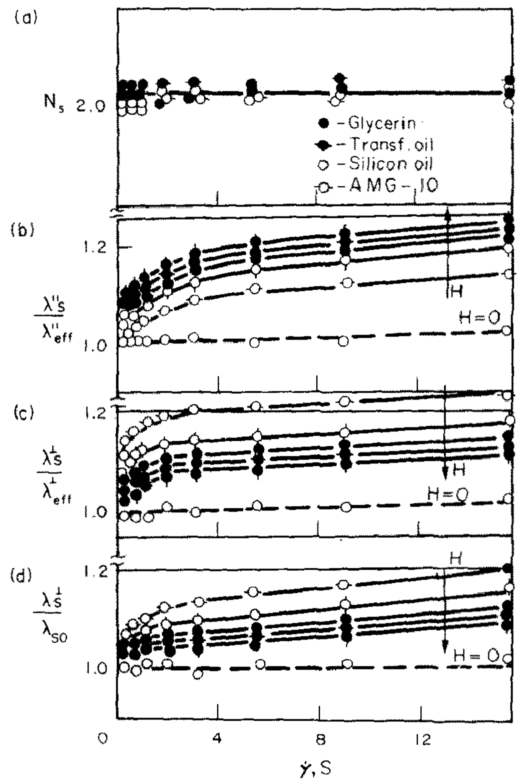
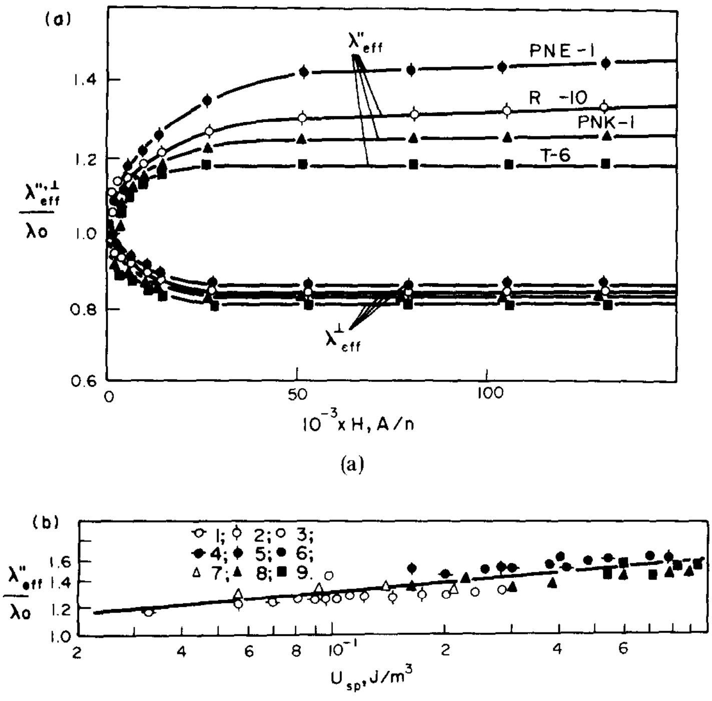


FIG. 3. The calibration results for checking the validity of equation (4) (a); The relative thermal conductivity of ferrosuspensions PNE-1 (1 vol %) vs shear rate. The constant magnetic field of transverse orientation, $H = 33.6 \times 10^3 - 53 \times 10^3$ A/m (b). The transverse constant magnetic field, $H = 29.4 \times 10^3 \div 206 \times 10^3$ A/m (c). The variable longitudinal magnetic field $H = 15.2 \times 10^3 \div 76 \times 10^3$ A/m (d).

cylinder of the viscometer was replaced by another one having identical dimensions but whose construction allowed a thermophysical experiment to be conducted. The schematic diagram of the set-up is shown in Fig. 2. The calibrating experiments with standard fluids (glycerin, vaseline and silicon oils and solidified AMG-10), the results of which are given in Fig. 3 and which can be fairly well correlated by



(a)

(b)

FIG. 4. The relative thermal conductivity of suspensions (20 wt.%) vs constant magnetic field intensity (a). The relative thermal conductivity vs specific interaction energy of ferromagnetic particles: 1,2,3, carbonyl nickel PNK-1; 4,5,6, carbonyl iron; 7,8,9, electrolytic nickel (b).

relation (1), make it possible to assume the thermal conductivity to be the main factor that controls heat transfer in the test cell under weak shear flow conditions studied.

3. DISCUSSION OF RESULTS

The experiments have revealed the heat conduction anisotropy of ferromagnetic suspensions in a constant magnetic field. If the heat flux direction coincided with that of the force lines of the magnetic field, the heat transfer enhanced, i.e. an increase in $\lambda_{\text{eff}}^{\parallel}$ was observed. With their perpendicular orientation, the thermal conductivity decreased. The plot of $\lambda_{\text{eff}}^{\parallel,\perp}/\lambda_0$ vs the constant magnetic field intensity for some suspensions with the same weight concentration (20%) is presented in Fig. 4. The largest increment of $\lambda_{\text{eff}}^{\parallel}$, up to 70%, with other conditions equal, was observed with electrolytical nickel suspensions. For other suspensions, this amounted to 30–50%.

For all of the suspensions investigated, a decrease in $\lambda_{\text{eff}}^{\perp}$ did not exceed 15–20% the value of λ_0 at $H = 0$ and slightly depended on the magnetorheological system concentration and field intensity.

As to the magnetic field effect on the coefficients of thermal diffusivity and heat capacity, it should be noted that the behaviour of the thermal diffusivity coefficient is similar to $\lambda_{\text{eff}}^{\parallel,\perp}$ variation. The heat capacity coefficient varied insignificantly under the magnetic field action. At some fixed intensity, H_{cr}, the magnetic field fails to affect thermal conductivity of the suspension. The onset of the saturation regime is likely to be associated with completion of the structure formation in the test magnetorheological system layer. The critical intensity depends on the nature, dispersion and concentration of a ferromagnetic powder. Thus, for example, for the suspensions P-10 (Fig. 4a) $H_{cr} = 80 \times 10^3$ A/m, and for the suspensions PNE-1, $H_{cr} = 160 \times 10^3$ A/m. The larger the particles of a disperse phase, the greater magnetic field intensity is required to complete the structure formation in the test suspension layer.

Intensification of heat transfer due to an applied magnetic field is of the same qualitative nature for all the test suspensions. With no magnetic field, the magnetorheological system behaves like an ordinary heterogeneous system. It may be described by a simple electrothermal analog. When thermal conductivity of the disperse phase is greater than that of the carrier fluid, i.e. $\lambda_d \gg \lambda_f$, and volumetric concentrations do not exceed 0.4, the effective thermal conductivity of the heterogeneous system of individual particles is defined by the formula from [6]

$$\lambda_{\text{eff}} = \lambda_f \frac{1+2\phi}{1-\phi}. \tag{2}$$

As is seen, λ_{eff} does not depend on λ_d of the disperse phase. However, in our case thermal conductivity of the layer affected by the applied magnetic field is, to a great extent, specified by the structure formation which, in turn, depends on nature, dispersion and volumetric concentration of a ferromagnetic powder. Therefore, formula (2) is not valid for this case. The data on the effective thermal conductivity of a ferromagnetic suspension, structurizing under the action of an external magnetic field, are well correlated by the empirical formula

$$\lambda_{\text{eff}}^{\parallel} = \lambda_0 + (\lambda_{\max} - \lambda_0)[1 - \exp(-BH)], \quad (3)$$

where B is the coefficient defined by magnetic properties of suspensions.

Below, an attempt is made to explain the heat-transfer mechanism in ferromagnetic suspensions. As is known [7], thermal resistance, R_T, of disperse systems is strongly dependent on the size, shape, nature and state of the surface of disperse phase particles. In addition, with an external magnetic field applied to ferromagnetic suspensions, R_T may be assumed to depend also on the closeness of contact being determined by the magnetic properties of ferromagnetic particles. In our experiments, the electrolytical nickel powder had the largest particles ($\sim 20\,\mu$m), i.e. the greatest uncompensated magnetic moment. This provided both a closer contact between the particles, affected by the magnetic field, and a considerable decrease in R_T. Moreover, an increase in the size of particles leads to a decrease in the total number of series contact resistances in heat-conducting bridges formed by the forces of the magnetic interaction. This also reduces thermal resistance of the system as a whole.

The effect of shear rate on thermal conductivity of the systems is noticeable even in the suspensions which are not subjected to magnetic field. The pertinent experimental results (Figs. 3b,c,d) show some tendency for the thermal conductivity to increase with the shear rate.

The picture changes markedly when a magnetic field is applied to the system. Figure 3(b) illustrates the behaviour of λ_s/λ_{s0} as a function of the transverse rate gradient in the system in the magnetic field of variable intensity. With shear rate growth, the thermal conductivity increases considerably. The effect becomes more pronounced as the magnetic field intensity increases. The same qualitative picture is observed with the magnetorheological systems in the longitudinal field (Fig. 3c). Here, the increasing field intensity diminishes heat transfer in the cell, which can be perfectly well explained with reference to anisotropic interaction of the particles in ferro-suspensions.

An insignificant discrepancy in the thermal conductivities measured in a coaxial-cylindrical cell is likely to be attributed to somewhat different heat flux orientation relative to the magnetic field.

Thermal conductivity of the magnetorheological systems in a variable longitudinal field also grows with shear rate. Since there are no appropriate data for a layer with a non-disintegrated structure, those in Fig. 3(d) have been obtained by comparing the above thermal conductivities with the values for zero shear rate. Just as in the case of constant field

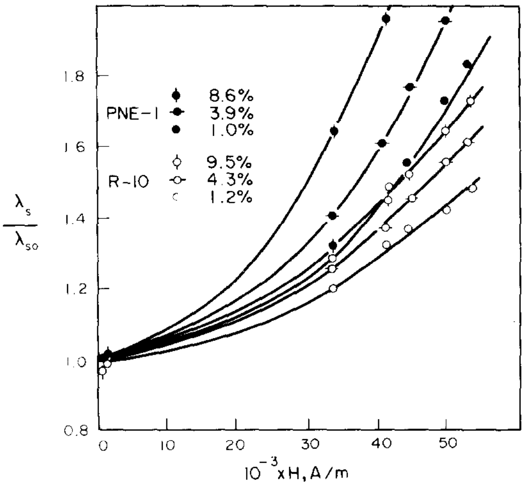


FIG. 5. The relative thermal conductivity of ferro-suspensions vs the transverse constant magnetic field intensity and disperse phase concentration.

situation, an increase in the variable longitudinal field intensity decreases heat-transfer rate. Evidently, it is also associated with predominant heat transfer in the direction of the field. The inspection of Fig. 5 reveals that in addition to the transverse field intensity, a growth of the disperse phase concentration also enhances shear flow heat transfer of magnetorheological systems.

The experimental results for the effect of the shear rate on thermal conductivity of ferrosuspensions with a disperse phase of different types and concentrations over a wide range of transverse magnetic field intensities can be correlated by a single empirical equation where the specific energy of interaction is taken as the reduction parameter (Fig. 6). In this case, the product $U_{sp} \times \dot{\gamma}$ is the energy dissipation rate per unit volume of a magneto-rheological system [8].

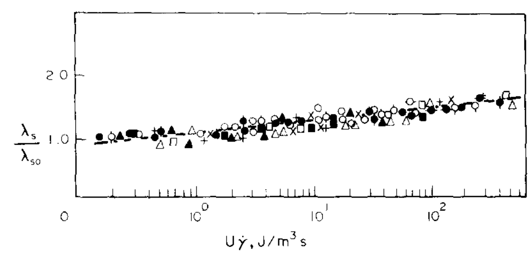


FIG. 6. The relative thermal conductivity of ferro-suspensions vs the specific interaction energy dissipation.

4. CONCLUSION

In a general case, the mechanism of heat transfer in a magnetorheological system may be related to two factors. In metal ferromagnetic powder particles, heat is transferred by electrons [9], while in a continuous phase, by phonon conductance. The contribution of both components is determined by the general state of the system that depends on whether an external electromagnetic field is applied or not.

The ferromagnetic powder particles are oriented along the force lines of the magnetic field and thus form a thermally anisotropic structure with the thermal conductivity of a tensor character. The interaction forces, arising between the particles, bring them closer together promoting essentially enhanced heat transfer than in the case of no field. Such an explanation of the heat-transfer enhancement in the magnetorheological systems is similar to an interpretation of the known electric conductance increase in highly concentrated disperse systems due to thermal emission of electrons through gaps between the filler particles. Thus, an exponential increase in thermal conductivity with the magnetic field intensity may be attributed to closer contacts between the structure elements along the field. Here, the interaction of particles plays a predominant role. The validity of this postulation is illustrated in Fig. 4(b), where the earlier obtained $\lambda_{\text{eff}}^{\parallel}$ values for the magnetic field, parallel to a heat flux, is a function of the specific interaction energy $U_{sp} \sim I^2/\phi$ [8].

A substantial decrease of thermal resistance in the magnetic field direction, in turn, reduces heat-transfer rate in the perpendicular direction. The $\lambda_{\text{eff}}^{\perp}$ values may be defined by the formula [6]

$$\frac{1}{\lambda_0} = \frac{1}{3}\left(\frac{1}{\lambda_{\text{eff}}^{\parallel}} + \frac{2}{\lambda_{\text{eff}}^{\perp}}\right). \qquad (4)$$

A discrepancy between the predicted and experimental thermal conductivities, $\lambda_{\text{eff}}^{\perp}$, was not more than 4%.

The above specific features of conductive heat transfer in the magnetorheological systems are related to a fixed plane layer with the non-disintegrated structure elements oriented in the direction of the magnetic field force lines.

The mechanism of the phenomenon observed in moving ferrosuspensions may be explained as follows. Thermal conductivity of such systems seems to be limited by the total thermal resistance of the contact zones between the aggregates. The forces arising in the aggregates in the shear flow situation result in the aggregate disintegration up to an equilibrium value. In this case, the number of parallel contacts increases, and at any time instant there exists the total contact area in the shear flow of the magnetorheological system whose thermal resistance is lower than that of the stationary layer. As before, heat is mostly transferred in the magnetic field direction. With the same shear rate, the aggregates across the flow are disintegrated more actively than those oriented by the external field parallel to the flow. As a result, increment in the effective thermal conductivity in the first case is considerably larger. It should be noted that the thermal conductivity vs the shear rate curves, obtained experimentally and interpreted as a cascade process of size reduction of the aggregates, is qualitatively similar to those of the flow of magnetorheological systems [2].

Thus, the experiments carried out have revealed a marked increase in thermal conductivity of the system broken down by shear flow. This fact should be taken into consideration when predicting heat transfer in the magnetorheological systems.

REFERENCES

1. J. Z. Neuringer and R. E. Rosensweig, Ferrohydrodynamics, *Physics Fluids* **7**(12), 1927–1937 (1964).
2. V. I. Kordonsky, M. Z. Shulman and T. V. Kunevich, The magnetorheological effect, in: *Rheology of Polymers and Disperse Systems and Rheophysics*. Izd. ITMO AN BSSR, Minsk (1975).
3. F. G. Veliev, Rheological study of petroleum-magnetic mixture in a transverse magnetic field, *Magnitnaya Gidrodinamika* No. 4, 139–140 (1972).
4. L. N. Novichenok, The unsteady-state method of determining thermophysical characteristics of varnish coatings, *J. Engng Phys.* **6**(9), 35–39 (1963).
5. L. A. Dorfman, *Hydrodynamic Resistance and Heat Transfer of Rotating Bodies*, p. 260. Fizmatgiz, Moscow (1960).
6. L. N. Novichenok and Z. P. Shulman, *Thermophysical Properties of Polymers*, p. 117. Nauka i Tekhnika Press, Minsk (1971).
7. W. Merl, Der Elektrische Kontakt, Wissenschaftliche Grundlagen und Ihre Anwendungen, Aus den Lab. der Firma Dr. E. Dürrwächter-Doduco-K. Pferzheim, Germany (1962).
8. E. E. Bibik, Some effects of particle interaction in ferrofluids in a magnetic field, *Magnitnaya Gidrodinamika* No. 3, 25–32 (1973).
9. S. V. Vonsovsky, *Magnetism*, p. 1032, Nauka Press, Moscow (1971).

LE MECANISME DU TRANSFERT THERMIQUE DANS DES SYSTEMES MAGNETORHEOLOGIQUES

Résumé—On décrit la procédure et les résultats d'une recherche sur le transfert thermique dans les suspensions ferromagnétiques avec une structure instable décrite par la magnétisation et l'intéraction magnétodipolaire des particules d'une phase dispersée. Un caractère anisotrope de la conduction thermique se révèle être la cause d'un accroissement du transfert thermique dans la direction du champ et d'une diminution dans la direction perpandiculaire. Une augmentation marquée du transfert de chaleur dans les systèmes magnétorhéologiques résulte de la destruction de la structure par le cisaillement. On propose une interprétation du mécanisme des phénomènes observés.

DER MECHANISMUS DER WÄRMEÜBERTRAGUNG IN MAGNETORHEOLOGISCHEN SYSTEMEN

Zusammenfassung—Der Aufsatz beschreibt die Versuchsanordnung und die Ergebnisse einer Untersuchung der Wärmeübertragung in ferromagnetischen Suspensionen mit einer instabilen Struktur, die durch die Magnetisierung und die Wechselwirkung der magnetischen Dipole der Partikel einer dispersen Phase gekennzeichnet ist. Dabei wird eine anisotrope Eigenart der Wärmeleitung festgestellt, die sich in der Form einer Vergrößerung der Wärmeübertragung in Feldrichtung und als Verminderung der Wärmeleitung senkrecht zum Feld bemerkbar macht. Es wird gezeigt, daß eine deutliche Erhöhung der Wärmeübertragung in magnetorheologischen Systemen bei Zusammenbruch der Struktur durch Scherströmung entsteht. Es wird eine Interpretation vorgeschlagen, die den Mechanismus der beobachteten Vorgangs beschreibt.

ОСОБЕННОСТИ ТЕПЛОПЕРЕНОСА В МАГНИТОРЕОЛОГИЧЕСКИХ ДИСПЕРСНЫХ СИСТЕМАХ

Аннотация — В работе излагаются методики и результаты исследования теплопереноса в ферромагнитных суспензиях с переменной структурой, определяемой намагничиванием и магнитодипольным взаимодействием частиц дисперсной фазы. Выявлена анизотропия теплопроводности, проявляющаяся в увеличении интенсивности переноса тепла в направлении поля и уменьшении теплопроводности в перпендикулярном направлении. Показано заметное повышение интенсивности теплопереноса в магнитореологических системах при разрушении их структуры сдвиговым течением. Предлагается интерпретация механизма наблюдаемых явлений.