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Magnetorheological control of heat transfer

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Abstract—Results of experimental investigation of the effect of magnetic fields on thermal processes taking place in magnetorheological suspensions (MRS) are presented. It is shown that by varying the orientation and strength of the field it is possible to control heat transfer within a wide range. Anisotropy of the thermal conductivity of MRS is established. In the case of the field lines being co-directional with a heat flux, the thermal conductivity coefficient increases by about 70%, whereas with their normal relative orientation it decreases by about 50%. The effect of a rotating magnetic field on MRS shear flow in a gap causes an almost 15-fold enhancement of heat transfer. Heat transfer of a turbulent suspension flow in a channel is intensified by an order of magnitude on superposition of a homogeneous field, transversely to the channel axis, and is suppressed twice as much in the case of parallel orientation. Examples and recommendation for practical application of the regularities revealed are given.

INTRODUCTION

THE CREATION of new, and the intensification of the existing, technological processes greatly depend on the availability of adequately developed scientific ideas and engineering solutions, connected with the control, flow and heat transfer of the media treated.

Recently, the arsenal of the means for controlling these characteristics is being supplemented with techniques based on the employment of physical effects on transfer processes, in particular, exposure to magnetic fields on condition that the working medium is sensitive to them. In the case of well conducting or well magnetizable rheologically simple fluid media—ferrofluids—the controllability is attributable to the magnetic field-induced origination of body forces acting on the medium—the so-called magnetohydryodynamic and ferrohydrodynamic effects [1, 2].

A fundamentally new approach consists in the magnetic field-caused change in the internal structure of the medium, which represents a suspension of magnetic particles, i.e. a magnetorheological suspension (MRS). In this case, in the dynamic system comprised of the structure (formed by the field) and of the moving medium interacting with this structure, to each combination of prescribed parameters (carrying medium viscosity, magnetic properties and volumetric content of particles, field strength, strain rate) there corresponds a definite set of structure elements and a fully defined morphology of the system, i.e. relative positions of the elements in space.

In the first approximation, a single structure element can be presented in the form of an ellipsoidal packet of particles [3]. The structure induced by an external magnetic field leads to the display by the system of non-linear rheological effects, i.e. to a sharp and controlled increase in effective viscosity, plasticity and viscoelasticity.

Besides the change in mechanical properties, other structural characteristics of MRS, that is, thermophysical, magnetic, acoustic, etc., also undergo significant variations in a magnetic field.

Thus, the magnetorheological effect allows one, by employing electrical signals, to control the hydrodynamics, heat and mass transfer, electric and magnetic characteristics of a fluid medium and this, in turn, makes it possible to create new technological processes and apparatus. The next section will consider, with several examples, the problems of monitoring heat transfer in such situations.

EXPERIMENTS AND DISCUSSION OF RESULTS

1. *Thermal conductivity of MRS*

Determination of the thermal conductivity of fluid systems and specifically of MRS requires the maximum suppression of natural convection in experiments. This is attained, for the most part, by the selection of the test layer geometry, and of the magnitude and orientation of the temperature gradient in it. It is well known that the critical condition for the origination of natural convection is $Gr\,Pr \gg 1000$, where Gr and Pr are the Grashof and Prandtl numbers, respectively. The creation of a uniform magnetic field in the studied MRS layer also requires a definite geometry of the layer. Starting from there, in the present work, a nonstationary plane-layer method is used, which is based on the solution of a heat conduction problem with boundary conditions of the first and fourth kinds [4].

In the experiment, we varied the type of MRS,

NOMENCLATURE

- a thermal diffusivity coefficient [$m^2 s^{-1}$]
- Al Alfven number
- C heat capacity [$J kg^{-1} K^{-1}$]
- d size of a particle [μm]
- D channel diameter [m]
- F heated surface area [m^2]
- E energy [J]
- G volumetric flow rate [$m^3 s^{-1}$]
- H magnetic field strength [$kA m^{-1}$]
- I current in magnetic field inductor [A]
- k heat transfer coefficient [$W m^{-2} K^{-1}$]
- L channel length [m]
- M mass [kg]
- Nu Nusselt number
- P pressure [$N m^{-2}$]
- p coefficient of linear equation
- r form parameter
- Re Reynolds number
- T temperature [K]
- t time [s]
- w heat power [W].

Greek symbols

- α heat transfer coefficient [$W m^{-2} K^{-1}$]
- λ thermal conductivity coefficient [$W m^{-1} K^{-1}$]
- μ_0 magnetic constant, 1.256×10^{-6} $H m^{-1}$
- ρ density [$kg m^{-3}$]
- τ thermal time constant [s]
- φ volumetric concentration of disperse phase
- ω angular velocity of field rotation [s^{-1}]
- Ω angular velocity of rotor rotation [s^{-1}].

Subscripts

- a aggregate of particles
- f carrying medium
- i local value
- H in a magnetic field
- m MRS
- n heater
- s disperse phase, on the wall
- 0 with no field
- $\perp$ perpendicular orientation
- $\parallel$ parallel orientation.

Superscripts

- $*$ reduced value
- I at the channel inlet
- II at the channel exit
- $\bar{}$ mean value.

the strength and the orientation of the magnetic field relative to the geometry of the MRS layer and to the heat flux.

The anisotropic character of the thermal conductivity of MRS has been established as well as its dependence on the thermal conductivities of the structure elements [5–7]. When the heat flux is co-directed with the magnetic field lines, heat conduction becomes significantly intensified. In this case, the greatest increase in the effective thermal conductivity coefficient attains 70%. These results have been obtained for an MRS of electrolyte nickel powder. For other suspensions the increase is somewhat smaller, that is, 30–50%. With a perpendicular orientation of the magnetic and thermal fields, the quantity $\lambda_{m\perp}$ decreases, with this decrease for all of the investigated systems not exceeding 16–20% of the value λ_{m0} and being almost independent of the concentration, types of fillers, and of the magnetic field strength. The effective thermal conductivity coefficient λ_m varies similarly to a_m, whereas the specific heat is not actually affected by the field. The effective thermal conductivity of MRS in the case of a simple shear deformation has been calculated by the method of the self-consistent field [3]. The results of numerical calculations have shown that the thermal conductivity of MRS is an effective value which depends not only on the field strength, but also on the shear rate, with the latter affecting it by more than 30%. For the limiting case ($r_y \gg 1$), the following equation has been obtained:

$$\frac{\lambda_{m\parallel}}{\lambda_f} = \frac{1 + \frac{2}{3}\frac{\lambda_y}{\lambda_f}\varphi_x}{1 + \frac{1}{3}\frac{\lambda_y}{\lambda_f}\varphi_x}.$$

2. *Heat transfer in narrow gaps*

The application of the capability of MRS to remain in place in the magnetic circuit gap so as to intensify heat removal from the power dissipating elements, e.g. from the oscillating voice coil of an electrodynamic transformer, was substantiated experimentally and theoretically [8, 9]. As compared with air, the presence of MRS in a steady-state mode makes the heat transfer coefficient increase by the value proportional to the increase in the thermal conductivity coefficient of the medium to which the heated wall is exposed. In an unsteady-state regime with a stepwise variation in the heat flux and on the assumption of regular heat transfer regimes, a relationship was obtained from the heat balance which determines the coupling between the coil temperature and the system parameters:

$$T_k = T_0 + \frac{w h_1 h_2}{F\lambda_m(h_1 + h_2)}(1 - e^{t/\tau})$$

where

$$\tau = \left(\frac{c_{pm}M_m}{2} + c_{pn}M_n\right)\frac{h_1 h_2}{\lambda_m F(h_1+h_2)}.$$

A similar approach can be used for heat transfer enhancement in a number of other electrotechnical devices, especially when they involve a magnetic field inductor, for example, electric motors, transformers, etc.

3. *Heat transfer in a rotating magnetic field*

Of particular interest is the experimentally discovered heat transfer enhancement in MRS due to the effect of a non-uniform rotating magnetic field [10]. Experiments were carried out in a coaxially cylindrical cell ($\dot{\gamma} = 0.333$–$16.2\ s^{-1}$) placed in a radial heterogeneous magnetic field.

The working media used were made of suspensions of acicular iron-gamma-oxide T-6 (2.6 and 3.6 vol. %) in transformer oil and of carbonyl iron R-10 (0.37, 1, 2.3 and 3 vol. %) in distilled water thickened with a water-soluble polymer (acrylic acid copolymer).

The dependence of the mean heat transfer coefficient $\bar{K}_m$ of the suspension T-6 on the angular speed of rotor rotation is shown in Fig. 1(a), curve 1. At $\Omega = 0$ the field causes an increase in the heat transfer rate due to the microrotations of the aggregates of particles and to the resulting motion of the medium as a whole. The mean heat transfer coefficient grows with the strength of the field and is independent of the direction of its rotation, however, in the case of the uniform strength of the rotational field (R-field), the heat transfer enhancement is almost directly proportional to the cyclic frequency of field rotation (157 and 314 s^{-1}).

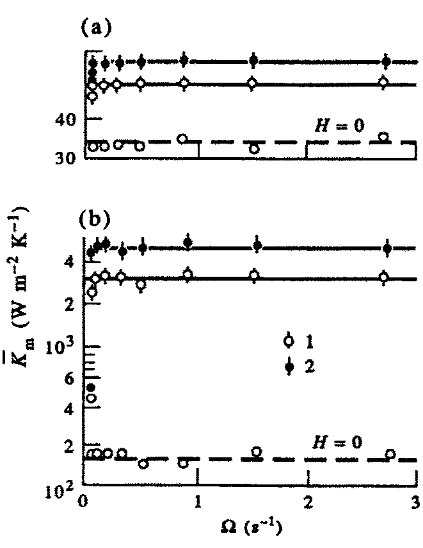

FIG. 1. (a) Mean heat transfer coefficient of the T-6 ferrosuspension ($\varphi = 2.6\%$) vs the rotor speed. (b) Mean heat transfer coefficient of the R-10 ferrosuspension ($\varphi = 1\%$) vs the rotor speed: 1, rotation of the rotor and of the field; 2, codirectional rotation of the rotor and of the field; $\omega = 314\ s^{-1}$.

The superposition of a shear field onto the system causes a still stronger intensification of the process investigated. Here, the mutual direction of the rotor and the field rotation begins to manifest itself. In the case of the co-directed rotation (in the situation discussed, the ferrosuspension volume moves opposite to the rotor rotation, Fig. 1(a), curve 2), $\bar{K}_m$ is somewhat higher.

A still sharper increase in the heat transfer rate in a magnetic field is observed in the suspensions of carbonyl iron in water. In this case the heat transfer coefficient increases more than 15-fold. Qualitatively, the dependences of $\bar{K}_m$ on such parameters as the speed of rotation of the inner cylinder, the direction of rotation and the strength of the magnetic field are similar to those presented above (Fig. 1(b)). The effect of the dispersed phase concentration and of the inductor winding current on heat transfer in such systems is shown in Fig. 2. The curves of $\bar{K}_m$ vs the dispersed phase concentration for all the field strengths have a clearly defined extremum (Fig. 2(b)), which is explainable in terms of the presumed dependence of the mobility of particles on their quantity in the volume of the carrying medium.

A brief note on the mechanism. On exposure to a rotating magnetic field, an MRS layer develops two kinds of motion: a microscopic intense rotational

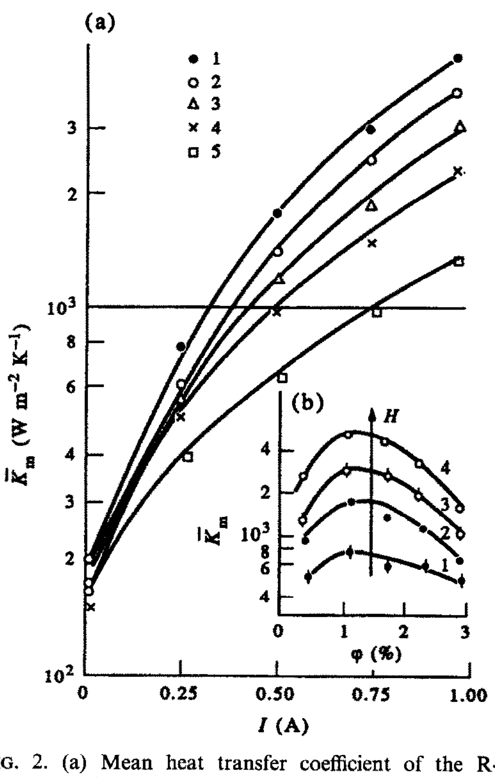

FIG. 2. (a) Mean heat transfer coefficient of the R-10 ferrosuspension vs the inductor current: 1, $\varphi = 1\%$; 2, $\varphi = 1.5\%$; 3, $\varphi = 2.3\%$; 4, $\varphi = 0.4\%$; 5, $\varphi = 3\%$; $\omega = 314\ s^{-1}$. (b) Concentrational dependences of $\bar{K}_m$ of the R-10 ferrosuspensions: 1, $I = 0.25$ A; 2, $I = 0.5$ A; 3, $I = 0.75$ A; 4, $I = 1$ A.

motion caused by the rotation of aggregates and a macroscopic motion of the entire volume of the medium. Such almost perfect stirring of the medium amplifies heat transfer in the system due to the convective component (macroscopic motion of the medium) and to the component stemming from the pseudoturbulization of the layer (rotation of the particle aggregates). The second component appears to be dominating. This is confirmed by the following fact: qualitatively, the relations that govern the mechanical behaviour of suspensions in a non-homogeneous R-field are characterized by a significant variation of torque with the rotor angular velocity. The phenomenon referred to owes its origin exactly to the macroscopic motion of the entire volume of the suspension. In heat transfer experiments the shear field does not alter the value of $\bar{k}_m$, thus pointing to the existence of another mechanism which determines the character of the relations, namely, pseudoturbulization of the layer by rotational motions of ferromagnetic particles and their aggregates.

Quantitatively, besides the strength, direction and rotation speed of the field, the heat transfer in the R-field is determined to a great extent by the kind of MRS. The R-10 suspension, for example, differed from the T-6 suspension by larger particles of the dispersed phase, thus being conducive to their better aggregation and higher intensity of the vortex rotation of such aggregates. Another essential feature characteristic for carbonyl iron suspensions is to be considered: its capability for being totally broken up on shear of the spatial structure of the carrying medium (distilled water thickened with acrylic acid copolymer). This considerably raised the effective viscosity of the medium and increased the freedom for the rotation of aggregate particles and this, in turn, assisted in a more intense pseudoturbulization of the entire body of the suspension.

4. *Heat transfer of a turbulent flow*

Considerable interest is attached to the study of the probable magnetorheological control of transfer processes in turbulent flows characteristic for many technological cycles. As an object for investigation we selected a turbulent flow of a low-concentrated MRS in a non-magnetic circular channel. In such a case, when there was no magnetic field, the particles of the dispersed phase virtually did not influence the flow character. The working medium was a low-concentrated ($\varphi \leqslant 1\%$) water suspension of ferromagnetic spherical particles of R-10 carbonyl iron ($d \sim 3.5$ μm, $\rho_s = 7.8$ g cm^{-3}).

The test facility used allowed one to determine the fluid existence and heat transfer of the flow under the action of a uniform magnetic field oriented either parallel with (longitudinal field), or perpendicularly to (transverse field), the channel axis. The strength of the magnetic field, the concentration and flow rate of MRS were varied, whereas the unknown characteristics were determined from the following relations: the fluid resistance coefficient $\xi = 2\Delta PgD/v^2\rho^*L$, where $v = 4G_m/\pi D^2$ is the mean volumetric flow velocity; $\rho^* = (1-\varphi)\rho_f + \varphi\rho_s$; the wall heat transfer intensity $Nu = \alpha D/\lambda_m = wD/\Delta\bar{T}F\lambda_m$, where $\Delta\bar{T} = (\bar{T}_s - \bar{T}_m)$ is the temperature difference: $\bar{T}_s = \frac{1}{5}\sum_1^5 T_{si}$

$$\bar{T}_m = \frac{1}{3}\left(\sum_1^3 T^{\parallel}_{mi} - \sum_1^3 T^{|}_{mi}\right).$$

It should be noted that for the studied range of MRS concentrations, the measurements revealed the absence of a noticeable effect of ferromagnetic particles on the thermal conductivity of the carrying fluid (water) being equal to 0.6 W m^{-1} K^{-1} at 20°C. A transverse magnetic field produces sharp changes in the flow character. As is seen from Fig. 3, the fluid resistance increases significantly and heat transfer is enhanced ($\beta = \xi_H/\xi_0$; $\gamma = Nu_H/Nu_0$), with a linear increase in the effect accompanying the increase in concentration.

In Fig. 4, the quantities β and γ vs the strength of the magnetic field H and the number $Re = vD\rho^*/\eta$ (η is the water viscosity) are presented. The effect grows according to the relation close to the quadratic law with an increase in H, and decreases following the same law with an increase in Re. Therefore, it would be logical to assume that the effect depends on the relationship between the energy of the magnetic interaction of particles ($E_M \sim H^2$) and the turbulent flow energy ($E_T \sim v^2$). Such a relationship is governed by the well-known Alfven condition $Al = \mu_0 H^2/\rho v^2$ [1]. Taking into account the linear functions $\beta = \beta(\varphi)$ and $\gamma = \gamma(\varphi)$, it is more convenient to use the reduced Alfven numbers $Al^* = Al\varphi$.

Presenting all experimental data in the coordinates β and $\gamma - Al^*$, we obtain a linear dependence of the effect on Al^* (Fig. 5) in the form $y = 1 + px$. In the

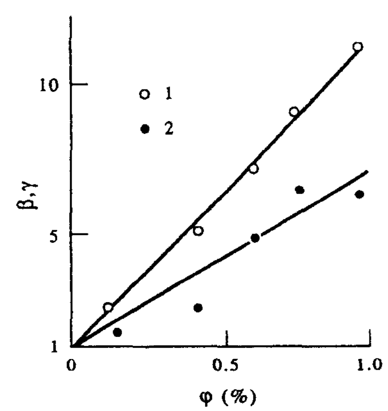

FIG. 3. The effect of the MRS concentration on the relative increase in fluid resistance and heat transfer in a transverse field: 1, β; 2, γ; $H = 320$ kA m^{-1}; $Re = 9600$.

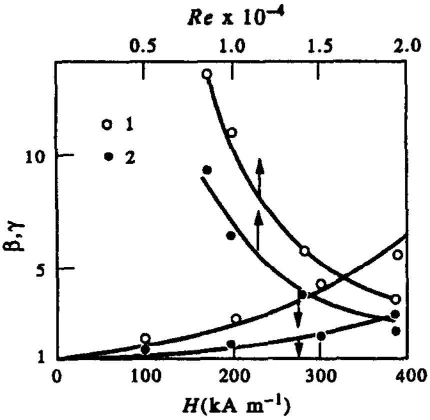

FIG. 4. Relative increase in fluid resistance and heat transfer vs Reynolds number ($H = 320$ kA m^{-1}) and the strength of the transverse field ($Re = 1.4 \times 10^4$) : 1, β; 2, γ; $\varphi = 1\%$.

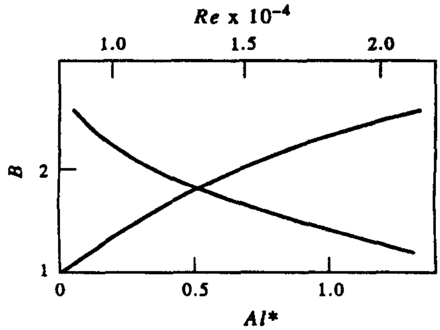

FIG. 6. Actual gain in heat transfer vs Reynolds number ($H = 320$ kA m^{-1}; $\varphi = 1\%$) and reduced Alfven number.

presence of fluid resistance, the coefficient p is equal to 13.5. For heat transfer $p = 7.5$.

Thus, the rate of increase in fluid resistance and heat transfer of a turbulent flow of a low-concentration MRS in a tube exposed to a transverse magnetic field can be predicted from the following empirical formulae:

$$\beta = 1+13.5Al^*, \quad \gamma = 1+7.5Al^*.$$

Relations (2) are valid for the range $0 \leqslant Al^* \leqslant 1.2$, which corresponds to $0 \leqslant H \leqslant 320$ kA m^{-1}; $1 \leqslant v \leqslant 2.4$ m s^{-1}; $0 \leqslant \varphi \leqslant 0.01$; $8 \times 10^3 \leqslant Re \leqslant 20 \times 10^3$.

Just as in the case of traditional methods for heat transfer enhancement [11], in our experiments, an increase in hydraulic resistance advanced an increase in Nu. It should be of interest to follow the character of the change in the pure gain factor in heat transfer $B = Nu_H/Nu^*$, where $N\ddot{u}^*$ is the intensity of heat transfer on the tube wall in the absence of a fluid, but at such a high MRS flow speed, when the condition $\Delta P_H = \Delta P_0$ is fulfilled. Taking into account the fact that in a turbulent regime $\Delta P \sim v^{1.75}$ and $Nu \sim v^{0.8}$, we obtain $B = \gamma/\beta^{0.457}$. Figure 6 illustrates the dependence of the gain on Al^* and Re, from which it is clear that the value of B over the whole range of the parameters is greater than unity and grows in regimes with small numbers, presumably reaching the largest value in the zone adjacent to the transient region, but necessarily in the turbulent area.

A longitudinal field exerts an opposite effect, causing a reduction in fluid resistance and in heat transfer (Fig. 7). Unlike a transverse field, here the functions $\beta(Al^*)$ and $\gamma(Al^*)$ have a nonmonotonic character with the maximum effect of $\beta = 0.45$ and $\gamma = 0.65$ at $Al^* = 5 \times 10^3$. As Al^* increases, the effect decreases, and at $Al^* = 14 \times 10^{-3}$ it practically ceases to exist.

The mechanism. Apparently, there is an interaction between a turbulent carrying medium and a dynamic microstructure formed by the field from ferromagnetic particles (anisodiametric aggregates which are stalled by the carrying medium flow and which change their geometrical characteristics depending on the magnitude of local stresses). Due to the aligning action of the field, the anisodiametric aggregates introduce a certain deterministic character into the random pattern of a turbulent flow and this affects the fluid resistance and convective heat transfer in a certain way.

CONCLUSION

The experiments showed that heat transfer processes in MRS are highly sensitive to the state of

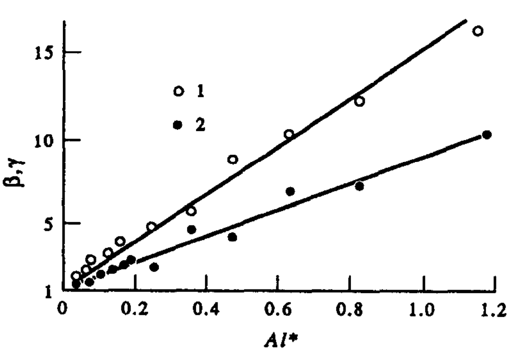

FIG. 5. The effect of a transverse magnetic field: 1, β; 2, γ.

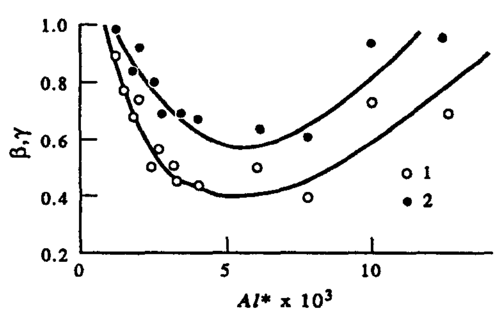

FIG. 7. The effect of a longitudinal magnetic field: 1, β; 2, γ.

its microstructure formed by a magnetic field from dispersed ferromagnetic particles. Transformation of the microstructure induced by varying the external field parameters (type, strength, orientation) leads to a substantial and reversible change in the heat transfer coefficients, resulting in the enhancement of heat transfer in some cases and its reduction in others. Thus, the thermal conductivity of MRS increases up to 70%, as compared with the initial value (in the case of the heat flux coinciding with the force lines of a constant magnetic field) and falls by about 50% in the case of perpendicular orientation of the magnetic field.

There is an essential change in a shear flow of MRS in the presence of a rotating magnetic field. A regulated increase in the heat transfer coefficient attains a value 15 times greater than the initial one.

Strong intensification of heat removal from the wall exposed to the flow is observed under the action of a uniform field on turbulent suspension flow in a channel when the field is at right angles to the channel axis. A 10-fold increase in the heat transfer coefficient has been attained. When in the parallel orientation, there was a controlled two-fold decrease in α_m.

The possibility for accomplishing control over heat transfer within a wide range may offer considerable promise in designing a new class of devices with magnetorheological thermal characteristics. This refers, first of all, to the apparatus functionally containing a magnetic field inductor, for example, electric motors, transformers, dynamic loudspeakers, etc. For thermal engineering, of particular interest is heat transfer equipment containing a magnetorheological heat carrier. Calculations showed [12] that for the simplest 'tube-in-tube'-type recuperator the application of MRS as one of the heat carriers will make it possible to increase the mean heat transfer coefficient of the heat exchanger 2–3 times due to the exposure to a magnetic field. It should be noted that a distinctive attribute of the devices with magnetorheological heat carriers, which is hardly possible or attainable in traditional equipment, is the possibility for operative control of the main operational characteristics (temperature drop, heat-producing capability) without changing the heat carrier flow rate due to the adjusted variation of the heat transfer coefficient.

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