TURBULENT FLOW AND HEAT TRANSFER OF MAGNETORHEOLOGICAL SUSPENSIONS

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Broad possibilities for control of transport processes are offered by the use of working media consisting of heterogeneous systems with a structure which can be reorganized by a magnetic field — noncolloidal suspensions of ferromagnetic particles, known as magnetorheological suspensions (MRS) [1]. The laws governing laminar flows and heat and mass transfer in MRS's have now been fairly well established, and new production processes and equipment have been proposed on this basis [1-3].

At the same time, there is considerable interest in studying the possibility of magnetorheological control of transport processes in turbulent flows as well. Such flows are characteristic of many production cycles and differ from laminar flows in the character of the stress state of the medium in space and time.

As the object of our study, we chose a turbulent flow of a low-concentration MRS in a channel of circular cross section. Here, we established the condition that, in the absence of a magnetic field, the particles of the disperse phase, with almost no delay, follow pulsating elementary volumes of the dispersion medium while exerting almost no effect on the character of motion of the medium. It is known that this condition is satisfied when [4, p. 194]

$$\frac{d}{D}\sqrt{\left|\frac{\rho_s}{\rho}-1\right|}\sqrt{\mathrm{Re}}\leqslant 0.2, \qquad (1)$$

where d is the mean particle size; D is the channel diameter; ρ_s and ρ are the density of the particles and dispersion medium (carrying fluid).

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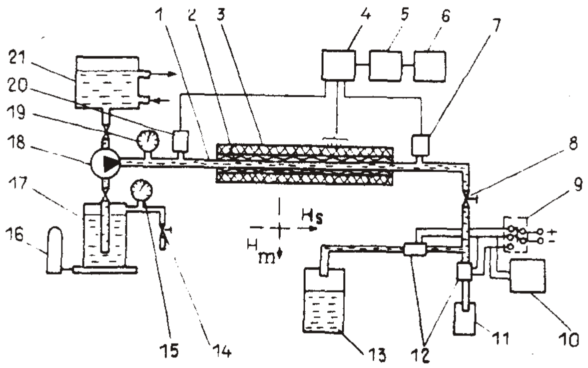


Fig. 1. Diagram of unit.

The effect of a magnetic field on integral characteristics (drag and heat transfer on the wall) of a turbulent flow of an MRS was studied on the unit schematized in Fig. 1. The working medium was low-concentration ($c_{vo} \leqslant 1\%$) water suspension of spherical ferromagnetic particles of carbonyl iron R-10 ($d \sim 3.5$ μm, $\rho_s = 7.8$ g/cm³). The measurement section (1) was a copper tube with an inside diameter D = 8 mm and length L = 1 mm. It had an electric heater (2) on the outside surface to create a constant heat flow (second-order boundary conditions). The tube also had thermal insulation 3. Thermostatted water entered the pump 18 from metering tank 21, and a concentrated water MRS ($c_{vo} = 40\%$) was delivered from pressure tank 17 by means of compressed air. The MRS was stabilized with low-molecular-weight sodium salt of carboxymethylcellulose Na-KMTs (1 wt. %). Layering of the suspension was prevented by mixing it on a vibrator 16. A flow of dilute MRS was produced at the outlet of the pump, the concentration of this flow corresponding to the air pressure in the tank 17. The air pressure was regulated with the cock 14 and monitored with the manometer 15. After passing the measurement section, the suspension fell into the discharge tank 13. Here, the solid phase was separated for its repeat use. The flow rate of the MRS was set with a valve 8 and was monitored from the pressure at the inlet of the manometer tube 19. It was measured by the volumetric method with a container 11 and switch 9 which controlled the signal to electric valves 12 working in opposite phase: "open—close." The switch synchronously started and stopped electronic timers 10 to measure the time intervals during which the container 11 was filled. The measurement section was located in the region of the uniform magnetic field created by an electromagnet (H_m, transverse field) or solenoid (H_s, longitudinal field). The drag of the channel 1 (pressure drop Δp) was determined from the difference in the readings of induction-type pressure gauges 7 and 20. Thermocouples measured the temperature of the MRS at the inlet and outlet of the channel, the walls of the channel, and the inside and outside surfaces of the insulation. Signals from the thermocouples and pressure gauges and signals proportional to the supply voltage and current of the heater were sent to commutator switch 4, measured with voltmeter 5, and recorded by an alphanumeric device 6.

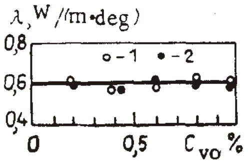
First we calibrated the unit to determine corrections for the readings of the gauges 20 (the effect of the field) and the relationship between the pressure on the manometers 19 and 15 and the flow rate and concentration of the MRS, respectively. We determined the weight concentration c_w by drying water from a sample of the suspension and weighing the dry residue. The volume concentration was determined from the formula $c_{vo} = 1/(1 + \rho_s/\rho)(1/c_w - 1)$. It should be noted that inequality (1) was satisfied in all regimes.

The tests were conducted in the following sequence: water was pumped through the channel at the rate G; the heater was turned on; after the steady-state regime was attained, all measured parameters were recorded on the tape of the printer. Then the same flow rate was used to create an MRS flow, and similar measurements were made with and without a magnetic field. We varied the strength of the field H and the concentration and flow rate of the MRS and determined the sought characteristics from the following well-known relations: for the drag coefficient

$$\xi = 2\Delta p g D/\omega^2 \rho^* L, \tag{2}$$

where $\omega = 4G/\pi D^2$ is the volume-mean flow rate; $\rho^* = (1 - c_{vo})\rho + c_{vo}\rho_s$; for the rate of heat transfer on the wall

$$\mathrm{Nu} = \alpha D/\lambda = (Q_{el} - Q_s) D/\Delta t F \lambda; \tag{3}$$



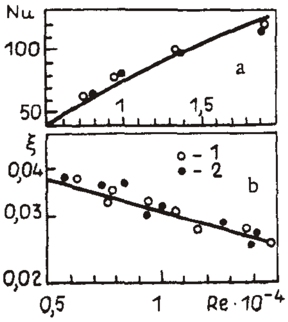


Fig. 2

Fig. 3

Fig. 2. Thermal conductivity: 1) water; 2) MRS.

Fig. 3. Heat transfer (a) and drag (b) of MRS flow in the absence of a magnetic field: 1) water; 2) MRS. $c_{vo} = 1\%$.

here, $Q_{el} = UI$ (U and I are the supply voltage and current of the electric heater); Q_s are heat losses through the external surface of the insulation; $\Delta t^* = t^*_{wa} - t^*_m$ is the temperature head; $t^*_{wa} = {}^1/_5 \sum_1^5 t^i_m$ is the mean temperature of the tube wall; t^i_{wa} is the local temperature of the wall; $t_m = {}^1/_6 \left(\sum_1^3 t'_i + \sum_1^3 t''_i \right)$ is the mean temperature of the MRS in the channel; t_i' and t_i'' are the temperatures of the MRS at the channel inlet and outlet; F is the heat-transfer surface; λ is the thermal conductivity of the MRS. It should be noted that measurements of λ for the investigated range of MRS concentrations by the method in [5] showed that the ferromagnetic particles have only a slight effect on the thermal conductivity of the carrying liquid – water. The latter is equal to 0.6 W/(m·deg) at 20°C (Fig. 2).

Tests conducted in the absence of a magnetic field confirmed that small quantities of noninteracting particles ($c_{vo} \leq 1\%$) of a size satisfying inequality (1) do not significantly affect the drag and heat transfer of the flow (Fig. 3). The points on the graph denote experimental data, while the lines were constructed from the criterional formulas [6]

$$\mathrm{Nu} = 0.021\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.43}; \quad \xi = 0.316\,\mathrm{Re}^{-0.25} \tag{4}$$

for a flow of pure water in the tube.

1. A transverse magnetic field sharply changes the character of the flow. It can be seen from Fig. 4 that there is a substantial increase in drag and an intensification of heat transfer ($\beta = \xi_n/\xi$; $\gamma = \mathrm{Nu}_n/\mathrm{Nu}$; ξ_n, Nu_n are in magnetic field). The effect increases linearly with an increase in concentration.

Figure 5 shows the dependence of β and γ on the magnetic field H and the number $\mathrm{Re} = \omega D\rho^*/\eta$ (η is the viscosity of water). The effect increases in accordance with a nearly quadratic law with an increase in H and decreases in the same manner with an increase in Re. Thus it is logical to suggest that the effect depends the relation between the energy of the magnetic interaction of the particles ($u_M \sim H^2$) and the energy of the turbulent flow ($u_t \sim \omega^2$). This relation is determined in accordance with the well-known Alfvén criterion $\mathrm{Al} = \mu_0 H^2/\rho\omega^2$ [7, p. 46]. With allowance for the linear relations $\beta = \beta(c_{vo})$ and $\gamma = \gamma(c_{vo})$, it is more convenient to use the corrected Alfvén criterion $\mathrm{Al}' = \mathrm{Al}c_{vo}$.

Having represented all of the experimental data in the coordinates β, γ–Al' and mathematically analyzing the results, we obtain a linear dependence of the effect on Al' (Fig. 6) in the form $\gamma = 1 + kx$. In the case of drag, the coefficient k is equal to 13.5. With allowance for the confidence interval in which it can be found with a probability $P = 0.9$, $k = 13.5 \pm 1.3$. For heat transfer, $k = 7.5 \pm 0.8$.

Thus, the rate of increase in drag and heat transfer of a turbulent flow of a dilute MRS in a tube under the influence of a transverse magnetic field can be predicted from the following empirical formulas:

$$\beta = 1 + (13.5 \pm 1.3)\mathrm{Al}'; \quad \gamma = 1 + (7.5 \pm 0.8)\mathrm{Al}' \tag{5}$$

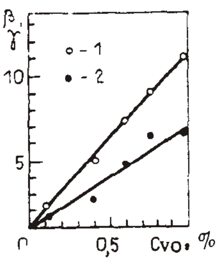


Fig. 4

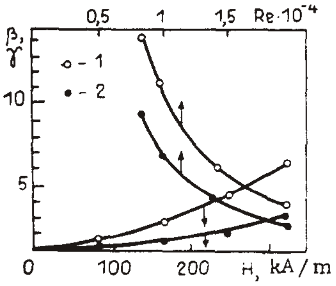


Fig. 5

Fig. 4. Effect of MRS concentration on the relative increase in drag and heat transfer in the transverse field: 1) β; 2) γ. $H = 320$ kA/m, Re = 9600.

Fig. 5. Dependence of the relative increase in drag and heat transfer on the Reynolds number ($H = 320$ kA/m) and transverse field ($\mathrm{Re} = 1.4 \cdot 10^4$): 1) β; 2) γ. $c_{v0} = 1\%$.

or changing over to the original quantities:

$$\xi_n = \xi + \frac{(13.5 \pm 1.3)\mu_0 H^2 c_{v0}}{\rho\omega^2}; \quad \mathrm{Nu}_n = \mathrm{Nu} + \frac{(7.5 \pm 0.8)\mu_0 H^2 c_{v0}}{\rho\omega^2}, \tag{6}$$

where ξ and Nu are quantities determined from Eqs. (3).

Equations (5) and (6) are valid for the interval $0 \leq \mathrm{Al}' \leq 1.2$, which corresponds to the ranges $0 \leq H \leq 320$ kA/m, 1 m/sec $\leq \omega \leq 2.4$ m/sec, $0 \leq c_{v0} \leq 0.01$, $8 \cdot 10^3 \leq \mathrm{Re} \leq 20 \cdot 10^3$.

As with traditional methods of intensifying heat transfer [8], in our tests as well the increase in drag occurs in advance of the increase in Nu. It is interesting to follow the character of the change in the net gain in heat transfer $B = \mathrm{Nu}_n/\mathrm{Nu}_*$, where Nu_* is the rate of heat transfer on the tube wall in the absence of a field but with a higher MRS flow velocity such that the condition $\Delta p_n = \Delta p_{n=0}$ is satisfied. Considering that in the turbulent regime $\Delta p \sim \omega^{1.75}$, $\mathrm{Nu} \sim \omega^{0.8}$ (see (2) and (4)), we obtain

$$B = \gamma/\beta^{0.457}. \tag{7}$$

Figure 7 shows the dependence of the gain on Al' and Re constructed from Eq. (7). It is evident that the value of B is greater than unity throughout the parameter ranges and increases in regimes with low Re. The value of B evidently reaches its maximum in the region bordering the transitional region.

2. A longitudinal field has the opposite effect, causing a reduction in drag and heat-transfer rate (Fig. 8).

In contrast to the transverse field, here the relations $\beta(\mathrm{Al}')$ and $\gamma(\mathrm{Al}')$ are nonmonotonic in character. The maximum effect $\beta = 0.45$, $\gamma = 0.65$ is attained at $\mathrm{Al}' = 5 \cdot 10^{-3}$. The effect decreases with an increase in Al' and practically disappears at the value $14 \cdot 10^{-3}$. Unfortunately, the available solenoid did not make it possible to create a strong field and, accordingly, to reach the highest values of Al'.

The results obtained regarding the effect of a magnetic field on the rheodynamics of a turbulent MRS flow differ qualitatively from data from similar tests with colloidal ferromagnetic fluids [9, 10], in which there was a slight (about 10%) reduction in ξ. Here, the ferromagnetic fluid was regarded as a homogeneous medium due to the very small particle sizes (on the order of 1 nm), while the field was regarded as a body force. Here, regardless of the orientation of the lines of force relative to the flow, one of the fluctuation components of velocity was suppressed. This led to a reduction in ξ [10].

The mechanism of action on the flow is different in the MRS. In this case, there is evidently an interaction between the turbulent dispersion medium and a certain field formed of ferromagnetic particles with a dynamic microstructure (we mean anisometric aggregates entrained by the dispersion medium which have geometric parameters that are a function of the local stresses). The time of formation of such a microstructure [11] is

$$t_p = \eta/0.35 c_{v0} \mu_0 \varkappa H^2, \tag{8}$$

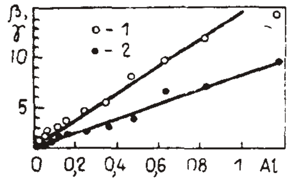


Fig. 6. Effect of transverse magnetic field: 1) β; 2) γ.

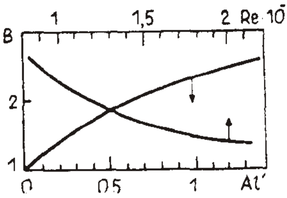


Fig. 7

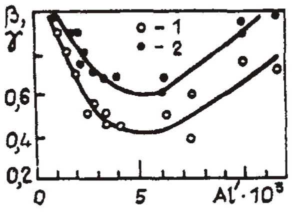


Fig. 8

Fig. 7. Dependence of the pure gain in heat transfer on the Reynolds number (H = 320 kA/m; c_{VO} = 1%) and the corrected Alfven number.

Fig. 8. Effect of longitudinal magnetic field: 1) β; 2) γ.

where $\varkappa$ is the magnetic susceptibility of an aggregate; it is on the order of 1 msec and is considerably shorter than the residence time of the particles in the region of action of the field ~0.5 sec. Due to the orienting action of the field, the anisometric aggregates introduce a certain determinancy into the random character of the flow. This in turn has a certain effect on drag and convective heat transfer. Thus, in a transverse field, the elements of the microstructure are oriented perpendicular to the flow. This probably reinforces transverse pulsations of the velocity of the dispersion medium and thereby increases turbulent friction and heat transfer. Also, the increase in the size and mass of the elements of the disperse phase due to the particle aggregation increases the relative velocity of the phases. This in turn increases turbulence in both the flow core and the viscous sublayer. Here, the aggregates become stronger and larger with an increase in Al'. As experiments show, the increase in aggregate strength and size results in a linear increase in β and γ.

In a longitudinal field, the anisometric elements of the dynamic microstructure are located along the flow axis and thus help extinguish transverse pulsations. This reduction in transverse pulsations leads to a decrease in ξ and Nu. In this case, there are two mechanisms having opposite effects on the character of the flow with an increase in Al': strengthening of the aggregates and more effective damping of pulsations on the one hand, and an increase in the size of the aggregates and additional agitation of the flow on the other hand. These competing factors can evidently be linked with the extreme character of the relations β(Al') and γ(Al') in a longitudinal magnetic field.

In the future, for a more complete and better description of the mechanism by which magnetic fields affect the turbulent flow of an MRS, it is suggested that studies be conducted using modern methods of diagnosing turbulence, including its fine structure.

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