coefficient of thermal diffusivity; μ, dynamic viscosity coefficient; ρ_1, dimensionless function of the density perturbations; ε, scale of the perturbations of the gasdynamic quantities; g, a dimensionless function of the radiation intensity distribution; α, absorption coefficient; n_0, refractive index of the unperturbed medium; and z_0, N, length and parameter of the thermal blooming.

LITERATURE CITED

1. D. C. Smith, Proc. IEEE, 65, No. 12, 1679-1714 (1977).
2. V. E. Zuev, Propagation of Laser Radiation in the Atmosphere [in Russian], Moscow (1981).
3. M. N. Kogan and A. N. Kucherov, Izv. Vyssh. Uchebn. Zaved., Fiz., No. 2, 104-110 (1983).
4. A. N. Kucherov, Zh. Tekh. Fiz., 52, No. 8, 1549-1558 (1982).
5. M. N. Kogan and A. N. Kucherov, Dokl. Akad. Nauk SSSR, 241, No. 1, 48-51 (1978).
6. F. G. Gebhardt and D. C. Smith, IEEE J. Quantum Electron., QE-7, No. 2, 63-73 (1971).
7. P. M. Livingstone, Appl. Opt., 10, No. 2, 426-436 (1976).
8. J. A. Fleck, J. R. Morris, and M. D. Feit, Appl. Phys., 10, No. 2, 129-160 (1976).
9. J. A. Thompson, J. C. S. Meng, and F. P. Boynton, Appl. Opt., 16, No. 2, 355-366 (1977).
10. P. J. Berger and P. B. Ulrich, Appl. Opt., 16, No. 2, 345-354 (1977).

ENERGY DISSIPATION AND HEAT EXCHANGE IN MAGNETORHEOLOGICAL SUSPENSIONS IN A ROTATING MAGNETIC FIELD

Z. P. Shul'man, V. I. Kordonskii,
S. R. Gorodkin, B. É. Kashevskii,
and I. V. Prokhorov

UDC 532.135

We present the results of experiments on the effect of the rheological properties of magnetic suspensions and the regime parameters on energy dissipation and heat transport in a rotating magnetic field.

A magnetorheological suspension is a stable suspension of noncolloidal single-domain ferromagnetic particles in a fluid dispersing medium. A rotating magnetic field causes a remagnetization of the elements of the microstructure of the suspension. There are two mechanisms: the turning of the particles themselves and flipflops of the moments of the particles from one direction of easy magnetization to the other. The latter is similar to the remagnetization of "solid" suspensions of single-domain particles, in the case when the external field strength exceeds the quantity $H_a/2$. When $H_a/2 < H < H_a$ the remagnetization has a jump-like discontinuity and is irreversible (so-called rotational hysteresis) [1].

If the rate of rotation of the external magnetizing field is small then the particles of the suspension can follow the field and rotational hysteresis does not occur. From the equation of motion of a uniaxial particle in the strong field limit ($H \gg H_a$) [2]

$$\mu_0 I_s H_a \sin 2\varphi = \alpha\eta\,(\omega_0 - d\varphi/d\tau)$$

we see that the particle can rotate with the field ($d\varphi/d\tau = 0$) up to a rotational frequency of the field given by

$$\omega_0 \leqslant \omega' = \mu_0 I_s H_a/\alpha\eta.$$

For larger frequencies the viscous forces "turn" the particle and it rotates with an angular velocity smaller than those of the field, so that there is a partial "freezing" in the fluid. Rotational hysteresis occurs under these conditions.

For a suspension of γ-ferric oxide ($I_s = 10^5$ A/m; $H_a = 6\cdot10^4$ A/m) in the hydraulic fluid AMG-10 ($\eta = 0.02$ Pa·sec) the quantity ω' is of order 10^3 sec^{-1}. However for a concentrated suspension ($C_{vol} \geqq 0.05$) ω' is much lower ($\omega' \sim 10$ sec^{-1}). This is explained by the fact

Institute of Heat and Mass Transfer, Academy of Sciences of the Belorussian SSR, Minsk.

Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 52, No. 1, pp. 57-61, January, 1987. Original article submitted November 22, 1985.

0022-0841/87/5201-0044$12.50

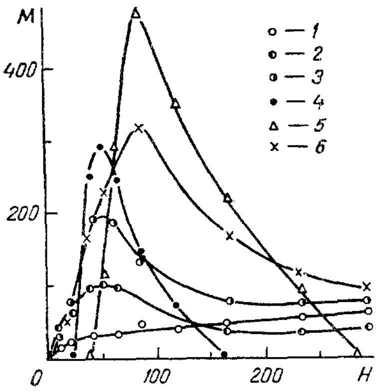

Fig. 1

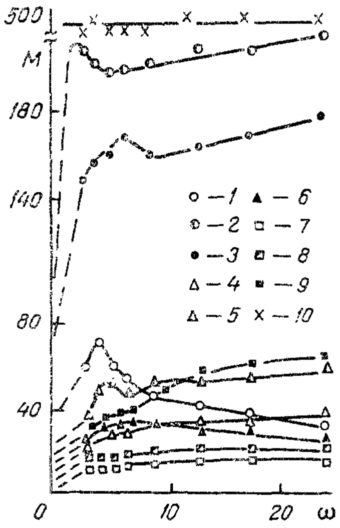

Fig. 2

Fig. 1. Dependence of the specific moment on the magnetic field strength ($\omega_0 = 26.2\ \mathrm{sec}^{-1}$): 1) C1, 2) C2, 3) C3, 4) C4, 5) C5, 6) C6. M, $N \cdot m/m^3$; H, kA/m.

Fig. 2. Dependence of the specific moment on the frequency of rotation: 1), 2), 3) C3; 4), 5), 6) C2; 7), 8), 9) C1; 1), 4), 7) H = 25 kA/m; 2), 5), 8) 50; 3), 6), 9) 250; 10) C4, H = 50 kA/m ω, sec^{-1}.

that extended aggregates of particles are formed in a magnetic suspension. Aggregation by an order of magnitude can increase the shape factor α, and at large concentrations, when the equilibrium sizes of the aggregates are larger than the distances between their centers, the rotation can become hindered. Hence the rotational hysteresis region in a suspension with given magnetic properties is determined by three parameters: the rotational frequency of the magnetic field ω_0, the concentration of ferromagnetic particles C_{vol}, and the viscosity of the dispersing medium η.

Experimentally, rotational hysteresis appears as a rotational moment M in the suspension, and the dependence of M on the field strength H shows a clear maximum [2].

Rotational hysteresis in magnetorheological suspensions and the effect of the above three parameters was studied experimentally using a set-up in which the volume of the sample was rotated. Then a strong electromagnet could be used and the entire interval of H necessary for the study could be covered. A hermetic cylindrical vessel (110 × 14 mm) made of a non-magnetic material and containing the suspension was rotated between the poles of an electromagnet. The field strength was measured with the help of a Hall transducer. The braking moment resulting from the application of a transverse uniform field was measured in terms of the phase of the voltage of the generator by means of a millivoltmeter. The rotational frequency was set by means of a set of interchangeable gears. The vessel was placed inside a container through which water from a reservoir was pumped.

The measurements were performed in the following sequence: a constant angular velocity of the vessel was set with the help of the one of the gears. The millivoltmeter was set to zero and the field strength was increased from a minimum value (10^4 A/m) to the limiting value ($3 \cdot 10^5$ A/m) and the corresponding braking moment was measured.

The first set of runs was performed in order to study the effects of the rotational frequency, the concentration of the solid phase, and the magnetic properties of the particles of the suspension on the moment. Three different suspensions of γ-Fe_2O_3 particles (0.1 × 1 μm, $H_c = 2.5 \cdot 10^4$ A/m) in hydraulic fluid AMG-10 were used, of different volume concentrations (C1 = 2.6%, C2 = 5%, C3 = 10%). Three other suspensions were also studied: a "solid" suspension of similar particles in wax (C4 = 10%), and also two suspensions with CrO_2 particles (0.05 × 1 μm, $H_c = 3.8 \cdot 10^4$ A/m), a "solid" suspension C5 = 10% and a fluid suspension in AMG-10 (C6 = 10%).

Figure 1 shows the results for the measured specific moment M (per unit volume of the suspension) as a function of the applied field H at the frequency $\omega_0 = 26.2\ \mathrm{sec}^{-1}$ for the above suspensions.

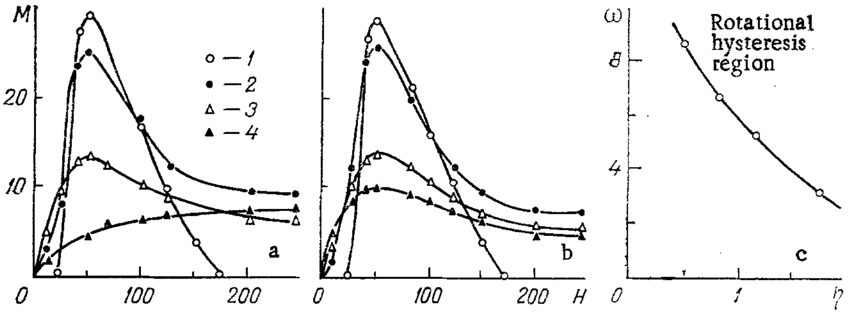

Fig. 3. Effect of the viscosity of the dispersing medium of the suspension on the specific moment and the existence region of rotational hysteresis: a) $\omega_0 = 8.7\ \mathrm{sec}^{-1}$, 1) $\eta = \infty$, 2) $\eta = 2.6$ Pa·sec, 3) 0.95, 4) 0.5; b) $\omega_0 = 26.2\ \mathrm{sec}^{-1}$, 1) $\eta = \infty$, 2) $\eta = 1.7$ Pa·sec, 3) 0.5, 4) 0.12. ω', sec^{-1}; η, Pa·sec.

The dependence M = M(H) for the "solid" suspensions C4 and C5 agrees qualitatively with the data of [1]. A moment on the rotor appears at a certain value of the field H = H', reaches a maximum M_{max} at H_{max}, and decreases with further increase of the field, reaching zero at H = H''. The rate of energy dissipation in the suspension $W=1/T\int_0^T \mathbf{H}\dot{I}(\tau)d\tau$ in the presence of the rotating field is $M\cdot\omega_0$ (M is the torque density) and is larger for C5; this is a consequence of the stronger magnetic anisotropy and the larger coercive force for CrO_2 particles in comparison with γ-Fe_2O_3 particles. We note that the coercive force of a ferromagnetic powder is much less than H_a of the separate particles, although these two quantities are related to one another in a definite way. The experiments showed that $H' = H_c$ and $H_{max} = 2H_c$.

The dependence M = M(H) is different for the fluid suspensions, where the particles can rotate in the dispersing medium. Here the moment is nonzero even for small fields and when H ~ H' it significantly exceeds M for the "solid" suspensions. The steepness dM/dH is smaller for the fluid suspensions. When the field is increased the moment for C3 and C6 goes through a maximum at $H = H_{max}$ and then decreases to a certain constant value M_{const} (at the field H'') and remains constant with further increase of H. M_{max} is smaller for C3 and C6 than for the "solid" suspensions C4 and C5 with the identical concentration.

There are two types of mechanical energy dissipation, corresponding to the two mechanisms of magnetic relaxation in magnetorheological suspensions described above. Energy dissipation shows up as a braking moment to the rotation, which has a contribution M_H from the magnetic interaction (rotational hysteresis) and a contribution M_η from friction of the rotating particles or aggregates of particles in the viscious dispersing medium. A pure M_H contribution only occurs in the "solid" suspensions. In fluid suspensions the measured moment is a superposition of M_H and M_η in the region H' < H < H'', and when H ≧ H'' we have $M_\eta = M_{const}$. The maximum in the dependence M = M(H) indicates the presence of losses by the particles.

A decrease in the concentration of the suspension leads to a proportional decrease in M_{max} and M_{const} (C2) because the number of aggregates in the volume goes down. But the dependence M = M(H) is monotonic in the dilute suspension C1, and this indicates that the rotation of aggregates is unhindered in this case and that there is no rotational hysteresis.

Figure 2 illustrates the effect of the rotational frequency on the dissipation rate in suspension of γ-Fe_2O_3 for three values of the field $H_1 = H'$, $H_2 = H_{max}$, $H_3 > H''$. The broken lines on the graphs extrapolate the moment to its "initial" value.

As in [3], in the "solid" solution C4 the moment does not depend on the rate of rotation for the frequency range studied here. For the fluid suspensions C2 and C3 the curve $M(\omega_0)$ agrees qualitatively with the discussion above: an initial linear growth, the presence of a maximum at a certain frequency ω', and then a decrease. It turns out that the decrease still occurs with further increase in ω_0 only for small H in the suspension C3 and for large H in C2. With this dependence, the existence of a critical frequency ω' lying in the interval 2 to 6 sec^{-1} implies that there is a partial "freezing" of the particles (aggregates) in these suspensions, and rotational hysteresis occurs. But for the dilute suspension C1 the dependence $M(\omega_0)$ is monotonic in the measured frequency range. This indicates that in the absence of aggregation hysteresis-free rotation of the particles is possible up to frequencies ω' exceeding the largest attainable frequency in the experiments.

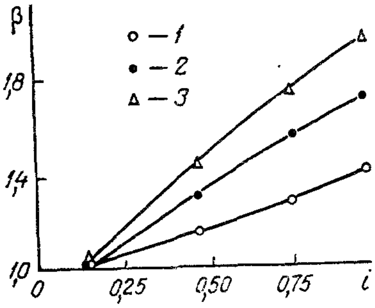

Fig. 4. Variation of the dimensionless heat transfer coefficient $\beta = k^i_{eff}/k_{eff}$ as a function of the current of the rotating magnetic field inductor: 1) η = 0.18 Pa·sec, 2) 0.14, 3) 0.1. i, A.

A second set of runs was carried out in order to study the effect of the viscosity of the carrier dispersing medium on the braking moment and to determine the existence region of rotational hysteresis. Wax was used, which has a significant dependence of the viscosity on temperature. The concentration of a γ-Fe_2O_3 suspension was chosen to be 2.6% in order to establish a limiting value of the viscosity corresponding to hysteresis-free rotation. A preliminary experiment was done to determine the temperature dependence of the effective viscosity of the wax.

Figure 3 shows the dependence of the moment on the field for different values of the viscosity of the wax at the rotational frequencies ω_0 = 8.7 sec^{-1} (Fig. 3a) and ω_0 = 26.2 sec^{-1} (Fig. 3b). As is clear from these graphs, the transition of the wax into the liquid state and the decrease of its viscosity with increasing temperature leads to an increase of M_η for fields smaller than H', because a larger number of particles can follow the field, and secondly to a decrease in the fraction M_H in the region $H' < H < H''$ and to a corresponding decrease in M_{max}. Finally there is a decrease in M for $H \geq H''$ because a smaller value of the viscosity corresponds to smaller dissipative losses, which imply a decrease of the braking moment (curves 1, 2, 3). At a certain value of the viscosity (curve 4 of Fig. 3a) the viscous torques are insufficient to turn the particles at the given frequency, and hysteresis-free rotation takes place, which is characterized by a monotonic dependence of M(H) for the entire range of fields. Increase of the rotational frequency to 26.2 sec^{-1} leads to a maximum in M(H) even for η = 0.12 Pa·sec (curve 4 of Fig. 3b); this implies a partial "freezing" of the particles in the fluid and the existence of rotational hysteresis.

Figure 3c shows the variation of the critical frequency ω' of the ferrosuspension γ-Fe_2O_3 (C_{vol} = 2.6%) with the viscosity of the carrier medium and defines the existence region of rotational hysteresis. Note that ω' increases with decreasing η and can reach a value equal to the estimate made earlier ~10^3 sec^{-1}. An increase in η causes a decrease in ω' and in the limit $\eta \to \infty$ (a "solid" suspension) dissipation occurs only because of rotational hysteresis.

The rotation of particles in the dispersing medium under the influence of a rotating field increases the heat exchange capacity of the suspension. For the example of radial heat exchange between two cylindrical walls (on one wall a boundary condition of the first kind is imposed, and on the other wall a boundary condition of the second kind) through an annular layer of the suspension Cl, a nonuniform rotating field causes a significant increase in the effective heat exchange coefficient $k_{eff} = q/\Delta t_{av}$ [4]. Figure 4 shows the dependence of the dimensionless coefficient $\beta = k^i_{eff}/k_{eff}$ on the current of the field inductor (which is linearly related to H) and the viscosity of the dispersing medium.

Note the increase of β with increasing H and decreasing η. This is probably due to an increase in the torque on the structural elements in the region $H < H_{max}$ (see Fig. 3) and to a corresponding increase in the rotation of the bulk of the suspension.

NOTATION

H_a, effective particle anisotropy field; H, magnetic field strength; H_c, coercive force of the dispersed ferromagnetic; $\mu_0 = 1.256 \cdot 10^{-6}$ G/m, magnetic permeability of free space; I_s, saturation magnetization of the particles; φ, angle between the easy axis of the magnetization of the particle and the direction of the field; α, shape parameter; η, viscosity of the carrier fluid; ω_0, rotational frequency of the magnetic field; C_{vol}, volume concentration of particles; T, period of rotation; q, specific heat flux; Δt_{av}, average temperature difference between the walls; K^i_{eff}, effective heat transfer coefficient of the suspension in the rotating magnetic field.

LITERATURE CITED

1. I. S. Jacobs and F. E. Luborsky, J. Appl. Phys., 28, No. 4, pp. 460-463 (1957).
2. S. R. Gorodkin, B. É. Kashevskii, V. I. Kordonskii, and I. V. Prokhorov, Pis'ma Zh. Tekh. Fiz., 10, No. 2, 94-98 (1984).
3. H. Seiwatz, J. Appl. Phys., 29, 994-995 (1958).
4. S. R. Gorodkin, Hydrogasdynamics, Heat and Mass Exchange in Power Plants [in Russian], Minsk (1984), pp. 28-35.

HEAT-TRANSFER DEVICE FOR HEATING OF EXTENDED HORIZONTAL OBJECTS

L. L. Vasil'ev, M. I. Rabetskii, and V. G. Kiselev

UDC 536.248

A heat pipe with total separation of vapor and liquid flows is described. The contruction allows transfer of high thermal fluxes over a significant distance with horizontal orientation of the object being heated.

In existing heat pipes the main limitations on the maximum thermal flux are the pressure and flow characteristics of the wick capillary structure. With increase in length of the heat pipe there is a decrease in thermal flux since hydraulic losses in the wick increase. For negative inclination of the heat pipe, where the evaporator is located above the condenser, a portion of the wick capillary potential is expended in overcoming the hydrostatic pressure of the heat-transfer agent column, which also leads to reduction of the achievable thermal load. Wickless heat pipes, i.e., thermosyphons, cannot transfer large quantities of heat in the horizontal position due to the braking action of vapor on the condensate, and they are not usable at all in a negative orientation.

The basic technique for improving the heat-transfer parameters of long heat pipes operating in a horizontal position or with negative inclination is the elimination of interaction between vapor and liquid fluxes by the use of separator inserts [1]. Use of individual channels for vapor and condensate and capillary-porous packing in the evaporator, playing the role of a hydraulic seal, led to development of antigravity heat pipes (AGTT's), which can operate with unfavorable orientations [2]. However, because of their complex structure and poor thermotechnical characteristics their use has been limited.

Heat-transfer devices have been proposed [3-7] which organize the interaction of the vapor and condensate to produce a positive effect. Constructions which produce this effect have permitted increasing the length of the heat-liberating surface and the limiting thermal flux by a factor of several times as compared to the parameters of known heat pipes. A diagram of the simplest such device, called a vapor-dynamic thermosyphon (VDTS), is shown in Fig. 1.

The vapor-dynamic thermosyphon consists of four major components: the evaporator 6, condenser 3, auxiliary reservoir-condenser 4, and transport zone, including the hydrostatic seal 5 and vapor guide 1. The evaporator is partially filled with the heat transfer agent, which is located in contact with the heating surface of the heating elements 9. The main condenser consists of tubes of different diameters arranged coaxially to form a vapor supply zone 2 and an annular gap zone 3 with heat liberating surface 7. At one end the annular condenser channel communicates with the evaporator through vapor guides 2 and 1, and at the other end

A. V. Lykov Heat and Mass Transfer Institute, Academy of Sciences of the Belorussian SSR, Minsk. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 52, No. 1, pp. 62-66, January, 1987. Original article submitted November 28, 1985.

0022-0841/87/5201-0048$12.50