NOTATION

a_1, a_2, a_3, volume absorptivities for the black incident flux for single, double, and triple passage through the volume; ε_1, ε_2, ε_3, volume emissivities under the same conditions; a_f, emissivity of the furnace space; q_r, resultant flux density, W/m^2; K, composite factor for multiple reflection from the envelope; A, absorption coefficient (emissivity); $R = 1 - A$; F, surface area, m^2; c, interpolation coefficient; M and S, the same for interpolation over the configuration. Subscripts: 0, *, heating and lining surfaces, respectively; 1, 2, 3, extreme models for configuration. Primes: values of gray and antigray surface-radiation spectra of the bulk medium.

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A METHOD OF MEASURING THE SHEAR AND ROTATIONAL VISCOSITY OF MAGNETIC FLUIDS

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The possibility of determining the shear and rotational viscosity of a magnetic fluid in a coaxial viscosimeter by means of two similar measurements of the rotational velocity of the inner cylinder in the dynamic regime is given a foundation.

1. The shear state of a magnetic fluid (MF) is determined by two viscosity coefficients, shear η, and rotational η_r. Up to now, the question of a simple method to measure the shear and rotational viscosity in one experiment remained urgent. A method is proposed in [1] for the determination of η and η_r in a coaxial viscosimeter by measuring the velocity of the inner cylinder and the friction moment of the outer cylinder in the steady-state regime. The advantage of the method is that the measurements are performed only in the stationary regime. However, measurement of the velocity and friction motion requires different realizations of the method from the accuracy and apparatus viewpoints, which is a substantial disadvantage.

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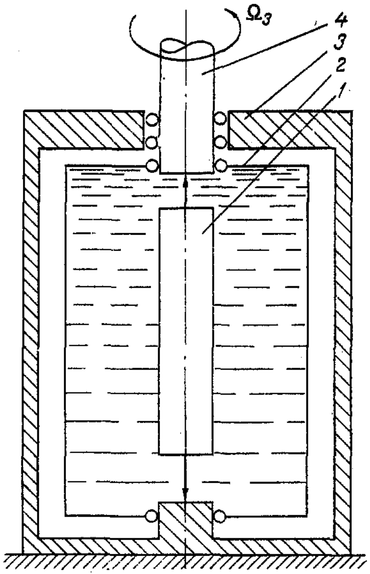

Fig. 1. Diagram of the rotational viscosimeter.

The idea of measuring the shear and rotational viscosities in the dynamic regime is proposed in [2, 3] on the basis of an exact solution obtained. In the limit cases, simple expressions are obtained to determine η and η_r for large moments of inertia of the inner cylinder for arbitrary gaps, as well as for narrow and broad gaps without taking account of the friction force in the supports. In the general case, the most substantial disadvantage of the expressions presented is the need to execute an inverse Laplace transform.

To this end, the authors propose utilization of residue theory, which requires the numerical solution of the equation in Bessel functions, which in addition to the complexity of search for each root has an infinite number of roots. Utilization of such expressions affords the possibility, in principle at least, of determining η and η_r; however, it does not permit their use to organize simple measurements, and even more, the determination of optimal structural parameters for the viscosimeter.

2. Let us examine MF flow in the rotational viscosimeter whose diagram is presented in Fig. 1. A magnetic fluid, whose characteristics must be determined, is in the gap between two coaxial cylinders placed in a fixed housing 3. The outer cylinder 2 rotates according to a given law, while the velocity of the freely suspended inner cylinder 1 is to be measured. In order to eliminate the transmission of a rotational momentum from the outer to the inner cylinder by means of friction in the supports, an independent suspension is used. By rotating the axis 4, the friction moment in the supports can be reduced, in principle, to zero.

The mathematical model for the flow in a rotational viscosimeter includes the equation of MF motion [1]

$$\frac{\partial U}{\partial \tau} = (1+\delta_\eta)\frac{\partial}{\partial r}\left[\frac{1}{r}\frac{\partial}{\partial r}(rU)\right], \tag{1}$$

as well as the boundary conditions for adhesion and the dynamic balance of the momentum of the tangential stresses on the surface of the unfastened cylinder with the friction moment in the supports of its axis:

$$U = U_2(t) \quad \text{for} \quad r = r_2 = r_1 + 1, \tag{2}$$

$$G\frac{\partial U}{\partial \tau} = r_1^2\left[(1+\delta_\eta)\frac{\partial U}{\partial r} - (1-\delta_\eta)\frac{U}{r_1}\right] - \delta_\alpha U \quad \text{for} \quad r = r_1, \tag{3}$$

where

$$U = V/\Omega_2^0 R_2;\ \tau = t\eta/\Delta R^2\rho;\ r = R/\Delta R;\ \Delta R = R_2 - R_1. \tag{4}$$

The problem (1)-(3) is determined by five dimensionless parameters characterizing the geometry $r_1 = R_1/\Delta R$, the MF properties $\delta_\eta = \eta_r/\eta$, the friction in the supports $\delta_\alpha = \alpha/\eta S\Delta R$, and the inertia $G = I/\rho S\Delta R^3$.

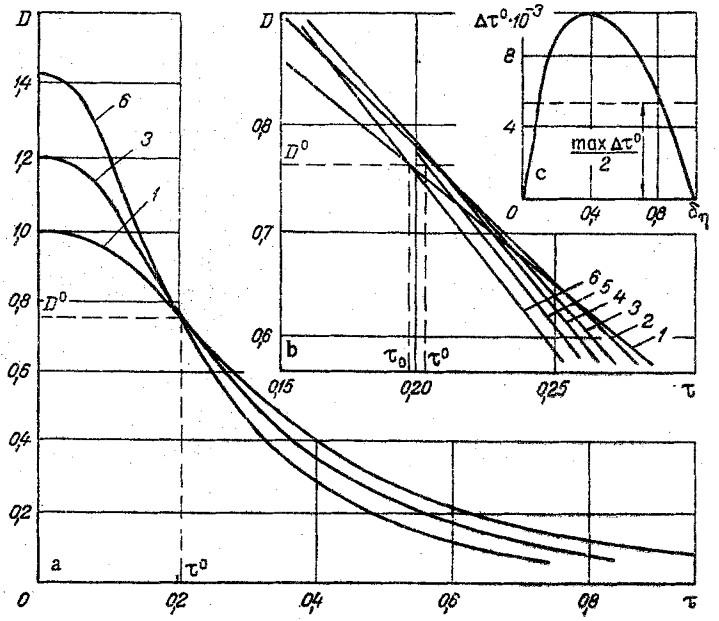

Fig. 2. Dependence of the dimensionless velocity of the inner cylinder D on the dimensionless time τ under instantaneous braking of the outer cylinder (1) $\delta_\eta = 0$; 2) 0.2; 3) 0.4; 4) 0.6; 5) 0.8; 6) 1.0): *a*) D(τ) for the whole range of τ under investigation; b) D(τ) in the domain (τ°, D°); c) change in the absolute error $\Delta\tau^\circ$ on δ_η for D = D°.

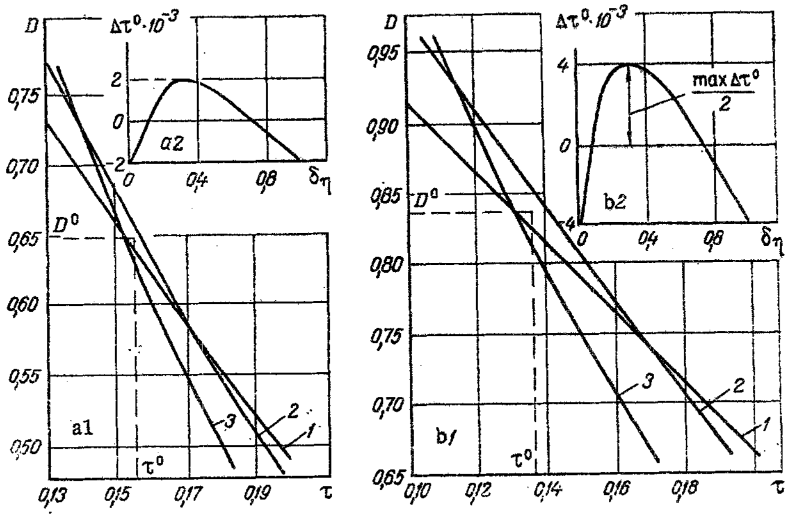

Fig. 3. To determine the values of τ° and D°: *a*1, b1) dependences D(τ) in the domain (τ°, D°); *a*2, b2) dependences of the absolute error $\Delta\tau^\circ$ on δ_η for D = D°; a) $r_1 = 0.6$; b) $r_1 = 2.0$; 1) $\delta_\eta = 0$; 2) 0.4; 3) 1.0.

The following assumptions are made in this model: a) a one-dimensional approximation (the cylinders should be sufficiently long to eliminate the influence of the endfaces); b) the magnetic field lines of force are perpendicular to the axis of the cylinders; c) the coefficients in (1)-(4) are constants (heat liberations are negligible, velocities are low).

3. The equations presented describe a linear object for which the input action is the angular velocity of the outer cylinder, while the output signal is the angular velocity of the inner cylinder. The behavior of a linear object under any input effects in dynamics is characterized completely by its transfer function $D(t) = \Omega_1(t)/\Omega_2^0$. It is determined by the solution of (1)-(3) with the boundary condition $U_2(t) = \begin{cases} 1, & t>0 \\ 0, & t<0 \end{cases}$ corresponding to a step effect.

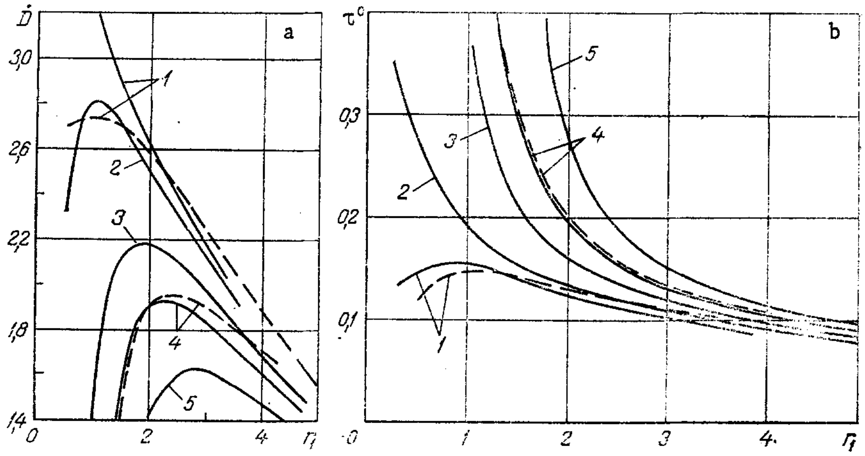

Fig. 4. To determine the optimal value of r_1: a) change in the derivative $D(\tau)$ at (τ°, D°) for different r_1; b) change in τ° as a function of r_1; 1) $\delta_\eta = 0$; 2) 0.1; 3) 0.5; 4) 1.0; 5) 2.0.

The problem (1)-(3) has an exact solution in the case of steady motion, from which

$$\dot{D} = \frac{\Omega_1}{\Omega_2^0} = \frac{1+\delta_\eta}{1+\Gamma^2\delta_\eta+\delta_\alpha(1-\Gamma^2)/2r_1}. \tag{5}$$

In the general case, the solution of (1)-(3) was constructed numerically by a mesh method. The mesh was selected sufficiently fine to assure an error of not more than 0.5%.

4. As a result of the numerical modelling in the parameter measurement range $0 \leqslant \delta_\eta \leqslant 1$; $0 \leqslant \delta_\alpha \leqslant 0{,}6$; $0 \leqslant G \leqslant 1$; $0{,}1 \leqslant r \leqslant 10$, the following is established.

The dependence $D(\tau)$ is monotonic in nature for any system parameters. For $\delta_\eta \neq 0$ an "effect of excess" of the inner cylinder angular velocity over the outer cylinder velocity is observed [1]. Starting with a certain time τ_1, $D(\tau) > 1$. As δ_η increases, the value of τ_1 decreases monotonically while D increases.

The influence of the cylindrical geometry is displayed in that as $r_1(\Delta R \to 0, R_1 \uparrow \infty)$ increases i.e., as the plane case is approximated, the "effect of excess" diminishes to zero, while the time τ_1 grows noticeably. The friction moment in the supports retards the inner cylinder, which results in growth of the steepness of the transient characteristic $D(\tau)$ and diminution in the "effect of the excess" with the growth of δ_α. The moment of inertia G exerts no influence on the form of the stationary solution. The build-up time grows with the increase in G, and as is especially essential, the rate of decrease of τ_1 with the growth of δ_η diminishes.

It is detected that if the cylinders are spun up to the stationary state, and then the outer cylinder is braked instantaneously (a step effect $\Omega_2(t)=\begin{cases}\Omega_2, & t\leqslant 0\\ 0, & t>0\end{cases}$ is produced) then the curves $D(\tau)$ have a narrow domain of intersection in the whole range of validity of the model (1)-(3) for G = const, δ_α = const. To a high degree of accuracy this domain can be taken as a point whose coordinates are denoted by τ° , D° (Fig. 2a).

The coordinate D° always corresponds to the point of intersection (τ_0, D°) of the curves $D(\tau)$ for the lower and upper boundaries of the range proposed $\delta_\eta \in [\delta_{\eta\min}, \delta_{\eta\max}]$ (Fig. 2b, curves 1 and 6).

The value of τ° is found from the dependence $\Delta\tau^\circ(\delta_\eta) = \tau(\delta_\eta, D^\circ) - \tau_0$ (Fig. 2c) constructed additionally by the formula $\tau^\circ = \tau_0 + \max(\Delta\tau^\circ/2)$. The relative error $\Delta\tau = \max(\Delta\tau^\circ)/(2\tau^\circ)\cdot 100\%$, as well as the location of D° depend on the parameters G, δ_α, r_1 and on the range selected $[\delta_{\eta\min}, \delta_{\eta\max}]$. As $\delta_{\eta\min}$, $\delta_{\eta\max}$ changes, the relative error $\Delta\tau$ will be the smaller, the smaller the difference $\delta_{\eta\max} - \delta_{\eta\min}$. A nonzero value of the friction moment $(\delta_\alpha \neq 0)$ results in an insignificant diminution in $\Delta\tau$ (by 0.4% for $\delta_\alpha = 0.6$), which is approximately the same as for $G \neq 0$ (by 0.7% for G = 1).

The geometric parameter r_1 (Fig. 3) exerts the most substantial influence on the accuracy of $\Delta\tau$, consequently in order to diminish $\Delta\tau$ it is desirable to select it minimal.

5. The method of determining η and η_r is the following: a) the outer cylinder in a rotation viscosimeter is spun up at a constant velocity to build up the velocity of the inner cylinder; b) the steady rate of inner cylinder rotation Ω_1 is measured, and the quantity $D = \Omega_1/\Omega_2$ is determined; c) the outer cylinder is braked instantaneously, and the time t° corresponding to the level $\Omega_1(t^\circ) = \Omega_2 D^\circ$ is measured; d) the shear viscosity η is found from the formula

$$\eta = \frac{t^0 \rho}{\tau^0 \Delta R^2}, \tag{6}$$

which is obtained from (4), τ° is taken from Fig. 2a; e) the rotational viscosity

$$\eta_r = \eta \frac{D^0 - 1 - D^0 \delta_\alpha (1 - \Gamma^2)}{1 - \Gamma^2 D^0} \tag{7}$$

is determined which follows from (5).

6. Selection of the structural parameters, error analysis. The measurement method described is simplest in the case $\delta_\alpha = G = 0$ since the τ°, D° are fixed here and known in advance. In this case the methodological error is governed by the error $\Delta\tau$, which as has already been remarked above, diminishes as r_1 diminishes. However, the error $\Delta\tau$ cannot be a decisive factor in the selection of r_1 since the apparatus error, which is considerably greater than the value of $\Delta\tau$, still also depends on r_1.

At first glance, the least possible value of the derivative $\dot{D}$ at the level D° is associated with the apparatus error: the higher the $\dot{D}$ the more exact the determination of the level D° and, naturally, the smaller the apparatus error. In order to determine the value of r_1 optimal in $\dot{D}$, the dependences $\dot{D}(r_1)$ were constructed for different values of δ_α and G (Fig. 4a). The computations displayed negligible influence of δ_α on the dependence $\dot{D}(r_1)$ and sufficiently strong influence of the parameter G on this dependence. As G increases, max $\dot{D}(r_1)$ diminishes from ∞ for G = 0 to $\approx$1.65 for G = 2.0, and the selection of a specific value of r_1 depends on the G_{max} to be assumed. Computations showed that in the very worst case $G_{max} = 1$, and consequently $r_1 \approx [1.8; 2.5]$.

The proposed method of measurement requires the production of an ideal step $\Omega_2(t)$ (the instantaneous braking of the external cylinder from Ω_2 to zero), which is realized with a definite error in practice. This error will be identical to high-frequency interference, and its influence will naturally be smaller, the lower the frequency of the linear object. In this sense the most indicative is the dependence of τ° on r_1 (Fig. 4b); the greater the value of τ°, the less will be the influence of the high-frequency error in $\Omega_2(t)$ on it. From this viewpoint $r_1 \in [1.8; 2.2]$ will be optimal for $G_{max} = 1.0$: for $r_1 \leqslant 1.8$ an abrupt increase in τ° is observed, i.e., τ° becomes critical to negligible deviations in r_1 which are possible in fabricating the installation. An analysis of the dependence $\dot{D}(r_1)$ arrives as this same result also, where an abrupt diminution in $\dot{D}$ is observed for $r_1 \leqslant 1.8$.

The investigations performed permit considering $r_1 \approx 2$ the optimal value for ranges realizable in practice $G < 1$, $\delta_\alpha < 0.6$. Refinement of the optimal r_1 for any G_{max} and $\delta_{\alpha max}$ is realized by using the data of Fig. 4.

The approximation $G = \delta_\alpha = 0$ can be used within 10% (5%) limits of the error $\Delta\tau (0 \leqslant \delta_\eta \leqslant 1)$ for $\delta_\alpha < 0.4(0.1)$ and $G < 0.2(0.06)$.

Taking account of the real G and δ_α complicates the measurement, which is associated with the need for an additional determination of the coordinates (D°, τ°). The dependence of D°, τ° on G, δ_α is described with a high degree of accuracy by the equations

$$\tau^0 = 0.131 + 0.076G + 0.014\delta_\alpha; \quad D^0 = 0.848 - 0.048G - 0.215\delta_\alpha, \tag{8}$$

which are obtained by processing the results of a numerical computation. The difficulty is that the η being measured enters the parameter δ_α in (8). The parametric equation for the curve $D^\circ(t)$ can be obtained from (8), where the parameter is δ_α: $D^\circ = 0.848 - 0.048G - 0.215\delta_\alpha$; $t = (0.131 + 0.76G + 0.014\,\delta_\alpha)\rho\Delta R^3 S\delta_\alpha/\alpha$.

Measurement of η now means finding the point of intersection of the dependence D(t), recorded experimentally, with the curve $D^\circ(t)$. The elimination of δ_α from (8), which is accomplished in the proposed rotational viscosimeter diagram, affords a possibility of determining η, η_r by the method for $G = \delta_\alpha = 0$ by taking τ°, D° from (8).

For high accuracy a) select $r_1 \approx 2$; b) try for $\delta_\alpha = 0$ and a possibly lower value of G.

If ρ is known, this method permits determination of the viscosities η and η_r. If the friction moment of the inner cylinder is measured in addition, ρ, η, and η_r can be found. A certain increase in the measurement accuracy can be achieved by rotating the magnetic field; however, the difficulty in realizing a field rotating according to a given law apparently makes such constructions without promise.

NOTATION

η, shear viscosity; η_r, rotational viscosity; R_1, R_2, radii of the inner and outer cylinders; t, running time; ρ, density; Ω_2^0, characteristic value of the angular velocity of the outer cylinder; S, surface area of the inner cylinder; I, moment of inertia of the inner cylinder; α, friction coefficient under the condition that the friction moment in the supports is proportional to the velocity of axis rotation; Ω_1, angular velocity of the inner cylinder; $\Gamma = R_1/R_2$; and τ, dimensionless time.

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MAGNETIC RELAXATION OF ELECTROTECHNICAL STEEL IN CONSTANT MAGNETIZING FIELDS AT VARIOUS TEMPERATURES

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Experimental studies are performed of magnetic relaxation in specimens of electrotechnical steel in weak constant magnetizing fields at room and liquid nitrogen temperature.

Experimental studies have shown that the magnetic properties of ferromagnets vary with time [1-8]. Time dependence of magnetic properties can be observed in both quasistatic magnetization and in magnetization in ac fields. Time effects in ferromagnets having a domain structure are caused by the fact that upon change in the external magnetic field H thermodynamic equilibrium in the domains is established only after a certain time period, due to a lag in the magnetization J with respect to the field. This thermodynamic equilibrium (magnetic relaxation) sets in because of interaction of spin waves (magnons) among themselves, and also with phonons, dislocations, impurity atoms, and other crytalline microdefects. The following may be potential sources of time effects in ferromagnets undergoing remagnetization: motion of dislocations and their Cuttler shells produced by magnetostriction stresses [9]; impurity atom diffusion; local heat liberation due to displacement of interdomain boundaries, which leads to localization of thermal stresses.

Study of time effects caused by relaxation processes in ferromagnets is of theoretical importance, since it clarifies the nature of all the various processes occurring during remagnetization, and of practical value as well, in connection with determination of magnetic

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