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MASS LOSSES OF MAGNETIZED RHEOLOGICAL MEDIUMS SUBJECTED TO MAGNETIC FIELD.

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Theoretical analysis and experimental research of the film flowing of magnetorheologic fluids when infinitive solid plate is retrieving from the former mediums were carried out. We have got dependencies of fluids mass losses m vs: velocity of moving plate V ; magnitude of magnetic intensity, its gradient and angle φ between direction of intensity lines and normal vector to plane of plate. It is shown that theoretical and experimental function $m(\varphi)$ is anisotropy one and may change its magnitude more than 10 times. Real behavior and extreme characteristics of $m(\varphi)$ depends on rhelogiacal parameters of MRS and its magnetization. Obtained experimental data of dependence $m(V)$ are in qualitative and quantitative agreement with the modernized theory.

1 Introduction

The problem of mass losses of rheologic liquids, such as magnetic suspensions or magnetic fluids of high volume magnetic concentration (denote them MRS), controlled by external magnetic fields - is very actual for technic applications: to seal gap between rotating, oscillating or linearly moving part of apparatus, installation, to control its damping or oscillations [1], to ensure a reliable acoustic contact between the object to be tested and the acoustic emitter [2] and etc. Clearly, that hydrodynamic, magnetostatic and capillary phenomena which occur while solid plate is travels through fluid and pulling out film layer, are interesting to study the structure of thin MRS layers and to discove new film effects in applied magnetic field.

There are works, for example [2, 3], where hydrodynamic equations, describing the process of drawing out of a magnetic fluid film from confined volume by plate, travelling with speed V, does not take account of rheologic properties, demagnetizing factor of fluid volume and inertial terms. And this theory is correct for dimensionless speed $Ca = \eta V/\sigma << 1$ only, where η and σ - are viscosity and liquid surface tension. The former problem [4] was analyzed for non-magnetic Newtonian film flowing in wide range $Ca=10^{-3}$ - 10 and for different magnitude of hydrodynamic parameter $\gamma = \frac{\sigma(\eta^4 g)^{-1/3}}{\rho}$. Mass losses of non-magnetic rheologic fluids (γ=0) have been investigated in [5]. We are going to consider the problem of MRS losses, when magnetic field and the volume forces $\vec{f} = \mu_0 M \nabla H$ in fluid and the jump of magnetostatic pressure on the MRS boundary $\Delta P_{M^2} \sim M_n^2$ arise, where M_n - normal component of the MRS magnetization

2 Theory

The results of theoretical research of authors [4 - 5] are used to develop the model of MRF mass losses, which takes account of magnetic field interaction with the surface of film meniscus and of rheologic properties. We consider hydrodynamic and capillary phenomena which accompany the process of retrieving of non-magnetic solid plate from infinitive fluid volume, when V=const and non-homogeneous magnetic field applied. Let infinitive plane plate travels vertically in x direction through MRS volume. Applied magnetic field magnetizes fluid to saturation and magnetization $\overline{M}_S$=const, so that magnetic intensity $\overline{H}$ *(x,y,z)* lines and direction of $\overline{M}_S$ are parallel to plane $x=0$. The plane $x=0$ intersects surface of meniscus at $h=h_s$, where the velocity of fluid particle $u=0$. Quantity of MRS mass losses (or height its film h_0 on moving plate) is determined by interaction of the complex factors, such as magnetic field, speed V , fluid properties. According to [5] there are two part of the fluid volume: the first is range of dynamic meniscus where the velocity of flowing $u \geq 0$ (system of coordinate xy); the second one - $u \leq 0$ – is proper to quasi-static part of the meniscus volume (system of coordinate $x_1.y$). x_1=0 is the plane of the infinitive fluid free surface when magnetic intensity $\overline{H}$ =0. Using the results of evaluation and approximation of inertia, viscous and capillary forces made in [4] and taking account of the effects of magnetic field interaction with magnetized fluid medium [5] the modified hydrodynamic equations and the boundary conditions for two parts of the meniscus volume are.

2.1 Dynamic meniscus

$$\partial \tau / \partial u + \partial x[\rho g x + \Phi] / \partial x - \partial p / \partial x = 0, \quad \partial p / \partial y = 0 \qquad (1)$$

$$p - p_0 = - \sigma d^2h/dx^2 + \Delta P_{M^2} \text{ at } y=h, \quad u=V \quad y=0, \quad \tau=0 \quad y=h, \qquad (2)$$

$$|d^2h/dx^2| \; |dh/dx| \to 0 \quad y \to h_0 \quad \text{for } x \to \infty \qquad (3)$$

where $\Phi = \mu_0 \int_{\infty}^{x} M dH$ - is magnetostatic potential; $\Delta P_{M^2} = 0{,}5\mu_0\ (M_0^2 - M_n^2)$ - *is* an effective magnetostatic pressure difference between the coordinate on the meniscus surface $x_1=0$ and x_1, caused by the jump of the normal component of magnetization at the boundary MF-air.

2.2 Quasi-static meniscus

There are space derivatives of the velocities and stresses much smaller than in zone of dynamic meniscus. Let neglect them in equation (4) and in edge condition (5) and suggest $|\partial H/\partial x_1| >> |\partial H/\partial y|$, and then the surface form of quasi-static meniscus is described by equations

$$\partial [\rho g x_1 + \Phi] /\partial x_1 + \partial p/\partial x_1 = 0, \qquad \partial p/\partial y = 0 \tag{4}$$

$$p - p_0 = -\sigma R_s^{-1} + \Delta P_{M^2} \quad \text{for } y=h, \tag{5}$$

$dh/dx_1 \to -\infty$ for $x \to I$

it is suggested that meniscus surface adjoins to the non-moving plane surface, so that

$$dh/dx_1 = 0 \quad x = x_m \quad \text{for} \quad h = h_0 \tag{6}.$$

It is clearly that if the process of MRS losing is stationary, than

$$Q = \mu_0 \int_0^h u dy = \text{const} = V h_\infty, \tag{7}$$

where h_∞ - is thickness of MRS layer, measured so far from $x_1=0$ that $u=V$ at $y = 0 - h$.

Let the rheologic equation, describing MRS flowing in applied external field, has the order law: $\tau = k\,|\partial u/\partial y|^{m-1} |\partial u/\partial y$, where k and m are constants and

$$G_m = \partial \rho^{-1} \partial [\rho g x + \Phi + \Delta P_{M^2}]/\partial x = \text{const} \tag{8}$$

Than on the base of (1 – 7) and using [4], it is possible to derive relations describing dependence of the MRS thickness vs. external forces, fluids properties and speed of plate for dynamic part of meniscus (9) and quasi-static one (10)

$$Ca_M^{-1} A_{11} (d^3 L_M /dz^3) = 1 - A_{11}\, l_M^{-(2n+1)} [A_{12}(l_M - 1) + A_{13}]^m \tag{9}$$

$$Ca_M^{1/2} A_{21} (L_M^{-1}) = B - (4 - Ca_M A_{22} z_1^2)^{1/2} + 0{,}5\ln[(1 + A_{23} z_1^2)(1 - A_{23} z_1^2)^{-1}]^{1/2} \tag{10}$$

where $=h/h_0$, $z = x/h_0$, $z_1 = x/h_0$, $Ca_M = h_0^{1-m} V^m k/\sigma$, $A_{11} = \xi_M^{--(m+1)}$, $\xi_M = h_0(V^{-m} G_m/k)^{1/(m+1)}$, $A_{12} = 2 + n^{-1}$, $A_{13} = \xi_M^{-(m+1)/m}$, $A_{21} = \xi_M^{(m+1)/2}$, $A_{22} = \xi_M^{-(m+1)}$, $A_{23} = Ca_M\, \xi_M^{m+1}/4$, B – is constant. Using the condition of continuity ("suiting") of the dynamic and quasi-static meniscus surfaces and calculation procedure [4] it is possible to find dependence of the MRS film thickness $\xi_M = \xi_M (Ca_M)$.

G_m evaluation. As follows from the theoretical analysis, for example [4], the meniscus surface form influences the MRS mass losses essentially in wide range of Ca_M and for h_0/x_m. <<1. Let analyze functions $\Phi (x_1)$ and $\Delta P_{M^2} (x_1)$. In accordance with conditions of magnetic field application, (mentioned above), it is possible to show that the more substantial ΔP_{M^2} and Φ variations are for $x_1=0 - x_m$. It is in this part of fluid volume the more intensive hydrodynamic and energy dissipation processes occur. Clearly, that there is impossible to solve the problem exactly because of complicated character of the the meniscus formation in applied magnetic field and its influence on hydrodynamic processes in MRS layer. That is why we simplify the problem according to equation (8) and assume, that

$$G_M = g + (\mu_0 \Delta H + \Delta P_{M^2})/\rho x_m = g + G_{M1} + G_{M2} = g + P_m/x_m = g + G_{M1}(1 + \varepsilon) \tag{11}$$

where ΔH - magnetic field difference between coordinate $x_1=0$ and x_m. in MRS; G_{M2} is caused by field of fluid magnetization; $G_{M1} = G_M$, when $g = G_{M2} = 0$. Using (11) and the former mentioned suggestions in regard of magnetic field. it is possible to show that $\vec{G}_M$ is function of the angle φ between $\overline{H}$ and the normal vector $\vec{N}$ to plane of the plate surface and

$$G_M\rho x_m \approx [1/2\mu_0(\overline{M}_S\vec{N})^2 + \mu_0 M_S\left\{H_{x_1=0} - \left[(H_{1y} - (\overline{M}_S)_y + H_{y2})^2 + H_{x2}^2 + (H_{z2} + H_{z1})^2\right]^{0,5}\right\}] \quad (12)$$

where $H_{1y} = H_y$ for $x_1 = x_m$. The method of surface "magnetic charges"[5] is used to find inducted magnetic intensity H_2 - by integration of magnetic field caused by magnetic charges ζ on the boundary surface MRF-air and MRF-plate. So that magnetic intensity inducted by effective "magnetic charges" on curved meniscus volume is $\sum_{i=1}^{i_0} I_i(x_m,\varphi)$ and G_M can be presented

$G_M = G_{M1}\{2[(1+T_M^2)^{0,5} - 1]^{-1} + 1\}$, (13)

where $G_M = G_{M1}$ if $M_S = 0$, $T_M^2 = 8\,\sigma\mu_0^{-2}\,G_{M1}\,\kappa_0^{-2}\,M_S^{-4}$; $\kappa_0 = \kappa_0(h_m, \varphi, \kappa_i, l_0)$, K_i - integral coefficients to characterize components of demagnetizing field.

If meniscus is alone (i_0=2) - there are two "charged" surfaces, if thin plate is retrieving through MRS - i_0=4. To simplify calculations, we suggest too that static meniscus surface ($0 < x_1 < x_m$) has curvature $\rho' = x_m^{-1}$ which coincides with the average meniscus curvature. $\tilde{\rho}' = \left(\int_0^{x_m}\frac{dx}{R}\right)/x_m \approx x_m^{-1}$ if G_M=const.

It follows from (11 - 13), that magnitude of an effective additive pressure gradient in the MRS, caused by meniscus demagnetizing factor, is close $G_{M2} \cong G_{M1}$ when

$$M_S \approx 32^{1/6}\left(\sigma\left|\nabla H_1\right|_x\right)^{1/3}\mu_0^{-1/3}k_0^{-2/3}$$

According [3] if $Ca_m \ll 1$ then $h_0 \sim (\tilde{\rho}')^{-1} \sim x_m$ and

$$\Omega = m_{\varphi=0}/m_{\varphi=\pi/2} \approx h_{0\varphi=\pi/2}/h_{0\varphi=0} \approx \left\{\left[T_M^{-2} + 1\right]^{0,5} - T_M^{-1}\right\}.$$

The results shown in fig. 1 are obtained using this method to calculate G_M

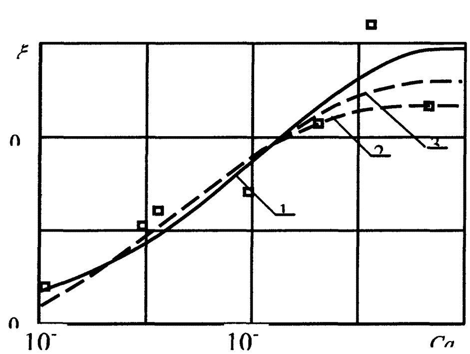

Fig. 1. The plot of $\xi_M(Ca_M)$. - Theory (1 - 3) and experiment ( ). n=1 (1); 0,84 (2); 0,56 (3). Sample - magnetic fluid.

3 Experimental methods

To check the theory and to find the dependencies of mass loss of MRS m_o against the velocity of moving solid surface and magnitude and direction of magnetic field the special installation was designed. Elastic metallic strip is retrieving from the fluid volume with the controlled speed $(0,5 - 250)10^{-3}$ m/s. Device H331 is used to pull the strip If a specimen of magnetic fluid used the strip is moving in horizontal direction through its volume held between two parallelepiped magnets polarized in opposite direction. So, $g=0$ $|\nabla H_x|=1,76\times10^7$ A/m^2, $H=1,04\times10^5$ A/m and they are measured in vicinity of coordinate $x=0$ $y=0$ when $H=0$.
Influence of direction and magnitude of the homogeneous external field lines on suspension (and magnetic fluid) mass losses is studied for conditions when metallic strip moves through mediums in vertical direction ($g\neq0$) and fluid is in cylindrical container with diameter D=0,08 m. Fluid height is 0,015 m. As our previous experiments show the more accurate method of MF mass measurements is the method of weighting. So, the specific mass loss m_o and the height of the fluid layer h_∞ for $x \to \infty$ are determined: $m_o = (m_2 - m_1)/2$; $h_\infty = m_o/\rho$, where m_1 and m_2 – weights of strip before and after movement through MRS.
The source of controlled magnetic field is a pair of two wire coils. To check (qualitatively) magnetic field influence on magnetic fluid meniscus form the automatic system of visualization is used. It consist of special video-camera with computer. The discrimination of this system is 10^4 points per 1mm^2.
Two samples of fluids were used in experiment: magnetic fluid on transformer oil and magnetic volume concentration q =23,2 % ; a sample of magnetorheological suspension (q=8%) on the oil base. Rheologic properties of concentrated MF (q=23,2 %) in applied magnetic field were measured by A. Reks (BSPA Minsk) from which rheologic constants k and n were found. Calculated and mentioned above parameter γ_M for characteristic magnitude of the velocity gradient ϖ is close to zero.

4 Experimental results and discussion

Some basic results of research are illustrated by fig. 1 - 3. The laboratory findings show good qualitative agreement with the modified theory. Our more accurate calculation of the meniscus surface formation on the base of suggested simplified model, gives, as a rule, the difference between calculated magnitude of ξ_M and experimental data 10 - 15% when Ca_M from $(2 \div 3)\times 10^{-3}$ and up to $1\div2$ This difference is not higher 20 - 25% at whole experimental range Ca_M and has maximum for Ca_M>1. It can be explained by necessity to have more accurate physical model of the processes to study. For example, to use a more accurate approximation of the rheological law and take account of the peculiarity of the meniscus formation in applied magnetic field. As seen in fig.2, and follows from experiment, mass losses of magnetic fluid (and suspension used) are function of the angle between field lines and normal vector to plate surface retrieving from fluid.

It is shown that that magnitude of parameter $\Omega = m(\varphi)_{=0} / m_{\varphi=\pi/2}$ is increasing function vs. φ and can be 10 and more. As for function $m_d(H) = m/m_0$, it is decreasing one when $\pi/2 > \varphi^* > \varphi > 0$. And magnitude of φ^*, in turn, depends on Ca_m. If $\varphi = \pi/2$ - $dm_d/dH > 0$.

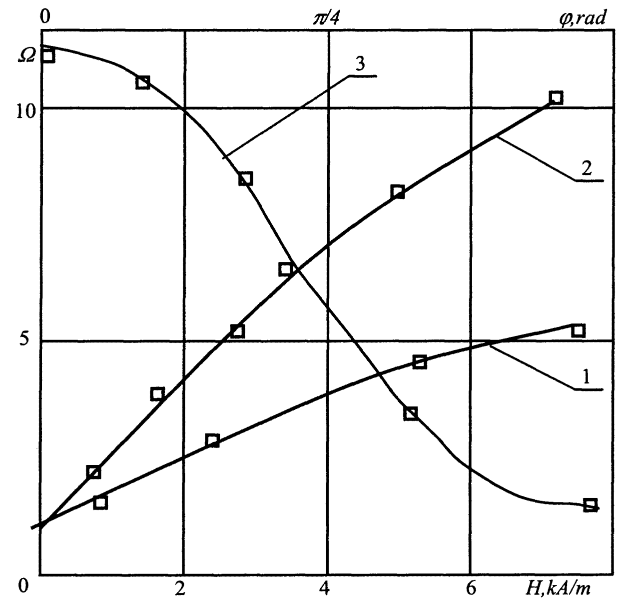

Fig. 2. The plot of $\Omega(H)=h_{0\varphi=\pi/2}/h_{0\varphi=\pi/2}$ (curves 1÷2) and $\Omega(\varphi)= h_0/h_{0g\neq0}$ - 3.
V, 10^{-2} m/s =0,5 - 1, 3; 2,5 - 2.

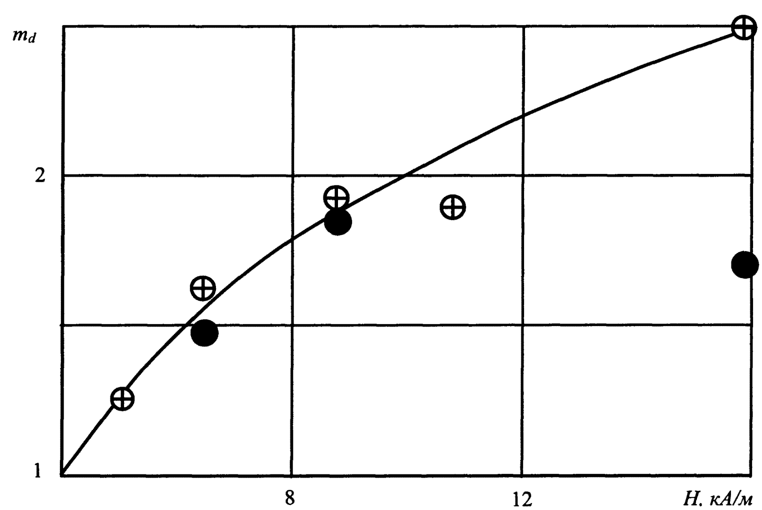

Fig. 3. The plot of $m_d(H)= m/m_0$. Sample – magnetorheological suspension.
V,10^{-4} m =1 (⊕); 10 (•).

This effect may be explained by predominant increasing of the fluid viscosity under action of magnetic field (primary homogeneous) [6]. In respect of ferromagnetic suspension used, function Ω (φ) is decreasing one when speed V is not high (10^{-4} - 10^{-3} m/s), but m_d increases predominantly vs. *H*. It shows that the viscous effect in applied field is more substantial than meniscus one. So we can conclude that the character of Ω (φ) and $\xi_M(Ca_M)$ behavior depends on concurrence of two effects: meniscus deformation, changing hydrodynamic resistance to film flow, while fluid is retrieving from the volume; variation of the viscosity properties under action of magnetic field.
These effects are to be taken into account while constructing of arrangements. As qualitative experiments show, a thickness of MF film on moving cylindrical objects is function like sinusoid against the angle ϕ - between direction of magnetic lines and direction of the object radius. Using dependence $\xi_M(Ca_M)$ it is possible: to use the developed method of "fluid film losses" to study the rheologic fluid properties; to measure speed and vector of acceleration of moving objects, measuring height of magnetizing fluid by electromagnetic or optic method.

5 Conclusions

Using the results of the theoretical research [3, 4], we develop a new aspects of the film flowing of magnetized fluids with rheologic properties in applied magnetic field.
To check the proposed theory which takes into account of rheological properties and interaction of magnetic field with film meniscus the experimental study has been made.
The obtained research results have shown:
qualitative agreement between experimental data and theory in wide region of plate velocity moving;
substantial dependence of mass losses *m* v.s. angle φ between direction of magnetic field lines and the normal vector to moving solid surface. For example, for concentrate MF
$m^* = m_{\varphi=0} / m_{\varphi=\pi/2}$ can be 5 -10 and more. If the sample is MRS- $m^* < 1$.
It is proposed to use the method of retrieving film to investigate and check the rheological properties of magnetorheological suspensions and magnetic fluids. The obtained results can be used to measure cinematic characteristics of moving systems and another practical applications.

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