Int. J. Multiphase Flow, Vol. 1, pp. 607–622. Pergamon Press, 1974. Printed in Great Britain.

THE EFFECT OF A MAGNETIC FIELD ON THE RHEODYNAMIC BEHAVIOR OF FERROMAGNETIC SUSPENSIONS

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(*Received* 20 *November* 1973)

Abstract—In this work a simplified analytical model and the results of an experimental investigation of the influence of an external magnetic field on the rheological characteristics of a suspension of iron particles in silicon oil is presented. The particles of iron were approximately of a circular shape, from 3 to 5 μm, with a maximum concentration of 10^{10} particles/cm^3. The viscosity of the carrying fluid varied from 80 to 240 cP.

The experimental channel was located in a closed circuit of forced circulation of the ferromagnetic suspension. The entire length of 750 mm was placed in an area of a homogeneous magnetic field, with the velocity vector of the suspension being perpendicular to the direction of the magnetic field. The strength of the magnetic field could be changed continually from 0 to 9000 G.

The results obtained are shown in the form of parametrical dependencies of the rheological characteristics of the ferromagnetic suspension. With that, the concentration of the solid phase of the suspension is parametrically changed, along with the strength of the external magnetic field and the viscosity of the carrying fluid.

In the range of parameters studied, the external magnetic field leads to a Bingham character of behavior of the ferromagnetic suspension.

INTRODUCTION

The present investigation of hydrodynamic properties of ferromagnetic suspensions can be divided into two main areas. The first is concerned with the study of suspensions with small and single-domain ferromagnetic particles (100–400 A) and with a volumetric concentration of 0·1 per cent. Stable suspensions, which have unconventional properties and great possibilities for practical application, can be obtained with a proper selection of the carrier and the coated particles. The viscous property of this kind of fluid has been extensively investigated by Rosensweig, Kaiser & Miskolczy (1969); McTague (1969); Hall & Busenberg (1969); Zaitsev & Shiomis (1968, 1969). Special attention has been paid to the magneto–caloric effects by Luikov, Berkovsky & Bashtovoi (1972) and also to the possibility of using ferrofluids for direct conversion (Resler & Rosensweig 1967) and (Nearinger & Rosensweig 1964). The main conclusions from these analyses have been based on the assumption of low concentration of ferromagnetic particles which allows the

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neglecting of hydrodynamic and magnetic interaction between the particles. By this, the effect of the external magnetic field and of the viscous characteristics of ferromagnetic suspensions has become the mechanical interaction of a single magnetized particle and the magnetic field. This has resulted in the increase of kinetic energy dissipation of the carrying fluid and the suspended particles. From the hydrodynamic point of view, this problem is only a correction of the Einstein relation for the determination of the viscosity of a diluted suspension. For this domain of volumetric concentration, the ferromagnetic suspensions have Newtonian characteristics. Nevertheless under some conditions it is possible to increase the viscosity of the fluid.

The second direction of investigation of the hydrodynamic properties of ferromagnetic suspensions is related to a higher concentration of ferromagnetic particles, with the size of the particles being an order of magnitude larger than the particles in previous studies. This paper is also devoted to this kind of ferromagnetic suspension. For ferromagnetic suspensions with this property, the influence of the external magnetic field leads to an interaction of magnetized particles as magnetic dipoles. As a result of this interaction, under certain conditions the suspension becomes "solidified", i.e. the formation of a dipolar structure. Viscous forces in the carrier of the suspension tend to destroy this structure, which results in the non-Newtonian behavior of ferromagnetic suspensions under the influence of an external magnetic field.

SIMPLE ANALYTICAL MODEL

The analytical model of the rheological behavior of a ferromagnetic suspension under the influence of an external homogeneous magnetic field is based on the assumption that the solid particles, as a result of mutual interaction, exhibit a spontaneous tendency towards "structure formation". That is the particles form a chain like structure. The configuration and rigidity of the structure will depend on the strength and distribution of the external magnetic field, the concentration of the particles in the suspension, the type of ferromagnetic particles, and the viscosity of the carrier. The rigidity of the structure is characterized by the binding energy which originated from the magnetic energy of the particles, and it is equal to the work performed by attracting forces between the particles in the process of structure formation.

With the assumptions that the particles are spherical and made from homogeneous linear magnetic materials and that the external magnetic field is stationary and homogeneous, the magnetic field and induction in the particles are given by Surutka (1971) as follows:

$$H_i = \frac{3}{\mu_r + 2} \cdot H_o \qquad [1]$$

and

$$B_i = \mu_r \mu_o H_i = \frac{3\mu_r}{\mu_r + 2} \mu_o H_o, \qquad [2]$$

where H is the magnetic field, μ is the relative magnetic permeability, and B is the magnetic induction.

Since $B_i = \mu_o(H_i + M)$, the density of magnetic momentum in the volume of a sphere, is given by

$$M = \frac{3(\mu_r - 1)}{\mu_r + 2} \cdot H_o \qquad [3]$$

and the total magnetic momentum of spherical particles is

$$m = \frac{d^3\pi}{6} M = \frac{d^3\pi}{2} \cdot \frac{\mu_r - 1}{\mu_r + 2} \cdot H_o \qquad [4]$$

with d being the diameter of the particles.

The potential energy of the "free" magnetic dipoles in the center of a sphere through the space around the sphere is shown by Whitmer (1961) to be as follows:

$$W_i = \frac{6\mu_o m^2}{\pi d^3} = \frac{3d^3\pi}{2} \cdot \frac{\mu_r - 1}{\mu_r + 2} \mu_o H_o. \qquad [5]$$

This potential energy of "free" dipoles is ununiformly distributed in the space surrounding the particles. At the surface of the spherical particles in the direction of the dipole, the energy is a maximum and is defined by

$$W_{\max} = \frac{9}{2} \cdot \left(\frac{\mu_r}{\mu_r + 2}\right)^2 \mu_o H_o \qquad [6]$$

and at the equatorial part of the particle surface, its magnitdde decreases to

$$W_{\min} = \frac{9}{2}\left(\frac{1}{\mu_r + 2}\right)^2 \cdot H_o^2. \qquad [7]$$

Assuming that the magnetization process is faster than the mechanical process in the carrier fluid, the magnetic poles of particles will be independent of mechanical movement, so that they will always be placed in the direction of the external magnetic field. This is a fundamental difference between this model and the models given by McTague (1969); Hall & Busenberg (1969); Brenner (1970); Brenner & Weissman (1972) which assume the particles as permanent magnets. From this assumption it is possible to draw the following two conclusions. First, the single "free" particle from "soft" magnetic material in the viscous flow is not affected by mechanical forces in the external magnetic field. Second, the formation of the magnetic dipolar structure in the suspension will be possible only when magnetic forces between the dipoles are larger than the viscous forces in the carrier flow. When the structure is formed, it should be in the form of the chain with the main axis in the direction of the external magnetic field. This form of the structure is a result of the distribution of potential energy around the dipoles, given by [6] and [7].

It should be pointed out that the structure of dipoles contained also the corresponding volume of the carrier, forming cells which resemble a weaved, porous structure filled by the

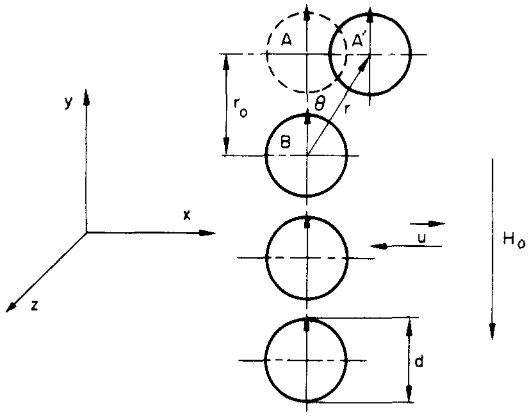

Figure 1. Suspension model at onset of the destruction of the chain structure.

fluids. If we consider a cross-section of the structured suspension perpendicular to the direction of the external magnetic field, the number of the chains per unit surface with the volumetric concentration of magnetic dipoles will be

$$n_2 = \frac{\Delta N_2}{\Delta S} = \frac{6\alpha}{d^2\pi} \qquad [8]$$

where α is the volumetric concentration of the ferromagnetic particles.

Any single chain of dipoles in the velocity field of the suspension which corresponds to our experimental condition, i.e.

$$u_x = u_x(y), \qquad u_y = u_z = 0 \qquad [9]$$

with the external magnetic field acting in the direction of the y-axis, the structures will be destroyed by the sufficiently high, shear strain acting on it. Considering the case of the beginning of the destruction of the chain structure, as it is shown in figure 1, the distribution of magnetic potential energy between dipoles A and B takes the form:

$$w = \frac{\mu_o}{4\pi} \cdot \frac{m^2}{r^3} (1-3\cos\theta). \qquad [10]$$

The force acting to prevent particle A from breaking off of B in the chain of dipoles is

$$F_i = \frac{\mathrm{d}w}{\mathrm{d}r} = \frac{\partial w}{\partial r} + \frac{\partial w}{\partial \theta} \cdot \frac{\partial \theta}{\partial r} \qquad [11]$$

where w is the binding energy.

If consideration is taken of the conditions for the velocity field [9], it follows in polar coordinates that $r\cos\theta = r_o$. Thus, we obtain

$$F_i = \frac{3\mu_o m^2}{4\pi r_o^4} \cos^4\theta \, (5\cos^2\theta - 1). \qquad [12]$$

For the dipolar chain structure, it can be assumed that $\theta = 0$ and $r_o = d$, so that the force F_i acting in the plane x–z will be

$$F_i = \frac{3\mu_o m^2}{\pi d^4}. \qquad [13]$$

In this case the total magnetic force which is reacting in the plane x–z per unit surface will be the magnetic component of shear stress. From [13] and [8], it may be written that

$$\sigma_o = n_2 F_i = \frac{9}{2}\left(\frac{\mu_r - 1}{\mu_r + 2}\right)^2 \mu_o \alpha H_o^2 \qquad [14]$$

where σ^o is the magnetic component of the shear stress.

It is important to emphasize that σ_0 is the only component of magnetic force for the considered velocity distribution in the suspension and external magnetic field. This force acts only as a result of the destruction of the thread structure of the dipoles.

A viscous shear stress in the x–z plane exists, in a liquid simultaneously with the destruction of the thread structure of dipoles, as a consequence of the velocity profile in the suspension, which is given by

$$\tau_s = \eta_s \left(\frac{\mathrm{d}u_x}{\mathrm{d}y}\right) \qquad (\eta_s = \text{viscosity}). \qquad [15]$$

It is assumed that after the destruction of the dipolar structure for the relatively small concentration of solid particles in the suspension, the Newtonian behavior of the suspension will be established with the Einstein correction for viscosity.

From this analysis it follows that the total shear stress in laminar flow of a ferromagnetic suspension is given by

$$\tau = \sigma_o + \tau_s = \frac{9}{2}\cdot\left(\frac{\mu_r - 1}{\mu_r + 2}\right)^2 \mu_o \alpha H_o^2 + \eta_s \left(\frac{\mathrm{d}u_x}{\mathrm{d}y}\right)_w. \qquad [16]$$

Keeping in mind the physical picture of the magnetic component of the shear stress, it can be assumed that it depends on the existence but not on the rate of shear strain. This component defines the condition at which formation of the magnetic dipole structure is possible. It means that at the surface which divided the structured part of the ferromagnetic suspension from the part where there is no structuring, the following condition should be

$$\text{as} \quad \frac{\mathrm{d}u_x}{\mathrm{d}y} \to 0, \quad \tau \to \sigma_o. \qquad [17]$$

From the rheodynamic point of view, [16] shows that the ferromagnetic suspension under the effect of an external magnetic field behaves as a Bingham fluid.

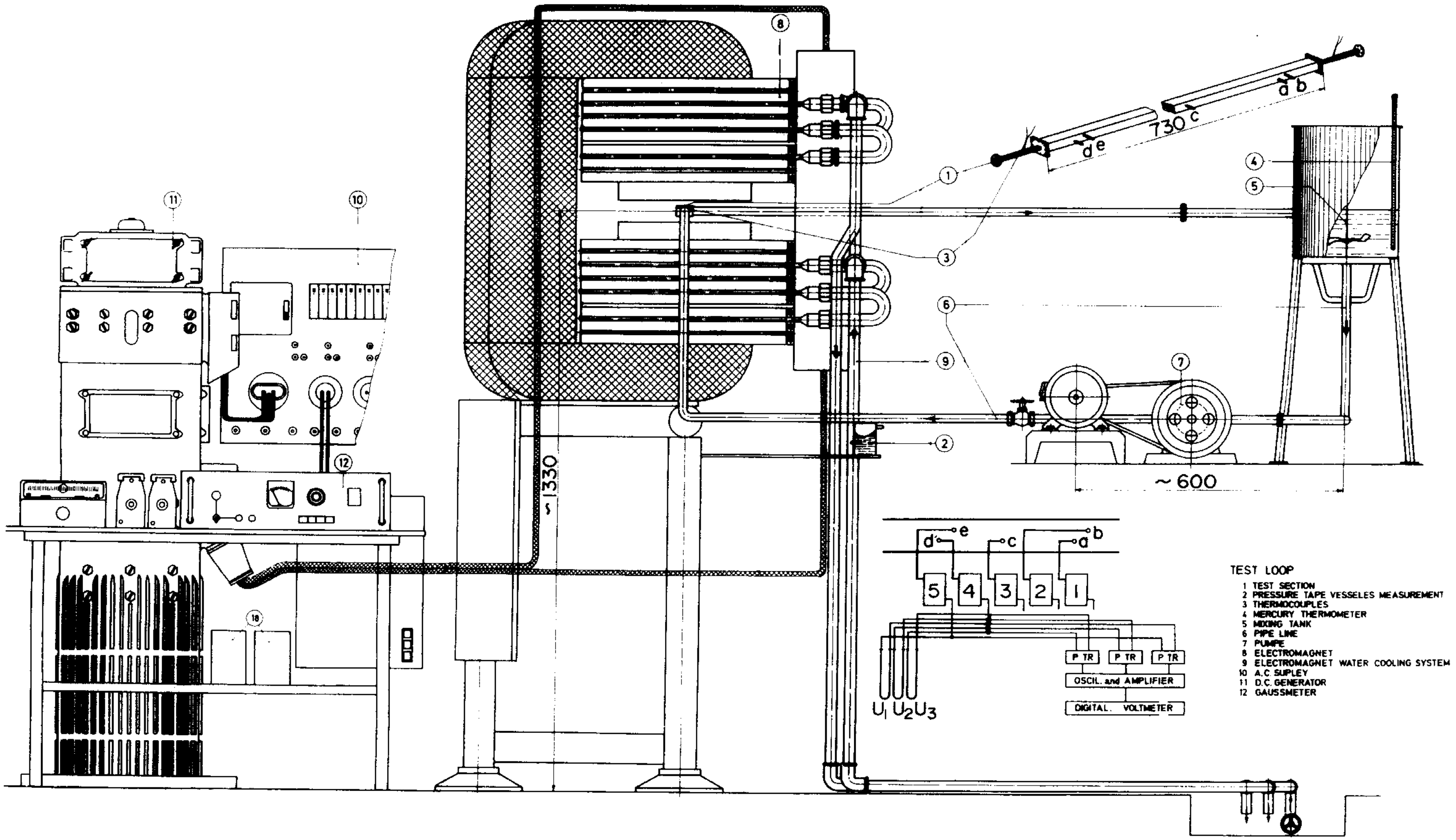

Figure 2. Experimental apparatus.

EXPERIMENTAL INVESTIGATION

Description of the experimental apparatus and measurement

The experimental apparatus is shown in figure 2. It consists of two main assemblies of components. One assembly is used for obtaining the prescribed magnetic field, and the second assembly is a circulation loop with corresponding measurement systems. The magnetic field space was 800 × 200 × 50 mm with a continuous change from 0 to 9000 G. The circulation loop consists of the following components: horizontal experimental channel, circulation pump, reservoir with a mixer for homogeneity of the suspensions, tubing and corresponding measuring elements. The experimental channel is 750 mm long (L) with a rectangular flow cross-section of $20 \times 2\,\mathrm{mm}^2$ made from plexiglass (figure 2). The channel was placed with the full length in a homogeneous magnetic field. The width of the channel (2a) is perpendicular to the direction of the magnetic field. The distance between the pressure taps was 150 mm along the channel length.

For each flow regime, the following measurements were performed:

—Volumetric flow rate (V) of the suspension was determined in the range from 3 to 50 cm^3/sec by a volumetric method with an accuracy of $\pm 0.2\,\mathrm{cm}^3$/sec.

—Volumetric concentrations of the solid phase in the suspension, which was determined by a gravimetric method in the range from 0.5 to 5 per cent vol with an accuracy of ±0·05 per cent vol.

—Inlet and outlet temperature of the suspension (t) in the range from 20° to 40°C with an accuracy of ±0.3°C.

—Pressure drop along the experimental channel (Δp) was determined by a differential method. The location of the pressure taps is shown in figure 2. The pressure difference was measured between 0–1500 mm Hg with an accuracy of 1 mm Hg.

—Intensity of the magnetic field was measured with a gaussometer. In the range from 0 to 1000 G the accuracy was ±5 G.

All measurements were performed in a steady state condition. All measurements presented in this paper include only those flow regimes where fully developed hydrodynamic flow was proven by the equality of the pressure drop in both halves of the experimental channel.

Experimental results

Three series of measurements were performed. The first series of measurements includes the measurement with water, transformer oil, silicon oil DM-100, silicon oil DM-300. From these measurements, the theoretical relation of $f = f(\mathrm{Re})$ was obtained. The characteristic length in the Reynolds number and the friction factor was the hydraulic diameter. This shows a satisfactory accuracy of the measuring methods and also the reproducibility using different fluids. The relation $f = f(\mathrm{Re})$ is shown in figure 3. It can be seen that all

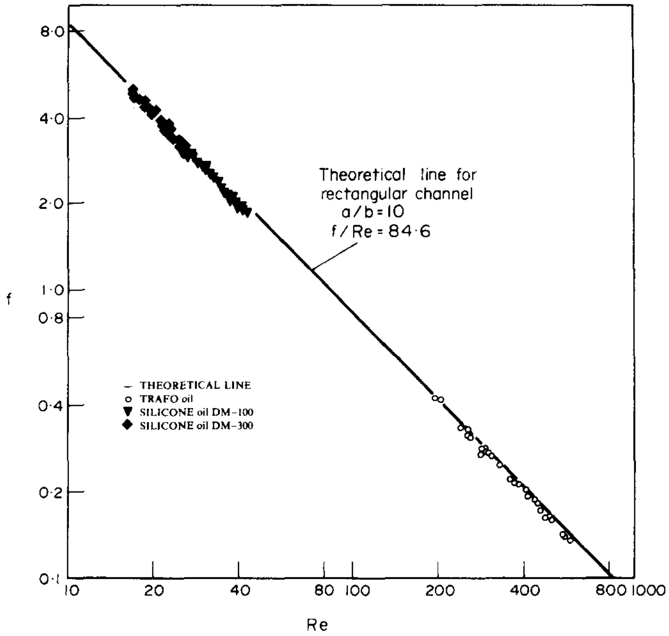

Figure 3. Friction factor vs Reynolds number—no magnetic field.

experimental measurements obtained in the entire length of the channel and also in both halves of the channel are about 3 per cent lower than the theoretical line which corresponds to the channel of rectangular cross-section with the ratio (width/height) $a/b = 10$. It can be assumed that the difference is a result of an error in the determination of the channel width. The actual channel width should be 0.03 mm larger than was used in the calculation, $2b = 2$ mm.

The second series of measurements were made with iron powder suspended in silicon oil DM-100. The diameter of the spherical particles of the powder were in the range 3–5 μm and viscosity of the carrier was $\eta_c = 80$ cP. The volumetric concentration of the solid phase in the suspension was between 0 and 5 per cent vol. The magnetic field intensity was changed from 0 to 600 G.

The third series of measurements was the same as the second but with a different carrier. The carrying fluid in this series was silicon oil with a viscosity of $\eta_c = 240$ cP. By using a carrier with larger viscosity the effect of the carrier viscosity on the rheological characteristic was studied. Also this offered the possibility to simulate the temperature effect on the suspension flow characteristics under the given experimental conditions.

The Manny–Rabinowitsch method was used for the identification of the rheological characteristics of the fluid. In this procedure the following conditions were assumed:

—steady laminar suspension flow;

—uniform temperature;

—no slip at the channel wall;

—uniform concentration of the particles in the suspension flow.

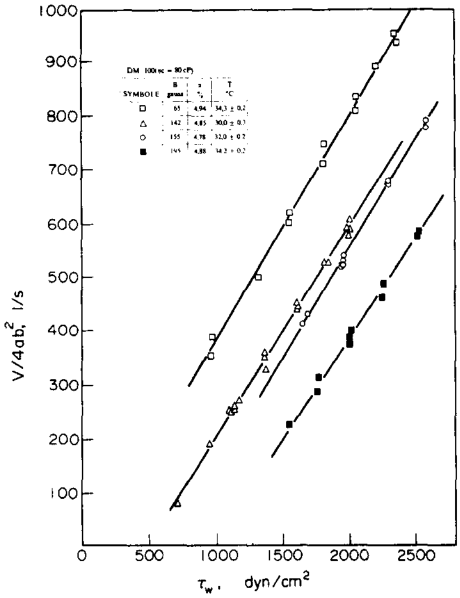

Figure 4. The quantity V/ab^2 vs wall shear for various magnetic field intensities.

With these assumptions, the suspension velocity field in the experimental channel can be described by [9]. On the basis of the Manny–Rabinowitsch method, the shear rate of the wall of the experimental channel is of the following form

$$\left(\frac{\mathrm{d}u_x}{\mathrm{d}y}\right)_w = F(\tau_w) = 2\cdot\frac{V}{4ab^2} + \tau_w\cdot\frac{\mathrm{d}\left(\dfrac{V}{4ab^2}\right)}{\mathrm{d}\tau_w}. \qquad [18]$$

By the measurement of the pressure drop in the channel, the shear stress can be determined using the relation

$$\tau_w = \frac{ab}{(a+b)L}\cdot\Delta p. \qquad [19]$$

Since the determination of the shear rate by relation [18] requires knowledge of $\mathrm{d}(V/4ab^2)/\mathrm{d}\tau_w$ all experimental results were presented in the form of relation $V/4ab^2 = f_1(\tau_w)$. One example of this relation is given in figure 4. This data corresponds to the suspension of iron particles in silicon oil DM–100. The concentration of the particles is $\alpha = 4.9$ per cent vol. The intensity of the magnetic field is 65, 142, 155 and 195 G. It can be seen that the experimentally obtained results for B = const. show a linear relation between $V/4ab^2$ and τ_w. It is interesting to note that the slope of the line with B = const. does not depend on the intensity of the magnetic field. The intensity of the magnetic field affects only the translation of the line $V/4ab^2 = f_1(\tau_w)$ in the direction of shear stress increase.

The linearity obtained between $V/4ab^2$ and τ_w simplifies the procedure for determining the relation between the shear stress and the shear rate, i.e. $\tau_w = f_2(e)$ with α, B and t =

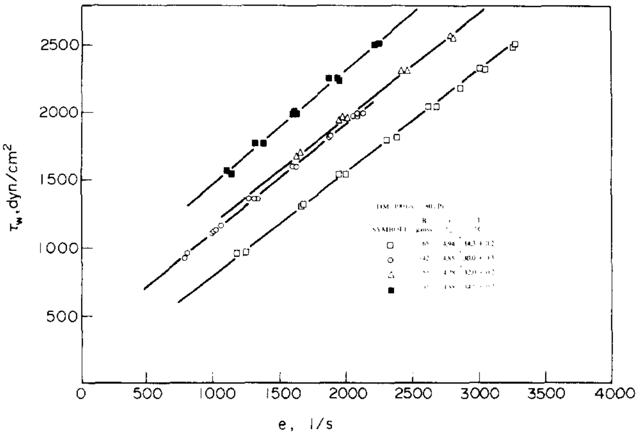

Figure 5. Wall shear vs shear rate for various magnetic field intensities.

const. By using experimentally obtained values of $V/4ab^2 = f_1(\tau_w)$, as shown in figure 4, the relation $\tau_w = f_2(e)$ was deduced and shown in figure 5. As a result of the linearity discussed above and [18], this dependence will be linear for all ferromagnetic suspension considered in this paper.

It can be seen that the shear stress to shear rate dependency for the different magnitudes of the intensity of the magnetic field and for a constant volumetric concentration of solid particles represents a family of parallel lines shifted with an increase of magnetic field intensity. For the stronger magnetic field the shear stress to shear rate dependency is shifted to the region of higher shear stress. The shear stress to shear rate dependencies for the suspension of solid iron particles in silicon oil DM–300 are given in figure 6. The character

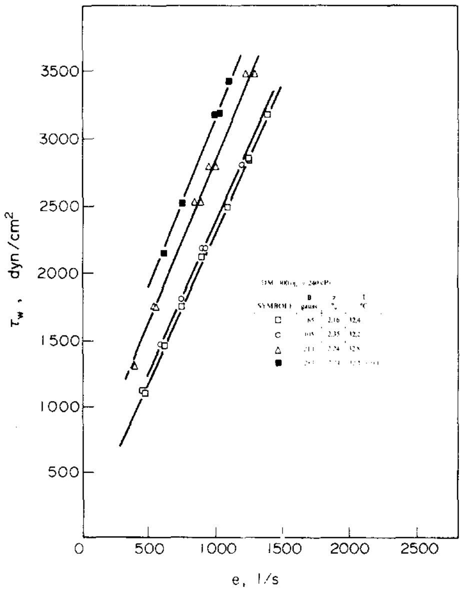

Figure 6. Wall shear vs shear rate for various magnetic field intensities.

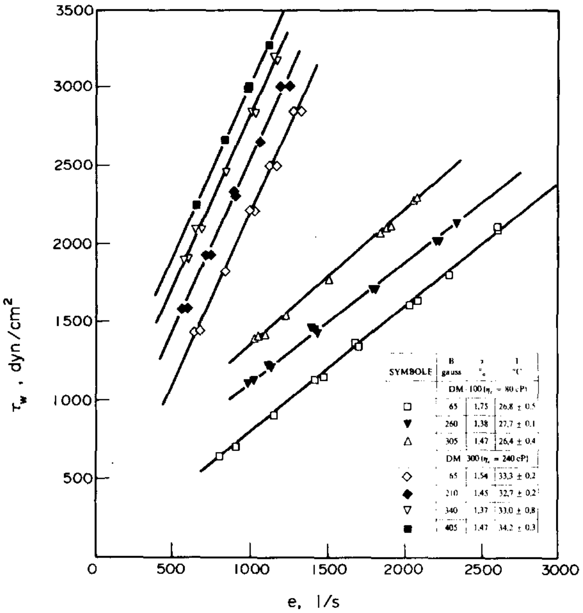

Figure 7. Wall shear vs shear rate for various magnetic field intensities and two different carriers.

of this dependency is the same as in figure 5. It is interesting to note that the increase of the carrier viscosity by a factor of three results only in a corresponding increase of the flow curve gradient. This is clearly shown in figures 7 and 8, where the effect of volumetric concentration on the flow curve is presented.

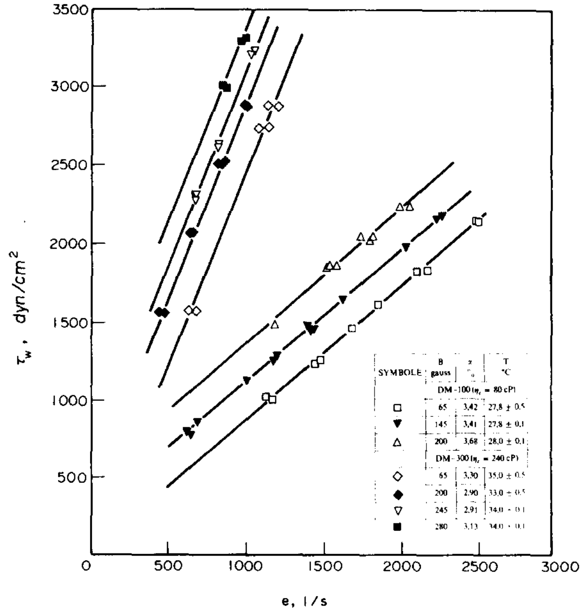

Figure 8. Wall shear vs shear rate for various magnetic field intensities and two different carriers.

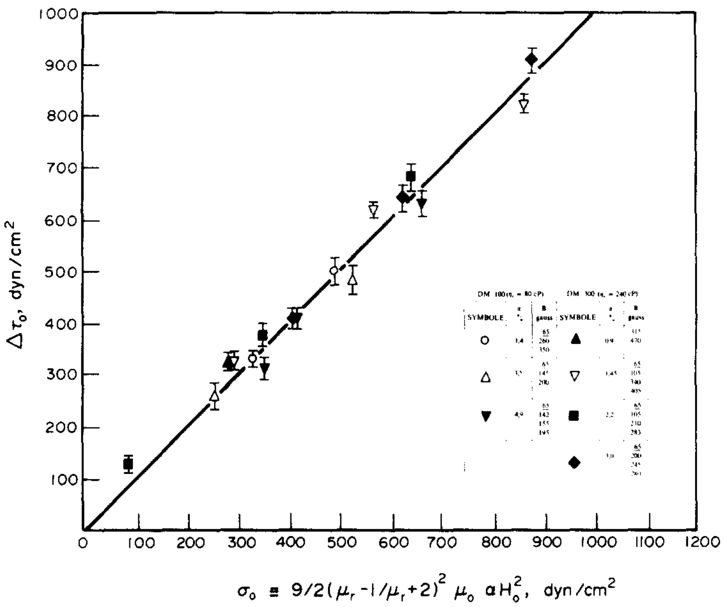

Figure 9. Shear stress changes vs magnetic component of the shear stress.

A comparison of the experimental results with the analytical model is given in figures 9–12. Within the limits of ±15 per cent the proposed analytical model corresponds to the experimental results.

DISCUSSION OF THE RESULTS

The analysis of the assumptions included in the model and also in the method of the intensification of the rheological characteristics require some clarification about their effect on the results.

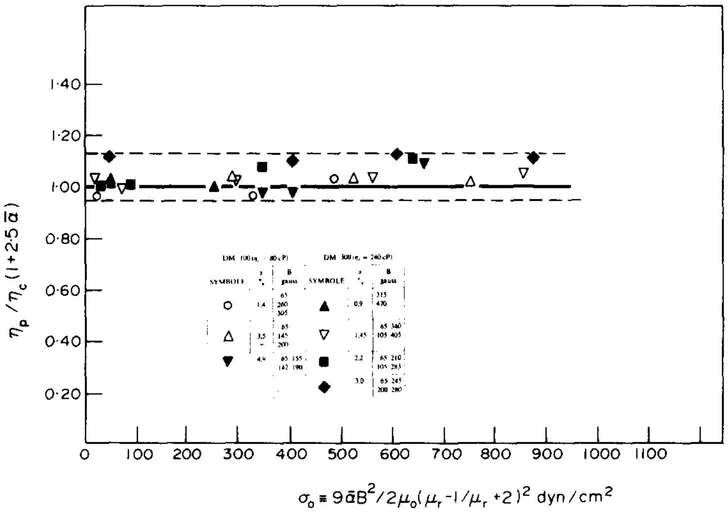

Figure 10. Viscosity ratio vs magnetic component of the shear stress.

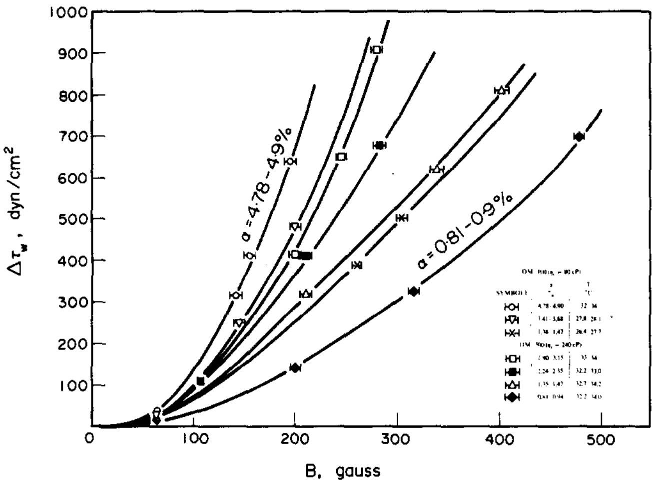

Figure 11. Wall shear stress changes vs magnetic field intensity.

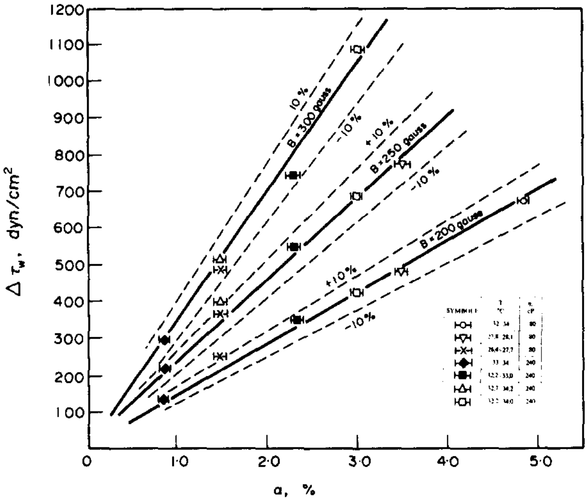

Figure 12. Wall shear stress changes vs volumetric concentration at different magnetic field intensities.

1. The large difference in specific weight between the solid particles (ρ_{Fe} = 7.8 g/cm^3) and the carrier fluid (ρ_c = 0.965 g/cm^3) requires the analysis of the effect of the sedimentation of solid particles in the horizontal channel flow. Taking into consideration that the sedimentation rate mainly depends on the shape and geometry of the particles, the viscosity of the carrier and the concentration of solid particles, it was shown that the sedimentation velocity of a particle with a diameter $d = 3.5$ μm in silicon oil DM–100 (η_c = 80 cP) is $u_{sed} = 0.6 \cdot 10^{-4}$ cm/sec respectively $u_{sed} = 0.2 \cdot 10^{-4}$ cm/sec in silicon oil DM–300 (η_c = 240 cP). Assuming that in the whole length of the experimental channel particles will not move in a vertical direction at a distance larger than the diameter of the particles, we can establish that the flow velocity must be $u_{s_{min}}$ = 10 cm/sec to allow the sedimentation

velocity to be neglected in our consideration. It is obvious that this can also be applied to the chain of structurized particles affected by the magnetic field.

2. Due to the "structure formation" of the solid particles in the suspension, it is necessary to insure that the velocity profile remains the same along the experimental channel. In order to take this into consideration, the design of the channel and the selection of the position of the pressure taps were such as to ensure this uniformity along the channel. In connection with this, the entry length was $L/De = 240/4 = 60$ and was also placed in the same magnetic field. The pressure drop was measured in the two independent halves of the channel. The fact that the pressure drop was the same in both halves indicated that not only was the entrance effect negligible but also the velocity profile was remaining the same.

3. In the case when a structured formation of the ferromagnetic suspension is achieved, the physical significance of the homogeneous distribution of ferromagnetic particles is in question. The assumption of the uniformity of the distribution of ferromagnetic particles is important because the formation of the structure takes place only when certain conditions are fulfilled. The distribution of the dipole chains in the flow is uniform. This means that the average volumetric concentration of the ferromagnetic particles is the same before and after structure formation.

4. A ferromagnetic suspension represents a specific type of two-phase flow with the possibility of an internal degree of freedom, i.e. relative movement between the phases. If a single particle is considered in the stream of viscous fluid, rotation of the particle is possible. In this respect a ferromagnetic suspension is the same as an ordinary suspension. The specific feature of a ferromagnetic suspension can be envisaged when the structure formation process is attained. For a high intensity of the magnetic field and a higher concentration of magnetic dipoles in the suspension, a slip of the carrier in relation to the formed structure is noticed. A possible explanation of this effect can be found in the hydrodynamic interaction of the dipole structures. This was the reason that the measurements were performed only with a maximum magnetic field intensity of $B = 600$ G.

5. Keeping in mind the Weiss theory of magnetization of ferromagnetic materials, we should discuss the validity of the assumption of the magnetization of ferromagnetic particles. From the point of view of the Weiss theory, the ferromagnetic particles are of polydomain character and the determination of the number and distribution of domains in the spherical particle is practically impossible. Thus the assumption of the homogeneous magnetization of the spherical particles was accepted. Nevertheless, it is obvious that it limits the model presented regarding the size of ferromagnetic particles.

CONCLUSIONS

The results of the experimental study of the rheological behavior of a ferromagnetic suspension under the effect of the external magnetic field show that the ferromagnetic suspension under this condition has a Bingham character, i.e. its rheological characteristic is given in the form

$$\tau_w = \Delta\tau_w + \eta_p \left|\frac{du_x}{dy}\right|. \qquad [20]$$

From the analytical model, which is based on the assumption of "structure formation" of ferromagnetic particles, the following expression was derived

$$\tau = \sigma_o + \eta_s \left| \frac{\mathrm{d}u_x}{\mathrm{d}y} \right|. \qquad [16]$$

A comparison of the experimental results [20] and analytical model [16] was given for the following range of the parameters

$$\begin{aligned} B &= 0\text{–}600\ \mathrm{G} \\ \alpha &= 0\text{–}5 \text{ per cent vol} \\ u_x &= 10\text{–}120\ \mathrm{cm/sec} \\ \rho_c &= 80 \text{ and } 240\ \mathrm{cP}. \end{aligned}$$

A satisfactory agreement was shown between the experimental results and the analytical model. Scattering of the experimental results is within the limits of ±15 per cent.

Acknowledgements—The authors wish to express their gratitude to Mr. I. Antić for his contribution in the realization and running of the experimental apparatus. Also, our appreciation should be expressed to Mr. A. Hajdarević for his help in producing drawings for this paper.

REFERENCES

Brenner, H. 1970 Rheology of a dilute suspension of dipolar spherical particles in an external field. *J. Colloid Interface Sci.* **32**, 141–158.

Brenner, H. & Weissman, M. H. 1972 Rheology of a dilute suspension of dipolar spherical particles in an external field, II. Effects of rotary Brownian motion. *J. Colloid Interface Sci.* **41**, 499–531.

Hall, W. F. & Busenberg, S. N. 1969 Viscosity of magnetic suspensions. *J. Chem. Phys.* **51**, 137–144.

Luikov, A. V., Berkovsky, B. M. & Bashtovoi, V. G. 1972 Convection in ferromagnetic fluid due to magnetocaloric effect. *Prog. Heat Mass Transfer* **5**, 327–331.

McTague, P. J. 1969 Magnetoviscosity of magnetic colloids. *J. Chem. Phys.* **51**, 133–136.

Neuringer, J. L. & Rosensweig, R. E. 1964 Ferrohydrodynamics. *Phys Fluids* **7**, 1927–1937.

Resler, E. L. & Rosensweig, R. E. 1967 Regenerative thermomagnetic power. *J. Engng Power* **89A**, 399–406.

Rosensweig, R. E., Kaiser, R. & Miskolczy, G. 1969 Viscosity of magnetic fluid in a magnetic field. *J. Colloid Interface Sci.* **29**, 680–686.

Surutka, J. 1971 *Elektromagnetika*. Gradjevinska knjuga.

Whitmer, M. R. 1962 *Electromagnetics*, Prentice Hall, Inc.

Zaicev, V. M. & Shliomis, M. I. 1969 Uvlechenie Ferromagnitnoi Suspenzii Vrashchaiuschimsia Polem PMTF, No. 5, 11–17.

Zaitsev, V. M. & Shiomis, M. I. 1968 K Gidrodinamike Ferromagnetinoi Zhidkosti PMTF, No. 1, 41–45.

Résumé—Cet ouvrage présente un modèle analytique simplifié ainsi que les résultats d'une étude expérimentale de l'influence d'un champ magnétique externe sur les caractéristiques théologiques d'une suspension de particules de fer dans une huile au silicium. Les particules de fer étaient approximativement de forme circulaire de 3 à 5 μm avec une concentration maximale de 10^{10} particules au cm^3. La viscosité du fluide porteur variait de 80 à 240 cP.

Le canal expérimental était placé dans un circuit fermé de circulation forcée de la suspension ferromagnétique. La longueur entière de 750 mm était placée dans une zone de champ magnétique homogène, le vecteur de vélocité de la suspension étant perpendiculaire au sens du champ magnétique. La force du champ magnétique pouvait être variée continuellement de 0 à 9000 g.

Les résultats obtenus sont montrés sous forme de dépendances paramétriques des caractéristiques rhéologiques de la suspension ferromagnétique. En même temps, la concentration de la phase solide de la suspension est changée paramétriquement avec la force du champ magnétique externe et avec la viscosité du fluide porteur.

Dans la gamme des paramètres étudiés le champ magnétique externe mène à un caractère Bingham de comportement de la suspension ferromagnétique.

Auszug—In dieser Arbeit wird ein vereinfachtes analytisches Modell und die Ergebnisse einer experimentellen Untersuchung des Einflusses eines äußeren magnetischen Feldes auf die rheologischen Eigenschaften einer Suspension von Eisenteilchen in Siliziumöl dargestellt. Die Eisenteilchen waren ungefähr kreisförmig, von 3 bis 5 μm, mit einer maximalen Konzentration von 10^{10} Teilchen/cm^3. Die Viskosität des Flüssigkeitsträgers wechselte zwischen 80 cP bis 240 cP.

Der experimentelle Kanal war örtlich in einem geschlossenen Kreislauf von erzwungener Zirkulation der ferromagnetischen Suspension festgelegt. Die Gesamtlänge von 750 mm wurde in einem Gebiet homogenen magnetischen Feldes untergebracht, mit dem Geschwindigkeitsvektor der Suspension in rechtem Winkel zu der Richtung des magnetischen Feldes. Die Stärke des magnetischen Feldes konnte kontinuierlich von 0 bis 9000 Gauss geändert werden.

Die erhaltenen Ergebnisse werden in Form parametrischer Dependenzen der rheologischen Eigenschaften der ferromagnetischen Suspension dargestellt. Mit diesem wird die Konzentration der festen Phase der Suspension parametrisch zusammen mit der Stärke des äußeren magnetischen Feldes und der Viskosität des Flüssigkeitsträgers geändert.

In dem Bereich der untersuchten Parameter führt das äußere magnetische Feld auf ein Bingham Verhaltungskennzeichen der ferromagnetischen Suspension.

Резюме—В настоящей работе представлена упрощенная аналитическая модель и результаты экспериментального исследования влияния внешнего магнитного поля на реологические характеристики суспензии железных частиц в силиконовой смоле. Частицы железа имели в приближении круглую форму с размерами от 3 до 5 микрон при максимальной концентрации до 10^{10} честиц в кубическом сантиметре. Вязкость несущей жидкости изменялась от 80 до 240 сантипуаз.

Опытный канал был расположен в закрытом контуре принудительной циркуляции ферромагнитной суспензии. Общая длина его в области однородного магнитного поля составляла 750 миллиметров, а вектор скорости суспензии был перпендикулярен направлению магнитного поля. Напряженность магнитного поля могла плавно изменяться от нуля до 9000 гаусс.

Достигнутые результаты показаны в форме параметрических зависимостей реологических характеристик ферромагнитной суспензии. При этом параметрически изменяется концентрация твердой фазы вместе с напряженностью внешнего магнитного поля и вязкостью несущей жидкости.

В описываемом диапазоне параметрических изменений внешнее магнитное поле приводит к бингхемову характеру поведения ферромагнитной суспензии.