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Volume 2, Chapter 1.

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SOLIDS DISPERSED IN LIQUIDS

D. G. Thomas

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SOLIDS DISPERSED IN LIQUIDS

I. FUNDAMENTAL RELATIONS

The relationships describing the transport of liquid-solid suspensions are complicated because the suspensions may be either Newtonian or non-Newtonian, and they may flow either homogeneously or heterogeneously.^{57,58,59} Newtonian and non-Newtonian materials are classified and compared by means of shear diagrams in which the rate of shearing strain, dV_r/dr is plotted against the shear stress, τ .

Newtonian fluids are characterized by a shear diagram in which the rate of shearing strain is directly proportional to the shear stress as shown in Fig. 1, the viscosity being given by:

$$\mu = \tau / (dV_r/dr), \quad (1)$$

where the coefficient of viscosity, μ , is independent of the rate of shearing strain.

On the other hand, non-Newtonian fluids have a variable viscosity that is a function of the rate of shear and in some cases upon the duration of shear.

A. Newtonian Suspensions

Einstein¹ has shown that the viscosity of dilute suspensions of rigid spherical particles is a function of the volume fraction of solids in the suspension and is independent of particle size, as shown in Equation 2,

Fig 1. Classification of Newtonian and Non-Newtonian Materials by Shear Diagram.

$$\mu_s = \mu(1 + 2.5\phi), \quad (2)$$

where ϕ is the volume fraction of solids in the suspension. It was assumed that the system was incompressible, that there was no slip between the particles and the liquid, no turbulence and no inertia effects and that the macroscopic hydro-dynamic equations held in the immediate neighborhood of the particles. Einstein's treatment for dilute suspensions has been extended by Guth and Simha², Simha³, de Bruyn⁴, Saito⁵ and Vand⁶ to suspensions of higher concentrations. In all these treatments the hydro-dynamic interaction between particles was considered, the extension usually taking the form of terms proportional to ϕ^2 and ϕ^3 , the terms to be added to the Einstein term 2.5ϕ . These results are summarized in Table I.

Theoretical treatments have also included such non-spherical particles as ellipsoids⁷ and dumbbells⁸ and an empirical relationship has been determined for rod shaped particles⁹:

$$\mu_s = \mu(1 + 2.5 F\phi + 8F^2\phi^2 + 40F^3\phi^3), \quad (3)$$

where F is dependent upon the axial ratio but not upon size or concentration of the rods. Values of F , determined with a Couette viscometer, are given in Table II.

B. Non-Newtonian Suspensions

Two general methods of classification of non-Newtonian materials have been proposed. In the first method, shear diagrams having particular characteristics are identified by different names. In some cases, simple

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TABLE I

Comparison of Theoretical and Empirical Extension of the Einstein Relation to Higher Concentrations. (All relations are of the form $\eta_s = \eta(1 + A_1\phi + A_2\phi^2 + A_3\phi^3) + \eta$

<u>Author</u>	<u>Reference</u>	<u>A₁</u>	<u>A₂</u>	<u>A₃</u>	<u>Comments</u>
V. Vand	6	1.5	7.349	0	Considers mutual hydrodynamic interaction and collisions between particles and pairs of particles.
E. Guth and R. Simha	2	2.5	14.1	0	Considered mutual hydrodynamic interaction; neglected formation of pairs.
H. de Bruyn	4	2.5	2.5	2.5	Considered only mutual hydrodynamic interaction.
N. Saito	5	2.5	2.5	2.5	Considered only mutual hydrodynamic interaction.
Gosting and Morris	13	3.35	0	0	Very dilute.
Oden	12	2.5	30 to 60	0	Sulfur sols.
Boutaric and Vuillaume	11	2.5	75	0	As ₂ S ₃ sols.
F. Eirich	9	2.5	9 to 13	0	Glass spheres in water.
V. Vand	10	2.5	7.17	16.2	Glass spheres in ZnI ₂ -water-glycerol solutions.

TABLE II

Values of Correction Factor, F, for Effect of Axial Ratio
of Rods in Viscosity of Suspensions

<u>L/D</u>	<u>F</u>
5	2.1
11	2.25
17	2.60
23	4.20
25	5.60
32	7.0
50	11.0
75	22
100	32
140	50

mathematical models are used to describe these shear diagrams and flow parameters are evaluated from capillary tube or rotational viscometer data. These parameters may be used to predict flow in commercial pipe when substituted in the appropriate relation. (Ref 14-17).

The second method is to develop an equation which accurately represents the shear-stress-shear-rate data for a large number of non-Newtonian fluids over a wide shear-rate range; then derive the relationship between the pipe-flow variables and this equation. (Ref 18-22).

1. Classification According to Shear Diagram

Using the first method, those non-Newtonian materials having no time dependent properties may be classified as:

- (1) Bingham plastics
- (2) Pseudo-plastic.
- (3) Dilatant.

Those having time dependent properties may be classified as:

- (1) Thixotropic
- (2) Rheopectic

a. Bingham Plastic Materials

A Bingham plastic²³ is characterized by the relations

$$-dv_r/dr = (g_c/\eta)(\tau - \tau_y) \text{ when } \tau \geq \tau_y \quad (4)$$

$$\text{and } -dv_r/dr = 0 \quad \text{when } \tau < \tau_y \quad (5)$$

where τ_y , the yield stress, and η , the coefficient of rigidity, are constants and properties of the fluid. A typical shear-diagram for Bingham plastics is shown in Fig. 1.

Note that Bingham plastics, as well as other non-Newtonian fluids, do not have true coefficients of viscosity in the sense that Newtonian fluids do, but rather have an effective viscosity (which is a variable dependent on the rate of shear) defined for point conditions as:

$$\mu_e = -g_c \tau / (dv_r/dr) \quad (6)$$

For Bingham plastics, the effective viscosity decreases with increasing rates of shearing strain.

b. Pseudo-Plastic Materials

A pseudo-plastic material is characterized by a stress-strain diagram similar to Fig. 1.¹⁴ A relationship of the form

$$-dv_r/dr = (g_c/\mu_o) \tau^n, \quad (7)$$

may be used to fit the data for pseudoplastics. As in the case of the Bingham plastic, the effective viscosity of a pseudo-plastic material decreases with an increase in the rate of shearing strain. Care should be used in attempting to extrapolate the data using Equation 7, because according to this model, the effective viscosity decreases to zero as the shearing strain is increased.

c. Dilatant Materials

The effective viscosity of a dilatant material increases with increasing rate of shearing strain, as shown in the shear diagram (Fig. 1). A theory for dilatancy has been advanced by Reynolds.³¹

d. Thixotropic Materials

At a constant rate of shearing strain, the effective viscosity of a thixotropic material decreases with time. This time dependent behavior is illustrated in Fig. 1. If the rate of shearing strain is held constant after the point B is reached on the up curve, the shear stress will decrease along the path BC until the point C is reached, beyond which there is no further decrease in effective viscosity. If the rate of shear is then decreased, the down curve CA is followed. Thus, thixotropy is the property exhibited by a system in which the effective viscosity decreases with time either at a constant rate of shearing strain or at a constant shearing stress. The material returns to its original state upon release of the shear stress. Many theories have been advanced for thixotropy (Ref 24-30).

e. Rheopectic Materials

Rheopectic materials are those which will set up or build up (increase in effective viscosity) very rapidly upon being rhythmically shaken or tapped. Very little work has been done to provide a more quantitative definition.

2. Generalized Shear-Stress-Shear-Rate Relations

Powell and Eyring¹⁸ have suggested a relation (based on the theory of absolute reaction rates) between the shear stress and the shear rate which has been applied to non-thixotropic non-Newtonian fluids,^{19,32} (Equation 8)

$$\tau = c \left(\frac{dv_r}{dr} \right) + \frac{1}{b} \sinh^{-1} \left(\frac{1}{a} \frac{dv_r}{dr} \right) \quad (8)$$

This relation is said to accurately represent shear-stress-shear-rate data for a large number of non-Newtonian fluids over a wide range of shear rate data.

Metzner²⁰ has rearranged the Mooney³³ equation to give the following relation between the pressure drop and velocity

$$\Delta P/4L = \eta' \left(\frac{3N+1}{4N} \right)^N \left(\frac{8V}{D} \right)^N \quad (9)$$

where η' and N are defined by

$$\eta' = K \left(\frac{4N}{3N+1} \right)^N \quad (10)$$

and

$$\frac{1}{N} = d \left[\ln (8V/D) \right] / d \left[\ln (\Delta P/4L) \right] \quad (11)$$

and are coefficients characteristic of the fluid.

Crowley and Kitzes have shown²² that a particular thorium oxide plastic non-Newtonian fluid had a viscosity which could be expressed in terms of the shear stress, τ , and concentration, ϕ , by the equation

$$\mu_s = \mu \frac{1.2 + \phi(K_3 \tau^{0.2} + 1)^3}{1.2 - 2\phi(K_3 \tau^{0.2} + 1)^3} \quad (12)$$

where K_3 was independent of the concentration.

C. Flow of Suspensions Through Circular Conduits

1. Laminar Flow

The pressure drop due to friction for viscous flow of Newtonian fluids through pipes is given by the Poiseuille equation:

$$\Delta p = 32 \mu LV / g_c D^2 \quad (13)$$

The same equation may be used for non-Newtonian suspensions, provided the apparent viscosity, μ_a , is substituted for the viscosity.

The shear stress of a fluid at a pipe wall is:⁶⁰

$$\tau_w = \frac{D \Delta p}{4L} \quad (14)$$

Rearranging Equation 13 to give τ_w and comparing with Equation 1 shows that a plot of $(8V/g_c D)$ vs $(D \Delta p / 4L)$ gives a "pseudo" shear diagram from which average fluid properties may be derived (as opposed to the point properties derivable from the true shear diagram). Rabinowitsch³⁴ presented an expression for the rate of shear at a pipe wall whose significance was not fully realized until Mooney³³ showed how the expression could be applied to pipe line data. The expression is:

$$-\frac{1}{g_c} \left(\frac{dv_r}{dr} \right)_w = \frac{3}{4} (8V/g_c D) + (D \Delta p / 4L) / 4 \cdot d(8V/g_c D) / d(D \Delta p / 4L) \quad (15)$$

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The true rate of shear at the pipe wall, $-(dv_r/dr)_w$, can be computed from Equation 15 together with a pseudo-shear diagram (from which values of the ordinate and the slope can be obtained for selected values of the shear stress).

This relation is independent of the shape of the flow diagram; its principal use is the comparison of data from pipe line viscometers with data from rotational viscometers.

Buckingham³⁵ has presented a mathematical relationship for the flow of Bingham plastics in circular pipe:

$$8V/\xi_c D = (1/\eta) (\tau_w - (4/3)\tau_y - (1/3)\tau_y^4/\tau_w^3). \quad (16)$$

For large values of τ_w , the last term of Equation 16 becomes small and the resulting expression when combined with Equation 13 gives

$$\Delta p = 32 \eta LV/\xi_c D^2 + (16/3) \tau_y L/D$$

for the pressure drop of a Bingham plastic in laminar flow.

A typical pseudo-shear diagram for a Bingham plastic flowing in a circular pipe is given in Fig. 2. A single curve with an intercept of $4/3 \tau_y$ is obtained for laminar flow for all sizes of pipe except when the material is thixotropic. As the rate of shearing strain increases, there is a transition to turbulent flow as indicated by the upper part of the curve (dotted). The branch off curve occurs at lower rates of shearing strain as the pipe diameter is increased. As can be seen from Fig. 3, the pseudo-shear diagram for thixotropic materials is similar to that for Bingham plastics in turbulent flow as the pipe diameter is increased, thus care should be used in interpreting pseudo-shear diagrams having this characteristic.

Pipe flow equations for the Powell-Eyring relation (Equation 8) have been derived and presented in the form of charts.¹⁹

Fig. 2. Pseudo-Shear Diagram for Bingham Plastic Material

Fig. 3. Pseudo-Shear Diagram for a Thixotropic Material

Metzner has derived a modified Reynolds number, $D^N V^{2-N} \rho / \gamma$, (where N is defined by Equation 11 and $\gamma = (g_c \eta' / 8) \left[\frac{6N + 2}{N} \right]^N$) which can be used in place of the standard Reynolds number on friction factor charts. The pressure drop in laminar flow may be calculated using the value of the friction factor (determined by using the modified Reynolds number) together with the conventional Newtonian relations.

The laminar flow equation for the Crowley-Kitzes relation²² is given by an integral equation of the form

$$\frac{8V}{g_c D} = \frac{4}{\pi \tau_w^3} \int_{\tau_y}^{\tau_w} \tau^3 \frac{1.2 - 1(K_3 \tau^{-0.2} + 1)^3}{1.2 + (K_3 \tau^{-0.2} + 1)^3} d\tau. \quad (17)$$

Plots have been prepared to aid in the evaluation of this integral.

Hedstrom³⁶ has proposed a simple criterion to distinguish between laminar and turbulent flow of Bingham plastic materials. The Reynolds number at which turbulence sets in is determined by the intersection of a parametric curve, defined by

$$H = g_c \rho \tau_y D^2 / \eta^2 \quad (18)$$

and the turbulent Newtonian friction curve on a Fanning friction factor-Reynolds number plot provided the Reynolds number is defined as $DV\rho/\eta$. The usefulness of the Hedstrom concept has been demonstrated by several investigators.^{36,37,38}

2. Turbulent Flow

In general, non-Newtonian fluids behave similarly to Newtonian fluids in the turbulent flow region in that they exhibit relatively constant apparent viscosity. Alves, Boucher and Pigford¹⁴ indicate that, in the absence of data, the conventional friction factor plot may be used to predict turbulent pressure drop to within $\pm 25\%$, provided the Reynolds number is evaluated by using the coefficient of rigidity or viscosity at infinite shear, and the density is taken as that of the slurry. However, it has been shown that a large amount of turbulent pressure drop data taken with both Newtonian and non-Newtonian slurries can be correlated using the usual friction factor-Reynolds number plot provided the density is taken as that of the slurry and the viscosity as that of the suspending medium.³⁹⁻⁴⁵

II. EXPERIMENTAL RESULTS

A. Uranium Oxide Slurries

The viscosities of suspension of $\text{UO}_3 \cdot \text{H}_2\text{O}$ rods and platelets with uranium concentrations of up to 250 g/liter were so close to the viscosity of water that the difference could not be measured by a Stormer or Brookfield viscometer.⁴⁶ Viscosities were measured with a modified Saybolt Viscometer and are shown in Fig. 4. There was no detectable difference in viscosity between the slurries of rods and those of platelets at these uranium concentrations. The viscosity values given in Fig. 4 were used to determine the value of the shape factor, F , in Equation 3, which was derived for rod-shaped particles. The value of F for the $\text{UO}_3 \cdot \text{H}_2\text{O}$ data

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Fig. 4 Viscosity of UO₃·H₂O Slurries as a Function of Temperature.

is 2.4 ± 0.7 corresponding to an L/D of about 14 (from Table II). This agrees very well with the dimensions reported for the rodlets of from 1 to 5 microns diameter and 10 to 30 microns long.⁴⁶ (The dimensions for platelets were 6 to 50 microns on edge and about 1 micron thick.)

B. Thorium Oxide Slurries

1. Newtonian Slurries

Thorium oxide slurries may be either Newtonian or non-Newtonian depending on the degree of flocculation.^a Figure 5 shows the effect of small additions of electrolyte on the shear diagram as determined with a rotational viscometer.⁵⁶ The first additions of electrolyte changed the slurry from an extreme non-Newtonian to a Newtonian fluid. Further addition of electrolyte tended to reverse this process. The degree of flocculation of ThO_2 slurries as exemplified in these shear diagrams is a physical-chemical phenomena which is not well understood at this time.

2. Non-Newtonian Slurries

a. Laminar Flow

Figure 6 shows pseudo-shear diagrams (where concentration was varied from 300 to 1075 g Th/kg H_2O) illustrating the effect of thorium-oxide slurry concentration on the shear diagram.⁴⁹ The lines were drawn through

^aIn a flocculated slurry, the particles stick together in the form of loose, irregular clusters in which the original particles can still be recognized. In a deflocculated slurry, the particles repel each other and the original particles are not in contact.⁴⁸

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Fig.5. Effect of Electrolyte on the Shear Diagram of a Thorium Oxide Slurry.

Fig. 6. Effect of Concentration on Pseudo-Shear Diagram of Thorium Oxide Slurry. (ThO₂ Fired At 800°C, Circulated 234 Hours At 300°C)

the data as if the slurry were a Bingham plastic; however, at the higher concentrations, it can be seen that there was considerable deviation from the behavior of a Bingham plastic slurry at the lower rates of shearing strain. This was true for about half the slurries that were tested provided the data were obtained down to shear stresses only 5 to 10% greater than the yield stress.⁴⁹ As a matter of convenience, these pseudoplastic slurries were treated as Bingham plastics in order to provide a basis for comparison with the data at lower concentrations. The relation between the yield stress and the slurry concentration, for a variety of different slurries, can be expressed as:

$$\tau_y = K_1 c^3 \quad (19)$$

where K_1 is a function of the particular slurry.⁵⁰ (Fig. 7). A similar relation was reported for a particular Bingham plastic clay-water suspension,⁵¹ where the exponent was reported to be 3.0 when concentration was expressed as volume fraction.

The relationship between the concentration and coefficient of rigidity for thorium oxide slurries (having a range of concentration from 200 to 1400 g Th/kg H_2O) is shown in Fig. 8. These data may be expressed as:

$$\eta = K_2 \exp (c/650) \quad (20)$$

where K_2 is a function of the particular slurry.

Shear diagrams for the same thorium oxide slurry were measured with a capillary tube and Brookfield viscometer.⁴⁷ For comparison purposes the data were calculated in terms of the true shear diagram using the procedure

Fig. 7. Effect of Slurry Concentration on the Yield Stress of Thorium Oxide Slurry.

Fig. 8. Effect of Slurry Concentration on Coefficient of Rigidity.

Fig. 9. Shear Diagram for Thorium Oxide Slurry.

Fig. 10. Shear Diagram for Thorium Oxide Slurry.

given by Alves, Boucher and Pigford¹⁴ for the Brookfield data and the Mooney³³-Rabinowitsch³⁴ relation (Equation 17) for the capillary tube data. The results are shown in Fig. 9 and 10 as arithmetic and logarithmic plots respectively. The data have been fitted with the Bingham plastic, (Equations 4 and 5) pseudo-plastic (Equation 6) and the Powell-Eyring relation (Equation 8). As can be seen, the Powell-Eyring relation gives the best fit to the data over the complete range; however, for some purposes (i.e., use with the Hedstrom plot³⁶ and in slurry heat transfer correlations⁵³), it would be advantageous to consider this pseudo plastic as a Bingham plastic.^a

b. Turbulent Flow

Turbulent flow data for thorium oxide slurries were plotted on standard friction factor-Reynolds number chart using the density of the slurry and the viscosity of water to calculate the Reynolds number.⁵⁵ Essentially all of the data were between the two curves for commercial pipe and smooth tubes. Thus, the conventional Reynolds number-friction factor plot⁵⁴ may be used to predict the turbulent pressure drop provided the density is taken as that of the slurry and the viscosity as that of water. This has also been shown to be true for such diverse Newtonian and plastic slurries as sand-water suspensions and sewage sludge.³⁹⁻⁴⁵

The Hedstrom plot for plastic slurries was modified⁵⁵ to include the viscosity of the suspending medium as shown in Fig. 11. The Reynolds number was defined as $DV\rho_s/\eta$ (instead of $DV\rho_s/\mu_{H_2O}$ as above) which translates the Newtonian turbulent friction factor curve by the ratio η/μ_{H_2O} .

^aIt must be recognized that the velocity profile of such an extreme pseudo plastic would differ very little from the plug flow profile described by the Bingham plastic relations.²⁰

Fig. 11. Friction Factor - Reynolds Number Diagram for Bingham Plastic Slurries in Smooth Pipes.

A family of turbulent friction factor curves is obtained for slurries with η/μ_{H_2O} as a parameter. The two families of curves give a generalized method for calculating the pressure drop of a Bingham plastic material in laminar flow as well as a homogeneous slurry in turbulent flow.

The Hedstrom number for non-Newtonian thorium oxide slurry systems is often of the order of 10^6 . It is apparent from Fig. 11 that the critical Reynolds number for thorium oxide slurries for transition from laminar to turbulent flow is not the value of 2100 commonly accepted for Newtonian fluids. For Hedstrom numbers of 10^6 , the critical Reynolds number, and hence the critical velocity, is at least ten times that of an ordinary fluid having identical properties other than yield stress.

NOMENCLATURE

A_1, A_2, A_3	Constants in Table I	dimensionless
a	Constant in Equation 8	sec^{-1}
b	Constant in Equation 8	$(\text{sq ft})/(\text{lb force})$
C	Slurry conc.	$\text{g Th/kg H}_2\text{O}$
c	Constant in Equation 8	$(\text{lb force})/(\text{sec})(\text{sq ft})$
D	Diameter	ft
d	"derivative of"	dimensionless
F	Shape factor in Equation 3	dimensionless
g_c	Conversion factor	$(\text{lb mass/lb force})(\text{ft/sec}^2)$
H	Hedstrom Number (Equation 18)	dimensionless
K	Coefficient in Equation 10	$(\frac{\text{lb force}}{\text{sq ft}})(\text{sec})^N$
K_1	Constant in Equation 19	$(\text{lb force/sq ft})/(\text{g Th/kg H}_2\text{O})^3$
K_2	Constant in Equation 20	$(\text{lb mass})/(\text{ft})(\text{sec})$
K_3	Constant in Equation 16	
L	Length	ft.
N	Coefficient in Equation 9, 10, 11	dimensionless
n	Exponent in Equation 7	dimensionless
p	Fluid pressure	lb force/sq ft
Δp	Pressure drop	lb force/sq ft
r	Radius	ft
V	Velocity	ft/sec
Subscripts		
w	wall	
r	radius	
γ	Coefficient	$(\text{lb mass})/(\text{ft})(\text{sec}^{2-N})$

Nomenclature (Continued)

η	Coefficient of rigidity	(lb mass)/(ft)(sec)
η	Coefficient in Equation 10	(lb force)/(sq ft)(sec) ^N
μ	Fluid viscosity	(lb mass)/(ft)(sec)
μ_a	Apparent viscosity	(lb mass)/(ft)(sec)
μ_0	Pseudo-plastic coefficient, dimensions are variable depending on n	
μ_s	Suspension viscosity	(lb mass)/(ft)(sec)
ρ	Fluid density	lb mass/cu ft
τ	Shear stress	lb force/sq ft
τ_y	Yield stress	lb force/sq ft
ϕ	Volume fraction solids	cu ft/cu ft

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