On the Calculation of the Limiting Shear Stress of Suspensions with Particles Possessing a Rigid Dipole Moment

`![Fig. 1](image)`

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Fig. 1

Figure 1: Fig. 1

Abstract

Full Text

Physical Chemistry

M. P. Volarovich and A. M. Gutkin

On the Calculation of the Limiting Shear Stress of Suspensions with Particles Possessing a Rigid Dipole Moment

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N. A. Tolstoi (^1) established the presence of a rigid dipole moment in colloidal particles in certain disperse systems. Recently, a dipole moment has been found in gum sols (^2). It is to be expected that interaction between particles possessing dipole moments may lead to the appearance of an ordered state (for example, quasi-crystalline order) in their arrangement, which in turn will affect the rheological properties of such a disperse system. Let us assume, for simplicity, that at some instant of time, in a small volume of the disperse system, the particles are arranged in the same order as the atoms of a cubic crystal (Fig. 1). The directions of the dipole moments shown in Fig. 1a correspond to the minimum of the potential energy.

Fig. 1

During flow of the system, the potential energy of interaction of the particles will change as a result of the mutual shear of planes A and B. After some time, the potential energy of interaction of the particles will reach a maximum. Such a state is shown in Fig. 1b. In this case, against the forces of mutual attraction of the particles caused by the presence of the dipole moment, a specific work will be performed that is approximately equal to:

$$A = \frac{nP^2}{a^3}, \tag{1}$$

where n is the number of particles per unit volume, P is the dipole moment of the particles, and a is the distance between particle centers.

It may be assumed that this dipole potential energy of the particles will be converted into heat (into the energy of thermal motion of the molecules of the dispersion medium and of the molecules of which the particles consist) as the arrangement of the particles again approaches that shown in Fig. 1a. Thus, shear of the system through an angle $\pi/4$ leads to the result that, in each unit volume, the energy $\frac{nP^2}{a^3}$ is converted into heat.

It is known that the specific mechanical power N, converted into heat in the process of flow of a medium, is expressed through the tangential stress τ in the following way (see, for example, (~3)):

$$N = \tau \frac{dv_t}{dy} = \tau \frac{d\gamma}{dt}. \tag{2}$$

Equating the value A obtained earlier to the value $N'\Delta i$, we arrive at the equality:

$$\frac{nP^2}{a^3} = N\Delta t = \tau\Delta\gamma. \tag{3}$$

Since $\Delta\gamma = \pi/4$, it follows from (3) that

$$\tau = \frac{4nP^2}{\pi a^3}. \tag{4}$$

If we take into account that $n = \frac{1}{a^3}$, then formula (4) becomes

$$\tau = \frac{4}{\pi} n^2 P^2. \tag{5}$$

Because, in deriving (5), the interaction between the molecules of the dispersion medium was not considered (the specific power expended in doing work against these forces is proportional to the square of the shear rate), the value of the shear stress obtained is independent of the rate of flow. The shear stress τ, expressed by (5), may therefore be regarded as the dynamic yield stress θ [1].

Let us estimate the value of θ on the basis of data obtained by N. A. Tolstoy [2]. For particles of radius $r = 0.5\mu$, the dipole moment is equal to $6 \cdot 10^{-11}$ CGSE. We shall assume that the particles are in a dispersion medium with a volume concentration $c = 10\%$. Since $c = \frac{4}{3}n\pi r^3$, we obtain

$$\theta = \frac{9P^2c^2}{4\pi^3 r^6} \simeq \frac{9(6 \cdot 10^{-11})^2(0.1)^2}{4\pi^3(0.5 \cdot 10^{-4})^6} = 160 \ \frac{\text{dyn}}{\text{cm}^2}.$$

Fig. 2

[1] M. P. Volarovich, *Transactions of the Institute of Applied Mineralogy*, No. 66, 5 (1934).
[2] N. A. Tolstoy, DAN, **100**, No. 5 (1955).

Fig. 2

Figure 2: Fig. 2

Values of θ of this order are characteristic of a number of disperse systems. Thus, the estimate given shows that the interaction of electric dipole moments can explain the experimentally observed values of the yield shear stress of suspensions with particles possessing a rigid dipole moment, in those cases where short-range forces between the surfaces of neighboring particles are insignificant. Experiments carried out by one of the authors with I. S. Erokhin [3] on a suspension of mica particles in vaseline oil may serve as qualitative confirmation of the considerations presented above. It follows from these experiments that, in agreement with formula (5), the dynamic yield shear stress is, to a sufficient approximation, proportional to the square of the concentration of the disperse phase.

It should be noted that the presence of rigid dipole moments can in some cases also explain the thixotropic properties of disperse systems. An ordered arrangement of dipolar particles in the absence of flow is observed only within small regions of space. A scheme of such an arrangement, with the presence of short-range order and the absence of long-range order, is shown in Fig. 2. During flow, these regions of short-range order must rotate relative to one another, since from the energetic point of view the most favorable arrangement of the regions is that in which the direction of flow and the straight line along which the axes of the dipoles are situated are collinear. Since additional work is expended on orienting the regions of short-range order, the resistance to flow at its initial stage must be greater than during steady flow. A thixotropic phenomenon of this kind was noted earlier [4].

Kalinin Peat Institute

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References

Note: Figure translations are in progress. See original paper for figures.

[3] M. P. Volarovich, I. S. Erokhin, ZhFKh, **12**, 277 (1938).
[4] M. P. Volarovich, I. S. Erokhin, ZhFKh, **12**, 277 (1938).