VISCOSITY REDUCTION IN LIQUID SUSPENSIONS BY ELECTRIC OR MAGNETIC FIELDS

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Reducing the viscosity of liquid suspensions is of great importance in science and engineering. We present a theory and experiments that a suitable electric or magnetic field pulse can effectively reduce the viscosity for several hours with no appreciable change of temperature. Positive experimental results with magnetorheological fluids and crude oil suggest a broad range of practical applications.

1. Introduction

Viscosity of liquid suspensions is of great importance in science and engineering. In electrorheological (ER) or magnetorheological (MR) fluids, electric field or magnetic field is used to *increase* the viscosity *(1-3)*. In many cases, on the contrary, one would like to *lower* the viscosity while maintaining the chemical compounds of the suspensions intact. For example, reducing the viscosity of blood improves circulation and prevents cardiovascular events and other diseases *(4,5)*. Lowering the viscosity of crude oil is vital for transportation of off-shore oil via undersea pipelines *(6)*. In spite of the importance, to date there are basically no effective methods for reducing the viscosity except by changing the temperature. In case that changing temperature is not an option, such as in the above two examples, reducing the viscosity becomes formidable.

In this paper, we present both a theory and experimental results showing that the apparent viscosity of liquid suspensions can be reduced for several hours with no appreciable change of temperature by application of a suitable electric or magnetic field pulse.

2. Theory

Einstein first studied the apparent viscosity of a dilute liquid suspension of uniform spherical particles in a base liquid and found $\eta/\eta_0 = 1 + 2.5\phi$, where η_0 is the viscosity of the base liquid, η is the suspension's apparent viscosity, and ϕ is the volume fraction of spheres inside the suspension. For spheres of radius *a*, $\phi = 4a^3 n\pi/3$ where *n* is the particle number density. Einstein formula is only correct for $\phi < 0.01$ *(7)*.

According to Einstein's formula, two mono-dispersed suspensions made of different size spheres in the same base liquid should have the same η if their volume fractions are the same. For $\phi \geq 0.01$, the above conclusion is incorrect. In fact, for the same ϕ, η

increases as the sphere size reduces. This can be understood from the mean free path of the spheres in the suspension, which is estimated by $a/(3\phi)$. As *a* gets smaller, the mean free path becomes shorter; thus η must go higher. The detailed calculation can be made with the Mooney equation *(8)*,

$$\eta/\eta_0 = \exp[2.5\phi/(1-k\phi)], \qquad (1)$$

where *k* is the crowding factor. The Mooney equation is derived by considering the available volume after the sequence of stepwise additions of particles. According to an experimental estimation,

$$k = 1.079 + \exp(0.01008/D) + \exp(0.00290/D^2), \qquad (2)$$

where *D=2a*, the particle diameter in micrometers *(9,10)*.

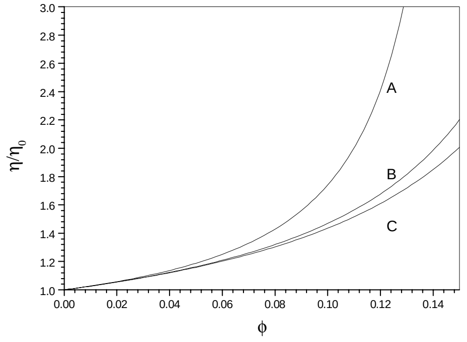


Fig.1 As the particle size decreases, the apparent viscosity increases. For curves A, B, and C, *D=0.05μm, 0.1 μm*, and *10 μm* respectively.

As *D* decreases, *k* increases. For example, for *D*=10.0 *μm, k*= 3.08, while for *D*=0.05 *μm, k*= 5.492. Thus for the same ϕ , η increases if *D* decreases. As shown in Fig.1, the apparent viscosity increases significantly as the particle size decreases. At $\phi = 12\%$, for instance, the suspension of *0.05μm* diameter particles has its viscosity 50% higher than that for suspension of 10.0 *μm* diameter particles. The above results also explain why suspensions of nanoparticles have very high viscosity.

For a suspensions of poly-dispersed particles, the Mooney equation takes the form $\eta/\eta_0 = \prod_i \exp[2.5\phi_i/(1-k_i\phi_i)]$, where ϕ_i and k_i are the volume fraction and crowding factor for the particles with diameter D_i respectively *(7-10)*. The viscosity of the poly-dispersed suspension may also be estimated from Eq.(1) and Eq.(2) with *D* in Eq.(2) replaced by the average particle size.

With the information in mind, we now show how to use either electric field or magnetic field to reduce the viscosity of suspensions. We discuss the magnetic field here, but the same physics also applies to the case of an electric field. We assume that the particles have a magnetic susceptibility μ_p different from the susceptibility of the base liquid μ_f. In a magnetic field, the particles are polarized along the field direction. If the particles are uniform spheres of radius *a,* the dipole moment is given by *(10)* $\vec{m} = \vec{H}a^3(\mu_p - \mu_f)/(\mu_p + 2\mu_f)$, where $\vec{H}$ is the local magnetic field, which should be close to the external field in dilute cases. The interaction between two induces magnetic dipoles has the form $U = \mu_f m^2(1 - 3\cos^2\theta)/r^3$, where *r* is the distance between the two dipoles and θ is the angle between the magnetic field and the line joining the two dipoles (Fig.2). If this interaction is strong enough to overcome the thermal Brownian motion, the dipoles aggregate and align in the field direction. If the dipolar interaction is very strong and the magnetic field stays on, the particles eventually aggregate into macroscopic chains or columns, which jam the liquid flow and increase the apparent viscosity (Fig.3), a well-known phenomenon in ER and MR fluids *(11).*

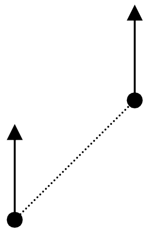


Fig.2 The interaction between two magneti dipoles.

Fig.3 As shown in the photo, the particles form macroscopic chains along the field direction, which jam the liquid flow and increase the apparent viscosity.

On the other hand, if the applied magnetic field is in such a short pulse that the induced dipolar interaction does not have enough time to affect particles separated by macroscopic distances, but has enough time to assemble nearby ones together, the assembled clusters are of limited size, say, in micrometer range. In the suspension, the average particle size is now increased, while the volume fraction ϕ is the same. The apparent viscosity is reduced because the crowding factor *k* decreases.

We can estimate the minimum magnetic field H_c required to form clusters as follows: If the particle number density is *n*, the typical separation of two neighboring particles is about $n^{-1/3}$. The dipolar interaction between two neighboring particles is about $m^2 n\mu_f$. This interaction must overcome the thermal Brownian motion in order to pull them together. Then it is required to have $\mu_f m^2 n/(k_B T) \geq 1$, where k_B is the

Boltzmann constant and T is the absolute temperature. Hence, we obtain the critical field

$$H_c = [k_B T/(n\mu_f)]^{1/2}(\mu_p + 2\mu_f)/[a^3(\mu_p - \mu_f)]. \qquad (3)$$

If the applied magnetic field is weaker than H_c, the thermal Brownian motion prevents particles from aggregating. In order to change the apparent viscosity of the liquid suspension, the applied magnetic field must be stronger than H_c.

Now let us estimate the duration of the required pulse. The force between two neighboring particles is about $6\mu_f m^2 n^{4/3}$. From this force and the Stoke's drag force $6a\pi\eta_0 v$, we estimate the particle's average velocity $v = \mu_f m^2 n^{4/3}/(\pi\eta_0 a)$. The time required for two neighboring particles to come together is about

$$\tau = n^{-1/3}/v = \pi\eta_0(\mu_p + 2\mu_f)^2/[\mu_f n^{5/3} a^5(\mu_p - \mu_f)^2 H^2]. \qquad (4)$$

If the duration of magnetic field is much less than τ, there is insufficient time for aggregation. If the pulse lasts much longer than τ, macroscopic chains are formed and the apparent viscosity may be increased because the chains may jam the flow. To reduce the viscosity, the duration should be of order τ. It is clear from Eq.(4) that τ decreases as the applied magnetic field increases.

The clusters formed as a result of the magnetic field are not spherical. They usually are elongated along the field direction. If the flow direction is parallel to the field direction, this may further reduce the apparent viscosity *(12)*.

Once the magnetic field is turned off, the induced dipolar interaction disappears. However, the aggregated clusters of particles could sustain for a while. In absence of other disturbances, the particles separate diffusively due to Brownian motion with a diffusion constant $k_B T/(6\pi a\eta_0)$. Two spheres of radius *a* which are initially in contact diffuse apart by a distance of *a* in time $3\pi a^3\eta_0/(k_B T)$. With $a = 3\mu m$ and $\eta_0 = 1$ poise, this estimated time is several hours at room temperature. Therefore, while the reduction of viscosity is temporary, it lasts for several hours, long enough for many important applications. After the clusters disintegrate, the rheological properties of the suspension return to the state prior to the magnetic treatment. Reapplication of the magnetic field pulse will again reduce the viscosity.

A striking feature of the above process is that the temperature does not change appreciably. As shown in Fig. 1, the reduction in apparent viscosity with decreasing crowding factor *k* becomes more pronounced as the particle's volume fraction ϕ

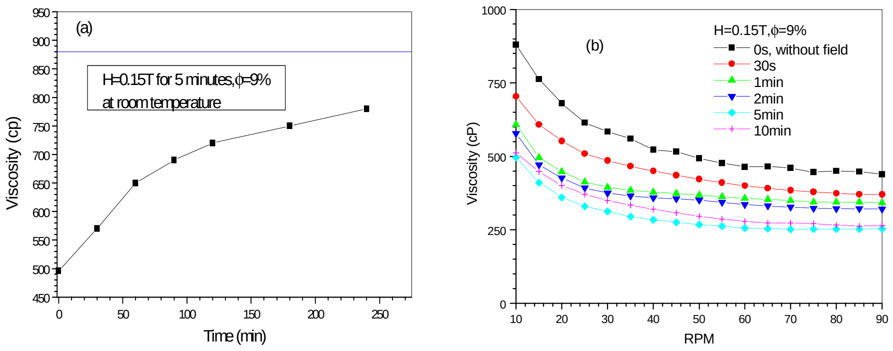
increases. The electric or magnetic field pulse is more effective in dense than in dilute suspensions.

3. Experimental Results

These theoretical predictions are confirmed by our experiments. Our first experiment was made with a dilute MR fluid of iron nanoparticles of diameter 35-40 nm in silicon oil. The volume fraction was $\phi = 9\%$. The MR fluid was in a thermal bath with a constant temperature of 23.5^{o}C and had viscosity 880 cp on our rotational viscometer at 10 rpm (rotations per minute). It is well known that for such a MR fluid, the viscosity increases in a constant magnetic field and the stronger the magnetic field, the higher the effective viscosity *(13)*. However, after applying a magnetic field pulse of 0.15 T lasting 5 minutes, the viscosity of the MR fluid decreased to 496 cp. Then the viscosity gradually returned to the original value (Fig.4a). After 240 minutes, the viscosity was up to 780cp, but still lower than 880cp. After 12 hours, the viscosity was back to the original value. As shown in Fig.4b, the viscosity right after application of a magnetic field pulse depended on the pulse duration. From 10rpm to 90 rpm, the 5-min pulse seemed to produce the maximum viscosity reduction. We also found that the viscosity of MR fluid decreased as the rotation speed increased, a well-known shear-thinning phenomenon. We measured the average size of aggregated magnetic particle cluster. The results are in Fig. 4c. To see the clusters clearly, we used a more dilute MR fluid of volume fraction $\phi = 1\%$. After a pulse of H=0.38T for 1 second, the 30-40 nm particles aggregated in to clusters with average size 9.9 μm; after a pulse of 10 seconds, the cluster size is about 15.4 μm, and so on. The increasing average cluster size leads to the viscosity reduction. We note that from Eq.(3), H_c should be 0.07T and 0.21T for $\phi = 9\%$ and $\phi = 1\%$ respectively. The applied fields were slightly stronger than the estimations.

We also applied our theory to crude oil, which is a mixture of many different molecules. Some of the molecules are much larger than others. For example, if the temperature is low, in paraffin-base crude oil, the paraffin crystallizes into many nanometer-size particles, suspended in the solvent. As a result, the apparent viscosity of crude oil increases significantly. The effect of a magnetic field on the viscosity of crude oil is very controversy *(6)*. Some experiments found that the magnetic field increased the viscosity of crude oil *(14)*, some reported no effect *(6)*, and some found that the magnetic field reduced the viscosity *(15)*. Applying our theory, we are able to clarify this controversy.

The paraffin particles are paramagnetic *(16)*. According to our theory and experiment, the viscosity of paraffin-base crude oil increases after exposing to a strong constant magnetic field for a long time. In contrast, we found that after a short magnetic field pulse was applied, the viscosity decreased. As shown in Fig.5a, the viscosity of a light paraffin-base crude oil was 40.97 cp at 10^{0}C. The apparent viscosity decreased to 33.1cp after a magnetic field of 1.33 T was applied for 50 seconds. Afterwards, the viscosity gradually increased, but remained substantially below the original value 120 minutes after the application of magnetic field. The original rheological state was recovered after about 8 hours.



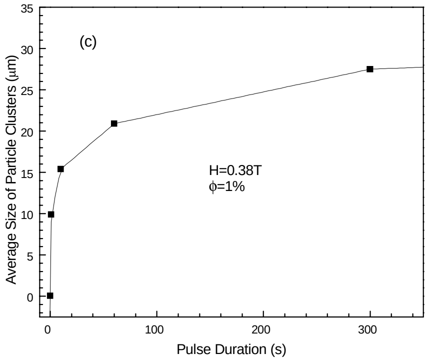


Fig.4.(a)The apparent viscosity of an MR fluid after applying a magnetic field of 0.15T for 5 minutes. (b) The viscosity right after a pulse magnetic field applied. (c) The average size of particle clusters after a pulse magnetic field applied.

For asphalt-base crude oil, the magnetic field has much weak effect on its viscosity since asphalt is fairly insensitive to a magnetic field. On the other had, asphalt has a dielectric constant 2.7, higher than for the rest oil. Therefore, to apply our theory to asphalt-base crude oil, we used a short electric field pulse. As the viscosity of the crude oil sample was very high, it was difficult to use a rotational viscometer and we used a capillary viscometer instead. The typical results were in Fig.5b. At 23.5°C, the oil sample had a kinetic viscosity 773.8 cSt and a density around 0.95g/cm^3. From Eq. (3) and Eq.(4), we estimated that the critical electric field was about 0.9kV/mm and the duration τ was around seconds. Therefore, we let crude oil flow through a capacitor, where it was subject to an electric field of 1000V/mm. The oil flow took about 8 seconds to pass through the capacitor, corresponding to a 8-second electric field pulse. The kinetic viscosity immediately dropped to 669.5 cSt, decreasing by 104.3 cSt. The viscosity then gradually increased. After 90 minutes, the kinetic viscosity was at 706.8 cSt, still 67 cSt below the original value. During the experiment, the temperature was maintained at

23.5°C since the whole capillary viscometer was immersed in a constant temperature bath.

In summary, the experiments fully confirm our theory that a suitable short pulse of electric field or magnetic field can effectively reduce viscosity of liquid suspensions for several hours. The results with MR fluids and crude oil indicate that the theory has broad applicability and may have broad practical applications.

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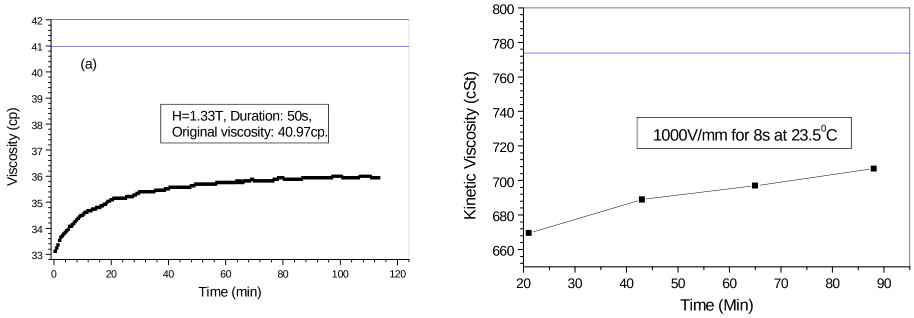

Fig.5 (a)Viscosity of a paraffin-base crude oil at 10°C and 10 rpm after application of a magnetic field of 1.33 T for 50 seconds. (b) Viscosity of a heavy asphalt-base crude oil at 23.5°C after an electric field of 1000V/mm was applied for 8 seconds.

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