Reducing the Viscosity of Crude Oil by Pulsed Electric or Magnetic Field

R. Tao* and X. Xu

Department of Physics, Temple University, Philadelphia, Pennsylvania 19122

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A method with pulsed electric or magnetic field to reduce the viscosity of crude oil is developed. Specifically, for paraffin-base crude oil, a magnetic field pulse can effectively reduce its viscosity for several hours, while, for asphalt-base crude oil or mixed-base crude oil, an electric field pulse can do the same. The method does not change the temperature of the crude oil; instead, it temporary aggregates paraffin particles or asphaltene particles inside the crude oil into large ones. This particle aggregation changes the rheological property of the crude oil and leads to the viscosity reduction. While this viscosity reduction is not permanent, it is suitable for many important applications, such as oil transport via deepwater pipelines, since it lasts for several hours and is repeatable.

1. Introduction

Lowering the viscosity of crude oil is important in the oil industry. It is especially important for transporting offshore oil via deepwater pipelines. As more and more heavy crude oil will be produced in the future, a reliable technology to lower crude oil's viscosity becomes urgent. The deepwater pipelines have some unique situations: The temperature is stable, but quite low, making the crude oil very viscous. Heating the oil undersea, if not impossible, is at least much more difficult than it is on the ground. The solution is thus a new technology that reduces the viscosity of crude oil with no requirement to raise its temperature. While this issue has received much attention for several years, unfortunately, to date there is no effective solution yet.[1]

In this paper, we will show that application of a suitable magnetic field pulse or electric field pulse can significantly reduce the viscosity of crude oil for several hours. Specifically, for paraffin-base crude oil, we can use a magnetic field pulse to reduce its viscosity, while, for asphalt-base crude oil or mixed-base crude oil, we can do the same with an electric field pulse. This viscosity reduction method does not change the temperature of the crude oil; instead, it temporary aggregates paraffin particles or asphaltene particles inside the crude oil into large ones. The particle aggregation changes the rheological property of the crude oil and leads to the viscosity reduction. While this viscosity reduction is not permanent, it lasts for several hours and is repeatable. This is suitable for many important applications, such as oil transport via deepwater pipelines.

The current paper is organized as follows. In section 2, we will discuss the proposed physical mechanism for this viscosity reduction method. The experiments and results are in section 3. Finally, we will have discussions in section 4.

* To whom all correspondence should be addressed. Phone: 215.204.7651. Fax: 215.204.5652. E-mail: rtao@temple.edu.

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2. Proposed Physical Mechanism

Einstein first studied a dilute liquid suspension of noninteracting uniform spheres in a base liquid of viscosity η_0.[2] The apparent viscosity η was found,

$$\eta = \eta_0(1 + 2.5\phi) \tag{2.1}$$

for the volume fraction of the spheres $\phi < 0.01$. Batchelor and others derived the second correction for the dilute case.[3,4]

For high ϕ, we must consider the maximum volume fraction, ϕ_m, to be available for adding particles. For liquid suspensions, ϕ_m is about 0.64, smaller than 0.74, the maximum packing fraction of a face-centered cubic (fcc) lattice. When we add dϕ volume fraction of spheres to a liquid suspension of volume fraction ϕ, the net available volume fraction to add spheres is only $1 - \phi/\phi_m$; the viscosity increase[5] would be $d\eta/\eta = 2.5 d\phi/(1 - \phi/\phi_m)$. Hence at high ϕ, the viscosity is given by $\eta/\eta_0 = (1 - \phi/\phi_m)^{-2.5\phi_m}$. Krieger-Dougherty introduced the intrinsic viscosity, $[\eta]$,

$$\eta/\eta_0 = (1 - \phi/\phi_m)^{-[\eta]\phi_m} \tag{2.2}$$

which enables us to estimate the viscosity for particles of any shape by choosing a suitable $[\eta]$.[6] For example, $[\eta] = 5/2$ for spherical particles and $[\eta] = 5.8$ for glass plates.[7] While $[\eta]$ changes significantly for particles of different shapes, the product $[\eta]\phi_m$ almost remains a constant, close to 1.9.

At a high ϕ, the particle size distribution has a strong effect on the viscosity. There are substantial experiments on monodispersed suspensions of particles on the order of micrometers and submicrometers, showing that, at constant ϕ, the viscosity goes down as the particle size increases.[8,9] As shown in Figure 1a, for example,

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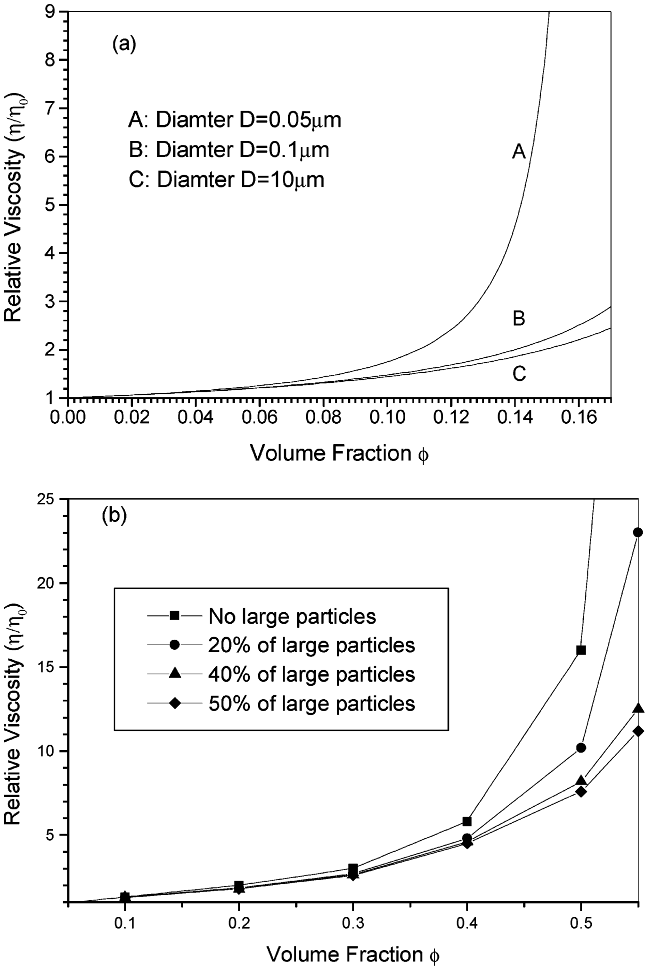

Figure 1. Effect of particle size and size distribution on the viscosity. (a) Viscosity versus volume fraction and particle size for monodispersed suspensions. (b) Viscosity versus particle volume fraction and particle size distribution for suspensions of a binary size distribution. The particle-size ratio is 5:1.

at $\phi = 15\%$, a suspension of 10.0 μm particles has a viscosity only 23.9% of the viscosity of a suspension of 0.05 μm particles.[8] An empirical formula was proposed to have the effective maximum packing fraction ϕ_m increased with the particle size in ref 8, $1/\phi_m = 1.079 + \exp(0.01008/D) + \exp(0.00290/D^2)$, where D is the particle diameter in micrometers. While a profound theory for this size effect is still lacking, the following qualitative explanation helps our understanding. Generally, the effective viscosity depends on how much freedom the suspended particles have in the suspension. The less freedom for the particles, the faster the energy dissipates and the higher the effective viscosity. The mean free path of the spheres inside the suspension is given by $\lambda \approx a/(3\phi)$, where a is the particle radius. As a gets bigger, λ becomes longer, indicating that the suspended particles have more freedom to move in the suspension. Thus, η goes down.

The values of ϕ_m in eq 2.2 also increase with increasing polydispersity.[7] For example, when the ratio of large particles to small particles increases in a suspension of binary particle-size distribution, the viscosity reduces significantly (Figure 1b): at $\phi \geq 50\%$, when this ratio reaches 1:1, the viscosity is reduced more than 50% from the monodisperse case. A qualitative explanation is as follows: for a binary particle-size distribution, we can consider that the small particles thicken the continuous phase and the next-size-up particles then thicken this phase; hence, $\eta = \eta_0(1 - \phi_1/\phi_{m1})^{-[\eta_1]\phi_{m1}}(1 - \phi_2/\phi_{m2})^{-[\eta_2]\phi_{m2}}$, which is lower than that of a suspension of uniform small particles with volume fraction $\phi_1 + \phi_2$.

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Figure 2. Image depicting liquid flow. In ER and MR fluids, the dipolar interaction is strong. If the field keeps on, the particles form chains along the field direction, which may jam the liquid flow.

In addition, experiments also show that in flow through capillary tubes the viscosity is further reduced for large suspended particles because of a tendency for large particles to migrate toward the center of the tube.[10]

It is clear from the above background that aggregating small particles into large ones in a liquid suspension will reduce the effective viscosity while ϕ remains the same. For most suspensions, this aggregation can be realized with either an electric or magnetic field.

We discuss the magnetic field here, but the same physics applies to the case of the electric field. We assume that the magnetic permeability μ_p of the particles is different from μ_f of the base liquid. 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 $\vec{m} = \vec{H}a^3(\mu_p - \mu_f)/(\mu_p + 2\mu_f)$, where $\vec{H}$ is the magnetic field acting on the sphere. The interaction between two induced magnetic dipoles takes $U = \mu_f m^2(1 - 3\cos^2\theta)/r^3$, where r is their distance and θ is the angle between the field and the line joining the two dipoles. If this interaction is strong enough to overcome the Brownian motion, the particles aggregate and align in the field direction. If this interaction is very strong, the particles quickly aggregate into macroscopic chains or columns to jam the liquid flow and increase the viscosity with the magnetic field (Figure 2), a well-known phenomenon in magnetorheological (MR) fluids and electrorheological (ER) fluids.[11−16]

On the other hand, if the applied magnetic field is in such a short pulse that the 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 the micrometer range. Although some particles may not join the aggregation, the aggregated particles have their size increased. During the application of field, the viscosity changes rapidly. However, after the magnetic field is turned off, the suspension has a reduced viscosity. This reflects the fact that while the volume fraction remains the same, the particle size distribution is changed: there are more large particles, and the polydispersity is also increased.

It is important to note that this viscosity reduction method does not come from a change of the suspension's temperature. The reduction becomes more pronounced as the volume fraction ϕ increases. The electric or magnetic field pulse is thus more effective in dense suspensions than in dilute ones.

Let us estimate the minimum magnetic field H_c required to form clusters. For particle number density n, the typical separation between two neighboring particles is about $n^{-1/3}$ and their dipolar interaction is about $m^2 n\mu_f$. This interaction must overcome the

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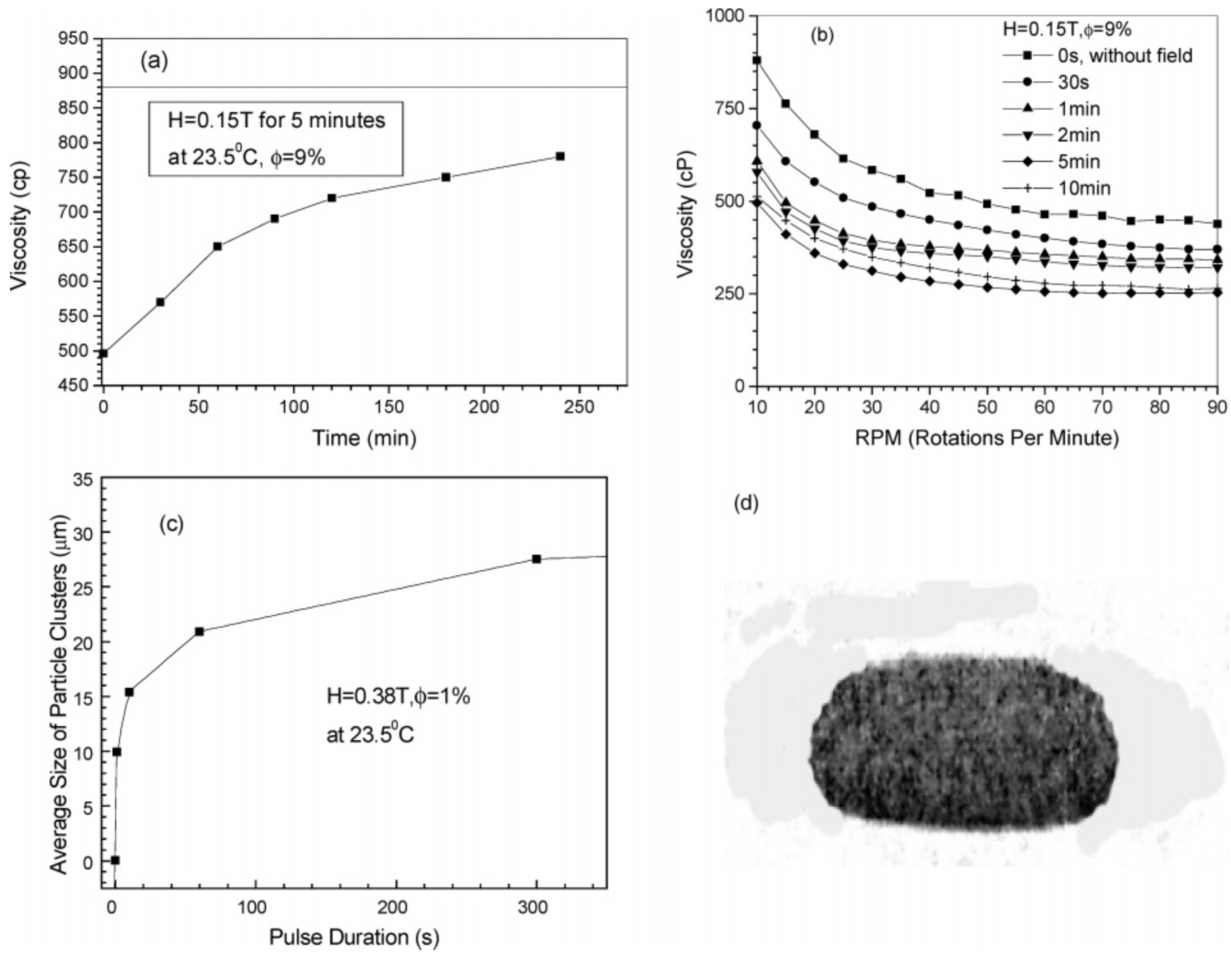

Figure 3. MR fluid after pulsed magnetic field exposure. (a) Plot showing the viscosity of an MR fluid which decreased to 496 cP from 880 cP after applying a magnetic field of 0.15 T for 5 min. It then gradually went up to return to the original rheological state. (b) Plot of the viscosity reduction after the application of a magnetic field pulse which depends on the pulse duration, which varies from 0 s to 10 min. (c) Plow showing that, with an increase of the magnetic field pulse duration, the average size of aggregated particles gets larger and larger. (d) Picture of an aggregated particle, which has the longitudinal axis about 25 μm in total.

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

$$H_c = [k_B T/(n\mu_f)]^{1/2}(\mu_p + 2\mu_f)/[a^3(\mu_p - \mu_f)] \quad (2.3)$$

To change the viscosity of the liquid suspension, the applied magnetic field cannot be lower than H_c. It is quite different from ER and MR fluids, where this ratio $\mu_f m^2 n/(k_B T)$ exceeds hundreds. Here, we only require that the dipolar interaction is not weaker than the thermal motion.

Now, let us estimate the required pulse duration. 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

$$\tau = n^{-1/3}/v = \pi\eta_0(\mu_p + 2\mu_f)^2/[\mu_f n^{5/3} a^5 (\mu_p - \mu_f)^2 H^2] \quad (2.4)$$

If the magnetic field pulse is much shorter than τ, there is insufficient time for the aggregation. If the pulse lasts much longer than τ, macroscopic chains may be formed to jam the flow, unfavorable for viscosity reduction. Thus, to reduce the viscosity, the pulse duration should be on the of order τ.

To apply the above equations for the electric field case, we only need to replace the magnetic permeability by the respective dielectric constant. The aggregated particles are usually elongated along the field direction.[17] The viscosity can thus be further reduced if the flow and the field direction are parallel.

After the field is turned off, the dipolar interaction disappears and the aggregated particles gradually dissemble under the Brownian motion. Therefore, the viscosity is expected to increase gradually and will return to the original value after all aggregated particles disintegrate. Let us estimate the time interval for the viscosity reduction. In the absence of other disturbances, such as those in a static or a constant flow state, the particles in the suspension separate diffusively only due to the 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 a time interval $3\pi a^3\eta_0/(k_B T)$. With $a = 3$ μm and $\eta_0 = 1$ P, this estimated time is about 2 h at room temperature. Therefore, this dissembling process is slow and the viscosity reduction lasts for several hours, long enough for many important applications.

After all aggregated particles are disintegrated, the suspension returns to the rheological state prior to the magnetic treatment. Thus, the viscosity returns to the original value. Reapplication of the magnetic field pulse will again reduce the viscosity. The process is repeatable.

3. Experiments and Results

3.1. Test with Magnetorheological Fluids. As a test of the above theory, we first conducted experiments with a dilute

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magnetorheological fluid of iron nanoparticles of diameter 35−40 nm in silicon oil. These iron particles were well-dispersed by the addition of a small amount of surfactant to coat the particle surface. The volume fraction was $\phi = 9\%$. The MR fluid was in a thermal bath with a constant temperature of 23.5 °C and had a viscosity of 880 cP on our rotational viscometer at 10 rotations per min (rpm). It is well-known that, for such an MR fluid, the viscosity increases in a constant magnetic field and the stronger the magnetic field is, the higher the effective viscosity.[18] However, after applying a magnetic field pulse of 0.15 T for 5 min, the viscosity of the MR fluid decreased to 496 cP. Then, the viscosity gradually went up (Figure 3a). After 240 min, the viscosity was up to 780 cP but was still lower than 880 cP. After 12 h, the viscosity was back to the original value. As shown in Figure 3b, the viscosity right after application of a magnetic field pulse depended on the pulse duration. From 10 to 90 rpm, the 5-min pulse seemed to produce the maximum viscosity reduction. We measured the average size of the aggregated magnetic particle clusters, which were similar to ellipsoids.[17] To see the clusters clearly, we used a more dilute MR fluid of $\phi = 1\%$. After a 1-s pulse of 0.38 T, the 30−40 nm particles aggregated into clusters with an average size of 9.9 μm; after a 10-second pulse, it was about 15.4 μm and so on (Figure 3c). The increasing average cluster size led to the viscosity reduction. As shown in Figure 3d, the aggregates were similar to ellipsoids. We note that from eq 2.3, H_c should be 0.07 and 0.21 T for $\phi = 9\%$ and $\phi = 1\%$, respectively. Our applied fields here were slightly stronger than the estimations. From the average aggregated particle size, as shown in Figure 3c, we calculate the reduced viscosity from eq 2.2, which is close to the measured value.

3.2. Paraffin-Base Crude Oil. Crude oil is a mixture of many different molecules. Gasoline and diesel, the liquid made of small molecules, have very low viscosities. If we treat the rest of the large molecules as suspended particles in such a low viscosity liquid, the crude oil is a liquid suspension. In paraffin-base crude oil, at low temperature, the high viscosity is mainly due to the suspended paraffin particles. Therefore, the above proposed theory provides the physical basis for the new method to reduce the viscosity of crude oil.

It is determined from experiments that the paraffin particles have different magnetic permeability from the solvent,[21] which is sufficient for our viscosity reduction method. Different from ER and MR fluids, our method does not require a strong dipolar interaction. While all ER and MR fluids require the particle's dielectric constant or magnetic permeability to be higher than that of the base liquid,[11−16] we only require a mismatch here. Even if the mismatch is small, a strong field pulse can still reduce the viscosity effectively.

The effect of a magnetic field on the viscosity of crude oil is very controversial.[1] Some experiments found that the magnetic field increased the viscosity of crude oil,[19] some reported no effect,[1] and some found that the magnetic field reduced the viscosity.[20] Applying the above proposed theory, we are able to clarify this controversy. Especially, from the theory, the viscosity of paraffin-base crude oil increases after being exposed to a strong magnetic field for a long time but decreases after a short magnetic field pulse is applied. Our experiment verified it.

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Figure 4. UL adapter consisting of a precision cylindrical spindle rotating inside an accurately machined tube to measure low viscosity accurately. It also has a water jacket to provide precise temperature control.

The sample of paraffin-base crude oil for our experiment was from a Sunoco refinery in Philadelphia. Since it was of light crude oil with low viscosity, we used a Brookfield viscometer LVDV-II+ and a Ultra Low (UL) adapter for the experiment. The UL adapter consists of a precision cylindrical spindle rotating inside an accurately machined tube to measure viscosity accurately and has a water jacket to provide precise temperature control (Figure 4). During the experiment, including application of the magnetic field, the sample remained inside the UL adapter and was maintained at the desired temperature.

The viscosity of crude oil increases as the temperature goes down. For paraffin-base crude oil, when the temperature passes a critical temperature, paraffin begins to crystallize into tiny particles inside the crude oil, making the viscosity increase faster. This critical temperature is usually called the wax appearing temperature (WAT). From the viscosity measurement of our sample, the curve of viscosity versus temperature had a slope change around 17 °C (Figure 5). This indicated that our sample had a WAT around 17 °C. If the temperature went below 17 °C, wax particles began to appear and raised the viscosity faster. As shown in Figure 5, the slope change was not dramatic for our sample, indicating that the paraffin content in the sample was not high, about 3−4% in weight. Our experiment with magnetic field was conducted at 10 °C, 7 °C below the WAT to ensure the existence of wax particles inside the crude oil.

As shown in Figure 6, the viscosity of our sample was 40.97 cP at 10 °C. It decreased to 33.1 cP after a magnetic field of 1.33 T was applied for 50 s. Afterward, the viscosity gradually increased but remained substantially below the original value 120 min after the application of the magnetic field. The original rheological state was recovered after about 8 h. If we apply the magnetic field pulse again, the same viscosity reduction pattern shown in Figure 6 was reproduced.

As usual, crude oil is not a Newtonian fluid. The viscosity declines as the shear rate increases. In measurements with our viscometer, at a higher rpm, the sample's effective viscosity was smaller than that at a low rpm. The result of Figure 6 was

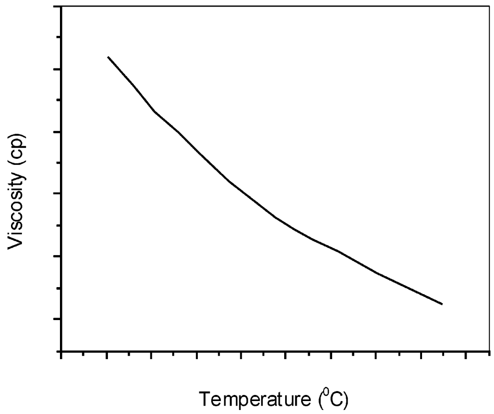

Figure 5. Viscosity of the paraffin-base crude oil sample versus temperature at 10 rpm. The curve slope changes around 17 °C, indicating that the wax particles appear in the sample as the temperature goes below 17 °C.

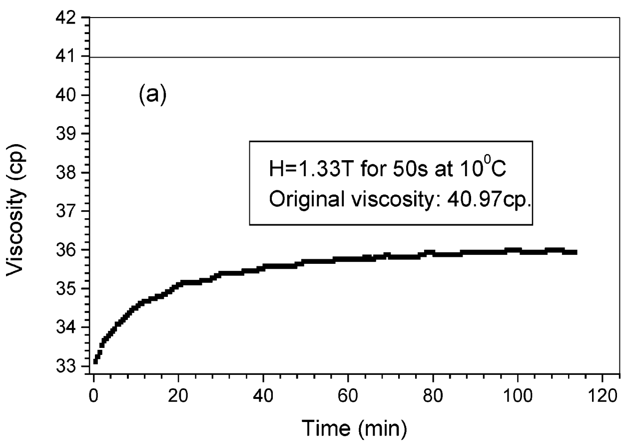

Figure 6. Viscosity of the paraffin-base crude oil sample at 10 °C and 10 rpm which was down to 33.1 cP from 40.97 cP after applying a magnetic field of 1.33 T for 50 s. Afterward, the viscosity gradually went up to return to the original rheological state.

for 10 rpm. However, the viscosity reduction after application of a magnetic field pulse was present for all different rotational speeds.

3.3. Asphalt-Base Crude Oil. The Shell Company provided a sample of asphalt-base crude oil from California for our experiment. Since asphalt has a very high melting temperature, at room temperature, the asphalt in the crude oil absorbs moisture and solidifies into asphaltene particles. As a result, the viscosity of asphalt-base crude oil is very sensitive to temperature. When the temperature goes lower, the viscosity of asphalt-base crude oil continuously increases quickly. However, different from the case of paraffin-base crude oil, the curve of viscosity versus temperature for asphalt-base crude oil is usually smooth and has no apparent slope change.

We applied a magnetic field pulse to the asphalt-base crude oil and found that the magnetic field pulse reduced the apparent viscosity, but the effect was much weaker than that for paraffin-base crude oil. The reason may be attributed to the fact that asphalt is much less sensitive to a magnetic field than paraffin particles are. It should be noted that most crude oil produced in North America is asphalt-based. This may be the reason that some tests in the USA found that a magnetic field had no effect on crude oil's viscosity.[1]

We note that, on the other hand, asphalt has a dielectric constant of 2.7, higher than that for the rest of the oils, which is about 2.0−2.2. The absorbed moisture in the asphaltene particles makes their dielectric constant even higher. Therefore, according to the theory, a short electric field pulse can effectively reduce the viscosity of asphalt-base crude oil.

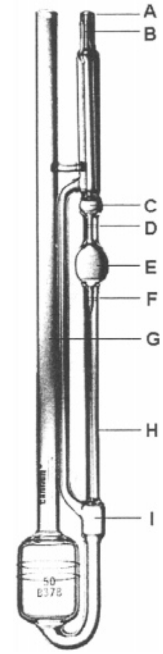

Figure 7. Capillary viscometer used to determine a liquid's viscosity by measuring the time interval for the liquid level to drop from mark D to mark F under gravity.

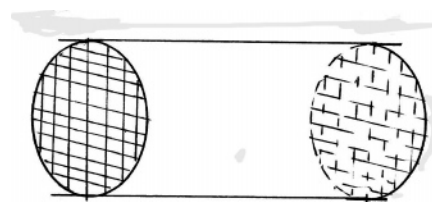

Figure 8. Capacitor made of two metallic meshes connected to the large tube G of the capillary viscometer (Figure 7). When the crude oil passes the mesh, the oil experiences a short pulse electric field as a voltage is applied to the capacitor.

Following this theoretical consideration, we designed an experiment and applied an electric field pulse to the asphalt-base crude oil. The viscosity of our California sample was very high. At 23.5 °C, it had a kinetic viscosity of 773.8 cSt. To have a precise measurement and to simulate the oil flow in pipelines, we used a capillary viscometer instead (Figure 7).

From eq 2.4 and eq 2.5, we estimated that the critical electric field was about 0.9 kV/mm and the duration τ was a couple of seconds. Therefore, we made a capacitor with two metallic meshes (Figure 8) and inserted the capacitor in the oil flow path, which was connected to tube G of the capillary viscometer to fill its reservoir (Figure 7). A high voltage was applied on the two electrodes to produce an electric field of 1000 V/mm parallel to the flow direction. The oil flow took about 8 s to pass through the two mesh-electrodes, corresponding to an 8-s electric field pulse. The current passing the capacitor during the experiment was very low, about 1 μA. This indicated that the power consumption was only about 1 mW, too low to raise the temperature of the crude oil. However, to avoid mixing any viscosity change due to the temperature change with the present viscosity reduction method, we maintained the oil sample at 23.5 °C as the whole viscometer and the oil flow path were immersed in a constant temperature bath.

The typical results are shown in Figure 9. At 23.5 °C, the oil sample originally had a kinetic viscosity 773.8 cSt. The kinetic

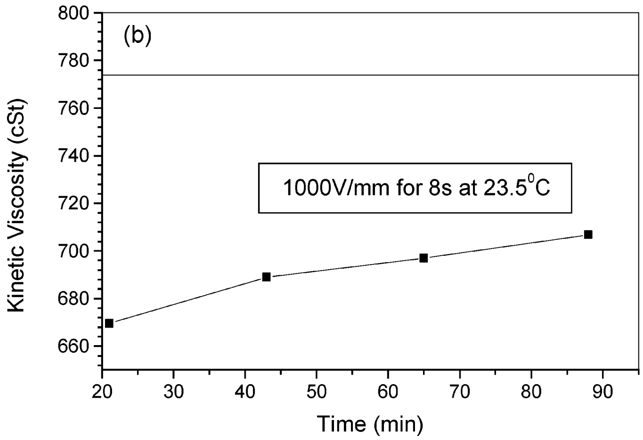

Figure 9. Kinetic viscosity of our asphalt-base crude oil sample at 23.5 °C which dropped to 669.5 cSt from 773.8 cSt after applying an electric field of 1000 V/mm for 8 s. The viscosity then gradually went to up to return to original rheological state.

viscosity immediately dropped to 669.5 cSt, decreasing by 104.3 cSt. The viscosity then gradually increased. After 90 min, the kinetic viscosity was at 706.8 cSt, still 67 cSt below the original value. It also took about 8 h for the oil sample to recover the original viscosity.

The result in Figure 9 was from a direct currnt (dc) electric field. We also tested with an alternating current (ac) electric field pulse of 100 Hz and found a similar viscosity reduction for our asphalt-base crude oil. We note that the electric field strength and duration in our experiment may not be the optimal. Searching for the optimal electric field and duration requires a series tests. At the optimal situation, the viscosity of heavy asphalt-base crude oil may be reduced more.

4. Discussions

Because of lacking the proper sample, we were unable to do experiments with mixed-base crude oil. Therefore, we applied the above electric-field method to our sample of paraffin-base crude oil and found that the electric field pulse could also significantly reduce the viscosity of paraffin-base crude oil. From these results, we are confident that the electric field method will reduce the viscosity of mixed base crude oil as well. On the other hand, as mentioned before, the dc magnetic field was found to have weak effect on asphalt-base crude oil. Therefore, the dc magnetic field may have some limited effect on mixed-base crude oil.

Although our viscosity reduction is not permanent, it lasts several hours, long enough for many important applications. For example, in transporting offshore oil via deepwater pipelines, the crude oil flows about 3 miles/h. Therefore, after one application of an electric field or magnetic field, the crude oil could flow several miles with a low viscosity inside the pipeline. Reapplication of the required field along the way can help in transporting the crude oil effectively.

The dark black color of crude oil prevented us from identifying any aggregated particles with microscopes as done in our experiment with the MR fluid. We hope to identify the aggregated particles in crude oil in future neutron scattering experiments, which may provide a quantitative comparison of our proposed theory with the viscosity reduction experiment for crude oil.

In concluding this paper, we want to emphasize that while the magnetic field method is safe and easy to apply, the electric field method is also safe and easy to adapt for practical applications, such as on oil pipelines. It is well-known that there is always some water content inside asphalt-base crude oil, and accidental sparks of discharge or dielectric breakdown may occur when the water content in crude oil passes the two meshed electrodes. However, as our experiment found out, since the capacitor is fully immersed inside the crude oil, accidental dielectric breakdown or sparks of discharge between the two electrodes inside the oil do not cause any fire because there is no oxygen available. Of course, the magnetic field method will have no such “dielectric breakdown” to occur and is thus, in some sense, safer than the electric field method.

Asphalt-base crude oil and mixed base crude oil constitute a large portion of world crude oil production. Especially in North America, most crude oil resources, including Alaska oil, are asphalt-based. We believe the finding reported in this paper is thus very significant.

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