

Investigate Effects of Magnetic Fields on Fuels

Rongjia Tao, Department of Physics, Temple University, Philadelphia, PA 19122

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1. Introduction

The effect of magnetic fields on viscosity of liquid fuel is very important. For example, offshore oil plays more and more important role in our society now. The transport of crude oil via pipeline undersea water faces a critical issue: paraffin wax problem. If magnetic fields can reduce the apparent viscosity of crude oil near the wax-appearance temperature (WAT), it may provide a novel solution to the transport of offshore oil [1]. The reduction of surface tension and viscosity of fuel may also lead to smaller droplets in the fuel ejection, which will improve the combustion efficiency and pollutant emission.

Under the sponsorship of RAND Corporation, we carried out this research project, starting in December 2003. Sunoco Refinery in Philadelphia provided us with samples of crude oil, pure gasoline, and pure diesel for our project. Our early experiment was carried out with an existing Brookfield viscometer DVIII, which is specialized in measuring high viscosity. Since gasoline has a very low viscosity, DVIII is not very suitable for the experiment with gasoline. In addition, a home-made spindle extension was not very reliable in measurements. Therefore, immediately after the contract was signed, we sent out a purchase order to acquire a Brookfield viscometer LVDV-II+ and an UL adapter (Fig.1), which are specialized in measuring low viscosity, such as viscosity of gasoline. After the new equipment arrived at Temple University in middle of February, 2004, we repeated all previous tests with the new equipment and carried out new experiments on gasoline and diesel.

While some previous data need to be revised, the experimental results with the new equipment are basically consistent with the finding obtained with the DVIII viscometer. This makes us very confident in our discovery. On the other hand, since the effect of magnetic fields on crude oil is very controversy [1-3], we were extremely cautious. As a result, we performed additional experiment on these fuels with capillary viscometers (Fig.2) to verify our findings. It is interesting to note that while capillary viscometers employ a different physics principle to measure viscosity, the results from capillary viscometers were also found to be consistent with the results from the Brookfield viscometers. Therefore, we can now safely conclude that a strong magnetic field will affect the viscosity of crude oil and refinery fuels, such as gasoline and diesel. If the applied magnetic field is a short pulse with sufficiently strength and suitable duration, the apparent viscosity of these fuels will be reduced significantly. The treated fuels will have their viscosity gradually increasing and return to the original value after several hours.

In this report, we will first review our theory and then present our experimental results. As it will be discussed in detail, our theory predicts a critical magnetic field H_c , which depends on the property of each individual fuel. In order to affect the viscosity of the fuel, the applied magnetic field cannot be lower than H_c . In addition, the duration of

applied magnetic field on the fuel must be short. We have also derived a formula to estimate the required duration. Our experiments confirm the theory very well.



Fig.1 The UL Adapter consists 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.

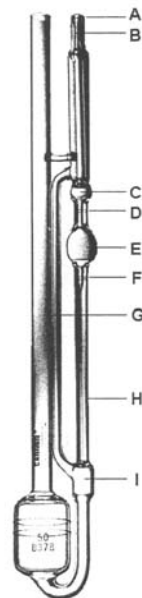


Fig.2 A capillary viscometer is used to determine a liquid's viscosity by measuring the time interval for the liquid level to drop from mark D to mark F under gravity.

2. Theory

Crude oil and refinery petroleum oils are all mixtures of many different molecules. Among them, some molecules are much larger than others. For simplicity, in our current theoretical discussion, we divide the molecules in petroleum oils into two classes: the small ones are the majority, forming the base liquid and the large ones, suspended in the base liquid, are called "particles". There is no difficulty to extend our discussion to include molecules of various sizes.

The viscosity of petroleum oil is thus clearly related to the viscosity of liquid suspensions or emulsions, which are quite different from single-molecule liquid, such as water and liquid nitrogen. This also explains why the viscosity of diesel and gasoline, for example, changes with the shear rate more than water and silicone oil.

Einstein first gave the basic analysis of the viscosity of a dilute suspension of rigid spheres in a viscous liquid, $\eta/\eta_0 = 1 + 2.5\phi$, where η_0 is the viscosity of the base liquid, η is the suspension's apparent viscosity or effective viscosity, and ϕ is the volume fraction of spheres inside the suspension. If the spheres have radius a , $\phi = 4a^3 n\pi/3$ where n is the particle number density. It is widely verified that Einstein formula is only correct for $\phi < 0.01$. For situations with $\phi \gg 0.01$, various formulas have been proposed. It is also well established that at the same volume fraction ϕ , the apparent viscosity depends on the particle size: As the particles get smaller, the apparent viscosity gets higher. This can be seen from the Mooney equation [4],

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

where the crowding factor k increases as the particle size decreases. Some experiments estimated $k = 1.079 + \exp(0.01008/D) + \exp(0.00290/D^2)$ for micrometer-size particles, where D is the particle diameter in unit of micrometers [5,6].

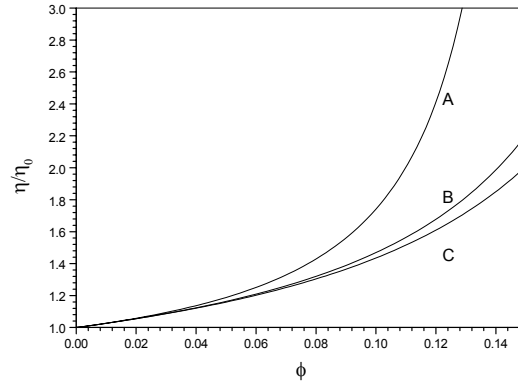


Fig.3 As the particles get smaller, the apparent viscosity gets higher. A for $D=0.05\mu m$, B for $D=0.1\mu m$, and C for $D=10\mu m$.

As shown in Fig.3, although the volume fraction ϕ remains the same, the apparent viscosity increases significantly when the particles get smaller. For example, at $\phi = 12\%$, the suspension of $0.05\mu m$ -diameter particles has its viscosity 50% higher than that of suspension of $10.0\mu m$ -diameter particles. The above results also explain why suspensions of nanoscale particles have very high viscosity.

With the above knowledge about apparent viscosity of suspensions, we now show how a magnetic field could reduce the viscosity of petroleum fuels. 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 thus polarized along the field direction. If the particles are uniform spheres of radius a , in the magnetic field each particle, the dipole moment is estimated by

$$\bar{m} = \bar{H}a^3(\mu_p - \mu_f)/(\mu_p + 2\mu_f), \quad (2)$$

where \vec{H} is the local magnetic field, which should be close to the external field in dilute cases. The dipolar interaction between the two induced magnetic dipoles is given by

$$U = \mu_f m^2 (1 - 3 \cos^2 \theta) / r^3, \quad (3)$$

where r is the distance between these two dipoles and θ is the angle between the joining line and the magnetic field (Fig.4). If this interaction is stronger than the thermal Brownian motion, these two dipoles will aggregate together to align in the field direction. If the dipolar interaction is very strong and the duration of magnetic field is long enough, the particles will aggregate into macroscopic chains or columns, which will jam the liquid flow (Fig.5) and increase the apparent viscosity, a well-known phenomenon in magnetorheological (MR) fluids [7].

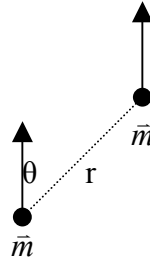


Fig.4 The interaction between two magnetic dipoles.



Fig.5 The photo shows that the particles form chains along the field direction, which is perpendicular to the flow direction. The chains jam the liquid flow and are bent. The field direction is perpendicular to the flow direction.

On the other hand, if the applied magnetic field is such a short pulse that the induced dipolar interaction does not have enough time to affect particles at macroscopic distance apart, but forces nearby ones into small clusters. The assembled clusters are thus of limited size, say, remain in micrometer size. While the particle volume fraction remains the same, the average size of new “particles” is increased. This leads to the reduction of apparent viscosity because the crowding factor k in Mooney’s formula is reduced.

We can estimate the required magnetic field as follows. If the particle number density is n , two neighboring particles are separated about $n^{-1/3}$. From Eq. (2), the dipolar interaction between two neighboring particles is about $m^2 n \mu_f$. This interaction must be

stronger than the thermal Brownian motion in order to pull neighboring particles together. Then it is required to have the following parameter

$$\alpha = \mu_f m^2 n / (k_B T) \geq 1, \quad (4)$$

where k_B is the Boltzmann constant and T is the absolute temperature. The parameter α specifies the competition between the dipolar interaction and the thermal motion. With Eq. (2), we derive the following critical field

$$H_c = [k_B T / (n \mu_f)]^{1/2} (\mu_p + 2\mu_f) / [a^3 (\mu_p - \mu_f)]. \quad (5)$$

If the applied magnetic field is weaker than H_c , the thermal Brownian motion prevents particles from aggregating together. In order to change the apparent viscosity of the liquid suspension, the applied magnetic field must be not lower than H_c .

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

$$\tau = n^{-1/3} / v = \pi\eta_0 (\mu_p + 2\mu_f)^2 / [\mu_f n^{5/3} a^5 (\mu_p - \mu_f)^2 H^2] = \pi\eta_0 a / (n^{2/3} k_B T \alpha). \quad (6)$$

If the duration of magnetic field is too shorter than τ , the particles do not have enough time to aggregate together. On the other hand, if the duration of magnetic field is much longer than τ , macroscopic chains will be formed and the apparent viscosity will be increased instead of reduction. Therefore, the suitable duration of the magnetic field should be in the order of τ . From Eq. (6), it is clear that if the applied magnetic field is getting stronger, the pulse duration should get shorter.

In MR fluids, $\alpha \geq 100$; the dipolar interaction is too strong and forces the particles into chains along the field direction in milliseconds. In petroleum oils, the induced magnetic dipolar interaction is much weaker than that in MR fluids. From our experiments, it seems that if α is between 1 and 10, we can reduce the apparent viscosity of a liquid suspension effectively by selecting suitable duration of magnetic fields.

We should note that the aggregated particles by the magnetic field are not spherical. They usually are elongated along the field direction and may rotate under the influence of magnetic field, which may further help the reduction of the apparent viscosity.

Once the magnetic field is turned off, the induced dipolar interaction disappears. However, the aggregated clusters of particles could sustain for a while due to hysteresis, a well-known phenomenon in granular particle aggregations. Only the Brownian motion and other disturbance will gradually break the assembled particles. After these assembled particles are completely broken, the rheological properties of the liquid suspension would return to the state prior to the magnetic treatment. From our experiments, we have found that it may take about 8-10 hours for these assembled particles to break completely.

3. Experiments with Gasoline

We repeated experiments with gasoline and found that a strong pulse of magnetic field can reduce the apparent viscosity of gasoline. It is clear from our theory that a

strong pulse magnetic field can reduce the viscosity of pure gasoline, pure diesel, and pure kerosene, no matter if they contain any additive or not. However, since current gasoline for vehicles contains additives, for practical purpose, we carried out experiments on gasoline with these additives.

3.1 Gasoline with 20% ethanol.

Ethanol is a main additive in gasoline on market. Therefore, we paid special attention to gasoline with 20% ethanol. It is interesting to note that pure gasoline has very low viscosity, about 0.8 cp at 10⁰C. However ethanol has quite high viscosity, about 1.7cp at 10⁰C. Therefore, a mixture of gasoline with 20% ethanol has a viscosity about 0.95 cp. We applied a strong magnetic field of 1.3 T to the sample for 5 seconds, the apparent viscosity dropped to 0.81 cp, but soon climbed to about 0.865cp, fluctuating there and gradually increasing (Fig.6). However, after 3 hours, the apparent viscosity remained at 0.88 cp, 8% below the original value. We expect that the viscosity returns to 0.95cp in about 10hours. Currently we are continuing the experiment to determine the optimal time duration for the magnetic pulse in order to reduce the apparent viscosity.

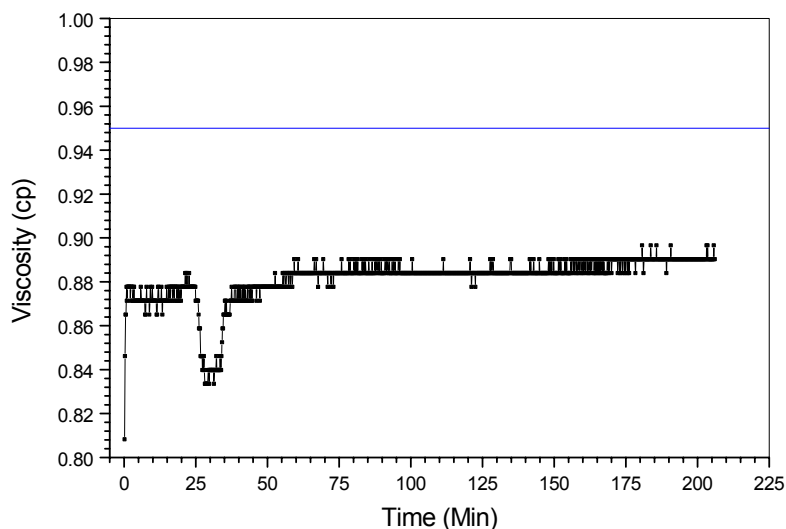


Fig.6 Viscosity of gasoline with 20% ethanol at 10⁰C and 95 rpm after application of a magnetic field of 1.3 T for 5 seconds. The original viscosity was 0.95 cp. The apparent viscosity remained substantially below the original value 200 minutes after the application of magnetic field.

3.2 Gasoline with 10% MTBE.

MTBE (methyl tertiary butyl ether) is still widely used as gasoline additive. Therefore, we conducted experiment to measure the viscosity of gasoline with 10% MTBE. Different from ethanol, MTBE has quite low viscosity. Therefore, a mixture of gasoline with 10% MTBE at 10⁰C has a viscosity of 0.84cp, slightly higher than that of pure gasoline. We applied a magnetic field of 1.3T on the sample for about 1 second. The apparent viscosity immediately dropped to 0.77 cp. Then it was fluctuating around 0.78 cp for several hours and gradually increasing (Fig.7). However, as shown in Fig.7, after

more than 2 hours, the viscosity remained about 7% below 0.84cp, the previous value. This behavior is quite similar to that of gasoline with ethanol in a pulse magnetic field, but we also note that for gasoline with 10% MTBE the magnetic pulse duration should be shorter than that for gasoline with 10% ethanol. This is consistent with Eq. (6) since τ should be proportional to η_0 .

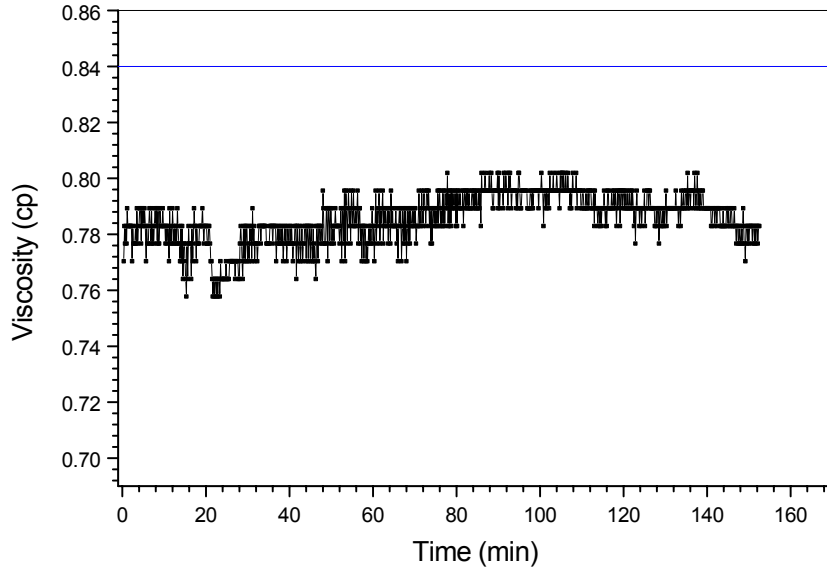


Fig.7 Viscosity of gasoline with 10% MTBE at 10⁰C and 95 rpm after application of a magnetic field of 1.3 T for 1 second. The original viscosity was 0.84 cp. The apparent viscosity remained substantially below the original value 150 minutes after the application of magnetic field.

4. Diesel fuel.

Diesel has much higher viscosity than that of gasoline. We conducted experiments with pure diesel and diesel with 0.5 % of ethylhexyl nitrate (EHN) as additive. The behavior for both samples is quite similar because the volume fraction of the additive is too small.

As show in Fig. 8, diesel has a viscosity of 5.80 cp at 10⁰C, which is considerably higher than that of gasoline. After application of a magnetic field of 1.1 T for 8 seconds, the apparent viscosity dropped to 5.64 cp, then remained at 5.70cp for several hours.

At this moment, we are in process to determine the optimal duration of magnetic pulse. On one hand, since diesel is more close to crude oil, we expect that the magnetic field induced dipolar interaction should be stronger than that in gasoline. On the other hand, since the diesel's original viscosity is higher than that of gasoline, we expect the magnetic pulse should have a slightly long duration. Our current results in Fig.8 indicate that a pulse magnetic field can reduce the apparent viscosity of diesel. We fully expect that under the optimal choice, this reduction may be larger than our current data.

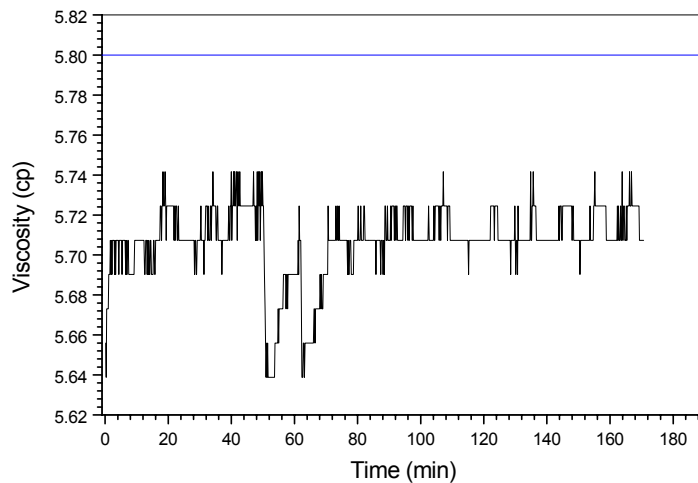


Fig.8 Viscosity of diesel at 10⁰C and 35 rpm after application of a magnetic field of 1.1 T for 8 seconds. The original viscosity was 5.80 cp. The apparent viscosity remained below the original value 160 minutes after the application of magnetic field,.

4. Crude Oil

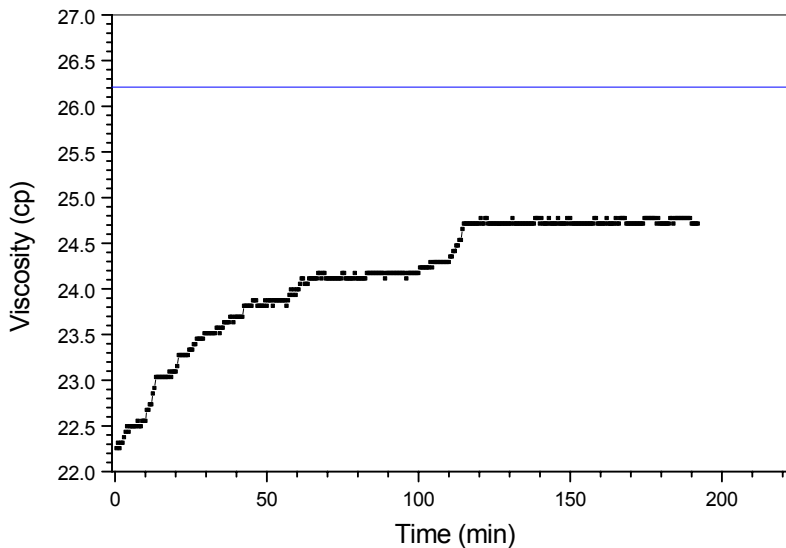


Fig.9 Viscosity of Sunoco crude oil at 10⁰C and 10 rpm after application of a magnetic field of 1.3 T for 4 seconds. The original viscosity was 26.2 cp. The apparent viscosity remained substantially below the original value 200 minutes after the application of magnetic field.

We also conducted experiment with Sunoco crude oil. Since Sunoco crude oil is light crude oil and has low wax-appearance temperature, our experiment was performed at 10⁰C. As shown in Fig.9, at that temperature Sunoco crude oil has a viscosity about 26.2 cp. After application of a magnetic field of 1.3 T for 4 seconds, the apparent viscosity dropped to 22.2 cp, which was 16% lower than the original value. After the magnetic field was turned off, the viscosity remained low, but was gradually increasing.

After 200 minutes, it reached 25.0 cp, but still 5% below the original value. From this curve, we expect the viscosity will return to the original value after about 10 hours.

5. Conclusion and Continuing Research

We are continuing our research to find the optimal conditions to reduce the apparent viscosity of gasoline, diesel, and crude oil. We will also conduct experiments on kerosene in the due course.

Since we have now found that a strong pulse magnetic field can reduce the apparent viscosity of gasoline and diesel, we are quite anxious to start atomization experiment to see the effect of magnetic field on the droplet size of these fuels.

When atomization occurs as a result of interaction between a liquid and the surrounding air, the overall atomization process involves several interacting mechanisms, among which is the splitting up of the larger drops during the final stages of disintegration. In equilibrium, a droplet's radius is determined by the liquid's surface tension and the pressure difference,

$$r = 2\gamma / \Delta p, \quad (7)$$

where γ is the surface tension and $\Delta p = p_i - p_a$ is the pressure difference between pressure inside the droplet, p_i , and the air pressure near the droplet surface, p_a . The size r in Eq.(7) is usually noted as the critical size. In the spray process, drops are initially much larger than r . They then break again and again into small droplets. The influence of liquid's viscosity, by opposing deformation of the drop, is to increase the breakup time. Therefore, low liquid's viscosity favors quick breaking of drops and leads to smaller size of droplets [8].

In addition, in many complex fluids, if a fluid's viscosity is reduced, its surface tension also goes down. At this stage, we are not sure, but have reasons to speculate that a pulse magnetic field may also reduce the surface tension of these petroleum fuels as well as their apparent viscosity. If this turns out to be true, it provides additional mechanism to reduce the droplet size in atomization process.

During this period of research, we compared the theory with experiments and refined our theory. As stated before, our theory now shows that a strong pulse magnetic field can reduce the viscosity of pure gasoline, pure diesel, and pure kerosene, no matter if they contain any additive or not. Our theory made predictions for our experiments and guided our experiments. While our current experimental results seem to agree with the theory qualitatively, we would like very much to compare the experimental results with our theory quantitatively. This can be done only after we have the information about these parameters, such as μ_p , μ_f , and particle size a etc. We will also carry out research in this direction.

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