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Suppressing turbulence and enhancing liquid suspension flow in pipelines with electrorheology

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Flows through pipes, such as crude oil through pipelines, are the most common and important method of transportation of fluids. To enhance the flow output along the pipeline requires reducing viscosity and suppressing turbulence simultaneously and effectively. Unfortunately, no method is currently available to accomplish both goals simultaneously. Here we show that electrorheology provides an efficient solution. When a strong electric field is applied along the flow direction in a small section of pipeline, the field polarizes and aggregates the particles suspended inside the base liquid into short chains along the flow direction. Such aggregation breaks the rotational symmetry and makes the fluid viscosity anisotropic. In the directions perpendicular to the flow, the viscosity is substantially increased, effectively suppressing the turbulence. Along the flow direction, the viscosity is significantly reduced; thus the flow along the pipeline is enhanced. Recent field tests with a crude oil pipeline fully confirm the theoretical results.

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I. INTRODUCTION

Flows through pipes and channels are the most common and important method of transportation of fluids. To enhance the flow output via pipeline requires reducing the fluid viscosity and suppressing turbulence. These issues are not only crucial for many industrial and engineering applications, but also important in basic science as turbulence is classified as the most important unsolved problem of classical physics [1–4]. Unfortunately, no method is currently available to reduce the fluid viscosity and suppress turbulence in pipelines simultaneously and effectively.

Abundant instances can illustrate the importance of this issue. Here we take crude oil in a pipeline as an example. In our broad definition, most fluids in nature are liquid suspensions. They can either be a fluid having solid particles suspended in a base liquid or a fluid made of different molecules: The large molecules are regarded as particles suspended in the base liquid, consisting of small molecules. Thus all kinds of crude oils, including paraffin base, asphalt base, and mixed base, are all suspensions. As hydrocarbons are our leading energy source, to transport crude oil via pipelines efficiently is crucial to our economy. Currently, the principal method to reduce viscosity is to raise the oil temperature, which not only requires much energy, but also impacts the environment adversely. Moreover, raising temperature does not suppress turbulence. As the Reynolds number goes up with temperature, the turbulence is, in fact, getting worse inside the pipe.

In the presence of turbulence, we need much more energy to transport the fluid. Typically, when the Reynolds number $N_R = \rho v D/\eta$ ™ 2300, the flow in the pipeline is laminar. Here D is the diameter of the pipeline, v is the average flow velocity, ρ is the fluid density, and η is the fluid viscosity. The friction factor for laminar flow is $f = 64/N_R$.

From the pressure drop, $6P/L = \frac{1}{2}\rho v^2 f/D = 32 v\eta/D^2$, the flow rate $Q = \pi D^2 v/4$ of the laminar flow is given by

$$Q = \frac{\pi D^4}{128\eta}(6P/L), \tag{1.1}$$

where L is the length of the pipeline.

For most crude oil pipelines, when $N_R > 2300$, the flow is turbulent. While the intention is for the oil to flow along the pipeline, the turbulence impedes this purpose by causing the flow to move in all other directions, resulting in significant loss of energy. Essentially, with turbulence, we need much more power to pump the oil to maintain the desirable flow rate.

A turbulent flow with $2300 < N_R < 100\,000$ can have its friction factor estimated by the Blasius relation [5],

$$f = 0.3164/(N_R)^{0.25}. \tag{1.2}$$

The flow rate of the turbulent flow is then given by

$$Q = 2.2526\frac{D^{19/7}}{\rho^{3/7}\eta^{1/7}}(6P/L)^{4/7}. \tag{1.3}$$

It is clear from Eqs. (1.1) and (1.3) that the transfer of fluids via laminar flow is energetically far more efficient than that via turbulent flow. For example, to increase the flow rate by 30% we only need to increase the pressure by 30% for laminar flow, but for a turbulence flow we need to increase the pressure by 58.3%; much more energy is needed. Therefore, suppressing turbulence is crucial. This is also the reason why many pipelines use a drag-reducing agent (DRA), an additive made of polymer chains, to suppress turbulence [6]. A DRA indeed suppresses the turbulence, but it increases the oil's effective viscosity; therefore, it has no effect on laminar flows.

This crucial issue is challenging: To enhance the flow output, the viscosity along the flow direction needs to be reduced. In parallel, to suppress turbulence, the oil's viscosity in the directions perpendicular to the pipeline axis need to be raised as turbulence always starts from vortices with the motion in the directions perpendicular to the flow first. Thus, we should make the oil's viscosity anisotropic: Along the pipeline direction it should be reduced and in the directions perpendicular to the flow, it should be significantly increased.

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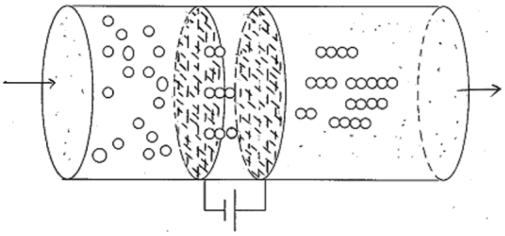

FIG. 1. As the liquid suspension flow passes a strong local electric field, the suspended particles are aggregated into short chains along the field direction.

Then the oil will only move along the pipeline axis to become laminar even if the Reynolds number is much higher than 2300.

In this paper, we report that electrorheology (ER) provides an efficient solution for this issue [7,8]. When we apply a strong electric field along the flow direction in a small section of pipeline (Fig. 1), the strong field polarizes the suspended particles inside the base liquid and aggregates them into short chains along the flow direction. Such aggregation breaks the rotational symmetry and makes the fluid viscosity anisotropic. Along the flow direction, the viscosity is significantly reduced, but in the directions perpendicular to the flow, the viscosity is substantially increased. Therefore, all vortices and rotating motions are suppressed; hence the turbulence is suppressed. Only the flow along the pipeline is enhanced. Our recent field tests on pipelines fully support the theoretical prediction. The method is extremely energy efficient since it only aggregates the particles and does not heat the suspensions.

Similar technology was initially introduced in 2006 for crude oil as a method to reduce crude oil viscosity [9]. However, its effect on turbulence was unknown then. Recently the Rocky Mountain Oilfield Testing Center (RMOTC) of the U.S. Department of Energy published three reports, showing that this new technology is energy efficient in reducing crude oil viscosity and is feasible for pipelines [10–12]. The rapid development of this new technology asks us to investigate this important issue. Now we have found that this method also effectively suppresses turbulence.

II. A MODEL AND TECHNOLOGY

The viscosity of most fluids is isotropic. The important exception is nematic liquid crystal. When its molecules are aligned by a magnetic field in the field direction, it has very low viscosity along the field direction. Meanwhile, its viscosity in the directions perpendicular to the magnetic field is very high [13]. The nematic liquid crystal example provides important insight for our case.

Let us consider a liquid suspension model which has small spherical particles of radius a suspended in a base liquid with viscosity η_0. According to Einstein [14], if the particle volume fraction ϕ is very low, the viscosity of the suspension η is given by

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

The factor 2.5 is the intrinsic viscosity for spheres. For high ϕ, Krieger and Dougherty derived the viscosity [15]

$$\eta = \eta_0(1 - \varphi/\varphi_m)^{-2.5\varphi_m}. \tag{2.2}$$

where φ_m is the maximum volume fraction for randomly packing the particles. This clearly indicates that the suspension's viscosity can increase dramatically as ϕ approaches φ_m even though η_0 is very low. For nonspherical particles, the generalized formula is given by

$$\eta = \eta_0(1 - \varphi/\varphi_m)^{-\nu\varphi_m}, \tag{2.3}$$

where ν is the intrinsic viscosity for the nonspherical particles.

We assume that the suspension is flowing along a pipeline. In a small section of the pipeline, we apply a strong electric field parallel to the flow (Fig. 1). Since the dielectric constant for the particles ε_p is different from the dielectric constant of the base liquid ε_f, the particles are polarized in the electric field,

$$\dot{p} = \varepsilon_f \dot{E}_{\text{loc}} a^3(\varepsilon_p - \varepsilon_f)/(\varepsilon_p + 2\varepsilon_f), \tag{2.4}$$

where $\dot{E}_{\text{loc}}$ is the local electric field acting on the sphere, which is stronger than the applied electric field. In cgs units, the interaction between two induced magnetic dipoles takes

$$U = p^2(1 - 3\cos^2\theta)/(\varepsilon_f r^3), \tag{2.5}$$

where r is the distance between the two particle centers and θ is the angle between the field and the line joining the two dipoles. When the two particles align in the field direction and touch each other, $\theta = 0$ and $r = 2a$, U has the minimum, $U_{\min} = -p^2/(4\varepsilon_f a^3)$.

Before the electric field is applied, the particles are randomly distributed. Therefore, the average distance between two neighboring particles is $n^{(-1/3)}$, where the particle density $n = \varphi/(4\pi a^3/3)$. If the two particles are not aligned as a chain along the field direction, their dipolar interaction energy is U_i, $U_i > U_{\min}$. The probability for two neighboring particles to aggregate is estimated as $\{1/[1 + \exp[(U_{\min} - U_i)/k_B T]]\}$. As $(U_{\min} - U_i)$ is negative and increases with the applied electric field, a strong electric field will force the particles to aggregate into short chains along the field direction.

In ER fluids, after a strong electric field is applied, the suspended particles quickly form chains and the chains aggregate into thick columns. The whole process only takes a couple of milliseconds [16,17]. While the field induced dipolar interaction in other liquid suspensions is not as strong as that in ER fluids, the basic physics remains the same. For example, in asphalt-base crude oil, the asphalt particles have $\varepsilon_p = 2.7$ while the base liquid, gasoline, has $\varepsilon_f = 2.0$. If the asphalt particles absorb moisture, their dielectric constant is further increased. In paraffin-base crude oil, the base liquid gasoline has $\varepsilon_f = 2.0$, the paraffin wax particles have dielectric constant 2.5, and the suspended sulfur dioxide particles have dielectric constant 15. Therefore, in a strong electric field, these particles are polarized and aggregate into short chains.

Now let us estimate the required time for such aggregation. The force between two neighboring particles is about $6p^2 n^{4/3}/\varepsilon_f$. From this force and the Stokes drag force $6a\pi\eta_0 v$, we estimate the particles' average velocity

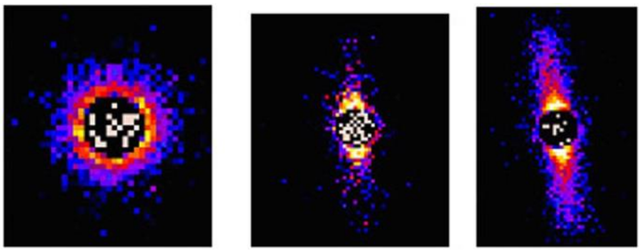

FIG. 2. (Color online) Small-angle neutron scattering has confirmed the aggregation. With no electric field, the scattering is isotropic and sparse, indicating the particles are randomly distributed in the oil (left). Under an electric field of 250 V/mm (middle), the scattering reveals short chains of particles aggregated along the field direction. When $E \geqslant 400$ V/mm, the short chain has a prolate spheroid shape (right).

$v = p^2 n^{4/3}/(\pi\eta_0 a\varepsilon_f)$. The time required for two neighboring particles to come together is about

$$\tau = n^{-1/3}/v = \frac{\pi(4\pi/3\varphi)^{5/3}\eta_0(\varepsilon_p + 2\varepsilon_f)^2}{\varepsilon_f(\varepsilon_p - \varepsilon_f)^2 E_{\text{loc}}^2}. \tag{2.6}$$

Take asphalt-base crude oil as an example. With $\varepsilon_p = 2.7$, $\varepsilon_f = 2.0$, $\varphi = 0.5$, $\eta_0 = 1$ P, and $E_{\text{loc}} = 1000$ V/mm, we have τ around 4.5 s. When the particles stay inside the electric field for a time longer than τ, the particles will be aggregated into short chains. Therefore, the aggregation for crude oil is quite fast.

A recent small-angle neutron scattering at the NIST Center for Neutron Research has confirmed this aggregation inside crude oil under a strong electric field [18]. As shown in Fig. 2, with no electric field, the scattering is isotropic and sparse, indicating the particles are randomly distributed in the oil. Under an electric field of 250 V/mm (middle), the scattering reveals short chains of particles aggregated along the field direction. When $E \geqslant 400$ V/mm, the neutron scattering signal clearly indicates that the short chain has a prolate spheroid shape. We note that the measured electric field here is the applied electric field. The local electric field E_{loc} acting on the particles is usually much stronger than the applied electric field.

Our neutron scattering experiment also found that the size of suspended particles inside crude oil varies, but most of them are around 30–40 nm. The interactions among the suspended particles are very weak; therefore, a suspension with noninteracting particles is a good model.

Before the electric field is applied, the suspension's viscosity is isotropic. After the short chains are aggregated, the viscosity becomes anisotropic. Along the field direction, the viscosity is significantly reduced, while in the direction perpendicular to the field, the viscosity is tremendously increased. Based on the neutron scattering information, we can approximate the short chain by a prolate spheroid with its rotational z axis along the flow direction,

$$(x^2 + y^2)/b^2 + z^2/a^2 = 1. \tag{2.7}$$

For such spheroid, the intrinsic viscosity along the z axis, ν_z, is much smaller than that of the intrinsic viscosity along the other direction, $\nu_\perp$ [19]. If $(a-b)/a = 0.9$, for example, we have $\nu_z = 2.01$, while $\nu_\perp = 4.48$.

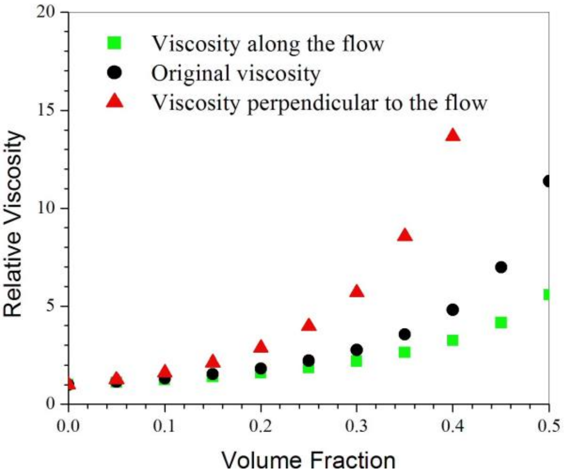

FIG. 3. (Color online) The electric field makes the viscosity along the flow direction much lower than the original viscosity, while it raises the viscosity perpendicular to the flow much higher than the original viscosity.

Before we use Eq. (2.4) and the above information to calculate the viscosity of treated oil, we also note that recent work finds that $\varphi_{\max}$ strongly depends on the particle shape. For spheres, $\varphi_{\text{sphere}} = 0.64$ and for spheroids, $\varphi_{\text{spheroid}} \approx 0.72$, higher than that for spheres [20,21].

If the suspension has $\varphi = 0.5$, the original relative viscosity from Eq. (2.3) is $\eta/\eta_0 = 11.38$. After the electric field is applied, with $\nu_z = 2.01$ and $\nu_\perp = 4.48$, the viscosity along the field direction is reduced to $\eta_z/\eta_0 = 5.56$, down 51.1%, while the viscosity perpendicular to the field is increased to $\eta_\perp/\eta_0 = 45.80$, up 302%. The electric-field-treated crude oil is now similar to a flow of nematic liquid crystal with its molecule alignment in the flow direction [13]. In Fig. 3, we plot the original viscosity versus the viscosities of treated suspensions at various volume fractions. As the volume fraction is getting higher, the viscosity reduction along the flow direction is getting more significant and the viscosity perpendicular to the flow is also getting much higher.

Since the viscosity in the directions other than the flow direction is increased substantially, the turbulence is suppressed as the vortices in turbulence must have the fluid moving in the direction transverse to the pipeline axis. For this purpose, the aggregated short chains play a similar function as polymer additives in DRA. However, this ER technology has no additives and thus is friendly to the refineries in the crude oil case. Moreover, the technology also significantly reduces the viscosity along the flow direction and enhances the flow output, while DRA cannot reduce the oil's viscosity.

Because of the Serge effect [22], the aggregated chains in the laminar flow will also migrate toward the center of the pipe where the shear rate is minimized. Therefore, this technology will also reduce the sedimentation on the pipeline wall. All of these factors are essential for significant improvement of the suspension throughput via pipelines.

There is an important question remaining to be answered. How long can such anisotropic viscosity last outside the electric field? In absence of other disturbances, such as in a constant laminar flow state, the particles in the suspension separate diffusively due to the Brownian motion. The aggregated short chains make the suspension as a viscoelastic fluid. On a short time scale, the force on a tagged particle inside the chains is elastic, proportional to the displacement. On a long time scale, the force on a tagged particle inside the chains becomes viscous, proportional to the velocity. For such viscoelastic fluid, it is well known that the velocity autocorrelation of a tagged particle has long time tails [23,24],

$$C(t - t') = \langle \dot{v}(t) \cdot \dot{v}(t') \rangle = \alpha(t - t')^{-3/2}, \qquad (2.8)$$

where $t > t'$, $\langle \rangle$ is the statistical average, $\alpha = k_B T \sqrt{\rho_f}/(12\pi^{3/2}\eta_0^{3/2})$, and ρ_f is the density of the base liquid. Because of the constraint for middle particles inside the short chains, the Brownian motion will diffuse off the particles at the ends first. In addition, the Serge effect also forces the particles to migrate toward the center of the pipe. Therefore, the end particles diffuse away from the chains mainly along the axial direction. As

$$\frac{\partial^2}{\partial t \partial t'} \langle [\dot{r}(t) - \dot{r}(t')]^2 \rangle = -2\langle \dot{v}(t) \cdot \dot{v}(t') \rangle = -2\alpha(t - t')^{-3/2}, \qquad (2.9)$$

the mean square displacement is given by

$$\langle [\dot{r}(t) - \dot{r}(t')]^2 \rangle = 2D(t - t') - 8\alpha(t - t')^{1/2}, \qquad (2.10)$$

where the diffusion constant $D = k_B T/(6\pi a \eta_0)$. Let assume that an end particle will be considered as detached from the chain if it deviates from the chain by a distance $\delta = 4$ μm or more. Then from Eq. (2.10), the required time for such separation of one particle is given by

$$\delta t = \frac{\delta^2}{2D} + \frac{4\alpha}{D}\sqrt{\frac{\delta^2}{2D} + \frac{4\alpha^2}{D^2}} + \frac{8\alpha^2}{D^2}. \qquad (2.11)$$

The first term is the conventional diffusion result. The addition terms slow the diffusion process. With $a = 1$ μm and $\eta_0 = 1$ P, the estimated time to let one end particle diffuse away is more than 1 h at room temperature. Therefore, while outside the electric field, the viscosity will return to the original value eventually, the process is quite slow and takes many hours, which is excellent for many applications. Our experiments have fully confirmed this prediction. On the other hand, after all aggregated particles are disintegrated, the suspension returns to the rheological state prior to the electric treatment. Reapplication of the electric field will again induce anisotropic viscosity. The process is repeatable.

III. FIELD TEST RESULTS

A. Viscosity reduction

Recently we conducted several field tests on a crude oil pipeline. The first set was carried out on the testing pipeline route at the RMOTC facility near Casper, Wyoming. As shown in Fig. 4, our viscosity reduction device, AOT (Applied Oil Technology), was connected in a 7.219-km testing route. Inside the pipeline, there were sensors to monitor the oil pressure and temperature. The inner diameter of the pipeline was $D = 14.163$ cm. The pump was a positive displacement (PD) pump, which could have a very stable flow rate.

FIG. 4. (Color online) The AOT device is placed downstream next to the pump.

The AOT device had a strong local electric field applied along the flow direction when it was turned on. The device was placed downstream next to the pump. The crude oil flowed through our device, and went to the pipeline. We have two choices for our field tests. (1) *Closed loop*. After one circle, the oil came back to the pump, through the device, and went back to the pipeline again, repeating the circulation. (2) *Open loop*. After one circle, the oil returned to a storage tank, while fresh oil from another supply tank continuously flowed to the pump, through the device, and went to the pipeline.

In our tests, we first checked the viscosity reduction along the flow direction in the laminar flow state. The pump was set at a constant flow rate 46.56 m^3/h. The flow velocity was 82.09 cm/s. The API 34 crude oil had a viscosity 81.6 cP at 12.1 °C, and density 0.8459 g/cm^3. Thus $N_R = 1205.24$ and the flow was laminar. Before the AOT device was turned on, the pressure loss was 1.07 bars/km. We turned on the device and applied an electric field of 2300 V/cm to the crude oil. The pressure loss was reducing as the treated crude oil flowed into the loop. After the loop was filled with all treated crude oil, the pressure loss was reduced to 0.641 bar/km, down 40%, indicating that the viscosity along the flow direction was also reduced by 40%, down to 48.95 cP. After the device was turned off, the pressure loss gradually returned to the original value as the untreated crude oil pushed the treated crude oil away (Fig. 5). We also paid attention to the pump power. Before the AOT device was turned on, the pump power was 14.2 kW. After the AOT device was turned on, the pump power was gradually reducing. When the treated oil filled up the whole pipeline, the pump power was down to 8.9 kW as the pressure loss was at the minimum. The energy saving was 5.3 kW, while the AOT only consumed less than 100 W electric power.

The viscosity reduction tests were repeated several times and the results were consistent.

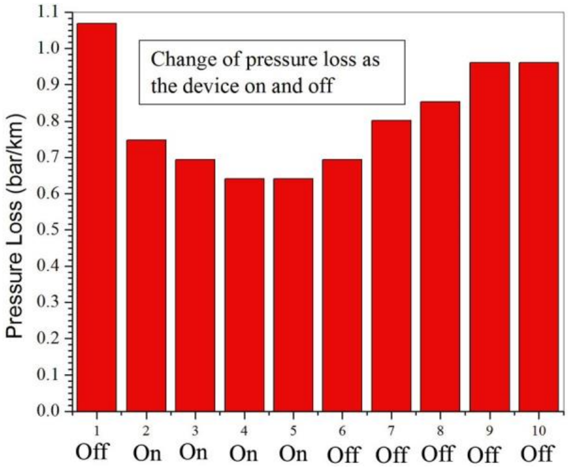

FIG. 5. (Color online) After the AOT device was turned on, there was less pressure loss. When the loop was filled with all treated crude oil, the pressure loss was down 40%. After the device was turned off, the pressure loss returned to the original value as the untreated crude oil pushed the treated crude oil away.

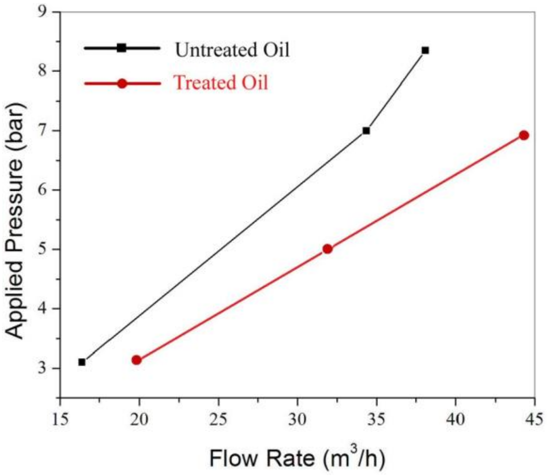

FIG. 6. (Color online) The electric-field-treated oil flow has pump pressure linearly proportional to the flow rate, indicating the flow remains laminar as the Reynolds number reaches 6348. The untreated oil has pump pressure increasing much faster than the linear relation with the flow rate, indicting the flow becomes turbulent when the Reynolds number >2300.

B. Suppressing turbulence

We first carried out the suppressing turbulence tests with Reynolds number N_R not too far from the critical value 2300. At RMOTC, we set the pump at a constant flow rate 95.392 m^3/h and the flow velocity $v = 168.2$ cm/s. Before we turned on the AOT device, the crude oil had viscosity 93.7 cP at 11.5 °C. Thus $N_R = 2160.82$ and the flow was laminar. The pressure drop along the pipeline was 2.51 bars/km. After we turned on the electric field 2300 V/cm, the viscosity along the flow direction was reduced to 85.5 cP. The Reynolds number along the pipe direction was increased to 2368.1, which could be in the turbulence region under the normal situation. If the flow were in the turbulence region, from Eq. (1.3), the pressure loss would be increased to 3.85 bars/km. In fact, the pressure loss along the pipeline was actually reduced to 2.296 bars/km and the pump power was reduced from 57.4 to 52.4 kW. This confirmed that the flow remained laminar.

To further reduce the viscosity along the flow direction, we increased the electric field to 3000 V/cm and the crude oil viscosity was down to 75.6 cP, and the Reynolds number along the pipeline increased to 2678.2. Under a normal situation, the flow should be in the turbulent region and the pressure loss would jump to 3.73 bars/km. In fact, the pressure loss was reduced to 2.03 bars/km, confirming that the flow remained laminar. The pump's power was down to 48.3 kW. The tests were repeated several times and the results remained the same.

Of course, it is more important to test the situation with N_R well above 2300. Thus we conducted another field test with the AOT device (Fig. 6) at Daqing oil field in China. The Daqing crude oil is a paraffin-base crude oil with a pour point around 32 °C, below which the oil is frozen inside the pipeline. Presently, heating is crucial to transport the oil via pipeline. The oil is typically heated at one heating station to 55 °C–72 °C and flows through a pipeline of 15–20 km to another heating station to be heated again. The pipeline has an inner diameter 14.5 cm.

Before the AOT device was operated, we made several tests to confirm that the oil flow was turbulent. For example, when the oil is heated to 55.6 °C, its kinetic viscosity was 20.36 cS. Under a pressure of 7.0 bars, the flow rate was 34.46 m^3/h and $N_R = 4128.3$. When we heated the oil to 71.1 °C, the oil viscosity was down to 14.92 cS, but the flow rate was only increased to 36.0 m^3/h, close to the estimation from the Blasius formula, Eq. (1.3), $34.46 \times (20.36/14.92)^{1/7} = 36.02\ \mathrm{m}^3/\mathrm{h}$. If the flow were laminar, the flow rate should be 47.02 m^3/h. This also indicated that heating cannot suppress turbulence. On the other hand, at 55.6 °C, if we increased the pressure to 8.35 bars, the flow rate only increased to 38.1 m^3/h, close to the estimation by the Blasius formula $34.46 \times (8.35/7)^{4/7} = 38.11$. If the flow were laminar, the flow rate should be 41.1 m^3/h. All these indicated that when $N_R > 2300$, the oil flow was turbulent inside the Daqing oil pipeline.

To test the AOT device, we started with a laminar flow. At 55.6 °C and under 3.1 bars pressure, the flow rate was 16.4 m^3/h and the Reynolds number $N_R = 1964.7$. Then we turned on the AOT device, producing an electric field 13.3 kV/cm to treat the oil. Its viscosity along the flow direction was down to 17.02 cS. When the pressure was remaining the same, as the treated oil filled the pipeline, the flow rate was gradually increased to 19.6 m^3/h, close to $16.4 \times (20.36/17.02) = 19.62\ \mathrm{m}^3/\mathrm{h}$. This indicates that the flow remained laminar while the Reynolds number was increased to 2808.9.

In order to test the situation at a much higher Reynolds number, we increased the pump pressure to 5.0 bars first while maintaining the electric field at 13.3 kV/cm. The flow rate was increased to 31.6 m^3/h with $N_R = 4528.6$. The flow remained laminar because the flow rate was close to $19.6 \times (5.0/3.1) = 31.61\ \mathrm{m}^3/\mathrm{h}$. Afterwards, we increased the pressure to 7.0 bars while keeping the electric field at 13.3 kV/cm. The flow rate was increased to 44.3 m^3/h with $N_R = 6348.7$. The flow

TABLE I. Test results with Reynolds number exceeding 2300.

Flow rate (m^3/h)	Kinetic viscosity (cS)	Reynolds number	Electric field (V/mm)	Pressure (bars)	Temperature (deg C)	Flow state
34.36	20.36	4128.3	0	7.0	55.6	Turbulent
36.0	14.92	5890.3	0	7.0	71.1	Turbulent
38.1	20.36	4565.6	0	8.35	55.6	Turbulent
16.4	20.36	1964.7	0	3.1	55.6	Laminar
19.6	17.02	2808.9	1333	3.1	55.6	Laminar
31.6	17.02	4528.6	1333	5.0	55.6	Laminar
44.3	17.02	6348.7	1333	7.0	55.6	Laminar

still remained laminar because the flow rate was close to $19.6 \times (7.0/3.1) = 44.25$ m^3/h. If the flow were turbulent, the flow rate could be only about $19.6 \times (7/3.1)^{4/7} = 31.2$ m^3/h. These results are plotted in Fig. 6 and listed in Table I. They clearly confirm that the treated crude oil suppresses turbulence effectively.

C. Duration of the effect

We also carried out tests to see how long such anisotropic viscosity can last after one treatment. Since the anisotropic viscosity is the result of the aggregated short chains along the flow direction, both the viscosity reduction along the flow direction and the effect to suppress turbulence will diminish if the aggregated short chains are completely disassembled.

To answer the above question, we first conducted a number of tests in our laboratory with various oil samples, including both asphalt-base crude oil and paraffin- base crude oil.

Shown in Fig. 7 are the results for asphalt crude oil produced in Canada. The untreated crude oil sample had viscosity 210.1 cP at 25 °C. After the electric-field treatment, its viscosity along the field direction was down to 142.5 cP at 25 °C, a reduction of 32.2%. We kept the treated oil sample at 25 °C in a container and measured its viscosity at various times afterwards. The viscosity reduction effect lasted over a span of several hours, with viscosities increasing only up to 164.3 cP after 2 h, 170.0 cP after 4 h, 176.1 cP after 8 h, 179.8 cP after 14 h, and 181.1 cP after 24 h. All these are plotted in Fig. 7.

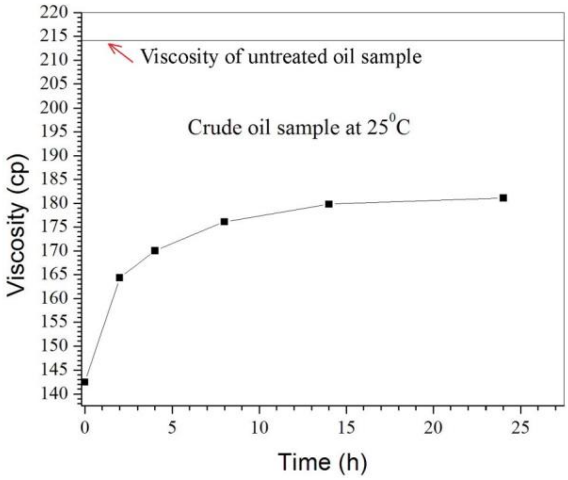

FIG. 7. (Color online) Outside the electric field, the viscosity of treated crude oil goes up slowly after the treatment.

The paraffin-base crude oil shows similar results. For example, at 35.1 °C, the untreated Daqing crude oil had viscosity 911 cP. We applied an electric field of 8 kV/cm to treat it first. We then store the treated oil sample at 35.1 °C for hours. The treated sample had viscosity 390 cP immediately after the treatment. It increased to 408 cP after 4 h, 421 cP after 8 h, 441 cP after 12 h, 480 cP after 23 h, and 487 cP after 26 h.

We also did tests with light crude oil at low temperature. For example, at −3.1 °C, the API 34 crude oil sample from RMOTC had viscosity 261.3 cP. Application of an electric field 1.6 kV/mm reduced it to 121.1 cP, down 53.7%. It increased to 151.2 cP after 12 h and 172.4 cP after 24 h [25].

All these lab tests indicate that while the aggregated chains are gradually disassembled with time, the process is slow and the viscosity reduction effect, i.e., the anisotropic viscosity, lasts more than 24 hours. This confirms the theoretical results in Eq. (2.11). On the other hand, we want to mention that our lab tests have also confirmed that the electric-field-treated crude oil will eventually have its viscosity returned to the original value. If the original viscosity is higher, this process takes more time.

Of course, it is more important to test the effect's duration on a pipeline directly. Thus at our recent field test on a pipeline at RMOTC, we studied this issue and found that the viscosity reduction lasted about 11 h in the pipeline. As shown in Fig. 8, in the evening we turned the AOT device on to treat the crude oil. The pipeline loop was closed. The PD pump drove the oil to go through the AOT device, flowing to the pipeline. After one circle, the oil came back to the pump and reentered the same route. The AOT device was continuously on for more than 6 h to allow all the oil inside the pipeline to be treated. The untreated oil had viscosity 118.06 cP. The electric field brought the viscosity along the flow direction to 51.8 cP, down 56.12%. At midnight, we turned off the AOT device and monitored the oil flow inside the pipeline. The treated oil kept the reduced viscosity for about 11 h and the pressure loss and pump power remained the same. Around noon the next day, we noticed that

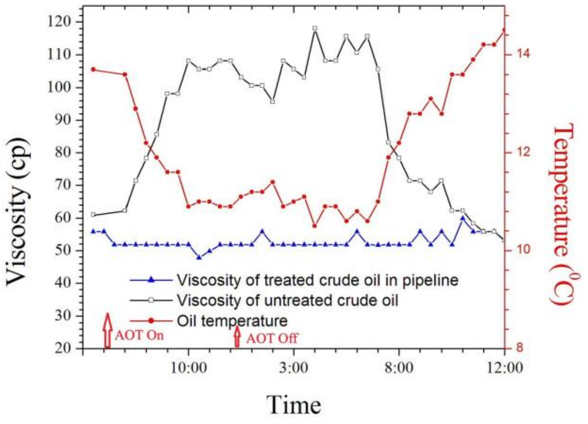

FIG. 8. (Color online) During the test, the treated crude oil kept its reduced viscosity for 11 h after the AOT device was shut off.

the pressure loss and pump power began to go up, indicating that the viscosity reduction effect had begun to disappear.

The 11-h duration with the oil flowing inside the pipeline is shorter than the duration found in our lab tests. This is understandable. During our 11-h field test, the oil circled the loop about 5 times. After every circle, the oil needed to pass the pump. While we selected a PD pump, not a centrifugal pump, to minimize the possibility of breaking the short chains by the pump, it was impossible to avoid breaking some chains during the pumping process. In addition, as crude oil flows via pipeline, besides the Brownian motion, the aggregated chains also experience some shear forces in the pipeline. Therefore, it was reasonable that our field test did not find that the effect in the pipeline lasted as long as that in our lab tests.

On the other hand, 11 h is long enough for industrial applications. If the oil does not need to pass through the pump several times, the effect's duration may be longer. Moreover, once all chains are broken, reapplication of the electric field to the oil will work again. If after the field is turned off, the suspension experiences some other disturbance in addition to the Brownian motion, the disassembly process may be accelerated and the viscosity reduction will last for a shorter period than the case without other disturbance.

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

The effect to suppress turbulence should have the same duration as the viscosity reduction because both of them are the result of anisotropic viscosity. In addition, if the turbulence were not suppressed, the aggregated short chains could be broken by turbulence quickly [26]. Therefore, in some sense, the two effects help each other.

IV. CONCLUSION

While further studies and tests about turbulence may be needed, our present test results confirm that application of electrorheology can aggregate suspended particles inside a liquid suspension to form short chains along the flow direction, making the suspension's viscosity anisotropic. Hence it suppresses turbulence in pipelines and enhances the flow output. While our present tests are limited to crude oil, this technology is universal and applicable to all kinds of liquid suspensions. The basic physics discussed here is also applicable to magnetic field if the suspended particles and the base liquid have different magnetic permeabilities [27].

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