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Chapter 6

Application of Electrorheology to Improve Crude Oil Flowing Properties Through Pipeline

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Additional information is available at the end of the chapter

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Abstract

This chapter describes a new technology based on electrorheology (ER) that simultaneously reduces oil viscosity and suppresses flow turbulence. The application of a strong electric field in a small section of the oil pipeline causes the polarization of suspended particles contained in the oil phase aggregating them into short chains along the flow direction. This particle aggregation breaks the rotational symmetry and makes the oil viscosity anisotropic, which in turn reduces the oil viscosity along the flow direction. Simultaneously, oil viscosity increases in the direction perpendicular to the flow, which supresses flow turbulence. This green technology does not involve the addition of chemicals to the oil phase and is environmentally friendly. This approach is also energy efficient because it only targets the particles suspended in the oil phase causing the formation of aggregates. Furthermore, heat is not required to reduce the viscosity of the oil phase. Neutron scattering experiments and field tests demonstrate the effectiveness of this technology. Electrorheology will play an important role during enhanced heavy oil recovery and/or production operations and transportation via pipeline.

Keywords: electrorheology, crude oil viscosity, turbulence suppression, anisotropic viscosity, pipeline

1. Introduction

Currently, hydrocarbons remain as the leading energy source. While the amount of conventional light crude oil becomes less and less available, heavy crude oils and offshore crude oils are becoming very important resources. The high viscosity of these hydrocarbons becomes a critical issue during oil recovery and/or production operations. This is also a problem for offshore crude oil production, which also shows very high viscosities because of the low temperatures (i.e. 1.5–1.6°C) of the reservoirs.

The flow of high viscosity oils through pipelines is very difficult, requiring much higher pumping power. This creates complications during oil production and transportation. Therefore, reducing the viscosity of the crude oil is paramount [1–4].

Although, there has been extensive research into this issue for more than 30 years, little progress has been achieved thus far. Currently, the dominant method to reduce the viscosity of heavy crude oil remains heating by the injection of steam and/or hot water. The application of these thermal processes requires time due to heat transfer issues. Furthermore, these processes are energy-intensive and environmentally unfavorable (i.e. large volumes of CO_2 emissions during the generation of steam). Moreover, the application of thermal methods for the recovery of offshore heavy crude oils is technically difficult and expensive.

Flow turbulence is an additional issue relevant here [5–9]. The efficient transportation of crude oil via pipelines requires the suppression of turbulence, because under turbulent flow regime, much more pumping energy is required.

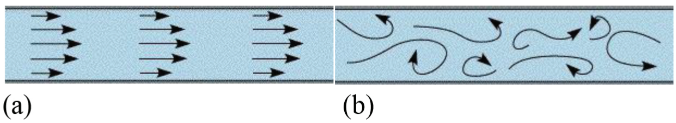

Figure 1. (a) Laminar flow in pipeline. (b) Turbulent flow in pipeline.

Flow is laminar when the Reynolds number is (**Figure 1a**):

$$N_R = \rho v D / \eta \leq 2300 \tag{1}$$

where D is the diameter of the pipeline, v is the average flow velocity, ρ is the oil density, and η is the oil viscosity. Equation (2) gives the friction factor for laminar flow:

$$f = 64 / N_R \tag{2}$$

The pressure drop ΔP is as follows,

$$\Delta P / L = \tfrac{1}{2} \rho v^2 f / D = 32 v \eta / D^2 \tag{3}$$

where L is the length of the pipeline.

Equation (4) gives the flow rate Q for laminar flow:

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

Figure 1b shows a turbulent flow inside a pipeline. Flow is turbulent when the Reynolds number is higher than 2300 ($N_R > 2300$), which causes an erratic flow pattern in all directions, resulting in significant loss of energy. Therefore, the flow of fluids (i.e. heavy crude oil) under turbulent flow regime requires much more pumping power.

The friction factor for turbulent flow within 2300 $N_R < 100000$ can be estimated by the Blasius equation [10] as follows,

$$f = 0.3164 / (N_R)^{0.25} \tag{5}$$

Equation (6) gives the flow rate for turbulent flow:

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

Equations (4) and (6) indicate that flow under laminar conditions is energetically more efficient than under turbulent conditions. For example, under laminar flow conditions, a 30% increase in the oil flow rate requires a 30% increase in pumping pressure; while under turbulent flow conditions, it requires a pressure increase of 58.3%; which means that the pump needs to provide 94.3% more power. Therefore, suppressing turbulence is crucial during oil transportation by pipelines. For instance, a common practice in the field is to add drag-reducing agents, DRA (i.e. chemical additives based on polymers) to the oil before pumping it through pipelines to suppress turbulence [11]. However, the addition of DRA agents increases the oil viscosity, and it has no effect on laminar flow.

The crucial and challenging issue is clear: the efficient transportation of oil through pipelines requires the simultaneous reduction of the oil viscosity and suppression of turbulence. These issues are not only crucial for the engineering field but also important for several other technical fields, because turbulence remains as one of the most important unsolved problems of classical physics [8].

Currently, conventional pipeline transportation methods cannot simultaneously and effectively reduce fluid (i.e. crude oil) viscosity and suppress turbulence. Thermal methods for crude oil viscosity reduction cannot suppress turbulence. As the temperature increases, the oil viscosity decreases, the Reynolds number increases, and as a result turbulence increases. Other conventional technologies to reduce oil viscosity, such as heavy oil dilution with solvents, cannot accomplish the simultaneous reduction of viscosity and suppression of turbulence, either.

An unconventional technology is required to solve these challenging issues. It is necessary to enhance oil flow output by simultaneously decreasing the oil viscosity along the flow direction, while increasing it in the direction perpendicular to the pipeline axis, because turbulence always starts from the vortices and expands perpendicular to the flow direction. In other words, oil viscosity must be anisotropic: reduced along the pipeline direction and increased in the direction perpendicular to the flow, which makes the flow regime laminar along the pipeline axis even if N_R>> 2300.

This chapter describes the electrorheology (ER) technology, which provides an efficient solution for the simultaneous reduction of oil viscosity and suppression of turbulence during crude oil transportation via pipeline [2, 3, 9].

Crude oil is a liquid suspension, which depending on the chemical composition might contain particles suspended within the liquid hydrocarbon phase, such as asphaltenes, resins, fine sand particles, and wax particles. The application of a strong electric field in a small section of the pipeline causes the polarization of the suspended particles contained in the oil phase, aggregating them into short chains along the flow direction. This ER application is significantly different from traditional ER fluids, where the applied electric field is perpendicular to the flow direction, leading to increase the effective viscosity or even solidify the ER fluids [12]. Here the applied electric field and the aggregated chains are in the flow direction (**Figure 2**).

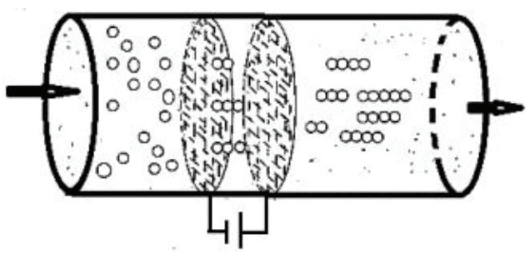

Figure 2. Aggregation of suspended particles into short chains under the influence of a local electric field.

Such aggregation breaks the rotational symmetry and makes the oil viscosity anisotropic, accomplishing two goals: the reduction of the viscosity along the flow direction and the substantial increase in the viscosity in the direction perpendicular to the flow. These viscosity changes supress all vortices and rotating motions; hence, turbulence is suppressed, which enhances the flow parallel to the pipeline horizontal axis. This green technology does not involve the application of chemical additives to the oil phase and is environmentally friendly. It is also energy efficient since it only aggregates the particles and does not heat the bulk of the oil phase. Neutron scattering experiments and field tests on pipelines fully support the theoretical approach of this technology. It is anticipated that electrorheology (ER) will play an important role during heavy crude oil recovery and/or production, enhanced oil recovery applications, and transportation through pipelines.

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2. The New Technology (ER)

Refined fractions of crude oil such as gasoline, kerosene, and diesel have very low viscosities and low dielectric constants. Paraffinic and heavier oils have higher viscosities because these oils contain randomly suspended paraffin, asphaltenes, resins, sulfur, and other solid compounds having large molecular weights. These suspended particles have higher dielectric constants that make them polarized in a strong electric field (**Figure 2**). Under the influence of a strong electric field, similar to conventional electrorheological fluids, these particles in crude oil form chains that aggregate into thick columns [12, 13, 15].

During the aggregation of dipoles into chains or chain-based columns, the total energy $U(N)$ of the system is negative making it energetically favorable. As the total number of particles, N, in the aggregated chain or column increases, the energy per particle $U(N)/N$ is more negative. The probability to have such structure of N aggregated particles is proportional to $\exp[-U(N)/k_B T]$. Therefore, an increase in N accelerates particle aggregation. The aggregated structure is more stable if it has more particles. For this reason, the formation of thick columns takes place in ER fluids under the application of an electric field.

In the ideal aggregated structure, all particles would aggregate into one thick column, body-centered tetragonal lattice [13, 14]. In reality, the aggregation process is very fast, and particle aggregation spontaneously spreads under the electric field leading to quick formation of many stable thick columns.

2.1. Neutron scattering experiments

Small-angle neutron scattering is a useful technique to confirm the induced aggregation of solid particles contained in crude oil when subjected to a strong electric field [15].

The NG7 Small-Angle Neutron Scattering or SANS facility, NCNR, is located in Gaithersburg, Maryland, USA. The SANS instrument is 30-m long, and it is equipped with a high-resolution

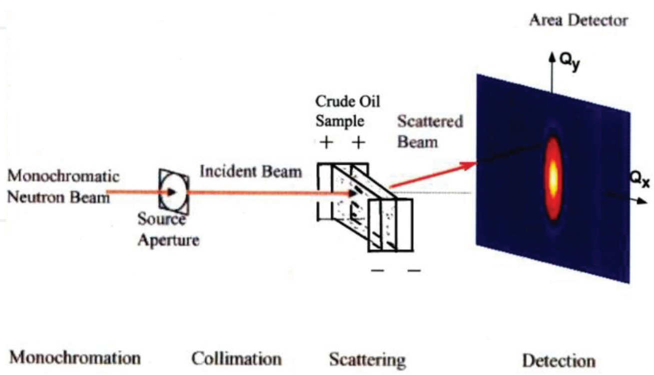

Figure 3. Neutron scattering experimental set-up.

2D detector and focusing refractive lenses. The *Q*-range of the instrument goes from 0.008 to 7.0 nm^{-1} to enable the detection of structural features in materials ranging from roughly 1 nm to over 500 nm.

As shown in **Figure 3**, the crude oil sample goes in a special capacitor, consisting of two pieces of cadmium electrodes and two pieces of quartz glass windows. The neutron beam passes through the quartz windows and through the crude oil sample into a detector. The application of a high voltage to the cadmium electrodes produces an electric field perpendicular to the neutron beam. Cadmium electrodes are suitable neutron absorbers, which reduces neutron scattering noise.

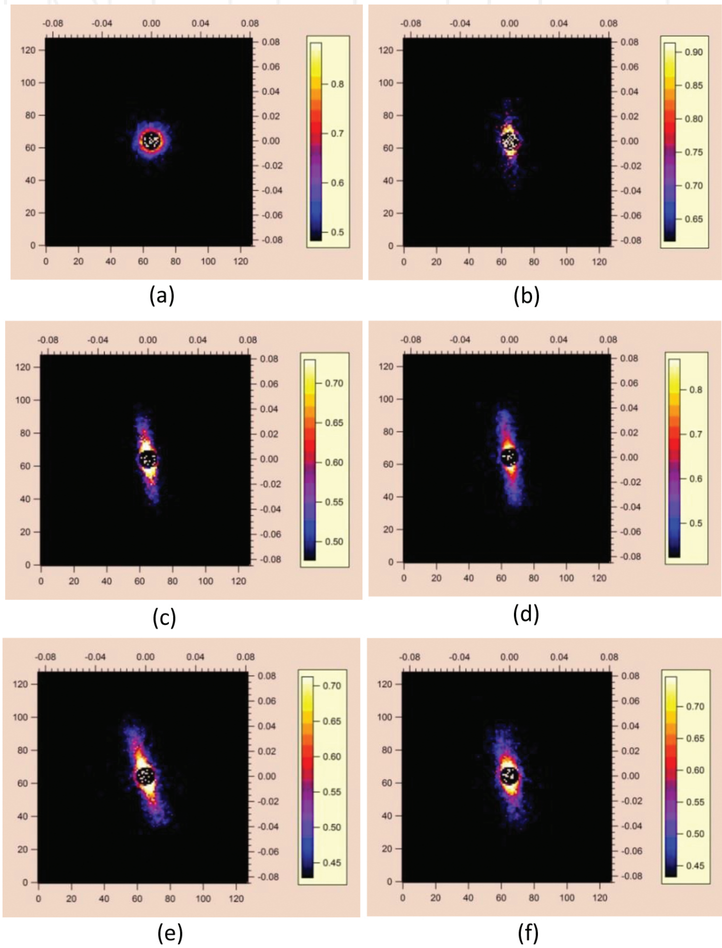

Figure 4. Scattering patterns at various electric fields obtained from a paraffin base crude oil. (a) E = 0 V/cm, (b) E = 2500 V/cm, (c) E = 4000 V/cm, (d) E = 7500 V/cm, (e) E = 11,000 V/cm, (f) E = 15,000 V/cm.

In this experimental work, the samples evaluated were a light paraffin base crude oil (API° 34) and a heavy asphalt base crude oil (API° 21). The test results have confirmed that under the influence of a strong electric field, the suspended particles from both the paraffin base crude and the asphalt base crude oil aggregated into short chains. As shown in **Figure 4a**, in the absence of an electric field, the scattering was isotropic and sparse indicating a random dispersion of particles in the oil phase. The application of an initial electric field of 250 V/mm induced the onset of particles aggregation. The scattering signal revealed that the particles suspended in the light paraffin base crude oil started to aggregate into a short chain with a length of 68 nm and a thickness of 34 nm (**Figure 4b**). As the applied electrical field increased to E = 400 V/mm, the neutron scattering signal indicated that the short chain acquired a prolate spheroid shape with a length of 75.2 nm and a thickness of 37.6 nm (**Figure 4c**). At a higher electrical field of E = 750 V/mm, the chain length increased to 94 nm long and the thickness to 38.4 nm (**Figure 4d**). At a higher electric field of 1100 V/mm, the chain reached a length of 94.8 nm and a thickness of 38.6 nm (**Figure 4e**). Finally, at the highest value of the electrical field applied of E = 1500 V/mm (**Figure 4f**), the chain dimensions were 94.8 nm length and 45 nm thickness. Therefore, as the electric field increases, the aggregated chains become longer and thicker (**Table 1**).

Electric field (V/mm)	Length 2a (nm)	Thickness 2b (nm)
0	~6	~6
250	68.0	34.0
400	75.2	34.8
750	94.0	38.4
1100	94.8	38.6
1500	94.8	45.0

Table 1. Aggregated short chains of light paraffin base crude oil.

The asphalt base crude oil showed similar behavior under the ER treatments at different electric field intensities. For example, under an electric field of 1000 V/mm, the asphalt particles aggregated into a short chain in a prolate spheroid shape with a length of 78 nm and a thickness of 50 nm [15].

Based on the neutron scattering information, it is possible to approximate the short chain to a prolate spheroid (**Figure 5**) with its rotational z-axis along the flow direction.

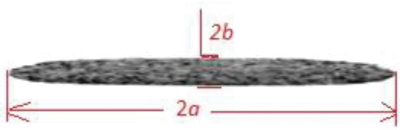

Figure 5. Aggregated short chains or prolate spheroids.

Equation (7) allows determining the dimensions of the prolate spheroid (short chain of agglomerates) as follows:

$$(x^2 + y^2) / b^2 + z^2 / a^2 = 1 \tag{7}$$

Here $a > b$ and the electric field is along the z-direction. Generally, a heavy crude oil contains numerous solid particles suspended within the bulk of the liquid hydrocarbon phase. In this case, the application of an electric field induces a strong aggregation of particles forming numerous short chains and/or prolate spheroids.

Einstein studied the viscosity of dilute liquid suspensions and found that the intrinsic viscosity for spheres is $[\eta] = 2.5$ [16]. For the prolate spheroids, the intrinsic viscosity along the z-axis $[\eta_{\parallel}]$ is smaller than 2.5, while the intrinsic viscosity along the directions perpendicular to the z-axis, $[\eta_{\perp}]$ is higher than 2.5. For crude oils with API° gravities lower than 34° (heavier crude oils), the aggregated chains will be longer than the aggregated chains observed in the nuclear scattering experiment for paraffinic oil. If for instance, it is assumed that $(a-b)/a = 0.8$, then $[\eta_{\parallel}] = 2.035$ and $[\eta_{\perp}] = 3.548$ [17]. This information of intrinsic viscosities enables the calculation of the viscosities using the Krieger-Dougherty equation [18],

$$\eta_i / \eta_0 = (1 - \phi / \phi_{\max})^{-[\eta_i]\phi_{\max}} \tag{8}$$

where η_i is the effective viscosity, η_0 is the viscosity of base liquid, $[\eta_i]$ is the intrinsic viscosity of the particles, and $\phi_{\max}$ is the maximum volume fraction for randomly packed particles. Recent work found that $\phi_{\max}$ strongly depends on the particle shape. For spheres, $\phi_{sphere} = 0.64$ and for spheroids $\phi_{spheroid} \geq 0.72$ [19, 20]. If the particle volume fraction $\phi = 0.5$, then the initial viscosity of the crude oil is $\eta = 11.38\eta_0$. After the electric field is applied, then the effective viscosity along the flow direction is reduced to $\eta_{\parallel} = 5.68\eta_0$, which corresponds to a viscosity reduction of 50.1%, while the effective viscosity perpendicular to the flow direction is increased to $\eta_{\perp} = 20.67\eta_0$ that represents a viscosity increase of 81.6%. The flow behaviour of this electric-field treated crude oil is similar to the flow of a nematic liquid crystal with its molecules in alignment with the flow direction [21].

A viscosity increase in the direction perpendicular to the flow causes the suppression of turbulence because the vortices in turbulent flow move in the direction transversal to the pipeline axis. For this reason, the formation of aggregated short chains in the bulk of the crude oil plays a similar function as the addition of drag-reducing agents (DRA) to the crude oil. However, the addition of DRA could cause further issues at the oil refineries. Moreover, the more significant aspect of this technology is the simultaneous reduction of viscosity, which enhances the flow output, while the addition of DRA to the oil phase cannot reduce the viscosity of the oil.

Another advantage of this technology is that the aggregated chains in the laminar flow migrate toward the center of the pipe that corresponds to minimum shear rate zone due to the Segré-Silberberg effect [22]. Therefore, this technology also reduces the sedimentation and/or deposition of particles on the pipeline walls. All these factors are essential for significant improvement of oil transportation via pipelines.

2.2. Laboratory evaluation of viscosity reduction

A series of laboratory tests evaluated the performance of different types of crude oils [23]. However, this chapter summarizes only the behavior of the Daqing crude oil, which is a well-known paraffinic crude oil with a pour point of around 30°C from the Daqing oil field, China.

The experimental procedure was as follows. The crude oil sample was loaded at the top of a cylindrical container. Underneath the cylinder, a valve allowed the flow of crude oil through three electrodes into a long capillary tube with a diameter of 0.2673 cm. A cup on a microbalance collected the crude oil that flowed down through the capillary tube. A computer connected to the microbalance recorded the oil mass as a function of time using a LabVIEW data acquisition system, which allowed determining the flow rate, Q. This experimental device was located inside an oven to keep the target temperature at 35.1°C during the experimentation. The middle electrode was connected to the positive output of the high-voltage power supply. The other two electrodes were connected to the negative output of the power supply. After the power supply was turned on, the strong electric field was produced in both capacitors along the flow direction, one vertically up and the other vertically down, forcing the suspended particles in the crude oil to aggregate into streamlined short chains along the flow direction causing the reduction of the crude oil effective viscosity. Since there are only dipolar interactions involved, such arrangement of the electrodes works well. It reduces the requirement of high voltage and makes the technology safer. **Figure 6** shows a picture of the experimental set-up.

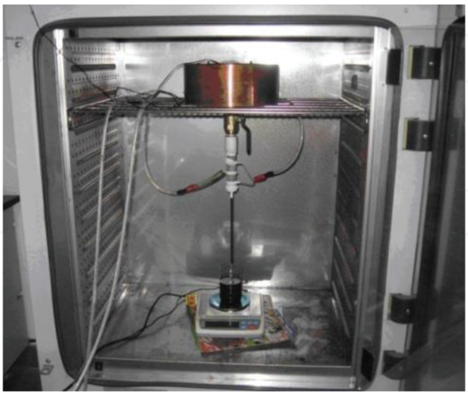

Figure 6. Experimental set-up.

In these experimental runs, the N_R was very low, and the crude oil flowed through the capillary tube under laminar flow conditions, which allowed determining the oil viscosity along the flow direction using Eq. (9),

$$\eta = \frac{\pi \rho^2 g R^4}{8Q}\left(1 + \frac{h}{L} - \frac{v^2}{2gL}\right) \tag{9}$$

where R and L are the respective radius and length of the capillary tube, h is the height of the oil level above the capillary tube, ρ is the density of the oil, and g is the acceleration of gravity. Equation (10) allows estimating the average flow velocity,

$$v = Q/(\rho \pi R^2) \tag{10}$$

where Q is the flow rate, R is the radius of the capillary tube, and ρ is the density of the oil.

In all the experimental runs, crude oil flowed down by gravity in the absence of electric field to allow the stabilization of the oil and to obtain the baseline behavior of the crude oil (i.e. initial oil viscosity). Afterwards, crude oil flowed down by gravity under the effect of different electric field intensities. The oil flow rate increased rapidly under the effect of the tested electric fields. **Figure 7** shows the mass of oil passing through the electric field as a function of time and electric field. In **Figure 7**, a sudden change of the slope corresponds to a rapid increase in the mass of oil passing down as a function of time. Therefore, it was straightforward to determine the viscosity of the oil before and after the application of the electric field.

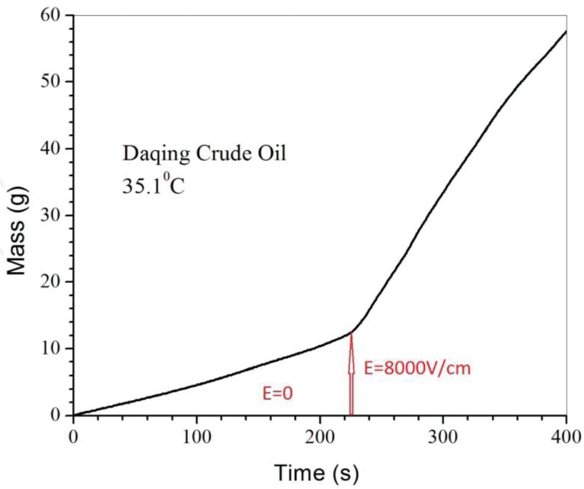

Figure 7. Mass of oil as a function of time and electric field.

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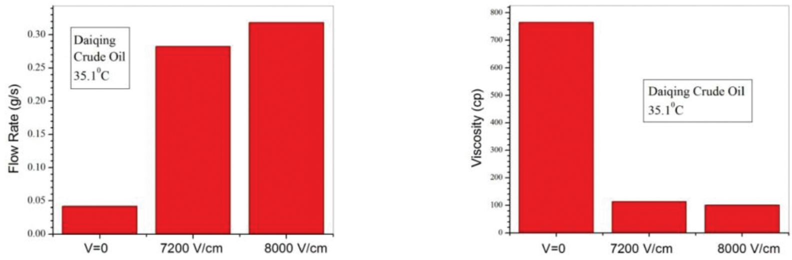

(a) (b)

Figure 8. Effect of electric field on Daqing crude oil. (a) Mass flow rate as a function of electric field (b) Viscosity as a function of electric field. Data obtained a temperature of 35.1°C.

This study allowed determining the optimum electric field that induced the largest reduction of oil viscosity. As shown in **Figure 7**, the mass flow rate in the absence of electric field was 0.04182 g/s, which corresponded to a viscosity of 764.5 cP. The application of an electric field of 7200 V/cm increased the flow rate to 0.28252 g/s, which corresponded to a viscosity of 113.16 cP. A further increase of the electric field to 8000 V/cm increased the flow rate to 0.318095 g/s that was equivalent to a final viscosity of 100.5 cP from an initial value of 764.5 cP.

Replication tests gave consistent results and confirmed that the application of the ER treatment effectively reduces irection.

Figure 8a plots the mass flow rate as a function of electric field. The mass flow rate of the oil increased by 661% when the electric field was increased from 0 to 8000 V/cm, which induced the simultaneous reduction of the crude oil viscosity by 86.9%.

Figure 9. The photo of the AOT device installed in the pipeline.

2.3. Field tests under laminar flow conditions

These field tests employed the testing pipeline route at the Rocky Mountain Oil Test Center (RMOTC) facility near Casper, Wyoming, equipped with a positive displacement (PD) pump. The electrical device or Applied Oil Technology (AOT) device was connected at 7.219 km of the testing route (**Figure 9**). Sensors inside the pipeline (inner diameter of 14.163 cm) at various locations measured the oil pressure and temperature.

Figure 9 shows a photo of the AOT device installed at the RMOTC pipeline system. The device was connected downstream the pump, which pumped the crude oil to the top of the device. Then, the oil flowed down through the electric field and the pipeline. Several mesh electrodes (39 units) inside the vertical pipe of the device with a gap of 3 cm between two neighboring ones induced the axial electric field inside the vertical pipe.

The field tests used two loops as follows:

(1) **Close loop**. The oil flowed through the pump, the AOT device, and the pipeline for several cycles.

(2) **Open loop**. In this case, after one cycle, the oil flowed to a storage tank and fresh oil from another supply tank was pumped through the device and pipeline.

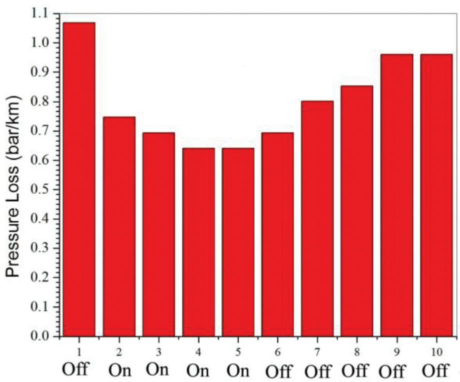

Figure 10. Pressure loss across the test loop as a function of the application of an electric field using the AOT device.

In these tests, the viscosity reduction was first determined along the flow direction under laminar flow regime (N_R = 1205.21). The pump was set at a constant Q of 46.56 m^3/h, which provided a linear velocity of 82.09 cm/s. The properties of the crude oil were API° = 34, initial viscosity = 81.6 cP at 12.1°C, and density = 0.8459 g/cm^3. As the untreated oil flowed through the pipeline, the pressure loss was 1.07 bar/km. The application of an electric field of 2300 V/cm caused a reduction of pressure loss across the loop from 1.07 to 0.641 bar/km (40% reduction). Similarly, the viscosity along the flow direction reduced from 81.6 cP to 48.95 cP (40% reduction). Then, the AOT device was turned-off and the pressure loss across the loop gradually returned to the original value in the absence of the electric field (**Figure 10**). Measurement of the pumping power requirements is useful to evaluate the effect of the ER treatment on the flow properties of the crude oil. Before the application the ER treatment, the pump required a total power of 14.2 kW. However, the ER treatment gradually reduced the pumping requirements to a steady value of 8.9 kW, which is equivalent to an energy saving of 5.3 kW. The AOT device utilized less than 100 W of electric power during the lifespan of the experimentation.

2.4. Suppression of turbulent flow conditions

These tests were conducted with a Reynolds number near the critical value of 2300 first, then extended to Reynolds number well above 6000. The pump was set at a constant Q of 95.392 m^3/h that corresponded to a flow velocity v of 168.2 cm/s. The conditions of the initial test were crude oil with an initial viscosity of 93.7 cP at 11.5 °C, a Q of 95.392 m^3/h, laminar flow with a N_R = 2160.82, and a pressure drop along the pipeline of 2.51 bar/km. The application of an electric field of 2300 V/cm reduced the oil viscosity to 85.5 cP, which increased the N_R to 2368.1, which corresponds to a turbulent flow regime. However, if the flow were turbulent, the pressure loss would increase to 3.85 bar/km (Eq. 3); while in fact, the pressure loss was 2.296 bar/km and the pump power requirement was 52.4 kW (reduced from 57.4 KW). This experimental run confirmed that the flow of crude oil under the influence of the ER treatment remained laminar.

A further increase of the electric field to 3000 V/cm caused an additional reduction of the oil viscosity to 75.6 cP and an increase in the N_R to 2678.2. Likewise, if the flow regime were turbulent at this condition, the pressure drop along the loop would increase to 3.73 bar/km. On the contrary, the pressure loss along the pipeline reduced to 2.03 bar/km, and the pump power requirement decreased to 48.3 kW, which corresponds to a laminar flow regime. Observations from replication tests were consistent.

Another field test evaluated the performance of the paraffin base Daqing crude oil, which has a pour point around 30°C. The transportation of this oil requires that the temperature within the pipeline system must be maintained in the range of 55–72°C through 15–20 km of insulated pipeline length (pipeline inner diameter 14.5 cm), before the pipeline system reaches another heating station.

Initially, several pre-tests established the conditions for turbulent flow regime within the temperature range previously indicated. For example, crude oil at 55.6°C and viscosity of 16.92 cP was flowed through the pipeline at a flow rate of 34.46 m^3/h and a pressure of 7.0 bar; under these conditions, N_R was 4128.3 (turbulent regime). In another pre-test, crude oil at 71.1°C and a viscosity of 12.4 cP was pumped at a pressure of 7.0 bar. The experimentally measured Q was 36 m^3/h. According to Eq. (6), under these flow conditions (i.e. pressure and oil viscosity), Q must be 36.02 m^3/h for a turbulent flow regime, which was in agreement with the experimentally measured Q. On the other hand, if the flow were laminar at the same flow conditions, the calculated Q using Eq. (1) should be 47.02 m^3/h, which is much higher than the measured Q.

In other pre-experimental run, crude oil at 55.6°C was flowed through the test loop at a pumping pressure of 8.35 bar. The measured Q was 38.1 m^3/h. If the flow were laminar, according to Eq. (1), the Q should be 41.1 m^3/h. However, the measured Q (38.1 m^3/h) was equal to the Q estimated using the Blasius formula (Eq. 6) of 38.11 m^3/h.

Overall, these pre-tests demonstrated that the flow of crude oil at 55.6 and 71.1°C was turbulent and more importantly that heating of the crude oil does not suppress turbulence.

The procedure used to evaluate the effect of the application of an electric field on the suppression of turbulence during the flow of crude oil through the test loop was as follows.

(1) AOT device turned-off

Flow conditions: temperature of crude oil = 55.6 °C, pumping pressure = 3.1 bar, Q = 16.4 m^3/h, and N_R = 1964.7 (laminar flow regime).

(2) AOT device turned-on

The application of an electric field of 13.3 kV/cm reduced the oil viscosity along the flow direction to 14.14 cP and gradually increased Q to 19.6 m^3/h. Although N_R increased to 2808.9, the flow regime was still laminar (based on the theoretical flow rate, which was in agreement with the experimentally measured Q).

In order to test the crude oil flow behavior at much higher N_R at a constant electric field of 13.3 kV/cm, the flowing pressure was increased from 3.1 to 5.0 bar and Q was increased to 31.6 m^3/h, which corresponded to an N_R of 4528.6. Nevertheless, under these conditions the flow remained laminar because the measured Q was in agreement with the theoretical estimation (Eq. 1) of Q = 31.61 m^3/h for a laminar flow regime.

A further increase in the pumping pressure to 7.0 bar, under a constant electric field of 13.3 kV/cm, caused an increase in Q to 44.3 m^3/h and an N_R of 6348.7. However, according to Eq. (1), the flow of crude oil remained laminar. **Table 2** summarizes these experimental observations.

Flow rate (m^3/h)	Viscosity (cP)	Reynolds number	Electric field (V/mm)	Pressure (bar)	Temperature (°C)	Flow regime
34.36	16.92	4128.3	0	7.0	55.6	Turbulent
36.0	12.40	5890.3	0	7.0	71.1	Turbulent
38.1	16.92	4565.6	0	8.35	55.6	Turbulent
16.4	16.92	1964.7	0	3.1	55.6	Laminar
19.6	14.14	2808.9	1333	3.1	55.6	Laminar
31.6	14.14	4528.6	1333	5.0	55.6	Laminar
44.3	14.14	6348.7	1333	7.0	55.6	Laminar

Table 2. Test results with $N_R > 2300$.

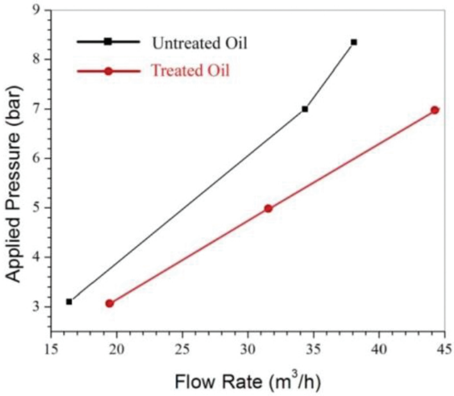

Figure 11. Pumping pressure versus flow rate.

Figure 11 plots the applied pumping pressure as a function of Q (m^3/h) for untreated and treated crude oil. It is clear that even at very high Q (40 m^3/h) and large N_R= 6348, the flow regime of the ER-treated crude oil remained laminar. On the contrary, the flow of the untreated oil became turbulent N_R >2300. These experimental observations clearly confirm that the ER treatment effectively suppresses the onset of turbulent flow regime.

2.5. Field tests on a section of the keystone pipeline

These field tests employed a section of the Keystone Phase II pipeline near Wichita, Kansas. **Figure 12** shows a picture of the AOT device installed in this pipeline system. The device was downstream of the pump, which pumped the crude oil to the top of the device, entering the four parallel cylinders through the mesh electrodes, and then to the pipeline downstream.

Figure 12. AOT device installed on the Keystone pipeline system.

These tests evaluated the performance of an asphalt base crude oil. The crude oil had a density of 0.887 g/cm^3 and a viscosity of 214.1 cP at 25°C. The inner diameter of the pipeline was 35 inch (88.9 cm) and Q was kept constant at 2280 m^3/h, which corresponds to a flow velocity of 1.02 m/s. Under these conditions, the N_R was 3757.9, which indicates turbulent flow conditions. From Eq. (5), the estimated friction factor for this turbulent flow is f_T = 0.04011; while the pressure difference along the pipeline was estimated using Eq. (11) as follows,

$$\Delta P = \tfrac{1}{2}\rho v^2 f_T L / D \tag{11}$$

where L is the distance between the Keystone pump station and the next downstream pump station, ϱ is the flow velocity, and D is the pipeline diameter.

Equation (12) allows estimating the required pumping power, P_{wi}.

$$Pwi = Q\Delta P = \pi\rho v^3 DLf_T / 8 \tag{12}$$

where Q is the flow rate and ΔP is the pressure difference in Eq. (11). The application of an electric field caused the reduction of the crude oil viscosity along the flow direction from 214.1 to 142.5 cP; while the viscosity of the oil in the direction perpendicular to the flow was significantly increased (>700 cP). Under these conditions, the treated oil flow was laminar. **Figure 13** shows that after the AOT device is turned-on, the treated crude oil flowing under laminar conditions pushes the rear of the untreated oil downstream the pipeline, which flows under turbulent conditions.

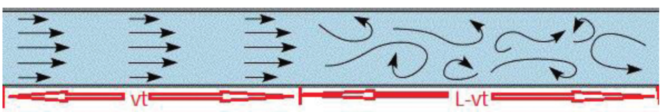

Figure 13. Treated oil under laminar flow conditions pushes the untreated oil under turbulent flow conditions downstream the pipeline.

If the AOT device was on for time t (**Figure 13**), the length of the laminar flow section is vt along the pipeline; while the turbulent flow had length of L-vt. The Reynolds number for the laminar flow was 5646.1, and the friction factor was f_L = 0.011335258. Equation (13) allows the estimation of the pump power requirements for the period $0 < t < L/v$ as follows,

$$Pw(t) = \pi\rho v^3 D[vtf_L + (L - vt)f_T] / 8 = Pwi[1 - (1 - f_L / f_T)vt / L] \tag{13}$$

Substituting the values for f_L and f_T, the pump power requirements for the period of $0 < t < L/v$ were calculated as follows (Eq. 14):

$$Pw(t) = Pwi(1 - 0.7195vt / L) \tag{14}$$

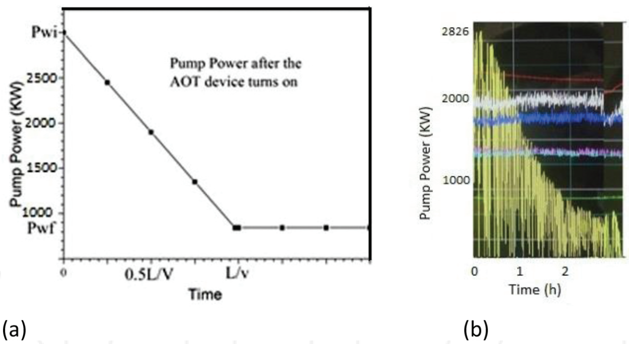

Figure 14. (a) Estimated pump power requirements as a function of time and electric field. (b) Experimental pump power versus time.

After $t \geq L/v$, only treated oil occupied the test section of the pipeline, and the calculated pump power was 0.28 P_{wi}. This indicates that the application of the ER treatment reduced the pumping requirements by 72%. **Figure 14** presents these calculated power requirements (**Figure 14a**) and the experimental pump power requirements (**Figure 14b**).

Figure 14b displays the experimental pump power reduction after the application of ER treatment. Before the treatment, the pump required a power of 2826 kW to transport the crude oil. After 2 hours of treatment, the pump power requirements stabilized at around 800 kW, while Q remained constant at 2280 m^3/h. In this case, the total reduction of pumping power requirements was 71.7%.

In this experimental study, the AOT device required <1 kW of power; while the pumping power required to transport the heavy crude oil at a Q = 2280 m^3/h was significantly reduced with overall power savings > 2000 kW. These experimental observations confirm the theoretical predictions and demonstrate the efficiency of this technology for transporting heavy crude oil via pipeline.

2.6. Lasting effect of the ER treatment on crude oil flowing properties

The anisotropic viscosity of the crude oil is the result of the aggregation of suspended particles into short chains along the flow direction under the effect of an electric field. Therefore, the reduced crude oil viscosity along the flow direction and the turbulence suppression effect will diminish if the aggregated short chains deassembled partially or completely.

Laboratory-bench scale tests evaluated the lifespan of the anisotropic viscosity effect after the ER treatment. The experimental procedure consisted in the application of the electric field to the oil sample at a pre-established temperature for about 5 seconds. Afterwards, the sample was stored at the corresponding temperature, and the crude oil viscosity was measured as a function of time. **Tables 3** and **4** summarize the experimental results obtained from the evaluation of two crude oils.

Viscosity (cP)	911	390	408	421	441	480	487
Time (h)	Untreated	0	4	8	12	23	26

Table 3. Viscosity performance of the Daqing crude oil after the ER treatment at 35.1°C. The applied electric field was 8 kV/cm for 5 seconds.

Viscosity (cP)	261.3	121.1	151.2	172.4
Time (h)	Untreated	0	12	24

Table 4. Viscosity performance of crude oil (API 34°) after the ER treatment at −3.1°C. The applied electric field was 1.6 kV/mm for 5 seconds.

These experimental results indicate that while the aggregated chains gradually deassembled as a function of time, the deaggregation process is slow and the viscosity of the crude oil increases very slowly. In these experiments, the anisotropic viscosity of the treated crude oil lasted for more than 24 hours.

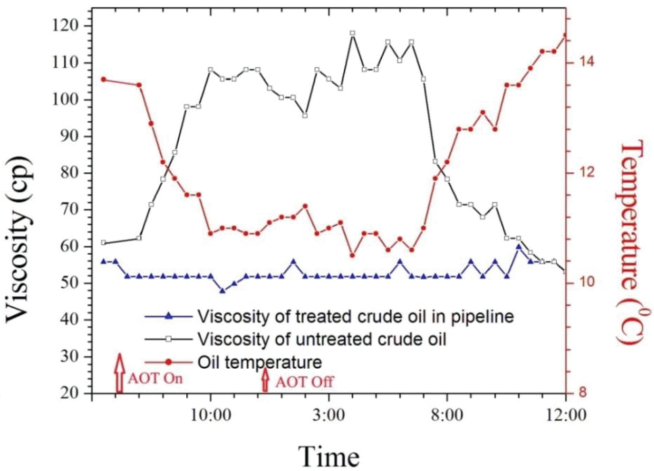

Figure 15. Crude oil viscosity and temperature as a function of time.

Tests at the RMOTC pipeline also evaluated the lifespan of the ER treatment. These field tests used the pipeline loop described in Section C and employed a crude oil with an API° 34° and an initial viscosity of 118.06 cP. The positive displacement pump drove the crude oil through the AOT device and the pipeline loop during six and half hours. The electric field applied was 2 kV/cm, which reduced the viscosity of the crude oil along the flow direction from 118.06 to 51.8 cP (viscosity reduction of 56.12%). After 6.5 hours, the AOT device was turned-off, but the crude oil circulated the pipeline loop for more than 11 hours. During this period, the pressure loss across the pipeline loop and the pump power requirements were continuously monitored.

The experimental observations indicate that the reduced viscosity of the treated oil, the pressure loss, and the pump power requirements remained stable during a period of 11 hours. Afterwards, the pressure loss and pump power requirements started to increase, signifying that the viscosity reduction effect on the treated crude oil began to disappear. **Figure 15** summarizes these experimental observations.

The lasting effect of the ER treatment (11 hours) obtained in the pipeline loop (field test) was shorter than the lasting effect determined at the laboratory scale (>24 hours). In the field test, the PD pump continuously pumped the crude oil through the pipeline loop. This continuous pumping through the PD pump could cause the disruption and breaking of the aggregated particles that induce the oil viscosity increase; while in the experiments conducted in the laboratory, only Brownian motion caused shear forces on the aggregated chains.

Nevertheless, in industrial ER applications, a treatment lifespan of 11 hours seems to be practical, considering that the electric field can be re-applied to adjust the viscosity of the crude oil as needed. Furthermore, the lasting effect of the ER treatment simultaneously suppresses turbulence [24].

3. Conclusions

Electrorheology, ER, is effective in simultaneously reducing the viscosity and suppressing turbulence during oil transportation via pipeline.

Experimental work at laboratory bench scale and field tests demonstrate the ER technology efficiently induces the aggregation of suspended particles contained in crude oils. These aggregated particles form short chains along the flow direction, which simultaneously reduce the crude oil viscosity and suppress turbulence, enhancing flow output.

Typical flow of crude oil in pipeline becomes turbulent when the Reynolds number exceeds 2300; the ER-treated crude oil remains laminar even at Reynolds numbers close to 10,000. Furthermore, field tests indicate that the ER effect on the viscosity and flow properties of the crude oil lasts 11 hours, after the ER treatment has ceased. The application of this technology for oil transportation via pipeline is in rapid development.

The ER technology shows great potential for heavy oil extraction and EOR operations; however, these applications require significant more research.

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