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Final Report

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

Submitted To

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Test Information:
Pulsed Electric Field Test and
Pulsed Magnetic Field Test
for
Crude oil (API11),
Crude oil (API15),
Crude oil (API21)

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March 4th, 2008

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By January 2008, we had received three crude oil samples, API 11, API 21, and API 15. At room temperature, around 21°C, API 11, API 21, and API 15 crude oil samples have a viscosity close to 100,000cp, 400cp, and 400,000cp respectively. In January, February and March 2008, our lab conducted systematic tests with these three crude oils to determine their viscosity and the influence of electric and magnetic fields on their viscosity. The following is the report.

1. The Mechanism of our viscosity reduction technology.

The detailed discussion about the mechanism of our viscosity reduction technology is in the following two published papers,
1. R. Tao and X. Xu, "Reducing the viscosity of crude oil by pulsed electric or magnetic field," *Energy & Fuels,* **20,** 2046-2051 (2006);
2. R. Tao, "The Physical Mechanism to Reduce Viscosity of Liquid Suspensions," (by R. Tao), International J. of Modern Physics B, V. 21, N28&29, pp4767-4773 (2007).

Here we summarize the main points.

Crude oil is a liquid suspension. The base liquid, consisting of small molecules for gasoline and diesel, has very low viscosity. In paraffin-base crude oil, at low temperature the high viscosity is mainly due to the suspended paraffin particles.
In asphalt-base crude oil, at room temperature the asphalt in the crude oil absorbs moisture and solidifies into asphaltene particles since asphalt has a very high melting temperature. These asphaltene particles raise the effective viscosity of crude oil.

The effective viscosity of a liquid suspension depends on the viscosity of the base liquid, the volume fraction and the size distribution of the suspended particles.

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

$$\eta = \eta_0(1 + 2.5\phi), \qquad (1)$$

for the volume fraction of the spheres $\phi < 0.01$.

For high ϕ, we must consider the maximum volume fraction, ϕ_m, to be available for adding particles. When we add $d\phi$ volume fraction of spheres to a liquid suspension of volume fraction ϕ, the net available volume fraction to add spheres is only $1-\phi/\phi_m$, the viscosity increase *(6)* would be

$$d\eta/\eta = 2.5d\phi/(1-\phi/\phi_m). \qquad (2)$$

Hence at high ϕ the viscosity is given by

$$\eta/\eta_0 = (1-\phi/\phi_m)^{-2.5\phi_m}. \qquad (3)$$

Krieger-Dougherty introduced the intrinsic viscosity, $[\eta]$,

$$\eta/\eta_0=(1-\phi/\phi_m)^{-[\eta]\phi_m}, \qquad (4)$$

which enables us to estimate the viscosity for particles of any shape by choosing a suitable $[\eta]$. For example, $[\eta]=5/2$ for spherical particles and $[\eta]=5.8$ for glass plates.

At a high ϕ, the particle size distribution has strong effect on the viscosity. There are substantial experiments on monodispersed suspensions of particles on the order of microns and sub-microns, showing that at constant ϕ, the viscosity goes down as the particle size increases. As shown in Fig 1, for example, at $\phi=15\%$, a suspension of 10.0 μm particles has a viscosity only 23.9% of the viscosity of a suspension of $0.05\mu m$ particles.

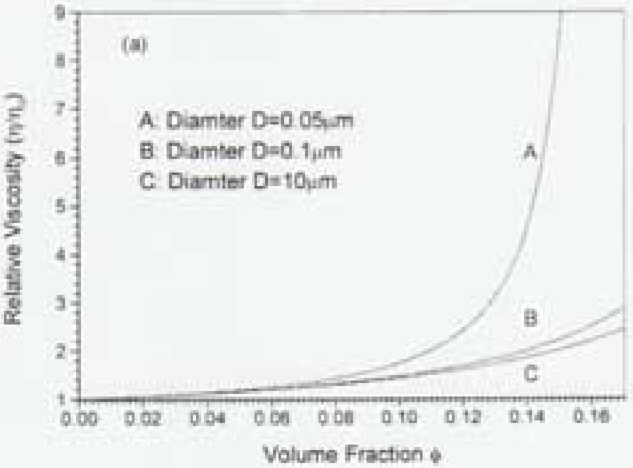

Fig.1 The viscosity versus volume fraction and particle size for mono-dispersed suspensions.

Generally, the effective viscosity depends on how much freedom the suspended particles have in the suspension. The less freedom for the particles, the faster the energy dissipates and the higher the effective viscosity is. The mean free path of the spheres inside the suspension is given by $a/(3\phi)$, where a is the particle radius. As a gets bigger, the mean free path becomes longer, indicating that the suspended particles have more freedom to move in the suspension. Thus η goes down.

Let us consider a liquid suspension with noninteracting spheres of diameter D suspended in a base liquid of viscosity η_0. Since D is on the order of nanometer or micrometer, the particles are classical ones. Because of the thermal vibration, these particles in the base liquid seem to be larger than their actual physical size D. This can be estimated as follows. From the thermal motion, $\frac{1}{2}mv^2 = \frac{3}{2}k_B T$, we have the average thermal velocity $\bar{v} = \sqrt{3k_B T / m}$. If the relaxation time is t_0, the length $\lambda = \bar{v}t_0$ is the additional dimension due to the thermal vibration. Therefore, in the base liquid, the particles seem to have a diameter,

$$D_s = D + \lambda . \qquad (5)$$

Then, the maximum volume fraction to be available for the particles is given by

$$\phi_m = \phi_{m0}(D / D_s)^3 = \phi_{m0} / (1 + \lambda / D)^3 , \qquad (6)$$

where ϕ_{m0} is about 0.64 for random close-packing. It is clear from Eq.(6) that as D increases, the maximum volume fraction ϕ_m is increased and the viscosity η is reduced from Eq.(3) or Eq.(4)

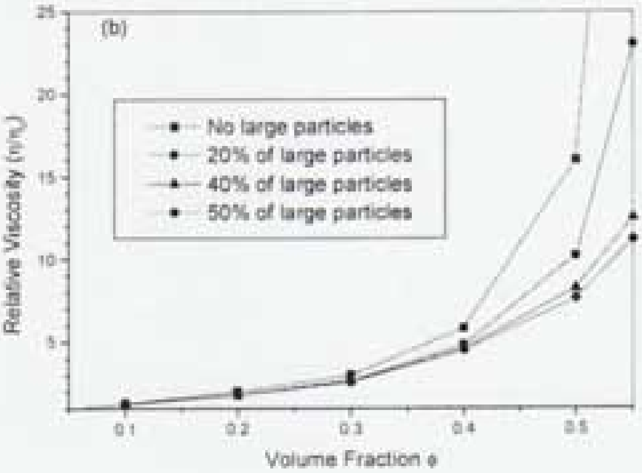

Fig.2 The viscosity versus particle volume fraction and particle size distribution for suspensions of a binary size distribution. The particle-size ratio is 5:1.

The values of ϕ_m in Eq.(4) also increases with increasing polydispersity. For example, when the ratio of the large particles to small particles increases in a suspension of binary particle-size distribution, the viscosity reduces significantly (Fig.2): At $\phi \geq 50\%$, when this ratio reaches 1:1, the viscosity is reduced more than 50% from the mono-disperse case. A qualitative explanation is as follows: For a binary particle-size distribution, we can consider that the small particles thicken the continuous phase and the next-size-up particles then thicken this phase, and hence

$\eta = \eta_0(1-\phi_1/\phi_{m1})^{-[\eta]\phi_{m1}}(1-\phi_2/\phi_{m2})^{-[\eta]\phi_{m2}}$, which is lower than that of a suspension of uniform small particles with volume fraction $\phi_1+\phi_2$.

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

We discuss the magnetic field here, but the same physics applies to the case of electric field. We assume that the magnetic permeability μ_p of the particles is different from μ_f of the base liquid. In a magnetic field, the particles are polarized along the field direction. If the particles are uniform spheres of radius a, the dipole moment is $\vec{m} = \vec{H}a^3(\mu_p-\mu_f)/(\mu_p+2\mu_f)$, where $\vec{H}$ is the magnetic field acting on the sphere. The interaction between two induced magnetic dipoles takes

$$U = \mu_f m^2(1-3\cos^2\theta)/r^3, \qquad (7)$$

where r is their distance and θ is the angle between the field and the line joining the two dipoles. If this interaction is strong enough to overcome the Brownian motion, the particles aggregate and align in the field direction. If this interaction is very strong, the particles quickly aggregate into macroscopic chains or columns to jam the liquid flow and increase the viscosity with the magnetic field on, a well-known phenomenon in magnetorheological (MR) fluids and electrorheological (ER) fluids.

On the other hand, if the applied magnetic field is in such a short pulse that the dipolar interaction does not have enough time to affect particles separated by macroscopic distances, but has enough time to assemble nearby ones together, the assembled clusters are of limited size, say, in micrometer range. Although some particles may not join the aggregation, the aggregated particles have their size increased. During the application of field, the viscosity changes rapidly. However, after the magnetic field is turned off, the suspension has a reduced viscosity. This reflects the fact that while the volume fraction remains the same, the particle size distribution is changed: There are more large particles and the polydispersity is also increased.

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

Let us estimate the minimum magnetic field H_c required to form clusters. For particle number density n, the typical separation between two neighbouring particles is about $n^{-1/3}$ and their dipolar interaction is about $m^2 n\mu_f$. This interaction must overcome the thermal Brownian motion in order to pull them together. Then it is required to have $\mu_f m^2 n/(k_B T) \geq 1$, where k_B is the Boltzmann constant and T is the absolute temperature. Hence we obtain the critical field

$$H_c = [k_B T/(n\mu_f)]^{1/2}(\mu_p + 2\mu_f)/[a^3(\mu_p - \mu_f)]. \tag{8}$$

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

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

$$\tau = n^{-1/3}/v = \pi\eta_0(\mu_p + 2\mu_f)^2/[\mu_f n^{5/3} a^5 (\mu_p - \mu_f)^2 H^2]. \tag{9}$$

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

To apply the above equations for the electric field case, we only need to replace the magnetic permeability by the respective dielectric constant. Different from ER and MR fluids, the viscosity reduction method only applies the electric field or magnetic field for a short period. During the application of field, particles may rotate due to some torques; therefore, the viscosity is not stable, fluctuating quite a lot. After the field is off, there are no polarization forces or torques and the viscosity soon becomes quasi-stable. The issue related to the rotations can be further reduced by choosing proper direction of the applied field. For example, in the flow state, if the applied field is parallel to the flow direction, the aggregated particles have a shape similar to ellipsoids with their long axis parallel to the flow direction. These ellipsoids do not rotate in the flow. The viscosity can thus be further reduced if the flow and the field direction are parallel.

After the field is turned off, the dipolar interaction disappears and the aggregated particles gradually dissemble under the Brownian motion. Therefore, the viscosity is expected to increase gradually and will return to the original value after all aggregated particles disintegrate. Let us estimate the time interval for the viscosity reduction. In absence of other disturbances, such as in a static or a constant flow state, the particles in the suspension separate diffusively only due to the Brownian motion with a diffusion constant $k_BT/(6\pi a\eta_0)$. Two spheres of radius a which are initially in contact diffuse apart by a distance of a in a time interval $3\pi a^3\eta_0/(k_BT)$. With $a = 3\mu m$ and $\eta_0 = 1$ poise, this estimated time is about 2 hours at room temperature. Therefore, this dissembling process is slow and the viscosity reduction lasts for several hours, long enough for many important applications.

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

In short, to reduce viscosity of crude oil by electric or magnetic field, we first need to know if the crude oil is paraffin-based or asphalt-based. Then we need to determine the optimal field strength and the optimal time duration for field application.

2. Effect of temperature to determine these original viscosities of 3 crude oils.

All three crude oil samples have strong temperature effect on their viscosity.

(2a) API 11 crude oil sample.

At 20.7°C, API 11 crude oil sample has viscosity 101,547cp. At 25.2°C, its viscosity is down to 65,289cp. The viscosity reduction rate in this region is about 7.96% per degree with increase of the temperature.

(2b) API 21 crude oil sample.

At 20.3°C, API 21 crude oil sample has viscosity 540cp. At 25.5°C, its viscosity is down to 410cp. The viscosity reduction rate in this region is about 4.63% per degree with increase of the temperature.

(2c) API 15 crude oil sample.

At 20.6°C, API 15 crude oil sample has viscosity 494,080cp. At 25.0°C, its viscosity is down to 325,120cp. The viscosity reduction rate in this region is about 7.77% per degree with increase of the temperature.

3. Tests in Temple University

We have conducted extensive tests for the three crude oil samples.

(3a) The effect of electric field on the viscosity of API 11 crude oil sample.

Electric field has a strong effect on the viscosity of API 11 crude oil sample. A moderate electric field can reduce its viscosity significantly. The following table summarizes the main test results.

RUN #	Original Viscosity (cp)	Field Strength (V/mm)	Appl. Time (S)	Viscosity afterwards (cp)	Reduction ratio	Original temp (^{0}C)	Temp after (^{0}C)	Current (μA)	Power (W)
1	105,387	277	35.5	93,867	-11%	21.2	21.2	0.15	0.002
2	102,400	273.8	40.36	92,160	-10%	21.6	21.6	0.15	0.002
3	111,787	451	45	102,827	-8.02%	21.6	21.6	0.35	0.0079
4	97,707	200	40.47	87,893	-10.04%	22	22	0.15	0.002
5	91,307	275	35	83,627	-8.4%	22	22	2.7	0.0312
6	112,640	279	40	102,400	-9.1%	21.3	21.3	0.1	0.001
7	112,640	305	35	94,293	-16.3%	21.3	21.3	0.2	0.0025

(3b) The effect of magnetic field on the viscosity of API 11 crude oil sample.

Magnetic field has some effect on the viscosity of API 11 crude oil sample, but moderate. The following table summaries the test results.

Run #	Original Viscosity (cp)	Magnetic field (gauss)	Irradiation time (s)	Viscosity afterwards	Reduction ratio	Original temp. (^{0}C)	Temp after. (^{0}C)
1	104,960	13,000	10	98,133	-6.5%	21.5	21.6
2	73,387	2,500	0.33	72,533	-2%	21	21
3	76,373	2,500	0.97	75,947	-1%	21	21
4	96,853	13,000	10	93,440	-3.5%	21.5	21.5

(3c) The effect of electric field on the viscosity of API 21 crude oil sample.

Electric field has a strong effect on the viscosity of API 21 crude oil sample. A moderate electric field can reduce its viscosity significantly. The following table summarizes the test results.

RUN #	Original Viscosity (cp)	Field Strength (V/mm)	Appl. Time (S)	Viscosity afterwards (cp)	Reduction ratio	Original temp (^{0}C)	Temp after (^{0}C)	Current (μA)	Power (W)
1	482.67	648	1200	413.33	-14.5%	22.7	24.3	33.5	0.77
2	469.33	652	600	429.33	-8.6%	21.6	21.8	30.6	0.71
3*	423.33	800	18.8	280	-34%	21.7	25	35	0.8

* The test #3 was a continuous flowing experiment (Fig.3). The crude oil sample passed through two metallic meshes along a tube. A voltage was applied on these two meshes to produce a strong electric field in the space between the two meshes. In the experiment, the crude oil took about 18.8 seconds to pass the two meshes. The current was moderate, 25μA. We also found the temperature was increased from 21.7^{0}C to 25^{0}C. The total

viscosity reduction was 34%. Among them, some was due to temperature increase and some was the electric field effect. According to the results described in Section 1, the viscosity reduction rate for API 21 is about 4.63% per degree with increase of the temperature. Therefore, the temperature effect would have the viscosity reduction 15%, while the remaining 19% viscosity reduction was due to the electric field effect.

Fig.3 The device for continuous flowing experiment.

(3d) The effect of magnetic field on the viscosity of API 21 crude oil sample.

Magnetic field has some effect on the viscosity of API 21 crude oil sample, but quite weak. The following table summarizes our experimental results.

Run #	Original Viscosity (cp)	Magnetic field (gauss)	Irradiation time (s)	Viscosity afterwards	Change Ratio	Original temp. (°C)	Temp after. (°C)
1	650	13,000	30	630	-3.1%	22.4	22.4
2	623.33	13,000	10	613.33	-1.6%	22.4	22.4
3	650	12,900	15	626.67	-2.6%	22.4	22.4

(3e) The effect of electric field on the viscosity of API 15 crude oil sample.

Electric field has effect on the viscosity of API 11 crude oil sample. However, the viscosity of API 15 is too high. We have some difficulties to find the optimal values for the electric field and application duration. In some sense, we believe that electric field could reduce the viscosity of API 15 crude oil much more. However, the applied electric field may need to be stronger than that we applied. Because of the limitation of our present high voltage power supply, we have not found the optimal condition for the viscosity reduction. The following table summarizes our current test results.

RUN #	Original Viscosity (cp)	Field Strength (V/mm)	Appl. Time (S)	Viscosity afterwards (cp)	Reduction ratio	Original temp (°C)	Temp after (°C)	Current (μA)	Power (W)
1	387,840	872	60	373,760	-3.7%	23	23.1	0.45	0.0196
2	375,040	872	120	363,520	-3.1%	23	23.1	0.5	0.022
3	428,800	864	240	407,040	-5.1%	21.6	21.6	0.4	0.017

(3f) The effect of magnetic field on the viscosity of API 15 crude oil sample.
Magnetic field has some effect on the viscosity of API 15 crude oil sample, but quite weak. A moderate magnetic field can reduce its viscosity by 3-4%. The following table summarizes our experimental results.

Run #	Original Viscosity (cp)	Magnetic field (gauss)	Irradiation time (s)	Viscosity afterwards	Change Ratio	Original temp. (^{0}C)	Temp after. (^{0}C)
1	439,040	5,550	1.46	426,240	-3%	21.	21
2	486,400	6,000	2.29	463,360	-4.7%	21	21
3	458,240	13,000	20	451,840	-1.4%	21.3	21.3

4. Rough design of the commercial pipeline

We currently have a project with an oil company to design and test devices on the pipeline to reduce crude oil's viscosity and speed up the transport of crude oil. However, due to the confidential agreement signed between Temple University and the oil company, I cannot discuss it in detail here. The following diagram sketches one of our devices, which will be installed and tested on the crude oil pipeline.

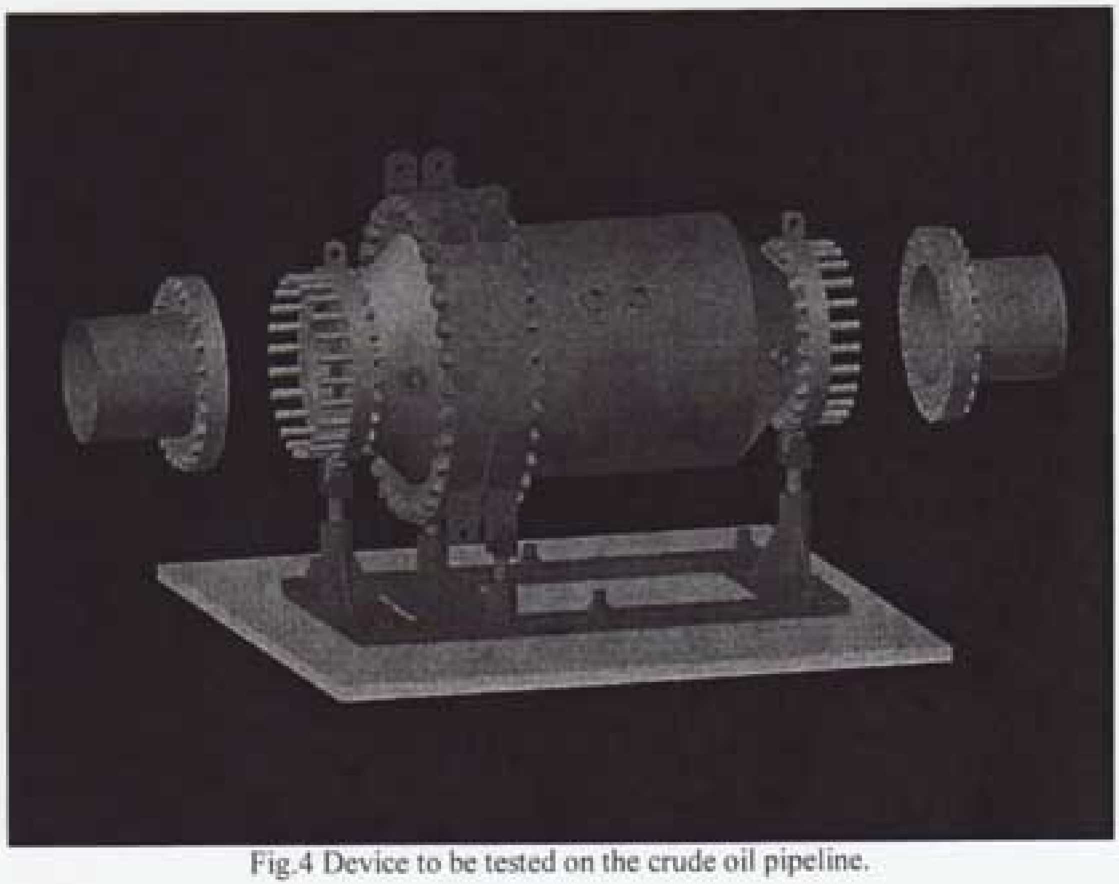

Fig.4 Device to be tested on the crude oil pipeline.

5. Rough estimation of CAPEX (Equipment cost) and OPEX of commercial pipeline.

For the electric field device, it is required to have power supplies and field device. Because of the low power requirement, the power supply is quite cheap. Normally around $650, one can buy a 40k-voltage power supply with about 1 watt. This power supply has enough power for the viscosity reduction. For the capacitor to be installed on the pipeline, the cost varies. Depending on the API requirements, the cost for fabrication can be varied from $50,000 to $100,000 a piece. However, once it is in mass production, the cost may be down to $5000 per device or even less. We expect to install one device every 15-20 kilometers along the pipeline.

For the magnetic device, the main costs are magnets. If one decides to use permanent magnets, the cost may be low. We also estimate that it is required to install one device for every 15-20 kilometers. After the device is in mass production, we estimate that one device may cost about $5000 or less.

For both electric field and magnetic field, the operation cost is very small. We estimate that the energy cost for the operation is about 0.02 KW-h/barrel. Therefore, the operation cost is almost negligible.

6. Conclusions

The tests of API 11 and API 15 crude oil samples were a challenge to us. Before these tests, we had not done any tests with crude oil of viscosity above 2000cp. The API 11 sample and API 15 sample with viscosity of 100,000cp and 400,000cp are completely different from any other crude oil samples we worked before. For example, with these two crude oils, our continuous flow device (Fig, 3) cannot work because the oil took much time to pass the two meshes. The API 11 crude oil took about 28 minutes to pass the two metallic meshes, resulting in an increase of the viscosity. Therefore, during the experiment, we had to make several new devices for the tests.

From our experience, we should be able to reduce the viscosity of these crude oils by about 30%. However, this requires us to search for the optimal parameters: suitable electric field and duration of field treatment. We spent most time with API 11. Because of the limitation of our power supply, we had some difficulties to reach the optimal parameters for the electric field. Just at the end of our test, we received a shipment of a power supply, which could produce voltage of 40 kV. With this new power supply, we were able to reduce the viscosity by 16.3% with no noticeable temperature change. If we have more time, we may be able to find better parameters and get better results.

We have some difficulties to find the optimal values for the electric field and application duration. Currently we were able to reduce its viscosity by 5% without temperature change for API 15. In some sense, we believe that electric field could reduce the viscosity of API 15 crude oil much more. However, the applied electric field may need to be much stronger than that we applied. Because of the limitation of our high voltage power supply, we have not found the optimal condition for the viscosity reduction.

As for API 21 crude oil sample, we are familiar with it. Utilizing our continuous device, we were able to reduce its viscosity by 34%. While some reduction was due to the temperature increase, the most reduction was from the electric treatment. We are very confident that we will able to reduce the viscosity of crude oils similar to API 21 by 30% with our electric treatment.

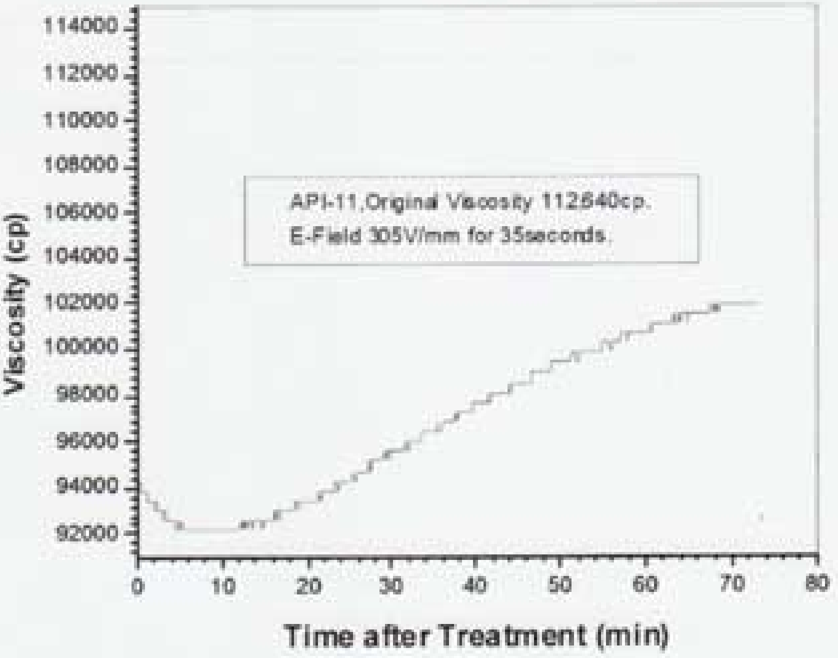

Fig. 5. The change of viscosity of API 11 crude oil sample after the electric field treatment.

The viscosity reduction by electric field or magnetic field is not permanent, but lasts for several hours. In Fig.5, we show the typical curve for the viscosity change after the electric treatment. The API 11 crude oil sample originally had viscosity 112,640cp. After application of an electric field of 305V/mm for 35 seconds, the viscosity was down to 94293cp, 16.3% reduction. We may note from the curve that the viscosity was continuously reduced to 92,160cp, then began to increase. After one hour, the viscosity reached 101,973cp, still 10% below the original viscosity. We expect that the viscosity came back to the original value of 112,640cp in about 8 hours. From the above results, if such viscosity reduction device is applied on the pipeline, we need one device every 15-20 kilometers if the pipeline is very long.

Finally, we would like to compare our viscosity reduction method with other methods.

As shown in this report, the electric field can effectively reduce viscosity of asphalt-based crude oil, as evidenced by the results for API 11 and API 21 crude oil samples. The operation cost is very tiny. Other methods, such as adding chemical or gasoline to heavy crude oil, require the operation cost about $20.00 per barrel. However, our electric field and magnetic field method only cost about energy 0.002 KW-h per barrel. If we use $0.1 for one KW-h, the operation cost is $0.002/barrel. On the other hand, our method requires some capital investment. Once the devices are in mass production, we expect the equipment cost will be down. The equipment is expected to have long lifetime. In addition to the oil pipelines, this viscosity reduction method may also be useful for heavy oil production at oil wells. Therefore, we believe that this viscosity reduction method has bright future for oil industry.