Fuel 134 (2014) 493–498

Contents lists available at ScienceDirect

Fuel

journal homepage: www.elsevier.com/locate/fuel

Neutron scattering studies of crude oil viscosity reduction with electric field

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HIGHLIGHTS

- Neutron scattering shows e-field induced particle aggregation inside crude oil.
- The aggregates are short chains along the field direction.
- The aggregation makes viscosity significantly reduced in the field direction.
- Electric field induced viscosity reduction is for all kinds of crude oil.

ARTICLE INFO

Article history:
Received 24 March 2014
Received in revised form 2 June 2014
Accepted 3 June 2014
Available online 18 June 2014

Keywords:
Crude oil
Neutron scattering
Viscosity reduction
Electric field
Aggregation of suspended particles

ABSTRACT

The small angle neutron scattering experiment has confirmed the theoretical prediction that a strong electric field induces the suspended nano-particles inside crude oil to aggregate into short chains along the field direction. This aggregation breaks the symmetry, making the viscosity anisotropic: along the field direction, the viscosity is significantly reduced. The experiment enables us to determine the induced chain size and shape, verifies that the electric field works for all kinds of crude oils, paraffin-based, asphalt-based, and mix-based. The basic physics of such field induced viscosity reduction is applicable to all kinds of suspensions.

1. Introduction

In 2006, a new technology to reduce the viscosity of crude oils by a strong electric field was proposed [1–3]. Comparing to the conventional heating method, this technology consumes much less energy and is much faster and, therefore, much more efficient. The work has received great general interest for its impact on energy production and transportation [4]. The technology also develops very fast. Rocky Mountain Oilfield Testing Centre (RMOTC) of Department of Energy recently published three reports, showing that the field tests have confirmed that this new technology is energy efficient and feasible on pipelines [5–7]. The TransCanada Keystone project recently decides to try this technology for its pipeline. These speedy developments urge us to resolve some controversy in the area quickly and clarify many important questions about the underlying physics.

Crude oil is a liquid suspension. The base liquid, consisting of gasoline, kerosene, and diesel, has a dielectric constant lower than that of the suspended particles, such as asphalt particles, paraffin particles and sulfur particles, etc. The proposed basic physics of the new technology is illustrated in Fig. 1. When a strong electric field is applied along the flow direction in a small section of the pipeline, the suspended particles are polarized by the electric field. The dipolar interactions quickly aggregate the particles into short chains along the field direction. Under such a condition, the space symmetry is broken. Similar to the flow of nematic liquid crystal with its molecule alignment in one direction, the viscosity is no longer isotropic [8]. Along the axial direction, viscosity is down to the minimum as these aggregates are streamlined along the flow direction with a very low intrinsic viscosity. Hence the crude oil flow inside the pipeline is greatly enhanced.

However, the theoretical prediction that the applied electric field could aggregate suspended particles inside crude oil was not obvious. The issue somehow becomes controversy. For example, I.N. Evdokinov and K.A. Kornishin in 2009 claimed that magnetic field and electric field cannot aggregate particles inside

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http://dx.doi.org/10.1016/j.fuel.2014.06.018
0016-2361/

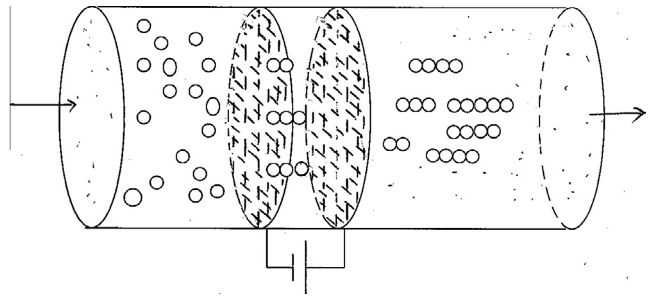

Fig. 1. As the crude oil flow passes a strong local electric field, the suspended particles aggregate to form short chains/ellipsoids along the field direction.

crude oil [9]. In the area of electrorheological (ER) fluids, it was well established that a strong electric field aggregates the suspended dielectric particles of micrometer size into chains and chain-based thick columns, which are close packed and have the body-centered tetragonal (BCT) lattice structure [10–12]. Similar electric-field induced aggregations have been observed in colloidal suspensions with particles in micrometer or sub-micrometer size [13]. It is also straightforward to show that at a sufficiently strong electric field, the interaction between induced dipole and local electric field inside crude oil is stronger than the thermal motion, leading to the particle aggregation. The controversy comes from a simple fact that crude oil is very dark and the suspended particles inside crude oil, such as paraffin particles, are typically in nanoscale; they cannot be observed under microscope or with conventional optical devices. In fact, we even did not succeed in using X-ray or TEM to monitor the suspended particles inside the crude oil. To resolve this outstanding issue, which is also the key for the new technology, we must have some direct evidence to show electric field induced particle aggregation inside crude oil. For this purpose, we recently carried out neutron scattering studies at NIST Center for Neutron Research (NCNR).

The small angle neutron scattering experiment fully verified our theoretical prediction. Under a strong electric field, the suspended nano-particles inside crude oil aggregate into short chains along the field direction. The experiment enables us to determine the induced chain size and shape, verifying that the electric field works for all kinds of crude oils, including paraffin base crude oil, asphalt base crude oil, and mixed base crude oil. The basic physics of such field induced viscosity reduction verified by the neutron scattering is general and should be applicable to many other areas [14].

2. Neutron scattering experiment

Our experiment was carried out at NG7 SANS (Small Angle Neutron Scattering) facility, NCNR, Gaithersburg, Maryland. This 30 m long SANS instrument is just ideal for our experiment. Jointly developed and sponsored by NCNR, ExxonMobil Research and Engineering Co., and University of Minnesota, the instrument has undergone a number of improvements over the years. The improvements, including a higher resolution 2D detector and focusing refractive lenses, have extended the Q-range of the instrument which now goes from 0.008 nm^{-1} to 7.0 nm^{-1} to enable structural features in materials ranging from roughly 1 nm to over 500 nm to be probed.

Our crude oil sample is in a special capacitor, consisting of two pieces of cadmium as electrodes and two pieces of quartz glass as windows (Fig. 2a). The neutron beam passes through the quartz windows and the crude oil sample and comes to the detector (Fig. 2b). A high voltage can be applied to cadmium electrodes to produce an electric field perpendicular to the neutron beam. We select cadmium for our electrodes because cadmium is a good neutron absorber, which reduces the neutron scattering noise and blocks the big angle scattering neutron.

Our tests were mainly with a light paraffin base crude oil sample (API 34) because the paraffin base crude oil is the controversial one. In 2006, it was also reported that magnetic field might be useful to reduce viscosity of paraffin base crude oil but had almost no effect on asphalt base crude oil [1]. However, the experiments by a Brazil group in 2011 showed that magnetic field has effect for some kind of paraffin base crude oil, but has little effect on other kinds of paraffin base crude oil [15]. This is related to the paraffin molecule structure: If the molecule has ring structure, the paraffin is diamagnetic; then, similar to electric field, a strong magnetic field in the flow direction could aggregate paraffin particles into short chains to reduce the viscosity along the flow direction. If the paraffin molecule's hydrocarbon chain has no ring structure, the paraffin is not sensitive to magnetic field; then the magnetic field basically has no effect on the crude oil. This finding indicates that in order to reduce the crude oil viscosity, we have to rely on the electric field for all kinds of crude oils, including paraffin base crude oil. Therefore, it is crucial to see if our neutron scattering experiment could verify the electric field induced particle aggregation inside paraffin base crude oil. Some tests with a heavy asphalt base crude oil (API 21) were also carried out in spite of the fact that the electric field aggregates asphalt particles inside crude oil is more established [1].

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. This quick transition can be explained as follows. When the dipoles aggregate into chains or chain-based columns, the total energy $U(N)$ is negative and the energy per particle $U(N)/N$ is more negative as N increases initially [10]. As the probability to have such structure of N aggregated particles is proportional to $\exp[-U(N)/k_BT]$, the aggregation is accelerated as N increases. The aggregated structure is more stable if it has more particles. For this reason, once the electric field is applied, many thick columns are formed quickly. If the final equilibrium can be reached, the ideal state should have all particles aggregated into one thick column, body-centered tetragonal lattice. In reality, in most cases we are unable to reach such ideal state, but we always see many stable thick columns quickly.

While the field induced dipolar interaction in crude oil is not as strong as that in ER fluids, the basic physics remains the same. Therefore, once the electric field is applied, the aggregation into chains or chain-based columns is accelerated as more particles get together. We should have sizable chains and chain-based columns quickly because the aggregated structure is more stable if it has more particles. This aggregation has been verified by our neutron scattering experiment.

Our test procedure was as follows: We first obtained the neutron scattering pattern without electric field applied. Afterwards, we turned on the electric field and gradually increased the field strength. When the suspended particles inside the crude oil were aggregated into structures by the electric field, the neutron scattering patterns changed. Hence, not only our theoretical prediction was verified, but the pattern itself also provided us with the information about the size and shape of the aggregated chains. Based on this information, we can calculate the viscosity reduction, further confirming our field tests.

3. Result analysis and conclusion

The Hamiltonian for the neutron particles is $H = -\hbar^2\nabla^2/(2m) + V$, where V is the neutron–nuclear interaction, responsible for the neutron scattering. For our tests, the first Born approximation