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AC field induced destabilization of water-in-oil emulsions based on North Sea acidic crude oil

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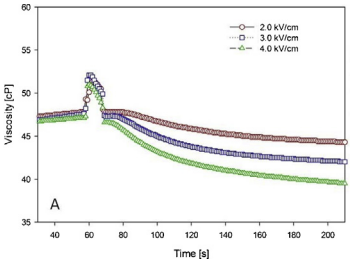
HIGHLIGHTS

- Viscosity drop and separation of water-in-crude oil emulsions.
- Droplet collision frequency enhanced by the shear movement.
- Combined effect of flow regime and voltage.
- High frequencies do not initiate drop deformation and breakage.

GRAPHICAL ABSTRACT



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ABSTRACT

The current work explores the effects of alternating current (AC) electric fields on coalescence of water droplets in crude oil. A North Sea crude oil emulsion with aqueous phase volume fraction of 0.3 and ~2 μm water droplets was used. The emulsions were prepared by an Ultra-Turrax disperser. Volume-specific energy input (E_v) has been calculated. Droplet collision frequency was enhanced by increasing the shear rate and initiating intense flow conditions. The flow conditions were verified to be within the valid flow regime for the specific rheometer geometry through calculations of the Taylor and Reynolds numbers. Viscosity alteration of water-in-oil emulsions as a result of electrocoalescence was investigated under the influence of electric fields in conjunction with variation of temperature, frequency, electric waveform, and duration of the applied electric field.

1. Introduction

When crude oil is processed in the production equipment, it is typically mixed with variable proportions of water, gas, and sand particles. A certain fraction of the energy used for transporting such mixtures in the pipelines produces shear forces. These forces greatly favor increase in interfacial area by water droplet formation inside the oil phase. Surface-active compounds and sand particles naturally present in the oil tend to stabilize these droplets, which makes resolution of water-in-oil systems a challenging task. Nowadays, numerous techniques are used for the separation of water from crude oils, including gravitational settling, thermal treatment, filtration, membrane separation, chemical demulsification, electrostatic destabilization, etc. [1–3]. Some of these methods are used independently, while others are more effective in combination with pre-coalescing step [1].

Electrostatic coalescence, or electrocoalescence, is one of the most efficient and eco-friendly ways for destabilization of water-in-oil emulsions. The technology is widely employed by petroleum industry for removal of water from crude oils [2]. It has a great potential for reducing time, amount of heat, and demulsifying chemicals typically used to separate emulsions into free water and oil. However, not all the aspects of the electrocoalescence mechanism have been fully understood up to now. It is still unclear how the combination of flow regimes, electric field strength, and frequency may affect hydrodynamic and electrostatic interactions

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Table 1
Physical and chemical characteristics of oil sample.

Characterization parameter	
Sara fractionation	
Saturates (wt%)	41.03 ± 0.51
Aromatics (wt%)	36.19 ± 0.23
Resins (wt%)	6.12 ± 0.02
Asphaltenes (wt%)	0.31 ± 0.02
Emulsified water (wt%)	0.01 ± 0.001
Density (g/cm^3, 20 °C)	0.881 ± 0.001
Total acid number, TAN (mg KOH/g)	2.58 ± 0.02
Total base number, TBN (mg/g)	0.74 ± 0.04

between the water droplets in various types of crude oils. Crude oil chemical composition, density, viscosity, water volume fraction, etc. may show large variations even within the same production well. All these parameters, especially in the presence of asphaltenes and resins as stabilizing agents for droplet interphase, will affect degree of emulsion stability and, consequently, the dehydration kinetics.

The type of electric field plays a significant role. Alternating current (AC) electric fields are usually utilized for the separation of water-in-crude oil emulsions, and applied values of the electric field strength are varied according to the water content of emulsions. There is a combination of dielectrophoretic and electrophoretic forces, as well as mechanical forces from gravity, inertia, and viscous effects, which act on a water droplet suspended in the continuous oil phase [4]. According to Taylor [5], the two driving forces of droplet coalescence are based on droplet distortion/deformation and dipolar forces arising from the polarization phenomenon in AC electric fields. In this type of electric fields, water droplets in oil emulsions change their shape and become elongated in the direction of the electric field. On the other hand, application of the field induces dipole–dipole interactions of the oppositely charged droplets, which would cause neighboring droplets to experience mutual attraction forces [6]. The dipolar attraction is strongly dependent on droplet sizes, concentration, and distances between droplets. Thus, low concentrated emulsions of small droplet sizes are typically subjected to laminar or turbulent flow conditions to initiate internal mixing and increase the probability of the droplets to come closer together and form chains. The attracting force between two droplets in close proximity to each other is inversely proportional to the square of the separating distance. As the distance decreases, the attracting force increases rapidly until contact occurs. The contact is followed by a film thinning between the droplets, its rupture and subsequent drop–drop coalescence. Enlarged water droplets will then separate from the oil phase and sediment under gravitational forces. The sedimentation velocity is known to be proportional to the square of the droplet diameter [3,7]. In spite of the well-accepted assumption that water droplets of opposite charges shall attract in electric field, a recent study [8] has shown that they may also repel each other at contact in high-strength electric fields. This phenomenon will clearly prevent coalescence.

In the present work, the electrostatic destabilization of water-in-oil emulsions in AC electric fields was studied by observing the changes in rheological properties of the emulsions (electrorheology). An emulsion with aqueous phase volume fraction of 0.3, with a large presence of small droplets, was used as the main experimental system. To compensate for the rather weak electrostatic forces, droplet collision frequency was increased by enhancing the shear movement. The viscosity drop occurred as a result of the emulsion breakdown when the electric field strength reached its critical value. Several parameters such as electric field strength, waveform, application time, frequency, and temperature were varied independently to evaluate their influence of the viscosity reduction, and to establish balanced conditions for the emulsion destabilization. Before applying the electric field, mean droplet sizes were calculated from the droplet size distributions obtained from digital video microscopy (DVM).

2. Experimental

2.1. Materials

A North Sea acidic crude oil sample was used in this study. The oil was characterized by SARA (saturates, aromatics, resins and asphaltenes) analysis, emulsified water content, density, total acid number (TAN), and total base number (TBN). The measured data are presented in Table 1.

Analytical grade sodium chloride (NaCl; ≥ 99.0% purity; Sigma-Aldrich, USA) was used for the preparation of synthetic brine (3.5% w/v of NaCl). The brine was further used as an aqueous phase for emulsion preparation.

2.2. Preparation of emulsions

Water-in-oil emulsions were prepared in a constant temperature water bath at 20, 40, and 60 °C. Emulsification was carried out in batches of 30 mL using an Ultra-Turrax (IKA, T18 with 18 and 12.7 mm of stator and rotor diameters) and aqueous phrase volume fractions of 0.2, 0.3, and 0.4. At constant speed of 21,000 rpm, highly homogeneous emulsions were obtained after 90 s of treatment. After emulsification, 18 mL of emulsion sample was immediately transferred to the rheometer cup, where electrorheological tests were performed at pre-selected temperatures.

2.3. Electrorheology

Flow curves of the emulsions were obtained using a stress-controlled Anton Paar MRC 301 rheometer (Anton Paar, Austria) equipped with an electrorheological temperature device (CC27/ERD; cup diameter 14.46 mm; external bob diameter 13.32 mm) and modified for allowing the connection with AC source. The electrical setup of the equipment consisted of a high voltage amplifier (605E-6, TREK) and Agilent InfiniiVision DSO-X 2022A 2 analog channel 200 MHz oscilloscope with built-in 20 MHz WaveGen function generator. The overall experimental setup is represented in Scheme 1. To avoid collapse of the electrostatic field due to a short circuit, the rheometer cup was insulated with 0.2-mm thick PVC electrical tape (PT 3900, Stokvis tapes) designed to perform in a temperature ranging from −10 to 80 °C.

All the emulsions were pre-sheared for 30 s (without data recording) to reach steady state before measurement. Viscosity monitoring was performed at 460 s^{-1} shear rate for 30 s before a voltage was applied for 1–10 s. The experiment was repeated at different temperatures (20, 40, and 60 °C), electric field strengths (2, 4, and 6 kV/cm), frequencies (50, 100, and 500 Hz), electric waveforms (sinusoidal, triangular, and square), and durations of the applied electric field (1, 5, and 10 s).

When emulsion is subjected to electric field, the formation of droplet chains (flocculation) and increase in droplet size (coalescence) occur. Viscosity reduction as a result of emulsion breakdown is expected when the strength of the electric field reaches the critical value. The expected shape of the viscosity curve is shown in Fig. 1. A reference viscosity value at 460 s^{-1} shear rate was calculated from an average of five separate experiments for each specific temperature: 47.0 cP at 20 °C, 28.0 cP at 40 °C, and 18.8 cP at 60 °C. The reduction in viscosity, expressed in percentage of the initial