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Effects of high-frequency and high-voltage pulsed electric field parameters on water chain formation

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ABSTRACT

Separation methods utilizing high-frequency and high-voltage pulsed DC electric fields have been used extensively in the oil and petroleum industries, where the occurrence of water-in-oil dispersions is highly unwelcome because of physical constraints and the high maintenance costs required to treat these dispersions. This paper reports the results of studies of the effects of applied electric field parameters, including electric field strength, frequency, and duty ratio, on water chain formation in water-in-oil emulsions. The investigations were performed in a rectangular Perspex® cell. The results of the studies show that dipole–dipole forces dominate the process of water chain formation. At low electric field strength, frequency, or duty ratio, dipole–dipole forces are negligible; therefore, the process of water chain formation and aqueous drop coalescence are inconspicuous. However, at high electric field strength, frequency, or duty ratio, significant dipole–dipole forces give rise to water chain formation and aqueous drop coalescence. At extremely high electric field strength, frequency, or duty ratio, aqueous drops are excessively polarized and disintegrate, inhibiting the processes of water chain formation and aqueous drop coalescence. The optimum electric field parameters for separation of water-in-oil dispersions are as follows: electric field strength, 3.80 kV cm^{-1}; frequency, 4.0 kHz; and duty ratio, 0.65.

1. Introduction

Crude oil in oil reservoirs always occurs together with water and mineral salts. In recent years, the water content of fluid from oil fields has reached as much as 90%. Water-in-oil (W/O) emulsions are readily formed during the production of crude oil and cause problems at several stages of production. The slow rate at which liquids naturally separate in most W/O dispersions has important consequences for many industries [1,2]. Moreover, crude oil contains surfactants such as resins, asphaltene, and paraffin, which stabilize W/O emulsions. In addition to the recent sharp increase in the water content of crude oil, the physical properties of crude oil mixtures have become more complex because of the widespread use of polymer flooding in recent oil field development. As a consequence of these developments, oil-water separation has become more difficult in recent years [3]. Therefore, novel methods that allow efficient removal of a dispersed water phase from a continuous oil phase are highly desirable and will have significant economic benefits for the oil industry.

Several techniques [4–8] are utilized to enhance the separation of W/O emulsions, including chemical demulsification, gravity or centrifugal settling, filtration, ultrasonic treatment, heating via microwaves and other methods, magnetic treatment, and electrostatic demulsification, each of which has advantages and disadvantages. For example, centrifugation is an effective separation method for some emulsions, but has a high operating cost [9]. Electrostatic demulsification [10] is one of the most effective and widely utilized methods of separating W/O emulsions. Historically, electrical treatment as a separation method was established by the pioneering work of Cottrell and Speed [11,12]. Electrostatic treaters use electric fields to enhance coalescence of aqueous droplets in crude oil, improving phase separation. Eow et al. [13] provided a comprehensive review of the fundamentals of the coalescence process. Furthermore, Bailes et al. [14,15,16] and Scott et al. [17] proposed pulsed DC electrical methods for dehydrating crude oil emulsions in the 1980s, after which favorable results were reported [18,19]. Obstacles to the effective separation of heavy oil using a pulsed electrostatic coalescence apparatus include electric field collapse [20], low efficiency [20], and substandard dewatering [20].

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Factors influencing pulsed electric field dehydration were reported by Eow et al. [21,22], Simone et al. [23], and Jin et al. [24–26]; however, although detailed knowledge of water chain formation is essential for controlling this process in W/O emulsions subjected to pulsed electric fields, few investigations on water chain formation in W/O emulsions during separation have been performed. The present study reports the results of a single-factor analysis of the influences of electric field strength, electric field frequency, and duty ratio on water chain formation in W/O emulsions subjected to pulsed electric fields.

2. Theoretical foundation

Electric dehydration [9,10,13] enhances the coalescence rate of water droplets in a W/O emulsion so that the droplets can grow to a size that allows them to be separated from the continuous phase under a gravitational field as a result of the difference between the density of oil and that of water. High-frequency and high-voltage pulsed DC electric dehydration are emerging methods that were introduced by Bailes [14]. The output voltage waveform is a conventional one with a high-frequency pulse signal. Aqueous droplets of crude oil acquire energy in high-frequency and high-voltage pulsed electric fields, enlarging the oscillation amplitude of the droplets and increasing the odds of collision, thus enhancing the dewatering efficiency. In addition, the polarized droplets twirl and repolarize according to variations in the electric field. Oscillation increases the chance of coalescence of fine droplets, improving dehydration efficiency [8,9].

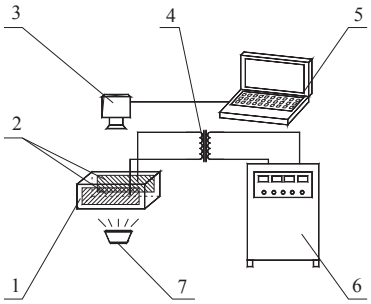
Water chain formation and break-up are the two patterns that occur during droplet coalescence [27]. Water chain formation gives rise to droplet oscillation and coalescence in the absence of short circuit chains, while water chain break-up hinders this process. Some of the dispersion phase droplets are oriented in line with the direction of the maximum electric field, forming water chains between electrodes [24–26]. However, water chains also occur without contacting electrodes. Jin et al. [24] proposed two criteria for water chains: the distance between droplets is less than the mean particle diameter and all droplets in the chain have the same movement pattern. The cause of water chain formation is controversial. Pearce et al. [28] held that the potential difference caused by induced charge was the principal factor in water chain formation. Bezemer and Goes et al. [29] believed that water chain formation was caused by an additional dielectrophoretic force between droplets. The water droplets in a W/O emulsion approach spheroidicity as droplet polarization is increased [26]. Droplet break-up occurs when critical deformation [27,30] is reached, at which point the drop apexes produce conical ends and liquid jets. It is generally acknowledged that dipole–dipole forces induced by electric fields are a major driver of water chain formation [10,31–33]. Waterman [31] provided a formula to calculate the coalescence force F between two adjacent droplets of the same size in a crude oil emulsion, that is:

$$F = \frac{6\varepsilon E^2 r^6}{d^4} \tag{1}$$

where ε is the dielectric constant of the crude oil emulsion, E is the externally applied electric field strength, d is the distance between droplets, and r is the aqueous drop particle radius.

3. Experimental set-up and procedure

The experimental set-up used to study the effects of electric field parameters on water chain formation is shown schematically in Fig. 1, which shows a cell under a digital camera (PH50-DB310U)



1-experimental cell; 2-electrical plate; 3-digital camera; 4-transformer; 5-image and video data processing system; 6-high-frequency and high-voltage power-supply system; 7-light source

Fig. 1. Experimental set-up of the microscopic test cell.

connected to an image and video data processing system (PHMIAS2008). The microimaging system consisted of a PH50-DB310U digital biomicroscope, computer, and PHMIA2008 micrograph processing software, all of which were obtained from Phenix Optical Instrument Co., Ltd. The high-frequency and high-voltage rectangular wave pulse dehydration power supply was developed by China University of Petroleum (East China). The voltage, frequency, and duty ratio of the power supply were continuously adjustable. The ranges of voltage, frequency, and duty ratio were 1.2–7.0 kV, 1.8–6.3 kHz, and 0.1–0.875, respectively. Fig. 2 shows a view of the cell. The cell was made of Perspex® and had dimensions of 85 mm × 11 mm × 11 mm. The high voltage electrode and grounded electrode were made of polished plates with an insulated coating. The arrangement shown in Fig. 1 can be used to study a system of one or more aqueous drops in a stationary dielectric liquid subjected to an electric field. With this arrangement, electric parameters can be easily controlled and manipulated.

The continuous phase liquid used in the investigation was conduction oil of good light-admitting quality. The relevant properties of the continuous phase liquid were measured with respect to air at 1 atm and 20 °C (Table 1). Surface tension was measured using a QBZY-1 surface tension auto-measuring instrument from Shanghai FangRui Instrument Co., Ltd. The Wilhelmy Slide method was used for the measurement of surface tension. A cambered interface was formed when the sensing platinum plate was immersed in the liquid. Surface tension exerted a downward force on the plate. When surface tension, buoyancy, gravity, and other related forces were balanced, the plate stopped sinking. The immersion depth was transformed into surface tension to give a direct reading of the surface tension of the liquid. When measuring the interfacial tension of the two tested liquids, the plate was kept clean and free from contamination by the organic phase liquid. A 50-mL beaker was used to measure interfacial tension. The high density

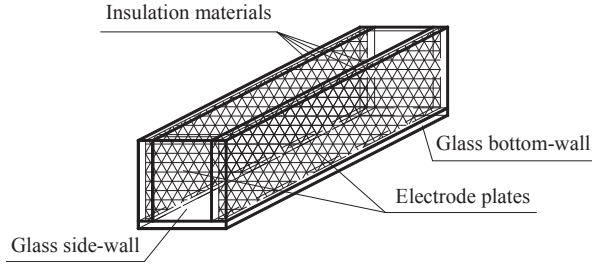


Fig. 2. Mini-sized electrostatic coalescence cell.