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The influence and optimisation of electrical parameters for enhanced coalescence under pulsed DC electric field in a cylindrical electrostatic coalescer

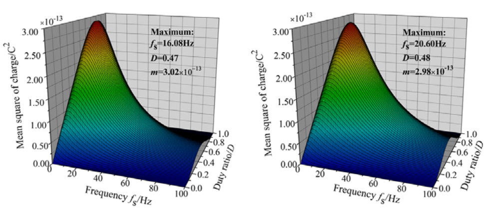
Donghai Yang*, Minghai Xu, Limin He, Xiaoming Luo, Yuling Lü, Haipeng Yan, Chengkun Tian

College of Pipeline and Civil Engineering, China University of Petroleum, Qingdao 266580, Shandong, China

HIGHLIGHTS

- The influence and optimisation of electrical parameters under pulsed DC electric field were investigated through experiments.
- Optimum electric field frequency and duty ratio were calculated based on two-layer capacitor theory.
- The two-layer capacitor theory is applicable in the low frequency range for a concentric cylindrical coalescer.
- The pulsed DC waveform is easily distorted when frequency is high.

GRAPHICAL ABSTRACT



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ABSTRACT

A pulsed DC electric field is usually used to enhance drop–drop and drop–interface coalescence in a water-in-oil (W/O) emulsion. The effect and optimisation of electrical parameters are important when designing an electrostatic coalescer. In this work, experiments were performed with a small-scale electrostatic coalescer and image processing technology using water in crude oil emulsions to investigate the influence of electric field intensity, frequency, duty ratio and rise time. The comparison between experimental data and predicted data based on the two-layer capacitor model of a cylindrical electro-coalescer was also obtained to validate whether the two-layer capacitor model is applicable for a concentric cylindrical electrostatic coalescer. Optimum electric field strength exists for different water content emulsions (525.6 kV m^{-1} for water content of 10% and 338.1 kV m^{-1} for 30%), which suggests that it is higher for lower water content emulsion. There are two optimum frequencies in the low and high frequency ranges. For water content of 10%, the optimum frequency is approximately 20 Hz, while for 30%, it is 10 Hz in the low frequency range. The coalescence effect is also high when the frequency is 2000 Hz. The droplet diameter is largest when the duty ratio is 50% for different electric field strengths, frequencies and water contents. The effect of rise time for pulsed DC is negative and the longer the rise time is, the worse the electrostatic coalescence effect is. The optimum frequency and duty ratio are obtained by using a theoretical formula and an empirical formula. The optimum frequency is nearly the same for the low frequency range especially for emulsions with a water content of 10%, but coalescence effects will increase at high frequency, which is different from the theoretical predicted value, indicating

* Corresponding author. Tel.: +86 532 86981224 86; fax: +86 532 86981222.
E-mail address: yangdonghai12@163.com (D. Yang).

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that the theory is applicable in the low frequency range for the concentric cylindrical coalescer. The predicted duty ratio is close to 0.5 and is nearly the same as the experimental results. In the electrostatic coalescer, the waveform of pulsed DC will be distorted to a triangle wave at high frequency. The high-frequency pulsed DC electric field is therefore not suitable for use in an electrostatic coalescer with an insulated electrode.

1. Introduction

Water commonly exists in crude oil and especially in flooding water oil recovery. When the liquid produced passes through pumps, shearing valves or orifice meters, the strong mixing enables micron-sized droplets to be finely distributed in the oil. Separation of fine aqueous droplets from crude oil is an essential process in the oil and chemical industries to meet the demand of product quality (Eow and Ghadiri, 2002; Mhatre et al., 2015). Several methods have been used to separate water from emulsion, including adding chemical demulsifier (Mohammed et al., 1994; Wu et al., 2003), gravity or centrifugal settling (Sun et al., 1999), heat treatment and electrostatic demulsification (Goto et al., 1989; Mohammed et al., 1993), among which the electrostatic coalescer is widely used since the application of external electric fields on crude-oil emulsions in 1919 (Cottrell, 1911; Cottrell and Speed, 1911). The presence of an electric field can promote contact between drops and facilitate drop–drop and drop–interface coalescence (Eow and Ghadiri, 2002; Eow et al., 2001; Førdedal et al., 1996), which will increase the droplet size, enhance the settling velocity and reduce the separation time. The alternating current (AC) electric field can tolerate high water content (Warren, 2002; Noïk et al., 2002), and the direct current (DC) electric field (Hirato et al., 1991) is commonly used to treat emulsions with low water content. The use of a pulsed direct current (pulsed DC) electric field has also been widespread since the 1980s (Bailes and Larkai (1981, 1982)). Lee et al. (2001) found that AC fields were more effective in increasing the coalescence rate than pulsed DC fields, but Bailes and Larkai (1981, 1982) found that a better effect could be obtained for pulsed DC fields than for constant DC, half-wave, triangular and AC fields.

The mechanisms involved in electrostatic coalescence include chain formation (Chen et al., 1994), dielectrophoresis, electrophoresis, the formation of intermolecular bonds, dipole coalescence, electrofining and random collisions (Atten, 1993; Chen, et al., 1998). For pulsed DC electric fields, the two fundamental processes of water droplet growth are migratory coalescence and dipole coalescence (Urdahl, et al., 1996). In addition, dielectrophoresis coalescence is also important for cylindrical electrodes (Rebolleda et al., 2015) because of the non-uniform electric field.

To understand the coalescence mechanisms of water droplets in oil under a pulsed DC electric field, studies were undertaken on micro-scale droplet movement and deformation (Eow et al., 2001; Bailes et al., 1999, 2000) and macro-scale research on the separation efficiency of electrostatic coalescers (Bailes and Larkai, 1981, 1982; Eow et al., 2007). Bailes et al. (1999, 2000) investigated the motion of a single drop in a uniform pulsed DC field. Eow et al. (2001) studied the deformation and break-up of aqueous drops in stationary dielectric medium under high-voltage pulsed DC fields. Eow and Ghadiri (2003) observed that water drop vibration is dependent on electric field frequency. Mousavi et al. (2014) investigated the effect of pulsatile electric fields on secondary droplet formation.

Bailes and Larkai (1981, 1982) believed that the coalescence of droplets was dependent on dielectric relaxation time. The results indicated that the optimum frequency depended on the thickness of the insulation layer and the structure of the electrostatic coalescer (Bailes and Larkai, 1984a). Bailes and Dowling (1985) believed this was an effective method to separate water from W/O emulsion with insulated electrodes by applying a pulsed DC electric field. Bailes (1995) provided a new electrical model for coalescers and deduced a new mechanism for droplet electro-coalescence. Bailes and Kuipa (2001) enhanced droplet coalescence in a stable W/O emulsion by the simultaneous use of pulsed DC electric fields and the mild bubbling of the emulsion with air. Eow et al. (2002, 2007) studied the electrostatic and hydrodynamic separation of aqueous drops in flowing viscous oil. An optimum electric field and frequency existed for the enhancement of drop–drop and drop–interface coalescence under a pulsed DC electric field.

1.1. Influence of electrical parameters

Several factors have influence on the coalescence effect of the electrostatic coalescer. Bailes and Dowling (1985) found that the coalescence rate is a function of pulse amplitude, frequency and its shape, which all have optimum values. Bailes (1992) found that the optimum frequency is related to the relaxation time of various dielectrics, electrical properties of the continuous phase and the electrode coating material and its thickness. Zhang et al. (2011a, 2011b) investigated the effect of several operational variables on the electrostatic demulsification of W/O emulsions that were subjected to a high-frequency pulsed DC electric field (higher than 1 kHz).

The electric field strength affects droplet coalescence. Drelich et al. (1992) reported a separation efficiency of approximately 63% when the pulsed electric field strength was 140 kV m^{-1}, whereas an increase in field strength from 140 kV m^{-1} to 1100 kV m^{-1} only resulted in an additional 15% increase in separation efficiency. Figueroa and Wagner (1997) found that for a pulsed DC field, a linear function existed between separation rate and applied potential, but under high electric field strength the droplet may break up. Eow et al. (2001) found that the onset of drop break-up occurred at an electric field strength of between 300 and 350 kV m^{-1}.

Frequency affects droplet coalescence. The existence of an optimum frequency in water separation efficiency under a pulsed DC electric field was first reported by Bailes and Larkai (1981, 1983, 1984a, 1984b). Separation efficiencies were maximised in the frequency range from 2.5 Hz to 13.5 Hz. The optimum frequency is 8 Hz when the experiments were performed under the frequency range from 0.5 to 60 Hz (Bailes and Larkai, 1984a). Drelich et al. (1992) found that the pulsed DC frequency had no significant effect on the demulsification efficiency in the range from 5 to 25 Hz. Nonetheless, a maximum efficiency was observed for pulsation frequencies between 8 and 11 Hz. Galvin (1986) found that the separation efficiency increased at low frequencies (up to 10 Hz) and that the performance was satisfactory up to 200 Hz. Taylor (1996) has also experimentally shown that there is an optimum frequency for maximum coalescence depending to some extent on the applied voltage. Zhang et al. (2011a, 2011b) reported that the water removal efficiency for a certain inter-electrode distance increased with decreasing frequency and increasing pulse duration. Bailes and Kuipa (2001) found that the optimum frequency was 6.0 Hz for the case of electrical resolution without air sparging, while for conditions with air sparging, the optimum frequencies were greater than 9.0 Hz. Eow et al. (2002, 2007) found the optimum frequency