CHEMICAL ENGINEERING RESEARCH AND DESIGN 104 (2015) 658–668

Contents lists available at ScienceDirect

Chemical Engineering Research and Design

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

Electrocoalescence of water drop trains in oil under constant and pulsatile electric fields

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ARTICLE INFO

Article history:
Received 30 April 2015
Received in revised form 18 September 2015
Accepted 6 October 2015
Available online 22 October 2015

Keywords:
Electrocoalescence
Electrostatic de-emulsification
Phase separation
Oil treatment

ABSTRACT

This study addresses the effectiveness of constant and pulsed DC fields in promoting coalescence of dispersed water drops in an oil-continuous phase. For this purpose, a train of drops of relatively uniform size is injected into a stream of flowing sunflower oil. This stream is then admitted to a coalescing section, where an electric field is applied between a pair of ladder-shape bare electrodes. The capability of this device to enhance coalescence of droplets in a chain is investigated at different field intensities, frequencies and waveforms. The effect of the initial inter-droplet separation distance on the process performance is also addressed under constant DC fields. The dominant coalescence mechanism is found to be due to dipole–dipole interaction at low field strength, whereas electrophoresis becomes predominant at higher field strength. Experiments reveal the existence of an optimal frequency, where the average droplet size enlargement is maximized, especially at low field strengths. The droplet size at the outlet of the coalescer is also found to be dependent on the field waveform.

1. Introduction

The application of electrostatic fields to destabilize water-in-oil dispersions is found in most refineries and oil fields since Cottrell's dust-collector patent (Cottrell, 1908) was first employed in the dehydration of crude-oil at the beginning of the 20th century (Cottrell, 1911). Over the following years, numerous patented designs have been filed and extensive research has been carried out to improve the basic process and understanding of the electrocoalescence mechanisms, as summarized elsewhere (Taylor, 1996; Eow et al., 2001; Eow and Ghadiri, 2002; Urdahl et al., 2001; Lundgaard et al., 2006; Less and Vilagines, 2012; Mhatre et al., 2015). The drive to enhance the electrostatically assisted phase separation stems from (i) the low operating costs associated with this process in comparison to other techniques such as centrifugal methods and heat treatment, and from (ii) its environmentally friendly nature as the need for chemical de-emulsifiers is eliminated or reduced (Eow and Ghadiri, 2002). Despite these advantages, capital costs are still high as conventional electrocoalescers are usually large vessels, with the whole operation requiring considerable residence time, typically 30–40 min (Urdahl et al., 2001). Hence, there is a strong need for process intensification by improving the performance and efficiency of the electrostatic treatment through the optimization of the coalescer design, electrode configuration and electric field parameters.

With respect to this last aspect, AC, DC, pulsed-DC fields and their combinations have been used to enhance

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http://dx.doi.org/10.1016/j.cherd.2015.10.006
0263-8762/

coalescence between water droplets. Each field acts according to different mechanisms in promoting phase separation (Taylor, 1996). In particular, pulsed-DC fields, in conjunction with insulated electrodes, have been proposed for applications involving higher water content to avoid short-circuiting (Bailes and Larkai, 1981). With this type of fields, the main mechanism for droplet growth is based on the induction of dipoles; however, the process seems to be detrimentally affected by the rapid build-up of charge carriers on the electrode insulation coating (Lundgaard et al., 2006). Also, the presence of insulation demotes the coalescence mechanism based on the rapid electrophoretic motion of water droplets that become charged by direct contact with bare electrodes.

The role played by the electric field parameters, namely: strength, frequency and waveform, has also been investigated. Generally, separation efficiency improves with increasing applied field strength, but various drop breakup mechanisms can occur if the strength becomes too high (Williams and Bailey, 1986). This behaviour results in the formation of tiny droplets which are difficult to separate. A too high field strength also increases the probability that secondary droplets form during droplet–droplet and droplet–interface coalescence (Mousavichoubeh et al., 2011a, 2011b).

The work of Brown and Hanson (1965) is one of the first studies investigating the effect of the electric field frequency on the coalescence of water droplets in oil at a flat liquid–liquid interface. By applying oscillating fields, they determined an optimum frequency at which the critical field strength, at which coalescence was single-staged (i.e. without formation of secondary droplets) and instantaneous, reached a minimum value. The authors explained their findings suggesting that certain frequencies of oscillations corresponded to the drop natural vibration or cavitation, setting up forced vibrations which facilitated coalescence. In a later study, Bailes and Larkai (1981) explored the possibility of applying pulsed DC fields to stable dispersions, whilst using insulated electrodes. They found that pulsating DC fields were more effective than constant DC fields in promoting coalescence, suggesting that, with the latter, more electrical energy is lost due to leakage through droplet chains. According to their interpretation, chains are continuously disrupted in pulsed fields, increasing the rate of collision between droplets. They also showed that an optimum frequency exists at a given field strength, especially at low electric field strengths. The frequency-dependent behaviour in the presence of insulated electrodes has been explained by modelling the emulsion-insulated electrode system as a two-layer capacitor (Joos and Snaddon, 1985; Bailes, 1995; Midtgard, 2009). According to this analysis, a too low value of frequency results in a significant time interval where the electric field is zero, due to the rapid migration to the insulation layer of mobile charge carriers contained in the oil (Bailes, 1995). On the other hand, too high frequencies would not allow for sufficient movement of these charge carriers, which are assumed to be responsible for the induced droplet charging and the resulting coulombic attraction (Bailes, 1995). However, the existence of an optimum frequency is still controversial. Galvin (1986) suggested that the voltage rise and fall time constants of the power supply circuit were important parameters and the existence of an optimum frequency was due to the limitation of the power supply circuit. According to Lundgaard et al. (2002), instead, efficient operations can be achieved by using AC voltage with high root mean square (RMS) value and applied frequency above a certain threshold, therefore rejecting the idea of the existence of an optimum value for the applied frequency. Similarly, Lesaint et al. (2009) obtained improved separation performance by increasing frequency until an upper limit. Recently, Mousavi et al. (2014) have shown that the formation of secondary droplets during droplet–interface coalescence can be suppressed when the pulsed-DC field has a frequency in the range 1–100 Hz. On the other hand, Zhang et al. (2011) reported that, in oil emulsions subject to AC voltage with frequency in the kHz region, the dehydration efficiency increased with decreasing frequency, suggesting that this behaviour is due to the smaller shape oscillations of droplets in high frequency electrical fields compared to their oscillation at lower frequencies.

The dependence of the electrocoalescence behaviour on the field waveform has been investigated in a few studies (Lundgaard et al., 2002; Lesaint et al., 2009; Mousavi et al., 2014; Berg et al., 2002; Ingebrigtsen et al., 2005), but is not well understood. The efficiency of the AC voltage waveforms in destabilizing the emulsions has been ranked as square > sinusoidal > triangular in some studies (Lundgaard et al., 2002; Lesaint et al., 2009). This was explained by considering that, for a given peak value, the RMS of the field is the highest with the square waveform and lowest for the triangular one. Berg et al. (2002) suggested that AC square waves are the most effective in promoting coalescence, as they ensure an electrostatic pressure equivalent to that obtained with a DC field. In contrast, Mousavi et al. (2014) have recently reported that pulsed DC triangular and sinusoidal waves are the most effective in suppressing the formation of secondary droplets, whereas square waves performance is less satisfactory. In another study, Ingebrigtsen et al. (2005) reported no appreciable difference in coalescence efficiency when either sinusoidal or square wave types were applied.

In the light of the above considerations, it appears that the effect of the electric field parameters on the electrocoalescence phenomenon is far from being understood. The overall picture is fragmentary and sometimes contradictory. Some confusion is also generated by the fact that the mechanism is strongly dependent on the presence of insulation and the application of AC or pulsed-DC fields. In particular, only few studies (Eow and Ghadiri, 2003; Eow et al., 2002) have addressed the electrocoalescence behaviour of multi-droplet systems that are subjected to pulsed DC fields between bare electrodes. However, a systematic analysis of the role played by the waveform has not been carried out. The presence of bare electrodes ensures higher rate of collision between droplets due to electrophoresis and dramatically increases the coalescence rate. Therefore research on this type of systems should receive more attention. Furthermore, the phenomenon should be studied under simplified conditions, while retaining the essential features of the real dehydration process. With respect to droplet–droplet and droplet–interface studies, the next level of sophistication is to observe the droplets behaviour when they are present as a train, as the formation of chains is important in electrocoalescence (Pearce, 1953). In this regard, Eow and Ghadiri (Ingebrigtsen et al., 2005) used a pair of ladder-shape electrodes to set up an electric field parallel to the flow direction of a train of drops, ensuring maximum attractive force between adjacent drops. Another advantage of this design is that the presence of the electrodes does not significantly disturb the hydrodynamics of the continuous phase. In the work reported here, the same electrode design has been used, with the aim to assess the effect of the field strength, frequency and waveform on the coalescence behaviour of a train