

The electrocoalescence behavior of surfactant-laden droplet pairs in oil under a DC electric field

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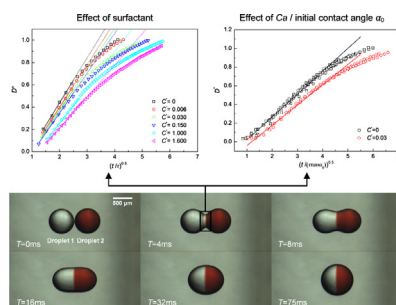
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HIGHLIGHTS

- The rule of liquid ridge evolution during droplet electrocoalescence is studied.
- Surfactant affects the initial growth rate of the liquid bridge.
- Initial contact angle is determined by electric capillary number and surfactant.
- Characteristic time considering contact angle is proposed.

GRAPHICAL ABSTRACT

The evolution of coalescence time, liquid bridge diameter and contact angle were discussed quantitatively with the effects of surfactant redistribution and electric capillary number, then the mechanisms of the surfactant and the electric field during the electrocoalescence is obtained.



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ABSTRACT

The electrocoalescence behavior of surfactant-laden droplet pairs in oil under a DC electric field was investigated in this paper. The characteristic parameters such as coalescence time, liquid bridge diameter and contact angle were analyzed for varying surfactant concentrations and electric capillary numbers. The results show that the horizontal electrocoalescence of two identical droplets with the same physical properties is symmetrical. Moreover, the surfactant has a significant influence on the pressure difference at the liquid bridge, which results in a variation of the liquid bridge growth and coalescence time. The pressure difference between the droplet and the liquid bridge is significantly dependent on the initial contact angle, which is determined by the electric capillary number Ca and surfactant concentration. The theoretical analysis and experimental results show that the large initial contact angle restrains the growth of the liquid bridge in the initial coalescence stage. Considering the effect of the initial contact angle, a characteristic time is proposed to describe the evolution of the liquid bridge.

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1. Introduction

The coalescence of droplets is an important mechanism, which has been applied in the petrochemical industry, environment engineering, and energy systems (Decent et al., 2006; Liao et al.,

2008; Weheliye et al., 2017). The application of electrocoalescence can speed up phase separation without the addition of chemical compounds (Mhatre et al., 2015a). However, surfactant originally present in the droplet is adsorbed on the droplet interface, which not only changes the properties of the droplet interface but also affects the inside and outside flow near the interface, and thus has an impact on droplet coalescence (Martin and Blanchette, 2015). Therefore, exploring the coalescence of surfactant-laden

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droplets under an electric field plays an important role in the optimization and improvement of electric demulsification.

The demulsification efficiency is closely related to the coalescence of droplets in the continuous phase. The coalescence of two droplets in an electric field occurs in three steps: droplet approach, film drainage, film rupture and coalescence (Sun et al., 1999). There have been a few experimental and theoretical studies on film drainage. First, the electric field force can reduce the coalescence time due to droplet polarization in an electric field (Williams and Bailey, 1986; Harpur et al., 1997). Lukyanets and Kavehpour (2008) discovered that the existence time for a liquid film is dependent not only on the amplitude of the electric field but also on the frequency of the AC electric field. The liquid film thickness model for the film drainage process was deduced by Karakashev et al. (2010). In addition, surfactant can change the interfacial properties, which can also affect film drainage (Chen et al. 1994). A non-uniform surfactant concentration on the interfaces leads to an interfacial tension gradient yielding the Marangoni effect (Bazhlekov, 2012). The Marangoni effect can significantly affect the film drainage rate (Rommel et al., 1992; Manev et al., 1976; Blawdziewicz et al., 1999). In the coalescence of a droplet onto a planar liquid-liquid interface, the Marangoni effect enables the droplet to reside on a liquid-liquid interface without coalescence, which reduces the coalescence efficiency (Amarouchene et al., 2001; Koehler et al., 1999). Moreover, subsequent studies have shown that the residence time is dependent on the surfactant concentration (Zhang et al. 2012).

The coalescence time, which depends on the liquid bridge evolution, is an important parameter for evaluating the coalescence efficiency. The pressure difference at the liquid bridge is the driving force for the liquid bridge evolution. Studies of the liquid bridge have been mainly focused on cases involving surfactant-free droplets. The results demonstrated in such works indicated that the morphological characteristics of droplets are largely influenced by the curvature of the liquid bridge, which determines the pressure difference at the liquid bridge (Choi et al., 2017). Numerical simulations show that the evolution of the liquid bridge diameter is proportional to $t^{0.5}$ when the coalescence is dominated by the inertial force (Duchemin et al., 2003). However, the viscous force can also affect the scaling laws for the liquid bridge diameter (Thoroddsen et al., 2005). Since the surfactant affects the inside and outside flow near the oil/water interface, the fluid dynamics in the liquid bridge can be changed, which influences the pressure difference at the liquid bridge. As a consequence, it can be inferred that the evolution of the surfactant-laden liquid bridge is different from that of the surfactant-free case. However, the characteristics of the surfactant-laden liquid bridge evolution currently attract less attention. In particular, few papers have yet discussed the characteristics of the surfactant-laden liquid bridge evolution.

When the electric field strength increases to a “critical value”, the coalescence form will transform from complete coalescence to non-coalescence. Before Bird et al. (2009), it has been generally acknowledged that excessive electric intensity leads to non-coalescence of droplet pairs in an electric field. Since there is a quick charge exchange redistributing the surface charges through the liquid bridge, the resulting electric force tends to draw the two contact droplets apart (Atten and Aitken, 2010; Saranin, 2011). However, Bird et al. (2009) put forward an innovative theory indicating that it is the contact angle, i.e., the angle of tangents between the droplets at the perimeter of the contact area forming the bridge, which really matters. The contact angle affects the pressure difference between the droplet and the liquid bridge, which dominants flow from the droplet to the liquid bridge; thus, it is an important factor in the liquid bridge evolution. By using an interface energy model, Bird et al. (2009) found that the calculated critical cone angle for electrocoalescence is close to 30.8° , which is

in agreement with the experimental results. The deformation shape and the induced circulation actually change the distribution of the surfactant at the interface (Teigen and Munkejord, 2010), which affects the cone angle, and therefore affects the flow from the droplet to the liquid bridge. However, for droplets with surfactant, limited study focused on the contact angle of droplet pairs during the electrocoalescence process.

To address the above problems, with the aid of high-speed photography technology, we organized detailed experiments and conducted thorough analysis of the electrocoalescence behavior of surfactant-laden droplet pairs in oil under a DC electric field. By changing the surfactant concentration and electric capillary number, the evolution of the coalescence time, liquid bridge diameter and contact angle are analyzed in detail, which is of great significance to improve the demulsification efficiency under an electric field.

2. Experiment

2.1. Experimental setup

The experimental setup was composed of a high-speed video camera, waveform generator, high-voltage power amplifier, transparent test cell and an LED light source, as shown in Fig. 1. Coalescence processes for droplet pairs were recorded using a high-speed video camera (NAC Hotshot 1280), which was equipped with a $100\times$ lens (Mitutoyo $5\times$ objective with a $20\times$ tube made by Pomeas). The camera was utilized with a frame rate of 1000 frames per second and resolution of 1280×512 pixels. The pixel length was $2.8 \mu\text{m}$. The features of the electrocoalescence process were analyzed using image-processing software.

The experiments were conducted at room temperature (20°C). The Perspex test cell containing two stainless steel electrodes (dimensions $40 \text{ mm} \times 30 \text{ mm}$, thickness 1 mm) is shown in Fig. 2. The high-voltage electrode was connected to a high-voltage power amplifier (Trek 20/20C), and the other electrode was grounded. The Perspex block, with a thickness of 4 mm, was attached to the high-voltage electrode as insulation. The high-voltage source was fed by the waveform generator (Rigol

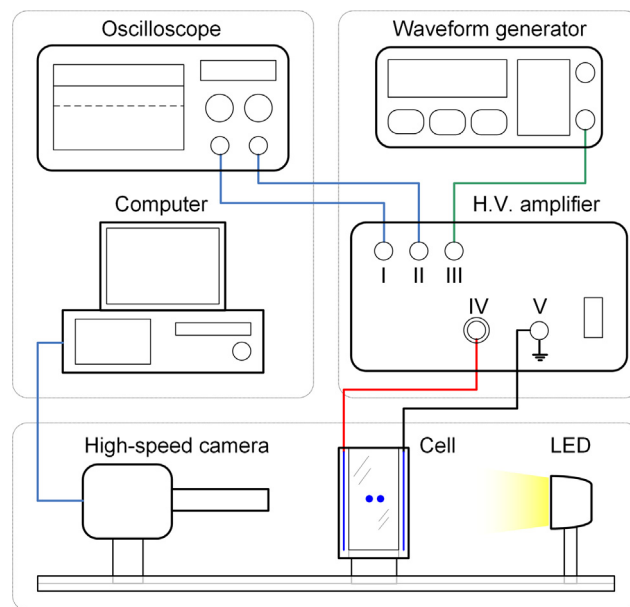


Fig. 1. Sketch of the experimental setup used for observation of the electrocoalescence of two droplets in oil under a DC electric field. I: voltage monitor port; II: current monitor port; III: signal input; IV: high-voltage output; V: grounded.

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