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Effect of surfactants on the deformation and break-up of an aqueous drop in oils under high electric field strengths

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ABSTRACT

Understanding the deformation and break-up of drops is of great significance in various applications such as emulsification and phase separation. Most practical systems contain surface-active agents that are present as impurities affecting the properties of the system, e.g. modifying the rigidity of the film that affects emulsion stability. In this paper, the effect of surfactants on the deformation and break-up of an aqueous drop in an immiscible dielectric oil under the action of an electric field is addressed. The experiments were carried out on a single drop in a microscopic cell under an applied external electric field. A nonionic surfactant, polyethylene glycol sorbitan monolaurate (Tween 20), and an ionic surfactant, sodium dodecyl sulfate (SDS), were used at different concentrations. The drop adopted in most cases a prolate shape. However, the presence of the surfactant affected both the extent of deformation and the modes of break-up. The drop deformation extent increased rapidly with the surfactant concentration, while smaller drops deformed less under the same external electric field strength. When the surfactant concentration was high, the position of break-up could be from both poles along the main axis of the drops in the direction of the electric field.

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1. Introduction

Electro-coalescence of aqueous droplets in oils is used extensively in the oil industry to separate water from oil. Under an electric field the drops deform and coalesce faster, enhancing the phase separation (Eow and Ghadiri, 2002). However beyond a threshold of the electric field, the drops disintegrate into small droplets (Sjöblom, 2006; Tuan et al., 2009). The formation of small droplets is of special concern, since their separation becomes extremely difficult and their presence can lead to short-circuiting of the electro coalescer.

Most practical systems contain surface-active agents often as impurities. These affect the system behaviour, for example modifying the rigidity of the film and hence the emulsion stability (Kokal, 2005). The accumulation of surfactants at the interface between two immiscible liquids alters the local thermodynamic environment, and consequently, the nature of the macroscopic interfacial boundary conditions for the dynamics and, in certain cases, the kinematics of a two-fluid flow (Ha and Yang, 1998). Adsorption of surfactants lowers the interfacial tension and hence the stress needed to deform or break the drops. The presence of surfactants interacts with the effect of the electric field in stressing

the drops. Nishiwaki et al. (1988) and Moriya et al., (2006) found the deformation due to electric field was proportional to the drop radius and the viscosities of the drop and medium phases. Ha and Yang (1995) used the small deformation theory to examine the effect of insoluble surface-active agents on the drop deformation and stability in a uniform electric field. Generally, drop deformation and break-up in high electric fields when surfactants are present are very complex phenomena, and there is little systematic study of their interactions, hence the reason for this investigation.

2. Mechanisms of droplet deformation and breakage influenced by electric field and surfactant

An aqueous spherical drop suspended in an immiscible dielectric medium deforms under the influence of an external electric field into an elongated prolate spheroid in the direction of the electric field due to the electric stress on the surface (Nishiwaki et al., 1988; Taylor, 1996; Venugopal et al., 1993). However, the drop deformation is resisted by the interfacial tension, which will keep the spherical shape of the drop. Taylor (1964) assumed that the drop takes the shape of a prolate spheroid (Fig. 1) under static conditions, such that the pressure difference across the drop interface is the same at any point on the surface. This pressure

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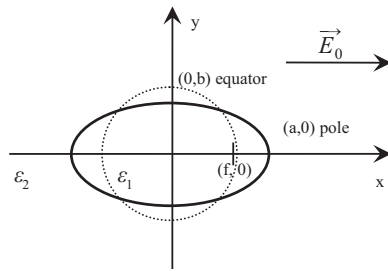


Fig. 1. Schematic diagram of a water droplet deformation in electric field.

difference is due to the effect of interfacial tension and electrostatic pressure.

Balancing the two pressure differences at the drop pole and the equator

$$\Delta p_{pole} = \Delta p_{eq} \quad (1)$$

gives

$$E_0 \sqrt{\frac{2r_0 \epsilon}{\gamma}} = 2 \left(\frac{b}{a}\right)^{4/3} \left(2 - \left(\frac{b}{a}\right) - \left(\frac{b}{a}\right)^3\right)^{1/2} I \quad (2)$$

where

$$I = \frac{1}{2} e^{-3} \ln\left(\frac{1+e}{1-e}\right) - e^{-2} \quad (3)$$

here e is the eccentricity defined by

$$e = \sqrt{\frac{1-b^2}{a^2}} \quad (4)$$

and a , b are the lengths of the major and minor axes of the prolate spheroid. Eq. (2) shows the deformation of the drop in the electric field is related to drop size, r , continuous phase permittivity, ϵ , interfacial tension between two liquids, γ , and the electric field strength, E_0 .

The charges present in the highly polar liquid can easily accumulate at the interface between the drop and the continuous phase, generating high electrically-induced stresses at the interface (Megias-Alguacil et al., 2004). The drop elongation increases with the field up to a limiting aspect ratio, above which the droplet becomes unstable. The corresponding field is called the critical field (Miksis, 1981).

In the presence of a surfactant on the interface between water and oil the interfacial tension is lower (Alguacil, et al., 2006). It was demonstrated that the electric deformation of droplets is proportional to γ^{-1} (Edwards et al., 1991; Shimomura and Ito, 2002).

According to Eq. (2), the limiting aspect ratio a/b for a stable prolate spheroid is equal to about 1.9. Taylor's model can be applied to experimental data with DC and low frequency alternating voltages (AC). In AC fields, raising the frequency makes the inertia forces comparable to the capillary and electric forces, and higher fields are required to reach the critical elongation. Other expressions for the critical field can be found in the literature (Atten, 1993; Waterman, 1965), where it is reported to be proportional to the ratio $(\gamma/r)^{1/2}$. Miksis (1981) numerically computed the drop shape in a uniform electric field, showing that shape is mainly determined by the dielectric constant of the drop. The results of this analysis showed that when the dielectric constant is larger than a critical value the drop will develop two obtuse-angled conical points at its ends, known as Taylor (1964) cones, for a certain field strength. Above the critical field strength, formation of a thin jet or ejection of small droplets at both ends of the drops has been observed. However, the observed drop disintegration is not always like the Taylor cone-jet formation. Different instabilities from the ends of the droplet were observed, leading to

ejections of droplets of various sizes to very fine clouds. The instability sometimes ended with separation into few droplets or a more explosion-like event (Sjöblom, 2006).

When the break-up of a large drop into the smaller droplets occurs, a large amount of surface energy is needed and the Laplace pressure (pressure difference between the pressure inside and outside the droplet) will increase. The adsorption of surfactant reduces the interfacial tension, that will decrease the Laplace pressure and make the droplets deform and break up easily (Sjöblom, 1996; Lucassen-Reynders and Kuipers, 1992).

Berg et al. (2002) reported increasing the conductivity of the water phase did not induce any noticeable effect on the critical field strength. This is expected, due to the huge difference in conductivity of water and oil. The influence of surface characteristics was also investigated by adding asphaltenes. Adding these compounds leads to a decrease in the stability of the water drops in an electric field, presumably due to the lowering of the interfacial tension. Water drops with asphaltene saturated surfaces are reported to exhibit elongation more than twice the break-up value of $a/b=1.9$ (Sjöblom, 2006) and significantly lower critical electric field strengths compared to clean drops.

Crude oil contains natural surfactants such as asphaltenes, resins, waxes, and naphthenic acids, and surfactants are also added to the system to act as demulsifiers. The effect of surfactants on the drops deformation and break-up mechanisms is therefore of high interest. Nevertheless, the currently available literature on drop behaviour in high electrostatic fields influenced by surfactant does not seem to give a concise view on the actual phenomena for drop break-up. This is addressed in this work by microscopic observations of drop deformation and disintegration in a uniform DC electric field in the presence of surfactants.

3. Experimental set-up and procedure

3.1. Experimental set-up

The experiments were designed to study the deformation and breakup of a water drop in a dielectric oil in a uniform electric field. A schematic diagram of the overall experimental set-up is shown in Fig. 2. The system consists of a microscopic cell equipped with two electrodes connected to a high voltage unit. The process is observed using a micro lens (Leica Monozoom 7) connected to a high speed digital video camera (Redlake MotionXtra HG-100K Motion Analyser), with the framing rate of up to 100,000 frames/s (the highest rates at reduced resolution).

The microscopic cell was made of Perspex to facilitate visualization of the phenomena occurring during the deformation and breakup. As illustrated in Fig. 3, the thick Perspex sheet of the base of the cell is designed to provide stability and insulation to the cell. The grounded electrode was fixed in position at the bottom of a Perspex container, while the distance between the two electrodes

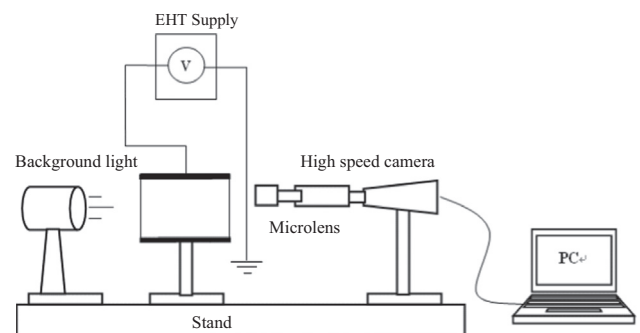


Fig. 2. Schematic diagram of experimental set-up.

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