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Deformation and breakup of aqueous drops in viscous oil under a uniform AC electric field

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ABSTRACT

Electric coalescence in alternating current (AC) electric fields is an important electrical dehydration technology. The deformation and breakup of water drops are crucial to the application of this process. In this study, these procedures were examined experimentally in an AC electric field using a high-speed camera. The deformation and breakup of drops depend on the intensity and frequency of this field. Deformation is aggravated by the increase in frequency under a constant electric field strength. Furthermore, the electric strength of breakup weakens as the frequency increases. Thus, understanding the deformation process can help advance electrocoalescencer design.

1. Introduction

Highly electric fields have been used to separate dispersed aqueous drops from oil phases in the chemical and oil industries [1–5]. Nevertheless, very highly electrostatic fields can disintegrate aqueous drops to the detriment of the overall efficiency of the electrocoalescence process [6,7]. In other words, the electrostatic field can deform and decompose the drops instead of coalescing them, and this limitation is of practical importance. Moreover, the addressing of this issue can be advantageous for other processes, such as the emulsification of an aqueous phase into an organic phase [8,9].

Numerous experimental and numerical studies have been conducted in the direct current (DC) electric field. Carton and Krasucki studied the bubbles of gas or liquid, which are immersed in a liquid medium and subjected to an electric field between parallel plate electrodes [10]. As the field strength is increased, the conducting and non-conducting bubbles elongate until a critical shape is attained when they are destabilised. The permittivity of these bubbles is over 20 times that of the medium. Taylor noted that a drop which has been elongated by an electric field becomes unstable when its length is 1.9 times its equatorial diameter [11].

The equilibrium shapes of drops are governed by the Young-Laplace equation of capillarity, which is augmented by an electrical pressure term [12–15]. Oscillation of an inclusion immersed in a quiescent fluid was studied [16]. According to the outcomes of an experimental investigation of drop deformation and breakup in several liquid–liquid systems, sunflower, calibration and palm oil contain inherent impurities such as surface active agents, minerals and protein molecules [17]. The effects of surfactant on the deformation and the stability of drops in an electric field have been investigated experimentally as well [18–20]. The shape of the deformed drop depends strongly on the electrical conductivity, viscosity, surface tension and density of both liquid phases [21–25]. The steady deformation and breakup of emulsion drops in a uniform electric field are also considered experimentally [26]. Moreover, the electrical charging of water drops on the electrode surface has been studied through experiments and through numerical simulation [27–29].

The form of the applied electric field is important. With pulsed DC fields, drop deformation and detachment rates are influenced by field strength and pulsing frequency [30].

Some studies have been conducted on the deformation of water drops in an alternating current (AC) electric field [31–35], but the breakup of water drops in this field has rarely been examined. In

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this paper, we report our observations of drop detachment in viscous white oil under AC electric fields with different frequencies.

2. Materials and methods

A rectangular test cell was constructed from Plexiglas to facilitate visualization. Its internal dimensions were $50(L) \times 80(W) \times 200(H)\,(mm^3)$. The cell was filled with white oil as an insulating liquid given its dielectric properties and transparency. Two rectangular copper plate electrodes which were 70 mm wide and 100 mm long were positioned parallel to the cell wall and were connected to a power supply. A high-voltage (HV) AC power supply was used to generate potential electric differences between the electrodes. Fig. 1 presents a schematic view of the experimental setup. The field strength was produced by applying an external voltage with a range of $5.4 < U\,(kV) < 15.0$ across a fixed distance of 30 mm between the two electrodes. The voltage is too high to be measured by oscilloscope directly. Resistors are connected in series, making a chain known as a potential divider, or voltage divider. The precision of the resistance is within 0.2% and the precision of the reduced voltage which is measured by oscilloscope is within about 4%. Therefore, the precision of the external voltage is within 4.4%. Therefore, the strength of a uniform electric field is dependent on the electrode distance, which varies in a range of E (V/m) from 1.8×10^5 to 5.0×10^5. The frequency of the electric field increased from 20 Hz to 180 Hz. To produce a clear imaging background, a cold light was used to illuminate the container from the back. During the experiments, videos of the drop traces were taken from the front of the container using a high-speed, charge-coupled device (CCD) camera (Redlake X4) at a frame rate of up to 10000 fps. The water droplet with radius of 0.9 mm is referenced to about 73 pixels in the pictures. Therefore, the resolution of deformation is about 1.37% (1/73). The precision of the amplitude is within 1.37%. Time resolution is 0.1 mS while a collection frequency of 10000 fps was used to obtain the images. If the vibrational frequency is 140 Hz, the vibration period is 7.14 mS. Hence, the precision of the phase is within about 1.40%. The camera was mounted on a ballhead which can move down with the droplets as driven by a stepping motor. The camera and the ballhead were positioned in front of the container as depicted in Fig. 1.

To suspend the water droplets in the oil, their density was adjusted with alcohol (28.5% water and 71.5% alcohol) [6]. The viscosity was measured by a rheometer (Malvern Gemini HRnano200). The interfacial tension was measured through the pendant drop method [36]. Several important parameters of the liquids used in this investigation are listed in Table 1.

Table 1
Physical and electrical properties of the liquids for testing.

Property	White oil	Water	Alcohol	Mixture
Viscosity (mPa s)	205.1	1.1	1.2	1.2
Density (kg/m^3)	860.5	999	789	879.3
Conductivity (S/m)	3.3e−12	1e−4	1.1e−5	1.5e−5
Relative permittivity	2.1	80.1	25.7	37.3
Interfacial tension between white oil and mixture (mN/m)				7.5

To determine the relationship between drop deformation and electric field intensity, two LEDs were placed behind the test cell. These diodes were linked to the HV power supply. To limit the potential difference between the LEDs, a resistance of approximately 10000 KΩ was connected in series to them. The directions of the LEDs varied; when one of the LEDs was turned on, the other was deactivated. The CCD camera recorded the brightness of the LEDs, and the electric field strength was calculated according the variations in brightness.

For the experiments, de-ionized water—alcohol drops with uniform diameters were released into the white oil using a syringe (as relatively conducting drops). The droplets were introduced into the space between the electrodes in the oil.

3. Results and discussion

3.1. Relationship between deformation times and electric field frequency

The drops require considerable deformation times. Without electricity, the water drops are ball-shaped because of the interface tension. In the oscillating electric field, drop deformation is a function of time. Specifically, the deformation of the water drops oscillates because the intensity of the electric field oscillates at a certain frequency. However, the deformed drop is not restored to its original shape when the field becomes zero temporarily; some residual deformation is retained. As a result, its deformation increases with each cycle until oscillatory deformation is stabilised.

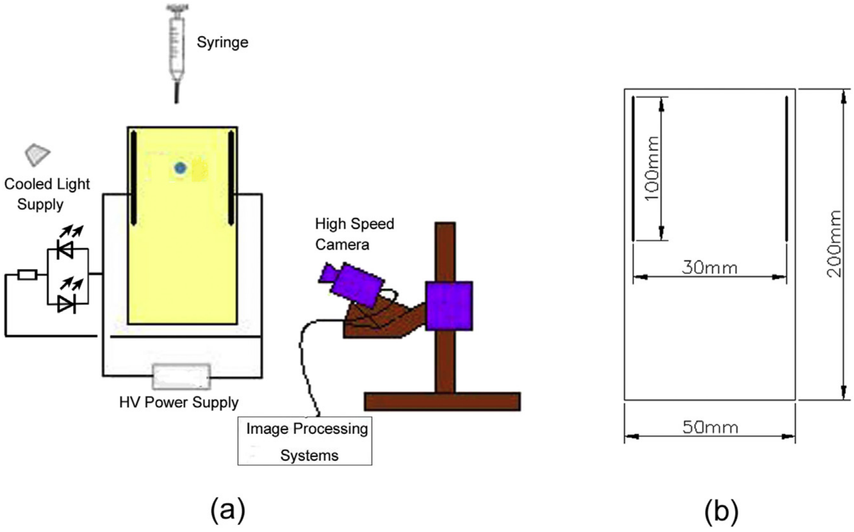

Fig. 1. (a) Schematic of the experimental devices; (b) dimensions of the cell.