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Spreading dynamics and oil film entrapment of sessile drops submerged in oil driven by DC electrowetting

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ABSTRACT

The effects of oil viscosity and drop size on the spreading behavior of sessile drops submerged in oil under various DC electrowetting actuation conditions are investigated systematically in this study. Settling time (i.e., time to reach 90% of the equilibrium radius) is found to be linearly proportional to the spherical radius of a drop and oil viscosity. The friction coefficient, which is almost linearly proportional to oil viscosity and is rarely affected by the applied voltage and drop size, is obtained by fitting a theoretical model to the results. Interestingly, sessile drops can jump in oil with low viscosity (0.65 cSt) when the applied voltage is turned off after the drops reach the equilibrium radius. This finding is attributed to the conversion of stored surface energy in the equilibrium state to kinetic energy for jumping when a stretched drop is released. The oil entrapment process and the instability of the entrapped oil film are also investigated by observing the bottom part of the spreading drops. The size of the oil drops generated by oil-film instability decreases as applied voltage increases and is rarely affected by oil viscosity.

1. Introduction

Electrowetting (EW) is the electric control of the wettability of a drop on an insulator-coated electrode surface. EW has several advantages, such as fast and reversible change in the contact angle and low driving voltage [1]. Thus, many EW-based practical applications, including digital microfluidics [2], liquid lenses [3], and reflective displays [4], have been developed. These applications are frequently used in water–oil systems because the oil medium reduces contact angle hysteresis (i.e., difference between advancing and receding contact angles) and lowers the driving voltage [5–7]. The oil medium also prevents drop evaporation and enables the drop to be manipulated at high temperatures [5,8]. In addition, the oil medium inhibits surface contamination caused by biomolecule adsorption [9,10]. On the contrary, the viscosity of the oil medium functions as a resistance force, thereby limiting transport speed [7,11]. The entrapment of the oil film between a drop and a solid surface also degrades the performance of EW-based devices in a water–oil system [12]. For instance, the numerous oil drops formed by oil-film entrapment and subsequent film instability occupy a large area in each pixel of display. Consequently, the oil drops reduce the maximum contrast ratio of the EW-based display [12]. A clear understanding of spreading dynamics and film instability in such a system is required to resolve EW problems in water–oil systems and improves the performance of EW-based practical applications. This has been one of the main challenges in EW research [13]. However, only a few studies have been conducted so far.

Kuiper and Hendriks [3] explored the effects of liquid properties (e.g., oil viscosity, density, and surface tension) and device size on the dynamics of liquid meniscus in EW-based liquid lens. They proposed an empirical formula to predict the critically damped condition under single DC voltage. Similarly, Roques-Carmes et al. [14] studied the switching phenomena as a function of several parameters, including applied voltage, oil viscosity, and device size, in EW-based reflective displays. The researchers were unable to establish any relationship between the aforementioned parameters and response time. Smith et al. [15] conducted experiments to determine the approximately linear dependence of settling time (i.e., time to reach the equilibrium radius) with respect to drop size. However, further systematic research is required to clearly establish this relationship. Lee et al. [16] experimentally and theoretically investigated the effects of device size on meniscus behavior in an EW-driven liquid prism.

A few studies on the temporal evolution of oil entrapment and the instability of the entrapped oil film under EW actuation have been reported. Herminghaus [17] studied the instability of dielectric liquid films between two electrically conducting media by applying electrical voltage to these media. Staicu and Mugele [18] investigated the entrapment process in a thin oil film and the

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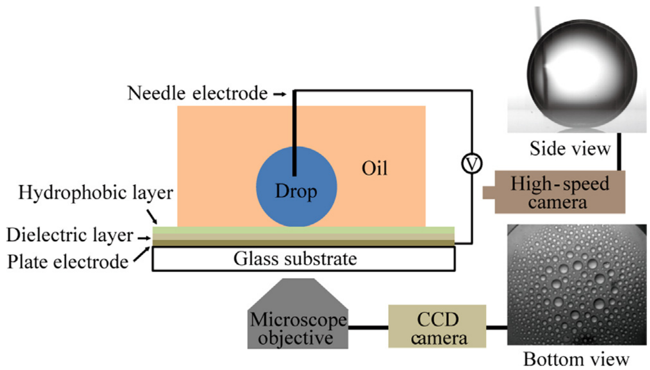

Fig. 1. Schematic diagram of the experimental setup.

film instability of spreading drops in response to ramp electrical voltages. Sun and Heikenfeld [12] explored the effects of dielectric thickness and applied voltage on oil-film instability in the pixels of an EW-based display. Kleinert et al. [19] studied the effects of the surfactant as well as AC amplitude and frequency on film instability during the EW-actuated transport of drops.

In our previous study, the effects of drop size and viscosity on the DC EW-driven spreading characteristics of drops (e.g., response time and maximum velocity) in air were investigated both experimentally and theoretically [20]. The main purpose of the present study is to extend our previous research in this field by investigating the effects of oil viscosity and drop size on spreading behavior in a water–oil system under various DC EW actuation conditions. The oil entrapment process and the instability of the entrapped oil film are observed during the spreading of drops in response to DC electrical, instead of ramp electrical voltages [18]. Lastly, the oil drops generated by oil-film instability are investigated as a function of oil viscosity and applied voltage.

2. Experimental setup

The experimental setup employed in this study (Fig. 1) is similar to that of the EW experiment in oil medium [15]. The indium tin oxide electrode plate coated with a dielectric layer (parylene-C, 5 μm thickness) and a hydrophobic layer (DuPont, AF1600® with 100 nm thickness) was combined with an acrylic cell (6 cm length, 3 cm width, and 2 cm height). The cell was filled with silicone oil, which has kinematic viscosities ranging from 0.65 cSt to 200 cSt. The conducting liquid was an aqueous 0.1 M NaCl solution. The interface tension between the saline solution and silicone oil was measured through an EW-based tensiometer method [21]. The detailed explanation on the method is described in Supporting Information section. The measured values of interfacial tension are 0.023 ± 0.002 N/m, except for silicone oil with a viscosity of 0.65 cSt (0.018 ± 0.002 N/m). These values are in good agreement with those previously reported [22]. A drop with a volume in the range of 0.5–10 μL, which corresponds to spherical radii ranging from 0.49 to 1.34 mm, was gently dispensed onto an electrode plate with a micro-pipette. To minimize the gravitational effect, the drop size was kept smaller than the capillary length $l_c = \sqrt{\gamma/(\Delta\rho g)}$ (approximately 3.4 mm for water–silicone oil with a viscosity of 0.65 cSt), where $\Delta\rho$ and g are the oil–water density difference and gravitational acceleration, respectively. A stainless-steel wire (80 μm in diameter) was inserted into a drop. DC electrical signals produced by a function generator (33220A, Agilent) were amplified (A800, FLC) and then applied between the wire and the electrode plate. The EW number η that ranged from 0.05 to 1.22, where $\eta = \varepsilon_d \varepsilon_o V^2/2d\gamma$ (i.e., the ratio of electrical force to surface tension), was used. Here, ε_d, ε_o, V, d, and γ represent dielectric constant of the

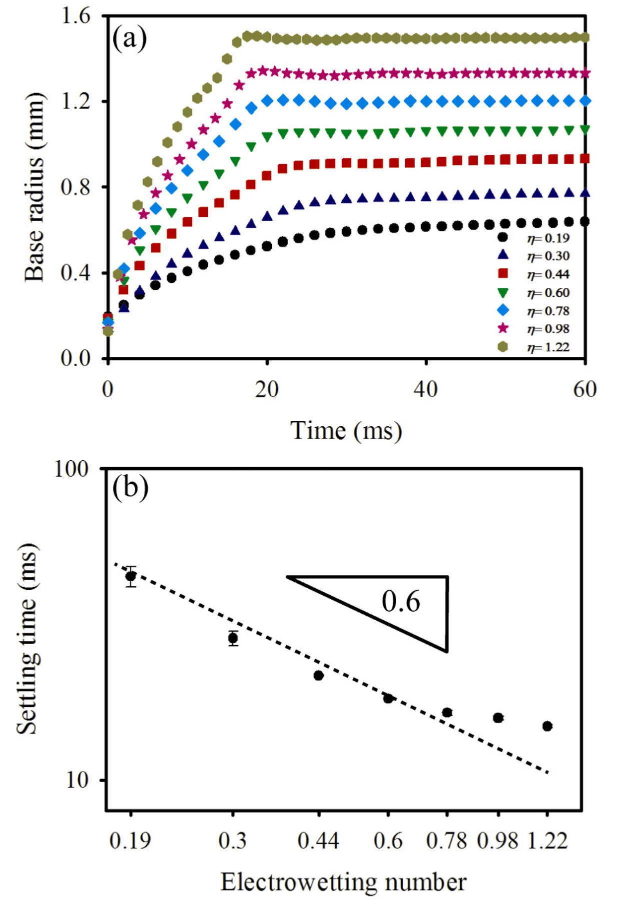

Fig. 2. (a) Temporal evolution of base radius (colored symbol) of spreading 5 μL drops submerged in oil with viscosity of 5 cSt at different electrowetting number η. (b) Power-law dependence of settling time on the electrowetting number η (log–log scale). The triangular inset indicates that the settling time is inversely proportional to 0.6th power of the electrowetting number. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

insulator, vacuum dielectric permittivity, applied voltage, thickness of the insulator, and surface tension, respectively. This number corresponds to electrical voltages of 20–100 V. The temporal evolution of the drop-spreading phenomena was recorded consecutively with a high-speed camera (Fastcam SA3, Photron) at 2000–4000 fps depending on the contact line speed. Another CCD camera (Pco Sensicam, Pco. Imaging) coupled with an inverted microscope (Zeiss Axiovert200, 10× objective Zeiss A-plan lens) was employed to record a bottom view of the contact area between the drop and the solid substrate. Digital image processing and data analysis were performed with MATLAB® and a public-domain image-processing program (ImageJ, NIH). Each experiment was repeated at least five times with new drops, and all data were statistically analyzed to obtain the averaged results. The experimental uncertainties in the measurements of the contact angle and contact radius were ±2° and ±0.02 mm, respectively.

3. Results and discussion

The spreading behaviors of the 5 μL drops in submerged oil with a viscosity of 5 cSt were observed at η = 0.19–1.22 to investigate the effects of applied voltage. The temporal evolution of the base radii of the drops was measured (Fig. 2a). At high EW numbers (η = 0.98 and 1.22), the drops spread to the maximum wetted radius and subsequently retracted to the equilibrium radius (i.e., under-damped response). However, the drops spread monotonically to the