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Short communication

Electric field induced deformation of hemispherical sessile droplets of ionic liquid

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ABSTRACT

Sessile droplets of an ionic liquid with contact angles close to 90° were subjected to an electric field $E = V/w$ inside a capacitor with plate separation w and potential difference V. For small field induced deformations of the droplet shape the change in maximum droplet height, $\Delta h = h(E) - h(0)$, was found to be virtually independent of the plate separation provided that $w > 3h(0)$. In this regime a scaling law obtains $\Delta h \propto E^2 r^2$, where r is the constant droplet radius, in agreement with the asymptotic predictions of Basaran and Scriven (*J. Coll. Int. Sci. 140*, 10, 1990).

Introduction

The study of the stability of charged water droplets was first reported by Lord Rayleigh [1]. This seminal paper established the field of electrohydrodynamics, which continues to be an area of intense interest and investigation including for understanding the behaviour of raindrops in rainclouds as well as for diverse technological applications based on electrospraying and in printing and coating processes [2–5]. When a conducting liquid drop is subjected to an electric field it tends to elongate along the direction of the electric field, as reported in relation to the stability of water droplets in an electric field [6]. Now consider the case where the liquid forms an axisymmetric sessile drop supported on the inside face of a parallel plate capacitor. The presence of the electric field distorts the shape of droplet away from the equilibrium spherical cap profile (assuming the droplet is smaller than the capillary length) and the droplet apex rises towards the opposite plate. The ability to control the shape via an externally applied electric field provided by this geometry has been exploited for applications including surface tension measurement [7], an optical display mode [8], and optimising the optical properties of polymer microlenses [9,10]. Further potential applications of this geometry are reviewed in Refs. [11] and [12]. Previous quantitative experimental and theoretical work on the distortions produced in conducting liquids in this geometry includes on soap bubbles [13–15], water droplets [16], and water droplets immersed in dielectric oil [17]. In the current work we consider small distortions, in which the voltage-induced height increase is less than 5% of the initial height, for droplets with contact angles close to 90°.

Materials and methods

Fig. 1(a) and (b) show the experimental geometry. A sessile droplet of liquid of maximum height $h(0)$ and radius r rests on the lower plate inside a parallel plate capacitor with variable gap w between the electrodes. The electrodes were formed from a continuous layer of transparent conductor, indium tin oxide (100 Ohm/square, 25 nm thickness, Praezisions Glas and Optik GmbH, Iserlohn, Germany) on borosilicate glass slides. The lower plate was coated with a commercial hydrophobic coating (Grangers International Ltd, Derbys., UK) which gave contact angles close to 90° with sessile droplets of the conducting ionic liquid butyl methyl imidazolium tetrafluoroborate. Applying either a D.C. voltage, $V = V_{d.c.}$, or an A.C. voltage, $V = V_{r.m.s.}$, between the capacitor plates deformed the shape of a sessile drop of the liquid within the capacitor and increased the maximum height by an amount $\Delta h = h(E) - h(0)$, where $E = V/w$. Fig. 1(c) and (d) show images of a sessile droplet for which $h(0) = 1.20$ mm and $w = 2.55$ mm with

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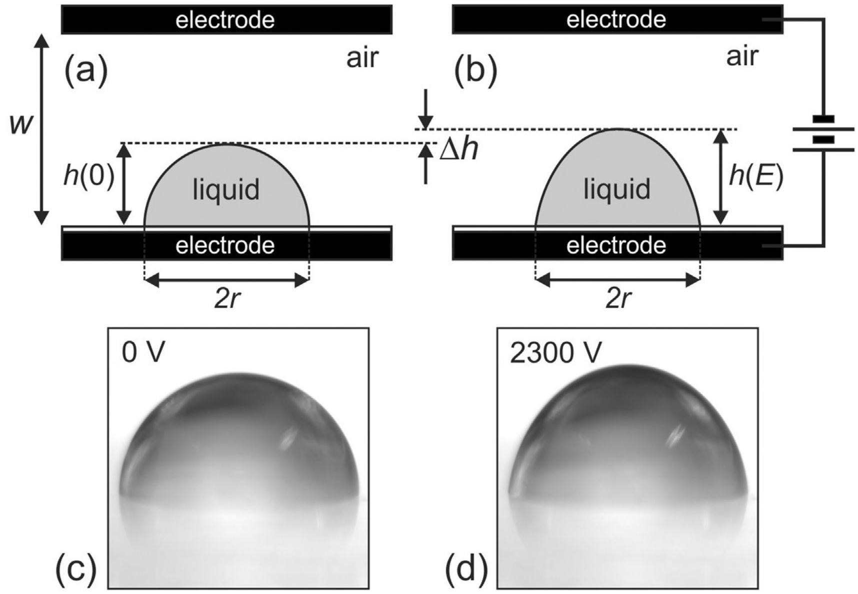

Fig. 1. (a) and (b) show the experimental geometry. A sessile drop with a contact angle close to 90° rests on the lower plate inside a parallel plate capacitor structure. A voltage applied across the capacitor plates deforms the drop which increases in height, (b). Images of a sessile droplet of the ionic liquid butyl methyl imidazolium tetrafluoroborate for which $h(0) = 1.20$ mm and $w = 2.55$ mm are shown (c) with both capacitor plates grounded and (d) with a D.C. voltage of 2300 V applied across the capacitor plates.

both capacitor plates grounded and with an D.C. voltage of 2300 V applied across the capacitor plates respectively. The ratio $w/h(0)$ for Fig. 1 is much smaller than the values actually used in the study.

The ionic liquid butyl methyl imidazolium tetrafluoroborate is an excellent conductor and has a low vapour pressure so shows negligible evaporation during the experiments [18–20]. The surface tension of the liquid was found from pendant drop measurements [21] (Drop shape analysis, A. Krüss Optronic GmbH, Hamburg, Germany) to be 40.9 ± 0.5 mN/m and taking a literature value of the density of 1120 kg/m^3 [22] this gives a capillary length of 1.9 mm. Since this capillary length is greater than the diameters of any of the drops used in the study, gravity can be neglected and the sessile droplets form a spherical cap in the absence of the electric field. In the study A.C. voltages (applied using a Trek model 609E–6 4 kV amplifier) at 1 kHz were used to avoid continuous charging effects. The D.C. conductivity of dry butyl methyl imidazolium tetrafluoroborate is reported to be 0.295 S/m at 303.2 K [23], and this increases significantly when the material is hydrated [24], which is expected as the droplet is used here in an ambient atmosphere. The estimated charge density of the liquid, at 10^{26}–10^{27} m^{-3} [25] is sufficient to screen and exclude electric fields many orders of magnitude higher than used in the experiment from the inside of the liquid droplet. The charge is also sufficiently mobile; the conductivity of the dry liquid increases with frequency and a relaxation which has been observed in the ionic motions is in the range 10^4–10^5 Hz [25] (at 280 K) is well above the value of 1 kHz used in our experiments at 293 K.

The height change values, $\Delta h = h(E) - h(0)$, in response to D.C. and A.C. voltages were found to agree to within ±1% over the full range of voltage, cell gap and drop heights used in the studies. Using transparent electrodes enabled the drops to be viewed both from above and from the side during the experiments. Accurate values for the small height changes in the range 1–40 μm were obtained using a 20 × microscope objective which imaged an area at the top of the droplets. The recorded images were contrast enhanced, thresholded, and the position of the top of the droplet was accurately obtained using a quadratic fit to the shape near to the apex.

Results and discussion

Fig. 2 shows data for the voltage induced change in maximum droplet height, $\Delta h = h(E) - h(0)$, plotted against the square of the electric field E^2, where $E = V_{r.m.s.}/w$. Data are shown for a droplet with a zero-field height of $h(0) = 0.71$ mm and contact angle 88.4° for 4 different cell gaps w: 1.15, 1.67, 2.33 and 2.90 mm. Data for the largest cell gaps, 2.33 and 2.90 mm, fall on the same straight line. When $w = 1.67$ mm there is still a linear relationship between Δh and E^2, but the gradient has increased. When the cell gap is reduced again to $w = 1.15$ mm the gradient is further increased and the plot becomes super linear for the higher electric fields shown. In order to elucidate the cell gap dependence the deformation of a droplet of

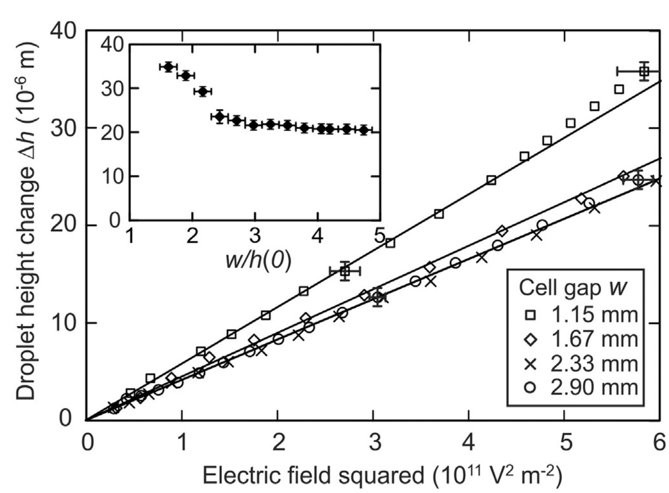

Fig. 2. The voltage induced change in height of the drop, $\Delta h = h(E) - h(0)$, plotted against the square of the electric field, E^2. Data are shown for a droplet of zero-field height of $h(0) = 0.71$ mm and contact angle 88.4° for 4 different cell gaps w. Inset: deformation Δh plotted against $w/h(0)$ for a droplet of zero-field height $h(0) = 0.74$ mm and contact angle 89.2° subject to a constant electric field of $(6.6 \pm 0.2) \times 10^5$ V m^{-1}.