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Dynamics and deformation of a drop in a DC electric field

A. Khayari[1], A. T. Pérez[1], F. J. García[2] and A. Castellanos[1]
[1] Dpto. de Electrónica y Electromagnetismo, Facultad de Física
Avda. Reina Mercedes s/n, 41012 Sevilla, Spain.
[2] Dpto. de Física Aplicada I, E.U.I.T.A., Ctra. Utrera km. 1, 41013 Sevilla, Spain.

Abstract: We consider a single conducting drop in suspension in a poorly conducting liquid between two horizontal electrodes. When a DC field is applied to the electrodes, the drop charges and rises within the liquid, then falls down as its charge leaks away, due to the finite electric relaxation time of the liquid. The drop keeps bouncing as long as the high voltage applied remains above a minimum threshold. We focus our study on the dynamics and the deformation of a water drop before the lift-off and during its motion. Electrodes of different materials are used in order to illustrate the role of interfacial energy between the electrode and the water.

Introduction

When a conducting particle immersed in a poorly conducting liquid between two electrodes is subjected to an external electric field, a bouncing motion of the particle is observed. The dynamics of the charged particle depends on many parameters, namely the particle size and physical characteristics of both the particle and the surrounding fluid. While solid particles are more easy to study, fluid phase particles (drops or bubbles) present a more complex behavior, due to their surface deformation and possible breakup. The deformation of liquid drops by an electric field has been extensively studied. It was experimentally found by many authors [1, 2] that, in sufficiently weak electric fields, conducting drops elongate along the field direction, producing a prolate shaped drop.

The present paper focuses on the study of dynamics and deformation of a drop that bounces under the action of an electric field. This study comes as continuation of the study done by the authors on a solid conducting sphere [3].

Experimental set up

The experimental set-up consists of a cubic cell made of Plexiglass and its dimensions are 70×70×50 mm. Inside the cell two electrodes, of circular shape and 20 mm radius, are fixed horizontally 2 cm apart. A metallic ring, 1 mm width and radius 20 mm, rests on the lower electrode in order to compensate for the field divergence at the center of the electrodes.

The upper electrode is connected to a high voltage supply, while the lower one is connected to a computer through an amplifier and an acquisition board. The cell is filled with a poorly conducting liquid. A drop of water is put initially at rest upon the lower electrode. Its volume is measured with an accurate micropipette. The volume of the drops used was 10μl, which corresponds to a radius 1.337 mm. The continuous phase liquid used was corn oil of density 916 kg/m^3, permittivity $\epsilon = 26.9\times10^{-12}$ F/m and conductivity $\sigma = 19\times10^{-12}$ S/m. Conductivity and permittivity have been measured by a conductivimeter LDTRP-2 supplied by IRLAB.

Along with the aluminum original electrode of the experimental cell, we used three discs which could be placed above the lower electrode. These three discs are made of steel, copper and titanium and are of the same diameter as the aluminum electrode fixed in the cell. Copper and steel electrodes are 1 mm thick, while the titanium one has a thickness of 3 mm.

A high speed camera VDS model HCC1000 was used to record the motion of the drop. A frame grabber permits the record of bitmap images at a resolution of 1024×1024 pixels. We used a free software, ImageJ, and programs developed with Matlab to process images and trace the drop profile.

Time of flight and lift-off voltage

When the drop is bouncing electric pulses are registered in the external circuit at every impact with the electrode. The time elapsed between current pulses corresponds to the time of flight of the drop. For voltages above, but close to, the lift-off voltage the particle bounces upon the lower electrode. Also, an oscillatory motion between the two electrodes was observed for some range of tension without breakup of the drop.

Let us study first how the time of flight of the drop depends on the applied electric field. As long as the drop is not too deformed and the first detachment has occurred, we expect the model for a solid particle [3] to be of application, with the appropriate change in the drag coefficient. In this model the inertial term is neglected and the motion of the particle is determined by the equilibrium between the electric, gravity and drag forces. The electric force is expressed as: $F_e = Q_0 e^{-t/\tau} E$,

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where t is the time elapsed since the last impact and $\tau = \epsilon/\sigma$ is the electric relaxation time of the liquid. (ϵ and σ are, respectively, the permittivity and the conductivity of the liquid). Q_0 is the initial charge of the particle acquired by contact with the lower electrode. It is expressed as [4]:

$$Q_0 = \frac{2}{3}\pi^3 \epsilon R^2 E_0, \quad (1)$$

In the case of a solid particle, the adhesion force between the particle and the electrode is negligible for a millimetric size particle. Therefore the minimum threshold E_c of the electric field needed to lift the particle corresponds to the equilibrium between the electric and the gravity forces. Therefore we can deduce E_c from: $Q_0 E_c = (m - m_l)g$.

Integrating the equation of motion [3] for a DC field leads to a relation between the time of flight Δt and the applied field E_0:

$$E_0 = E_c \sqrt{\frac{\Delta t/\tau}{1 - e^{-\Delta t/\tau}}}. \quad (2)$$

In the case of a fluid phase particle, a drop, the main differences with the solid state particle are the deformation of the drop and the adhesion to the electrode. The adhesion force acts just when the particle is in contact with the electrode. However during a rebound there is not physical contact between the drop and the electrode. This is due to the fact that electric breakdown takes place when the drop is very close to the electrode. This breakdown produces an electrical conducting path that charges the drop before the contact is produced. Experiments show that the charging process, when the drop comes close to the electrode, is a very quick process. The electric force dominates and the rebound is very fast and occurs before the contact is produced. On the other hand, the drop deforms much at the impact than when in flight, but during the flight of the drop, which takes few seconds, its shape can be approximated to a sphere. In conclusion, the model derived for the time of flight of a solid particle is applicable to a drop as long as the first detachment has occurred.

We must emphasize here that the threshold field E_c determined from equilibrium between electric force and gravity is not the lift-off field in the case of a drop. Indeed, the electric force necessary to first lift the drop has to overcome both gravity and adhesion force. Thus the lift-off field, that we will refer to as $E_{lift-off}$, must be higher than E_c. E_c can be measured experimentally by slowly decreasing the voltage for an already bouncing drop until it returns to rest. We have observed that the voltage at which the drop first detaches from the electrode is clearly higher than that at which it returns to rest when decreasing the voltage.

Experimental records of time of flight of the drop for a range of applied electric field fits well the theoretical model (2). From the fit we get a value of the threshold voltage E_c = 1.1 $\times 10^5$ V/m, and a relaxation time τ = 2.0 s. These values are to be compared with the value directly observed for E_c, E_c^{exp} = 1.6 $\times 10^5$ V/m, and the value obtained from the liquid properties, $\tau^{exp} = \epsilon/\sigma$ = 1.4 s.

When the drop is at rest on the electrode, and due to the adhesion of the drop to the electrode, an increase of the applied field leads to a higher deformation of the drop before it lifts. Two scenarios are possible at lift-off. One is that the drop lifts entirely conserving its initial volume and recovering a less deformed spheroidal shape. The second possibility is that the major volume of the drop rises within the surrounding liquid, and a small droplet remains stuck at the electrode. In the latter case the drop engenders regular bounces upon the tip of the droplet at rest on the electrode. If the voltage is kept at some value slightly higher than the lift-off threshold, an amount of the liquid in the resting droplet passes to the moving drop at each contact. After a few rebounds the drop recovers completely its initial volume. Then, as long as the applied voltage is kept somewhat above the threshold, the drop bounces without any loss of mass. What kind of behavior we encounter depends on the material chosen for the electrode.

To evaluate the lift-off field $E_{lift-off}$, we have to consider the adhesion of the drop to the electrode. The adhesion force, which tends to retain the drop in contact with the electrode can be expressed as: $F_a = 2\pi\gamma r \sin\theta$, where θ is the contact angle and r the radius of contact area.

For a small contact radius r the contact angle is $\pi/2 < \theta < \pi$. The lift-off of the drop requires an electric force equal to the adhesion plus the gravity forces, that is: $Q_0 E_{lift-off} = 2\pi r\gamma + (m - m_l)g$, where we have taken $\sin\theta \simeq 1$. Assuming that the drop charge Q_0 is that of the initial spherical drop (1), an estimation of the minimum electric field necessary to lift the drop against gravity and adhesion force can be expressed as follows: $E^2_{lift-off} = \frac{2\pi r\gamma + (m-m_l)g}{(2/3)\pi^3 \epsilon R^2}$.

Studying the drop deformation (following sections), permits an estimation of the surface tension $\gamma \simeq 1.0$ mN/m. Therefore an evaluation of the lift-off field for a radius contact r = 0.44 mm and R = 1.34 mm, gives a value: $E_{lift-off}$ = 1.63$\times 10^5$ V/m. The experimental value found was $E^{exp}_{lift-off}$ = 1.71$\times 10^5$ V/m, which is near the theoretical value.

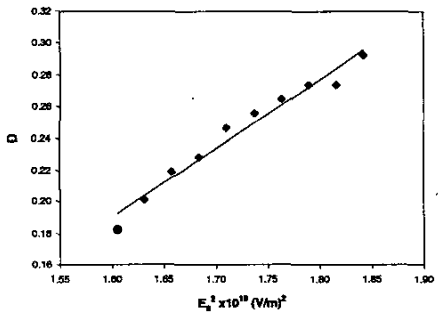

Figure 1: Deformation of a bouncing water drop of radius 1.34 mm as function of E_0^2.

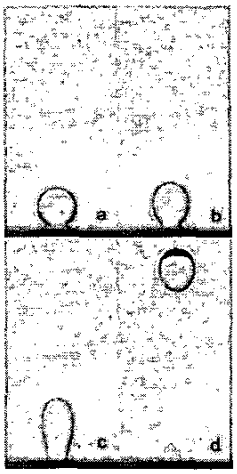

Figure 2: A water drop of radius 1.34 mm resting on a steel electrode and subjected to an electric field: a) E_0= 0, b) E_0 = 1.316×10^5 V/m, c) E_0 = 1.711×10^5 V/m, d) after lift-off at E_0 = 1.716×10^5 V/m.

Deformation of the drop

For an ellipsoidal drop of semi axes $a > b$, the degree of drop deformation can be expressed conveniently by the parameter: $D = \frac{a-b}{R}$ with R the radius of the non-deformed spherical drop. For a non charged conducting drop in a constant electric field, the deformation is determined by minimizing the total energy of the drop: electric plus surface energy. According to Taylor [1], for small deformations is: $D = \frac{a-b}{R} \simeq \frac{9}{8}\frac{\epsilon E_0^2 R}{\gamma}$.

In figure 1 we show how the deformation D of the drop varies with the applied field. From the slope of the best fit we obtain an estimation of $\gamma \simeq 1$ mN/m. In this estimation we suppose that the drop has lost enough charge for the theory of a neutral drop to be of application.

As we mentioned at the beginning, when the drop is still at contact with the electrode, its deformation under an electric field depends highly on the magnitude of the adhesion force. The governing parameters are the area of contact and the angle of contact. For lift-off of the drop to be possible, the area of contact has to be small or equivalently, the contact angle has to be high. This is related to the wetting characteristic of the electrode material. Partial wetting surfaces have a contact angle less than 90° while not wetting (or hydrophobic) surfaces have contact angles greater than 90°.

The area and angle of contact highly affect the shape taken by the drop and the lift-off process. We have observed this process with four different types of electrode material. Along with aluminum electrode, we used steel, titanium and copper. It was seen that for steel and copper electrode lift-off and bounces of small drops are possible. While for aluminum and titanium electrodes no lift-off is possible. In this case, increasing the applied electric field leads to a deformation of the drop into a bell shape. Further increase of the electric field leads first to oscillations of the upper tip of the drop and then to an ejection of small droplets from this tip towards the upper electrode.

Figure 2 shows a water drop immersed in corn oil on a steel electrode for different electric field values. In the last frame the drop is moving within the liquid just after first lift-off. At first, the shape of the drop is quite spherical and the contact radius estimated from recorded images is about 0.44 mm. The contact angle is $\sim$ 160° with no applied field. This angle reaches a value $\sim$ 115° for a value of the electric field E_0 = 1.71×10^5 V/m.

The deformation D of the drop for a steel electrode is plotted in figure 3 as a function of the electric field. It is seen that the degree of deformation, for a drop attached to the electrode, is largely greater than that for the bouncing motion. Also its dependence is not linear. A theoretical model for the deformation in this case is much more involved than for the drop in motion. The charge on the drop is not negligible and its distribution over the surface depends on the shape. In turn, this shape will be determined by the local equilibrium of the electrostatic, gravity and capillary pressures onto the surface. Therefore, a complete theoretical model must take into

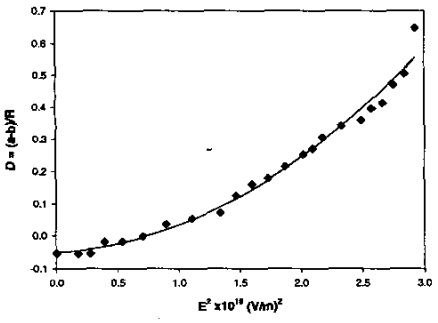

Figure 3: Deformation of a water drop of radius 1.34 mm, at rest on a steel electrode and subjected to an electric field E_0.

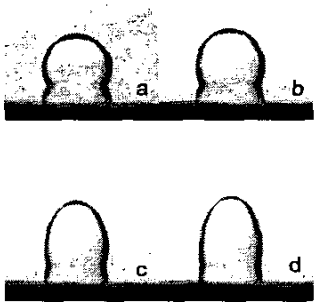

Figure 4: Shape taken by a drop of radius 1.34 mm resting on a titanium electrode, a) without applied field, b) with field E_0 = 1.18×10^5 V/m, c) E_0 = 1.77×10^5 V/m, d) E_0 = 2.71×10^5 V/m.

account the electric field distribution around the charge drop.

For titanium electrode, the contact radius is estimated to be 1.1 mm which is about two times and half that for a steel electrode. That is the area of contact is more than six times greater for the titanium electrode than the steel electrode. The contact angle without external field is estimated to be $\sim$110°; and for E_0 = 2.71×10^5V/m (near breakup value) it reaches approximately 90°, (see figure 4). This is consistent with a less interfacial energy for the interface titanium-water than for the interface steel-water.

Conclusions

We have carried out an experimental study of a bouncing drop under effect of an external electric field. It has been shown that a formerly established model for a bouncing ball describes well the dynamics of the drop in the limit of small deformation. Unlike the solid particle case, two critical voltages are of importance, the first one is the threshold voltage necessary to the first lift-off of the drop. The second one is that for which the drop returns to rest when decreasing the voltage. The former is higher than the latter due to the adhesion force which acts before the first lift-off.

The deformation of the drop in motion for the range of electric field used (between 1 and 2.5 $\times10^5$ V/m) was found to be less important in comparison to the deformation before the first lift-off. Indeed, the deformation can reach a value of 0.65 for a water drop of radius $\sim$ 1.34 mm before it lifts, whereas during its motion the deformation do not exceed 0.3. It has also been shown that the material from which the electrode is made influence highly the degree of the deformation and the critical field necessary for lift-off. As a consequence, for some material the contact area is so high that the adhesion force prevents any lift-off of the drop. Increasing the applied field only leads to the breakup of the drop.

Acknowledgments

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