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Onset of sliding motion in sessile drops with initially non-circular contact lines

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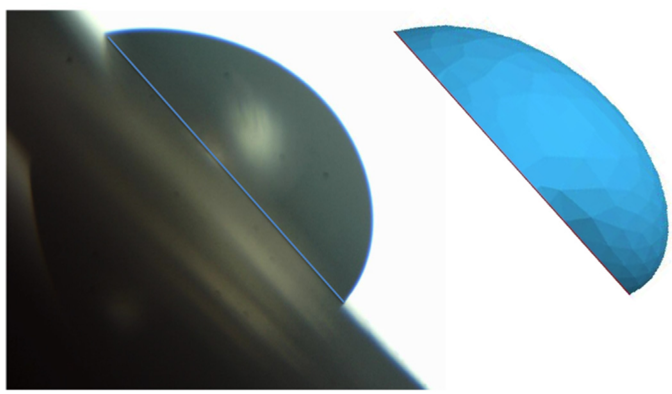
HIGHLIGHTS

- Impending motion in nearly elliptical drops is dependent on drop orientation.
- Experiments and computations are used to determine moving and sliding angles.
- Drop profile width is an important characteristic dimension.

GRAPHICAL ABSTRACT



Comparison of Surface Evolver and experimental image at the critical sliding condition

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ABSTRACT

The onset of motion of a drop with an initially non-circular three phase contact line was studied experimentally and numerically. Two drops of volume 10 μl were made to coalesce and form a composite 20 μl drop. The contact line of this drop was approximately elliptical and the local contact angle along the contact line was not a constant (as would have been the case with a circular contact line). The orientation of the drop to the impending direction of motion was varied. Inclined plate experiments were performed and the moving and sliding angles were noted in each case. It was observed that the moving and sliding angles of the drop were strongly dependent on this orientation. Specifically, the local conditions on the contact line at the front and back edges of the drop as well as the drop profile width were found to be the determining parameters. Surface evolver simulations were performed to understand the results of the experiments. It was found that the evolution of the contact line for non-circular drops was rather counter-intuitive when compared to the results from a drop with a circular contact line and resulted from a competition between gravity and the local contact angle hysteresis forces.

1. Introduction

The physics of sessile drops and the onset of their motion down an inclined plane have been studied extensively over the past

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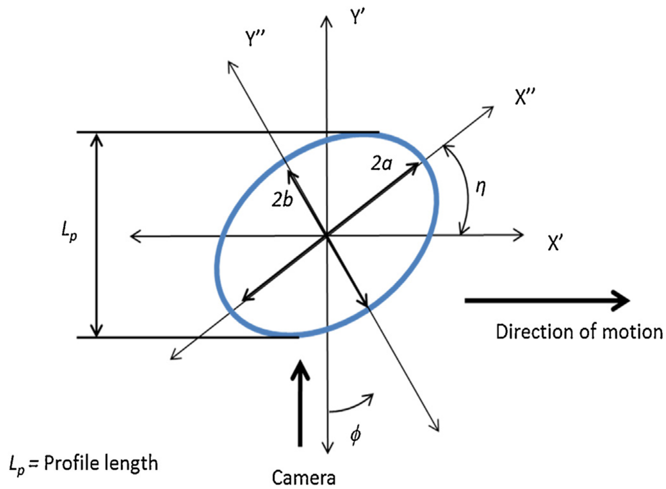

Fig. 1. Schematic of the drop with a non-circular contact line.

couple of decades [1–19]. The focus in this area of research, however, has been on sessile drops with an initially circular three phase contact line [5,7,20,21]. A sessile drop with an initially circular contact line has no concept of orientation associated with it. In this initial state, the profile of the drop is the same when viewed from any direction. This also implies that the distribution of the local contact angle (θ) along the contact line is uniform. Therefore, one section of the three phase contact line is indistinguishable from the other. The onset of motion of such a drop is a problem that has been studied before by us and others [2,3,5,10,22–24] and is relatively well understood. However, when the contact line is non-circular, the contact angle distribution is no longer uniform; the contact angle varies from one section of the three phase contact line to another [25–27]. The onset of motion of a section of the contact line is dependent on this local contact angle (θ_l). Therefore, it is anticipated that the onset of motion of a drop with an initially non-circular contact line will be different from the onset of motion of a drop with an initially circular contact line even if the volumes of the two drops were to be the same. The orientation (η) of such a non-circular drop to the direction of motion will begin to play a key role in such onset of motion. In this manuscript, we present the results of a study on the onset of motion of drops with three phase contact lines that are nearly elliptical.

The terminology and nomenclature that was introduced in our previous work [5] will be used here too. The interior angle that is subtended by the substrate and the free surface of the drop at the contact line is called the local contact angle $\left(\theta_l\right)$. If the surface is ideal, then this value is unique and is obtained from Young's equation. A real surface, however, manifests two limiting contact angles that are called the advancing $\left(\theta_a\right)$ and receding $\left(\theta_r\right)$ contact angles. These contact angles are the maximum and minimum values that the contact angle can take and all the values in between $\left(\theta_r < \theta < \theta_a\right)$ are admissible as possible local contact angle values. This phenomenon is referred to as Contact Angle Hysteresis (CAH). Throughout this study, we will work with real surfaces.

Fig. 1 shows a schematic of the contact line of the drop for purposes of representation. The direction of motion of the drop is along the axis$X\prime$. The direction along which the camera observes the drop is the axis $Y\prime$. The contact line is initially non-circular in shape. The contact line (which is nearly elliptical) can be described by a major axis of length, 2a and a minor axis of length, 2b. The major axis of the drop is along the axis X''. The orientation of the drop is defined as the orientation of the major axis to the direction of motion, i.e. the angle between $X\prime$ and X'', which will henceforth be referred to as η. The profile length $\left(L_p\right)$ is the width of the drop that is visible from the direction of motion. ϕ is the azimuthal angle of a point on the three phase contact line. It is defined with respect to the axis $Y\prime$, and is the angle between the axis $Y\prime$ and the line joining the aforementioned point to the origin.

Extrand and Kumagai [1] were the first to study the behavior and the contact angle distribution of a sessile drop with a non-circular contact line. They assumed that the contact angle distribution was linear in $cos\theta_l$ with $cos\theta_\alpha$ and $cos\theta_r$ being the bounds of the distribution. They also assumed that a normal to the local segment of the contact line was along the radial direction, but this has been shown to be incorrect later [26].

Recently, Antonini et al. [25] performed studies on measuring the adhesion force that resists the motion of the sessile drop. They developed a methodology to measure the contact angle distribution around the three phase contact line. Chini and Amirfazli [26] have also developed a methodology to determine the adhesion force for drops with an arbitrarily shaped contact line. This adhesion force is the same as the hysteresis force that has been referred to in Janardan and Panchagnula [5]. An important point to be noted was the perspective error that arises while measuring the contact angle of drops with an elliptical contact line. When the major axis was not perpendicular to the camera (the direction of viewing), it was seen that the point of measurement on the contact line was incorrectly determined. The radial position of the point of measurement (as determined from the images of the drop) from the origin is incorrect and leads to errors in the reconstruction of the contact line. However, there was no perspective error in the measurement of the contact angle itself. In our experiments and simulations, we have not measured the radial positions of the points of measurement. We have merely measured the contact angle at the extremes of the drop profile, and compared the same with results from Surface Evolver (SE). Therefore, the question of perspective error in contact angle measurement does not arise in our case.

The inclination angle (α) is the angle through which the substrate is tilted. The front edge and the back edge of the drop are those parts of the drop, which are downstream and upstream respectively, with respect to the direction of motion of the drop. As detailed in our earlier work [5], the motion of the drop is governed by the equilibrium between the gravitational force $\vec{F}_g$ and the hysteresis force$\vec{F}_h$. This hysteresis force is the magnitude of the total impeding force that acts on the contact line as a result of CAH. The gravitational force is the driving force for the motion and the hysteresis force resists said motion.

$$m\vec{g}\ \sin(\alpha) = \vec{F_g} \tag{1}$$

Here, m is the mass of the drop and α is the angle of inclination of the substrate of the drop. In a case involving drops with a circular contact line, the contact line of the drop begins to deform locally at either the back edge or front edge at a critical angle of inclination of the inclined plane called the moving angle (α_m). When a second critical angle of inclination (at which the other edge starts to deform) is reached the drop begins to display the onset of motion. This angle is called the sliding angle (α_s). The resisting force due to CAH is given by

$$\vec{F}_h = \oint \gamma_{LV} |\left(\cos\theta_Y - \cos\theta\right)| \hat{n} dl \tag{2}$$

where θ_l is the local contact angle of the drop on the contact line, γ is the surface tension of the liquid-air interface and dl is an infinitesimal element of the contact line with the dimension of length. The closed integral is performed along the contact line in order to determine the sum of the forces that are acting on all such infinitesimal elements of the contact line.