1. Introduction

Normally, a liquid drop introduced on a horizontal surface may spread, but its center of mass does not move. In this study, a method for inducing such center of mass motion, identified by Greenspan (1978), and demonstrated experimentally by Chaudhury and Whitesides (1992), is investigated. The mechanism that causes motion is a gradient in wettability on the solid surface. The resulting imbalance of forces acting at the contact line around the drop periphery leads to a driving force in the direction of increasing wettability (decreasing contact angle). Daniel et al. (2001) recently demonstrated that drops move even more rapidly when condensation occurs on the gradient surface. Some theoretical models of drop motion on a gradient surface are given in Greenspan (1978), Brochard (1989), and Ford and Nadim (1994), but all of these models employ the lubrication approximation. The objectives of the present work are to conduct simple experiments to establish the scaling laws governing this motion, and to develop a theoretical description.

This phenomenon can be useful in condensation heat transfer, removal of debris in ink jet printing, and for moving drops in a laboratory on a chip.

2. Experimental section.

2.1 Surface preparation. Strips of 30 mm × 20 mm with no visible scratches were cut from a silicon wafer with a diamond cutter. The surface was cleaned by repeated rinsing with deionised water followed by acetone. The surface was then dried uniformly before applying the flame from a propane torch to burn off any organic contaminants.

2.2 Preparation of wettability gradient. The gradient was formed inside a desiccator. The surface of silicon is normally hydrophilic (wetted by water). A silk thread saturated with Dodecyltrichlorosilane is suspended 1 mm above the strip for approximately 2 min. This chemical evaporates from the thread and diffuses along the silicon surface, reacting with it. The closer a location on the surface is to the thread, the more hydrophobic (non-wettable) it becomes. Therefore, this process generates a gradient of wettability on the surface.

2.3 Experimental measurements. Once a good gradient with a clean, shiny surface was prepared, the gradient was quantified by making contact angle measurements. The strip was placed on a microscope stage and drops of the test liquid were introduced at known positions using a nanoliter pump. A video microscopy technique coupled with a computer was used to grab and digitize video frames from which the interface shape near the contact line region could be obtained, permitting the contact angle to be measured. The source light direction and intensity are critical parameters for good images. Drop motion along the gradient was analyzed in the same manner by grabbing video images and using software to analyze the images and obtain the drop size and velocity.

3. Velocity prediction.

The motion occurs under conditions such that Stokes flow can be assumed and the drop shape approximated by a spherical cap. The viscous relaxation and Newton acceleration time scales are small compared with that over which the drop moves an appreciable distance. Therefore, a quasi-steady velocity is predicted by equating the driving force with the drag.
3.1 The driving force. The force exerted on the drop by the solid surface per unit length of the contact line is the difference between the solid-gas and the solid-liquid surface tensions \( \gamma_{SG}, \gamma_{SL} \), which is related to the liquid gas surface tension \( \gamma_{LG} \) through Young’s equation as \( \gamma_{LG} \cos \theta \). The difference between the forces acting on the advancing and receding sides of the drop constitutes the driving force. To include the effects of contact angle hysteresis, the advancing \( (\theta_a) \) and receding \( (\theta_r) \) angles are used at the appropriate sides of the drop

\[
F_d = 2R \gamma_{LG} \int_0^\pi \left[ \cos(\theta_a(\phi)) \cos \phi \, d\phi - \cos(\theta_r(\phi)) \cos \phi \, d\phi \right]
\]

for the driving force calculation as shown below.

Here, \( R \) is the drop’s planform radius and \( \phi \) is the azimuthal angle. Both advancing and receding contact angles are assumed linear with distance along the strip.

\[
\theta_a = A_a + B_a R \cos \phi \\
\theta_r = A_r - B_r R \cos \phi
\]

3.2 The drag. It is assumed that the dominant contribution to the drag comes from the wedge region near the contact line. The drag in this region is calculated from Cox’s (1986) asymptotic solution for Stokes flow, and its component in the direction of the contact angle gradient is obtained.

\[
F_{\text{Drag}} = \pi R \mu \left( E_{\text{adv}} + E_{\text{rec}} \right) U \ln\left( x_{\text{min}} / x_{\text{max}} \right)
\]

\[
E_{\text{adv,rec}} = -\frac{\sin \theta_{a,r}^2}{\theta_{a,r} - \sin \theta_{a,r} \cos \theta_{a,r}}
\]

Here, \( \mu \) is the liquid viscosity, \( U \) the drop velocity, and \( x_{\text{min}} \) and \( x_{\text{max}} \) are the wedge region boundaries, taken to be of a molecular length scale and the drop radius, respectively.

4. Preliminary Results and Discussion.

The measured advancing and receding contact angles are displayed in Figure 1, along with the straight lines fitted by the method of least squares. A typical prediction for the velocity as a function of drop size is compared with measured velocities in Figure 2. The cause of the discrepancy noted in Figure 2 is currently under investigation.

References


Brochard, F. “Motion of droplets on solid surfaces induced by chemical or thermal gradient”, Langmuir 5, 432-438, 1989.