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Electrowetting induced droplet jumping over a bump

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ABSTRACT

We study electrowetting induced droplet jumping over a system consisting of a flat surface and a topographical bump mounted on the surface. Different bump shapes including triangular and elliptical configurations are considered and the results are compared with the results of the flat surface. The results indicate that droplet jumping is enhanced over the bumps and the droplet jumps to larger heights compared with the flat surface because of the lower viscous dissipation. The shape of the bump can considerably affect the droplet dynamics. Between the considered shapes the triangular bump provides a larger dynamic and the droplet on the surface with this bump can jump with larger velocity. The electrowetting number, intrinsic contact angle, droplet–ambient liquid viscosity ratio, and the Ohnesorge number have also significant effects on the jumping process. By increasing the electrowetting number, intrinsic contact angle and droplet–ambient liquid viscosity ratio, the droplet height increases. However, increasing Ohnesorge number reduces the droplet height.

1. Introduction

Droplet manipulation has various applications due to its advantages in comparison with conventional continuous-flow-based systems [1]. Therefore, it has attracted a significant amount of attention [2–5]. Currently, droplet manipulation in digital microfluidics is possible in 2D [6,7]. However, many processes in microfluidics require 3D droplet manipulation and improving the existing 2D droplet manipulation to 3D is important for these kinds of processes [8,9]. One of the important droplet manipulation processes which has ubiquitous biological and industrial applications is the removal of the droplet from the surface or droplet detachment.

Detachment of droplets is essential in applications such as dropwise condensation [10,11], fuel cell [12,13], self-cleaning surfaces [14,15], and soft printing [16]. Several methods have been proposed to achieve droplet detachment of the surface. Mechanical vibration by a specific acceleration and frequency can lead to the atomization of the sessile droplet on a surface [17,18]. However, it has the disadvantage of high noise generation and the difficulty of integration. Electrostatic droplet jumping is another method that can be used to lift a droplet from a surface toward the upper substrate [9,19]. This phenomenon is easily possible for droplets in an oil environment. However, the oil environment is not acceptable in many applications [20]. On the other hand, because of the high voltage needed to provide the essential electric field, this method is not efficient. Besides that, in this method, precise control of the Coulomb force is necessary to prevent droplet splitting [21]. Nanoparticle suspension is another method for droplet detachment which needs the addition of surfactant or nanoparticles [22,23]. Recently electrowetting, which is the process of controlling surface wettability electrically, has been introduced as a promising method for the droplet detachment [24,25].

In electrowetting, a voltage is applied between the conductive droplet and the substrate and due to the change in the contact angle, the droplet spreads on the surface. In fact, the change in the droplet contact angle in electrowetting leads to droplet stretching which results in the storage of the energy in the droplet. If the voltage is released suddenly, the droplet recoils and for the cases that the stored energy is high enough, the droplet can detach from the surface.

To improve the efficiency of energy conversion from the surface energy to the kinetic energy, there have been numerous studies for better understanding the droplet detachment. Different parameters such as the applied voltage [25], the intrinsic surface wettability [26], the surrounding fluid density and the viscosity [27], the droplet volume [28], the width of the square pulse [29] and the number of the square pulses [28] are among the parameters studied. It has been shown that low intrinsic contact angle can reduce the height of droplet jumping. It is also observed that AC square pulse voltage in comparison with the DC voltage needs a lower threshold voltage for detachment and leads to higher detachment heights. On the other hand, higher effectiveness of the double pulse signal in comparison with the single pulse signal has been verified.

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Fig. 1. The Schematic shape of the bumps on the surface (a) Elliptical bump (b) Triangular bump.

All the previous studies on the droplet detachment have been conducted on flat surfaces. However, there are many applications in which a flat surface is not the case [30–32]. A superhydrophobic surface with micro- and nanoscale structure for decreasing the wettability is an important example [33,34].

In the present study, electrowetting-induced droplet jumping by considering the topographical modulations of the solid surface has been studied to enhance the performance of droplet jumping with improved solid–liquid interactions. Three different types of substrates including the hydrophobic flat, elliptical and triangular bumps are investigated in our simulations in order to evaluate the effect of the bump on the detachment process. We also examine the effect of the intrinsic substrate contact angle, the viscosity ratios, and the surface tension on the droplet detachment from the different hydrophobic surfaces. Considering the fact that in our study interfacial tension plays an important role, we need a numerical method that can calculate interfacial tension accurately. It is shown that the level set method (LSM) is very accurate in calculating the interfacial tension [35,36] and for this reason, we will employ this method in our study.

2. Theory of electrowetting

When a droplet is placed on a flat surface, the contact angle of the droplet with the surface is the result of the balance between pairs of the three phases. At this state, the contact angle is defined as:

$$cos\theta_Y = \frac{\gamma_{so} - \gamma_{sw}}{\gamma_{ow}} \tag{1}$$

where γ_{so}, γ_{sw} and γ_{ow} are the oil–solid, the solid–water and the oil–water surface tensions, respectively, and θ_Y is the equilibrium contact angle in the absence of the electrical potential. When a voltage is applied between the droplet and the electrode below it, the droplet spreads on the surface. The new droplet contact angle θ_0 due to the applied voltage can be expressed by the Young–Lippmann equation as follows:

$$cos\theta\,(V) = cos\theta_Y + \eta \tag{2}$$

where $\eta = \frac{\varepsilon_0 \varepsilon_d}{2\gamma_{ow}\varDelta} V^2$, ε_0 is the dielectric permittivity in a vacuum, ε_d is the dielectric constant of the dielectric layer, $\varDelta$ is the thickness of the insulating layer and V is the applied potential. The change in the contact angle causes an increase in droplet free energy. When the voltage is released, the excessive energy in the droplet leads the droplet to recoil toward the equilibrium configuration and if the droplet energy is high enough to overcome the energy loss due to excitation of the surface wave and flow-induced dissipations it will leave the surface and jump. It is concluded that the higher the energy difference between the stretched and the equilibrium configuration of the droplet the more energy will be available in the droplet for droplet detachment and; therefore, the higher height the droplet can jump.

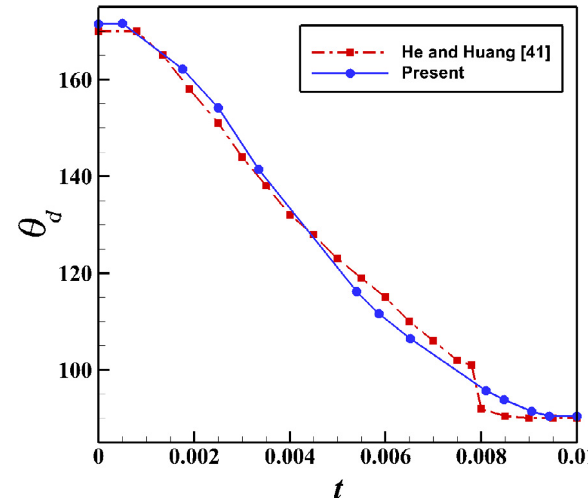

Fig. 2. The droplet contact angle variations with time for a spreading droplet for our study and He and Huang study [37].

3. Methodology

3.1. Description

We have investigated the effect of surface topography on the electrowetting-induced detachment of water droplets in a continuum oil environment. For this purpose, we have considered two different forms, namely, triangular and elliptical configurations for the bump on the surface as shown in Fig. 1. The bump height (I) and its width (W) were considered to be 70 μm and 100 μm, respectively. The simulation starts at a time that the droplet is stretched to its largest extent and the applied voltage is released. For each case, the effects of the intrinsic contact angle, the oil viscosity, and the Ohnesorge number have been examined. The results of the simulation have been compared with those of the flat surface droplet detachment.

3.2. Numerical method

We assume that both the droplet and the ambient fluids are incompressible and their motions are governed by the incompressible Navier–Stokes equations:

$$\nabla \cdot \vec{u} = 0 \tag{3}$$

$$\rho\left[\frac{\partial \vec{u}}{\partial t} + \left(\vec{u}\cdot\nabla\vec{u}\right)\right] = -\nabla p + \nabla\cdot\tau + \rho\vec{g} + \overrightarrow{F_b} \tag{4}$$

$$\begin{cases} \tau = 2\,\mu S \\ S = \dfrac{1}{2}\left[\left(\nabla\vec{u}\right) + \left(\nabla\vec{u}\right)^T\right] \end{cases} \tag{5}$$

where $\overrightarrow{u}$ is the velocity vector, t represents the time, P denotes the pressure, τ stands for the viscous stress tensor, $\overrightarrow{g}$ is the gravitational acceleration vector, and $\overrightarrow{F_b}$ represents the body force.

In the level set method (LSM), the following function is used to determine the type of the fluid in the domain:

$$\emptyset\left(\vec{x}, t\right) = \begin{cases} > 0 & \text{outside the interface} \\ = 0 & \text{at the interface} \\ < 0 & \text{inside the interface} \end{cases} \tag{6}$$

This function is calculated by the following equation:

$$\frac{D\emptyset}{Dt} = \frac{\partial\emptyset}{\partial t} + \left(\vec{u}\cdot\nabla\right)\emptyset = 0 \tag{7}$$