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Experimental study on the evaporation of sessile droplets excited by vertical and horizontal ultrasonic vibration

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ABSTRACT

Interaction between sessile droplets and solid surfaces is a fundamental science and engineering problem, with ubiquitous presence in various applications. In this paper, we study the effect of imposing vertical and horizontal ultrasonic vibration (40 kHz) on dynamics (oscillations) and evaporation of sessile droplets of dimethylformamide (DMF), isopropyl alcohol (IPA) and water on Teflon and glass substrates. There is no or very few works considering dynamics and evaporation aspects of excited droplets, simultaneously. The theory concerning the force balance and pinning/depinning in pristine and excited sessile droplet systems is elucidated. Time varying left and right contact angles and contact radius are measured for the duration of the droplet lifetime, where the stick-slip phenomena are observed and interpreted for various liquids. Imposing substrate vibration results in significant decrease in droplet lifetime and affects the behavior of the stick-slip mechanism. Droplets excited by horizontal vibration have the shortest lifetime. It is also experimentally shown that in the case of vertical vibration, the left and right contact angles oscillate in-phase, whereas in the case of horizontal vibration, there is 180° phase difference between left and right contact angles.

1. Introduction

Sessile droplets have ubiquitous presence in nature and have numerous applications, such as in droplet-based coating methods, as well as in emerging microfluidic and micro/nano devices, e.g. [1]. Analysis of sessile droplets involves surface science, thermodynamics, hydrodynamics, and heat transfer, making them an interesting but complex research topic. The present study focuses on dynamics (oscillations) and evaporation of ultrasonically-excited sessile droplets. Therefore, first the literature concerning evaporation and then dynamics and oscillation of excited droplets is reviewed to substantiate the novelty and demand for this work.

Numerous studies have been performed on behavior of evaporating sessile droplets on a substrate. Erbil [2] and Kovalchuk et al. [3] have reviewed and discussed some works pertinent to the basic theory and some special topics related to droplet evaporation. Evaporation of a sessile droplet in the most general case is a complex problem, due to possible internal liquid motion, gas phase motion, and heat transfer between solid, liquid and gas phases. However, based on some assumptions, various simplified evaporation models have been developed, as discussed in Ref. [4]. For instance, in the case of a sessile droplet evaporating in a stagnant surrounding gas, based on the diffusion-controlled model [5], droplet evaporation rate is controlled by diffusion rate of the liquid vapor in the surrounding gas. The evaporation rate varies with the droplet size and density, substrate temperature and substrate thermal properties [6–9], the choice of the ambient gas and pressure, which affect the diffusion coefficient [10], the vapor concentration in the ambient, and hydrophobicity of the substrate (contact angle) [11,12]. Obviously, if convective effects are present, the diffusion-controlled model is not sufficient to predict the experimental data [3], and more sophisticated multiphase flow models are needed [13–15]. Murisic and Kondic [4,13] provide a clear picture of the underlying physics and modeling of evaporation of sessile droplets with moving contact lines under various conditions and assumptions. They considered two commonly used evaporative models based on either the liquid phase or the vapor phase [13]. Of relevance to the present work is their simulation on the behavior of various liquids, where it was shown that the time variation of the base radius significantly changes with the choice of the liquid, as our experimental data also corroborate. In another comprehensive numerical study, Saenz et al. [14] presented a coupled two-phase model based on the diffuse-interface method to conduct three-dimensional direct numerical simulations of deformed evaporating droplets. The stick-slip modes, to

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Nomenclature

A	surface area of sessile droplet (m^2)
F_1	maximum pinning forces per unit length of the triple line (N/m)
F_2	minimum pinning forces per unit length of the triple line (N/m)
F_{depin}	depinning force per unit length of the triple line (N/m)
F_{pin}	pinning force per unit length of the triple line (N/m)
G	gibbs free energy of droplet (J)
$\bar{G}$	gibbs free energy of droplet per unit length of the triple line (J/m)
H	geometrical factor (m)
r	contact radius of sessile droplet (m)
t	time
U	potential energy barrier (J/m)
V	volume of sessile droplet (m^3)

Greek symbols

γ	liquid-gas surface tension (N/m)
γ_{SG}	solid-gas surface tension (N/m)
γ_{SL}	solid-liquid surface tension (N/m)
θ	apparent contact angle (°)
θ_{max}	maximum value of contact angle due to vibration (°)
θ_{min}	minimum value of contact angle due to vibration (°)
θ_0	equilibrium contact angle (°)
θ^* or θ_r	receding contact angle (°)
θ_a	advancing contact angle (°)
$\Delta\theta$	contact angle hysteresis (=$\theta_a - \theta_r$) (°)

be discussed below, and the possibility of the presence of Marangoni convection were studied.

One influential study that has shed light on the research path in mechanism or physics of evaporation of sessile droplets is a work conducted by Picknett and Bexon [16], in which two extreme modes of evaporation are identified: constant contact angle (CA) and constant radius (CR) modes of evaporation. Based on their investigation, droplet mass varies linearly with time in the CR mode, while it changes with a power law in the CA mode. In reality, the droplet evaporation usually proceeds based on a combination of multiple modes with various time durations, called stick-slip or stick-slide (SS) modes, where the stick mode is essentially the same as the CR mode, but in the slip mode, both radius and contact angle may change [17]. The duration and sequence of the stick-slip modes are hard to predict and vary with the choice of the liquid and substrate energy and texture, as well as the ambient conditions [18–22]. In some cases, after a period of evaporation in the CR mode, the droplet may quickly jump to a new position, in lieu of a slip mode [22]. Bormashenko et al. [23] showed that evaporating water droplets on polymer surfaces show stick-slip behavior, whereas on metal substrates the droplets show a stick or CR mode behavior only. Dynamics of sessile water droplets on wrinkled anisotropic wetting surfaces was investigated by Bukowsky et al. [24], where as expected, it was found that the wrinkles affect the energy barrier for slipping, in that, the droplets slip in the grooves, whereas their motion is restricted in the direction perpendicular to the grooves. Anantharaju et al. [25] conducted experiments on dynamics and evaporation of sessile droplets on patterned surfaces, with squared pillars and holes, where multiple stages of the stick-slip behavior were observed. The works on grooved and patterned surfaces are performed to support the research on emerging microfluidic devices [1]. In this context, Rowan et al. [21] studied the evaporation of microdroplets on polymer substrates, where it was found that evaporation occurs in the CR mode. Also, Hu and Larson [26] experimentally, analytically, and numerically studied evaporation of microdroplets, taking into account the Marangoni convection, and found a constant evaporation rate during the droplet lifetime. Erbil et al. [27] investigated the CA mode of evaporation of sessile droplets of various organic solvents. Strauber et al. [28] theoretically obtained the droplet lifetime in the CR and CA modes and showed that the droplet lifetime may not be always constrained by the lifetime in the extreme modes. In other words, since the time of evaporation in the CA and CR modes are different, and since the real stick-slip behavior of an evaporating droplet is a combination of the CA and CR extreme modes, one may expect that the lifetime of an evaporating droplet would be in between of those of the extreme modes. However, Strauber et al. [28] showed that this may not be necessarily the case.

The abovementioned works were concerned with the evaporation of sessile droplets on stationary substrates. Apart from such natural effects as oscillations due to the capillary waves induced by an inclined surface or self-excitation, e.g. [29,30], droplet excitation by imposed vibration can be exploited to manipulate dynamics and evaporation of sessile droplets. The vibration and oscillation of free-standing liquid droplets is a classic hydrodynamic problem tackled by Kelvin and Rayleigh in more than a century ago, and gradually completed by others. A literature survey reveals that study of imposed vibration on sessile droplets in the form of acoustic waves was first performed by Smith and Lindberg [31] to hinder contact angle hysteresis encountered in contact angle measurements. This is simply because the excitation by vibration helps the system overcome local energy barriers due to surface roughness and heterogeneity and minimize the contact angle hysteresis. Then later Andrieu et al. [32] showed that the cosine of the final contact angle associated with a non-wetting substrate vertically vibrating at 50 Hz roughly equals the arithmetic average of the cosines of the receding and advancing contact angles. Decker and Garoff [33] imposed vertical vibrational pulses to sessile droplets and studied how the pulses affect contact angle measurements and the droplet rise height. They also put forward the idea of droplet retention on inclined surfaces, by the aid of imposed vibration. Given that it is difficult to obtain the value of the equilibrium contact angle, more recently Volpe et al. [34] added vibration generated by loudspeaker to a standard Wilhelmy microbalance to obtain the equilibrium state of the meniscus and therefore the equilibrium value of the contact angle. Similarly, Meiron et al. [35] developed a method for the measurement of the apparent contact angle using well-controlled imposed vertical vibrations at low frequencies (~100 Hz).

Inspired by some of the above-mentioned works, Daniel and Chaudhury [36] showed that imposed horizontal vibration (100 Hz) assists the movement of a droplet along the gradient of wettability on the surface. As one of the first theoretical works, Lyubimov et al. [37] performed an analytical study on hydrodynamics of a hemispherical sessile cap excited by horizontal vibration and obtained the natural frequencies of oscillations. Lyubimov et al. [38] studied the hydrodynamics, oscillations and contact line dynamics of a hemispherical, inviscid droplet on a vertically vibrating solid surface, where oscillation modes were obtained. They identified a viscous layer, called Stokes layer, close to the surface, whereas the rest of the droplet was assumed invis-