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Study of internal flow and evaporation characteristics inside a water droplet on a vertically vibrating hydrophobic surface

Chang-Seok Park, Hun Kim, Hee-Chang Lim *

School of Mechanical Engineering, Pusan National University, 2, Busandaehak-ro 63beon-gil, Geumjeong-gu, Busan, 46241, Republic of Korea

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ABSTRACT

The purpose of this study is to gain understanding of the flow and evaporation characteristics inside a water droplet, on a hydrophobic surface that is vertically vibrated by an external force. To predict the resonance frequencies of a droplet, two theoretical equations on natural frequency (Lamb's and Strani and Sabetta's) are used. This study assesses the validity of one of these equations, which yields results that are closer to the experimentally measured values by comparing them with the calculated values. With the use of a high-speed camera, macro-lens and continuous laser, visualisation of the shape and the modal frequencies of a droplet were generated, and the results show that a droplet attains various shapes at different modes, resulting in complicated vortices inside the droplet. In the visualisation, the flow moves upwards starting from the bottom centre of the droplet along the symmetric axis. It then moves closer to the three-phase contact line along the surface of the upper part of the droplet. The resulting flow visualisation indicates a Y-shaped bifurcation flow pattern from a bottom surface at the second and fourth modal frequencies, while a large-sized oval shape is presented at the sixth and eighth modal frequencies. The flow velocity is the fastest at the fourth modal frequency. Correspondingly, the velocities at the eighth, sixth and second modal frequencies appear smaller than the fourth modal frequency, in that order. The evaporation rate is faster at the resonant frequency than at the rates of other neighbouring frequencies.

1. Introduction

The droplets have been a topic of interest for many researchers. For example, Dietz et al. [1] observed that an increased surface per unit volume allows the enhancement of heat and mass transfer within the fluid. Recently, microfluidic research has grown substantially due to its vast potential for use in a wide range of chemical, biological and biomedical application [2]. In particular, vibration and evaporation of droplets have garnered increasing interest, and numerous studies have been conducted in the fields of fundamental/applied and chemical/mechanical science and engineering. Even today, these topics are being actively studied.

Predictions of oscillation frequencies and mode shapes of an inviscid free drop date back to Lord Rayleighs [3] study on an incompressible droplet vibrating with force. The study was conducted on a free drop under the assumption that the drop was inviscid. Lamb [4] later solved the Rayleigh drop equations to calculate the natural frequency in small amplitude vibrations (see also Chandrasekhar [5] and Bostwick and Steen [6]). Strani and Sabetta [7] conducted a study on an inviscid droplet in partial contact with a concave solid surface. Their study can be differentiated from the study by Lamb in that Strani and Sabetta theoretically analysed the oscillation of a droplet with a pinned-contact line on a surface that can be considered to be more practical than other previous studies. Strani and Sabetta's study found that the first mode shape of the droplet is similar to the second mode shape of a free droplet if the droplet is placed on a surface with a pinned-contact line. It was also found that the dimensionless natural frequency in the nth mode vibration (ω_n^*) can be expressed as a function of the ratio of the contact circle radius and the droplet radius.

Since those early studies, a number of similar studies have been reported. Some representative studies among them are the following: (1) Daniel et al. [8,9] investigated the motion characteristics of a droplet moving in one direction on an oblique surface, (2) regarding horizontal or vertical movement of water drops, some literatures (Dong et al. [10], Noblin et al. [11], and Brunet et al. [12], and more recently Chang et al. [13], Bostwick & Steen [6], Chang et al. [14], Kim and Lim [15]) examined the motion and shape characteristics of the water drop vibrating horizontally or vertically, (3) a different study [16] examined the resonance of a free droplet falling in the air, and (4) yet another study used the principle of the

* Corresponding author.
E-mail address: hclim@pusan.ac.kr (H.-C. Lim).

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electro-wetting phenomenon with electronic energy. Owing to the rapid response and low-power consumption, the electro-wetting phenomenon [17–19] is being applied to micro-systems such as the lab-on-a-chip, electro-display, and liquid lens.

Droplet vibration is a phenomenon that has been applied to a wide variety of industrial applications, especially to the condenser of heating, ventilating, and air-conditioning (HVAC). Droplet vibration is useful to improve the maximum efficiency of a system related to heat transfer. In addition, the droplet oscillation that occurred in a periodic forced vibration can overcome the contact-line pinning phenomenon of the droplet on the solid surface. In practical industrial fields, this can be applied to effectively remove drops from a surface by maintaining an active droplet vibration. A number of related studies have been performed as follows: (1) a study [20] on heat transfer in the case where a droplet impacts a heated surface of a wall, (2) a study [21–23] on a pendant drop hanging on the upper side of a wall, (3) a study [24,12] on the motion of a droplet placed on an oblique surface, and (4) a study [25,26] on the measurement of the surface tension of the droplet and the contact angle. The fact that numerous studies are being conducted indicates that the study of droplets is an important area that can be applied to various fields.

Apart from the work that investigates whether the droplet behaviour was associated with a simple resonant frequency, experiments investigating the evaporation of a pendant droplet in acoustic resonance and the behaviour of a droplet placed on a heated flat surface [27] have also been conducted. A close investigation of the interiors of the droplet placed on a heated surface reveals the occurrence of a flow. This flow is called heat Marangoni flow [28–30]. The flow significantly affects the pattern [31,32] of deposits. The phenomenon has been investigated and adopted in many applications in mechanical and manufacturing engineering industry, including spray painting, coating, thin-film deposition, and cleaning. The experiments related to the evaporation of small-scale droplets have been conducted by Wachters and Westerling [20]. In those experiments, the evaporated droplet falling at different speeds was observed and compared to a theoretically estimated value in terms of its heat transfer. Makino and Michiyoshi [27] observed the evaporation of a droplet placed on the surface of various metals. They showed that when the droplet is evaporated, the droplet radius remains relatively constant but the contact angle drastically decreases.

Reviews on previous work indicate that most of the studies on the internal flow of droplets are biased towards natural evaporation and heat Marangoni flow. Most of the studies on the internal flow of vibrating droplets, however, have been conducted using numerical analysis [32] level, which means that experimental attempts have rarely been conducted. Additionally, in-depth studies have not been conducted. Therefore, this study aims to investigate the flow and evaporation characteristics of a vertically vibrating droplet under various resonant modes, while the droplet surface is hydrophobic and has a low-contact angle hysteresis, thereby allowing the droplet to move freely with a spherical shape. Furthermore, for better applicability and adoptability, the influence of the resonating droplet on the evaporation is also explored by comparing with those from natural evaporation.

2. Experimental apparatus and procedure

2.1. Experimental apparatus and conditions

To treat a hydrophilic silicon wafer surface to be hydrophobic, Teflon® AF1600 (601S2-100-6, Dupont) was diluted in a fluorocarbon solvent of FC-40 (3M) to form a concentration of 1 wt%. The silicon wafer surface was then spin-coated for 30 s with a spin speed of 2000 rpm (Revolution Per Mins). The silicon wafer was baked at 165 °C for 60 min for strengthening the adhesion of the Teflon thin film. De-ionised water was then used to create a pure water drop. The size of the drop was 5 μl and the equilibrium contact angle of the droplet was 115° ± 1°. The experiment was carried out under conditions at which the temperature and the relative humidity was maintained as constant as possible using an acrylic chamber in the range of 25 °C ± 1 °C and 30% ± 5%, respectively. In order to describe the detailed information of our experiment, Table 1 shows the parameters of response and forcing by plane-normal displacement $A\sin(2\pi ft)$ where the amplitude $A = a(2\pi f)^2$ (see Chang et al. [14]). Regarding the influence of forcing and viscosity, the Ohnesorge number was found to be around 0.0037 in our study.

To visualise the internal flow of the droplet and measure its flow velocity, the flow visualisation using particle image velocimetry (PIV) was conducted as shown in Fig. 1. The Continuous Wave (CW) laser (Excel 532-2000) was used with a wavelength of 532 nm in this experiment. A low-pass filter with a cut-off wavelength of 600 nm was installed in front of the macro-lens so that the strong laser beam might not exceed the recognition threshold of the camera CCD sensor. The laser beam was expanded using a beam expander and a thin laser sheet was created using a cylindrical focus lens. The internal flow of the droplet was observed by making the thin laser sheet penetrate the central section of the droplet. The width of laser sheet was 0.2 mm. Visualisation of the droplet flow was achieved by injecting polystyrene fluorescence particles (Nile Red F8825, Molecular Probes) with a diameter of 2.0 μm and a density of 1.05 g/cm^3 to droplets. Two high-speed cameras (FASTCAM SA3, Photron) were in charge of measuring the flow velocity. The two cameras were installed to capture the displacement of the lobe at the top of the droplet and the displacement of the substrate at a frame rate of 2000–5000 fps at the same time. The velocity field was then calculated using MATLAB® and Insight 4G. In addition, a digital camera was used to capture the internal flow structures of a water drop with an exposure time of 1.6–2 s. For the camera lens, Canon MP-E 65 mm *f*/2.8 and Canon Macro 100 mm were selectively used. In order to observe the shape of the droplet that periodically oscillates in a vertical way, we have performed an experimental setup that is suitable for producing a forced excitation. The spin-coated hydrophobic silicon wafer was installed on the surface of the speaker that produced the forced excitation to the wafer. The heater also was placed adjacent to the wafer so as to maintain the substrate's temperature constant. The contact angle of the droplet was determined by averaging five values that were separately measured using a contact angle analyser (CAM 100, KSV).

All experimental data contain an element of uncertainty. Uncertainty analysis was carried out for all experimental results to assess confidence levels, following the method suggested by Coleman and Steele (for details, see Coleman and Steele [33]). The total error consists of bias error and precision error. The bias error can be minimised with careful calibration of the measuring instruments. To evaluate the precision error, the standard deviation of

Table 1
Parameters of response and forcing by plane-normal displacement $A\sin(2\pi ft)$ where the amplitude $A = a(2\pi f)^2$.

Frequency (f)	Amplitude (A)	Acceleration (a)	
Physical parameters			
95–655	9.3–32.6 μm	0.9–26 g	
Frequency (λ)	Ohnesorge	Reynolds, forcing	Bond, forcing
Dimensionless parameters			
$\lambda \equiv 2\pi f(\rho r^3/\sigma)^{1/2}$	$\epsilon \equiv \mu/\sqrt{\rho r\sigma}$	$Re \equiv ar/f\nu$	$Bo_a \equiv \rho ar^2/\sigma$
0.7–4.81	0.0037	100–700	0.01–0.35