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An experimental investigation of sessile droplets evaporation on hydrophilic and hydrophobic heating surface with constant heat flux

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ABSTRACT

Droplet evaporation widely exists in the daily life and industrial production. In most of previous experimental studies, the evaporation of sessile droplets was conducted under a constant substrate temperature condition. However, drops often evaporating on a heating surface under a constant heat flux condition in many practical applications. In this paper, we have carried out an experiment on sessile 3 μl DI water droplets evaporated on hydrophilic and hydrophobic heating surfaces under constant heat flux in the range from 1153 W/m^2 to 6919 W/m^2. A high-speed camera was used to record the changing shapes of two sessile droplets on a hydrophilic and a hydrophobic heating surface placed side by side. The droplet height, dynamic contact angle, droplet contact diameter, evaporation mode and evaporation rate are presented.

1. Introduction

Droplet evaporation widely exists in daily life and industrial applications, such as phase change cooling [1,2], inkjet printing [3,4], spraying of pesticides [5], combustion engineering [6], spray painting, thermal spray coating, and cold spray coating for the fabrication of organic coatings and thin film devices, e.g., [7], etc. In 1977, Picknett and Bexon [8] investigated the evaporation of methyl droplet and described two distinct evaporation modes: the single constant contact radius (CCR) and the constant contact angle (CCA) modes. In reality, the droplet evaporation usually proceeds based on a combination of multiple modes with various time durations, called mixed mode or stick-slip modes [9]. In CCR mode, the contact angle reduces while the contact radius is pinned, and in CCA mode the contact radius shrinks while the contact angle is kept constant. Birdi and Vu [10] as well as Uno.et al. [11] found that the droplet evaporation followed CCR mode on a hydrophilic surface, while the droplet dominated by the CCA mode on a hydrophobic surface. YU et al. [12] as well as Fang et al. [13] found that when droplets evaporation on a hydrophobic surface, at the initial stage the droplets followed the CCR mode, and then the CCA mode was dominated. Furthermore, Shin et al. [14] suggested that a mix mode existed at the end of droplet evaporation, where both the contact angle and contact area changed with evaporation time. They investigated characteristics of natural diffusion evaporation of water droplets on hydrophobic and hydrophilic surfaces experimentally. They found that during the evaporation of droplet on a hydrophilic surface, the measured contact angle, liquid volume, and height of droplet were in good agreements with numerical predictions, and on hydrophobic surfaces the total evaporation time was longer. The water droplet on a super-hydrophobic surface did not have three distinct stages that normally appeared on a hydrophobic surface.

In addition to the above mentioned droplet evaporation modes, many researchers have studied droplet evaporation rates. They often used V/V_0 vs. t/t_a to represent the droplet evaporation rate (where V is the droplet volume, t is the evaporation time with subscript 0 representing the initial droplet volume and subscript a representing the total evaporation time). Some researchers [15–17] found that $(V/V_0)^{\beta} \sim t/t_a$ with $\beta = 2/3$ in the CCA mode. Other researchers [10,18] found that droplet volume in the CCR mode decreases almost linearly with time (i.e., $\beta = 1$ which is the so-called 1/1 power law). Tuan et al. [19] found that β depends on both initial and transient contact angles, showing that β significantly deviates from 2/3 and 1 when the droplet base is pinned. The 1/1 power law presents the upper limit of $\beta = 1$, while $\beta = 2/3$ is the lower limit if contact angles are smaller than 148°, and when the contact angles are larger than 148°, β can be smaller than 2/3. Misyura [20] investigated water evaporation in a wide range of initial droplet volumes on the structured and smooth surface. In his experiments where the heating surface temperature was kept at a steady temperature (such as 75 °C or 95 °C), he founded that linear dependence of evaporation rate (dV/dt) on a droplet radius varied when its volume was greater than 40–60 μl.

Most of previous experimental studies [20,21] were carried out

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under constant wall temperature conditions. Misyura [20] kept the heating surface temperature at steady temperatures of 25 °C, 75 °C and 95 °C. In experiments of Crafton and Black [21], two heater materials, aluminum and copper, were maintained at 60 °C, 80 °C, and 95 °C for water droplets while wall temperatures at 60 °C and 75 °C were maintained for n-heptane experiments. Kim et al. [22] studied droplet evaporation in an extreme condition, where a liquid droplet was placed on a heating block whose temperature was significantly higher (over 250 °C) than the boiling point of the liquid. They found the droplet could hover over the heated surface without contact due to the Leidenfrost effect. Other investigators conducted their experiments under natural diffusion condition [8,11–14,16,17]. For example, Yu et al. [12] kept the substrate temperature at 23 °C in the ambient conditions, Fang et al. [13] kept at 25 °C, Picknett and Bexon [8] kept at 22–23 °C, and Shin et al. [14] kept at 20 °C. In fact, the natural diffusion conditions are equivalent to the condition of the constant wall temperature. This is because the substrate temperature in experiment was equal to the ambient temperature, and the volume of droplets were usually only a few microliter. Therefore, its evaporation would not affect wall temperature.

As seen from the above literature review, most of previous experimental investigations on the evaporation of sessile droplets were conducted on surfaces with constant temperature. As far as the authors are aware, no previous experiments were carried out on droplet evaporation on a constant heat flux heating surface. However, in many practical applications, e.g. condensate droplets removal from rearview mirror or observation window, droplets often evaporate at a heating surface under constant heat flux conditions. In this paper, we investigated evaporation of sessile droplets on hydrophilic and hydrophobic heating surfaces with constant heat flux. The droplet height, dynamic contact angle, droplet contact diameter, evaporation mode and evaporation rate are presented in the paper.

Nomenclature

D	Contact diameter, mm
H	Droplet height, mm
t	Evaporation time, s
t_a	Total evaporation time, s
q	Heat flux, W/m^2
V_0	Initial droplet volume, m^3
θ	contact angle, °
V	volume of droplet, m^3

Greek symbols

β	power exponent

Subscripts

0	Initial parameter
a	Total parameter

2. Experimental investigation

2.1. Experimental setup

A schematic diagram of the experimental system is sketched in Fig. 1(a), and a photo of experimental setup is presented in Fig. 1(b). As can be seen from the figure, the experimental setup mainly consisted of the following parts: high speed camera, microscale amplification system, droplet evaporation experiment section, DC regulated power supply, and lighting source. During the experiment, the temperature and relative humidity of the experimental environment were adjusted by indoor air conditioning and air humidifier. The environmental temperature and humidity were maintained at 25 ± 0.5 °C and at 68 ± 2%, respectively.

A DC regulated power supply was used to adjust and achieve constant output of the heating power. In this experiment, the experimental section of droplet evaporation was made of ITO (Indium Tin Oxide) conductive glass, which was a solid solution of indium oxide (In_2O_3) and tin oxide (SnO_2), typically 90% In_2O_3, 10% SnO_2 by weight, and it had good electrical conductivity and workability. ITO conductive glass was made of Pyrex glass and ITO-coating (180 nm thick). In this experiment, the ITO-coating was used as the heating surface, and the test section was 50 mm × 30 mm. One half of the heating surface was covered with Teflon coating (hydrophobic), the other half was the bare ITO coating (hydrophilic). When DC voltages were applied at edges of the heating surface with electric current passing through the heater, constant heat flux conditions were generated.

Deionized water (DI water) was used in the present experiment, and the volume was controlled by high precision injection syringe, the precision of the droplet volume was 3 ± 0.1 μl. During the experiment, two equal volume DI water droplets were dripped onto the hydrophilic and hydrophobic regions respectively, and a high speed camera (Giga View ™, with 16 GB memory) was used to record the images at a speed of 50 frames per second. The experiments were repeated 10 times at every heat flux. In our experiments, we used a standard steel ball as a reference. The droplets were compared with the steal ball diameter, so we can accurately know the sizes of the droplets.

2.2. Experimental data record and analyze

The wettability of heating surface was mainly characterized by the contact angle. In order to measure the droplet contact angle accurately, we adopted a professional measuring software (provided by Swiss Federal Polytechnic School of Lausanne) to measure the contact angle. The results are presented in Fig. 2, where the static contact angle of droplet on ITO surface was about 67° and about 110° on Teflon surface at ambient temperature.

In this paper, heat fluxes ranging from 1153 W/m^2 to 6919 W/m^2 were applied, and the shapes of droplet on hydrophilic (with a static contact angle of about 67°) and hydrophobic (with a static contact angle of 110°) surfaces under different heat fluxes were recorded by a high speed camera. Fig. 3 are the images of the droplet at a heat flux of 1153 W/m^2 and 4541 W/m^2 during the evaporation process at different times. It can be seen from the figure for the same 3 μl droplets: the droplet was of hemispherical shape on the hydrophobic surface while the droplet was of spherical crown shape on the hydrophilic surface. Moreover, the contact area on the hydrophilic surface was larger than that on a hydrophobic surface, and the time on which the droplet disappears on the hydrophobic surface was longer than that on a hydrophilic surface.

3. Results and discussion

3.1. Evaporation time and dynamic contact angle

Fig. 4 shows the droplets evaporation time (defined as the total time from beginning of droplet evaporation to the disappearance of the droplet) at a heat flux ranging from 1153 W/m^2 to 6919 W/m^2 on a hydrophilic and on a hydrophobic surface, respectively. It can be seen that the droplet evaporation time decreased with the increase of heat flux, and the evaporation time on hydrophobic surface was higher than that of hydrophilic surface at the same applied heat flux. It can be seen from this figure, the evaporation time ranged from 80 to 440 s, which was shorter than previous researchers' data conducted under constant wall temperature conditions. For example, the water evaporation time ranged from 50–90 min in Uno's experiments and the droplet volume was 0.5 μl [11], and 19–42 min in Shin's experiments and the droplet volume was 5 μl [14]. Such a short evaporation time in our experiments can be attributed to the constant heat flux heating mode, which has a