Experimental Thermal and Fluid Science 98 (2018) 712–718

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

journal homepage: www.elsevier.com/locate/etfs

Evolution of thermal patterns during steady state evaporation of sessile droplets

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ARTICLE INFO

Keywords:
Steady state evaporation
Sessile droplet
Thermocapillary flow
Thermal patterns
Infrared thermography

ABSTRACT

The steady state evaporation process of sessile isopropanol droplets was experimentally investigated by utilizing the infrared thermography. The steady state was achieved by replenishing the droplet from its base. Results indicate that once the evaporation is initiated, the interfacial temperature closed to the triple line is higher than that at the apex, which induces a thermocapillary flow along the interface from the contact line to the apex. With the increase of the evaporation rate, the temperature gradient is enlarged; the flow is enhanced and loses its stability. Then, several thermal patterns, including the forked pattern, the curved hydrothermal waves, the rosebud pattern and the petal-like pattern, were observed. The evolution of thermal pattern is highly correlated with the droplet height and the thermal wave number increases with the substrate temperature. Meanwhile, the global evaporation rate is higher and the surface flow is more intense on copper substrate than that on aluminum substrate.

1. Introduction

Sessile droplet evaporation is important in cooling [1,2], inkjet printing [3], surface coating [4] and novel medical diagnosis technology [5]. It is also a phenomenon commonly encountered in nature [6]. Moreover, sessile droplet evaporation is a complicated heat and mass transfer process due to the interacted effect among the solid, liquid, gas phases and other boundary phases. Therefore, it is of much practical and full of academic significance to study sessile droplet evaporation.

In the past few decades, sessile droplet evaporation has attracted wide attention in the scientific community. Many researchers devoted themselves to investigating sessile droplet evaporation from various aspects. As early as 1977, Picknett and Bexon [7] had found the possible existence of two evaporation modes throughout the whole life cycle of sessile droplet evaporation, i.e. the constant contact angle (CCA) mode and the constant contact area (CCD) mode. Birdi and Vu [8] studied the evaporation characteristics of water droplets on glass surface. They found that, when the contact angle is less than 90 degrees, the evaporation rate varies linearly with time and the evaporation mode is CCD mode. However, when the contact angle is greater than 90 degrees, the evaporation rate has a nonlinear relationship with time and the evaporation mode is CCA mode. Shanahan and Bourgès [9] investigated the contact angle characteristics of water droplets on three different polymer surfaces and divided the evaporation process of water droplets on smooth surface into three stages. Hu and Larson [10] studied sessile droplet evaporation with constant contact line by experimental and theoretical calculations. It was shown that the evaporation rate is almost constant when the initial contact angle is less than 40 degrees. Recently, Gleason et al. [11] investigated the steady state evaporation of water droplets placed on a heated substrate and found that the evaporation rate increases with the increase of the contact angle. However, the evaporation mass flux is inverse with the contact angle.

In recent years, the researchers are paying more attention to the coupling effects in the sessile droplet evaporation process, especially liquid flow induced by droplet evaporation. Deegan et al. [6] pointed out that the deposition patterns produced by droplet evaporation are closely related to thermocapillary convection. Hu and Larson [12] confirmed that thermocapillary convection during the evaporation process could restrain the formation of the deposition ring. Ristenpart et al. [13] found that the direction of the surface flow is determined by the relative magnitude of the thermal conductivities of the substrate and the droplet. They also confirmed that thermocapillary convection would affect the deposition pattern. Recently, Sefiane et al. [14] experimentally studied the evaporation process of methanol, ethanol and

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https://doi.org/10.1016/j.expthermflusci.2018.07.016
Received 8 April 2018; Received in revised form 24 June 2018; Accepted 17 July 2018

FC-72 droplet by utilizing the infrared imager. It was found that the hydrothermal waves appear on the free surface of methanol and ethanol droplets, while the cellular flow pattern arises in the FC-72 droplet. Furthermore, the wave number of hydrothermal waves increases with the liquid volatility and the substrate thermal conductivity. Sobac and Brutin [15] reported that the hydrothermal waves appear in the ethanol evaporation process. Brutin et al. [16] pointed out that there are three stages during the process of droplet evaporation on a heating substrate. Initially, the droplet is in warm-up phase. After the preheating stage, the droplet begins to evaporate with thermal-convective instabilities. At the last stage, the droplet evaporates without any thermal patterns. Sefiane et al. [17] experimentally studied the sessile FC-72 droplet evaporation, and found that the temperature distribution and heat transfer of the substrate will be affected by thermal patterns. Bouchenna et al. [18] investigated the flow pattern inside an evaporating sessile droplet by means of numerical calculation. They found that during the evaporation process, the thermocapillary force is the main driving force of the internal flow pattern. However, at the end of the evaporation process, the strong evaporation around the triple line turns into the main influencing factor of the internal flow pattern. In general, many researchers investigate the liquid flow throughout the whole life cycle of sessile droplet evaporation. However, the droplet shape changing during the evaporation process is not conducive to quantitative analysis of liquid flow.

Up to now, there are only a few reports about the liquid flow in steady state evaporation of sessile droplet. Mahmud and MacDonald [19] observed experimentally the steady state evaporation of sessile water droplet and found that both thermal conduction and thermal convection provide energy for the droplet evaporation. They also found that the convective cell in droplet seems increasing with the substrate temperature. In present work, we reported a series of experiments on the thermal pattern of sessile isopropanol droplet evaporation at steady state. The thermal pattern evolution and the relationship of evaporation rate and liquid flow are exhibited.

2. Experimental apparatus and procedures

To observe the thermal patterns at different evaporation conditions, we cautiously designed the experimental apparatus and the experimental procedures to satisfy the need on feeding liquid smoothly, controlling substrate temperature accurately, and measuring droplet surface temperature precisely.

2.1. Experimental apparatus

The experimental apparatuses consist of substrate, liquid injection system, temperature control and measurement system, data acquisition system, and droplet shape monitoring system, as shown in Fig. 1(a). The details of substrate are shown in Fig. 1 (b) and (c). It contains two parts: a small substrate and a base substrate. In order to achieve the steady state evaporation, droplets are always entirely covered on the small substrate surface, which is different from the case that droplet evaporating on large flat substrate. The small substrate is glued together with the base substrate. The glue is thermally conductive epoxies (OB-101 produced by OMEGA Engineering, INC). The base substrate is made of copper, which can conduct thermal energy to the small substrate rapidly because of the excellent thermal conductivity. Moreover, two different materials, copper and aluminum, are used to make the small substrates. The thermal conductivities of copper and aluminum are different, which are respectively 401 W/(m·K) and 237 W/(m·K). The radius and the thickness of the small substrate are $R = 2.5 \pm 0.05$ mm and $\delta = 0.5 \pm 0.05$ mm, respectively. The radius of the central hole is 0.25 ± 0.05 mm. In order to eliminate the effect of surface roughness, both copper and aluminum substrate surfaces were mirror-polished by the company.

The liquid injection system includes a storage bottle and a syringe pump (KDS 200 series). The injection rate of syringe pump ranges from 2.757 μl/h to 70.56 ml/min, which can meet the experimental requirement. The customized storage bottle is made of quartz glass, which is used for storing the pre-prepared isopropanol. The liquid feed tube is passed through the thermostatic bath to keep the feeding liquid and the substrate at the same temperature.

A thermostatic bath (Shanghai Qiqian Electronic Technology Co. Ltd, DC-2006, temperature ranges from −20 °C to 100 °C, and the accuracy is ± 0.05 °C) was used to keep the base substrate temperature constant. Twelve K-type thermocouples with a accuracy of ± 0.5 °C were evenly embedded into the base substrate to monitor the substrate temperature. Their locations are exhibited in Fig. 2. All temperature data from the thermocouples were collected by a multi-channel data acquisition instrument (Agilent, 34972A). During the experiments, the temperature obtained by twelve thermocouples show that the substrate can be heated evenly by the thermostatic bath. In order to measure the droplet surface temperature distribution, an Infrared thermal camera with 25 μm lens (FLIR SC325, resolution: 320 × 240, the field of view: 8 × 6 mm, heat sensitivity: 0.05 °C) was vertically installed above the substrate. The droplet shape was recorded by the CMOS camera (PixeLINK, PL-B761U, resolution: 752 × 480). ImageJ (Image Processing and Analysis in Java) was used to measure the droplet height [20]. As the sessile droplet was evaporated in atmospheric environment, a self-designed glass cover was installed around the substrate to avoid the disturbance of the ambient air circulation during the experimental process. The experimental fluid is isopropanol, which is supplied by Chongqing Chuandong Co. Ltd. The purity grade of isopropanol is analytical pure grade (Purity greater than 99.7%). The infrared emissivity of isopropanol liquid is 0.95 [21]. The physical properties at 25 °C are shown in Table 1.

2.2. Experimental technique

Initially, the base substrate temperature was maintained at a constant and uniform value by thermostatic bath. Then, the experimental fluid was carefully prepared and stored in a storage bottle. During the experiment, it was filled into to the syringe without exposing it to air. After that, the fluid was continuously pumped by syringe pump to form a droplet on the small substrate. At the beginning of the droplet evaporation, we adjusted the injection rate of syringe pump based on the real-time monitoring droplet shape according to the CMOS camera. It was considered to be steady-state evaporation when the variation of the droplet height measured by ImageJ is no more than 45 μm for half an hour. Then, the Infrared thermal camera was used to measure the temperature field of the droplet surface. It should be pointed out that the isopropanol is semi-transparent to infrared at the wavelengths of (7–14) μm, which means that the temperature distribution captured by the infrared camera is the temperature signature of the liquid layer very close to the droplet surface. Moreover, it is worth mentioning that the infrared thermal imaging technology has been applied in many sessile droplet evaporation researches [22–24]. Therefore, it is reliable to capture the surface temperature in present experiments.

3. Results and discussion

3.1. Thermal patterns induced by droplet evaporation

The experiments were carried out at atmospheric environment. During the experiment, we always set the ambient temperature at 26 ± 1 °C and only adjust the substrate temperature to change the temperature difference between substrate and ambient.

As shown in Fig. 3, the temperature closed to the triple line is always higher than that at the apex via the analysis of the surface temperature distribution captured by the infrared thermal imager. Fig. 3(a) shows the infrared image of droplet surface, in which the red dotted circle represents the edge of the droplet. The temperature distribution