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REFLECTING HYDROTHERMAL WAVES FROM FLOW MEASUREMENT IN SESSILE DROPLET

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1. ABSTRACT

Hydrothermal waves have been reported in the droplet with the phase change, they can be spontaneously observed at the droplet interface of a sessile droplet. We have conducted the experiments with the support of thermography and particle image velocimetry to link the hydrothermal waves with the flow in a droplet under evaporation conditions. The splitting and merging of the hydrothermal wave patterns can be explained with the flow field as the droplet contact angle decreases during drying.

2. INTRODUCTION

The sessile droplet phase change can be found in nature and many engineering applications. The evaporation or condensation process is accompanied with the temperature variation and fluid flow in the droplets. The investigation conducted in the evaporating volatile sessile droplets generated the circumferentially distributed thermal patterns with changing interfacial temperature at the liquid surface [1]. In the reported thermographic experiments for the droplet, the hydrothermal waves (HTWs) were found [2]. The evaporating sessile droplet could lead to spatial temperature gradients, it was explained to be responsible the complicated thermocapillary instabilities and HTWs [2-4], which were also proposed to the formation of interfacial thermal patterns. However, the explanations are waiting for the further experimental flow measurement. We thus present experiments for sessile droplet with the constant contact radius in the most phase change lifetime on the heated substrate, as for linking the temperature and flow patterns.

3. METHDOLOGY

The thermographic and optical measurements were performed in a chamber with the viewing windows. Inside, a copper pillar, which is 5 mm in diameter and 5 mm in height, was installed with the embedded heating components. An infrared (IR) camera (Infratec 8300) was applied to track the temperature distribution at the sessile droplet surface from the top view through an IR window. A CCD camera (HiSpe2) was used to capture the side-view shape of the sessile droplet through a glass window of the chamber. The temperature measurement on the top view of the droplet and the instant contact angle and contact radius measurement from the side view were conducted simultaneously during the experiments. Additionally, the flow filed were measured through micro-PIV via a microscope system (Nikon LV100ND). The seeding particles for micro-PIV were the fluorescence particles (FlouShperes 580/605, normal diameter 1 μm, and weight concentration < 0:004%). The PIV analysis was done with PIVLab. The resolved vector map was smoothed by using the moving average method. During the experiments, the ethanol (Sigma-Aldrich, ACS reagent, and purity > 99:5%) was used as the working fluid to generate a droplet on the substrate by a pipette in the

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*Corresponding Author: feiduan@ntu.edu.sg experiments. The time was counted when the droplet was fully settled on the substrate. The environmental conditions had the room temperature at around 23 °C and the humidity at about 50%.

4. RESULTS

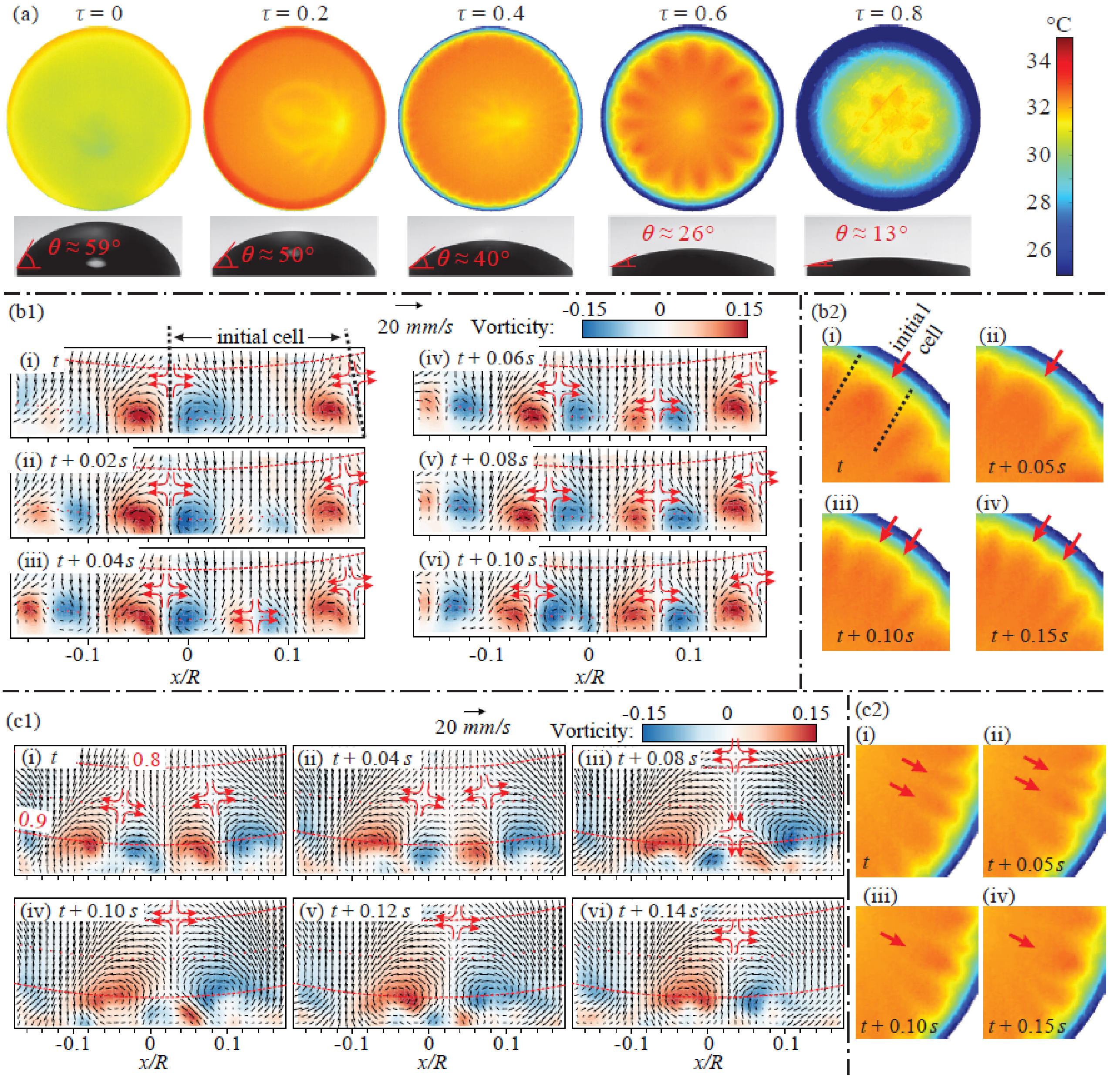

Fig. 1 (a) Evaluation of sessile droplet drying, the contact angle decreases in the phase change process. Convective cell splitting from micro-PIV (b1) and IR images (b2). Convective cell merging from micro-PIV (c1) and IR images (c2).

Figure 1(a) illustrates the evolution of temperature distribution of the sessile ethanol droplet. The initial volume of the droplet is about 15.1 μL with the initial contact angle at 59°. From the IR images, the evolution of thermal patterns can be divided into three stages. In the first stage, the temperature near the edge is higher than that in the inner part, showing a hot ring pattern, for the sessile droplet on the heating substrate. In the second stage, the regular petal-like thermal patterns (HTWs) forms along the droplet edge. With decreasing of the contact angles, the number of HTW becomes smaller, but the size of each petal becomes larger. In the final stage, the petal patterns are cell-like. The convective cell splitting is shown in Figures 1(b1) from the micro-PIV measurement and Figure 1(b2) from the IR images, the original convective cell looks large before the splitting. Figure 1(b1) demonstrates that the size of the right side cell is approximately twice of the one at the left. After t

+ 0.02 s, a pair of opposite vorticity concentrations appear in the middle of the original cell, showing the forming of a new tiny vortical structure at the droplet edge. At t+0.04 s, a saddle point is formed inside the new structure, suggesting that the inward flows are from the liquid surface to the inner of the droplet through the structure. The splitting of the convective cell is fount at the edge of the sessile droplet. Both the size and the vorticity magnitude of the new structure are increasing with time. At t + 0.10 s, the original convective cell fully splits into two new cells with size and strength almost the same as their neighbours. In Figure 1(b2), the marked hot spot, which representing an original convective cell, then it expands till splitting into two new hot spots. Figures 1(c1) and (c2) show a merging process of the cells. The process begins with the shrinking of one cell. At t+0.04 s, the cell at the middle is much smaller than its neighbours. The two saddle points then get closer. At t + 0.08 s, the two saddle points merge at the inner region of the evaporating droplet. Simultaneously, the middle cell becomes even smaller, and another saddle point is formed among these three cells. The central saddle point has an orthogonal direction to other saddle points. It almost disappears at t+0.10 s due to the middle cell being even weaker. At t+0.14 s, the two neighbouring cells fully connect, suggesting the ending of the local merging process. Figure 1(c2) shows the merging process in IR image. As marked by the two red arrows, one cell shrinks while the other expands. At t+0.10 s, the smaller convective cell is pushed toward the droplet edge, like a secondary cell. At t+0.15 s, only the larger cells can be seen, occupying the place of the merged cell. The qualitative agreements between the micro-PIV measurements IR images indicates that the observed HTW is a result of the convective cells.

5. CONCLUSIONS

The agreements between the IR images and the micro-PIV measurements suggested the linkage between hydrothermal waves to the convective cell at the interface of the evaporative ethanol droplets sessile on a heated substrate. The convective cells were formed by the outward capillary flow and inward thermocapillary flow induced by the complex temperature gradient near the droplet contact line. The number of Benard-Marangoni cells was found to be related to the instant contact angle under a substrate temperature. The three stages of the evolution of thermocapillary instability in the sessile ethanol droplet were identified. The hydrothermal wave splitting and merging were explained with flow pattern from the micro-PIV and IR measurements.

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REFERENCES

[1] L. Shen, J. Ren, F. Duan, Surface Temperature Transition of a Controllable Evaporating Droplet, Soft Matter, 16 (2020), 9568-9577.

[2] K. Sefiane, J. R. Moffat, O. K. Matar, R. V. Craster, Self-excited Hydrothermal Waves in Evaporating Sessile Drops, Applied Physics Letters, 93 (2008), 074103.

[3] D. Brutin, B. Sobac, F. Rigollet, C. Le Niliot, Infrared Visualization of Thermal Motion Inside a Sessile Drop Deposited onto a Heated Surface, Experimental Thermal and Fluid Science, 35 (2011), 521-530.

[4] X. Zhong, F. Duan, Stable Hydrothermal Waves at Steady State Evaporating Droplet Surface, Scientific Reports, 7 (2017), 16219.