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Evaporation Process of Sessile Liquid Droplet and Layer in Steady State

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Abstract

The ethanol liquid droplet with constant contour and liquid layer with constant height in steady-state contained in the heated substrate under evaporation have been experimentally investigated utilizing infrared thermography and volume control technique. The heat and mass transfer and thermal flow patterns at the gas–liquid interface during droplet and layer evaporation are analyzed through their heat flux curves and interface temperature fields. Experimental results reveal that the steady-state evaporation of liquid droplet and layer at surface emerges after the evaporation rate is equal to replenishment rate by continuous liquid refilling and temperature filed becomes uniform. For evaporating droplets, there are two main stages during the evaporation evolution: unstable evaporation with decreasing heat flux and steady evaporation with constant heat flux. In the steady stage, the interface temperature gradually becomes uniform, and convection cells at the interface disappear. For evaporating layer, three main stages are present: first, the formation and splitting of Marangoni convection cells, then the hydrothermal wave propagating from "source" to "sink", and finally the stable flow stage without vortex cells. The results also show that the direction of the temperature gradient at evaporating droplet interface is opposite under different substrate materials (Aluminum and PTFE). The heat flux density of the evaporating droplet on Aluminum substrate is larger than that on PTFE, resulting in a higher evaporation rate. These new findings help to gain a better understanding of the coupling mechanism between phase change and thermal convection inside evaporating liquid droplets and layers.

Keywords Evaporation · Liquid droplet · Liquid layer · Steady state · Thermal flow pattern · Heat flux

Introduction

Liquid evaporation is one of the most common phenomena in natural and industrial processes. In the past few decades, it has attracted growing research attention from various fields, not only for its fundamental interests in nature but also for its practical importance in the improvement of many industrial applications, such as microgravity fluid management, heat pipe, and micro-fluidics technique (Toth et al. 2011; Yamada

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¹ Institute of Mechanics, Chinese Academy Sciences, Beijing 100190, China

² University of Chinese Academy of Sciences, Beijing 100049, China et al. 2019; Cummings et al. 2018). A liquid layer or droplet placed under an applied temperature gradient tends to become unstable, thereby inducing surface tension-driven flow. According to the direction in which the temperature gradient was applied, Schatz and Neitzel (2001) divided these flows into two categories in their review paper: If the temperature gradient was perpendicular to the interface, Marangoni convection instability occurred; if it was parallel to the interface, the thermocapillary convection instability appeared. In a liquid layer heated from the bottom, when the temperature difference exceeded a certain threshold, multicellular Marangoni convections were observed in different shape and scale ratio containers (Schatz et al. 1995; Koschmieder and Prahl 1990; Cerisier et al. 1996).

Smith and Davis (1983) performed, for the first time, a linear stability analysis of a planar liquid layer subjected to a temperature gradient along the free surface. This pioneering work predicted the regular thermal fluctuations which are called hydrothermal waves (HTWs). Subsequently, more experimental and numerical attention was focused

on HTWs to attempt to find the mechanism (Ezersky et al. 1993; Daviaud and Vince 1993). With the HTWs propagating at the liquid–vapor interface, thermal flow inside the liquid could also be induced by temperature gradients imposed along with the free liquid–vapor interface. Riley and Nietzel (1998) utilized IR thermography, i.e. an infrared camera, to investigate the hydrothermal-wave instability of thermocapillary convection in a thin liquid layer. This non-destructive method takes advantage of preventing any disturbance in thermal measurements. However, the difficulty is then incorrectly distinguishing whether the infrared camera measures the temperature distribution exactly at the liquid–vapor interface or a mean value over a depth adjacent to the interface within the liquid (Brutin et al. 2011).

In laterally heated liquid layers or liquid films with phasechange gas-liquid interfaces, the occurrence of hydrothermal waves was also observed in thermocapillary instabilities induced by evaporation effects (Kavehpour et al. 2002; Shi et al. 2017). In volatile droplets, hydrothermal waves due to evaporation effects were frequently observed experimentally (Sobac and Brutin 2012a; Sefiane et al. 2013). Using infrared thermography, Sefiane et al. (2008) observed the spontaneous formation of a hydrothermal wave rotating in the circumferential direction in the droplet evaporation experiments of methanol. In the more volatile FC-72 droplet, a petal-like flow pattern occurred in the center of the droplet and propagated in the radial direction. They also found that FC-72 drops displayed cellular structures whose size was proportional to the local liquid thickness (Sefiane et al. 2010). Carle et al. (2012) and Brutin et al. (2010) performed some droplet evaporation experiments to study the HTWs behavior under both normal gravity and microgravity condition. They found that the hydrothermal wave would occur with or without gravity, again indicating that HTW is a thermocapillary instability driven by surface tension gradient. On the other hand, numerical simulations facilitated a better understanding of thermal flow instabilities. Karapetsas et al. (2012) applied linear stability analysis in the quasi-steady-state approximation to predict the formation of stationary cells and traveling hydrothermal waves in drops. Sefiane et al. (2015) investigated numerically and theoretically the formation of hydrothermal waves in evaporation drops. Liu et al. (2020) revealed that phase change played a twofold role in liquid layer flow stability: evaporation not only destabilized the flow but also stabilized it, depending on the position where the temperature gradient caused by evaporation was applied.

It is known that there are two types of heat transfer during the droplet evaporation process. One is phase change, leading to mass transfer into the vapor phase along with energy exchange. While the other one is dynamic wetting, corresponding to the triple line movement and deformation of the free surface. The comprehensive influence of these two aspects has been theoretical and experimental investigated in previous work, see the review article by Brutin and Starov (2018). Sobac et al. (2012b) and Chen et al. (2017) studied the effects of different substrate materials and thermophysical properties on the evaporation of droplets, and they found that the droplet evaporated faster under the conditions of higher coefficient of heat conductivity and higher temperature of the substrate.

It is noted that these abovementioned experiments focused on the free diffusion evaporation at the drop interface, that is, volume and contour of the liquid drop varies with time. The coupling of phase change and deformation of the free liquid–vapor interface induced complicated factors to solve, especially for numerical simulations. Therefore, maintain the free surface constant is a better way to understand the mechanisms of thermal energy transportation during the evaporation process. Zhong and Duan (2017) observed stable hydrothermal waves during the steady state droplet evaporation process by continuously replenishing the liquid from the bottom to keep the droplet size constant. And it was found that the number of HTWs was approximately linearly increasing with the substrate temperature and the droplet aspect ratio.

Nevertheless, the combined mechanism of heat and mass transfer during droplet evaporation is still poorly understood. In this paper, we conduct a series of experiments using volatile sessile droplets of constant size deposited and cylindrical layer with a constant thickness on a heated substrate in the steady-state approximation. In contrast to the free evaporation case studied by Chen et al. (2015), the temperature gradients and height of the drop vary spatially and temporally, the present work aimed at investigating the formation of internal convective rolls and interfacial hydrothermal waves in evaporating droplet and layer.

Experiment Set Up

A schematic diagram of the experimental apparatus is shown in Fig. 1. The apparatus consists of an enclosed test cell $(100 \times 80 \times 80 \text{ mm})$, an injection system coupling with an image feedback control system (Yu et al. 2010), an infrared (IR) thermography, temperature controller, and a measurement system. The working fluid chosen is highly volatile liquid ethanol with the relatively lower latent heat of vaporization of 846 kg/kJ, indicating that it has a fast and significant phase change process. All the experiments are carried out in the atmosphere, whose temperature, humidity, and pressure are separately kept at $T_a = 298 \text{ K} (\pm 1 \text{ K})$, $H = 40\% (\pm 5\%)$, and P = 1 atm.

As shown in Fig. 1, The substrates can be heated from the base by a thin-film heater with PID control loops to achieve a stable temperature with an accuracy of ± 0.2 °C. Two kinds of materials, polytetrafluoroethylene (PTFE) and Aluminum



Fig. 1 Schematic diagram of the experimental apparatus

(Al), with different thermal conductivity of 0.25 W/m·K and 270 W/m·K, respectively, are used to investigate the thermal effect of the substrate. Before the experiments, the surface roughness of the two substrates is characterized using an atomic force microscope (AFM). The results illustrate that both surfaces are extremely smooth to eliminate the influence of surface roughness, as shown in Fig. 2. To measure the heat transfer resulted from evaporation and thermal flow, a heat flux meter is mounted just below the substrate to measure the heat flux distribution between the drop liquid and solid substrate. The delivered signals and data are recorded on data acquisition equipment (Agilent 34970A). The IR camera used is ImageIR (640×512 pixels), which is fitted with a microscope lens achieving a view field of 10 mm \times 7.5 mm at a minimum pixel size of 15 μ m. The spectral range of the system is 3-5 mm and the thermal sensitivity is 30 mK. To obtain images of the evolution of thermal flow behavior inside a drop, the IR camera is mounted directly above the substrate, facing vertically downwards onto the evaporating drop.

For purpose of remaining the drop size as initial state, a droplet image feedback control system is developed. As shown in Fig. 3, the initial droplet of fixed volume is injected



Fig. 2 AFM picture of the PTFE (left) and Al (right) coating

to deposit on the heated substrate from the bottom by a syringe pump with the injection rate of 30.8μ L/s. Meanwhile, a CCD camera records images of the liquid drop at each time step and conveys them to a computer for analysis. After that, image processing software extracts the contour of the liquid drop and calculates the volume employing the numerical integration method. Also, we can obtain the evaporating rate by calculating the change of the drop volume during a given interval. If the volume is less than the initial value, then the feedback control system will control the syringe pump to supply liquid. After iterated matching of the adjusted syringe-pumping rate and the evaporation rate, the liquid drop can be maintained at a relatively constant size.

First of all, we perform some experiments to verify the controlling precision of the drop image feedback control system. As exhibited in Fig. 4, a 20.6µL ethanol droplet is injected and maintain its size on the heated Al substrate (T_s = 40 °C) during the feedback control process. It can be seen that the drop volume keeps a relatively stable value ranging from 20.4 µL to 20.8 µL, the maximum deviation is 0.2 µL (less than 1%), indicating that the system has a highlevel accuracy and the drop size can be perfectly maintained by the feedback control process.

In addition, in order to carry out the evaporation experiment of the quasi-static liquid layer, we replace the evaporation platform in Fig. 1 with the platform containing an annular sidewall, as shown in Fig. 5. Similarly, a cylindrical shallow liquid layer with a thickness of about 2 mm and a diameter of 20 mm is formed on the substrate by injecting liquid from the bottom. A thickness gauge directly above the liquid layer is used to measure the height change of the gas–liquid interface during the evaporation process, which also can be used to calculate its instantaneous evaporation rate. Based on this, a suitable continuous refilling rate is obtained to maintain the thickness of the liquid layer unchanged. In the present paper, for the evaporation process



Fig. 3 The schematic of droplet image feedback control system



Fig. 4 Volume fluctuations of ethanol droplet ($V_0 = 20.6 \ \mu$ L) deposited on the heated ($T_s = 40 \ ^{\circ}$ C) Al substrate during the control process

of the ethanol liquid layer under 1 W heating power, a liquid replenishment rate of $11.96 \,\mu$ L/ min can be used to maintain the height of the liquid layer at 2.20 ± 0.02 mm. Its thickness fluctuation range is less than 1%, so we can consider that the height of the liquid layer can be maintained at a certain value during the evaporation process through the continuous refill feedback system.

Results and Discussion

Evaporation Droplet

To obtain the heat transfer characteristic of volatile droplets evaporation, we measure the heat flux density variations during ethanol droplet evaporation on Al and PTFE substrate, respectively. As pointed in Fig. 6, the evaporation process of a constant height droplet can be separated into three phases:

Phase 0: warm up stage (or prepare stage). At the beginning, there is no liquid on the substrate. The heat flux density with lower value and less fluctuation is the heat



Fig. 5 The schematic of evaporation layer platform

transfer characteristic under the natural convection of the air on the hot substrate. When the droplet at room temperature is initially deposited on the heated surface, the heat flux exhibits a sharp increase, which means a large amount of thermal energy from the substrate is absorbed to warm up the liquid droplet.

Phase 1: unstable evaporation with decreasing heat flux. The heat flux distribution during this phase decreases continuously from a maximum value to nearly a constant value. As soon as the cooling drop is deposited on the heated substrate, thermal energy is transported to the solid-liquid interface to warm up. According to the theory of Ghasemi and Ward (2011), only a small part of the energy is transported perpendicular to the bulk liquid, while most fraction is transported parallel to the three-phrase line where thermocapillary convection distributes this energy along the liquid-vapor interface to balance the energy consumes by evaporation process. Consequently, at the preliminary period, it will absorb most thermal energy to balance the larger temperature difference between solid and liquid. On the other hand, according to the Hertz- Knudsen equation, with the drop evaporation, the ethanol vapor concentration increases in the cell so that the evaporation rate slowly decreases at the following period.

Phase 2: steady evaporation with constant heat flux. A steady phase of evaporation is characterized by the relatively constant value of heat flux density. It indicates that the drop is evaporating under an equilibrium condition, which means the number of molecules evaporated from the liquid phase equals those condensed from the vapor phase.

Taking into account the influence of different substrate materials on evaporation, it shows that the heat flux generated by the evaporation of droplets placed on the aluminum substrate is higher (about 200 W/m²) than that of the droplets placed on the PTFE substrate. This is because the thermal conductivity of Aluminum (270 W/m·K) is much greater than that of PTFE (0.25 W/m·K). As a result, the droplet on the aluminum substrate can absorb more heat than on the PTFE, and thus obtains a higher evaporation rate. Consequently, the higher evaporation rate makes the transition from Phase 1 to Phase 2 for Al longer than that for PTFE, that is, it takes more time to achieve evaporation balance for Al substrate.

As revealed in Fig. 7, the spontaneous formation of various thermal flow patterns during the droplet evaporation process including the presence of hydrothermal waves (HTWs). When a cooling drop is deposited on the hot substrate, a temperature gradient is induced naturally. It becomes hotter in the region

different heated ($T_s = 40 \text{ °C}$)

the conditions)



near the triple line and colder in the center due to the larger drop height leading to a larger thermal resistance. Then the temperature gradient forms along the liquid-vapor interface owing to the evaporation, and the HTWs are observed near the triple line where most of the phase change occurs. It seems to contribute to thermal energy transport and ultimately influences the droplet evaporation rate. The thermal patterns are organized radically resembling a wave train of clockwise or anti-clockwise propagation from a source to a sink location at the beginning as it occurs in the free evaporation case (Sefiane et al. 2008). When the temperature distribution at the drop apex is higher and the extent of the cool region is enlarged, the overall temperature gradient decreases with the fade tend of thermal cells. It is worth noticing that, for a long period of evaporation time, no cellular structure can be detected. This can be explained that the internal thermal flow coupling with





thermal conduction and convection homogenizes the temperature distribution and the thermocapillary effect becomes more confined, and finally, the drop evaporates under the equilibrium state.

Furthermore, other observations from these experiments show that the temperature field exhibits opposite distribution at different substrates. For Al substrate with large thermal conductivity, energy is readily supplied to the contact line region, so the interface is able to maintain a comparatively high temperature despite the energy consumed by evaporation. Therefore, when the droplet evaporates on the Al substrate, the vertical temperature gradient dominates in the droplet. The evaporation is the most intense at the threephase line, and the temperature at the three-phase line is the lowest due to the efficiency of evaporative cooling. In contrast, energy is not readily transported for PTFE substrate, therefore it is extracted from the drop itself to evaporate at the drop apex because of the large heat conduction distance. Due to the short heat conduction path at the three-phase line, the energy required for evaporation here can be obtained from the heated substrate. Consequently, the apex of the drop on PTFE is coldest which mainly agrees with former numerical analysis (Ristenpart et al. 2007).

Evaporation Layer

A typical evaporation condition of the ethanol liquid layer with constant height $(2.20 \pm 0.02 \text{ mm})$ is selected to investigate its flow instability. The main experimental process of this working condition is: first, a thin liquid layer of about 2.2 mm is quickly injected from the substrate bottom, and the evaporation platform is slowly heated with constant power (the highest heating temperature is set to 30 degrees Celsius); and then, slowly infuse the liquid at an injection rate of 11.96 µL/min to maintain the constant thickness of the layer, and observe the flow pattern in the evaporation process in real-time through infrared thermography above the liquid layer; finally, when the substrate temperature reaches the set 30 degrees Celsius, the heating is stopped and the experiment ends.

A quasi-steady-state evaporation experiment of a continuously slowly heated ethanol layer is performed to investigate its flow instability. Based on the heat flux density curve during the layer evaporation process and the infrared camera's observation of the surface temperature field of the liquid layer, the quasi-steady layer evaporation process is divided into 4 stages, as shown in Fig. 8:

- Stage 0 Liquid injection and heat absorption stage (or prepare stage). The liquid is injected by the micro-injection pump from the bottom of the substrate to form a thin layer of about 2.2 mm, while a large amount of heat is absorbed from the heated substrate with the rapid rise of heat flux density curve;
- Stage 1 The stage of formation and division of vortex cells. Marangoni convective vortex cells continue to form and split on the layer surface. At the same time, the heat flux density increases slowly with small fluctuations;
- Stage 2 HTWs propagation stage. The "source" and "sink" appear in the liquid layer, and the hydrothermal



ethanol layer evaporation process (h = 2.20 mm, R = 10 mm)

waves move from the "source" to the "sink" clockwise and counterclockwise, respectively, accompanied by a large fluctuation of the heat flux;

• Stage 3 – Vortex cell merger and disappearance stage. The temperature of the liquid layer gradually becomes uniform, and the vortex cells merge and disappear. Finally, a stable flow pattern without vortex cells appears, and the heat flux density also stabilizes.

Two thermocouples are installed under the substrate and the sidewall of the evaporation platform, respectively, in order to monitor the substrate temperature (T_0) and sidewall temperature (T_s) during the evaporation process. It can be seen from Fig. 8 that when no liquid is on the substrate, these two temperatures are approximately equal; and when the liquid is injected and begin to evaporate, the temperature of the sidewall (T_s) is lower than the substrate (T_0) , and the temperature difference between them finally reaches about 3 °C. This is due to the evaporation cooling effect on the layer surface causing the sidewall temperature to decrease.

In stage 1, it can be observed from the infrared camera that vortex cells are constantly generated and split, and the formation and splitting of vortex cells is approximately a quasi-periodic process. In order to facilitate the expression, we mark the vortex cells and the direction of movement in the figure, while drawing polar coordinates on the surface of the liquid layer, with the center of the layer surface as the origin, and the horizontal radius corresponding to the coordinate axis at $\phi = 0^\circ$, as shown in Fig. 9. At t = 548 s, vortex cell A generates from the center of the liquid layer at an azimuth angle $\phi = 19^{\circ}$ and moves outward, while vortex cells B1 and B2 move away from cell A in counterclockwise and clockwise directions, respectively, as shown in Fig. 9a; when t = 576 s, the scale of vortex cell A becomes larger and splits into two vortex cells, labeled A1 and A2, respectively. The vortex cell B1 disappears after moving to $\phi = 90^{\circ}$, and B2 disappears at $\phi = -56^{\circ}$, as shown in Fig. 9b; when t = 595 s, the cell A1 and A2 move to a near disappearing position, and a new cell appears between A1 and A2, and the next vortex cell generation and division cycle begins.

When entering Stage 2, with the continuous increase of the substrate temperature, it can be seen from Fig. 8 that the fluctuation range of the heat flux density value starts to increase, indicating that the heat exchange inside the layer is more intense and the flow is enhanced. At the same time, obvious source and sink, as well as hydrothermal waves (HTWs) propagating circumferentially from the source to the sink, are observed at the interface. A vortex cell generated from the source is divided into two cells, moves clockwise and counterclockwise toward the sink, and eventually disappears at the sink. In addition, new vortex cells are constantly generated from the source, and the existing vortex cells continue to move to the sink and disappear, forming continuous hydrothermal waves. The vertical and horizontal temperature gradient of the liquid layer determines the location of "source". Therefore, the factors that affect the temperature distribution of the liquid layer (such as the layer thickness, shape, size, substrate temperature, etc.) will affect the position of "source". In order to conveniently describe the propagation of hydrothermal waves, we record the entire process of a vortex cell generated from the "source", and then moved to the "sink" to disappear, as presented in Fig. 10. It can be seen from Fig. 10 that the azimuths of "source" and "sink" at this period are near $\phi = 25^{\circ}$ and $\phi = 180^{\circ}$, respectively.

At t = 2175 s, a new vortex cell A appears at the position of the radius 2R/3 and the azimuth angle $\phi = 25^{\circ}$ (source) and continues to grow. The upper vortex cell B1 and the lower vortex cell B2 move clockwise and counterclockwise toward the "sink" position, respectively, as shown in Fig. 10a. When t = 2189 s, the vortex cell A grows to a certain extent and begins to split into two cells A1 and A2, and gradually moves away in opposite directions, as shown in Figure b. When t = 2207 s, the vortex cells A1 and A2 move toward the "sink". In addition, a new vortex cell C appears on the "source" position. When t = 2277 s, the vortex cell A2 starts to become smaller, and there is a tendency to merge with the nearby cell. Cell B1 moves to a position close to the "sink" and merges with the cell below, and cell C splits into two new vortex cells C1 and C2, as shown in Fig. 10d. When t = 2331 s, vortex cell B1

Fig. 9 Vortex cell division in Stage 1 of ethanol layer evaporation







has completely disappeared at the "sink", while vortex cell A1 has moved to the "sink", and vortex cell A2 has merged with the nearby cell B2 to become a new cell A2', which tends to merge with vortex cell A1, as shown in Figure e. When t=2363 s, the cells A1 and A2' merge and disappear at the "sink". At the same time, a new vortex cell is generated again on the "source", and a new cycle begins, as shown in Fig. 10f.

By calculating the moving angle of vortex cells A1 and A2 per unit time, the velocity of the hydrothermal wave propagating clockwise and the hydrothermal wave propagating counterclockwise can be obtained, respectively 1.45×10^{-2} rad/s and 2.07×10^{-2} rad/s. It can be seen that the velocity of the hydrothermal wave propagating counterclockwise is about 43% faster than propagating clockwise. The larger the horizontal temperature gradient, the faster the speed of the vortex transmission. Therefore, the velocity can be controlled by controlling the size of the surface temperature gradient (such as heating or cooling the side wall).

As the substrate temperature increases and the liquid is replenished, the hydrothermal waves propagation gradually stops, no new vortex cells are generated. Moreover, the scale of vortex cells also begins to decrease, vortex cells begin to merge and disappear, and the evaporation process enters Stage 3. We track the evolution of several pairs of vortex cells during Stage 3, as shown in Fig. 11.

When t=2475 s, the cells A1 and A2 approach each other and begin to merge, and the cells B1 and B2 also begin to merge. Subsequently, cells A1 and A2 have merged into one cell A, which approaches cell C. Then, cells B1 and B2 have merged into one cell B, and vortex cells A and C have gradually merged. After the cells in the layer merge for a period of time, the vortex cells continuously disappear and decrease. When t = 2775 s, there are no obvious vortex cells on the layer surface, but a stable flow state with a high temperature at the center of the liquid layer and a low outside temperature is formed.

Because the liquid injected from the layer bottom is heated by the evaporation platform in the pipeline, during the evaporation process, the hot liquid is continuously added in the layer center, so that the temperature in the center area gradually increases and becomes uniform., which causes the vortex cells to merge and disappear, and the flow of the liquid layer enters a stable state without vortex cells, as shown in Fig. 10d. As the interface temperature increases, the evaporation effect is enhanced.



Fig. 11 Merger and disappearance of vortex cells in Stage 3 of ethanol layer evaporation

Evaporative convection further homogenizes the temperature in the liquid layer, which promotes the liquid layer to develop into a stable state.

Conclusion

In summary, experimental investigation of volatile droplets and layer evaporating in steady-state approximation has been reported using infrared thermography and volume feedback control technique. The present work focuses on the heat and mass transfer and thermal flow patterns which are spatially and temporally varying during droplet and layer evaporating.

The droplet evaporation evolution can be separated into three periods: after a transient warm-up period with a sharp increase of heat flux as soon as a volatile droplet is injected onto the heated substrate, the droplet enters an unstable evaporation period with heat flux caused by evaporation decreasing gradually, subsequently, the droplet evaporates under a quasi-equilibrium condition with constant heat flux and convection cells at the interface gradually disappear. The latter two stages are the main stages of droplet evaporation and contain various flow pattern information. The results also present that the direction of the temperature gradient at the evaporating droplet interface is opposite under Aluminum and PTFE substrate. A larger heat flux of evaporating droplets results in a higher evaporation rate on Aluminum substrate.

Four stages present during liquid layer evaporation. Stage 0: Liquid injection and heat absorption stage with the rapid rise of heat flux density curve, also called prepare Stage; Stage 1: The stage of formation and division of vortex cells. Marangoni convective vortex cells continue to form and split on the layer surface which can be regarded as a quasi-periodic 3D flow. As temperature increases, the size of vortex cells becomes larger and the heat flux density increases slowly with small fluctuations. Stage 2: HTWs propagation stage. In this stage, the vortex cells generate from the "source" and disappear in the "sink". It can be shown that the velocity of the hydrothermal wave propagating counterclockwise is about 43% faster than propagating clockwise. Stage 3: Vortex cells merger and disappearance stage. With the continuous replenishment of fresh liquid, the propagation of hydrothermal waves gradually stops, no new vortex cells are generated, and the size of the vortex cells also begins to decrease. Meanwhile, the surface temperature in the central area of the layer is gradually uniform, resulting in the merger and disappearance of the vortex cells, and finally, it enters a stable state without vortex cells.

The present experiments show that both liquid droplet and layer evporation process can obtain a steady-state period after the interface temperature filed becomes uniform by continuous liquid refilling, which means the interface temperature plays an important role in evaporation process of liquid droplet and layer. However, the steadystate phenomenon observed in the experiment is only the state of the gas-liquid interface, and whether the inside of the droplet or liquid layer is also in a steady state remains to be further studied.

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Declarations

Conflict of interests The authors declare that there is no conflict of interest.

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