Experimental Investigation of Thermocapillary Convection in a Liquid Layer with Evaporating Interface *

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Thermocapillary convection coupling with the evaporation effect of evaporating liquids is studied experimentally. This study focused on an evaporation liquid layer in a rectangular cavity subjected to a horizontal temperature gradient when the top evaporating surface is open to air, while most previous works only studied pure thermocapillary convection without evaporation. Two liquids with different evaporating rates are used to study the coupling of evaporation and thermocapillary convection, and the interfacial temperature profiles for different temperature gradients are measured. The experimental results indicate evidently the influence of evaporation effect on the thermocapillary convection and interfacial temperature profiles. The steady multicellular flow and the oscillatory multicellular flow in the evaporation liquid layer are observed by using the particle-image-velocimetry method.

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In the past few decades, there has been growing interests on the instability of thermocapillary convection in a fluid layer subjected to a horizontal temperature gradient both on fundamental and applied fields. Practically, thermocapillary convection plays a very important role in many industrial applications such as crystal growth in materials processing, chemical and heat-energy engineering. Many theoretical and experimental works have been carried out since Bénard[1] observed cellular flow patterns in a planar liquid layer with a free surface heated from bottom, i.e. the imposed temperature gradients were perpendicular to the interface, known as Marangoni–Bénard convection. While for another case, with the externally imposed temperature gradients parallel to the interface, namely thermocapillary convection, there was not general research before Smith and Davis[2,3], who analysed the instability of thermocapillary convection and found a new convective instability called hydrothermal wave. Since then, many scientists have carried out a series of works to study the instability of this kind. Villers and Platten[4] and Riley and Neitzel[5] studied the flow pattern transition from a unicellular flow to an oscillatory flow state numerically and experimentally, respectively.

In previous works, the researches only involved single thermocapillary or buoyancy-thermocapillary convection. Nevertheless, much has been learned about the instability of thermocapillary convection from such studies, in which most of the researchers did not take the evaporation effect into account, and they usually applied unvapourized fluids or took methods to suppress the evaporation effect. While recently, some experimental and theoretical studies have found that evaporation plays an important role in the stability of thermocapillary convection, also in many industrial aspects such as thin-film evaporator, boiling equipments and space processing. Zhang and Chai[6,7] have studied experimentally the influence of evaporation effect on the instability of Marangoni–Bénard convection and proposed a modified Marangoni number to verify the convection stability. A new two-side model[8] has been proposed to perform linear instability analysis at the evaporative liquid-vapour interface. Ruiz and Black[9] numerically studied the interior flow fields in a sessile evaporating droplet. Savino and Fico[10] carried out experimental and numerical analysis to investigate the Marangoni effect during the evaporation of pendant droplets. Hereinbefore, most works have focused on the Marangoni–Bénard convection instabilities of a evaporating liquid layer heated from below, i.e. instabilities induced by the vertical temperature gradient. While with regard to the analysis of thermocapillary convection with evaporation, i.e. instabilities induced by the horizontal temperature gradient, there are few experimental studies except some numerical work[11]. Nevertheless, evaporation and thermocapillary convection are classical phenomena which have varieties of applications, but the combination of them have been seldom studied experimentally, which is of absence of comprehensive understanding. In this Letter, we present the new experimental results on the investigation of the coupling of evaporation and thermocapillary convection in a planar thin liquid layer with a mass and heat exchanging interface.

The working fluid we chose in our experiments is a Dow Corning silicone oil with the viscosity of 0.65 cSt. In addition to its relatively full property parameters, this fluid is resistant to contamination, and it is trans-

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parent to permit a laser beam to enter into the interior of the flow for optical investigation. Most importantly, this oil has relatively high saturated vapour pressure, indicating that it could evaporate under the atmosphere condition. For comparison, another 5 cSt Dow Corning silicone oil was applied which rarely evaporates at atmosphere.

The schematic diagram of the experimental apparatus for the investigation of thermocapillary convection in an evaporating liquid layer is presented in Fig. 1.

The apparatus consists of a rectangular container, of which the length L and the width W are 80 mm and 40 mm, respectively. The streamwise (x direction) walls are made of glasses for optical investigation, while the spanwise (y direction) walls are made of aluminium for thermal control. The bottom of the test cell is an adiabatic glass.

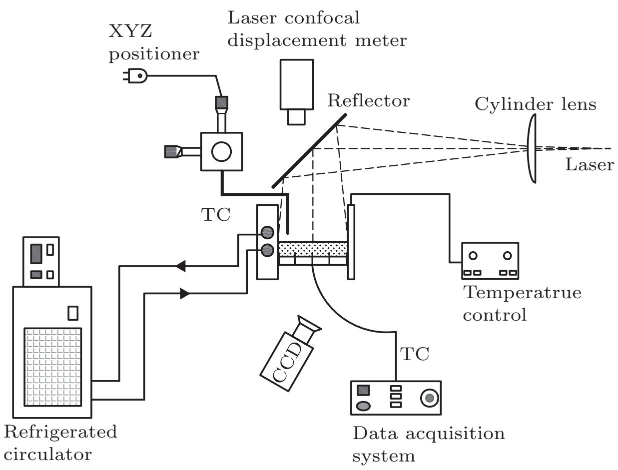

Fig. 1. Schematic diagram of the experimental apparatus.

The horizontal temperature difference $\Delta T = T_h - T_c$, is imposed by the temperature control of the two aluminium walls. The hot wall and the cold wall are controlled by an electrical heater by means of PID loops with an accuracy of about 0.05°C and a refrigerated circulator with an accuracy of about 0.02°C, respectively. Two thermocouples are mounted at the two walls to monitor the temperatures. To minimize the disturbance of the room temperature, the two walls are coated with insulating material.

There is always buoyancy effect in the ground experiments. To suppress the influence of Rayleigh convection, the depth of liquid layer must be as thinner as possible, which is set to be $h = 2.0$ mm in our experiment. In the experiment, we used a laser confocal displacement meter to measure the height of the liquid layer. In despite of the fast evaporating rate of the silicone oil, we neglected the change of the total height of evaporating liquid with the decrease of height by about 5%, due to the relatively short time in our experiment.

In order to measure the temperatures along the interface, a thermocouple with a diameter of 50 μm is applied. The thermocouple links to an XYZ motorized micrometer to move at different directions. The temperature data are acquired by a data acquisition system which could change the scan intervals. Hereby, we could obtain the temperature profiles at different space and time intervals. In our experiments, the thermocouple reading for each position is recorded each second for a period of 40 s and the mean temperature is calculated. This measuring interval (1 s) could ensure the temperature accuracy because of the much smaller of the response time of the thermocouple, which is only 0.02 s. The particle image velocimetry (PIV) is introduced to measure the flow field of the flow. A laser sheet in thickness of about 1 mm illuminates the cross section at the streamwise direction. To obtain the flow visualization, some glass particles of 5 μm in diameter are seeded in the illuminated plane, and a CCD camera is used to record the images of the flow fields for computer analysis.

Several experiments of the thermocapillary convection coupling with evaporation effect have been carried out for different horizontal temperature differences. Firstly, we used a 50 μm thermocouple to measure the temperature just below the interface from the cold wall to the hot wall. Note that we measured the temperature 10 mm away from the cold and hot wall to ignore the influences of the side wall effect and the meniscus, i.e. ranging from $x = 10$ to $x = 30$, which was the most stable region in the liquid layer, and the measuring spatial interval was 5 mm. The interfacial temperature profiles of the evaporating interface for 0.65 cSt silicone oil are presented in Fig. 2.

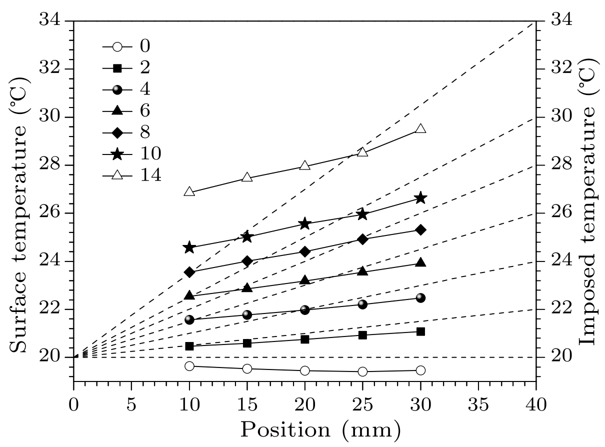

Fig. 2. Temperature profile of 0.65 cSt silicone oil along the interface under different temperature differences. The dashed lines represent the imposed temperatures gradients.

As soon as the temperature difference (ΔT) is established, there will be a thermocapillary convective flow from the hot side to the cold side. This flow will bring the heat energy from the hot side to the cold side, as shown in Fig. 2, the overall imposed temperature gradients are always greater than the local temperature gradients at the middle of the liquid layer. The mismatch of the two gradients will be increased as the imposed temperature differences growing. When $\Delta T = 0$, 2°C, all the five temperatures are smaller than the imposed temperature because of the influence of the evaporation effect, which takes the heat energy from the interface to the ambient air and reduces the interfacial temperatures. When ΔT grows from 4°C to 14°C, the strengthening convective flow will bring more heat energy from the hot side, which will increase the interfacial temperatures to smoothen the temperature gradients. In general, the rising temperatures will also enhance the average evaporation rates of the liquid layer. The higher the temperature is, the faster the liquid evaporates, and the more heat will be taken out of the interface. Thus the evaporation effect will also smoothen the interfacial temperature gradients. The interaction of thermocapillary convection and the evaporation effect makes the interfacial temperature profiles more smooth along the evaporation interface.

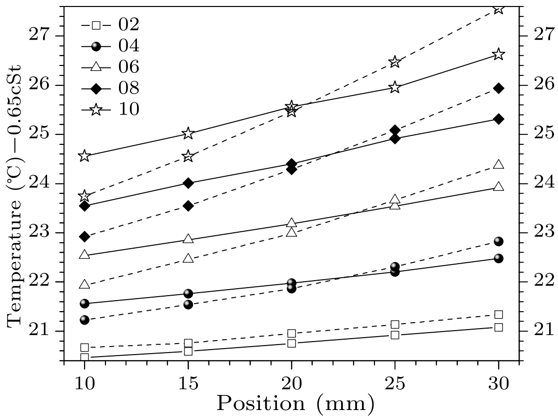

Fig. 3. Interfacial temperature of 0.65 cSt and 5 cSt silicone oil (solid line: 0.65 cSt dash line: 5 cSt).

In Fig. 2, the mean temperature profiles at the measuring region are approximatively linear, while out of the measuring region, i.e. the region ranging from $x = 0$ to $x = 10$ and $x = 30$ to $x = 40$, we could infer that the mean temperature profiles of high temperature differences are not linear. The temperature profiles bend to the lower temperature at the cold wall and the higher temperature at the hot wall, respectively. This phenomenon is mainly induced by the thermocapillary convection, which increases the interfacial temperatures close-by the cold wall and decreases the interfacial temperatures neighbouring the hot wall synchronously, achieves the balance at the middle of the liquid layer eventually.

To verify the influence of the evaporation effect, we repeat the above experiments in the same experimental conditions by using the 5 cSt silicone oil with a very low evaporation rate under atmosphere, in order to compare with the observations obtained for the high evaporating-rate 0.65 cSt silicone oil. The corresponding temperature differences with the constant temperature at the cold side were kept same for both liquids under the same room temperature. The measured temperature profiles at the evaporation interface for the liquids of 0.65 cSt and 5 cSt silicone oil are given together in Fig. 3.

When $\Delta T = 2^\circ$C, the temperature in 0.65 cSt silicone oil is lower than that in 5 cSt silicone oil because of the evaporation effect. The two profiles have approximately the same slope, just because the thermocapillary convection is relatively weak at this condition. As the temperature difference in 0.65 cSt silicone oil grows from 4°C to 10°C, the liquid close to the hot side evaporates more to reduce the interfacial temperature. At the same time, more heat energy is brought to the cold side than that in 5 cSt silicone oil because of 5 cSt oil's larger viscosity which relates to the flow velocity. The coupling of convection and the evaporation makes the difference of the two temperature profile's slopes larger with the increasing ΔT.

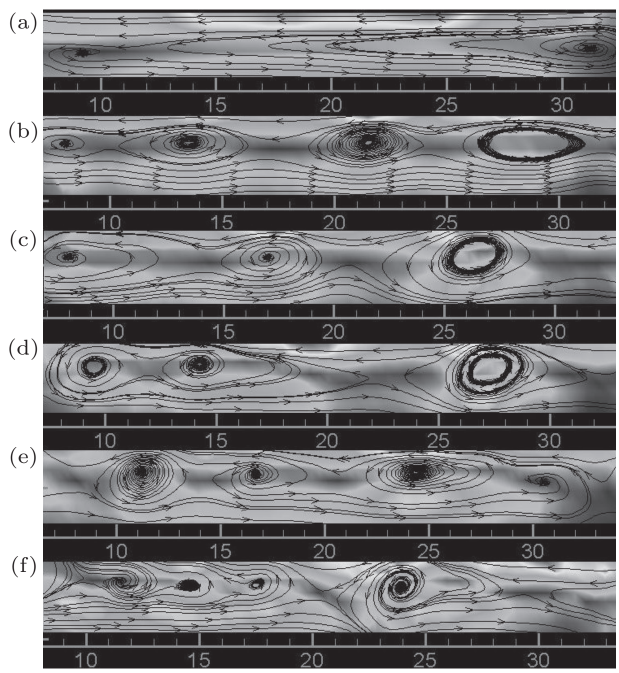

Fig. 4. Flow visualization of 0.65 cSt silicone oil by PIV: (a) $\Delta T = 2^\circ$C, (b) $\Delta T = 4^\circ$C, (c) $\Delta T = 6^\circ$C (d) $\Delta T = 8^\circ$C, (e) $\Delta T = 10^\circ$C, (f) $\Delta T = 14^\circ$C (scale ratio of X direction to Y direction is 1:2).

The cavity was always open during our experiments, and there was always the coupling of the thermocapillary convection and the evaporation effect for the 0.65 cSt silicone oil. The evaporation effect plays a more important role than the thermocapillary convection under low temperature differences (ΔT = 0, 2°C), exhibiting the local interfacial temperature smaller than the imposed ideal temperature. While for higher temperature differences (ΔT = 4°C to 14°C), the thermocapillary convection plays the more important role, and the flow inside the liquid layer exhibits the thermocapillary convection behaviour. Also our experimental results are consistent with the numerical results in Ref. [11].

As soon as $\Delta T \neq 0$, the surface tension gradient on account of the temperature gradient along the interface will induce a surface flow from the hot side to the cold side, and there will be a reversed return flow at the bottom of the liquid for the conservation of mass. The flow patterns of 0.65 cSt silicone oil versus ΔT is present in Fig. 4. To see the flow fields more clearly, the scale ratio of X direction to Y direction we applied in the flow visualization is 1:2.

The flow has different patterns depending on ΔT and h. The basic flow appears a unicellular roll perpendicular to the thermal gradient (see in Fig. 4 when ΔT = 2°C). A transition from the unicellular flow to a steady multicellular flow is observed when the temperature difference increases (ΔT = 4, 6°C). The cells of flow are steady and locates at the same positions. A subsequent transition from the steady multicellular flow to a oscillatory flow as ΔT increases to 8–10°C. The cells are not located at the same positions and have periodic behaviour. When ΔT continually increases to 14°C, the flow pattern turns out to be a turbulent flow, for which the buoyancy effect is thought to be responsible.

In summary, we have investigated experimentally the coupling phenomena of the evaporation and thermocaillary convection in an evaporating liquid layer, which is different from the previous works on the studies of the pure thermocapillary convection. The temperature profiles at the evaporation interface have been measured accurately for the high evaporating liquid 0.65 cSt silicone oil in comparison with that of rarely evaporating liquid 5 cSt silicone oil. We find that evaporation effect influences evidently the temperature profiles at the interface and weaken the thermocapillary convection in the evaporating liquid layer. The heat energy transferred from the hotter side to the colder side by the driving of thermocapillary convection increases the interfacial temperatures in the field near the cold wall, even in fact that the liquid evaporation makes the interfacial temperature lower which is shown when $\Delta T = 0$. It is noted that this phenomenon is more evident when the horizontal temperature differences augment. We present the primary experimental results of the temperature and convective structure in the evaporation and thermocapillary convection, the more details on the evaporation flux and the temperature jump[12,13] at the higher evaporating rate interface coupling with thermocapillary convection will be investigated in near future.

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