Microgravity Sci. Technol (2009) 21 (Suppl 1):S241–S246
DOI 10.1007/s12217-009-9123-y

Experimental Study on the Combined Evaporation Effect and Thermocapillary Convection in a Thin Liquid Layer

Zhi-Qiang Zhu · Qiu-Sheng Liu · Jing-Chang Xie

Received: 12 February 2009 / Accepted: 11 May 2009 / Published online: 27 May 2009

Abstract The coupling mechanisms and flow characteristics of thermocapillary convection in a thin liquid layer with evaporating interface were studied. The planar liquid layer, with the upper surface open to air, was imposed externally horizontal temperature differences. The measured average evaporating rates and interfacial temperature profiles indicated the relative importance of evaporation effect and thermocapillary convection under different temperature gradients. A temperature jump was found at the interface, which was thought to be related to the influence of evaporation effect. All above mentioned results were repeated in a rarely evaporating liquid to compare the influence of evaporation effect.

Keywords Thermocapillary convection · Evaporation · Temperature profile

Introduction

Thermocapillary convection is driven by surface tension gradient induced by the temperature variations along the free interface. The study of thermocapillary convection was firstly performed in the area of crystal growth (Schwabe et al. 1978; Gatos 1982), which was also the most mentioned application of thermocapillary convection in the past decades. Many works have been done to understand the instability of thermocapillary convection and explore the technologies of manufacturing less flawed crystals. Actually, there are many physical fundamental problems and industrial applications, in which the thermocapillary convection plays an important even a dominant role. The applied aspects include thin-film coating, laser welding and heat-energy engineering. Smith and Davis (1983a, b) analyzed linear stability of a liquid layer subjected to a horizontal temperature gradient to identify the instability mechanisms of thermocapillary convection. They found two different models of instabilities, hydrothermal wave and surface wave. Subsequently, many scientists have done a series of works to testify and widen the theory of Smith and Davis. Taking many other parameters into account, such as buoyancy convection, Plandtl number and aspect ratios of the test cell, these works have explained the transition of thermocapillary flow from stationary flow to hydrothermal wave and the instability of temperature oscillations (Villers and Platten 1992; Gillon and Homsy 1996; Mercier and Normand 1996; Riley and Neitzel 1998; Burguete et al. 2001). Nevertheless, additional mechanisms have been revealed by the use of new numerical ideas and experimental methods.

The thermocapillary convection was thought to be involved into the heat transfer in the liquid layer, in which the physical mechanisms were very complex. With the development of the research, many other effects were shown to be coupled with thermocapillary convection. Among these studies, a typical and com-

Z.-Q. Zhu · Q.-S. Liu (✉) · J.-C. Xie
Key Laboratory of Microgravity (National Microgravity Laboratory), Institute of Mechanics, Chinese Academy of Sciences, Beijing 100190, China
e-mail: liu@imech.ac.cn

Z.-Q. Zhu
e-mail: zhuzhiqiang@imech.ac.cn

J.-C. Xie
e-mail: jcxie@imech.ac.cn

plicated study was the thermocapillary convection coupling with the evaporation effect in a thin evaporating liquid layer.

The study of evaporation has attracted more and more scientific interests because of its great applications in industry engineering, such as nuclear reactor, thin-film evaporators and heat pipe in space. In above mentioned literatures, the researchers usually used rarely evaporating fluids to avoid the additional influence of evaporation effect. Even if the liquids evaporated at atmosphere, these researchers always covered their test cells to suppress the evaporation effect and performed the measurements in a simple but well-controlled conditions.

Recently, a new work has found that the evaporation effect could influence the instability of Marangoni-Bénard convection (Chai and Zhang 1998), which was induced by the vertical temperature gradients across the liquid layer. A new two-side physical model (Liu and Liu 2005, 2006) was carried out to explain the experimental phenomena. As regards the thermocapillary convection in a evaporating liquid layer, the researchers were started just recently. During evaporation, the heat and mass are taken out of the liquid-vapor interface. The evaporation effect would influence the interfacial temperature and temperature gradients, which influence the thermocapillary convection.

In most of previous works, people usually treated the liquid-vapor interface as thermal equilibrium, i.e. the temperatures are continuous at the interface. However, a recent research found a temperature discontinuity at the liquid-vapor interface. Ward and Duan (2004) have found a temperature discontinuity as big as 8°C at the interface of evaporating water. They thought the evaporation effect generated the non-equilibrium. However, they only performed the experiments by use of water at 4°C. It is not certain if the temperature discontinuity could be investigated in other liquids and other experimental conditions.

The combined mechanisms of evaporation effect and thermocapillary convection are complex and need to be understood. In this paper, we will present the experimental results concerning the coupling of evaporation effect and thermocapillary convection in a thin evaporating liquid layer. The numerical simulation of this similar physical model and the problem has been done in parallel (Ji and Liu 2008).

In the following, we will first specify the details of the experimental apparatus and the measurement techniques in "Experimental Setup and Measurement Techniques". In "Results and Discussion", we will present and discuss our experimental results, including the interfacial temperature profiles, average evaporating rates and temperature jump at the interface. Finally, conclusions are stated in "Conclusion".

Experimental Setup and Measurement Techniques

The overall schematic setup of the experimental apparatus is shown in Fig. 1. The experiments were carried out in a rectangular cavity, of which the length and the width are 80 mm and 40 mm, respectively. The two longer sidewalls of the cavity, which are placed at opposite directions, are made of aluminum for temperature control. The thermal conductivity of the aluminum is three orders of magnitude better than that of liquids used in the experiments. This could ensure that the temperatures of the sidewalls are uniform. The shorter sidewalls, which are placed perpendicularly to the aluminum walls, are made of optics glass for observations. The bottom of the cavity is an optics glass to play the role of insulation and permitting light through. The top of the cavity is open to air to ensure that the liquid would evaporate freely.

A silicone oil with kinematic viscosity of 0.65 cSt, Plandtl number of 10 is put into the experimental cavity. The liquid is resistant to the surface contamination and transparent to visible light for optical observation. Most importantly, the liquid has a relatively high saturated vapor pressure, which means that it evaporates under atmosphere condition. Other different fluids which rarely evaporate at atmosphere (1.5 cSt and 5 cSt silicone oil) were used to study the influence of the evaporation effect.

The horizontal temperature difference was achieved through the temperature control of the two aluminum sidewalls. Cool water with constant temperature flow-

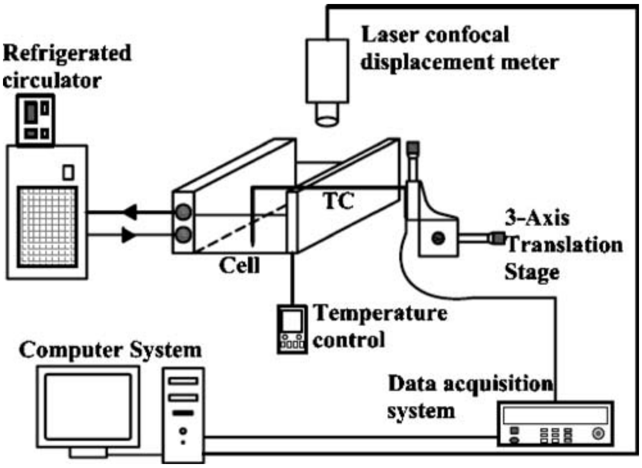

Fig. 1 Schematic drawing of the experimental apparatus

ing out of a refrigerated circulator is circulated into the left sidewall, and the accuracy of the temperature could be 0.02°C. Meanwhile, the temperature of the other sidewall is controlled by means of PID loops with an accuracy of 0.05°C.

In order to measure the interfacial temperature profiles accurately, a thermocouple with a diameter of 50 μm is used, which is small enough to avoid disturbance to the inner flow. The thermocouple could be moved at different directions with the help of a 3-axis translation stage. The temperature data are acquired by a data acquisition system. The two devices could be programmed and controlled by a computer to obtain the temperature data at different spatial and temporal intervals.

During evaporation, the position of the interface will decrease with time. A laser co-focal displacement meter is introduced to track the liquid–vapor interface with an accuracy of 0.3 μm. Under a hypothesis of steady flows in the liquid layer, we could consider that the change of the interface height with time reflects the average evaporating rate.

Results and Discussion

The physics of evaporation is complicated. Making use of the above experimental apparatus and measurements techniques, several experiments have been carried out to study the coupling mechanisms of evaporation effect and thermocapillary convection. There are many parameters to influence the evaporation and thermocapillary flow. In this paper, we only took the imposed horizontal temperature difference into account to simplify the physical problem. By altering the temperature gradients, interfacial temperature profiles, average evaporating rates and interfacial temperature discontinuity were measured to analyze the physical mechanisms.

As we know, there is always buoyancy effect in the ground experiments. And usually, Rayleigh convection and thermocapillary convection exist together in the liquid layer. Based on the definition of Bond number, the depth of the liquid layer should be set as thin as possible to suppress the buoyancy effect. In our experiments, the depths of the liquid layers were always kept smaller than 2.0 mm. The curving meniscuses at both sidewalls introduce new problems to analyze the evaporating mechanisms, which are bout 5.0mm in length at each side. In addition, the return flow is another factor to influence the experimental results, and it will disturb the flow fields and thermal fields close to the sidewalls. Therefore, we only chose the middle plane area of the liquid layer ranging from $x = 10$ mm to $x = 30$ mm to perform measurements.

Interfacial Temperature Profiles

The interfacial temperature profiles could directly reflect the influence of evaporation effect and thermocapillary convection. Figure 2 shows the interfacial temperature profiles of the evaporating interface for 0.65 cSt silicone oil, and the depth of the liquid layer is 2.0 mm.

As shown in Fig. 2, the local temperature profiles (solid lines) are approximately linear. And the overall imposed temperature gradients (dash lines) are always greater than the local temperature gradients at the middle of the liquid layer. The difference of the two gradients will be increasing as the imposed temperature differences growing. Actually, the difference results from the co-operation of the evaporation and thermocapillary convection. As we know, evaporation effect takes heat energy from the liquid-vapor interface to the ambient air and reduces the interfacial temperatures. While for thermocapillary convection, there is no threshold to start. In other words, there will be an immediate convective flow from the hot wall to the cold wall of the cavity as soon as the temperature gradient along the interface is created. This flow will bring the heat energy from the hot side to the cold side. When the temperature difference is small (lower than 2°C), the evaporation effect is relatively stronger than thermocapillary convection, and thermocapillary flow could not supply the heat loss taken by evaporation. As a result, the all five interfacial temperatures are smaller than the imposed temperatures. When the

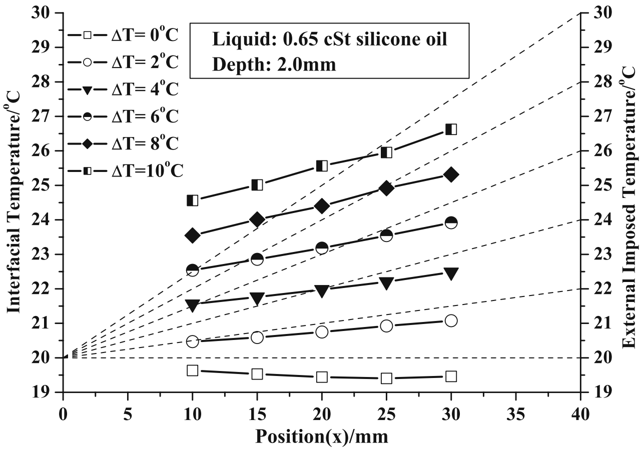

Fig. 2 The interfacial temperature profiles in 0.65 cSt silicone oil at different temperature differences (*Dash line*: external imposed temperature gradients)

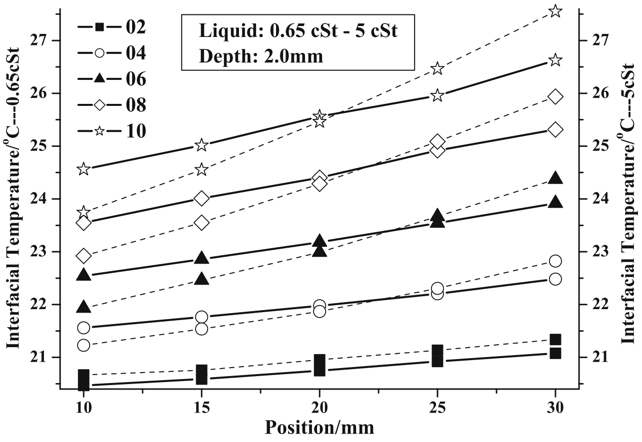

Fig. 3 The interfacial temperature profiles of 0.65 cSt and 5 cSt silicone oil at different temperature differences (*Solid line*: 0.65 cSt *Dash line*: 5 cSt)

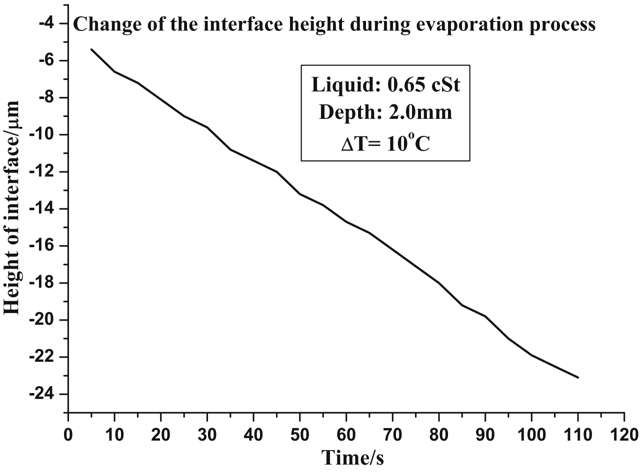

Fig. 4 Variation of the interface height during evaporation process

imposed temperature difference increases larger than 4°C, the strengthened thermocapillary convection will bring more heat energy from the hot wall to the cold wall, which increases the temperatures closed to the cold wall. In the Meanwhile, the rising temperature will also enhance evaporation effect to take more heat from the hot side of the layer to reduce the temperature. Eventually, the interaction of the evaporation effect and thermocapillary convection makes the interfacial temperature profiles smooth along the interface.

A repeated experiment of 5 cSt silicone oil was performed at same conditions to verify the role of the evaporation effect. Figure 3 shows the interfacial temperature profiles of 0.65 cSt and 5 cSt silicone oil under same temperature differences. When temperature difference is low (2°C), the two profiles have approximately the same slope. At this condition, thermocapillary convection is relatively weak, evaporation plays a main role to decide the temperature along the interface. As the temperature difference growing, the liquid close to the hot wall in 0.65 cSt evaporates more to reduce the interfacial temperature. In the meantime, more heat is brought to the cold side than that in 5 cSt because of the lower flow velocity in 5 cSt. The coupling of thermocapillary convection and the evaporation makes the slope of temperature profile in 0.65 cSt smaller than that in 5 cSt silicone oil.

Average Evaporating Rates

As mentioned above, the change of the interface height with time reflects the average evaporating rate when the inner flow in the liquid layer is steady. We measured the variation of the interface height at one surface position during evaporation process when the temperature difference was relatively large, as shown in Fig. 4. It could be seen that the height of interface decreased linearly during the measuring period of 2 min, and the fluctuation of the interface in magnitude is much smaller than the decrease of the interface height by evaporation. Therefore, it is reasonable and feasible to use the height change to reflect the average evaporating rate in our experiment.

Under the hypothesis of steady flow in the liquid layer, we found that there are some differences of the average evaporating rate at different positions of the liquid layer. Figure 5 presents the average evaporating rates at different horizontal positions. When the temperature difference is small (lower than 6°C), the average evaporating rate grows approximately linear from the cold side to the hot side, of which we think

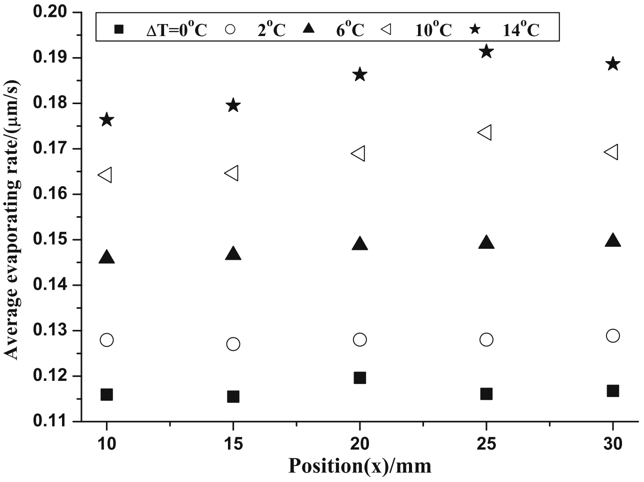

Fig. 5 Average evaporating rates at different positions for different temperature gradients

owing to the interfacial temperature increasing from the cold wall to the hot wall. While when the temperature difference increases to larger than 10°C, a maximum average evaporating rate was found in the middle of the interface. Actually, there is always unavoidable buoyancy convection in the ground experiments. The thermocapillary convection decides the average evaporating rates along the interface when the temperature difference is low. While at higher temperature difference, there will be three main effects to influence the average evaporating rates. Firstly, more heat is transported by thermocapillary convection from the hot wall, which accelerates the average evaporating rate. Secondly, according to the results of flow visualization (Zhu and Liu in press), the place with maximum evaporating rate usually has a biggest flow velocity, which means more heat is transported to this place to increase evaporation. Actually, the coupling of thermocapillary convection and evaporation could be reflected from Fig. 3. Although more heat is transported to here, highest evaporating rate will decrease more temperature to make the temperature profile linear. The last effect is the buoyancy convection in upper air. It will influence the concentration gradient of the oil gas, which also influence the average evaporating rate. Anyhow, the co-action mechanisms of the above three effects are very complicated, which need more work to be well understood.

Temperature Jump at the Interface

The temperature profiles at the vertical direction near the interface were measured by a 50 μm thermocouple. A 3-axis motorized translation stage was used to determine the vertical positions of the thermocouple with an accuracy of 1 μm. Near the interface, the distance between two measurements in the vertical direction was 50 μm. Figure 6 shows the temperature discontinuity of 0.65 cSt and 1.5 cSt silicone oil near the interface when the temperature difference is 8°C.

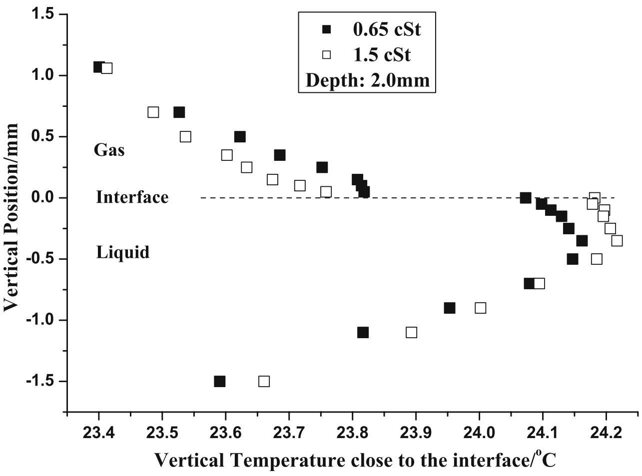

Fig. 6 Temperature discontinuity of 0.65 cSt and 1.5 cSt silicone oil close to the interface when the temperature difference is 8°C

It could be seen that there are temperature jumps in both 0.65 cSt and 1.5 cSt interface, and the temperature discontinuity in 1.5 cSt is larger than that in 0.65 cSt. In liquid phase near the interface, the thermocapillary convection is strong enough to bring heat energy to increase the interfacial temperature in both two liquids. On the other hand, the evaporation effect in 0.65 cSt reduces the interfacial temperature. While in vapor phase near the interface, the relatively stronger thermocapillary convection in 0.65 cSt drives more heat from the heat wall in the vapor. In other words, the stronger thermocapillary convection in 0.65 cSt increases the vapor temperature, and the stronger evaporation effect in 0.65 cSt decreases the liquid temperature. As a result, the coupling of thermocapillary convection and evaporation effect decreases the temperature discontinuity in 0.65 cSt. Note that our results are different from Ward's results in temperature scales and temperature gradients(Ward and Duan 2004). It is mainly because of differences in experimental conditions and the low evaporating rates in our experiments.

Conclusion

The coupling of evaporation effect and thermocapillary convection is experimentally investigated in a thin 0.65 cSt liquid layer with the interface open to air. The interfacial temperature profiles, average evaporating rates and the temperature discontinuity were measured to analyze the physical mechanisms.

The mismatch of the local interfacial temperature profiles and the imposed temperature gradients reflects the co-operation of evaporation effect and thermocapillary convection. The evaporation effect and the thermocapillary convection play a more important role at low and large temperature difference, respectively. Comparing repeated results in 5 cSt, evaporation effect is found to influence the interfacial temperature evidently.

Under the hypothesis of steady flow in the liquid layer, the average evaporating rate exhibits dependence on the measuring position and temperature gradient, which we think is partly due to the influence of buoyancy effect.

A temperature discontinuity was found in both two liquids with different evaporating rates. Coupling of thermocapillary convection and evaporation effect could change the temperature discontinuity obviously.

Acknowledgements This research was financially supported by the National Natural Science Foundation of China (Grant Nos. 10772185 and 50890182) and the Knowledge Innovation Project of Chinese Academy of Sciences (KGCX-SW-409).The authors thank Prof. C. A. Ward and Dr. Fei Duan of University of Toronto for their discussion.

References

Burguete, J., Mukolobwiez, N., Daviaud, F., Garnier, N., Chiffaudel, A.: Buoyant-thermocapillary instabilities in extended liquid layers subjected to a horizontal temperature gradient. Phys. Fluids **13**(10), 2773–2787 (2001)

Chai, A., Zhang, N.: Experimental study of Marangoni-Bénard convection in a liquid layer induced by evaporation. Exp. Heat Transf. **11**, 187–205 (1998)

Gatos, H.C.: Semiconductor crystal growth and segregation problems on earth and in space. In: Materials Processing in the Reduced Gravity Environment of Space, pp. 355C71. Elsevier, Amsterdam (1982)

Gillon, P., Homsy, G.M.: Combined thermocapillary-buoyancy convection in a cavity: an experimental study. Phys. Fluids **8**(11), 2953–2962 (1996)

Ji, Y., Liu, Q.S.: Coupling of evaporation and thermocapillary convection in a liquid layer with mass and heat exchanging interface. Chin. Phys. Lett. **25**(2), 608–611 (2008)

Liu, R., Liu, Q.S.: Marangoni-Bénard instability with the exchange of evaporation at liquid-vapor interface. Chin. Phys. Lett. **22**(2), 402–405 (2005)

Liu, R., Liu, Q.S.: Vapour recoil effect on a vapour-liquid system with a deformable interface. Chin. Phys. Lett. **23**(4), 879–882 (2006)

Mercier, J.F., Normand, C.: Buoyant-thermocapillary instabilities of differentially heated liquid layers. Phys. Fluids **8**(6), 1433–1445 (1996)

Riley, R.J., Neitzel, G.P.: Instability of thermocapillary-buoyancy convection in shallow layers. Part 1. Characterization of steady and oscillatory instabilities. J. Fluid Mech. **359**, 143–164 (1998)

Schwabe, D., Scharmann, A., Preisser, F., Oeder, R.: Experiments on surface tension driven flow in a floating zone melting. J. Cryst. Growth **43**, 305 (1978)

Smith, M.K., Davis, S.H.: Instabilities of dynamic thermocapillary liquid layers. Part 1. Convective instabilities. J. Fluid Mech. **132**, 119–144 (1983a)

Smith, M.K., Davis, S.H.: Instabilities of dynamic thermocapillary liquid layers. Part 2. Surface-wave instabilities. J. Fluid Mech. **132**, 145–162 (1983b)

Villers, D., Platten, J.K.: Coupled buoyancy and Marangoni convection in acetone: experiments and comparison with numerical simulations. J. Fluid Mech. **234**, 487–510 (1992)

Ward, C.A., Duan, F.: Turbulent transition of thermocapillary flow induced by water evaporation. Phys. Rev. E **69**(5), 056308 (2004)

Zhu, Z.Q., Liu, Q.S.: Coupling of thermocapillary convection and evaporation effect in a liquid layer when the evaporating interface is open to air. Chin. Sci. Bull. (2009, in press)