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Experimental Study of Thermocapillary Flows in a Thin Liquid Layer With Heat Fluxes Imposed on the Free Surface

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EXPERIMENTAL STUDY OF THERMOCAPILLARY FLOWS IN A THIN LIQUID LAYER WITH
HEAT FLUXES IMPOSED ON THE FREE SURFACE

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ABSTRACT

To study thermocapillary flows in a two-dimensional thin liquid layer with heat fluxes imposed on the free surface experimentally, a long tray configuration was employed to simulate the infinite layer. The surface temperature distribution due to thermocapillary convection for different flow regimes were measured and compared with theoretical predictions. A short tray configuration was also employed to study the end wall effects (insulating or conducting). The results show that for a strong convective flow with an insulating wall as the boundary, the surface temperature distribution became quite uniform. Consequently, the thermocapillary driving force was greatly reduced. On the other hand, a strong fluid motion always existed adjacent to the conducting wall because of the large surface temperature gradient near the wall.

INTRODUCTION

The space environment can be very beneficial for material processing as both the gravitational body forces and the buoyancy convection are greatly reduced, so are the sedimentation caused by such forces, and turbulences generated by such convection. Among the various applications in material processing, float-zone crystal growth offers not only a promising technique in the practical sense but also a challenging opportunity in understanding the thermocapillary flow phenomena.

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There are basically two configurations considered in the past studies. One is that with fixed end temperatures, the other, with imposed heat flux. Most of the studies have dealt with the former. For the imposed-heat-flux configuration, there still exists certain basic and important phenomena to be understood before further studies can be properly pursued. The surface temperature distribution of the thin liquid layer as a result of the coupling between the imposed heat flux and the thermocapillary convection in a two-dimensional thin liquid layer is the one of particular interest to us. For a finite container, which is more realistic than the infinite layer, the end wall effects (insulating or conducting) on the flow structure are important. The present study is aimed at understanding the above mentioned flow phenomena experimentally.

Based on the analysis done by Lai and Chai [1], a long tray with 50 cm in length and 9.5 cm in width filled with silicone oil with 0.5 cm to 1.0 cm in depth was used to simulate a two-dimensional, infinite thin layer. Heat fluxes were generated by a heating element extending above the center of the container in the width direction. Flow patterns induced by the imposed heat fluxes through the thermocapillary effect should be symmetric and perpendicular to the heating element. The silicone oil, the layer depth, and the distance between the heating element and the liquid surface were varied to cover a certain flow range with A^2Ma between 10^2 and 10^4 , where $A = D/L$, with D denoting the layer depth and L , the reference length scale in the flow direction, is the aspect ratio and Ma , the Marangoni number. The surface temperature distribution was then measured and compared with the theoretical predictions [1].

In order to study the end wall effects, a short tray (10 and 12 cm in length) was employed. Copper was used for the conducting wall; plexiglass, for the insulating wall. For ease of comparison of the flow structures with

and without end wall effects, the heating element was purposefully installed not at the midplane of the tray parallel to the minor axis. The heating element extended above the tray was placed 2 cm from the conducting (or the insulating) wall. The long side (with respect to the heating element) of the tray behaves like a two-dimensional layer without end wall effects. The short side (with respect to the heating element), on the other hand, would demonstrate the end wall effects clearly. Procedures for conducting the experiment were similar to those with a long tray configuration. Flow structures were observed and recorded. The results are discussed in Section V.

MOTIVATIONS

Two-dimensional, Infinite Layer Experiment

In studying thermocapillary flows, accurate information on surface temperature distribution is of great importance since it determines the driving force. In a thin liquid layer with a nonuniform heat flux imposed on the free surface the surface temperature distribution is a result of the coupling of the thermocapillary convection and the imposed heat flux. In a previous publication [1], the authors analyzed the coupling effects, made estimates on the characteristic length and temperature scales by nondimensional analysis, and numerically calculated these characteristic quantities. Their analysis predicted that

$$\frac{L}{L_R} \sim (A^2 Ma)^{1/4}$$

and

$$\frac{\Delta T_o}{\Delta T_R} \sim (A^2 Ma)^{-1/4}$$

where ΔT_o and L are the characteristic temperature and length scales in the flow direction when convection is important. ΔT_R and L_R , on the other

hand, are the reference scales obtained from the conduction-dominant situation. A and Ma are the aspect ratio and Marangoni number based on the ΔT_p and L_R . The present study intends to confirm experimentally these theoretical predictions.

Finite Layer Experiment

In a real situation, the liquid layer is always confined in a finite container. The wall effect on the flow structure then becomes important. With an insulating wall, the surface temperature distribution should be quite uniform and the thermocapillary driving force, therefore, is greatly reduced, when convection becomes important. On the other hand, when a conducting wall is employed and maintained at the ambient temperature, a sharp surface temperature variation exists. As a result, a strong cellular fluid motion should result near the conducting wall.

EXPERIMENTAL APPARATUS

Long-tray experiment

The thin liquid layer is contained in a shallow tray of dimensions 9.5 by 50 by 1.2 cm. The lateral dimensions were chosen to be sufficiently large so that temperature gradients present at the sidewalls were well outside of the region of interest. The sidewalls are fabricated from acrylic plastic to permit optical access for flow visualization. The bottom of the tray is made of copper of 5 mm thickness. In order to impose the fixed temperature boundary condition on the lower surface of the tray, the copper bottom is held in contact with a recirculating water bath whose temperature is controlled to an accuracy of ± 0.05 °C. The imposed heat flux is supplied by a 0.063 in. diameter Inconel wire heater which is suspended above the midplane of the tray, parallel with the minor axis. A thermocouple is affixed to the surface of the heating wire to provide the temperature data necessary to determine the

heat flux distribution. All thermocouples are referenced to an electronic ice point bath, and read with a high impedance microvoltmeter. The surface temperature distribution of the liquid layer is measured using a single thermocouple with a tip diameter of 75 μm . This dimension was chosen to be smaller than the minimum thermal boundary layer thickness as calculated. The fluid surface is scanned with a single thermocouple in order to avoid the interdevice variations present with multiple thermocouples. The scan is implemented with a programmable micropositioner having a positioning accuracy of $\pm 1 \mu\text{m}$.

The resulting flow structure is observed by illuminating a plane of interest within the flow field with a thin sheet of laser light. The flow is seeded with 3 μm aluminum oxide particles at a density of 300 μg per liter. Light scattered by the particles is recorded photographically. A pair of cylindrical lenses with focal lengths in the ratio of 1:25 are used to expand the output beam of a 6 mw HeNe laser, providing a light sheet of dimensions 0.7 by 18 mm ($1/e^2$). Exposure times are controlled by an electromechanical shutter located at the common focal plane of the cylindrical lens pair.

The schematic diagram of the experimental set up is shown in figure 1.

Short-tray Experiment

In order to study the wall effects (conducting or insulating) on the flow structure, a short tray with dimensions 9.5 by 10 (or 12) by 1.2 cm was employed. Copper was used for the conducting wall; plexiglass for the insulating wall. For ease of comparison of the flow structures with and without wall effects, the heating element was intentionally placed closer to one of the end walls. The heating element extended above the tray in the minor axis direction was placed 2 cm from the conducting (or insulating) wall. The long side of the tray behaves like a two-dimensional layer with no significant

end wall effects. The short side, on the other hand, will display end wall effects. All the other apparatus are the same as those used in the long-tray experiment.

EXPERIMENTAL PROCEDURE

As indicated in a previous paper [1], the salient parameter describing the thermocapillary flow phenomenon in a two-dimensional thin liquid layer is (A^2Ma) . In the present study, the value of (A^2Ma) varies over the range of 10^2 to 10^4 . In order to cover the entire range, several system parameters - the heat flux strength, the distance from the heating element to the fluid surface, the depth of the liquid layer, and the viscosity of the silicone oil were varied or adjusted. The experimental conditions under consideration are summarized briefly below:

- (1) Temperature of the heating element: 200 to 850 °C
- (2) Distance from the heating element to the surface of the liquid layer: 0.5 to 1.0 cm
- (3) Depth of the liquid layer: 0.5 to 1.0 cm
- (4) Viscosity of the liquid: 5 to 50 csts

For each configuration, the system was allowed to attain thermal equilibrium for a period of roughly 30 min. The surface temperature distribution was then measured, allowing the thermocouple to rest for several minutes at each location. In the mean time, the laser was turned on to facilitate flow visualization. The flow pattern was also recorded by a movie camera.

RESULTS AND DISCUSSION

Buoyancy Effect

Dynamic Bond number, i.e., $B_{o,d} = \frac{\rho g D^2 (\beta \Delta T_o)}{|\sigma_T| \Delta T_o}$ gives the relative importance of the buoyancy effect to the thermocapillary effect. The value

of $B_{O,d}$ for the present study is about 3 to 7. Although the value of $B_{O,d}$ is not less than unity, the buoyancy effect can still be considered as a minor one as compared to the thermocapillary effect. The reasons are as follows: Imposing heat fluxes on the top free surface results in horizontal temperature gradients and hence surface-tension driven convections. This provides a thermally stabilizing effect on the flow field, which reduces the flow motion due to buoyancy. Furthermore, when convection is strong, the temperature variation in the depth direction due to heat transfer is confined only within the thermal boundary thickness, which further reduces the buoyancy effect.

Long-tray Experiment

The surface temperature distribution is the main concern in this experiment. As examples, the surface temperature distribution for $(A^2Ma) = 1.3 \times 10^3$, 3.2×10^3 , and 6.0×10^3 are shown in figure 2. From the surface temperature distribution, the characteristic temperature difference, ΔT_0 , i.e., the difference between the surface temperature underneath the heating element and that at the far down stream, can be obtained. To estimate the characteristic length scale L in the flow direction, a straight line was drawn to intersect with the surface temperature profile in such a way that the shaded areas, as shown in figure 2, are equal. Physically, it means that the surface temperature is redistributed in a linear way such that the global energy is conserved for the main portion where the surface temperature varies appreciably. The intersection point farther down stream then determines the characteristic length scale L . As predicted and numerically calculated in a previous paper [1]

$$\frac{L}{L_R} \sim (A^2Ma)^{1/4}$$

$$\frac{\Delta T_0}{\Delta T_R} \sim (A^2Ma)^{-1/4}$$

It can be seen from figure 3 that the 1/4-power variations of L/L_R and $\Delta T_o/\Delta T_R$ with respect to (A^2Ma) as predicted by the nondimensional analysis are quite reasonable.

Short-tray Experiment

The main interest in this experiment was the wall effect (insulating or conducting) on the flow structure. Two extreme cases were investigated:

Insulating wall. - A series of data set ($A^2Ma = 4.0 \times 10^2, 1.3 \times 10^3, 3.2 \times 10^3$ and 6.0×10^3) were collected with an insulating plexiglass end wall serving as the boundary. The flow structures are shown in figure 4. For $A^2Ma \sim 10^2$ the flow structure near the heating element seems to be qualitatively symmetric with respect to the heating element. For $A^2Ma \sim 10^3$ when convection becomes stronger, the flow in the long side begins to penetrate onto the short side region and the flow pattern in the short side begins to distort. For $A^2Ma \sim 10^4$, the small cellular flow motion on the short side almost disappears; finally, only a uni-cell flow pattern generated by the thermocapillary force on the long side existed. This transition from two locally symmetric (with respect to the heating element) cellular flow pattern to a unicell flow pattern demonstrate the decrease of the thermocapillary driving force due to insulating wall effect when convection became important.

Conducting wall. - The experimental set up in this study was the same as that used for the insulating-wall experiment except a copper end wall instead of the plexiglass end wall was used as the boundary. The temperature of the conducting wall was maintained at the ambient temperature which was also the temperature of the bottom boundary. The same series of data sets as that in the insulating-wall case was collected in the present situation. Some results are shown in figure 4. For $A^2Ma \sim 10^2$ the flow structure near the heating

element is also qualitatively symmetric with respect to the heating element, similar to that for the insulating-wall situation. When convection became important, a strong surface temperature variation existed only near the conducting wall, which resulted in a strong thermocapillary driving force in that small region.

It can be seen from figure 4 as convection grew stronger, the cellular flow motion on the short side became smaller and stronger but never disappeared. This strong flow motion on the short side demonstrated that there existed a sharp surface temperature gradient and, consequently, a strong thermocapillary driving force near the conducting wall, as discussed in Section II.

CONCLUSIONS

The experimental study of the thermocapillary flow phenomenon in a two-dimensional thin liquid layer with heat imposed on the free surface was conducted herein with the aid of a long-tray and a short-tray configurations. The following conclusions are drawn from the present study.

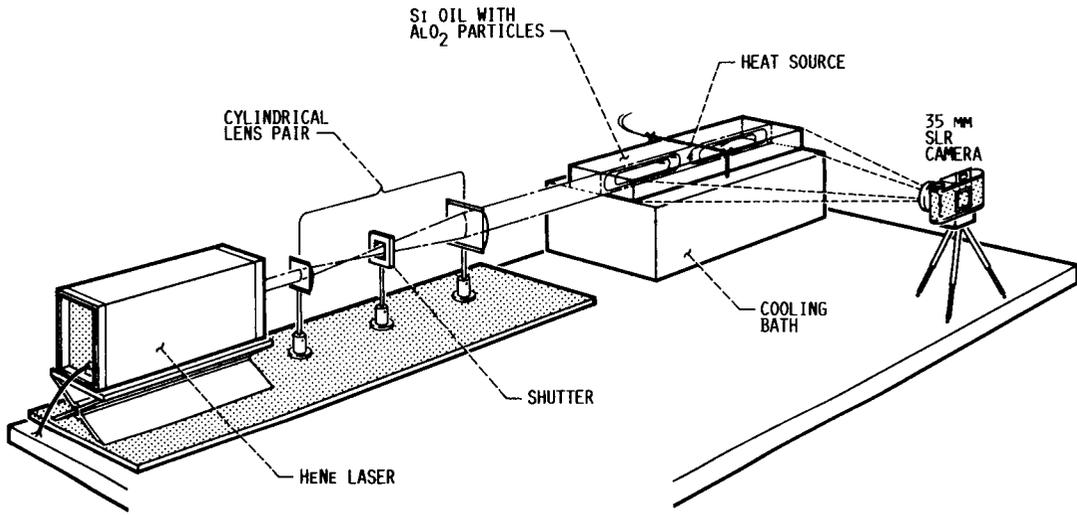
1. The $1/4$ - power variations of L/L_R and $\Delta T_o/\Delta T_R$ with (A^2Ma) , i.e., $L/L_R \sim (A^2Ma)^{1/4}$ and $\Delta T_o/\Delta T_R \sim (A^2Ma)^{-1/4}$, as predicted by the authors in a previous paper were confirmed by the experimental results.

2. For a strong convection flow with an insulating wall as the boundary, the surface temperature distribution becomes quite uniform on the short side. Consequently, the thermocapillary force for the small cellular flow motion is much reduced.

3. With a conducting end wall as the boundary, a strong cellular flow motion always exists near the wall because of the strong surface temperature variation in that small region.

REFERENCE

1. C.L. Lai and A.T. Chai: NASA TM-87115, National Aeronautics and Space Administration, Washington, D.C., 1985.



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FIGURE 1. - THERMOCAPILLARY FLOW EXPERIMENT.

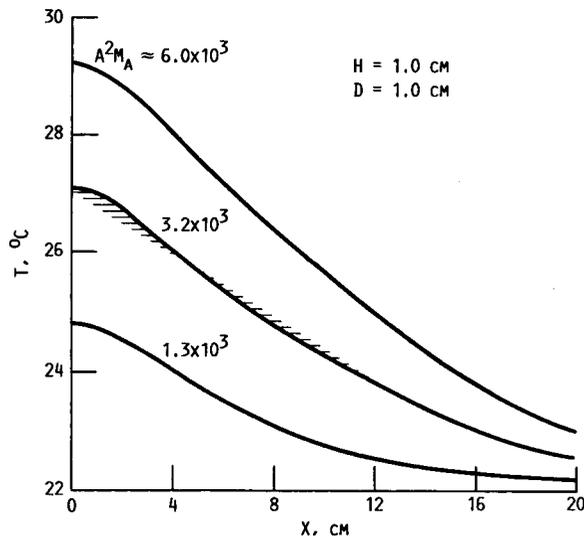


FIGURE 2. - TEMPERATURE DISTRIBUTION ALONG THE FREE SURFACE.

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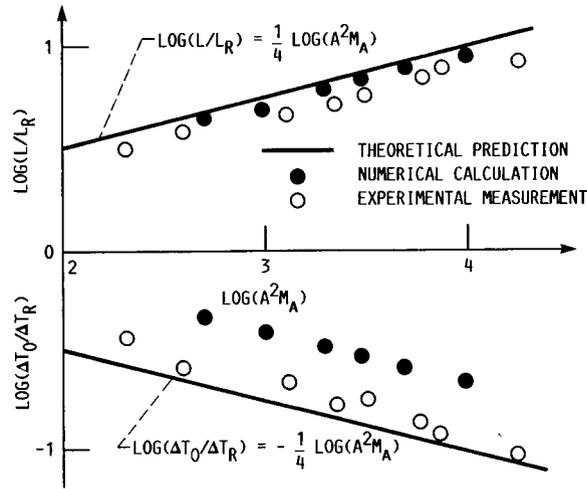


FIGURE 3. - VARIATIONS OF L/L_R AND $\Delta T_0/\Delta T_R$ WITH RESPECT TO $A^2 M_A$.

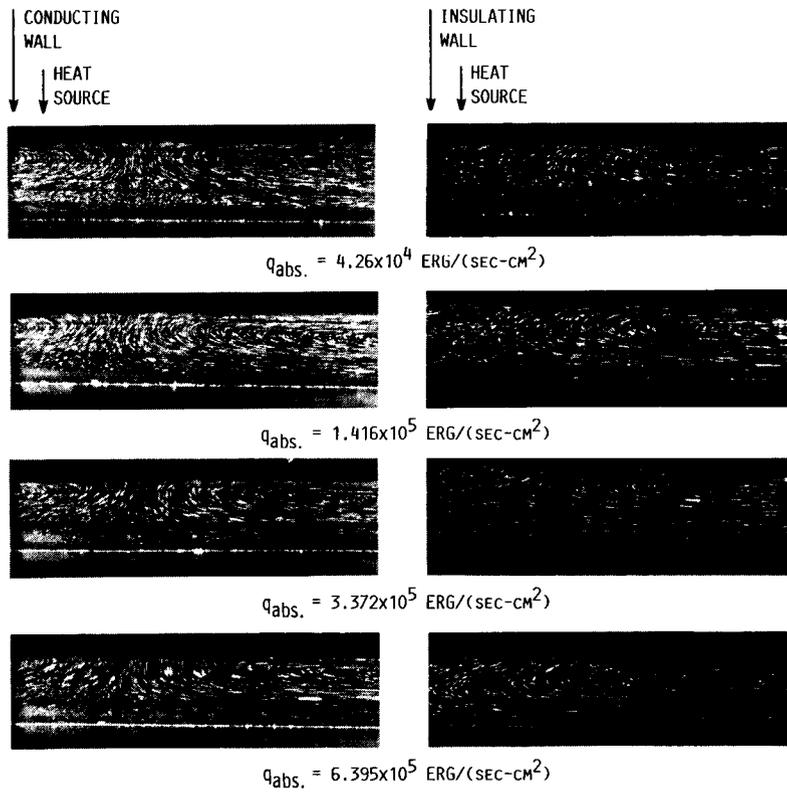


FIGURE 4. - COMPARISON OF THEORETICALLY CONDUCTING AND INSULATING END WALLS ON THE RESULTING FLOW STRUCTURE.



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