J. Jpn. Soc. Microgravity Appl. Vol. 28 No. 2 2011 (S105–S108)

8th Japan-China-Korea Workshop on Microgravity Sciences
for Asian Microgravity Pre-Symposium

The Measurement of Liquid Free Surface in Buoyant-Thermocapillary Convection by the Optical Grid Line Method

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Abstract

An optical grid line method with image correlation analysis processor has been developed for study of the kinetics of buoyant-thermocapillary convection, it gives out the information of liquid free surface of buoyant-thermocapillary convection in a rectangular cavity. In the present paper, the free surface deformations of the thin liquid layer and the thick liquid layer have been discussed and compared. The present experiment results prove that surface deformation is related with temperature gradient and the thickness of liquid layer. In other words that surface deformation depends on capillary convection and buoyancy convection.

1. Introduction

The Buoyancy convection is important flow in ground environment, and the thermocapillary convection is primary flow in microgravity environment, they are important to influence heat and mass transfer of fluid. Exploring the process of heat and mass transfer is available in controlling many materials growing, and obtaining the advanced materials. In ground experiment, the flow is the coupling of thermocapillary convection and buoyancy convection, it is generally named as buoyant-thermocapillary convection. When this convection occurs, surface deformation appears. It is important to research the phenomena for understanding the mechanism of fluid convection. The fluid interface is essential factor for forming the thermocapillary convection. In the transition process, the coupling of the interface and the convection expresses complicated physics mechanism.

Shu and Hu et al.[1)] studied the influence of free-surface deformation of a liquid bridge by optical diagnostics. Riley and Neitzel [2)] observed surface deformations using the shadowgraphy technique, and revealed the importance of surface temperature gradient. Ezersky[3)] observed unstable flow's free surface using shadowgraphic image, and detected the presence of flow-induced surface wave. Duan, Kang, and Hu[4,5)] systemically measured surface deformation and surface oscillation of buoyant thermalcapillary convection in a cavity, and studied their physical characteristics. Dabiri[6)] measured free surface deformation caused by near-surface turbulence, and it was concluded that energy was stored in surface deformation during the relaxation of deformation. The techniques of measuring large-deformation have been advanced. Leneweit[7)], Lapham[8)] and Saylor[9)] separately used the optical technique to measure fluid surface deformation in millimeter order of magnitude.

But measuring deformation in micron order is very difficult. In these experiments, a new optical diagnostic system with image processor has been developed. This system is made up of structure light system with optical grid lines. It gives out the displacement of free surface at both the central region and the edge region of the liquid free surface in a cavity, further more, it gives out the relation and the mechanism between the convection and surface deformation. As the temperature gradient increases, the liquid near the sidewalls will be higher and higher. The present experiment proves that surface deformation is related with temperature gradient and the thickness of liquid layer. In other words that surface deformation depends on capillary convection and buoyancy convection.

2. The experiment setup

In the present research work, the buoyant-thermocapillary convection consists of a rectangle cavity with open top as shown in **Fig. 1**. The horizontal cross-section of the cavity is 52mm×42mm. The two opposite lateral walls are made of transparent K9 glass for flow visualization. Other two opposite lateral walls are made of copperplates. There is silicon oil layer in the experimental cavity. One of the copperplates is heated by an electro-thermal film, and other one is cooled by semiconductor cooling sheet and a radiator. Temperature difference between the two copperplates in liquid layer will forms, which will be measured by thermocouple, and the hot side is controlled by DC power source. The bottom of the cavity is made from adiabatic materials, and it also can not reflect light.

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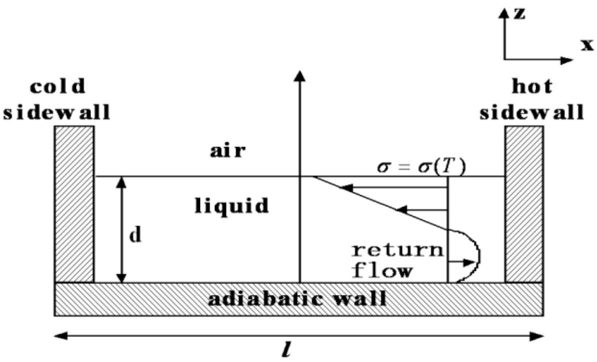


Fig. 1 The controlling system of the convection

In the present experiment, temperature difference is increased gradually, and the flow in liquid layer will develops from stable convection to un-stable convection and then to oscillatory state. Optical grid lines technique has been used to measure free surface deformation, in order to analyze the relation and the mechanism between the convection and surface deformation.

3. The optical grid lines method and image analysis system

An optical grid lines method has been designed, shown as in **Fig. 7**. A He-Ne laser beam passes through wollaston prism, wave slice, polarimeter and forms a baroque light with the grid lines. This baroque light passes through assembling lens, and focuses on liquid surface, and then reflects and comes to ground glass. The grid lines on the ground glass carry information of surface deformation caused by the buoyant-thermocapillary capillary convection. A CCD camera captures the grid lines images to the computer.

In order to calculate surface deformation from the grid line images, correlation analysis has been used. The subimage chosen from the image at 0°C temperature difference is expressed by a matrix $A(m,n)$, $0\leq m\leq Ma-1$, $0\leq n\leq Na-1$, $Ma=576$, $Na=720$. And $B(m+i, n+j)$ is the matrix which expresses the template image chosen from the image at another temperature difference (10℃, 20℃, 30℃, 40℃, 50℃), then $\rho(i, j)$ is the standard correlation function of *A* and *B*. *i, j* are the relatively pixel displacement when $\rho(i, j)$ get to maximum. (*m* ,*n*, *i, j*, *Ma*, *Na* have unit of pixel, $\rho(i, j)$ no unit.). Then we can get the grid line's excursion：

$$X = i/54 \tag{6}$$

The numeration of $\rho(i,j)$：

$$C(i,j) = \sum_{m=0}^{Ma-1}\sum_{n=0}^{Na-1} A(m,n)\ conj(B(m+i,n+j)) \tag{7}$$

$0\leq i < Ma+Mb-1$ and $0\leq j < Na+Nb-1$ $\quad Ma=576$, $Na=720$ (8)

$$\rho(i,j) = \frac{C(i,j)}{\sqrt{\sum_{m=0}^{Ma-1}\sum_{n=0}^{Na-1} A^2(m,n)}\sqrt{\sum_{i=0}^{Ma-1}\sum_{j=0}^{Na-1} B^2(m+i,n+j)}} \tag{9}$$

The grid line's excursion is *x*, the distance between the ground glass and liquid surface is *d* = 270mm, *x* and *d* is labeld in **Fig. 2**. the excursion angle of the lines is α = arctan（*x/d*）, surface excursion angle is $\beta = 0.5*\alpha$. The slope's alteration is $\Delta k = \tan(\beta)$; *k* is the slope of the surface at temperature difference of zero, so we get the last slope $K = k - \Delta k$; now we can get the curve of the liquid surface by integral formula. On the assumption that volume of the liquid is changeless, we can confirm the zero point. Then the height of liquid surface is confirmed.

4. The experimental results

In the present experiment, surface deformations of silicon oil layers in different thickness (h =3.5mm, 6.0mm) have been observed separately. Temperature difference between the two sides of the cavity is increased from 0°C to 50°C at the rate of 0.6°C/minute. The experiment results is shown in **Fig. 3** and **Fig. 4**. With the increasing of the temperature difference, the grid lines move to the right when the thickness of the liquid layer is 3.5mm, and the grid lines move to the left when the thickness of the liquid layer is 6.0mm. The movement stands for the changing of the liquid free surface, we can obtain the surface deformation of the convection by correlation analyzing the images.

The correlation analysis has been used to calculate the surface deformation of the convection. The subimage has been chosen from the image of **Fig. 3(a)**, and expressed by a matrix A(m,n), shown as in **Fig. 5(a)**. The template image has been chosen at the corresponding region in **Fig. 3(b)**, and expressed by a matrix B(m+i,n+j), shown as in **Fig. 5(b)**. According to the correlation analysis method, the similarest region with the subimage has been searched in the template image, and the correlation peak

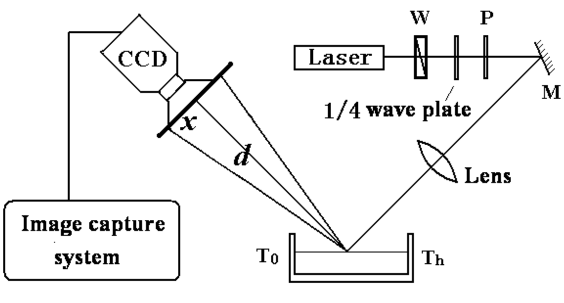
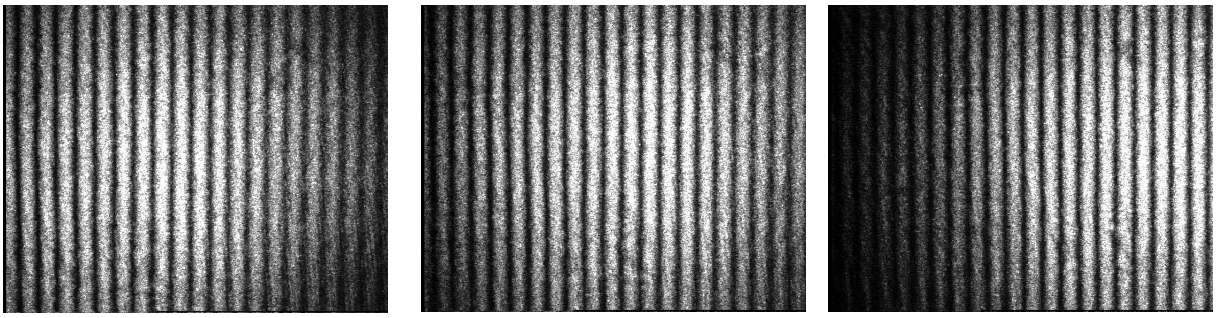
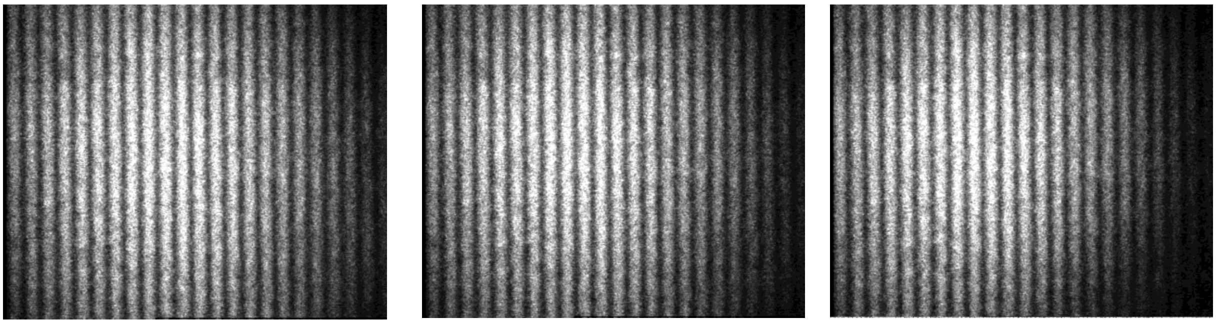


Fig. 2 The optical diagnostic system



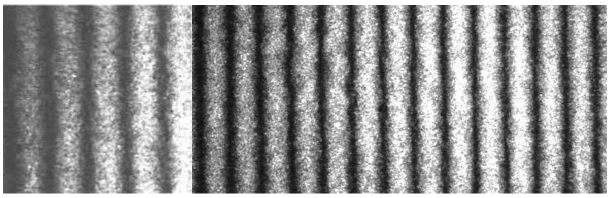
Δ T=0℃ Δ T=20℃ Δ T=50℃

Fig. 3 The grid line image of the thickness of the liquid layer h = 3.5mm



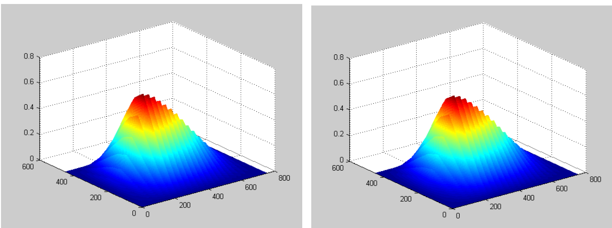
Δ T=0℃ Δ T=20℃ Δ T=50℃

Fig. 4 The grid line image of the thickness of liquid layer h = 3.5mm



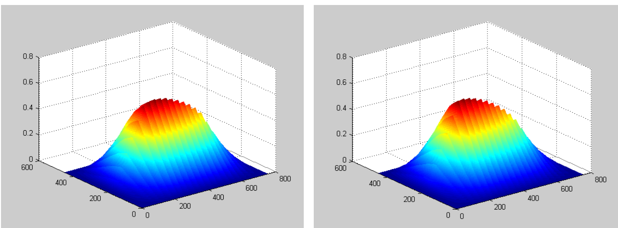
(a) the subimage at ΔT=0°C (200×200)
(b) the template image at ΔT=10°C (250×550)

Fig. 5 The subimage and the template image



(a) Δ T=0℃vs Δ T=20℃ (b) Δ T=0℃vs Δ T=50℃

Fig. 6 The correlation peak values (h = 3.5mm)



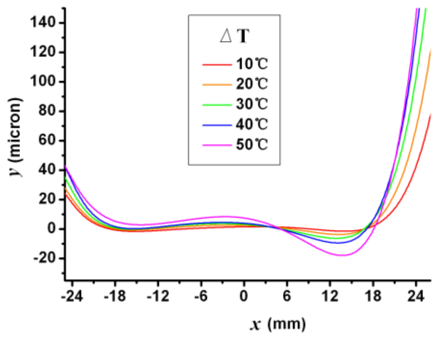
(a) Δ T=0℃vs Δ T=20℃ Δ T=0℃vs Δ T=50℃

Fig. 7 The correlation peak values (h=6.0mm)

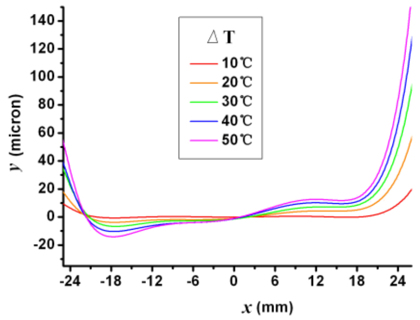
value between the images at the temperature difference 20℃ and 0℃ when the thickness of the liquid layer h = 3.5mm has been obtained, shown as in fig. **Fig. 6(a)**. The other correlation peak values have been shown as in **Fig. 6(b)** and **Fig. 7(a)**, and **Fig. 7(b)**. The calculate results express that the peak value moves to the right when the thickness of the liquid layer is 3.5mm, and the peak value moves to the left when the thickness of the liquid layer is 6.0mm.

According the geometrical relationship in the optical diagnostic system, the deformation on central line of the cavity for different thickness (h=3.5mm and h=6mm) of the liquid layer has been calculated, shown as in **Fig. 8**. First, the deformation is increased with the increasing of temperature gradient. The experiments also demonstrate the function of the capillary and buoyancy. For thin layer, the gradient of surface tension mainly controls the convection, in the central region, the cold side is higher than the hot side because of liquid moving from the hot side to the cold side with increasing temperature difference. For thick layer, buoyancy mainly controls the convection, in the central region, the hot side is higher than the cold side because of the effect of buoyancy convection.

In addition, it can be found that the liquid climbs up the sidewalls of the cavity, which is the soakage phenomenon between solids and liquids. And the thickness of the layers in both sides are higher and higher with the increasing of the temperature, shown as in **Fig. 8**, which is well-regulated.



(a) h = 3.5mm



(b) h = 6mm

Fig. 8 The deformation on central line for different thickness of layer by optical bar lines method

5. Conclusion

A grid line technique and a correlation analysis method have been developed to measure the free surface of the liquid. Surface deformation of buoyant-thermocapillary convection in a rectangular cavity with different temperature's sidewalls has been measured. With the increasing of temperature gradient, the liquid surface slant gradually, it's deformation has been calculated. The surface inclining direction is different between the convections in thin and thick liquid layer, which expresses the different functions of thermocapillary effect and buoyancy effect. In addition, the soakage phenomenon between solids and liquids influence the liquid free surface.

Acknowledgement

This work was supported by the National Nature Science Foundation of China (11032011, 10972224) and Knowledge Innovation Program of Chinese Academy of Sciences (KJCX2-YW-L08).

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(Received 21 Oct. 2010; Accepted 12 Sept. 2011)