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P01

加熱位置を考慮した薄液膜内温度差マランゴニ対流の抑制制御

Consideration of Heating Depth from Free Surface in the Control of Oscillatory Thermocapillary Convection in a Shallow Layer

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1. Introduction

Marangoni convection is induced by surface tension difference due to temperature and concentration difference on a free surface. "Thermocapillary convection", one of Marangoni convection, is caused by temperature difference. When the temperature difference increases on the surface, the flow transitions from steady to oscillating one at critical temperature difference. In this case, crystal growth rate changes and defects occur in single crystals. One of the causes is "Hydrothermal Wave instability1)" (Hereafter referred to as HTW), in which temperature oscillation propagates as thermal wave.

In this study, we aim to reduce the strength of HTW to suppress crystal defects. We investigate effect of heating timing on suppression of HTW and whether the change of the heating depth in the liquid layer affects the reduction.

2. Experimental Apparatus and Method

2.1 Geometry and Physical Property of Liquid Layer

Figure 1 shows the liquid layer to be investigated. The liquid layer is placed in a rectangular container. The left side wall of the container is heated, the right one is cooled. Then a temperature gradient is applied parallel to the free surface of the layer. The bottom, front and rear wall of the container are insulated thermally. Top is the free surface in contact with the atmosphere.

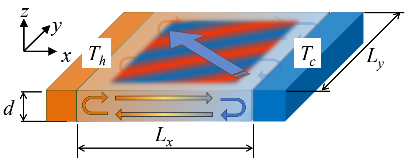

Fig. 1 The geometry of liquid layer.

Table 1　Physical properties of silicone oil (KF96L-1CS).

density ρ[kg/m^3]	818
viscosity μ [Pa·s]	8.18×10^{-4}
temperature coefficient of surface tension γ[N/(m·K)]	7.60×10^{-5}
thermal diffusivity α[m^2/s]	6.11×10^{-8}
Prandtl number Pr[-]	16.4

As shown in **Fig. 1**, the coordinate system on the liquid layer has x as temperature gradient, y as depth of the layer, and z as thickness direction respectively. The size of the liquid layer is defined as Lx: the temperature gradient direction, Ly: the depth direction, and d: the thickness direction respectively. The size were fixed at Lx = 30 mm and Ly = 50 mm. The temperature of the hot wall is Th, the temperature of the cold wall is Tc. So, the temperature difference ΔT between the heating and the cooling wall is ΔT = Th − Tc. A silicone oil of 1 cSt (Shin-Etsu Chemical KF96L-1CS) was used as the test fluid. The physical properties are shown in Table 1. Marangoni number MaL which indicates the strength of thermocapillary convection is defined below.

$$Ma_L = \frac{\gamma d^2 \Delta T}{\mu \alpha L_x} \quad (1)$$

2.2 Control System

A liquid layer is formed on the its forming device. Control devices are arranged around it. The forming device has a hot and a cold wall, then a temperature gradient can be applied in the horizontal direction along the free surface of liquid layer. Two thermocouples (φ 0.025 mm) is used to measure the temperature of HTW. A chromel wire (φ 0.025 mm,) is used as the line shaped heater for heating the liquid layer. Temperature data from all thermocouples are input to the control program of "LabVIEW". The timing of power output from the heater and arbitrary power can also be controlled on the same program.

2.3 Control Method

Figure 2 shows the bird view of the position of the heater and sensors to HTW. HTW is heated by the line shaped heater placed in or above the free surface. Temperature of HTW is obtained from the thermocouples in the layer. The heater is installed parallel to the HTW propagation angle. The region from the cold wall to the heater and the heater to the hot wall are defined as "upstream" and "downstream" respectively. The thermocouples A and B are located away from the heater in HTW propagation direction.

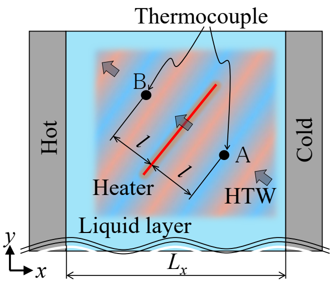

Fig. 2 Arrangement of heater and thermocouples (bird view).

When the effect of the heating timing on reduction of HTW was studied, the heater was placed slightly above the free surface and thermocouples were inserted slightly in the surface. The signal from thermocouple A was used for control input. The heater was turned on when the temperature of HTW at the heater location decreased below its average value. As shown in **Fig. 2**, the thermocouple A and the heater were placed at an appropriate interval, so the temperature signal is not directly affected by the heat input and delay time Td is required. Td was changed from 0 to 10 s.

When the effect of the heating depth on reduction of HTW was investigated, the heater and thermocouple A and B were moved together vertically by a micrometer. The surface of the liquid layer was defined as 0 mm in z direction. The depth of heater and thermocouples' location were changed by every 0.1 mm from 0 to 0.9 mm. A dimensionless depth Θ defined as Θ = 1 − z/d was introduced. A heater input was the voltage of sine wave which amplitude was from 0 to 2.5 Vpp and frequency was the same as the temperature oscillation of HTW.

The suppression of HTW was evaluated by the amplitude ratio of temperature oscillation A. The ratio was calculated by A = θ2/θ1, where θ1 and θ2 mean temperature amplitudes obtained by thermocouple B before and during control respectively.

3. Result

3.1 The Relation between Amplitude Ratio and Heating Timing

Each reference has a unique reference number. The reference number should be sequential in order of appearance. The reference number is described as a number with a right parenthesis, like [1)].

Figure 3 shows the amplitude ratio A when the Td is changed by every 0.2 s. After smoothing of the data, a periodicity of interpolated curve was found as about 2.5 s. The reason why the amplitude ratio A fluctuated every ± 2.5 s with respect to delay time is that the fluctuation coincided with the period of the temperature oscillation of HTW.

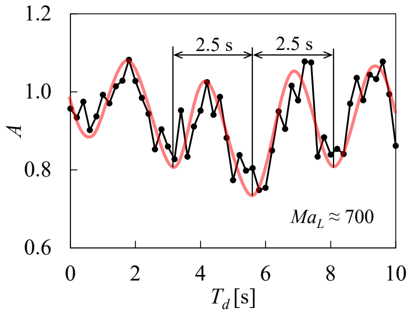

Fig.3 Amplitude ratio for various delay times.

3.2 The Relation between Amplitude Ratio and Temperature Amplitude

Figure 4(a) shows the amplitude ratio when the depth of the heater and the thermocouples were changed from Θ = 0 to 0.92. The amplitude ratio A was smallest at around Θ = 0.25 and was largest at around 0.75. **Figure 4(b)** shows the temperature amplitude of HTW. The temperature amplitude of HTW varied depending on the depth of the liquid layer and increases toward the centre of the liquid layer. From these result, we concluded that the temperature amplitude has little relation to the amplitude ratio A.

3.3 The Relation between Amplitude Ratio and Flow Velocity Distribution

The variation of amplitude ratio A to Θ are compared with the velocity distribution of the base flow of the thermocapillary convection. Since the fluctuation of data is larger in the upstream than that in the downstream, the amplitude ratio A in the downstream is only examined in detail. This is because the heat output from the heater is difficult to be conducted to the inside of the liquid layer and the influence of the noise of the thermocouples were relatively large. In **Fig. 4(a)**, it is clear that the difference between the amplitude ratio near the surface (Θ = 0 ~ 0.17) and other shallow regions (Θ = 0.17 ~ 0.33) is large. Figure 4(c) shows a theoretical curve of base flow velocity obtained by past experiments2). By comparing these figures, we found that the depth of U = 0 in z direction and of the minimum amplitude ratio A were almost same, and the tendency of variation in the A is similar to that of the flow velocity in the region where the velocity is in the negative direction. From these result, we concluded that the velocity distribution of base flow and the amplitude ratio A are closely related, and the base flow influence the amplitude ratio.

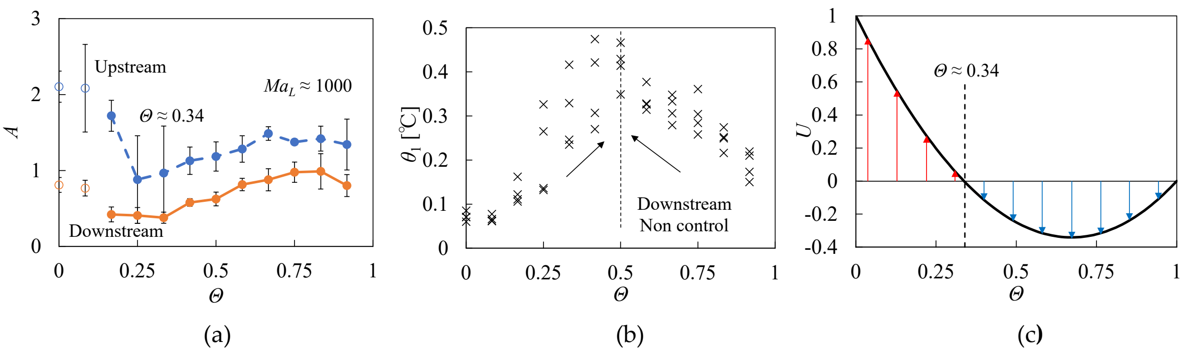

Fig.4 Comparison amplitude ratio (a), temperature amplitude (b) and theoretical curve of base flow velocity (c) with the liquid layer in various depth.

4. Conclusion

In this study, hydrothermal wave instability in thermocapillary convection in a thin liquid layer was controlled to suppress by a line shaped heater and sensors. The following conclusions were obtained.

(1) The delay time of the heating timing depended on the period of temperature oscillation of HTW.

(2) At all heating depths, the downstream amplitude ratio was below 1 and most of the upstream amplitude ratio was above 1.The downstream amplitude ratio depended on the heating depth in the liquid layer. In heating depth around the Θ = 0.25, strong suppression was realized. In the upstream amplitude ratio, the temperature amplitude increased regardless of the heating depth.

(3) The amplitude ratio was strongly depended on the velocity profile of base flow in thickness direction, but these had a little relation with the temperature amplitude profile of HTW.

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1) M.K.Smith and S.H.Davis: Journal of Fluid Mechanics, 132 (1983) 119.
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