P18

温度差マランゴニ対流を用いた液膜内部の対流制御

Control of Convection Inside a Liquid Film Using Marangoni Convection

小川秀真[1]，西野耕一[2]

Shuma OGAWA[1] and Koichi NISHINO[2]

1 横浜国立大学大学院理工学府，Graduate School of Engineering Science, Yokohama National University

2 横浜国立大学大学院工学研究院，Faculty of Engineering, Yokohama National University

1. Introduction

Marangoni convection is localized, small-scale flow caused by the surface tension gradient over a gas-liquid interface. The surface tension gradient is often given by the temperature difference between heating and cooling walls of the liquid container. The temperature difference can also be imposed by the local heating of liquid film surface. The purpose of this study is to see the effect of such local heating, both stationary and moving, on Marangoni convection in a liquid film. The local heating is provided by the irradiation of CO_2 laser beam, 2.4 mm in diameter, and the motion of the beam spot is controlled accurately with a two-axis traversing system. PIV measurements have been carried out to observe the generation and development of the Marangoni convection along the liquid film surface under the local heating. Various parameters such as moving speed, heating power, liquid film thickness and viscosity of liquid are examined.

2. Experiment

2.1 Experiment Equipment and Conditions

Figure 1 shows a schematic of the present experimental equipment for local heating of the liquid film (LF, hereafter). The LF container is 60 mm wide, 60 mm long and 20 mm high. It is made of acrylic plates except for the bottom which is made of an aluminum plate which is kept at a constant temperature (20 °C) using a Peltier device during each run of experiment. A CO_2 laser with a beam diameter of 2.4 mm and a full-angle beam divergence of 5.5 mrad is used to realize spot heating of the LF. The spot-heating position is controlled accurately using a two-axis traversing system (referred to as Auto-Stage, hereafter). Two mirrors are mounted on the X and Y carriers driven by the stepping motor systems whose step-wise displacement resolution is 0.36 mm with an accuracy of 0.1 mm. The laser beam is guided using the mirrors so that it hits the LF surface vertically from above.

For visualization and measurement of the convection in the LF, a light sheet is irradiated from the side of the LF container to illuminate the tracer particles suspended in the LF. A CW green laser (532 nm in wavelength) is used to generate a 1 mm thick light sheet. The tracer particles are nylon powder whose average diameter is 5μm. The flow in the LF is observed by capturing images with a high-speed camera (300 fps) from the position perpendicular to the light sheet.

The present experimental conditions are summarized in Table 1. The working fluid is silicone oil and two different viscosities, 5 and 10 cSt, are considered. The liquid film thickness is either 2 or 3 mm and the laser power chosen is either 0.6 or 0.9 W. The stage speed, which is the traversing speed of spot heating, is either 7.2 or 14.4 mm/s.

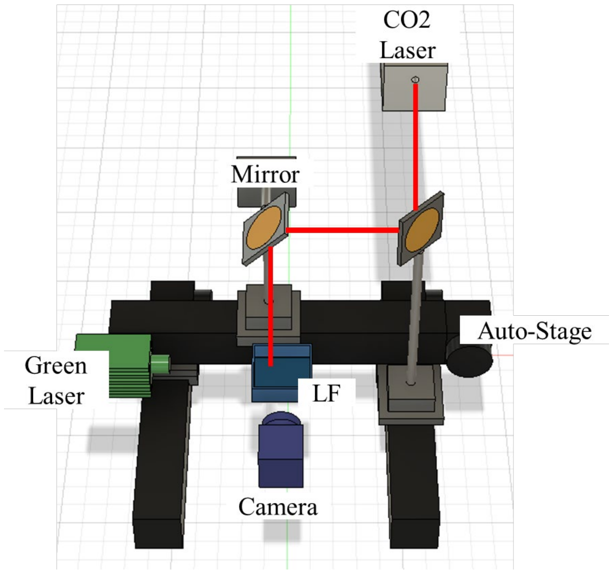

Fig.1 Schematic of the present experimental equipment

Table 1 Experimental conditions

Liquid film thickness ***D***	2, 3 mm
Kinematic viscosity ***ν***	5, 10 cSt
CO2 laser output ***P***	0.6, 0.9 W
Moving speed ***S***	7.2, 14.4 mm/s

2.2 Experimental Procedures

The experimental procedures are as follows.

(1) Supply silicone oil into the LF container using a micro-syringe until to the target LF thickness is achieved.

(2) Start irradiation of the laser light sheet to illuminate the tracer particles inside the liquid film, and the camera is focused.

(3) Start synchronous operation of the high-speed camera, the CO_2 laser and Auto-Stage by using an operation system consisting of Raspberry pi and Arduino. This operation begins with high-speed image capturing, followed by the motions of the mechanical shutter for the CO2 laser and Auto-Stage. A delay time 0.5 s is given between the image capturing and the motions to reduce undesired influences due to the power rise of the CO_2 laser.

(4) Traverse the spot heating in the x-direction until it travels 15 mm along the LF surface, as depicted in Fig. 2. schematically.

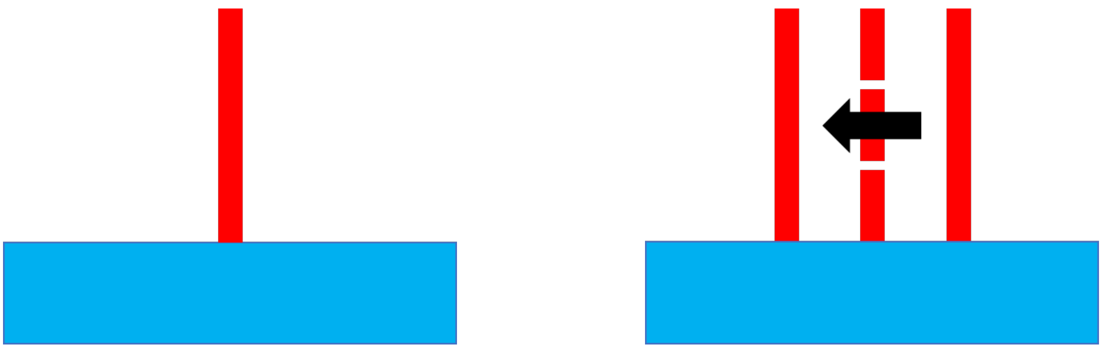

Fig.2 Schematic of spot heating and traversing of spot heating

An example of captured images is shown in Fig. 3. The LF is located in the area surrounded with a blue line, and the tracer particles are visualized as white dots. Standard PIV analysis is performed to extract information of instantaneous flow field. Figure 4 is a color contour of the velocity component in the x-direction. It is seen that strong positive and negative surface velocities exist along the LF surface while weak negative velocity exists in the interior of the most of the LF. The region of surface velocity to be discussed in detail in Chapter 3 is indicated by a red box superimposed on the color contour.

Time series of instantaneous velocity fields with a temporal resolution of 0.1 s and a spatial resolution of about 0.33 mm are obtained from the tracer particle images acquired at 300 fps. Figure 5 shows three profiles of instantaneous surface velocity obtained from separate runs of experiment where the LF thickness is 3 mm, the viscosity is 5cSt, the moving speed is 14.4 mm/s and the laser power is 0.6 W. Three profiles agree reasonably well with each other, thus demonstrating good reproducibility of the present experiment and measurement. The discussion of the results to be presented in Chapter 3 is based on the average of the three measurements such as shown in Figure 5.

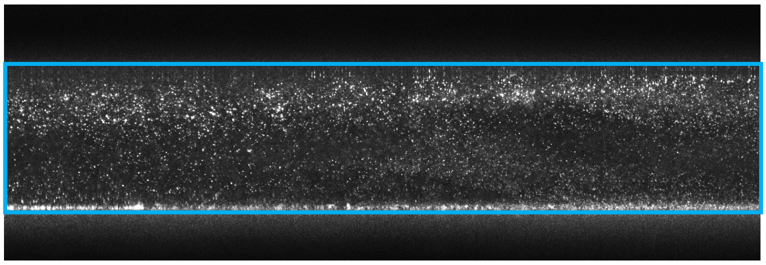

Fig.3 Example of captured images.

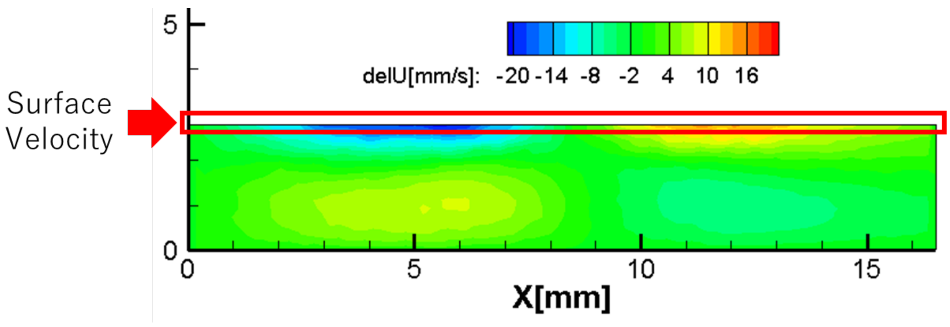

Fig.4 Result of PIV analysis showing a color contour of the velocity component in the x-direction. A red box defines the surface region.

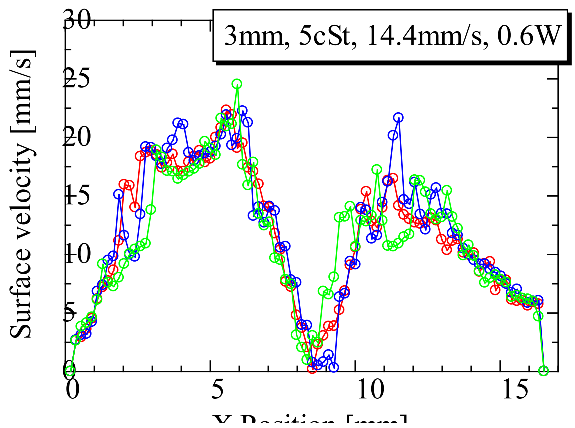

Fig.5 Three profiles of instantaneous surface velocity to indicate its reproducibility.

3. Result and Discussion

The imaging range of the flow is about 16 mm, and the moving distance is about 15 mm. Moving spot heating is discussed for the flow when the moving distance is about 7.5 mm (when the CO2 laser is irradiated in the middle of the imaging range). The discussion is about the surface velocity at which the driving force, surface tension, acts. Surface for measurement is 0.33 mm depth from the liquid film surface.

3.1 Stationary Spot Heating vs Moving Spot Heating

Compare stationary spot heating and moving spot heating for the case of D = 3 mm, v = 5 cSt, P = 0.6 W. And the moving spot heating is S = 14.4 mm/s and the direction of motion is left (X is negative). Figure 6 shows stationery spot heating at 0.1 s and 0.2 s and moving spot heating, and Figure 7 shows at 0.3s and 0.4s and moving spot heating. In the case of moving spot heating, the flow in the direction of moving is referred to as the "flow in the advancing region", and the flow after moving is referred to as the " flow in the retarding region". In stationary spot heating, the flow is distinguished by the irradiation time. For example, if the flow is after 0.1 second, it is described as "0.1 s flow".

[Regarding Moving Spot Heating]

The surface velocity and flow range in the advancing region is higher and wider than those in the retarding region. The temperature difference of the advancing region is larger than in the retarding region because the CO2 laser advances into the advancing region. Therefore , the difference in surface tension on the advancing region is larger and the flow velocity in the advancing region is higher. In addition, since the flow is pushed in the direction of the CO2 laser, the range of the flow in the advancing region is wide.

[Flow in the Advancing Region vs Stationary Spot Heating]

The magnitude of velocity in the advancing region is large, close to 0.1 s flow. The flow in the advancing region is like the 0.1 s flow, the velocity is higher because the unheated area is heated rapidly. However, the range of the flow is wider on flow in the advancing region. This is because the left-side flow is already flowing before it reaches the heating point.

[Flow in the Retarding Region vs Stationary Spot Heating]

The surface velocity in the retarding region is almost the same as the 0.3 s and 0.4 s flows. That is the flow after the CO2 laser passes through, and like the 0.3 s and 0.4 s flow, it is thought that the temperature difference is small due to sufficient heating.

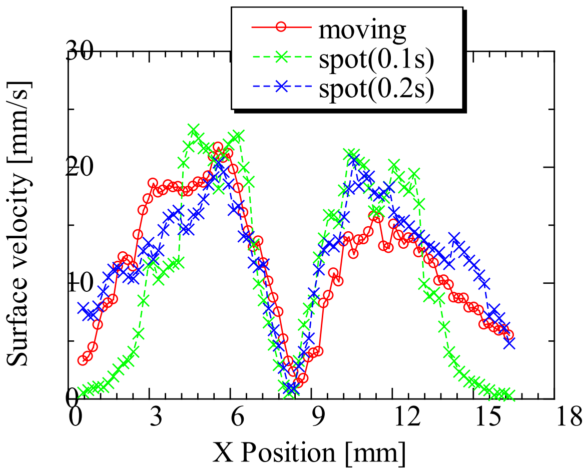

Fig.6 Comparison between moving spot heating and stationary spot heating at 0.1 s and 0.2 s.

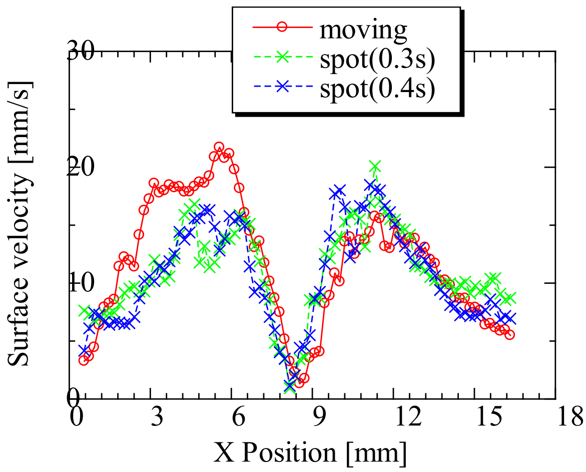

Fig.7 Comparison between moving spot heating and stationary spot heating at 0.3 s and 0.4 s.

In the discussion that follows, comparisons will be made with moving heating when thickness, kinematic viscosity, power, or moving speed is varied, and with stationary spot heating under the same conditions. Stationary spot heating basically shows 0.1 s flow where the flow velocity is maximum and 0.4 s flow. The reason why the 0.4 s flow is shown is that the light path in the experiment is about 600 mm, so the beam diameter is about 5.7 mm. If the heating area by the laser is within this beam diameter, the time required for a point to be heated is about 0.4 s (for S = 14.4 mm/s).

3.2 Effect of Moving Speed

The experimental results for the case of D = 2mm, v = 5cSt, P = 0.6W, S = 7.2 mm/s are shown in Figure 8 and 9. The red dots and lines are the results under those conditions.

[Flow in the Advancing Region vs Stationary Spot Heating]

The surface velocity in the advancing region is smaller than 0.1 s flow because the moving speed is slower and the heating is not as rapid. The maximum surface velocity in the advancing region is almost the same as the 0.8s flow. But the flow range in the advancing region is wider than stationary spot heating. It's because the flow in the advancing region has been pushed out.

[Flow in the Retarding Region vs Stationary Spot Heating]

The surface velocity in the retarding region is very similar to the 0.8 s flow. As in 3.1, because it is sufficiently heated after passing through the CO2 laser and the flow is calm.

[Comparison of moving heating with different moving speed]

The flow in the retarding region has little effect on velocity and is almost the same. In the flow in the advancing region, the faster the moving speed, the greater the surface velocity. And if the moving speed is slow, the range of flow is wide. When the liquid film surface is sufficiently heated, the maximum velocity slows down and the flow range becomes wider. When the moving speed is slow, the heating is long. Therefore, the results shown in Figure 9 is obtained.

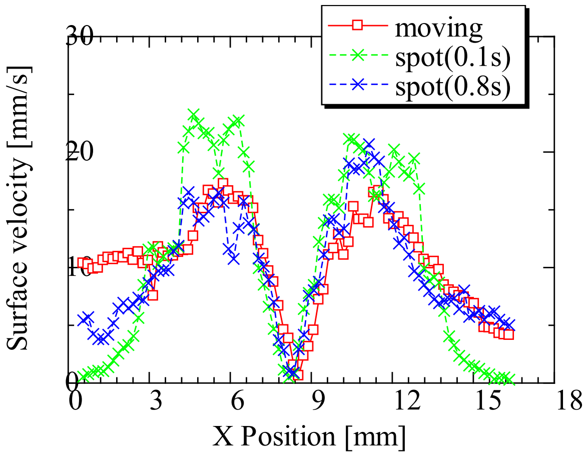

Fig.8 Comparison between moving spot heating and stationary spot heating at 0.1 s and 0.8 s.

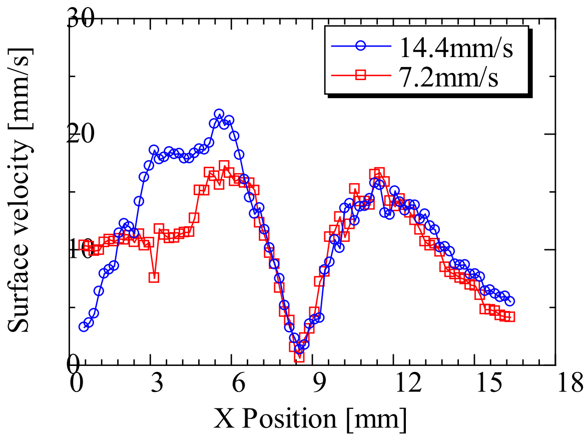

Fig.9 Effect of moving speed on the surface velocity.

3.3 Effect of Laser Power

The experimental results for the case of D = 2mm, v = 5cSt, P = 0.9W, S = 14.4 mm/s are shown in Figure 10 and 11. The red dots and lines are the results under those conditions.

[Flow in the Advancing Region vs Stationary Spot Heating]

For P=0.9W, the flow in the advancing region shows a similar trend to the 0.1 s flow. The maximum flow velocity in the advancing region is like that of 0.1 s flow. The range of the flow is about 1.2 mm wider for the flow in the advancing region.

[Flow in the Retarding Region vs Stationary Spot Heating]

The right-side flow is close to the 0.4 s flow. The reason for this is that it is heated sufficiently, like 3.1.

[Comparison of moving heating with different laser output]

The effect of laser power is apparent in the advancing region. The magnitude of the surface velocity is about the same for both 0.9 W and 0.6 W. But the flow range of 0.9 W in the advancing region is wider than the flow range of 0.6 W. When the laser power is large, the range of high laser intensity is extended. Therefore, the effective heating area becomes larger. In the case of laser power of 0.9 W, the temperature difference occurs in wider range, and the range of flow in the advancing region becomes wider than laser power of 0.6 W. and the ratio of the flow ranges is about 0.9 W/0.6 W = 4.8/3.0 = 1.6. The ratio of the heating area at an intensity of 0.6 W beam diameter is 0.9 W/0.6 W = 1.09 which implies that the actual heating area is narrower than the beam diameter.

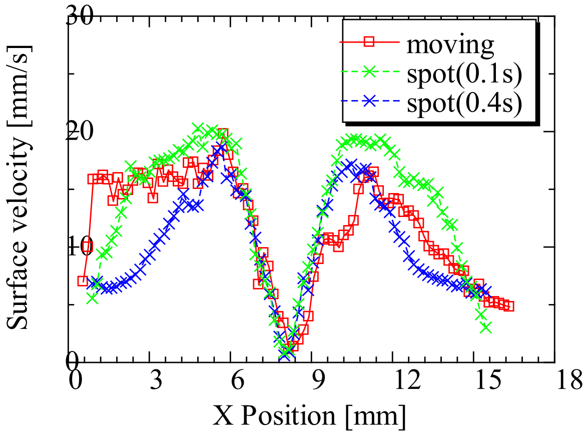

Fig.10 Comparison between moving spot heating and stationary spot heating at 0.1 s and 0.4 s.

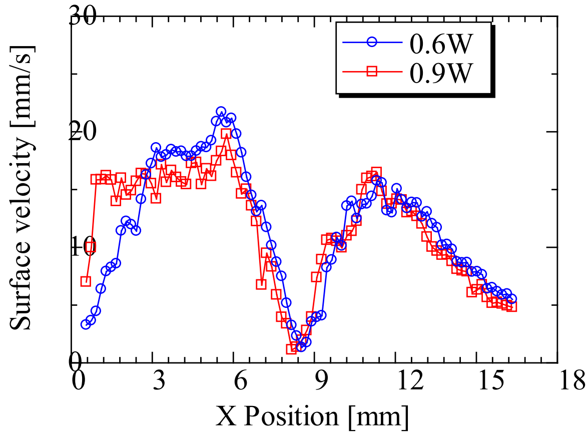

Fig.11 Effect of laser power on the surface velocity.

3.4 Effect of Liquid Film Thickness

The experimental results for the case of D = 2mm, v = 5cSt, P = 0.6W, S = 14.4 mm/s are shown in Figure 12 and 13. The red dots and lines are the results under those conditions.

[Flow in the Advancing Region vs Stationary Spot Heating]

For D=2mm, the surface velocity in the advancing region is like the 0.4 s flow, although the surface velocity is a little larger. Because of the narrow imaging range, it is not possible to determine which has a wider range of flow, so future experiments with a wider imaging range will be necessary.

[Flow in the Retarding Region vs Stationary Spot Heating]

The surface velocity in the retarding region is like the 0.4 s flow near the laser irradiation point. But the velocity is smaller than the 0.4 s flow away from the laser irradiation point. Where the laser irradiation points are far away from each other, the temperature gradient becomes smaller because the heating area is farther away. In the case of LF thickness of 2 mm, this effect is likely to occur.

[Comparison of moving heating with different thickness]

Similarly in stationary spot heating, the flow velocity becomes slower overall when LF thickness is small. However, both surface velocity in the advancing and retarding region show the same tendency even if the thickness is changed. While showing a similar trend, the flow range is wider when the thickness is smaller.

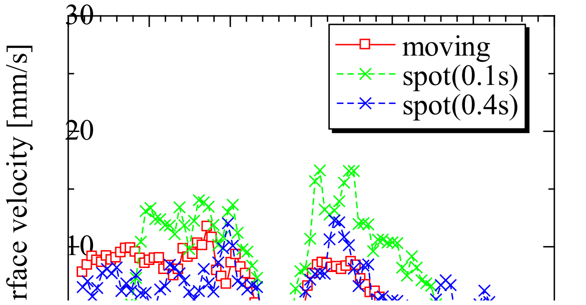

Fig.12 Comparison between moving spot heating and stationary spot heating at 0.1 s and 0.4 s , where the LF thickness is 2 mm.

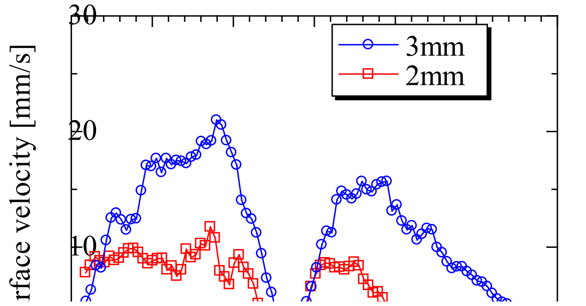

Fig.13 Effect of LF thickness on the surface velocity

3.5 Effect of Kinematic Viscosity

The experimental results for the case of D = 3 mm, ν = 10 cSt, P = 0.6 W, S = 14.4 mm/s are shown in Figure 14 and 15. The red dots and lines are the results under those conditions.

[Flow in the Advancing Region vs Stationary Spot Heating]

The surface velocity in the advancing region is the same as 0.1 s flow. In addition, the range of the flow is almost identical to that of the 0.1 s flow, which is a different feature from 3.1,2,3 and 4. This is thought to be because a higher kinematic viscosity has less effect on pushing the flow in the direction of movement.

[Flow in the Retarding Region vs Stationary Spot Heating]

The surface velocity in the retarding region is slower than that of 0.4 s flow. This is also a different feature from 3.1,2,3 and 4, where the effect of viscosity is high.

[Comparison of moving heating with different kinematic viscosity]

High kinematic viscosity slows down the overall flow velocity due to its high viscosity. The flow range also becomes narrower with higher kinematic viscosity.

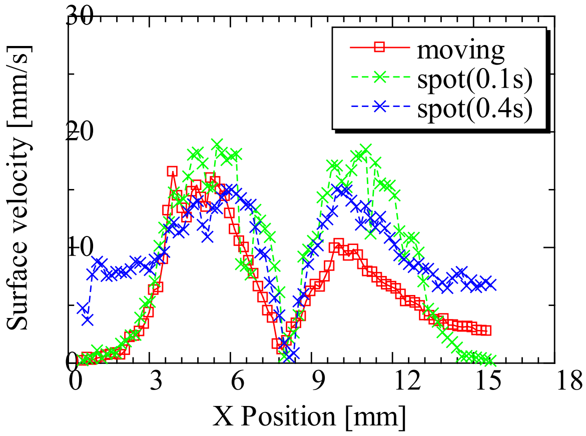

Fig.14 Comparison between moving spot heating and stationary spot heating at 0.1 s and 0.4 s , where the kinematic viscosity is 10 cSt.

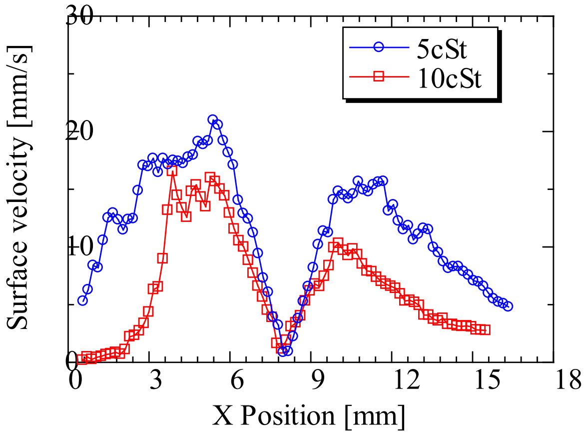

Fig.15 Effect of kinematic viscosity on the surface velocity.

4. Conclusion

A series of experiments and PIV analysis have been conducted to understand the effect of moving spot heating on the flow field of temperature-driven Marangoni convection in a liquid film. This understanding is utilized for the control of Marangoni convection in a liquid film. The spot heating is given by the irradiation of a CO_2 laser beam and the spot-heating position is moved accurately by the use of a two-axis traversing system. Various parameters such as moving speed, heating power, liquid film thickness and viscosity of liquid are examined. The stationary spot heating generates an axisymmetric surface flow along the liquid surface in the direction away from the heating spot. This surface flow develops with time after the start of heating, thus referred to as 0.1 s flow, 0.2 s flow and so on to indicate the elapsed time after the start of heating. The moving spot heating generates a non-axisymmetric surface flow which is represented by the flows in the two regions, i.e, an advancing region and a retarding region. The advancing region is located in front of the moving spot heating and therefore the surface flow in this region has the same direction as the motion of spot heating. On the other hand, the surface flow in the retarding region has the opposite direction to the motion of spot heating. The present observations and measurements may be summarized as follows:

(1) The characteristics of the retarding flow are similar to those for the axisymmetric surface flow at 0.4 s generated by the stationary spot heating. This observation holds true regardless of the moving speed, the heating power, the liquid film

thickness and the viscosity of liquid. The axisymmetric surface flow at 0.4 s can be regarded as the flow subjected to sufficient heating.

(2) The maximum surface velocity in the advancing region is almost the same as that of the 0.1 s flow generated by the stationary spot heating, but the advancing region is wider than the region for the stationary spot heating where the liquid film thickness is 3mm, the viscosity if 5 cSt, the laser power is 0.6 W and the moving speed is 14.4 mm/s.

(3) The magnitude of the surface flow in the advancing region decreases with decreasing moving speed and approaches that for 0.8 s flow for the stationary spot heating.

(4) The advancing region gets wider with the laser power, as expected from the fact that the effective heating area for moving spot heating becomes more elongated.

(5) Decrease of the liquid film thickness results in the decrease of the magnitude of the surface flow but in the increase of the width of advancing region.

(6) As the kinematic viscosity increases, increase of the viscosity of the silicone oil results in the decrease of both the magnitude of the surface flow and the width of the advancing and retarding regions. And when the kinematic viscosity is high, the flow range in the advancing region is the same as that of stationary spot heating.