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(Original Paper)

Effect of Surface Temperature Profile on Surface Velocity Distribution of Marangoni Convection in High Pr Liquid Bridge

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Abstract

Marangoni Convection transits from laminar to oscillatory flow under the certain temperature difference. Recently, it is shown that the transition condition is significantly affected by the heat transfer at the free surface. It should have occurred that the driving force is changed as a result of the surface temperature variation due to the surface heat loss. Marangoni convection induced in a half-zone liquid bridge is observed to investigate the relation between the surface temperature distribution and onset condition of oscillatory flow with changing relative temperature range of liquid bridge against the ambient temperature. Critical Marangoni number is clearly reduced in larger heat loss. In this regime, the surface temperature distribution is also changed

Keyword(s): Thermocapillary Convection, Liquid Bridge, Heat Transfer.
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1. Introduction

It is well known that Marangoni convection transits from steady to oscillatory when the driving force becomes strong. Onset of the oscillatory convection depends on the parameters such as the Parandtl number, aspect ratio, and volume ratio to the right liquid column[1)].

Another important parameter is the Biot number, which is non-dimensional parameter to indicate the quantity of heat transfer at the free surface[2-4)].

Recently, the onset condition is found to be quite susceptible to the surface heat transfer. It was clarified that Critical Marangoni number rapidly decreased for $Bi_{ave} < 0.7$, and was constant for $Bi_{ave} > 0.7$ by Y. Kamotani *et al*[2)]. It was considered that the surface temperature was changed by heat transfer. However, the mechanism is not clarified yet.

So, we focus on the relationship between the surface temperature formation and surface velocity profile near the onset of oscillatory flow when the heat transfer conditions at the free surface changes. The liquid bridge configuration with high Prandtl number (Pr = 68) was employed to observe Marangoni convection in our experiments. In order to vary the heat transfer at the free surface, relative temperature difference between the mean temperature of liquid bridge and the ambient gas temperature was changed. The surface temperature distribution was observed by an infrared imager, and the surface velocity was measured by a velocimetry using the photochromic method. The critical temperature difference became smaller with increasing the heat transfer from liquid bridge to ambient gas. By changing the surface temperature distribution, the surface velocity was affected. Surface velocity becomes faster due to by large heat loss. In this study, we compare the surface temperature distribution, the surface velocity distribution, and the internal flow velocity for two different heat transfer conditions.

2. Experimental Apparatus and Conditions

An experimental setup is illustrated in **Fig. 1**. The liquid bridge is retained vertically between the circular disks having a diameter D = 10 mm. In order to impose the temperature difference between the upper and lower ends of the liquid bridge, the upper disk is heated by a nichrome wire and the lower disk is cooled by a Peltier device. Temperature of each disk surfaces is measured by thermocouple. The upper and lower disks are made of aluminum. Fine particles with diameter of 5 ~ 25 μm are mixed in the fluid for the flow visualization (Matsumoto Microsphere MHB-R). A thermocouple with a fine gage wire of 0.25 μm diameter is employed to detect the minute temperature fluctuation at quite vicinity of the free surface.

Marangoni number Ma, which is a dimensionless number indicating the strength of the Marangoni convection, is introduced in Eq (1):

$$Ma = \frac{\sigma_T \Delta T L}{\rho \nu \bar{\kappa}}, \tag{1}$$

where σ_T is the temperature coefficient of surface tension, ΔT

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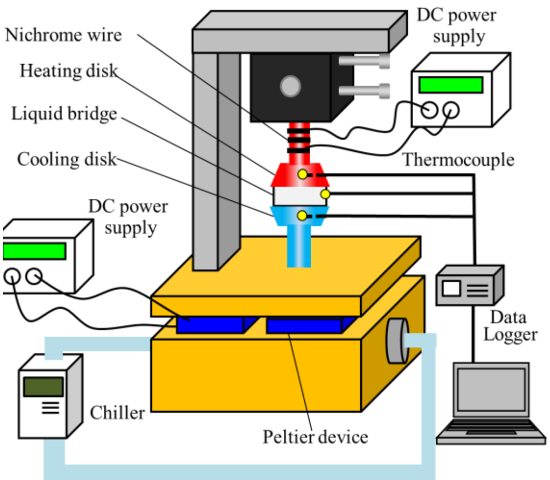

Fig. 1 Schematic of experimental apparatus.

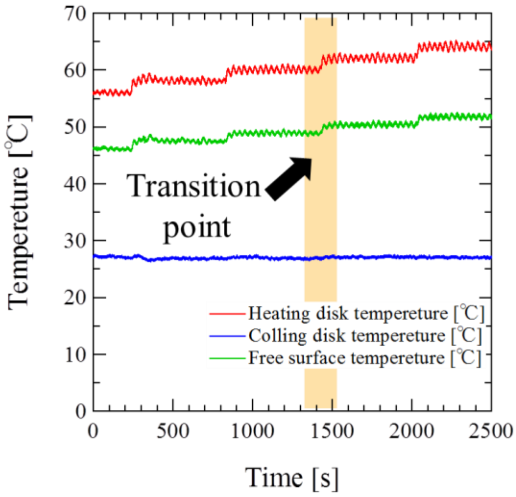

Fig. 2 Time series of temperature at liquid bridge ends and free surface.

temperature difference between upper and lower disk surfaces, L liquid bridge height, ρ density of liquid, $\bar{\nu}$ average kinematic viscosity between upper and lower disks, and κ the temperature diffusivity. Marangoni number at the onset of oscillatory convection is called the critical Marangoni number Ma_{cr}.

In this experiment, the liquid bridge height L is fixed at 2.5 mm, so that the aspect ratio ($Ar = L / D$) is 0.25. Volume ratio Vr is adjusted to 0.95, which is the ratio of actual volume against the true cylinder volume of a liquid bridge. We define the average temperature T_{ave}, as $(T_h + T_c)/2$, where T_h is the upper disk surface temperature and T_c is the lower one. In this experiment, relative temperature difference between the ambient gas temperature T_a and liquid average temperature T_{ave} is changed to investigate the effect of heat loss at the free surface. Increasing (T_{ave} - T_a) means an increase of the heat loss from the liquid bridge surface to the surrounding gas.

3. Experimental Results and Discussions

3.1 Oscillatory Flow Transition

In order to transit from steady flow to oscillatory one, the temperature difference ΔT is increased. In this study, the cooling disk temperature is kept constant at 27 [°C] and the heating disk temperature is raised stepwise by 2 [°C] increments. Time series of the temperature at heating-disk and cooling-disk surfaces, and at near free surface, is shown in **Fig. 2**.

Time variation of free surface temperature is analyzed by short time FFT. The spectrogram is shown in **Fig. 3**. A clear peak in frequency of 0.85 [Hz] appears after time of 1500 [s]. It can be considered that a transition point exists in the vicinity of starting point of peak appearance. Therefore, an average value of the temperature difference, ΔT in the time from 1470 to 1530 [s] is estimated. We determine a critical temperature difference ΔT_{cr} and Ma_{cr} by Eq (1). **Figure 4** shows the relationship

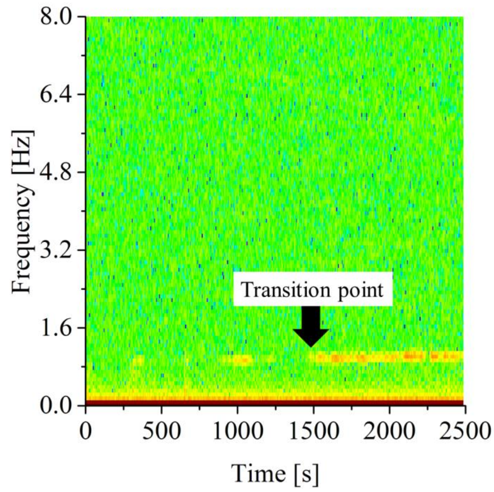

Fig. 3 Spectrogram of surface temperature by short-time FFT.

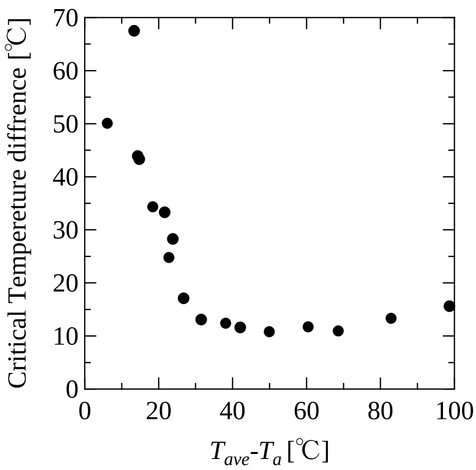

Fig. 4 Effect of (T_{ave}-T_a) on critical temperature difference.

between ΔT_{cr} and (T_{ave} - T_a).

We introduce the average Biot number, Bi_{ave}, defined by Eq. (2) as a dimensionless number indicating the heat loss[2]:

$$Bi_{ave} = \frac{Q}{2\pi Lk\Delta T}, \tag{2}$$

where Q is the total heat flux in the liquid interface, L liquid bridge height, k thermal conductivity of the liquid, and ΔT temperature difference between the upper and lower disks. Q is estimated by the measured radial temperature distribution from the surface to the circumstances and thermal conductivity of the circumstances.

Bi_{ave} was calculated with (T_{ave} - T_a) = 17, 25, 30, 55, 76 [°C], in **Fig. 4**. **Figure 5** shows the relationship between Ma_{cr} and Bi_{ave}. Ma_{cr} sharply decreases for Bi_{ave} < 1.3 and subsequently increases slightly for Bi_{ave} > 1.3. It was due to the sharp decrease for Bi_{ave} < 1.3 and almost no change for Bi_{ave} > 1.3 of the critical temperature. Since Bi_{ave} is estimated with the heat loss from the liquid bridge surface, Ma_{cr} is significantly affected by the heat loss for Bi_{ave} < 1.3. It indicated that oscillatory flow easily appeared with lower heat loss (Bi_{ave} < 1.3). The heat loss will surely change the surface temperature distribution. Then, the surface velocity should vary as a result of the surface driving force change. So we investigate the surface temperature distribution, the surface flow velocity distribution, and the internal flow velocity at Bi_{ave} of both 0.55 and 1.27 when the temperature difference is set the 90 % of each critical temperature difference ΔT_{cr}.

3.2 Surface Temperature Distribution

The surface temperature distribution was observed by an IR camera. The measurement results obtained by IR camera are calibrated by thermocouple at the upper and lower disks. **Figure 6** shows vertical temperature distribution normalized by temperature difference ΔT. We introduce the dimensionless surface temperature, T^*, defined by Eq. (3):

$$T^* = \frac{T_s - T_c}{\Delta T} = \frac{T_s - T_c}{T_h - T_c}, \tag{3}$$

where T_s is the measurement temperature along center line of the liquid bridge. The dimensionless surface temperature is lowered in the case of higher heat loss (Bi_{ave} = 1.27) compared with lower heat loss around normalized position from 0.1 to 0.9. The temperature gradient becomes larger in the wide area of liquid bridge surface. It was considered the liquid surface is cooled with increasing the heat loss. Consequently, it was found that the local driving force is affected by the heat loss at the liquid surface.

3.3 Surface Velocity Distribution

A photochromic dye activation technique is employed to measure the velocity at the liquid bridge surface. The technique is the method to obtain the instantaneous velocity distribution

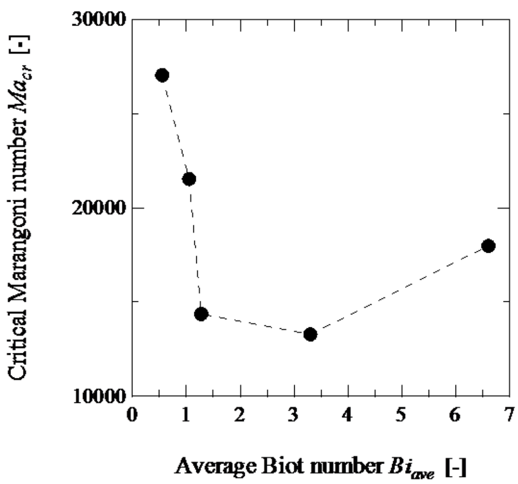

Fig. 5 Effect of Bi_{ave} on critical Marangoni number Ma_{cr}.

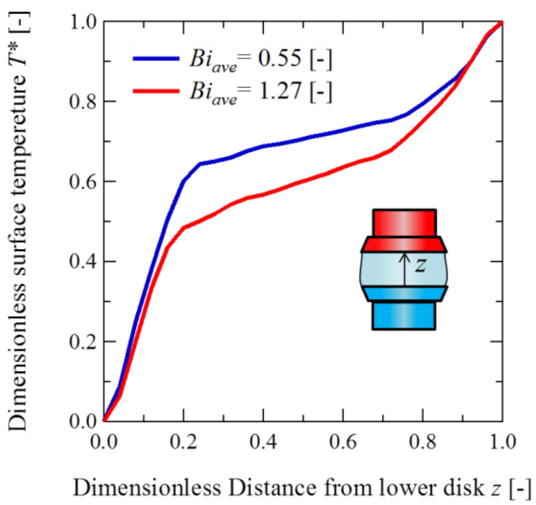

Fig. 6 Surface temperature distribution.

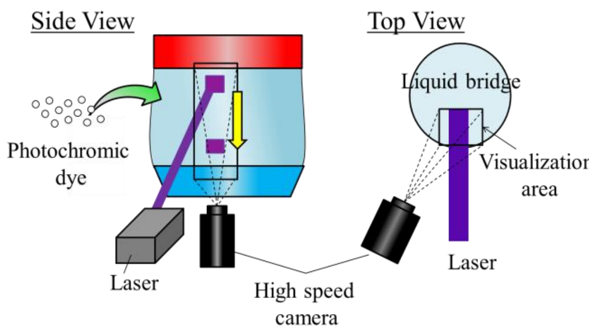

Fig. 7 Schematic of experimental apparatus for photochromic method.

by tracing the local change of the color line in the liquid including TNSB[5]. The pulse GN2 laser beam with 0.2 mm spot diameter is irradiated to the targeted position on liquid bridge surface. The color of the liquid surface is changed by the laser beam. An experimental setup is illustrated in **Fig. 7**.

The velocity is evaluated by tracking the tip of colored surface in each time (**Fig. 8**), where 0 [s] is the moment to have hit the laser on the surface. Then the tip positions moved to the cooling disk direction. The surface flow velocity distribution is shown in **Fig. 9**. In the case of Bi_{ave} = 1.27, faster surface velocity from the vicinity of the heating disk toward the cooling disk is observed. As a result, it is suggested that the surface velocity can be evaluated by not only the temperature difference ΔT of the liquid bridge upper and lower ends but also the local temperature difference.

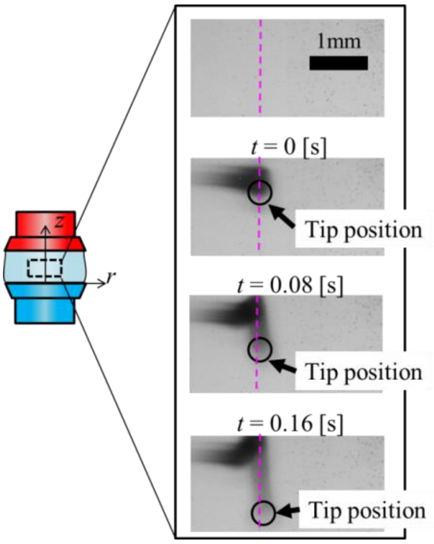

Fig. 8 The surface flow visualization image on the liquid bridge.

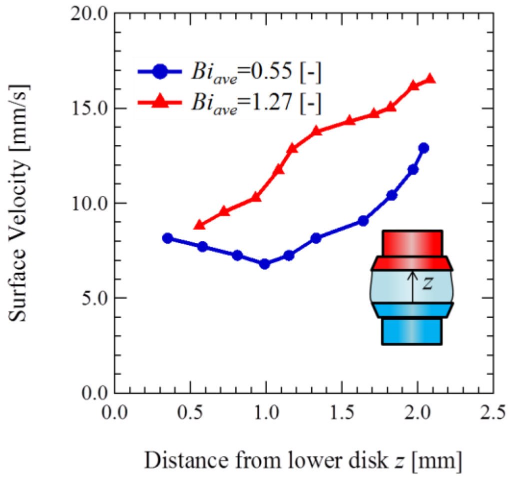

Fig. 9 The surface velocity distribution.

Also, it was found that the surface velocity corresponds to the changes in the local temperature difference between the upper and the lower end vicinity (z > 0.1 and z < 0.9).

3.4 Internal Flow Velocity

The internal flow velocity of a vertical cross section is visualized via a high-speed video camera. The sheet laser is illuminated the liquid bridge. The velocity vector field for 2 [s] was shown in **Fig. 10**. The internal velocity for the case of Bi_{ave} = 1.27 is faster than one of 0.55. It is considered that, since the surface velocity is faster than smaller Bi_{ave} as shown in **Fig. 9**, the internal flow velocity is therefore similarly fast. The radial velocity of the return flow is also accelerated. Path lines for 1 [s] are shown in **Fig. 11**. A vortex structure for the case of Bi_{ave} = 1.27 becomes wider toward the radial direction than one of 0.55.

3.5 Effect of Heat Loss on the Oscillatory Flow Transition

The critical temperature difference significantly deviated between two average Biot numbers Bi_{ave}. Even though, the surface velocity and the internal flow velocity are fast in case of larger Biot number.

The local temperature gradient along the vertical direction becomes larger when the heat loss increases. Then the driving force of convection is strong and it destabilizes flow.

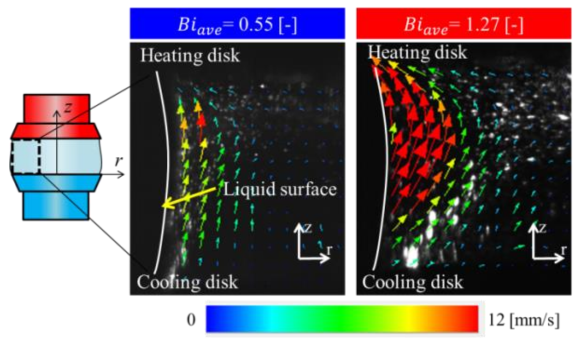

Fig. 10 The velocity field of the internal liquid bridge.

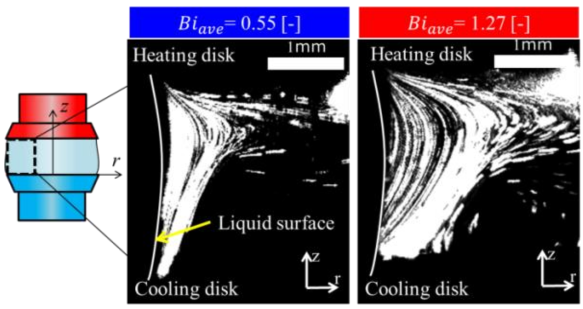

Fig. 11 The path line of the internal liquid bridge.

4. Conclusion

We investigated the effect of heat loss on the oscillatory flow transition point. Then Ma_{cr} decreased with increasing the heat loss for $Bi_{ave} < 1.3$, and increased with increasing the heat loss for $Bi_{ave} > 1.3$. each other. In order to investigate the effect of heat loss on the flow field, we compared the relation among the surface temperature distribution, the surface velocity distribution, and the internal flow for $Bi_{ave} < 1.3$. As a result, it was suggested that, when the local temperature difference in the bridge height direction is changed by reduced surface temperature due to increased heat loss, the transition point (to oscillatory flow) changes responding to the change in the surface flow velocity distribution and the internal flow velocity.

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