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液柱内温度差マランゴニ対流における表面温度場の乱雑性の発達

Entropy of Surface Temperature Fluctuations on Marangoni Convection in Liquid Bridge

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1. Introduction

The floating zone method is used in the production of high-purity crystals. In this manufacturing process, it is important to understand the flow behavior which results in significant effects on crystal quality. The Marangoni convection induced by the driving force of the surface tension gradient might also be a factor in degrading the quality[1)]. As a basic study to understand the characteristics of Marangoni convection, we performed microgravity experiment in a half-zone (HZ) liquid bridge onboard the International Space Station (ISS). The microgravity provided by ISS has very good experimental environment for observing Marangoni convection, as the buoyancy effect disappears. In the past, as a study on the transition to the chaotic flow in the HZ liquid bridge, Matsugase *et al.* analyzed the temperature fluctuation at the specific point of the free surface of the liquid bridge and confirmed the transition to the chaotic flow[2)], but there are few detailed knowledges about the spatial temperature field so far. In this study, for the purpose of elucidating the chaotic characteristics, we observed the spatiotemporal variation of the surface temperature with an infrared (IR) camera and investigated the transition process to the chaotic flow.

2. Experimental Method

The experiment was performed under microgravity condition in the Japanese Experiment Module (Kibo) on the ISS. A schematic of the liquid bridge setup is shown in **Fig. 1**. A liquid bridge with diameter D of 50 mm and length L of 25 mm was formed between heating and cooling disks. The aspect ratio ($AR = L / D$) is 0.5. Temperature difference ΔT is applied between both end surfaces of the liquid bridge to generate Marangoni convection. The cooling disk temperature T_C was kept constant at 20 °C, and the heating disk temperature T_H was decreased from 70 to 20 °C. The surface temperature was observed by the thermal infrared camera with a bit depth of 8 bit per pixel (bpp). The test fluid was 5 cSt silicone oil. The physical properties are shown in **Table 1**.

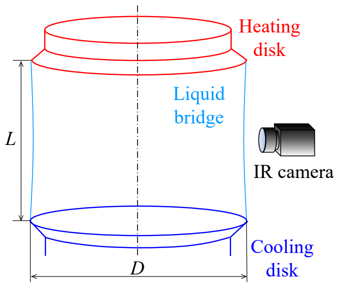

Fig. 1 Schematic diagram of liquid bridge setup

Table 1 Physical properties of silicone oil (KF96L-5CS)

Density ρ [kg/m^3]	915
Kinematic viscosity ν [m^2/s]	5×10^{-6}
Temperature coefficient of surface tension σ_T [N/(m·K)]	-6.58×10^{-5}
Thermal diffusivity α [m^2/s]	7.46×10^{-8}
Prandtl number [-]	67

The Marangoni number Ma, which is a dimensionless number indicating the strength of Marangoni convection, is defined by eq. (1).

$$Ma = \frac{|\sigma_T|\Delta TL}{\rho\bar{\nu}\alpha} \tag{1}$$

Since the temperature dependence of the kinematic viscosity is larger than other physical property values, the average of the kinematic viscosities at the cooling disk temperature T_C and the heating disk temperature T_H is used as a representative value ($\bar{\nu} = \{\nu(T_C) + \nu(T_H)\}/2$). The kinematic viscosity at each temperature is calculated by eq. (2).

$$\nu(T) = \exp\left(5.892\frac{25 - T}{273.15 + T}\right) \times \nu(25) \tag{2}$$

Further, Ma at the transition point from steady flow to oscillatory flow is named as the critical Marangoni number Ma_{cr}, and the distance from the critical point is defined as the supercritical parameter ε denoted as eq. (3).

$$\varepsilon = \frac{Ma - Ma_{cr}}{Ma_{cr}} \tag{3}$$

Grayscale image entropy H was used to evaluate the randomness of the surface temperature distribution obtained from the IR camera. This is an application of the information entropy in information theory to a grayscale image, and is expressed by the following equation[3]. Where $p(m_i)$ is the probability that a specific gray value m_i exists for the total number of gray values N. For an 8 bpp IR image, $N = 255$, and a completely random grayscale image has 8 bits entropy.

$$H(m) = -\sum_{i=0}^{N} p(m_i) \times \log_2 p(m_i) \tag{4}$$

3. Results and discussion

From the image entropy of the IR camera (image for each frame), the randomness change in the surface temperature distribution of the liquid bridge is obtained. The temperature distribution is obtained from the brightness of the IR image. The IR image is analyzed by extracting the surface area close to the camera (**Fig. 2**), considering the influence of the curvature of the liquid bridge surface[4]. The upper and lower temperature range indicating in grayscale thermal image data is adjusted according to the surface temperature of the liquid bridge. Therefore, the difference in noise generated for each range appears as entropy. Hence, when the measurement range is changed due to the variation of ε, the entropy value is offset so that there is no difference depending on the range.

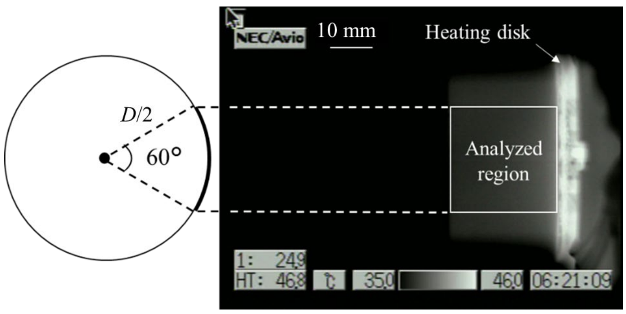

Fig. 2 Analyzed region of the liquid bridge obtained by the IR camera

Figure 3 shows the change in entropy for each ε by adjusting the average entropy of the steady flow ($\varepsilon < 0$) to 1. The break in the waveform is the part that was not analyzed because the thermal image was interrupted owing to changing temperature indicating range and calibration of image sensor. In **Fig. 3**, the entropy increases with increasing ε. The entropy changes periodically from around $\varepsilon = 0$ to 3, the period and amplitude begin to be disturbed around $\varepsilon = 3$ to 7, and the disordered state continues when ε exceeds around 7.

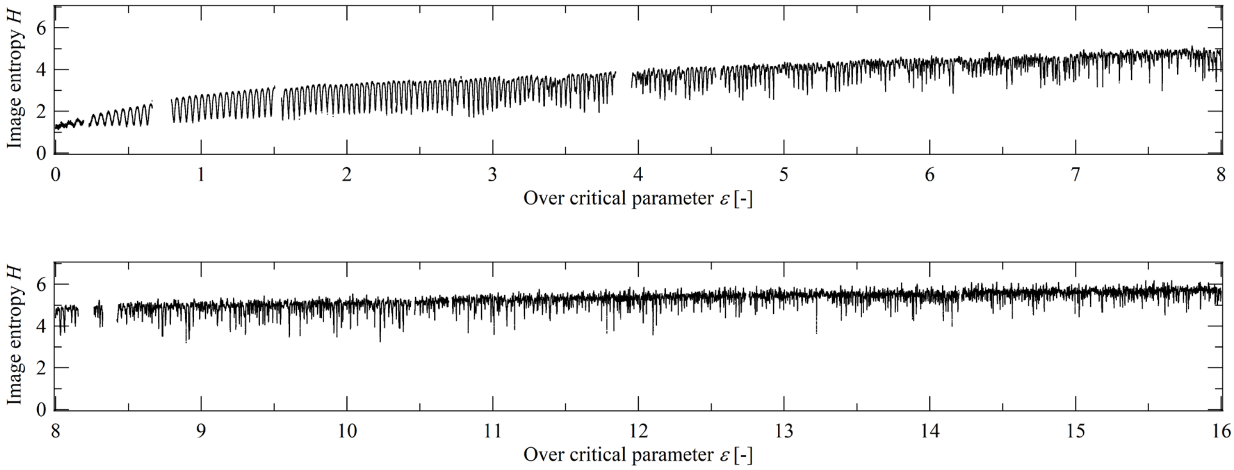

Fig. 3 Variation of Image entropy H with over critical parameter ε

Frequency analysis was performed for the entropy fluctuations. **Figure 4** shows the frequency distribution for each ε. The color map shows the normalized frequency intensity. Overall, the frequency distribution expands to the high frequency side as ε rises. When ε is from 0 to around 3, there are several frequency peaks with strong intensity, so it is considered to be an oscillatory flow. When ε is around 3 to 7, the frequency distribution spreads to the high frequency side and the intensity of each peak decreases slightly, suggesting that the oscillatory flow is transitioning to the chaotic flow. When ε exceeds around 7, the frequency distributes widely to the high frequency side. In addition, the frequency peak can be confirmed when ε is 0 to around 7, but it is difficult to determine the peak after ε is around 7, so it is considered to be a chaotic flow.

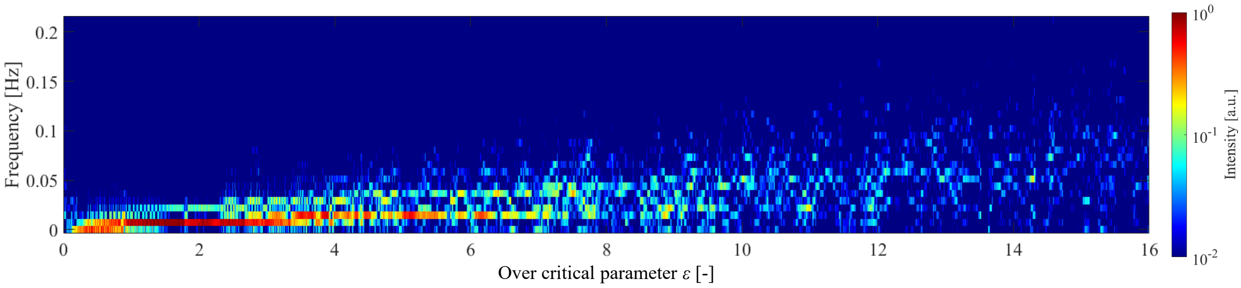

Fig. 4 Frequency analysis of Image entropy H fluctuation with over critical parameter ε

4. Conclusion

In order to investigate the chaotic characteristics of Marangoni convection induced in the liquid bridge, the surface temperature fluctuation due to flow instabilities after the onset of oscillatory flow was evaluated from the time series data obtained by the surface temperature of the liquid bridge. The liquid bridge surface temperature distribution was obtained from an IR camera and quantitatively analyzed using grayscale image entropy and frequency analysis. The range of the supercritical parameter transit to the chaotic flow is clarified.

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