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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カオス流遷移

Chaotic Flow Transition of Surface Temperature of 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 because the Marangoni convection induced by the driving force of the surface tension gradient causes the poor quality of the grown crystal[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). In a microgravity environment, a large liquid bridge can be formed, and the flow and temperature fields of pure Marangoni convection can be observed because buoyancy convection and surface deformation due to gravity do not occur. 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 is no detailed knowledge 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 a diameter D of 50 mm and a height 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 to the upper and lower end surfaces of the liquid bridge to generate Marangoni convection. The cooling disk temperature T_L was kept constant at 20 °C, and the heating disk temperature T_H was set so that the temperature gradually changed by about 2.5 °C. The surface temperature was observed by the IR camera. At the same time, thermocouples set to very close to the liquid bridge surface was employed to measure the single point of temperature at the surface. The test fluid was 5 cSt silicone oil. The physical properties are shown in **Table 1**. The Marangoni number Ma, which is a dimensionless number indicating the strength of Marangoni convection, is defined by eq. (1). 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 defined as eq. (2).

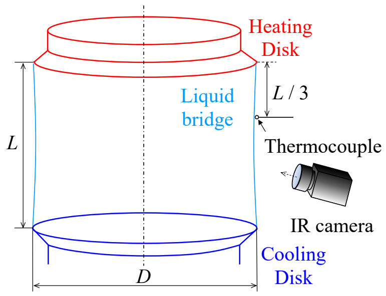

Fig. 1 Schematic diagram of liquid bridge setup

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

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

$$\varepsilon = \frac{Ma - Ma_{cr}}{Ma_{cr}} \quad (2)$$

3. Result

By using IR camera, the temperature distribution along height can be obtained as a function of time. The spatiotemporal temperature map with several supercritical parameters is shown in **Fig. 2**. In each image, the horizontal axis shows time, the vertical axis shows the distance from cooling disk, and the color map shows the normalized value of the liquid bridge surface temperature. It can be confirmed that the vibration becomes faster as ε rises. The regularly periodic waveform can be seen up to around $\varepsilon = 4.5$. After that, the irregularity appears at $\varepsilon = 5.4$, then the fluctuations have a chaotic or a turbulent appearances around $\varepsilon = 8.1$ to 16.1.

Figure 3 shows the global entropy H calculated by adapting the proper orthogonal decomposition to the obtained spatiotemporal temperature distribution and evaluating the transition behavior of the flow. When H is close to 0, the number of main components of temperature fluctuation is small and simple. In contrast, higher value of H increases complexity[3)]. Most of ε show $H = 0.1$ to 0.15, but some H are small up to around $\varepsilon = 1.3$ to 8.1, and thereafter the change is small.

Figure 4 shows the translation error E_{trans} obtained from the time-series of liquid bridge surface temperature obtained by thermocouples. E_{trans} represents regularity, which is one of the chaotic characteristics, and indicates regular when its value of 0 and irregular when it is larger than 0[2)]. E_{trans} is on the rise until $\varepsilon = 1.3$ to around 8.1, then it is almost flat thereafter.

From the time series data from the thermocouple, it is considered that the transition from oscillatory flow to chaotic flow occurs when ε is 1.3 to around 8.1. In addition, in the time-series data taken by the IR camera, the change in the temperature distribution structure is large when ε is at 5.4.

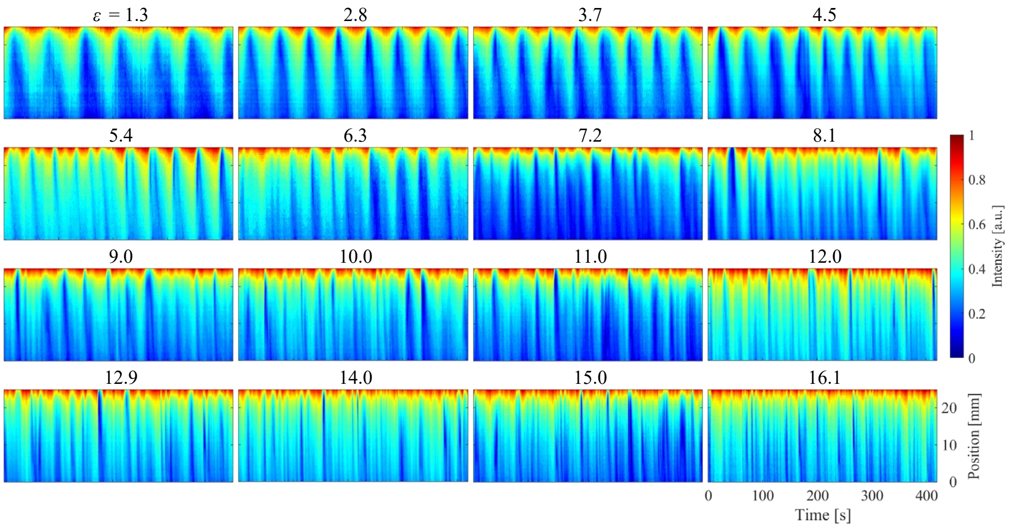

Fig. 2 Spatiotemporal temperature map with over critical parameter ε

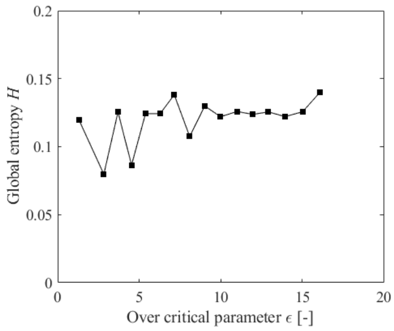

Fig. 3 Variation of Global entropy H with over critical parameter ε

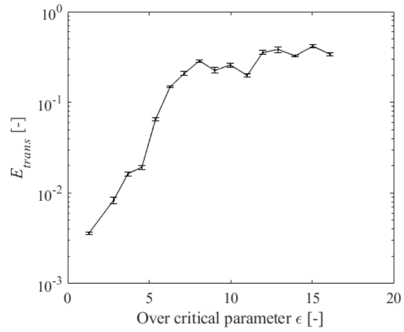

Fig. 4 Variation of Translation error E_{trans} with over critical parameter ε

4. Conclusion

In order to investigate the chaotic characteristics of Marangoni convection induced in the liquid bridge, the temperature after the onset of oscillatory flow was evaluated from the time series data obtained by the surface temperature of the liquid bridge. The spatiotemporal temperature structure was acquired from the spatial data in the axial direction of the liquid bridge, and analyzed quantitatively using global entropy H and transition error E_{trans}. The range of the supercritical parameter transit to the chaotic flow is clarified.

References

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