OR3-2

高 Pr 液柱内表面張力流の 3D-2C 計測―振動周波数の不連続な変化に伴う流動構造の変化

3D-2C Measurement of Thermocapillary Convection in a High-Pr Liquid Bridge—Change of Flow Field Accompany with "Frequency Skip"

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1. Introduction

Thermocapillary convection in a half-zone liquid bridge shows a rich variety of flow structure depending on physical conditions such as properties of working fluid, size of liquid bridge, existence/absence of gravity, thermal environment, and so on. In the case of high-Prandtl-number fluids (say, Pr > 1), thermocapillary convection transits from a steady state to an oscillatory state at the critical condition of hydrothermal wave instability [1]. The flow structure at the supercritical condition is spatially complex; therefore, three-dimensional and three-component (3D-3C) measurement of flow field is preferable to understand this phenomenon. Yano et al. [2] visualized the spatial structure of thermocapillary convection using particle tracking velocimetry (PTV) in microgravity (μg, hereinafter) experiments conducted on board the International Space Station (ISS). They found the change of oscillation mode (i.e., from an oscillatory flow to another type of oscillatory flow) from the observation of flow field. Such change in oscillation mode was caused by the increase in driving force of thermocapillary convection and was accompanied with a drastic change in oscillation frequency. The success of their measurement has received benefit from the on-orbit experiment on the ISS that a large-scale liquid bridge (say, more than 10 mm in diameter) can be formed under μg environment. On the other hand, under normal-gravity environment, the measurement of spatial structure of thermocapillary convection is very difficult because the size of liquid bridge is limited to a small one due to gravity (say, less than 10 mm in diameter). In this study, measurement of velocity field in a small-scale liquid bridge by particle image velocimetry (PIV) was attempted to understand the structure of thermocapillary convection under normal gravity. The two-dimensional and two-component (2D-2C) velocity fields in horizontal cross section (i.e., plane perpendicular to the axis of the liquid bridge) at various axial positions were stacked, and the 3D structure of thermocapillary convection was reconstructed like scanning PIV [3].

2. Experimental Results

In this study, a silicone-oil liquid bridge of Pr = 28 was formed in a gap between coaxial rods aligned vertically. The rods had the same diameter D = 4 mm and the clearance between these rods was varied in the range H = 1.2–2.4 mm. Therefore, the aspect ratios of the liquid bridge were A_r (= H/D) = 0.3–0.6. The spherical fine tracer particles, with average diameter of 5 μm, were seeded into the liquid bridge. The upper rod was made of transparent sapphire and the high-speed CMOS camera captured particle images for PIV data analysis. The thermocapillary convection was induced by a given temperature difference between upper and lower rods $\Delta T = T_H - T_C > 0$, where the temperature of lower rod T_C was kept constant at 20°C and that of upper rod T_H was increased stepwise. After the transition to the oscillatory state, velocity and temperature fields of thermocapillary convection changes periodically with constant frequency f. The magnitude of f increases linearly with further increase in ΔT as shown in **Fig. 1**, where ΔT_c is the critical ΔT for the onset of oscillatory flow and m is the azimuthal mode number. In **Fig. 1**, it should be noted that the oscillation frequencies for $A_r = 0.4$ and 0.5 drop discontinuously at $\Delta T/\Delta T_c \approx 1.35$, then start increase again. Such discontinuous change in oscillation frequency was observed by several researchers, and it is referred to as the "frequency skip". [4]

In many cases, the appearance of "frequency skip" is accompanied with the change in oscillation mode such as m; however, no change in oscillation mode was observed before and after the "frequency skip" in the present experiments. Instead, the change in flow structure was recognized from the results of PIV measurement. **Figure 2** shows the velocity fields measured with PIV for $A_r = 0.5$ and for (a) $\Delta T/\Delta T_c = 1.3$ and (b) $\Delta T/\Delta T_c = 1.5$. These temperatures correspond to the conditions before and after the "frequency skip", respectively. The velocity fields were measured from $z = 0.2$ mm to 1.8 mm at 0.2 mm intervals, with a total of nine horizontal cross sections ($z = 0$ mm corresponds to the end surface of the lower rod). The arrows indicate the in-plane velocity vectors $\boldsymbol{u}$ and the color contour indicates the magnitude of in-plane velocity $|\boldsymbol{u}|$. We note that the phase relationship of velocity fields in different axial potion is synchronized by the temperature fluctuation near the free surface of the liquid bridge measured by thermocouple sensor. In **Fig. 2**, the overall flow pattern seems similar, but there are some differences in detail. First, the difference in flow speed is far from that expected from the difference in driving force. The Marangoni velocities defined as $U_{Ma} = |\sigma_T|\Delta T/\rho\nu$ are 0.73 mm/s and 0.86 mm/s for (a) and (b), respectively, where σ_T is the temperature coefficient of surface tension, ρ is the density, and ν is the kinematic viscosity. It is obvious that the difference in flow speed shown in **Fig. 2** is greater than the difference in U_{Ma}. Second, the high-speed regions appear near the free surface for both cases but their trends in axial direction are different. For $\Delta T/\Delta T_c = 1.3$, this region rotates counterclockwise as it approaches to the lower rod. On the other hand, for $\Delta T/\Delta T_c = 1.5$, it stays at same tangential position. These comparisons indicate that the flow structures are different between the conditions before and after the "frequency skip".

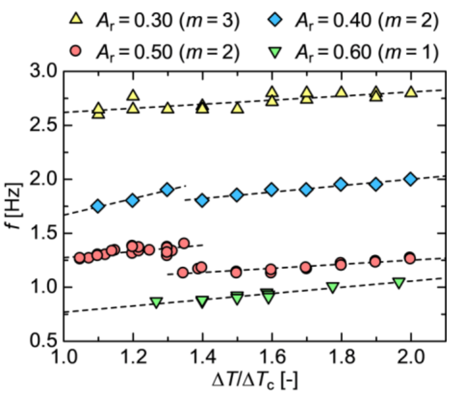

Fig. 1 Plots of f as a function of $\Delta T/\Delta T_c$.

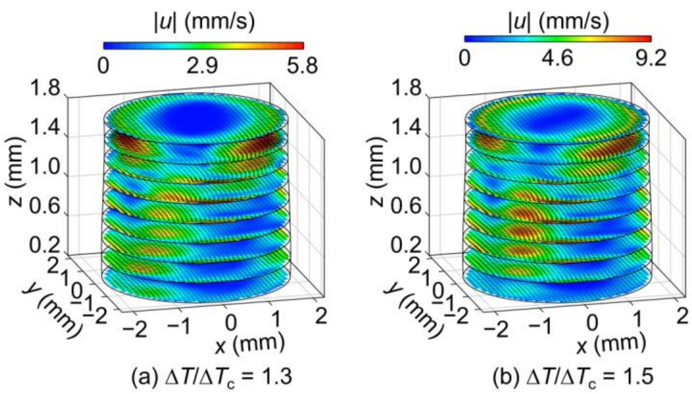

Fig. 2 Results of PIV for (a) $\Delta T/\Delta T_c = 1.3$ and (a) $\Delta T/\Delta T_c = 1.5$.

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