Formation of Particle Accumulation Structure (PAS) in Half-Zone Liquid Bridge under an Effect of Thermo-Fluid Flow of Ambient Gas

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Thermocapillary-driven flow is realized in a liquid bridge by a non-uniform surface tension distribution caused by an axial temperature difference. It is known that a unique behavior of the particles suspended in the liquid bridge emerges after the onset of the oscillatory flow states, which is named the particle accumulation structure (PAS) after Schwabe et al (Microgravity Sci. Technol. 1996). In the present study, we focus on one of the two types of the PAS, SL-2 PAS (after Tanaka et al. (Phys. Fluids 2006)), appeared under larger thermocapillary effect. Especially we pay our special attention to the effect of ambient gas flow around the liquid bridge on the SL-2 PAS. We reconstruct the spatio-temporal variations of the trajectory and velocity of the particles on the SL-2 PAS by applying three-dimensional particle tracking velocimetry (3D PTV).

Key Words: Particle Accumulation Structure (PAS), Half-Zone Liquid Bridge, SL-2 PAS, 3D-PTV, Ambient Gas Flow

Nomenclature

d	: hydraulic diameter
H	: height of liquid bridge
m	: azimuthal mode number
Ma	: Marangoni number $\equiv \sigma_T \Delta T \cdot H / (\rho \nu \kappa)$
Pr	: Prandtl number $\equiv \nu / \kappa$
Q	: flow rate
R	: radius of the bottom rod
Re	: Reynolds number $\equiv U d / \nu$
T	: temperature
ΔT	: temperature difference between the top and the bottom rods
t	: time
U	: velocity of ambient gas
V	: liquid bridge volume
ε	: overcritical parameter $\equiv (Ma - Ma_C) / Ma_C$
Γ	: aspect ratio $\equiv H / R$
θ	: angle of the camera
κ	: thermal diffusivity
ν	: kinematic viscosity
ρ	: density
σ	: surface tension
ξ	: volume ratio of liquid bridge $\equiv V / (\pi R^2 H)$

Subscripts

0	: initial
amb	: ambient gas
avg	: in averaged
C	: under critical (transition) condition
ES	: external shield
H	: hot rod

L	: cooled rod
T	: temperature coefficient
σ	: surface tension

1. Introduction

Convective flow driven by surface tension difference over the free surface is well-known as Marangoni convection or thermocapillary convection. This type of convective flow emerges dominantly under microgravity conditions, where the buoyancy effect is almost negligible. Although high quality crystal growth had been anticipated under microgravity condition, the thermocapillary-driven flow in the melt does result in striation in the crystal. In order to understand and control of such a flow due to the surface tension difference over the free surface, there exist a large number of researches; in the fundamental researches, the half-zone (HZ) method has often been applied to simplify the floating-zone crystal growth configuration. In the HZ method, the liquid is sustained between two coaxial cylindrical rods. One end is maintained hotter, and the other cooler to realize temperature difference ΔT . The thermocapillary flow is developed from hotter rod to colder rod over free surface because of non-uniform temperature distribution over the free surface between two rods. It has been known that the induced flow in the HZ liquid bridge exhibits a transition from two-dimensional (2D) steady flow to three-dimensional (3D) flow when a temperature difference between two rods exceeds a critical value. The intensity of flow field is described by Marangoni number, defined as

$$Ma = \frac{\sigma_T \Delta T H}{\rho \nu \kappa} = \frac{\sigma_T \Delta T \cdot H}{\rho \nu^2} \cdot \frac{\nu}{\kappa} = Re_\sigma \cdot Pr \quad (1)$$

where σ_T is the absolute value of the temperature coefficient of the surface tension. The Marangoni number is described as the product of thermocapillary Reynolds number Re_σ and the Prandtl number Pr .

The critical condition under which the flow in the liquid bridge exhibits a transition is described as the critical Marangoni number Ma_C with the critical value of the temperature difference ΔT_C . A large number of terrestrial experiments have been carried out to apply for the high quality single crystal since 1970s¹⁻⁸⁾. Preisser et al.¹⁾ conducted a half-zone experiment slightly above Ma_C by using transparent liquid to visualize the flow field and revealed the appearance of azimuthal wave. This azimuthal wave number can be shown by integer number m ^{1,6)}. This azimuthal wave number is strongly dependent on Γ . In a narrow range of Ma beyond the critical condition, the particle accumulation structure (PAS) emerges in the bridge, which was firstly observed by Schwabe et al.²⁾ The PAS is the phenomenon that the suspended particles accumulate like a closed rope in the liquid bridge and seems to rotate with constant angular velocity. The three-dimensional structure of PAS was firstly reconstructed by Tanaka et al.³⁾ and named spiral loop PAS (SL-PAS). They observed the particle behaviors through the transparent top rod, and from the side by CCD cameras, and two different types of SL-PAS were clearly defined, that is, SL-1 and SL-2 PASs. Abe et al.⁷⁾ conducted a series of experiments on SL-1 PAS to reveal that the volume ratio of the liquid bridge affects the axial velocity of the particles on the SL-1 PAS. Very recently we have vigorous contributions to understand the physical mechanism of the PAS formation from the theoretical approaches; Pushkin et al.⁸⁾ proposed an idea of ‘phase locking’ in the liquid bridge to form a PAS inside the liquid bridge. Hofmann & Kuhlmann⁹⁾ indicates that the ‘collision’ between the particles and the free surface of the liquid bridge is the essential source to form a PAS. One can find invaluable review articles on the PAS by Kuhlmann & Muldoon¹⁰⁾ and Melnikov et al.¹¹⁾

We have accumulated knowledge on the SL-1 PAS owing to those contributions. Knowledge on the SL-2 PAS, however, has not been clearly understood; especially the particle behaviors to form the SL-2 PAS. In addition to this, we recently have an information that the heat transfer between the liquid bridge and the ambient gas does affect the flow field inside the liquid bridge and the critical Marangoni number¹²⁾.

In the present study, we focus on two things; (1) to understand the behaviors of the particles on the SL-2 PAS, and (2) to detect the effects of the ambient gas flow around the liquid bridge on the particles’ behaviors on the SL-2 PAS.

2. Experiment

Experimental apparatus is described in Fig. 1. Whole system is drawn in the frame (a), and the A-A’ cross-sectional view is shown in the frame (b). The system is basically the same as employed by Ueno et al.¹²⁾ A liquid bridge of silicone

oil of 2 cSt in kinematic viscosity (Prandtl number $Pr = 28.1$ at 25°C) is formed between two cylindrical rods. The top rod is made of sapphire so we observe the particles suspended in the liquid bridge from above through the rod. The bottom rod is made of aluminum. The disk of the bottom rod has the sharper edge to prevent of the leakage of the test fluid. The surface of the bottom rod is aluminized to prevent light reflection. In addition, the side wall of the bottom rod is chemically coated to prevent wetting by the liquid. The radius of the end surfaces of the both rods, R , is kept at 2.5 mm.

The geometry of the liquid bridge is described with two parameters; the aspect ratio, $\Gamma = H/R$, and the volume ratio, $\xi = V/\pi R^2 H$, where H is the height of the liquid bridge, and V the liquid bridge volume. In the present study, the aspect ratio of the liquid bridge is kept constant at $\Gamma = 0.64$ to steadily realize the SL-PAS of $m = 3$ in the case of null ambient gas flow as indicated by Tanaka et al.³⁾ The volume ratio is also kept constant at $\xi = 1.0$.

The temperature difference between the end walls of the rods, ΔT , is realized by heating the top to maintain at $T = T_H$, and by cooling the bottom one at $T = T_C$. The increasing rate of ΔT is small enough to guarantee long-enough relaxation time of the flow field. The temperatures of the top and bottom rods are measured with Cr-Al thermocouples of 100 μm in diameter. The temperature of bottom rod is kept constant by cooling water supplied from a bath.

Fig. 1. Experimental apparatus; (a) whole view and (b) layout of the liquid bridge and the external shield at A-A’ cross-section in (a).

The liquid bridge and the rods sustaining the liquid bridge are wrapped by placing the concentric cylinder as the external shield. The geometry of the ambient gas region is almost the same as Ueno et al.¹²⁾ In this paper we extract the essential parts of the system to be explained. The dried air maintained at the designated temperature is used as the ambient gas. The shield is made of Pyrex® glass of 1.5 mm in thickness. The inner diameter of the external shield $D_{ES} = 2R_{ES}$ is of 25 mm (see Fig. 1. (b)). The external shield is fixed in the apparatus

by the shield holders made of aluminum. Four channels for inlet/outlet of the ambient gas flow are prepared for each shield holder. This apparatus enables us to vary the direction of the external flow, that is, upward or downward, by changing the direction of the ambient gas flow. It is noted that we confine ourselves to treat only the upward flow in the present manuscript. This is due to the much less possibility to realize SL-PAS in the case of downward ambient gas flow under the present experimental conditions.

A diffuser is placed right after the inlet and before the external shield to realize a uniform flow field inside the shield.

The flow condition of the ambient gas in the external shield is described with an averaged velocity $U_{\text{avg}} = Q/\pi(R_{\text{ES}}^2 - R^2)$ and the Reynolds number $Re = U_{\text{avg}}d/\nu_{\text{amb}}$, where Q is the controlled flow rate in the external shield, d the hydraulic diameter of the granular channel ($= 2R_{\text{ES}} - 2R$) and ν_{amb} is the kinematic viscosity of the ambient gas. In the present study, upward forced flow in the external shield is defined as positive in Re_{amb} after Ueno et al.⁽¹²⁾

We use the high-speed cameras at the top and the side of liquid bridge to observe the flow field, and employ the 30- μm gold coated cross-linked acrylic particle to visualize that. This particle has the features of electrically neutral, little accumulating and good reflection of the light.

Particle tracking velocimetry (PTV) is applied to reconstruct the particles' trajectories to form the SL-PAS. A cubic beam splitter is set above the top rod to locate the camera systems close to such a small flow field. Camera calibration procedures introduced by Nishimura et al.⁽¹³⁾ are employed before/after experiment. In this PTV experiment, the frame rate is 500 fps and the camera calibrated by using calibration plate that has 25 calibration points.

3. Results & Discussion

SL-PAS can be observed if we introduce a large-enough temperature difference on the liquid bridge, that is, in the range of $1.0 < \varepsilon \equiv (Ma - Ma_C)/Ma_C < 3.1$ in average. At first, the SL-1 PAS emerges in the liquid bridge in increasing ε . The SL-2 PAS is then observable at higher Ma ⁽³⁾. The SL-2 PAS of m in azimuthal wave number consists of m 'blades,' as shown in Fig. 2 as well as the SL-1 PAS⁽³⁾. In each blade, there exists an additional loop near the free surface, so that each blade maintains two parts; the 'primary' blade and the 'secondary' blade.

The primary blade is the one located at the front part of the blade in terms of the rotating direction of the SL-PAS and the hydrothermal wave⁽¹⁴⁾, that is, the one on which the particles travel outward from the central region of the liquid bridge, and flow downward in the velocity of the free surface from the region near the hot rod. The secondary blade is located at the rear part of the blade, on which the particles penetrate into the shallow region from the free surface as additional loop. Then the particles flow downward again toward the cold rod after coming back to region near the free surface. This SL-2 PAS seems to rotate at a constant angular velocity without changing its shape (see Fig. 3) as well as the SL-1 PAS.

Fig. 2. Typical example of the SL-2 PAS in the case of $Ma = 4.8 \times 10^4$ and $Re_{\text{amb}} = 0$; (a) snapshots of top and side views of the SL-2 PAS, and (b) schematic image of the SL-2 PAS observed from the top. Arrows indicate the direction of the propagation of the hydrothermal wave.

Fig. 3. Successive images of the top view of the SL-2 PAS in the case of $Ma = 4.8 \times 10^4$ and $Re_{\text{amb}} = 0$; detected images in the experiment (left) and their sketches (right). Primary and secondary blades indicate as 'α' and 'β', respectively in the sketches. Δt_{HTW} corresponds to the fundamental period of the hydrothermal wave.

In the following part, we discuss on the spatio-temporal correlation between the particle behaviors and the shape of the SL-2 PAS. Figure 4 shows an example of the behavior of a

particle on the SL-2 PAS observed from above in the case of $Ma = 4.8 \times 10^4$ and $Re_{amb} = 0$. The rotating direction in the figure is counter-clockwise. This figure consists of the trajectory for a particle traveling along one pair of the primary and secondary blades; the frame (a) indicates of the trajectory in the absolute coordinate, and the frame (b) the trajectory in the coordinate rotating with a fundamental frequency for the traveling of the SL-2 PAS. The starting instance of the tracking is referred as $t = t_0$ [s].

Fig. 4. Typical example of the behavior of a particle on the SL-2 PAS observed from above in the case of $Ma = 4.8 \times 10^4$ ($\Delta T = 46.5$ K) and $Re_{amb} = 0$; (a) the trajectory in the absolute coordinate, and (b) the trajectory in the coordinate rotating with a fundamental frequency for the traveling of the SL-2 PAS (counter-clockwise in this case).

In the absolute coordinate (the frame (a)), when the particle travels along the primary blade, the net direction of the particle's travel is opposite to that of the SL-PAS. The particle flows near the hot disk from the central region of the liquid bridge toward the free surface ($0 < t-t_0 < 0.13$). Once the particle comes very close to the free surface, it drastically changes its direction (clockwise in this case) ($t-t_0 \sim 0.13$). After the abrupt falling down the free surface ($0.13 < t-t_0 < 0.16$), the particle again comes back to central region of the liquid bridge ($0.16 < t-t_0 < 0.28$). This is a common behavior that is also seen in SL-1 PAS⁷⁾. In the case of SL-2 PAS, the particle changes its direction to the one that PAS seems to rotate, and then flows back to the free surface again to form the secondary blade ($0.28 < t-t_0 < 0.47$). In the secondary blade, the azimuthal position of the particle seldom changes in flowing toward the free surface and backward the central

region of liquid bridge ($0.47 < t-t_0 < 0.62$). In the absolute coordinate, one cannot see any significant spatial relation between the pathline and the PAS shape. Once the particle is observed in the rotating coordinate as shown in the frame (b), the correlation between the particle motion and shape of the SL-PAS is clearly emerged. The direction change at the central region of the bridge after the primary blade results in forming the additional loop.

The 3D PTV enables us to resolve the velocity field into the spatio-temporal variations. We now compare the decomposed velocity variation of both of the primary and secondary blade as a function of the Re_{amb} . Figures 5 and 6 indicate typical examples of the temporal variation of the velocities of the primary and the secondary blades, respectively. The conditions are $(\Delta T, Ma) = (46.5, 4.8 \times 10^4)$, which are the same for Fig. 4. Noted that the time in $t-t_0$ does correspond to that shown in Fig. 4.

Fig. 5. Typical examples of the temporal variations of the velocities of the primary blade. The conditions are $(\Delta T, Ma) = (46.5, 4.8 \times 10^4)$, which are the same for Fig. 4. Noted that the time in $t-t_0$ does correspond to that shown in Fig. 4.

Fig. 6. Typical examples of the temporal variations of the velocities of the secondary blade. The conditions are $(\Delta T, Ma) = (46.5, 4.8 \times 10^4)$, which are the same for Fig. 4. Noted that the time in $t-t_0$ does correspond to that shown in Fig. 4.

First, we focus on the primary blade as shown in Fig. 5. We track the particle for 0.14 s ($0.122 < t-t_0$ [s] < 0.262) in the primary blade under different $Re_{amb.}$. For this blade, the radial and azimuthal components of the particle velocity are almost independent of the upward ambient gas flow. The axial component is almost independent up to $Re_{amb} \leq 100$ as well.

The axial component of the particle velocity near the free surface is affected in the case of $Re_{amb} = 200$.

As for the secondary blade as shown in Fig. 6 tracked for 0.12 s ($0.464 < t-t_0$ [s] < 0.584), on the other hand, the azimuthal component is affected by the ambient gas flow. As increase Re_{amb} , the amplitude of the v_θ does increase. Right after the particle falls down over the free surface toward the cold rod, the azimuthal velocity indicates the minimum, and it takes maximum when the particle turns its direction toward the central part of the liquid bridge. It is found that the secondary blade is more sensitive to the ambient gas flow.

4. Concluding Remarks

We focus on one of the two types of the particle accumulation structure (PAS), SL-2 PAS, which consists of the primary and secondary blades. We pay our special attention to the spatio-temporal correlation between the behaviors of the particles on the PAS and the resultant shape of the SL-2 PAS. We also pay our attention to the effect of ambient gas flow around the liquid bridge on the SL-2 PAS. We reconstruct the trajectory and velocity of the particles on the SL-2 PAS by applying three-dimensional particle tracking velocimetry (3D PTV). We find out that the secondary blade is rather sensitive to the ambient gas flow.

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