VISUALIZATION OF PARTICLE ACCUMULATION STRUCTURE IN MARANGONI CONVECTION OF LIQUID BRIDGE FOR PREPARATION OF ON-ORBIT EXPERIMENT AT INTERNATIONAL SPACE STATION

Shiho TANAKA, Ichiro UENO and Hiroshi KAWAMURA
Dept. Mech. Eng., Science University of Tokyo,
Noda-shi, Chiba-ken, 278-8510, Japan

Thermocapillary flow in a half-zone liquid bridge has been widely investigated. Induced convection was visualized by using particles as tracers. Special attention was paid to the distribution of the dispersed particles in the present study. The particles were found to get accumulated in a certain experimental conditions. This is called as PAS, particle accumulation structure, after Schwabe (1996). Several structures was observed. The condition of the occurrence of PAS was investigated carefully. It's structures and the occurrence conditions are discussed.

INTRODUCTION

The International Space Station (ISS) is now under construction and expected to be devoted to various researches from 2004. The floating-zone method is a way to produce a higher-quality single crystal avoiding any contact impurity. Convective flow is induced by the temperature difference *DT* between two cylindrical rods sustaining the liquid bridge. It is well-known that the induced flow exhibits a transition from 2-D steady to 3-D time-dependent flow with increasing *DT*. The author's group is going to perform a series of experiment on the Marangoni convection in a liquid bridge at the international space station in a yare of 2005. After the onset of the time-dependent flow, modal oscillatory structures emerge in the liquid bridge. The flow field is usually visualized by small particles put into the fluid as tracers. Accumulations of the particles were occasionally observed (1) in the particle-suspending flow. Recently Schwabe *et al.* (2) and Schwabe (3) concentrated their attention upon the dynamics of the particles or the particle accumulation structure (PAS) in the vortex flows. We research on the particle accumulation structures in the liquid bridge focused upon the thermocapillary flow structures at larger temperature differences.

EXPERIMENT

Experiment apparatus is described in Fig.1. The upper rod was made of sapphire, which enabled us to observe the flow field in the bridge from the top end surface. The bottom rod was made of aluminum whose side wall was chemically coated to prevent wetting by the liquid. Silicone oil was employed as the test fluid. Liquid bridge of the silicone oil with small particles was formed between the cylindrical rods of 5 mm in diameter. Aspect ratio A_r (= H / D) was varied from 0.20 to 0.50, where H and D are the height and the diameter of the bridge, respectively. The volume ratio of the bridge was kept constant at very close to the unity. Temperature difference *DT* between the rods was imposed by heating the upper rod. The temperature difference was increased up to 100 K with a constant small increment of 0.1K approximately, which was confirmed in advanced to have little influence upon the critical condition for the flow-field transition. Temperature oscillation of the free surface was measured with a Cr-Ar thermocouple. Ambient temperature was kept at about -20 °C in order to realize the large temperature difference while suppressing the evaporation of the fluid.

Visualization of flow structures and particle accumulation

Flow field was observed by two CCD cameras; one from the top and the other from the side. Whole field was illuminated by two light source; again one from top and the other from side. The light was introduced through fiber glass to avoid the direct thermal heating from the light source. The bottom rod that made from Al was coated with dim black pigments to defend from halation. In order to grasp the condition for flow structures, various kind of particles with different the diameters, shapes, and dispersion densities employed; that is crushed Nylon 12 particles of 50 μm, spherical polystyrene of 8, 17 and 20 μm, spherical polyethylene of 6, 10 and 12 μm, and spherical Al_2O_3 of 3 μm in diameter were examined as tracers. The density of these particles except Al_2O_3, are almost matched with that of fluid. The disperse density of the particle was ranged from 0.05 to 1.00 % in mass ratio. Three kinds of liquids with different viscosities 1, 2 and 5 cSt were also tested.

RESULTS AND DISCUSIONS

Definitions of the flow structures

The flow structures can be categorized into several regimes owing to the Fourier spectrum of the surface temperature variation and the particle motions as shown in Table1. Regime *Rg* with a higher number mainly corresponds to the structure emerging at a larger temperature difference. The flow regime is primarily determined by the temperature difference and the aspect ratio. Convective flow showed modal structures in *Rg2* and *3* as indicated experimentally by the preceding works(4). Existing works have mainly focused upon the regime up to *Rg3*. With increasing the temperature difference from *Rg3*, the flow in the bridge once became disordered (*Rg4*). This is a transition state in which rotating and pulsating flows coexist competitively. Further increasing *DT*, ordered structures again emerged as *Rg5* and *6*. In the regime of *Rg 7*, the flow became apparently chaotic. The fundamental frequency is buried in the broadband noise. The flow in Rg8 shows a distinctly difference appearance from the one that in Rg7 apparently. Note that the structures beyond *Rg8* were not able to be observed because such a large temperature difference could not be attained in this system.

Variations of PAS

The particle distribution at a very early stage of *Rg1* is presented in Fig. 2. The particles were dispersed uniformly in the whole bridge. With increasing *DT*, the flow field exhibited structures from *Rg1* to *Rg8*, and each regime except *Rg4*, 7 and *8* demonstrated its own particle accumulation structure. That is, 'Steady Ring' at the final stage of *Rg1*, 'Lump' in *Rg1*, *2* and *5*, 'Twisted Loop (TL)' in *Rg6* and 'Lump & Loop Combination' in *Rg3* and *6*. Figures 3 -(a) to -(f) present the top and side views of the PAS's. The exposure time of CCD camera was rather short (1/60 s). The particle accumulation structures of 'Steady Ring' and 'Lump' have been reported in the preceding researches (2)-(3). Special attention was paid to the TL-PAS as shown in Figs. 3 -(c) to -(f) in this study.

Twisted Loop PAS

There existed two types of TL-PAS; Twist I and II in *Rg6* at a smaller and a larger *DT*, respectively. Particle accumulation named Twist I here was observed occasionally in the previous studies (3)-(4). The 3-D structures of the Twisted Loop were firstly captured in the present study by simultaneous observations of the top and side views. A Twisted wire models of Twist I and II are shown in Fig.4. Particles accumulated along one closed path. The path came down in the vicinity of the free surface obliquely against the temperature gradient direction. At the bottom of the bridge the path rose up towards the center of the bridge and then curved with rising up towards the free surface. It is interesting that rotating direction of this structure was opposite from that of tracer particles movement. Twist II contained an additional twisted loop inside of the Twist I in the vicinity of the free surface. The existing region of Twist I laid at a lower *DT*, that is, at the region with a weaker thermocapillary effect. Those surviving ranges were still narrower than those of the corresponding flow regime *Rg2* and *Rg3* themselves. Furthermore, it is of significance that the TL-PAS was always observed in conjunction with the azimuthally rotational flow. That is, it would not be formed even though an enough *DT* was imposed, in case that only pulsating convection emerged in the bridge. In that case, one must once increase *DT* to excite rotational convection and then decrease it to obtain the TL structures. All runs with different conditions brought almost the same PAS formations. The TL-PAS was easily destroyed by a small disturbance such as insertion of a thermocouple. It was reformed saucily by the elimination of the disturbance.

Modal structures of Twisted Loop PAS

T-L PAS possessed the modal structures corresponding to those of the convection field itself. Figures 3 -(c) to -(f) indicate the TL-PAS with mode number $m = 3$. The mode number of TL-PAS was mainly determined by the liquid bridge aspect ratio A_r as that of the convection field. TL-PAS's of different mode number m are shown in Fig 5. The TL-PAS, however, was observed in a rather limited region of A_r than the flow field itself as seen in Fig. 5. The reason why the particles become accumulated is not known yet. Further studies will be continued to realize experiments with a longer diameter at the ISS.

REFERENCES

(1) Kawamura, H. and Harada, N., Observation of Oscillatory Marangoni Convection in a Liquid Column, *Proc. 35th National Heat Transfer Symp. of Japan*, III (1998), pp. 749-750 (in Japanese). (2) Schwabe, D. *et al.*, New Features of Thermocapillary Convection in Floating Zones Revealed by Tracer Particles Accumulation Structures (PAS), *Microgravity Sci. Technol.*, IX/3 (1996), pp.163-168. (3) Schwabe, D., Particle Accumulation Structures (PAS) in Thermocapillary Flow in Floating Zones, Proc. 2nd European Symp. on the Utilization of the International Space Station (Noordwijk, The Netherlands, Nov. 1998), (1999), pp. 233-240. (4) Ono, Y. *et al.*, Transition and Modal Structure of Oscillatory Marangoni Convection in Liquid Bridge, *J. Jpn. Soc. Microgravity Appl.*, Vol. 16, Supplement (1999), pp. 96-97.

Table1.Flow regime in the liquid bridge

Rg	*Rg1*	*Rg2*	*Rg3*	*Rg4*	*Rg5*	*Rg6*	Rg7	Rg8
Status	Steady	Pulsating I	Rotating I	Transition	Pulsating II	Rotating II	Chaotic	Turbulent-like

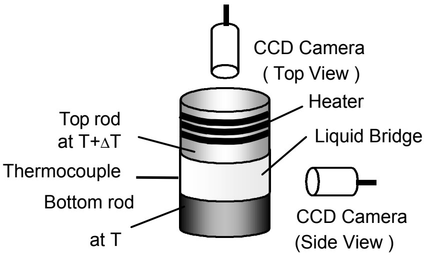

Fig.1 Experimental arrangement

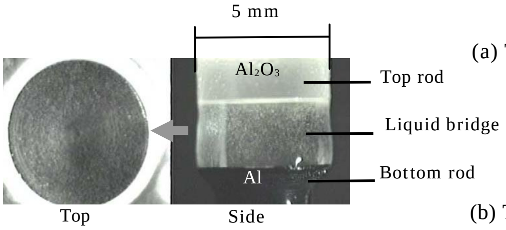

Fig.2 Initial condition of the experiment

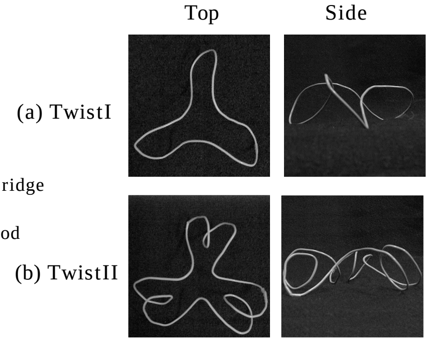

Fig4 Models of Twisted-Loop PAS (T-L PAS)

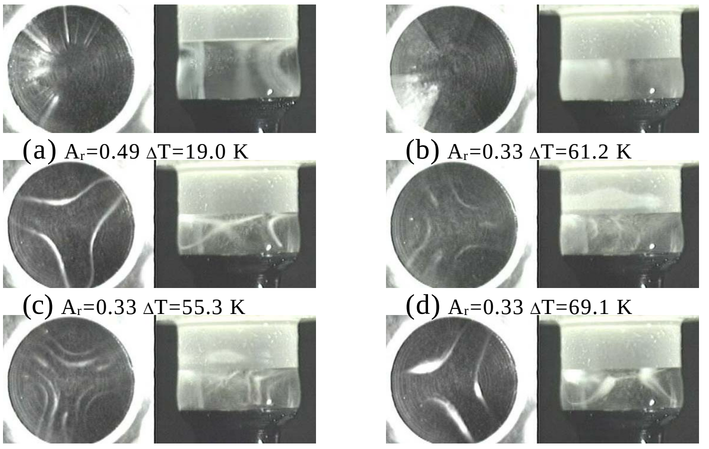
(a) A_r=0.49 ΔT=19.0 K
(b) A_r=0.33 ΔT=61.2 K
(c) A_r=0.33 ΔT=55.3 K
(d) A_r=0.33 ΔT=69.1 K
(e) A_r=0.33 ΔT=74.5 K
(f) A_r=0.33 ΔT=64.7 K

Fig.3 Variation of Particle Accumulation Structures
top view (left) and side view (right)

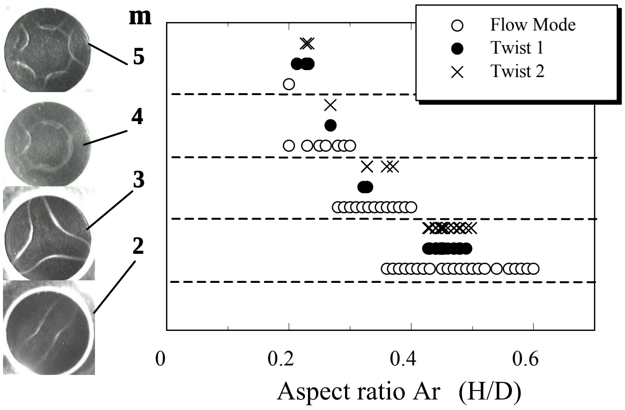

Fig.5 Mode number of the Twist Loop PAS and the flow field itself against the aspect ratio in the case of 2 cSt silicone oil. The photographs exhibit the top view of Twist I.