ISSN 1349-1113
JAXA-RR-05-023E

JAXA Research and Development Report

Thermocapillary Flow in Low Pr Number Liquid Bridge

- Annual Report of Fluid Dynamics Instability Research -

S. MATSUMOTO, H. OHIRA, T. MASHIKO, H. SASAKI
E. YODA, N. IMAISHI and S. YODA

March 2006

Japan Aerospace Exploration Agency

Thermocapillary Flow in Low Pr Number Liquid Bridge

—Annual Report of Fluid Dynamics Instability Research—

By

S. MATSUMOTO[1], H. OHIRA[1], T. MASHIKO[1], H. SASAKI[2], E. YODA[3], N. IMAISHI[4], S. YODA[1]

Abstract : Experimental study on thermocapillary convection of low Prandtl number fluid was carried out to estimate the mode structure after the onset of oscillatory flow. The half-zone liquid bridge of molten tin was used as a experimental configuration. In order to detect very slight temperature changes, the temperature measurement system was improved. Temperature oscillations at the interface between liquid and cold rod were obtained by several thermocouples. The first transition could be detected and the transition processes have been clarified. The mode structure appeared in a low frequency oscillation region after the onset was presumed from the phase differences among them. The mode structure was supposed to be 2 and rotation with a frequency of 0.008 Hz. Furthermore, the rotation of the temperature field was elucidated through the multipoint measurements. In addition to above experiment, the preliminary test to visualize the flow field by using ultrasonic wave was performed. The result demonstrates us to be able to visualize the internal flow filed in low Prandtl number liquid column.

Key words : Thermocapillary Flow, Liquid Bridge, Low Prandtl Number Fluid, Fluid Instability

1. Introduction

A thermocapillary convection is well known phenomena but there are still open problems in both scientific and technical points of view. Due to fluid dynamic instabilities, convection changes its flow motion with increasing the control parameter (e.g. temperature difference) one by another. The liquid bridge configuration, which simulate the floating-zone crystal growth techniques, is often used for fundamental investigation. Half-zone (HZ) liquid bridge is a simplified system in which the cylindrical liquid is sustained by surface tension between upper hot disk and lower cold disk. In this configuration, many researches have been actively performed to reveal the fundamental issues. In particular, onset of oscillatory convection is the important topic because temperature fluctuation due to time-dependent flow produces inhomogeneous impurity distribution in grown crystal called striation.

In higher Pr number fluids ($Pr > 10$) with half-zone configuration, the transition behaviours have investigated experimentally in detail and the flow regimes have been clearly shown (Ueno *et al.* (2003)). It was experimentally proved that a transition from axisymmetric steady to 3D oscillatory flow occurs at a critical Marangoni number (Ma_c). However, in the case of low Prandtl number fluid ($Pr \sim 0.01$), quite few experimental work exists because of its difficulties. It has been numerically predicted that an axisymmetric steady flow transit to asymmetric 3D steady flow.

[1] ISS Science Project Office, Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, Tsukuba, Ibaraki, Japan
[2] Chiba Institute of Technology, Narashino, Chiba, Japan,
[3] Advanced Engineering Services, Co.Ltd, Tsukuba, Ibaraki, Japan
[4] Kyushu University, Kasuga, Fukuoka, Japan

After that, convection becomes oscillatory under certain condition. Namely, the thermocapillary convection of low Prandtl number fluid go through two transition points to become an oscillatory flow(Kuhlmann(1994)). Those are, transition from axisymmetric to 3D steady will occur at a first bifurcation point (first critical Marangoni number, Ma_{c1}), and transition from 3D steady to oscillatory at a second one (second critical Marangoni number, Ma_{c2}). The prediction needs to be experimentally proved.

We need to understand the transition mechanism because the oscillatory flow has an undesirable effect on the crystal growth of semiconductors by the floating zone methods, which lead to striations of the dopant in the crystal. The previous studies, in which a half zone liquid bridge have been often used as a model configuration of the floating zone, have shown that flow and temperature fields were governed by dimensionless parameter of Marangoni (*Ma*) or Reynolds (*Re*) number defined as follows:

$$Ma \equiv \frac{|\sigma_T| \Delta T L}{\mu \kappa} \tag{1}$$

$$Re \equiv \frac{Ma}{Pr} \tag{2}$$

where, σ_T is a temperature coefficient of surface tension, ΔT is a temperature difference between hot and cold disks, L is a characteristic length of the fluid, μ is dynamic viscosity, (is thermal diffusivity, and Pr is Prandtl number of the fluid.

A detail experiment around the bifurcation point, in which even the Ma_{c2} is predicted to be in the order of 10^1 for a Pr =0.01 liquid bridge (Imaishi *et al.* (2001)), is required to prove the transition behavior of Marangoni convection. However, many studies have been conducted at a Marangoni number that is far from the Ma_{c2}. Cröll *et al.* (1989) carried out crystal growth in space. The striation appeared in the obtained crystal. It was concluded the origin of striation was oscillatory Marangoni flow. So they observed oscillatory flow indirectly and estimated critical Marangoni number from grown crystal. Han *et al.* (1996) experimentally investigated thermocapillary convection in a liquid bridge of mercury. Free surface fluctuations were measured by a non-contacted diagnostic system, and they found the Ma_{c2}, detecting it to be 900 with a frequency around 5Hz. Nakamura *et al.* (1998) measured a surface temperature fluctuation with a thermocouple in a molten silicon column of 10 mm in diameter and 10 mm in length, and found that a frequency of the fluctuation was 0.1 Hz at a temperature difference of 100 K. However, the imposed temperature difference was far from the second bifurcation point. Azami *et al.* (2001) observed quite strong convection induced in the silicon liquid bridge. Yang and Kou (2001) reported the onset point of temperature fluctuation and its frequency (Ma_{c2}=194 and 1.1Hz) of a molten tin column by the contacted diagnostic, i.e. J-type thermocouple. However, disturbances on the flow and temperature field are caused by a thermocouple which contacts with a fluid and a thermocouple often acts as a cold spot which makes it a complicated temperature gradient along a free surface. Takagi *et al.* (2001) observed the first and clear experimental evidence for the transition to oscillatory flow in a low Pr fluid by a non-contact diagnostic. It should be noted here that there is no successful experiment to verify the first and second transition behaviour of thermocapillary flow by a non-contact diagnostic. Furthermore, the first transition has not been found yet and the transition processes have never made clear experimentally. Therefore, we performed the experiment to reveal these unclear phenomena.

2. Experiment

Thermocapillary convection induced in half-zone liquid bridge of low Prandtl number was observed. Molten tin which $Pr \sim 0.01$ was employed as a working fluid. The experimental apparatus consists of a liquid bridge formation part, a measurement region, a sample supplying system and a sample cleaner. The liquid bridge was formed by sandwiching between a pair of pure iron disk (purity: 99.5%). Solid tin (purity: 99.999%) is melted in a quartz tube. The melt is supplied onto the lower disk via the capillary portion (1mm in inner diameter) of the quartz tube where bulk oxide in the crude fluid can be removed. All experiments were done in the ultra high vacuum conditions, which were under 10^{-5} Pa, to keep clean sample surface and less heat loss of molten tin liquid bridge.

To impose the temperature difference, the lower disk was cooled by helium gas and the upper disk was heated by an electric resistant heater. The electric heaters were not controlled by PID (Proportional, Integral and Derivative) control to circumvent the temperature hunting phenomena. The temperature difference was gradually increased from around 0K. An imposed ΔT was measured with the thermocouples embedded at near the end face of the disks. The measurement of temperature field was necessary to understand the oscillatory thermocapillary convection. Because the motion of temperature field was coincided with the one of oscillatory flow. The lower disk was optimized to measure the temperature field of liquid bridge as shown in Fig. 1. Several ϕ0.3 mm thermocouples (TC) sheathed by a stainless steel were inserted into 0.35 mm-holes at cold disk. The top of thermocouples was adjusted the same position as lower disk plane.

For low Prandtl thermocapillary flow, the temperature change or fluctuations at transition points is very small (e.g. 0.01 K for the first transition, 0.1 K for the second transition). Therefore, the sensitivity of temperature measurement system must be high. As mentioned, thermocouples and radiation thermometers are used to detect the temperature field of a liquid bridge. However, a temperature resolution of radiation thermometer used in this experiment is about 0.3 K. It is not enough to detect fluctuations. So, we used several thermocouples. Output signal from thermocouples is very tenuous in this case. E-type thermocouples that could produce relatively large thermal electromotive force were employed. In this experiment higher temperature resolution is important rather than absolute temperature. Such weak electromotive force of thermocouples was amplified. The voltage corresponding to thermocouple was produced by the DC signal generator (DC-SG). The signal from thermocouple was input to DC amplifier with the signal of DC-SG differentially in order to remove DC component. This signal was amplified to 5×10^4 times. The frequency of temperature fluctuation was estimated in order of several Hertz. So the low-pass filter was used to reduce the higher frequency noise. The signals were digitized by A/D converter and stored in PC. The temperature resolution of less than 0.01 K achieved by using this measurement system.

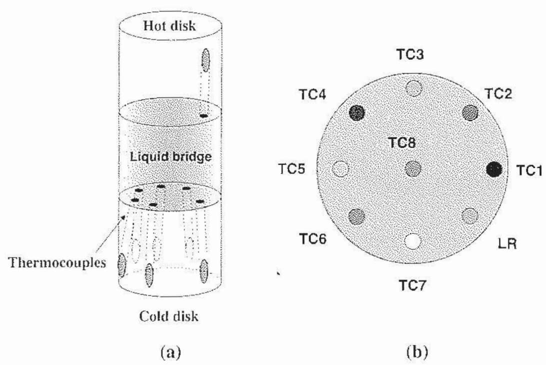


Fig. 1 Temperature measurement points (a) Schematic diagram of tin liquid bridge and disks (b) Position of thermocouples located between liquid bridge and cold disk ends (Top view)

3. Results and discussion

3.1 Observation of first transition

Fig. 2 shows time variations of temperature which were measured by three thermocouples located in cold disk. Temperature suddenly jumped around 1510 s which time is elapsed time from start of experiment. Since there could not be any oscillatory behavior after the temperature jump, this seems to be the first transition point which have been predicted by numerical simulation. In this case, aspect ratio of liquid bridge was 1.8, a temperature difference, ΔT, was 1.7 K, and Marangoni number was 11. From the relation between thermocouple position and temperature change, the mode structure seems to be unity and the cold spot located in the center of liquid bridge near cold disk moved to peripheral region as shown in Fig. 3.

3.2 Transition process of oscillatory flow

It was estimated by numerical simulation that several transitions occur after the onset of oscillatory flow. We divided each region as shown in Fig. 4. The onset of oscillation is called the second critical Maragoni number Ma_{c2} or $Mac_{2\text{-}1}$. The transitions after $Ma_{c2\text{-}1}$ were named $Ma_{c2\text{-}2}$ and $Ma_{c2\text{-}3}$ sequentially. In previous experiment, $Ma_{c2\text{-}1}$ could not detect because its signals was very small. Improvement of temperature measurement method provides us precise observation of just onset point.

An oscillatory transition was detected with larger temperature difference after an occurrence of first transition. The temperature fluctuation measured by thermocouple is shown in Fig. 5. At first, relatively higher frequency fluctuation with a frequency f = 1.2 Hz appeared at Ma_c = 43 (see Fig. 5 (i)). The amplitude of this fluctuation was about 0.1 $K_{p\text{-}p}$ (Peak to Peak). It was considered that this transition was the second critical point since the frequency was same order of numerical result which was 2.5 Hz. In this case, $Ma_{c2\text{-}2}$ could not detected. In Fig. 5 (ii), (iii), the lower and middle frequency fluctuations were depicted in case of As=1.2. The lower frequency with f = 0.02 Hz and an amplitude 0.4 $K_{p\text{-}p}$ appeared at Ma = 82 ($Ma_{c2\text{-}2}$). The middle frequency with f = 0.3 Hz and an amplitude 0.08 $K_{p\text{-}p}$ appeared at Ma = 125 ($Ma_{c2\text{-}3}$). The frequencies by numerical simulation were 0.04 Hz and 0.25 Hz respectively. Therefore, we believe that the transition process was detected very precisely.

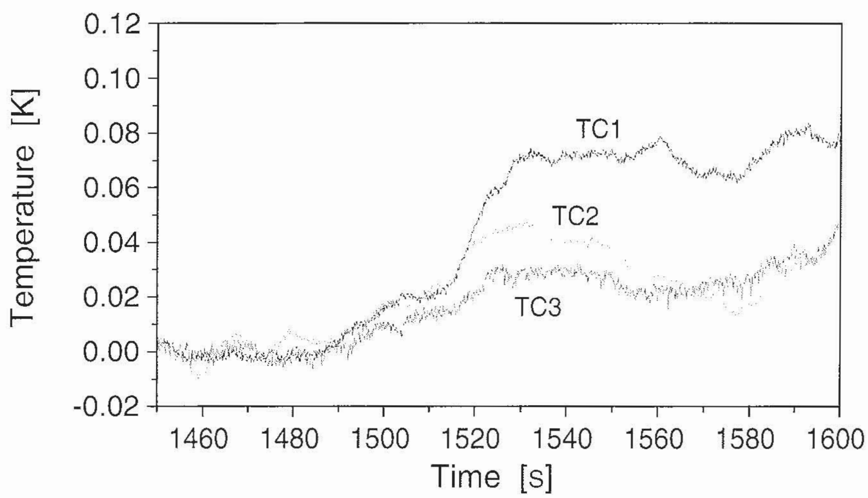


Fig. 2 Time variation of temperature near first transition

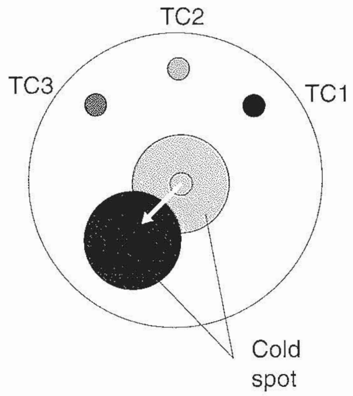


Fig. 3 Estimated mode structure

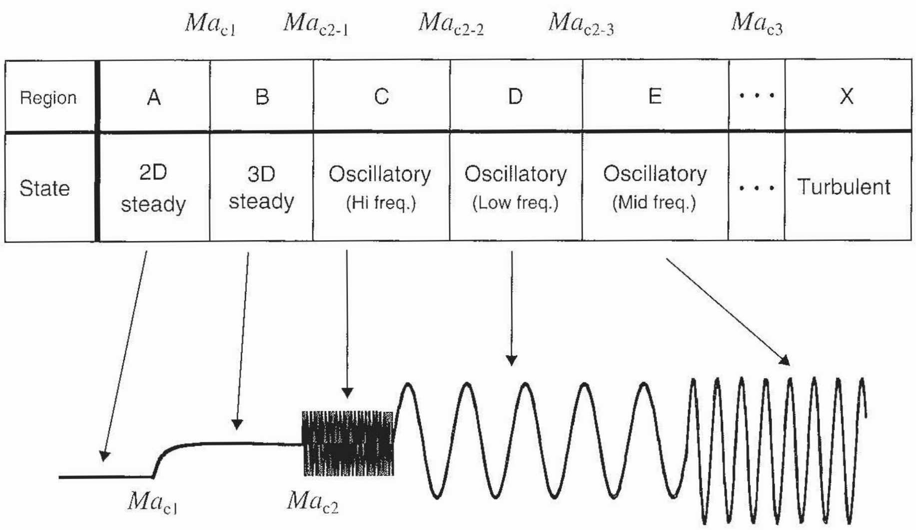
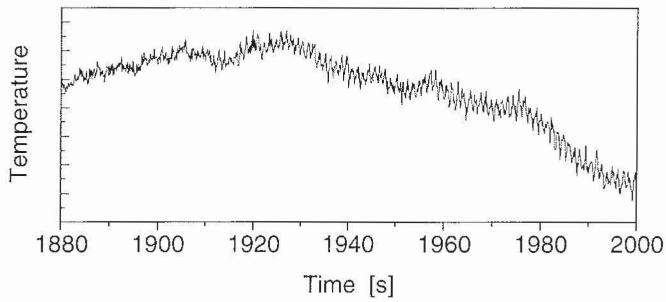
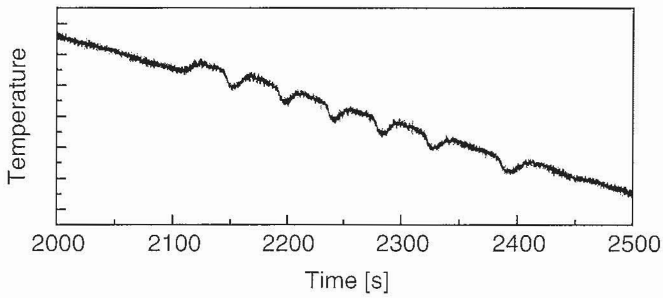


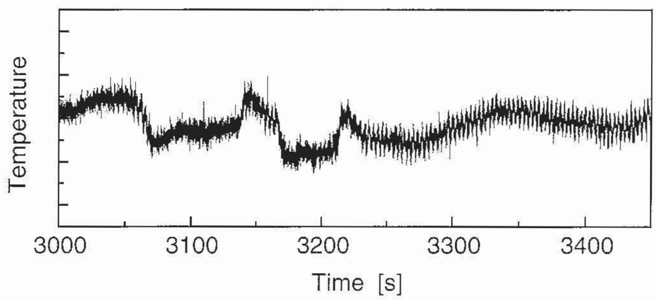
Fig. 4 Estimated transition process



(i) Region C (Higher frequency: 1.2 Hz)



(ii) Region D (Lower frequency: 0.02 Hz)



(iii) Region E (Middle frequency: 0.3 Hz)

Fig. 5 Time series of temperature after Ma_{c2}

Here, we will mainly mention about mode structure in *Region C* after $Ma_{c2\text{-}2}$. In this case, Aspect ratio was 1.4. Figure 6 shows time series of temperature in low frequency part, which frequencies were 0.016 Hz. Phase differences between each wave forms were clearly seen. Phase space diagram based on TC1 is shown in Fig. 7. Temperature fluctuations of TC3 and TC5 are in-phase and out of phase against that of TC1 respectively. That of TC2 is advance $\pi/2$ rad. Because diagonal position of TCs is in-phase and, special mode number m might be 2. And temporal mode seemed to be clockwise rotation. Taking into account of m=2, rotation rate would be 0.008 Hz which was half of frequency of temperature variation detected in the certain position.

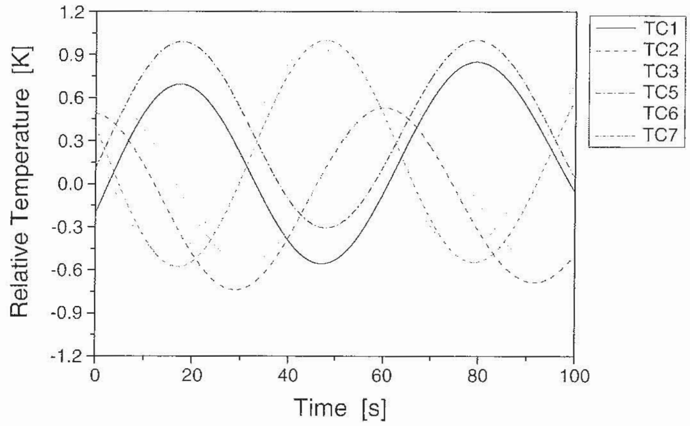
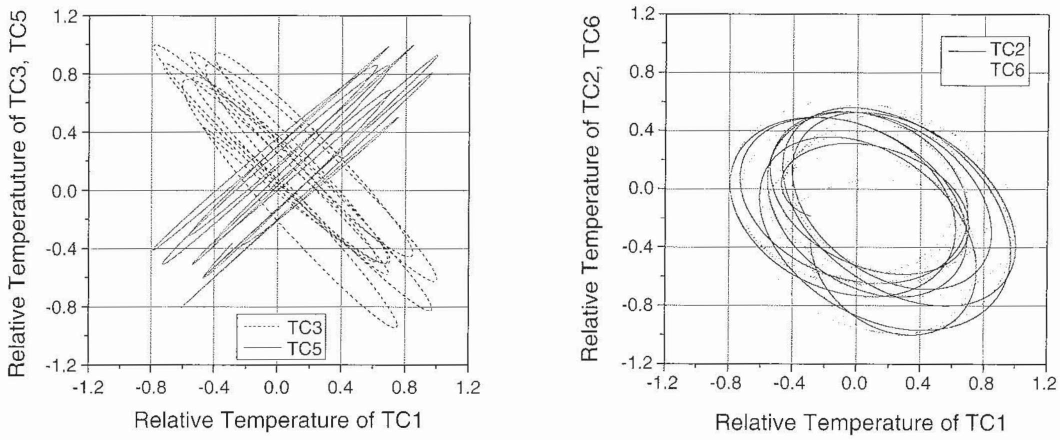


Fig. 6 Time variation of temperature at bottom of liquid bridge measured by thermocouples.



(i) TC3 and TC5 (ii) TC2 and TC6

Fig. 7 Phase space diagrams

Figure 8 shows the typical temperature time series measured by one of the thermocouples on the bottom disk. The inset of Fig. 8 is the closeup of area A. Looking this closeup, we notice that there is a boundary of time after which some coherent oscillation mode is observed. In fact, as shown in Fig.9 (a,b), the power spectra for both areas A1 and A2 obviously differ. While the spectrum P(f) for A1 is broad without any particular frequencies, that for A2 has a sharp peak at $f = f_{2\text{-}1}$ = 1.43 Hz. According to the value of ΔT = 6.08 K at the boundary time, we identified the value of $Ma_{c2\text{-}1}$ as 26.9.

For area B of Fig. 8, somewhat away from $Ma_{c2\text{-}1}$, the power spectrum has a peak at f = 1.58 Hz, which is a little different from the value just after $Ma_{c2\text{-}1}$. Although the variation of $f_{2\text{-}1}$ is continuous and gradual, hence no critical points can be identified, we note here the shift of $f_{2\text{-}1}$ with the increase of Ma.

Having specified $Ma_{c2\text{-}1}$ at which the f2-1-mode oscillation begins, we now try to specify $Ma_{c2\text{-}2}$. Looking Fig. 8 again, we notice that another mode of slow oscillation emerges at higher Ma. It was found that P(f) for area C has a peak at $f = f_{2\text{-}2}$ = 0.02 Hz, as shown in Fig. 9(c). We identify here the value of $Ma_{c2\text{-}2}$ as 31.0 (ΔT = 6.99 K). It was also found that for a region at much higher Ma, the spectrum comes to peak at a higher frequency, e.g., 0.08 Hz. Thus it was elucidated that $f_{2\text{-}2}$ shifts with the increase of Ma as in the case of $f_{2\text{-}1}$. As far as we know, the shift of these peak frequencies has not been reported so far

Figure 10 shows the dependence of critical Marangoni numbers on the aspect ratio of liquid bridge, where the data of the present experiment and of numerical simulation by Imaishi *et al.* (2001) are compared. Although the quantitative accordance between them may not be satisfying, they roughly agree well in a qualitative point of view.

Another notable result in the present experiment is the observation of the superposition of multiple modes. The closeup (figure not shown) of the temperature time series in area C of Fig. 8, which was characterized by the slow oscillation of $f_{2\text{-}2}$-mode, suggests that a fast oscillation mode is superimposed on the slow oscillation. In fact, P(f) has another peak at f = 1.64 Hz (see Fig. 9 (c)). Thus we conclude that coexistence of $f_{2\text{-}1}$- and $f_{2\text{-}2}$-modes was confirmed.

As was already mentioned, the superposition of multiple oscillation modes in Marangoni convection has been observed only in numerical simulations, but not in experiments so far. Therefore, we strongly notice here that the present observation of the coexistence of $f_{2\text{-}1}$- and $f_{2\text{-}2}$-modes is the first experimental confirmation of multiple oscillation modes.

Now that the temperature measurements are performed with the use of multiple thermocouples, we can derive some information taking advantage of the multipoint measurements, especially when the temperature evolution of each signal is quite similar to that of harmonic oscillation, as shown in Fig. 11. We now take notice of time lags between the signals. As mentioned above, the temperature time series $T_n(t)$ measured by the thermocouple Bn is well approximated by a trigonometric function;

$$T_n(t) = A_n \cos(\omega_0 t + \phi_n) \tag{3}$$

with a common frequency ω_0, specific amplitude An, and phase shift ϕ_n. We try to extract ϕ_n and take the following procedure. At first, $T_n(t)$ is multiplied by reference signals of $2\cos(-\omega_0 t)$ and $2\sin(-\omega_0 t)$ (the factor 2 is just for convenience),

$$\begin{aligned} T_n(t) \cdot 2\cos(-\omega_0 t) &= A_n \{\cos(\phi_n) + \cos(2\omega_0 t + \phi_n)\} \\ T_n(t) \cdot 2\sin(-\omega_0 t) &= A_n \{\sin(\phi_n) - \sin(2\omega_0 t + \phi_n)\} \end{aligned} \tag{4}$$

to produce two frequency components of 0 and $2\omega_0$. Then, the latter component is eliminated with the use of a low-pass filter;

$$\begin{aligned} I_n &\equiv [T_n(t) \cdot 2\cos(-\omega_0 t)]_{LP} = A_n \cos(\phi_n) \\ J_n &\equiv [T_n(t) \cdot 2\sin(-\omega_0 t)]_{LP} = A_n \sin(\phi_n) \end{aligned} \tag{5}$$

Now An and ϕ_n can be calculated by the following formulas:

$$\begin{aligned} A_n &= \sqrt{I_n^2 + J_n^2} \\ \phi_n &= \arctan(\frac{J_n}{I_n}) \end{aligned} \tag{6}$$

The values of ϕ_n calculated in this way are arranged in Table 1. This table suggests that the phase of temperature oscillation of one channel precedes that of its neighbor on the left by $\pi/2$. This then suggests the clockwise rotation of mode(2,1)-like temperature distribution as schematically shown in Fig. 12. This suggestion was confirmed by observing the time evolution of the temperature field reconstructed from the data of the thermocouples, where values at other points than the thermocouple positions are estimated by Kriging Interpolation.

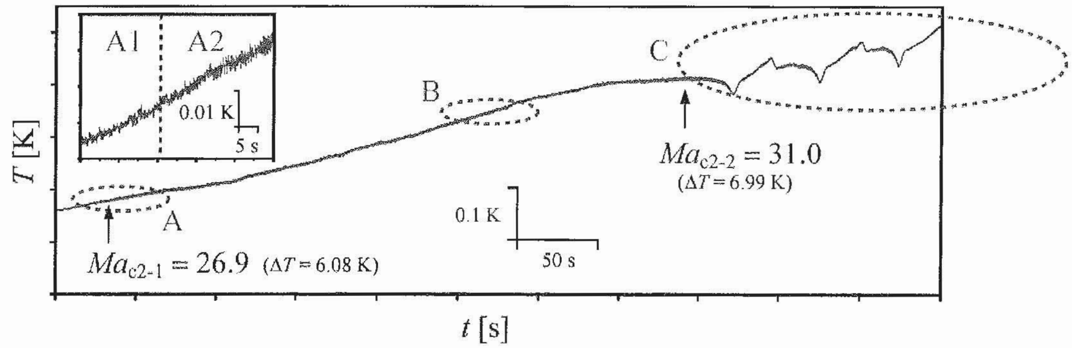


Fig. 8 Typical time series of temperature $T_n(t)$. Inset: Closeup of Area A.

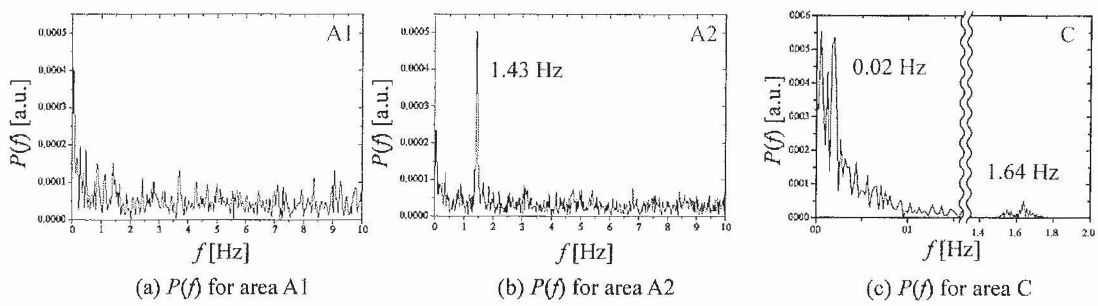


Fig. 9 Power spectra P(f) for areas A1 without particular frequencies (a), for A2 with a sharp peak (b), and for C having bimodal distribution (c).

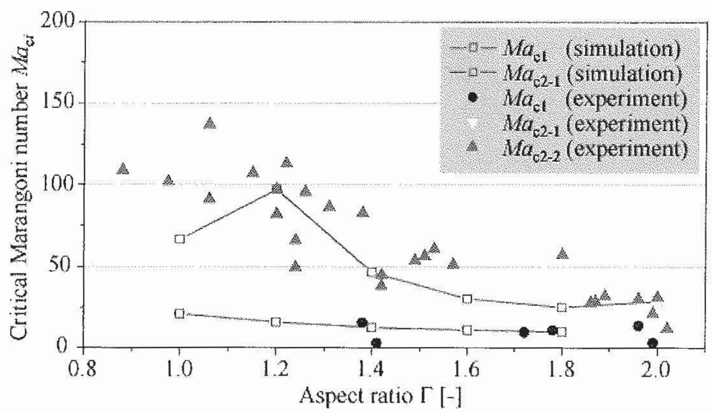


Fig. 10 Dependence of critical Marangoni numbers Ma_{ci} on aspect ratio A.

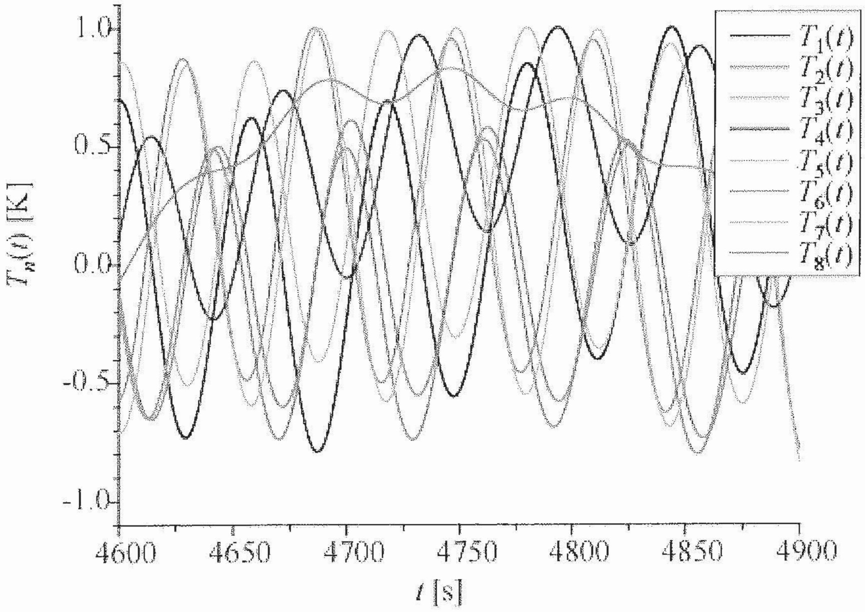


Fig. 11 Typical time series of $T_n(t)$ obtained in multipoint temperature measurements.

Table. 1 Values of phase shift ϕ_n.

TC	A_n	ϕ_n / π	$(\phi_n - \phi_1) / \pi$
B1	0.63	-0.48	0.00
B2	0.54	0.12	0.60
B3	0.65	0.58	1.06
B4	0.39	1.09	1.58
B5	0.64	-0.50	-0.02
B6	0.49	0.04	0.53
B7	0.70	0.52	1.00

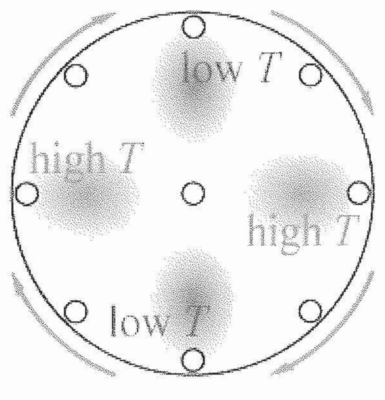


Fig. 12 Suggested temperature distribution and its rotation.

4. Preliminary test of flow visualization by using ultrasonic

One of still open problems concerning the thermocapillary flow is to reveal the transition of flow pattern and the mechanism of onset of oscillatory flow. In low Prandtl number fluid, few experimental works performed because of its difficulties which were relatively high temperature, necessity of anti-oxidation, measurement of very small temperature change, and so on. By overcoming those difficulties, we detected the transition behavior from axisymmetry to asymmetry steady flow and to oscillatory flow by the very fine temperature measurement. However, the flow field have never been observed directly since almost of low Prandtl number fluid (e.g. molten metals and semiconductors) were opaque. So, visualization techniques using a visible light could not used. Therefore, in order to obtain the internal flow pattern directly, the visualization technique using an ultrasonic wave has been developed. In this paper, we introduced the concept of visualization technique, the constitution of system, and the result of the verification test to check the capabilities. Visualization target is thermocapillary convection of molten tin liquid column.

The concept of visualization is quite conventional idea which is particle tracking technique. The three-dimensional positions of particles mixed into the working fluid are detected every moment. Therefore, the flow pattern can obtain by tracking the tracer positions. Nevertheless, the important issue of the system is how the particle positions can be searched in an opaque liquid. We employed the ultrasonic wave and spherical reflector as a tracer particle. The pulse-like ultrasonic wave was radiated to the working fluid and the echo from the tracers was sensed by eight transducers as shown in Fig. 13. As a result, the particle positions are made clear by a three-dimensional synthetic aperture method. Accordingly, the internal flow pattern can be visualized from dynamic position change of the tracers.

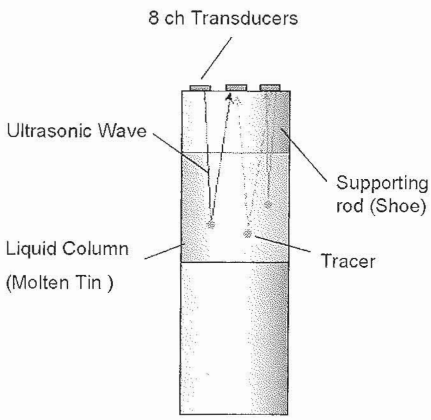


Fig. 13 Concept of Tracer Tracking in Liquid Column Configuration

The transducer/sensor design was determined by utilizing a numerical simulation and some tests. The $LiNbO_3$ (LN) single crystal was used as a piezoelectric element which was attached on titanium shoe. Eight array-like piezoelectric elements were attached on titanium shoe which also worked as upper hold rod of liquid column. The interface between titanium shoe and tin liquid column was chromized to avoid the reaction with each other.

For obtaining strong echo signal from a tracer particle, the particles are required to have high reflectance of ultrasonic beam. Since the target value of the reflectance is up to 95 %, acoustic impedance of a tracer particle should be less than 0.4×10^6 kg/m²/s. Considering this acoustic impedance, it is only attainable to make a "balloon like structured tracer particle" because acoustic velocity is extremely high. The tracer's base material is Shirasu-balloon (SB). With regard to the shape as a tracer particle, high sphericity is required. The moderate wettability and low reactivity strongly requires a thin metal coating layer on the SB particle too. Therefore, multi-layer structure, which diameter is from 100 to 500 μm, was adopted as shown in Fig. 14. The iron (Fe) layer reacts with molten tin in moderation, and keeps wettability with the surround liquid. The thickness of the layer plays a very important role of adjusting a density of the SB particle with molten tin on ground.

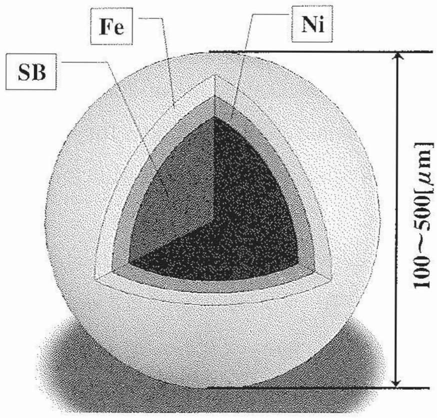


Fig. 14 Multi-layer Structure Tracer

The employed tracer particles are very small. Therefore, the reflective echo signal would be a very low level. Moreover, the transducer was attached on the shoe in order to protect an LN element to the molten tin. While the echo measured with a shoe attenuates, the sound noise by the inside reflection of a shoe was added. For realization of this system, it becomes very important to acquire the echo signal from the tracer by sufficient the signal to noise (SN) ratio.

The speed of the ultrasonic wave is very high compared with the speed of the moving tracer. Consequently, the noise which originates in the shoe by the subtraction processing technique was removable. And the SN ratio could be improved by the addition processing by repetition measurement, and the SN ratio improved about 3 times by calculation supposing actual measurement. Digital data acquisition after the 8 ch analog-digital converted. Maximal length interval of sound propagation is 15[μs] in molten tin liquid column. Run over time on measurement is 150 [μs] in consideration of reverberant sound. Imaging of aperture synthesis is 8 times transmission and 8 times reception on 1 flame. As well averaging procedure is FPGA on A/D converted hereby speeding up of processing time. This ultrasonic wave echo data was aperture synthesis photographic processing after the delta calculation. Aperture synthesis photographic processing is cut across the liquid column 8[mm]×8[mm]×6[mm] field about 32×32×384 mesh size compliant. Figure 15 shows the typical results of visualization in the acutual configuration, which is voxel expression after the aperture synthesis photographic processing. At the upper left cell is X-Y plane viewing angle of molten tin liquid column. At the upper right cell is Y-Z plane viewing angle, and at the lower left cell is X-Z plane viewing angle. This result demonstrates us to be able to visualize the internal flow filed in low Prandtl number liquid column.

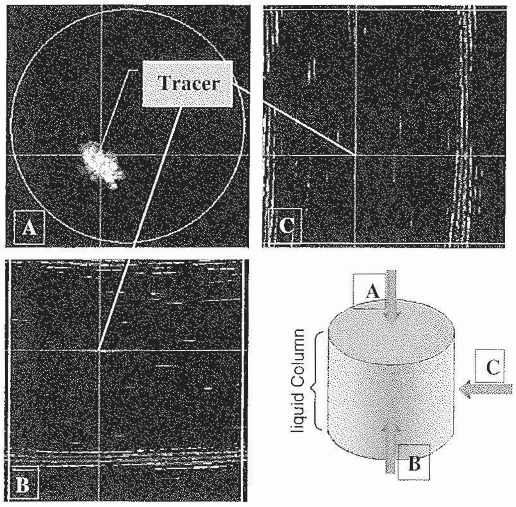


Fig. 15 Detection of Tracer Position in Actual Liquid Column Configuration by Aperture Synthesis

4. Conclusion

Experimental study on thermocapillary flow induced in the half-zone liquid bridge of low Prandtl number was carried out. Minute temperature variations could be detected by highly precise measurement system. Accordingly, the first transition process could be find for the first time. For the aspect ratio of 1.8, the first critical Marangoni number Ma_{c1} was 11. Moreover, the transition process from axisymmetric to oscillatory flows could be revealed and the mode structure appeared after $Ma_{c2\text{-}2}$ was made clear in case of aspect ratio 1.4. Just after the onset of oscillatory flow, high frequency (order of 1 Hz)and small amplitude temperature fluctuation appeared. Then the fluctuation has transited to low frequency ($\sim 10^{-2}$ Hz) and lager amplitude. After that, middle frequency ($\sim 10^{-1}$ Hz) has indicated. The mode structure appeared in a low frequency oscillation region after the onset was presumed from the phase differences among them. The mode structure was supposed to be 2 and rotation with a frequency of 0.008 Hz

The above results roughly agreed with those of numerical analyses, and motivate further studies. We quote the following issues as examples of our future works: Additional critical Marangoni numbers should be detected. For example, an oscillation mode of middle-frequency ($f_{2\text{-}3}$ = 0.2 Hz) has been known to exist beyond a certain value of Marangoni number ($Ma_{c2\text{-}3}$, so to speak). It would be reliable if $Ma_{c2\text{-}3}$ is detected in the series of detection of $Ma_{c2\text{-}1}$ and $Ma_{c2\text{-}2}$ in the present study. Also, the coexistence of $f_{2\text{-}1}$-, $f_{2\text{-}2}$- and $f_{2\text{-}3}$-modes, which has been observed in numerical simulations, should be confirmed in experiments. Furthermore, fluctuation behaviors at much higher Ma such as transition processes to chaotic or turbulent flow will be investigated in detail.

In addition to above experiment, the preliminary test to visualize the flow field by using ultrasonic wave was performed. The result demonstrates us to be able to visualize the internal flow filed in low Prandtl number liquid column.

Nomenclature

L	characteristic length	σ_T	temperature coefficient of surface tension
Ma	Marangoni number		
Pr	Prandtl number	**subscript**	
Re	Reynolds number	c1	first critical
α	thermal diffusivity	c2	second critical
ΔT	temperature difference		
μ	dynamic viscosity		

5. Acknowledgement

Part of this study is supported by the grant-in-aid for scientific research from the Japan Society for the Promotion of Science.

References

Azami, T., Nakamura, S. and Hibiya, T., 2001, Observation of periodic thermocapillary flow in a molten silicon bridge by using non-contact temperature measurements, J. Crystal Growth, 231 82-88.

Cröll, A., Muller-Sebert, W. and Nitsche, R., 1989, The critical marangoni number for the onset of time-dependent convection in silicon, Mat. Res. Bull., 24, 995-1004.

Han, J., Sun, Z., Dai, L., Xie, J.C. and Hu, W., 1996, Experiment on the thermocapillary convection of a mercury liquid bridge in a floating half zone, J. Crystal Growth, 169 129-135.

Imaishi, N., Yasuhiro, S., Akiyama, Y. and Yoda, S., 2001, Numerical simulation of oscillatory Marangoni flow in half-zone liquid bridge of low Prandtl number fluid J. Crystal Growth, 230, 164-171.

Kuhlmann, H., 1994, Hydordynamic Instabilities in Thermocapillary Flows, Microgravity Sci. Tech., VII/2, 75-82.

Li, K., Yasuhiro, S., Imaishi, N. and Yoda, S., 2005, Marangoni flow in half-zone liquid bridge of molten tin under ramped temperature difference, J. Crystal Growth, 280, 620-631.

Takagi, K., Otaka, M., Natsui, H., Arai, T., Yoda, S., Yuan, Z., Mukai, K., Yasuhiro, S. and Imaishi, N., 2001, Experimental study on transition to oscillatory thermocapillary flow in a low Prandtl number liquid bridge, J. Crystal Growth, 233, 399-407.

Nakamura, S., Hibiya, T., Kakimoto, K., Imaishi, N., Nishizawa, S., Hirata, A., Mukai, K., Yoda, S. and Morita, T., 1998, Temperature fluctuations of the Marangoni flow in a liquid bridge of molten silicon under microgravity on board the TR-IA-4 rocket, J. Crystal Growth, 186, 85-94.

Ueno, I., Tanaka, S. and Kawamura, H., 2003, Oscillatory and chaotic thermocapillary convection in a half-zone liquid bridge, Phys. Fluids, 15, 408-416.

Yang, Y.K. and Kou, S., 2001, Temperature oscillation in a tin liquid bridge and critical Marangoni number dependency on Prandtl number, J. Crystal Growth, 222, 135-143.

Yasuhiro, S., Akiyama, Y., Imaishi, N., Fujino, S. and Yoda, S., 2004, Oscillatory Marangoni flow in half-zone liquid bridge of molten tin supported between two iron rods, J. Crystal Growth 262, 631-644.

JAXA Research and Development Report JAXA-RR-05-023E

Date of Issue : March 31, 2006
Edited and Published by : Japan Aerospace Exploration Agency
7-44-1 Jindaiji-higashimachi, Chofu-shi, Tokyo 182-8522, Japan
URL: http://www.jaxa.jp/
Printed by : FUJIPLANS Co., Ltd.

Inquires about copyright and reproduction should be addressed to the Aerospace Information Archive Center, Information Systems Department, JAXA.
2-1-1 Sengen, Tsukuba-shi, Ibaraki 305-8505, Japan
phone: +81-29-868-5000 fax: +81-29-868-2956

Japan Aerospace Exploration Agency

Printed on Recycled Paper