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IIII Review IIII

Overview of "Dynamic Surf" Project in Kibo–Dynamic Behavior of Large-Scale Thermocapillary Liquid Bridges in Microgravity

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Abstract

This paper reports the overview of *Dynamic Surf* project conducted in the Japanese Experiment Module Kibo on board the International Space Station (ISS), especially focusing on the experimental conditions, the measurement systems, and the g-jitter effects. Oscillatory Marangoni convection in the liquid bridge is associated with oscillatory motion of the liquid-gas interface due to velocity oscillation inside the liquid bridge, where such a motion is called dynamic surface deformation (DSD). The present project aims at understanding the DSD effect in the transition mechanisms of temperature gradient-driven Marangoni convection in large-scale liquid bridges of high-Prandtl-number fluids through the long-term microgravity experiments on board the ISS. A series of microgravity experiments have been conducted in the period from September 2013 to November 2016 to understand the instability mechanisms and the role of DSD in Marangoni convection.

Keyword(s): Marangoni convection, Dynamic surface deformation, Micro-imaging displacement meter, G-jitter, High Prandtl number
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1. Introduction

Since the pioneering works by Thomson[1)] and Marangoni[2)] who studied fluid motions driven by the surface tension difference caused by the concentration distribution of the mixture of liquids, numerous studies on the surface tension-driven convection have been conducted. The surface tension (σ) depends on the concentration (C) and the temperature (T) of the liquid and many liquids have a negative temperature coefficient of σ (i.e., $\partial\sigma/\partial T < 0$) except for some special liquids such as self-rewetting fluids.[3)] The presence of non-uniform temperature distribution along the liquid-gas interface generates a flow from warmer surface toward cooler surface, known as Marangoni (or thermocapillary) flow. This Marangoni flow has been attracting many researchers in the fields of crystal growth, interfacial fluid mechanics, two-phase heat transfer, microgravity science and so on. In microgravity (μg, hereafter), the effect of surface tension on the fluid motion becomes of particular importance because of the absence of the body force.

The Marangoni flow occurs in liquid films, droplets, bubbles and liquid bridges (LBs, hereafter), and the present study focuses on the LBs heated differentially in the axial direction. Typical heating configurations are found in full-zone LBs and half-zone LBs. The former is observed in the floating-zone crystal growth[4)] while the latter is used for the fundamental study of Marangoni flow as proposed by Schwabe *et al.*[5)] **Figure 1** illustrates a half-zone LB in which the working liquid is suspended between the coaxial disks heated differentially. The temperature difference between the disks, $\Delta T = T_H - T_C$, drives the surface flow in the direction from the heated disk toward the cooled disk. The pressure gradient induced by the surface flow generates the return flow in the direction opposite to the surface flow to satisfy the mass conservation in the LB. These flows consequently form a toroidal flow pattern inside the LB as depicted in **Fig. 1**.

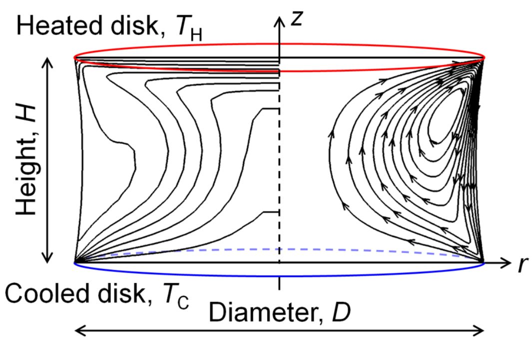

Fig. 1 Marangoni convection in a half-zone liquid bridge. The left and right parts exhibit the temperature contours and the streamlines, respectively.

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The Marangoni convection in a half-zone LB remains in an axisymmetric steady state for small ΔT but it starts to exhibit non-axisymmetric steady motions or oscillatory motions for large ΔT. The onset condition for such instability is specified by the critical temperature difference, ΔT_c, or the critical Marangoni number, Ma_c. Wanschura *et al.*[6] reported that the transition for low-Prandtl-number (Pr) liquids is due to the hydrodynamical instability that initiates the flow transition from an axisymmetric steady state to a non-axisymmetric steady state while the transition for high-Pr liquids is caused by the hydrothermal wave instability that triggers the flow transition from an axisymmetric steady state to a non-axisymmetric oscillatory state.

To understand better the instability mechanisms of Marangoni convection in LBs, a large number of μg experiments have been conducted since 1980s.[7] **Figure 2** is a chronological plot of the previous μg experiments conducted in the sounding rockets, in the Space Shuttles, and on the International Space Station (ISS). The disappearance of buoyancy and hydrostatic pressure in μg can provide an optimal environment for the study of Marangoni convection in LBs. In particular, large-scale LBs and resultant high-Marangoni-numbers (Ma) can be realized only in μg environment. Such an advantage is recognized from **Fig. 3** which compares the dimensions of the LBs formed (a, b) in the terrestrial experiments and (c-e) in the μg experiments. Note that all the LBs shown here have the same aspect ratio ($AR = H/D$) of 0.50, where AR denotes the ratio of the LB height to the disk diameter.

As for the effect of LB dimensions on the instability of Marangoni flows, Masud *et a l.*[8] have found from the data taken in the μg and on the ground that Ma_c increases with increasing LB dimensions and varies more than one order of magnitude within the data available at that time. Their findings were consistent with the experimental data of Ma_c for the instability of Marangoni flows in open cylindrical containers with high-Pr silicone oils.[9,10] Those findings suggest that Marangoni number

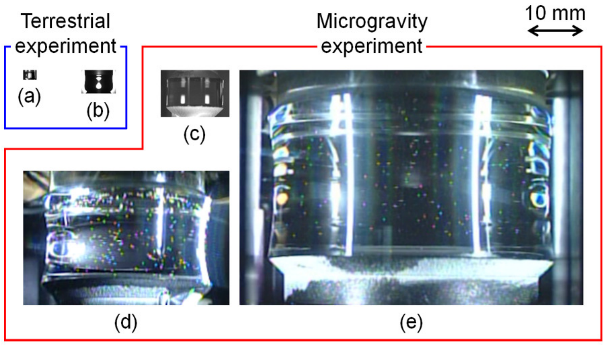

Fig. 3 Liquid bridges of $AR = 0.50$, where disk diameters, D, are (a) 2 mm, (b) 5 mm, (c) 10 mm, (d) 30 mm, and (e) 50 mm.

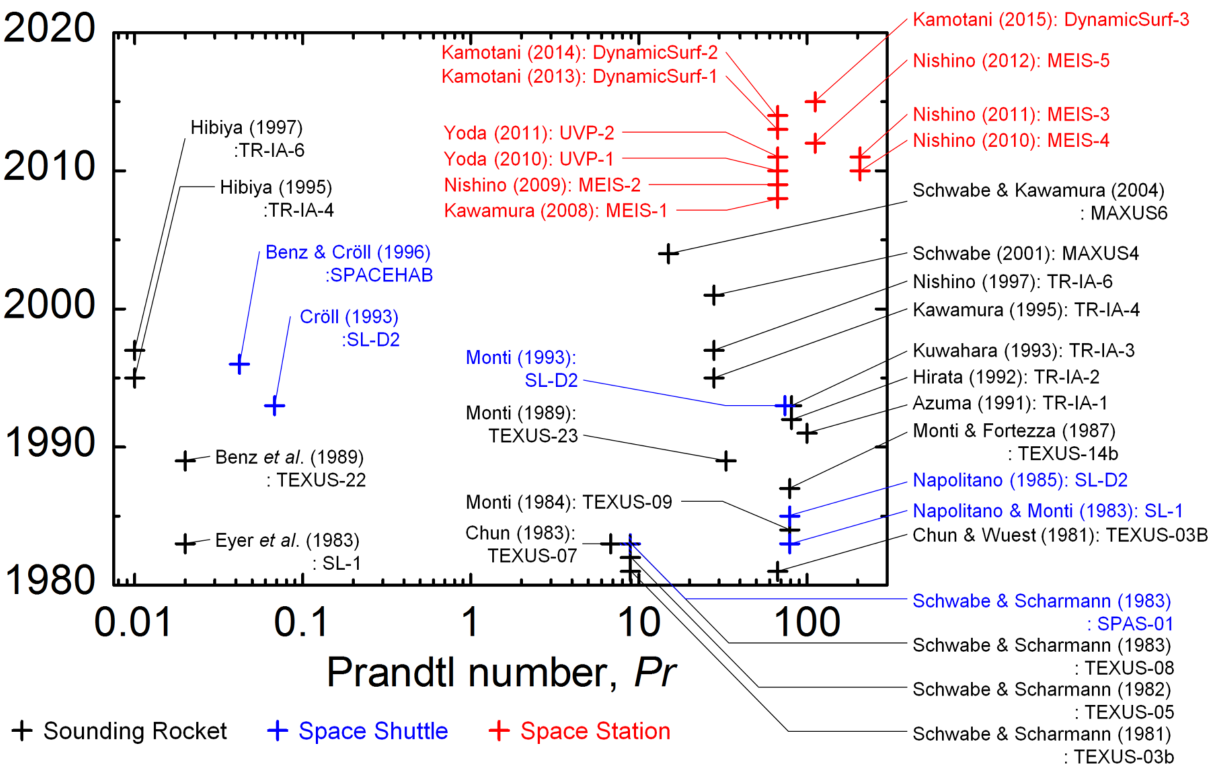

Fig. 2 The history of microgravity experiments on Marangoni convection in liquid bridges.

alone cannot specify the onset of oscillations and lead to the consideration of several effects such as the effect of dynamic surface deformation (DSD, hereafter), too fast heating of disk temperature in μg experiments, LB shape, and heat loss from the free surface. Kamotani & Ostrach [11] paid special attention to the effect of DSD on the onset of instability of Marangoni convection in large-scale LBs of high-*Pr* fluids. They assumed that DSD should play an active role in the instability mechanisms and proposed the *S*-parameter as a new non-dimensional number to explain the effect of LB dimensions on the instability mentioned above. Some papers reported small (or negligible) effects of DSD [12] and contradicted this hypothesis; however, the relation between the DSD and the instability of Marangoni convection is not fully understood yet due to the lack of data in μg.

A series of μg experiments called *Dynamic Surf* have been carried out in the Japanese Experiment Module Kibo on board the ISS. The unique aspects of the experiments are (1) to relate the onset conditions of oscillation to DSD near the hot corner, (2) to advance the oscillation model including DSD and *S*-parameter, (3) to take the free surface heat loss into account, and (4) to employ a novel technique to measure small DSD. The μg environment allows the formation of large-scale LBs, which is inevitable for checking the postulated oscillation model and clarify the physical mechanisms of oscillations. The present paper provides an overview of *Dynamic Surf* with placing emphasis on the experimental apparatuses and measurement technique that are specially designed and developed for this project as well as the gravitational condition in the Kibo.

2. Outline of *Dynamic Surf*

In the Kibo, two projects of μg experiments on Marangoni convection in the LB have been already conducted: *Marangoni Experiment in Space (MEIS)* [7] and *Marangoni-UVP*. The *Dynamic Surf* is the third project selected as an international collaboration of Japan, USA, and Canada. Its main target is the DSD generated by oscillatory Marangoni convection, and it is the first opportunity to measure the DSD in the μg environment. The general information of the present μg experiments are summarized in **Table 1**. The *Dynamic Surf* consists of three series of μg experiments with different experimental conditions, which are referred to as DS-1, 2, and 3 in this paper. The first series started on September 30, 2013 and the last one finished on November 30, 2016. A total of 92 runs of experiment were conducted.

Table 1 Summary of *Dynamic Surf* project.

	DS-1	DS-2	DS-3
Period	2013/09/30 ~ 2014/02/27	2014/12/17 ~ 2015/04/15	2015/11/19 ~ 2016/11/30
Disk diameter	$D = 30$ mm	$D = 10$ mm	$D = 30$ mm
Aspect ratio	$AR \leq 2.0$	$AR \leq \pi$	$AR \leq 2.0$
Working liquid	5 cSt silicone oil	5 cSt silicone oil	10 cSt silicone oil
Ambient gas	Argon	Argon or Neon	Argon
Cooled disk /Heated disk	Aluminum /Sapphire	Aluminum /Aluminum	Aluminum /Sapphire

The disk diameter is 30 mm in DS-1 and 3 while it is 10 mm in DS-2. These two types of disks with different diameters are used to investigate the effect of LB dimensions on the DSD. The working liquids are silicone oils (KF-96L-5cs and KF-96-10cs) manufactured by Shin-Etsu Co., Ltd., whose kinematic viscosities at 25 °C are 5 cSt in DS-1 and 2, and 10 cSt in DS-3 (cSt = mm^2/s). Their *Pr* ($= \nu/\alpha$) are 67 and 112, respectively. Other physical properties of the working liquids at 25 °C are summarized in **Table 2**, where ν is the kinematic viscosity, ρ the density, α the thermal diffusivity, k the thermal conductivity, and σ_T the temperature coefficient of surface tension. In this study, the constant physical properties are assumed except for σ and ν whose values at a temperature T [°C] are estimated from

$$\sigma(T) = \sigma(25\,^\circ\mathrm{C}) + \sigma_T (T - 25), \tag{1}$$

$$\nu(T) = \nu(25\,^\circ\mathrm{C}) \times \exp\left(5.892 \times \frac{25 - T}{273.15 + T}\right). \tag{2}$$

During DS-2, the ambient gas is changed from argon to neon in order to study the effect of interfacial heat transfer because the thermal conductivities of argon and that of neon are quite different (0.018 W/(m·K) vs. 0.049 W/(m·K)).

The *Dynamic Surf* project team consists of the science coordinator (Dr. Matsumoto from JAXA, Japan), the principal investigator (Prof. Kamotani from Case Western Reserve University, USA), the co-investigators (other authors of this paper), students (from Yokohama National University, Tokyo University of Science, Tohoku University, and University of Tsukuba), the user integration team, the facility development team, and other supporting members. Each run of experiment is conducted in the nighttime of the ISS, i.e. from 21:00 to 6:00 in Greenwich Mean

Table 2 Physical properties of working fluids at 25 °C.

	KF-96L-5cs	KF-96-10cs
Pr	67	112
ν [m^2/s]	5.0×10^{-6}	10.0×10^{-6}
ρ [kg/m^3]	915	935
α [m^2/s]	7.46×10^{-8}	8.94×10^{-8}
k [W/(m·K)]	0.12	0.14
σ [N/m]	19.7×10^{-3}	20.1×10^{-3}
σ_T [N/(m·K)]	-6.58×10^{-5}	-6.12×10^{-5}

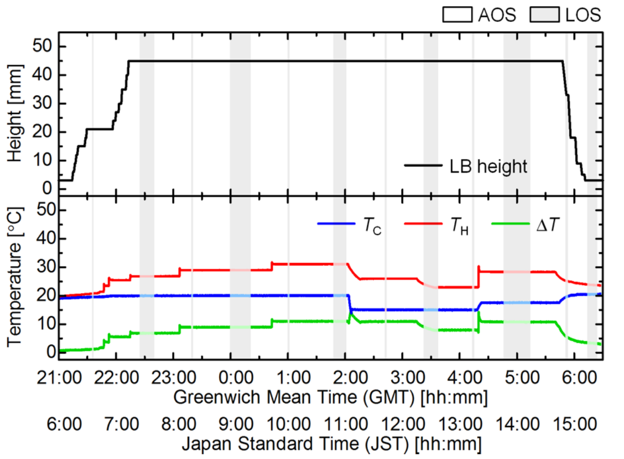

Fig. 4 Example of experimental procedure (GMT 2015/11/26 21:00 to 2015/11/27 6:30): liquid bridge height (upper) and disk temperatures (lower). AOS (Acquisition of Signal)/LOS (Loss of Signal) means the time zone during which the communication between ISS and ground is active/inactive.

Time (GMT). This period corresponds to the sleep time of the astronauts and therefore minimum disturbances due to crew activities are expected. The facility in the Kibo is operated from JAXA's Tsukuba Space Center in Japan. The time lag in the transmission of commands from the ground to the Kibo is only several seconds, realizing almost real-time operation. More details of the operation of μg experiments can be found in the paper reported by Nishino *et al.*[13]

Figure 4 shows an example of the experimental procedures. Firstly, they setup the gap between disks and form the LB with target height. Secondary, they start the temperature control of both cooled and heated disks and achieve constant T_{C}, T_{H}, and ΔT. Thirdly, after sufficiently long waiting time for the thermal diffusion, they collect the data (e.g., flow and temperature fields, images for DSD analysis), and then move to the next temperature step. Lastly, they stop the temperature control and close the disks. The waiting time for the thermal diffusion is estimated as L^2/α, where

$$\frac{1}{L^2} = \frac{1}{(D/2)^2} + \frac{1}{H^2}. \tag{3}$$

Nishino *et al.*[13] reported the significant effect of disk-heating speed on the measurement of Ma_{c}. They found that the difference of Ma_{c} between terrestrial experiments and μg experiments, as mentioned above, is due to the insufficient thermal diffusion time in the previous experiments in sounding rockets and Space Shuttles. However, the effect of DSD on the Marangoni convection is not completely understood yet, and the measurement of the DSD for large-scale LBs of high-*Pr* fluids is still important.

3. Experimental Apparatuses

Measurement systems of Marangoni convection in the LB of $D = 30$ mm and $D = 10$ mm are shown in **Figs. 5(a)** and **5(b)**, respectively. The nickname of experimental apparatus with 30 mm-diameter disk is MD30 and that with 10 mm is MD10. The common measurement devices for MD30 and MD10 are an infrared (IR) camera, a side-view camera, and a micro-imaging displacement meter (MIDM).

The IR camera is used to measure the surface temperature distribution, and this hardware is very important to visualize the propagation of hydrothermal waves (HTWs). The temperature resolution of present IR camera is 3 K per 256 gradation levels; however, its actual temperature resolution is order of ± 0.1 K due to the noise. The side-view camera is used to observe the LB shape as well as the overall flow pattern. As reported in some previous studies,[8] the LB shape is one of the important parameter for the instability of Marangoni convection. Therefore, the LB shape is always monitored by the side-view camera and the liquid volume is kept constant within the accuracy of ± 1 % during each temperature step. The DSD is measured by MIDM which consists of microscope objective, CCD camera, and traverse system. The LB surface is illuminated by a light-emitting diode (LED) array from the backside; therefore, the LB is appeared as a shaded area in the blighter background. Since the present MIDM system is traversable in axial, lateral, and focal directions, the axial distribution of DSD can be measured with well-focused images.

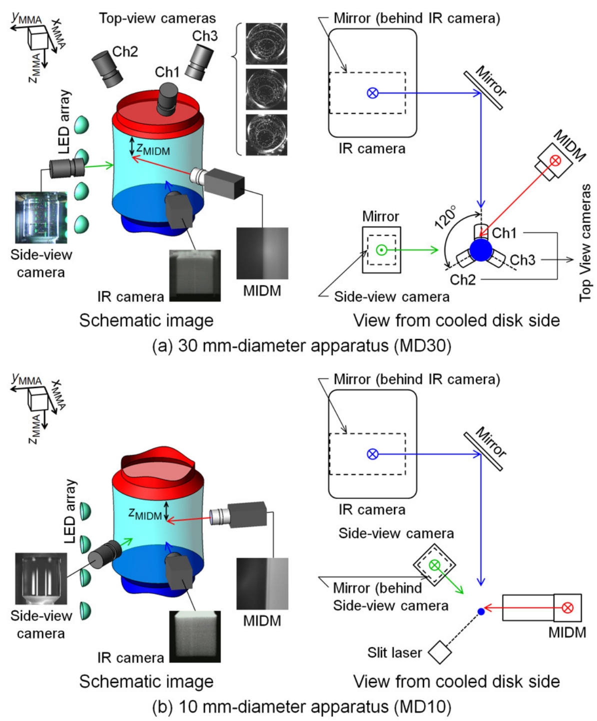

Fig. 5 Measurement apparatuses installed in the FPEF for (a) $D = 30$ mm and (b) $D = 10$ mm.

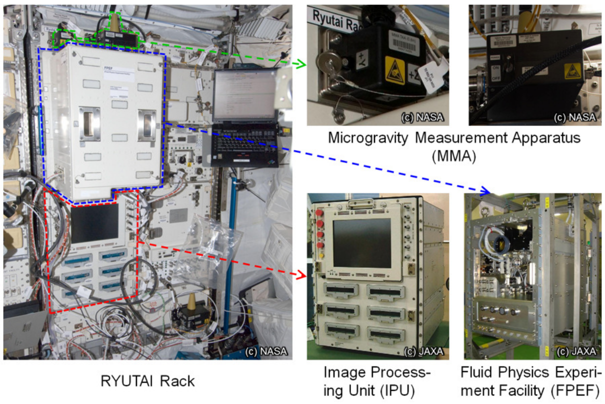

Fig. 6 Pictures of RYUTAI Rack, Fluid Physics Experiment Facility (FPEF), Image Processing Unit (IPU), and Microgravity Measurement Apparatus (MMA) installed in the Kibo (courtesy of NASA/JAXA).

Three top-view cameras are unique for MD30, which have been used for the three-dimensional flow measurement.[14] Those cameras can observe the flow field inside the LB through the transparent sapphire disk from the different view angles. The working liquids are seeded with metal coated tracer particles for the flow visualization and their positions on the planar images are converted to the three-dimensional space by means of stereo reconstruction technique. All these experimental apparatuses are installed in the Fluid Physics Experiment Facility (FPEF) in the payload rack specialized in the fluid dynamics research, which is named as RYUTAI Rack[13] (**Fig. 6**). The images captured by each camera are downlinked through the Image Processing Unit (IPU).

4. Measurement of Dynamic Surface Deformation (DSD)

The DSD of the small-scale LBs has been measured in the previous terrestrial experiments by several researchers, e.g., Kanashima *et al.*[15], Ferrera *et al.*[16], and Montanere *et al.*[17] In this study, the measurement method of DSD is basically same with the method of Kanashima *et al.*, where the original technique for the interface detection was developed by Nishino *et al.*[18]

Figure 7 shows the example of DSD measurement in DS-2 for the LB of $AR = 0.50$. **Figure 7(a)** shows a part of image captured by microscope camera (200×200 μm^2) and **Fig. 7(b)** shows the distribution of brightness level at the middle height in the image, where the analyzed region is marked with bashed lines in **Fig. 7(a)**. The actual field of views in radial and axial directions are 635×475 μm^2 for MD30 and 242×321 μm^2 for MD10, respectively. The procedures for the detection of the liquid-gas interface are as follows.

(1) Average the brightness level in the longitudinal direction to improve the signal-to-noise ratio (SNR). In **Fig. 7**, the brightness level is averaged over 11 pixels, thus the SNR is improved by a factor of $\sqrt{11} \approx 3.3$.

(2) Calculate the gradient of averaged brightness level along the horizontal direction. The tentative liquid-gas interface is obtained as the point with the maximum brightness gradient.

(3) Obtain the third-order polynomial fitting curve of averaged brightness level in the region ±12 pixels before and behind the tentative liquid-gas interface. Inflection point of this fitting curve is regarded as the actual liquid-gas interface.

Resultant displacement of the liquid-gas interface at 1.1 mm below the heated disk is shown in **Fig. 8(a)**, where the data were obtained in the period from 3:24:49 to 3:25:04 GMT on December 17, 2014. Note that ΔT is 20.8 K and the flow regime is the oscillatory state. The detection of the liquid-gas interface is successful in understanding the characteristics of the DSD and this result is used for further data analysis. Amplitude spectrum of **Fig. 8(a)** is calculated by means of discrete Fourier analysis and the result is shown in **Fig. 8(b)**. The sampling rate of CCD cameras used in the present μg experiments is 29.97 frames/s, thus the maximum frequency resolution is around 15 Hz. There are two typical peaks of amplitude spectrum: one appears at around

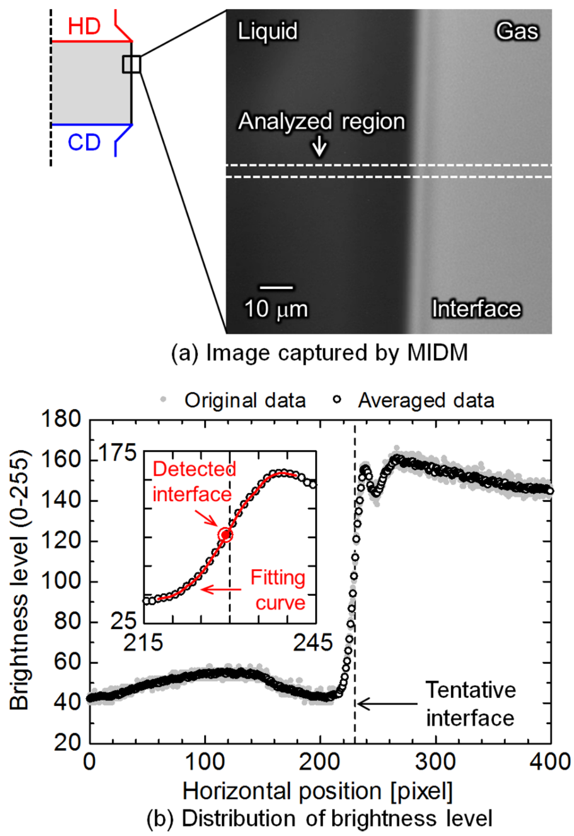

Fig. 7 Example of DSD measurement: (a) image captured by MIDM, and (b) horizontal distribution of brightness level.

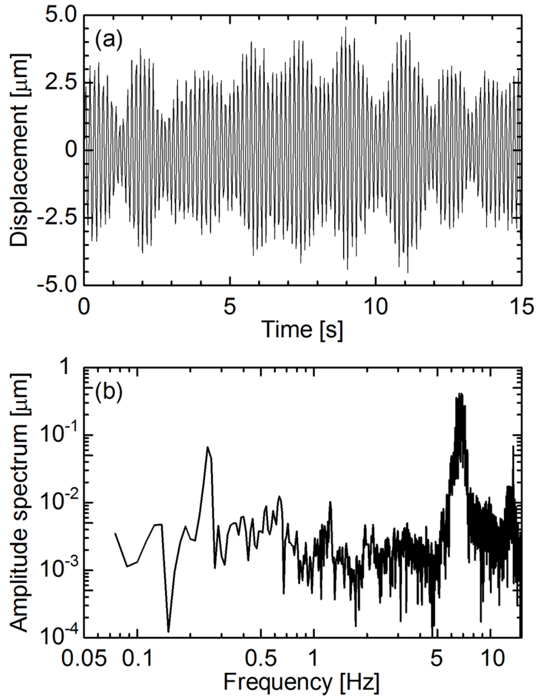

Fig. 8 Result of DSD measurement: (a) displacement of liquid-gas interface, and (b) its amplitude spectrum.

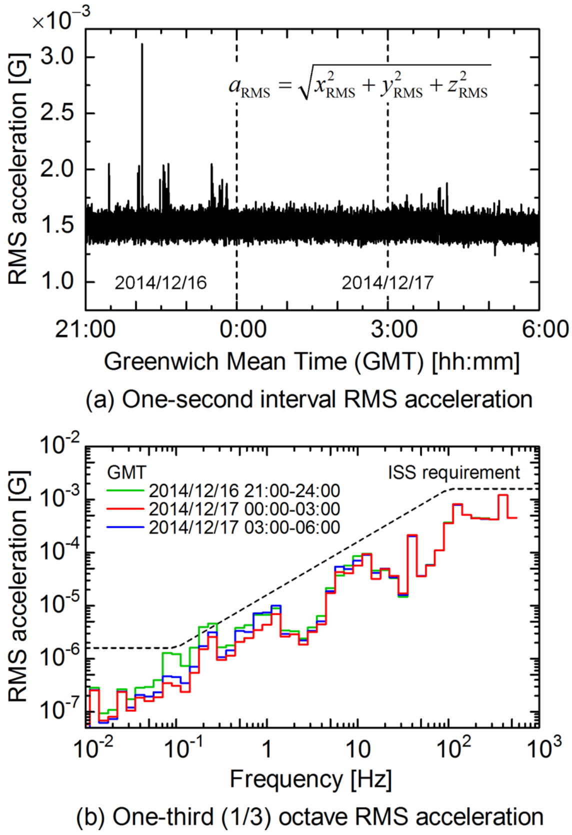

Fig. 9 G-jitter on the Kibo in the period from 2014/12/16 21:00 to 2014/12/17 6:00 GMT: (a) one-second interval RMS acceleration, and (b) one-third octave RMS acceleration.

0.25 Hz and the other at around 6.5 Hz. It is found that the former peak is due to the oscillatory Marangoni convection in the LB and the latter is due to the external disturbance, i.e., g-jitter. More detail of the relation between the DSD and the instability of Marangoni convection will be reported in near future.

5. Residual Acceleration of Gravity (G-Jitter)

There is a residual acceleration of gravity called g-jitter on the ISS, which is caused by the crew activities, thruster firing, mechanical vibration, docking/undocking with spacecrafts, and so on.[13,19] Such an external disturbance affects the dynamic motion of the LB, therefore, g-jitter during each experiment was measured to understand its influence. As shown in **Fig. 6**, the acceleration sensor called Microgravity Measurement Apparatus (MMA) is installed near the FPEF and its measured data can be downloaded from the NASA's website, i.e., Principal Investigator Microgravity Services (PIMS).

Figure 9(a) shows the magnitude of one-second interval root-mean-square (RMS) accelerations in the period from 21:00 GMT on December 16, 2014 to 6:00 GMT on the next day, where G denotes the acceleration normalized by the earth gravity ($\approx$ 9.8 m/s^2). It is obvious that g-jitter condition in the early period of the experiment (before 0:00 o'clock) is rather severe than that in the later period (after 0:00 o'clock). To understand the characteristics of g-jitter in more detail, the one-third (1/3) octave band analysis[19] is applied. The original acceleration data are divided into three groups and the resultant 1/3 octave RMS accelerations are plotted in **Fig. 9(b)**. Also plotted in this graph is the vibratory requirement of the ISS (a_{ISS}),[20] where

$$a_{\mathrm{ISS}} \le 1.6 \times 10^{-6} \text{ G for } f \le 0.1 \text{ Hz},$$

$$a_{\mathrm{ISS}} \le f \times 1.6 \times 10^{-5} \text{ G for } 0.1 \le f \le 100 \text{ Hz, and}$$

$$a_{\mathrm{ISS}} \le 1.6 \times 10^{-3} \text{ G for } f \ge 100 \text{ Hz}.$$

The difference of RMS accelerations is remarkable for $0.03 < f < 2$ Hz. It is known that the frequency band of g-jitter caused by the crew activities is $0.06 < f < 4$ Hz,[19] following that the difference of RMS accelerations shown in **Fig. 9(b)** is mainly due to the crew activities. In other words, sleeping/waking of the astronauts definitely affects the experimental environment in the Kibo. Thanks to the contribution of the ISS crews, the RMS accelerations after 0:00 o'clock are lower than the ISS requirement for every frequency range and it is very helpful for the success of this project. The detailed relation between the DSD and g-jitter will be reported in near future.

6. Summary

This paper reports the overview of a series of microgravity (μg) experiments on the instability of Marangoni convection. This science mission is called *Dynamic Surf* and it has been conducted in the Japanese Experiment Module Kibo on board the International Space Station (ISS). The present μg experiments started on September 30, 2013 and finished on November 30, 2016. The main target of *Dynamic Surf* project is to understand the dynamic surface deformation (DSD) effect on the transition scenario of temperature gradient-driven Marangoni convection in large-scale liquid bridges of high-Prandtl-number fluids. Due to the velocity variation of the surface flow of oscillatory Marangoni convection, the small oscillation of liquid bridge surface, i.e., DSD, occurs. The DSD for large-scale liquid bridges were measured by using the micro-imaging displacement meter (MIDM) and the precise measurement of DSD was realized. The residual acceleration of gravity called g-jitter crucially affects the motion of the liquid-gas interface. G-jitter was measured during each experiment and its characteristics were studied through the frequency analysis.

Acknowledgments

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References

1) J. Tomson: Philos. Mag. Ser. 4, **10** (1855) 330.
2) C. Marangoni: Ann. Phys. Chem., **143** (1871) 337.
3) Y. Abe, A. Iwasaki, K. Tanaka: Microgravity Sci. Technol., **16** (2005) 148.
4) P. H. Keck: Physica, **20** (1954) 1059.
5) D. Schwabe, A. Scharmann, F. Preisser, R. Oeder: J. Cryst. Growth, **43** (1978) 305.
6) M. Wanschura, V.M. Shevtsova, H.C. Kuhlmann, H.J. Rath: Phys. Fluids, **7** (1995) 912.
7) H. Kawamura, K. Nishino, S. Matsumoto, I. Ueno: J. Heat Transfer, **134** (2012) 031005-1.
8) J. Masud, Y. Kamotani, S. Ostrach: J. Thermophys. Heat Transfer, **11** (1997) 105.
9) Y. Kamotani, S. Ostrach, J. Masud: Int. J. Heat Mass Transf., **42** (1998) 555.
10) Y. Kamotani, S. Ostrach, J. Masud: J. Fluid Mech., **410** (2000) 211.
11) Y. Kamotani, S. Ostrach: J. Heat Transfer, **120** (1998) 758.
12) H.C. Kuhlmann, Ch. Nienhüser: Fluid Dyn. Res., **31** (2002) 103.
13) K. Nishino, T. Yano, H. Kawamura, S. Matsumoto, I. Ueno, M. K. Ermakov: J. Cryst. Growth, **420** (2015) 57.
14) T. Yano, K. Nishino, I. Ueno, S. Matsumoto, Y. Kamotani: Phys. Fluids, **29** (2017) 044105-1.
15) Y. Kanashima, K. Nishino, S. Yoda: Microgravity Sci. Technol., **16** (2005) 285.
16) C. Ferrera, J. M. Montanero, A. Mialdun, V. M. Shevtsova, M. G. Cabezas: Meas. Sci. Technol., **19** (2008) 015410-1.
17) J. M. Montanero, C. Ferrera, V. M. Shevtsova: Exp. Fluids, **45** (2008) 1087.
18) K. Nishino, H. Kato, K. Torii: Meas. Sci. Technol., **11** (2000) 633.
19) M. Goto, K. Murakami, H. Ookuma: J. Jpn. Soc. Microgravity Appl., **28** (2011) 9 (in Japanese).
20) N. J. Penley, C. P. Schafer, J.-D. F. Bortoe: Acta Astronaut., **50** (2002) 691.