Proposal of Experimental Setup on Boiling Two-phase Flow on-orbit Experiments onboard Japanese Experiment Module "KIBO"

S Baba¹, T Sakai¹, K Sawada¹, C Kubota¹, Y Wada¹, Y Shinmoto¹, H Ohta¹, H Asano², O Kawanami³, K Suzuki⁴, R Imai⁵, H Kawasaki⁶, M Takayanagi⁶ and S Yoda⁶

¹ Department of Aeronautics and Astronautics, Kyushu University, 744 Motooka, Nishi-ku, Fukuoka, Japan
² Department of Mechanical Engineering, Kobe University, 1-1 Rokkoudai-chou, Nada-ku, Kobe, Hyogo, Japan
³ Department of Mechanical and System Engineering, University of Hyogo, 2167 Shosha, Himeji, Hyogo, Japan
⁴ Department of Mechanical Engineering, Tokyo University of Science, Yamaguchi, 1-1-1 Daiga-kudori, Sanyo-Onoda, Yamaguchi, Japan
⁵ IHI Corporation, 1 Shin-nakahara-chou, Isogo-ku, Yokohama-shi, Kanagawa, Japan
⁶ Japan Aerospace Exploration Agency, 2-1-1 Sengen Tsukuba-shi, Ibaraki, Japan

E-mail: s_baba@aero.kyushu-u.ac.jp

Abstract. Boiling is one of the efficient modes of heat transfer due to phase change, and is regarded as promising means to be applied for the thermal management systems handling a large amount of waste heat under high heat flux. However, gravity effects on the two-phase flow phenomena and corresponding heat transfer characteristics have not been clarified in detail. The experiments onboard Japanese Experiment Module “KIBO” in International Space Station on boiling two-phase flow under microgravity conditions are proposed to clarify both of heat transfer and flow characteristics under microgravity conditions. To verify the feasibility of ISS experiments on boiling two-phase flow, the Bread Board Model is assembled and its performance and the function of components installed in a test loop are examined.

1. Introduction
Recent increase in the size of space platforms requires the management of larger amount of waste heat under high heat flux conditions and the transportation of it along a long distance to the radiator. Flow boiling applied to the thermal management system in space attracts much attention as promising means to realize high-performance heat transfer and transport. In microgravity two-phase flow phenomena are quite different from those under normal gravity conditions because buoyancy effects are significantly reduced and surface tension becomes dominant.

Although a number of experiments on boiling heat transfer in microgravity were conducted worldwide from the 1970s to the present, and reviewed by Di Marco [1], Kim [2] and Ohta [3]. Ohta [4] investigated for flow boiling in a transparent heated tube coated with gold thin film for different gravity levels along the parabolic trajectory of an aircraft. In the annular flow regime, at heat flux not high enough to initiate the nucleate boiling, the heat transfer coefficient in microgravity deteriorates...
due to the increase in the thickness of annular liquid film and the reduction of turbulence in it. No marked gravity effect on the heat transfer is observed when the heat transfer is dominated by nucleate boiling.

On the other hand, the effects of direction of gravity vector on flow boiling were conducted by the researchers. Zhang et al. [5] changed orientation of narrow channel and examined the influence on the critical heat flux. Flow boiling experiments were conducted by using the rectangular narrow channel with heating surfaces of lengths 101.6mm, width 30mm and gap size 2.5mm. At low velocity experiments, especially for saturated conditions, critical heat flux for downward flow was much smaller than for upward flow. Kandlikar and Balasubramanian [6] conducted effects of channel orientation on flow boiling heat transfer by using the rectangular narrow channels with 1.054mm width, 0.197mm depth and a hydraulic diameter of 0.333 mm. They also observed heat transfer coefficients in the vertical downward flow are higher than those in vertical upward flow and horizontal flow. Bower and Klausner [7] proposed the gravity dependent/independent regime map on subcooled flow boiling heat transfer by changing orientations of in rectangular narrow channel. They employed Jakob number $Ja$ and dimensionless flow rate parameter $\psi$ as important parameters for defining the gravity dominant regime.

However, gravity effects on the two-phase flow phenomena and corresponding heat transfer characteristics have not been clarified in detail. The experiments onboard the International Space Station (ISS) is proposed to clarify systematically the data and corresponding mechanisms for both of heat transfer and of flow characteristics under microgravity conditions. The establishment of dominated force regime maps by the introduction of appropriate dimensionless groups is also an important objective, because the design of space thermal devices under the conditions of no gravity effect becomes more reliable based mainly on the ground test. In Figure 1, red lines in the figure are the proposed boundaries based on the recent data for flow boiling in mini-channels [8]. Bond number $Bo$, Weber number $We$ and Froude number $Fr$ are defined here

$$Bo = \frac{(\rho_1 - \rho_v)gd_i^2}{\sigma} \quad (1)$$

$$We = \frac{\rho_m u_{m}^2 d_i}{\sigma} = \frac{G^2 d_i}{\rho_m \sigma} \quad (2)$$

**Figure 1.** Existing results on dominated force regimes map (Black dashed lines) and latest boundaries (Red solid lines).
where, $d_i$: tube inner diameter, $G$: mass velocity, $u_m$: mean velocity, $\rho_m = 1/[x/\rho_l + (1-x)/\rho_v]$: mean density of liquid and vapor, $x$: vapor quality. Therefore, $Bo$, $We$ and $Fr$ represent ratios of buoyancy to surface tension, inertia to surface tension and inertia to buoyancy, respectively. In the body force dominated region, effects of gravity level and flow direction become significant. In the Inertia dominated region, effects of mass velocity and vapor quality are observed, and in the surface tension dominated region, effects of gravity, mass velocity and vapor quality become small. There are four points to be clarified concerning the present regime map.

1. Boundaries of regimes are doubtful.
2. Definitions of parameters should be revised.
3. Parameters and boundaries should be changed by different targets such as heat transfer coefficient, flow patterns, pressure drop and critical heat flux.
4. Influence of vapor quality is unknown. Increase in vapor quality increases inertia force due to the increase in liquid-vapor mixture velocity despite of decrease in mixture density.

It is doubtful that the effect of gravity level is equivalent to the effect of the gravity direction on definition of regime boundary between the body force dominated and the surface tension dominated through Bond number. The microgravity experiments are useful for the verification of the effect of gravity level on these regimes. Figure 2 shows points of experimental conditions for the ISS and ground experiments on the dominated force regime map. In further studies, the results obtained under microgravity conditions are to be reflected to confirm the effect of gravity level on the boundaries at very low Bond numbers.

In the present paper, a test loop is proposed for ISS experiments under the limited resources of volume size and power supply, and preliminary experiments on flow boiling are performed on ground.
2. Experiment

2.1. ISS experimental overview

The experiments are conducted using the Multi-purpose Small Payload Rack (MSPR) onboard Japanese Experiment Module (JEM) "KIBO" in ISS and the experimental apparatus developed for MSPR. MSPR is resource platform providing user equipment; space, power, communication (Ethernet, IEEE1394), video, cooling and fluid interface (nitrogen, vacuum). Experiment utilizing MSPR expands from life science to fluid science. They are launched in HTV (H-IIA Transfer Vehicle). The
Table 1. Experimental conditions for ISS.

| Parameter                  | Condition |
|----------------------------|-----------|
| Tube inner diameter        | $d_i = 4.0$ mm |
| Working fluid              | FC72 (deaerated) |
| Mass velocity              | $G = 30-600$ kg/m²s |
| Heat flux                  | $q = 1-100$ kW/m² |
| Inlet condition            | $\Delta T_{sub,in} = 0-10$ K, $x_{in} = 0-0.9$ |

Table 2. Experimental conditions in the present study.

| Parameter                  | Condition |
|----------------------------|-----------|
| Test section               | Metal heated tube |
| Tube inner diameter        | $d_i = 4.0$ mm |
| Tube outer diameter        | $d_o = 10.0$ mm |
| Heated length              | $L = 368$ mm |
| Working fluid              | FC72 (deaerated) |
| Outlet pressure            | $P_{in} = 0.10-0.25$ MPa |
| Mass velocity              | $G = 40-500$ kg/m²s |
| Heat flux                  | $q = 0.5-60$ kW/m² |
| Inlet condition            | $\Delta T_{sub,in} = 0$, $10$ K, $x_{in} = 0.1$ |
| Flow direction             | $\phi = 0^\circ$ (Horizontal flow) |
|                           | $\phi = 90^\circ$ (Vertical upward flow) |

flight model is installed in Work Volume (WV) which is a workspace for the experiments; 600mm height $\times$ 900mm width $\times$ 700mm depth. WV can provide cooling water system through contact with cold plate installed on the bottom panel of WV and avionics air for cooling the equipment.

2.2. Experimental apparatus on ground

Outline of BBM test loop similar to the flight model is shown in Figure 3 and 4. The components are assembled horizontally inside a two-dimensional rectangular frame to replace the components easily and to change the flow direction against the gravity. The experimental apparatus has two different heated test sections of a transparent heated tube and a metal heated tube, and unheated test sections of acrylic tubes placed at downstream of each heated tube. Inner diameter of these tubes is 4 mm. Thermal conditions at the inlet of the test section are adjusted by a preheater. The total power input is
removed in a condenser to obtain the steady state data, where inlet cooling water temperature and flow rate were regulated simulating the system of cooling water circulated in KIBO. The experimental conditions for ISS and these in the present study are shown in Table 1 and 2, respectively. The pressure at the accumulator is kept at near atmospheric pressure, where the saturation temperature is 56 °C for fluorinert FC72 employed as a test fluid. Nevertheless, outlet pressure of the tube is the range from 0.10–0.25 MPa depending on the pressure drop downstream. Flow boiling heat transfer with FC72 in a small diameter tube is influenced by dissolved air, as mentioned in our previous report [9]. Test fluid in the reservoir was initially degassed by preheating of the experiments.

2.2.1. Metal heated tube. The metal heated tube is used for the measurement of critical heat flux and the detailed distribution of local heat transfer coefficients along a tube axis. Test tube is shown in Figure 5. The distribution of inner wall temperature, heat flux, fluid temperature, vapor quality, and

**Figure 6.** Transparent heated tube, one segment.

**Figure 7.** Images of liquid-vapor behaviors thorough a transparent heated tube in horizontal flow for different flow patterns. (a) Bubble flow, (b) Slug flow, (c) Separated flow.
heat transfer coefficient along the heated section is calculated as discrete values at each location of 10 thermodocytes based on the measured outer wall temperatures, flow rate, inlet liquid temperature, and inlet/outlet pressure. The heat loss from the outer tube wall to the ambient is evaluated by the difference between the outer wall temperature and ambient temperature, which is calibrated in advance. By the introduction of insulation and thin thermodocytes, the heat loss is minimized to 45% even at the lowest heat flux tested. The inner wall temperature and the inner wall heat flux at each thermodocyte location are evaluated by the radial heat conduction from the measured outer wall temperature and the local heat generation rate, taking into account the heat loss.

The inlet liquid temperature is measured by a K-type sheathed thermodouple inserted. The local heat transfer coefficient $\alpha$ at the location of each thermodouple is defined by

$$\alpha = \frac{q}{T_w - T_f}$$  \hspace{1cm} (4)

where, $q$: inner wall heat flux to fluid, $T_w$: inner wall temperature, $T_f$: mean fluid temperature. $T_f$ is evaluated from the heat balance equation. The saturation temperature $T_{sat}$ is used as $T_f$ in the vapor quality region $x > 0$.

A value of two-phase pressure drop in the vapor quality region is obtained by subtracting the value in the unheated section and the subcooled region from the pressure drop across the entire test section. The single-phase pressure drop is evaluated in the subcooled region, ignoring the possibility of partial boiling. In the vapor quality region, linear pressure drop is assumed using the pressures at the end of the subcooled region and at the outlet of the test section. Distribution of saturation temperature in the vapor quality region is obtained by the pressure distribution. All of the instruments used are carefully calibrated. The uncertainty in temperature measurement is ± 0.15 K, pressure measurement ± 0.5%, and flow rate setting ± 0.25%. The accuracy of heat transfer coefficients is evaluated to be ± 6.4%.

2.2.2. Transparent heated tube. Transparent heated tubes, which enable the heating, the observation through the glass tube and the measurement of inner wall temperature simultaneously, are introduced to clarify the mechanisms of heat transfer by the relationship between liquid-vapor interfacial behaviors and heat transfer characteristics. The tube is made of pyrex glass, and it has an ID of 4 mm and a wall thickness of 1 mm. The heated length of the tube is approximately 50 mm, and its inner wall is uniformly coated with a transparent gold film with a thickness of the order of 10 nm. Both ends of the tube are coated with a thick layer of silver film for use as electrodes and are in contact with a brass flange, as shown in Figure 6. The thin gold film for heating is operated as a resistance thermometer for the temperature measurement. As only the averaged heat transfer characteristics along the heated length can be obtained because of its structure, the test section is assembled by three segments in series, i.e., total heated length is 150 mm. At each segment of transparent heated tube, the measurement of the heat transfer coefficient and the observation of liquid-vapor interfacial behaviors by CCD camera are performed. Figure 7 shows an example of images of liquid-vapor behaviors in horizontal flow for different flow patterns recorded by CCD camera through the glass tube wall.

2.2.3. Unheated test section of acrylic tube. The unheated sections enable to observe detailed liquid-vapor interfacial structures, especially of void fraction and the distribution, and behaviors of annular liquid film, additionally to the measurement of pressure drop. The tube is made of polymethyl methacrylate, and the tube length between installed pressure taps is 80 mm.
3. Experimental result and discussion

3.1. Heat transfer coefficient at metal heated tube

Figure 8 shows the relation between the heat transfer coefficient and vapor quality at $G = 100 \text{ kg/m}^2\text{s}$ for different values of inlet condition in horizontal flow. Almost no effect of inlet liquid subcooling and inlet vapor quality is observed, and the heat transfer coefficient does not depend on the heating history in the upstream by the use of the metal heated tube installed in the test loop for the ground test.

Figure 9 shows the relation between the heat transfer coefficient and vapor quality for subcooling of inlet liquid $\Delta T_{\text{sub,in}} = 10 \text{ K}$ at the test section inlet under all mass velocity conditions in horizontal flow and vertical upward flow. In the range from low to moderate vapor quality at $G = 40−300 \text{ kg/m}^2\text{s}$ and in low vapor quality $x < 0.2$ at $G = 500 \text{ kg/m}^2\text{s}$, heat transfer coefficients is almost independent of mass velocity and vapor quality for both tube orientations. On the other hand, under the moderate vapor quality region, the trends of transition from the nucleate boiling region to two-phase forced convection region where the heat transfer coefficient increases with vapor quality are not clearly observed. This is explained as follows. Under low heat flux conditions, the length of heated tube is too short to realize the moderate or high vapor quality even at the outlet of the tube. On the other hand, under high heat flux conditions, nucleate boiling is dominant even in annular flow regime at moderate and high vapor qualities. It is needed to perform experiments in high vapor quality under lower heat flux conditions by adjusting inlet vapor quality in further studies. In addition, under the highest heat flux condition for $G = 40−300 \text{ kg/m}^2\text{s}$, the deterioration of heat transfer due to dryout is observed. The trend in the nucleate boiling region is confirmed by the existing researches, for example, for Freons by using the tubes with 1.10−4.26 mm inner diameter [10−12]. The relationship between the heat transfer coefficients and heat flux in the nucleate boiling region is shown in Figure 10 for both tube orientations. For the nucleate boiling, the relation of heat transfer coefficient $\alpha$ and heat flux $q$
Figure 9. Heat transfer coefficient versus vapor quality. (a) Horizontal flow, (b) Vertical upward flow.
Figure 10. Heat transfer coefficient versus heat flux. (a) Horizontal flow, (b) Vertical upward flow.

can be expressed by the existing relation Eq. (6) within the error ± 30%.

\[ \alpha \propto q^n \]  

(6)

Horizontal flow: \( n = 0.84 \)
Vertical upward flow: \( n = 0.80 \)

Incidentally, at \( G = 500 \text{ kg/m}^2\text{s} \), the two-phase forced convection region and the dryout region is not observed because no test are conducted under higher heat flux conditions because of the restriction of the limited power supply 400W from the candidate facility in MSPR.

3.2. Visualization of flow regime at unheated tube

Figure 11 shows images of flow pattern transition recorded by a CCD camera at vertical upward flow, \( G = 120 \text{ kg/m}^2\text{s} \) for an example. Four principal flow patterns, i.e., slug flow, churn flow, semi-annular flow and annular flow, were observed. Figure 12 shows flow patterns at vertical upward flow in present study and existing flow pattern map proposed by Barnea et al. [13]. Superficial liquid velocity \( J_l \) and superficial vapor velocity \( J_v \) are calculated from the test results as follows;

\[ J_l = \frac{(1-x)G}{\rho_l} \]  

(7)

\[ J_v = \frac{xG}{\rho_v} \]  

(8)

The results are in good agreement with extrapolating their air-water map to the two-phase mixture of FC72.
Figure 11. Images of flow pattern transition recorded by a CCD camera at $G = 120 \text{ kg/m}^2\text{s}$ in vertical upward flow. (a) Slug flow. (b) Churn flow. (c) Semi-Annular flow. (d) Annular flow.

Figure 12. Comparison of the observed flow patterns at vertical upward flow with the transition lines by Barnea et al [13].
4. Conclusions
In order to verify the feasibility of the experiments on boiling and two-phase flow onboard ISS, a test loop similar to the flight model was developed and preliminary ground experiments on flow boiling were performed.
1. The operation and performance of all components installed in the test loop was confirmed.
2. The tendency of heat transfer coefficient obtained from the metal heated tube and images of flow patterns were checked in detail and they coincide with those of existing researches despite of the restrictions in the length of test sections. Then, the flight model with similar specifications will produce the reliable reference data for the normal gravity condition if it is operated on ground before the experiment onboard ISS.

Acknowledgments
The present authors express appreciation for the support by the following project members. Koutaro Tanaka (Shibaura Inst. Tech.), Satoshi Matsumoto, Atsushi Okamoto, Kengoh Ohkubo (JAXA), Shinichi Shinozaki, Kazumi Kogure (JSF), Atsushi Murakami, Yukihiro Ueda, Toshiharu Oka, Yoko Nakagawa (IHI Aerospace), Nobuo Ohtani, Takahiro Hayashida, Kazuaki Ae and Tomoki Hirokawa (Kyushu Univ.).

References
[1] Kim J 2003 Journal of the Japan Society of Microgravity Application 20 (4) pp 264
[2] Di Marco P 2003 Journal of the Japan Society of Microgravity Application 20 (4) pp 252
[3] Ohta H 2003 Journal of the Japan Society of Microgravity Application 20 (4) pp 272
[4] Ohta H 1997 Nuclear Engineering and Design 175 pp 167–180
[5] Zhang H, Mudawar I and Hasan M M 2002 International Journal of Heat and Mass Transfer 45 pp 4079
[6] Kandlikar S G and Balasubramanian P 2005 Journal of Heat Transfer 127 (8) pp 820
[7] Bower J S and Klausner J F 2006 Experimental Thermal and Fluid Science 31 pp 141
[8] Baba S, Ohtani N, Kawanami O, Inoue K, and Ohta H 2011 Eurotherm Seminar on Gravitational Effects on Liquid-vapor Phase Change 92
[9] Ohta H, Inoue K, Ando M and Watanabe K 2009 Heat Transfer Engineering 30 (1–2) pp 19
[10] Bao Z Y, Fletcher D F and Haynes B S 2000 International Journal of Heat and Mass Transfer 43 pp 3347
[11] Huo X, Chen L, Tian Y S and Karayiannis T G 2004 Applied Thermal Engineering 24 pp 1225
[12] Shiferaw D, Karayiannis T G and Kenning D B R 2009 International Journal of Thermal Sciences 48 pp 331
[13] Barnea D, Shoham O, Taitel Y, Dukler A E 1985 Chemical Engineering Science 40 (1) pp 131