Experiment on nucleate pool boiling in microgravity by using transparent heating surface – Analysis of surface heat transfer coefficients

C Kubota¹, O Kawanami², Y Asada¹, Y Wada¹, T Nagayasu¹, Y Shinmoto¹, H Ohta¹, O Kabov³, P Queeckers³, S Chikov³ and J Straub⁴

¹Department of Aeronautics and Astronautics, Kyushu University, 744 Motooka, Nishiku, Fukuoka 814-0395, Japan
²Department of Mechanical and System Engineering, University of Hyogo, 2167 Shosha, Himeji, Hyogo 671-2201, Japan
³Physical-Chemistry Department of the Faculty of Applied Sciences, Université Libre de Bruxelles, Av. F.D. Roosevelt 50c, B-1050 Bruxelles, Belgium
⁴Technische Universität München, Lehrstuhl für Thermodynamik, Bolzmannstrasse 15, D-85748 Garching, Germany

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

Abstract. Investigation of mechanisms in nucleate boiling under microgravity conditions is essential for the development of the cooling systems handling a large amount of waste heat. A transparent heating surface with multiple arrays of 88 thin film temperature sensors and mini-heaters was developed for the clarification of boiling heat transfer mechanisms in microgravity. To investigate gravity effects on the microlayer behaviors and corresponding local heat transfer coefficients, images of liquid-vapor behaviors underneath attached bubbles and local heat transfer data were simultaneously obtained in microgravity pool boiling. The present paper reports the analysis of the data measured during the ESA parabolic flight campaign. It was found that the liquid-vapor behaviors were strongly affected by the direction and the level of residual gravity. Various patterns of liquid-vapor behaviours and corresponding enhancement or deterioration of the heat transfer are observed.

1. Introduction
Nucleate boiling is one of the most effective modes of heat transfer due to the latent heat transport during liquid evaporation. Investigation of mechanisms in nucleate boiling is essential for the design of the thermal management systems handling a large amount of waste heat. Although many researches in the relevant subject are exited, the heat transfer mechanism was not yet enough clarified for various bubble behaviors observed under different combination of dominant parameters [1],[2].

Because bubbles are growing up in a large size under microgravity conditions due to the reduction in buoyant force, the employment of observation techniques and measurement methods become easier keeping the essence of elementary processes in nucleate boiling unchanged. In such a situation, behaviours of liquid microlayer underneath vapor bubbles dominate the heat transfer. The model of
heat transfer around a single bubble in nucleate boiling was analyzed by Stephan and Hammer [3] using the concept of Wayner et al. [4]. Distribution of liquid microlayers underneath vapour bubbles is unsteady and their thickness varies along local positions on the heating surface. Hence, to investigate the relation between the microlayer behaviors and local heat transfer characteristics becomes a key to solve problems on the mechanisms of nucleate boiling also in microgravity.

In the present study, to investigate gravity effects on the relation between local heat transfer and liquid-vapor behaviors, pool boiling experiments in microgravity are conducted by using a transparent heating surface with multiple sensors and heaters array during the 49th parabolic flight campaign by ESA. In this paper, based on the analysis of detailed distribution of local surface heat transfer coefficients, the change of local heat transfer is discussed relating to the observed liquid-vapor behaviors.

2. Transparent heating surface
A transparent heating surface as shown in Figure 1 was developed for the measurement of local heat transfer characteristics. The heating surface, 76 mm in diameter and 2 mm in thickness, was made of sapphire glass with very high thermal conductivity ($\lambda = 42$ W/mK) to realize quick control of heating conditions from backside and the observation of liquid-vapor behaviors simultaneously. Artificial cavities were located at the center of heating surface for the enhancement of nucleation. The present heating surface with effective heating area of 40 mm in diameter located on the center is quite enlarged from the surface developed by Kim et al. [5] who have already developed the structure of the sensor/heater array for the clarification of local heat transfer characteristics using the heater with a size

| Table 1. Specifications of temperature sensors and mini-heaters. |
|--------------|--------------|-----------------|-----------------|
| Materials    | Ti/Pt        | Ti/Au           |
| Size         | 1.3 $\times$ 1.3 mm | 3 $\times$ 3 mm |
| Thickness    | 0.1 $\mu$m   | 0.04 $\mu$m     |
| Nominal resistance | 800 $\Omega$ | 350 $\Omega$   |

Figure 1. Schematic of transparent heating surface.
The present heating surface has 88 pairs of temperature sensors and mini-heaters coated directly on both sides of the substrate. The sensor and the heater are 1.3 mm × 1.3 mm and 3 mm × 3 mm in size, respectively. Temperature sensors are operated as resistance thermometers and they are made by platinum thin films. The temperature coefficient is 0.0012 - 0.0013 K⁻¹. Mini-heaters are made of gold. They are heated individually by the electric circuits controlled by a computer. The specifications of temperature sensors and mini-heaters are summarized in Table 1. Each pair is connected to the feedback circuits controlling the relation between local surface temperature and mini-heater power. The substrate of heating surface is transparent, which allows to relate the observed liquid-vapor behaviors underneath bubbles directly to the measured local heat transfer. More detailed description about the heating surface was presented in our previous papers [6],[7].

3. Experimental setup and conditions
The outline of experimental setup for aircraft experiments is shown in Figure 2. The setup consists of 2 racks. A main rack consist of a boiling vessel as a core part of the experiment, the pressure regulation system of the boiling vessel and the experimental container operated as an air bath. An auxiliary rack consists of the measurement and control system for the heating surface, i.e. the measurement system of liquid temperature and liquid pressure, and the observation system. The boiling vessel with 120 mm in diameter and 260 mm in length is filled with 3 L of degassed FC-72 as a test fluid. Two CCD cameras are installed above the heating surface and at the side of the boiling vessel to observe liquid-vapor behaviors. The orientation of the transparent heating surface, installed at the top of the chamber, is facing downward. Detailed illustration about the experimental apparatus was reported by a previous paper [8].

![Figure 2. Outline of experimental setup.](image-url)
Experiments described in this paper were conducted under the heating mode of uniform surface temperature. The target temperature $T_{\text{target}}$ and liquid subcooling $\Delta T_{\text{sub}}$ are selected as experimental parameters. These experimental conditions are shown in Table 2.

A reduced gravity environment is obtained by the flight of Airbus A300 Zero-G through a series of parabolic maneuvers, which result in approximately 20 second periods of microgravity condition. Each parabola is initiated with a 1.8g pull up and terminated with a 1.8g pull out. During 1g period, power is supplied to mini-heaters to keep the surface temperature near a desired value. The data measurement and the video recording were synchronized to relate the heat transfer data to the observed liquid-vapor behaviors directly. The sampling period of the data measurement system is 108 ms.

### 4. Analytical method

To obtain local heat transfer coefficient, the heat flux distribution on the liquid side of heating surface is calculated from heat conduction across the substrate by using the three-dimensional analysis tool, MSC.Nastran. The three-dimensional grids for heat conduction analysis are shown in Figure 3. The grids for this analysis are generated by using the function of finite element modeling of MSC.Patran. The structured mesh was used in the central heated area and the unstructured mesh was used around it. The division number in z-direction is ten. The details of the finite element model are shown in Table 3. The temperature distribution on the entire surface area is obtained by the cubic spline interpolation of measured surface temperatures at the prescribed locations on the central heated area and at the periphery of the sapphire disk. The boundary conditions are shown in Table 4. The time-series temperature distribution data on the entire surface area is used to give one boundary conditions for the calculation of temperature distribution in the heated disk which, in turn, gives the local surface heat flux distribution at each instances of data acquisition. The time-series heat flux data from mini-heaters located on the central heated area, which is equated to the power input to each mini-heaters element taking account of heat loss to the surrounding air, is also used as a boundary conditions. The boundary condition of the rear surface around the central heated area is given by the convection to surrounding air ($\lambda = 10 \text{ W/mK}$). The condition of disk periphery is assumed to be thermal insulation, and a uniform temperature along the peripheral direction is given by the averaged value of measured temperatures. The error of temperatures measured by the resistance temperature sensors is less than 0.7 K. The evaluated error of the local heat flux to z-direction on the heating surface is less than 1%.

### 5. Results and discussion

Various patterns of liquid-vapor behaviors were observed in this experiment [9],[10]. The typical patterns during microgravity period are shown in Figure 4. In the case of low liquid subcooling condition, during positive microgravity period, where bubbles are pushed toward the downward-facing heating surface, generated bubbles became more larger on the surface. The heat transfer seemed to be deteriorated because of the emergence of the dry patches underneath the bubbles (Figure 4-Pattern 1). On the other hand, during negative microgravity period, bubbles were detached without distinct condensation, where bubbles were generated from heating surface with high frequency (Figure 4-Pattern 2). In the case of high liquid subcooling condition, fine bubbles detached from the heating surface during the negative microgravity period, where no marked enhancement or deterioration of heat transfer was expected. (Figure 4-Pattern 3).

| Table 2. Experimental conditions. |
|----------------------------------|
| Test liquid | FC-72 (deaerated) |
| Pressure range in boiling vessel | $P = 0.06 - 0.1 \text{ MPa}$ |
| Target temperature of heating surface | $T_{\text{target}} = 50.0 - 85.0 \degree \text{C}$ |
| Liquid subcooling | $\Delta T_{\text{sub}} = 3.0 - 17.0 \text{ K}$ |
| Heating mode | Uniform surface temperature |
Table 3. Details of finite element model.

|                       | Heated area | Periphery of the sapphire disk |
|-----------------------|-------------|--------------------------------|
| Number of elements    | 15210       | 20720                          |
| Number of nodes       | 17600       | 13984                          |
| Number of layers      | 10          | 10                             |
| Material              | Sapphire glass | Sapphire glass               |

Table 4. Boundary conditions.

| Location                                      | Boundary condition           | Value of parameter |
|-----------------------------------------------|------------------------------|--------------------|
| Surface of entire disk                        | Surface temperatures         | variable           |
| Rear heated area                              | Heat flux from mini-heaters  | variable           |
| Rear surface of disk around central heated area| Air convection              | \( \lambda = 10 \) W/mK |
| Periphery of disk                             | Thermal insulation           | \( \lambda = 0 \) W/mK |
| Periphery of disk                             | Averaged temperature         | variable           |

One of the analytical results for low liquid subcooling condition is described here. The images of liquid-vapor behaviors and corresponding heat transfer coefficient distributions are shown in Figure 5. The transitions of gravity, surface temperatures, local heat fluxes and local heat transfer coefficients at the points A and B on Figure 5 are shown in Figure 6 for the same experimental conditions. The nucleation site density depending on the surface texture of heating surface is high around point B, while it is low around point A, because artificial cavities is located at the center of heating surface. Generally, the nucleation site density increase with increasing the surface temperature and the heat transfer is enhanced with the nucleation site density.

In positive microgravity (Figures 5-(a) and 6, Point B, Pattern 1 in Figure 4), boiling bubbles were pressed against the heating surface and grew. Underneath attached flattened bubbles in a large size,
dry patches were extended. As a result, the local surface temperature increased reducing surface heat flux, and marked heat transfer deterioration was observed. On the other hand, under negative microgravity conditions (Figures 5-(b), (c) and 6, Pattern 2 in Figure 4), small bubbles were detached from the surface. At \(-0.07\, g\) (Figures 5-(c) and 6), the periods of detachment were short and the bubble size was very small. As a result, heat transfer characteristics were similar to those on ground and they were dependent on the surface nucleation characteristics. The heat transfer coefficients were relatively lower at the upper left part of the heating surface around Point A because of the shortage of active nucleation sites, while the heat transfer coefficients were relatively enhanced at the center of the surface around Point B with a lot of active cavities. At \(-0.02\, g\) (Figures 5-(b) and 6), the periods of

Figure 4. Schematics of liquid-vapor behaviors on the heating surface during microgravity period.

Figure 5. Liquid-vapor behavior and heat transfer coefficient distribution. \(T_{\text{target}} = 75.0\, ^\circ\, C, \Delta T_{\text{sub}} = 3.0\, K, \pm \mu g\)
detachment became longer compared with those at \(-0.07\,g\). Generated bubbles grew up slowly sliding from the upper right to the lower left on the heating surface, where the heat transfer was enhanced to same extent along the flow direction of sliding bubbles.

**Figure 6.** Transitions of local heat fluxes, surface temperatures, local heat transfer coefficients at points A and B on Figure 5 and gravity acceleration.
In these figures, negative values of heat transfer coefficient was observed due to calculated negative surface heat fluxes. Such a situation occurred when the heat flow was directed to the backside of the heating surface substrate because of the deteriorated heat transfer or of the heat loss at the corner of the heated area.

6. Conclusions
A transparent heating surface with multiple arrays of 88 thin film temperature sensors and mini-heaters was developed for the clarification of boiling heat transfer mechanisms in microgravity. The images of liquid-vapor behaviors and corresponding data of local heat transfer were simultaneously obtained in microgravity pool boiling experiments by ESA parabolic flight campaign. To obtain local heat transfer coefficient, the heat flux distribution on the liquid side of heating surface was calculated from heat conduction across the substrate by using three-dimensional analysis tool.

(1) It was found that the liquid-vapor behaviors were strongly affected by the direction and the level of residual gravity, which in turn resulted in the variation and the distribution of local heat transfer coefficients.

(2) During a positive microgravity period, bubbles grew being pushed towards the heating surface. The heat transfer was deteriorated because dry patches were extended underneath attached flattened bubbles in a large size.

(3) During a negative microgravity period, bubbles are detached from the heating surface. The heat transfer was dependent on the surface nucleation characteristics. The heat transfer coefficients were relatively enhanced at the center of the surface with a lot of active cavities.

(4) When bubbles grow up slowly sliding on the heating surface, the heat transfer was enhanced along the flow direction of sliding bubbles.

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References
[1] Merte H. Jr 1990 Progress in Astronautics and Aeronautics 130 15
[2] Straub J. 2001 Boiling heat transfer and bubble dynamics in microgravity Advances in Heat Transfer 35 57-172
[3] Stephan P. and Hammer J. 1994 Wärme und Stoffubertragung-thermo and Fluid Dynamics 30 119
[4] Wayner P. C., Kao Y. K. and LaCroix L. V. 1976 J. Heat Mass Transfer 19 487
[5] Kim J., Benton J. F. and Wisniewski D. 2002 Int. J. Heat Mass Transfer 45 3919
[6] Sato Y., Inoue K. and Ohta H. 2007 J. Japan Society of Microgravity Application 24(1) 71
[7] Akagi S., Sakata Y. and Ohta H. 2008 J. Japan Society of Microgravity Application 25 327
[8] Sakata Y., Akagi S., Yoshioka S., Shinmoto Y. and Ohta H. 2008 Proc. 26th International Symposium on Space Technology Science 2008-h-27 in CD-ROM
[9] Sakata Y., Kawanami O., Kotani Y., Asada Y., Nagayasu T., Shinmoto Y., Ohta H., Kabov O., Queeckers P., Chikov S. and Straub J. 2009 (in Japanese) J. Japan Society of Microgravity Application 26(3) 204
[10] Kawamami O., Ohta H., Kabov O., Sakata Y., Kotani Y., Asada Y., Nagayasu T., Shinmoto Y., Chikov S., Queeckers P. and Straub J. 2009 Microgravity Science and Technology 21(Suppl 1) S3