Planning of Aircraft Experiments for the Clarification of Heat Transfer Mechanisms in Microgravity Nucleate Boiling

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Abstract

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 through the investigation of the relation between local heat transfer coefficients and behaviors of liquid microlayer underneath vapor bubbles. Local surface temperatures were controlled to keep a constant on the entire heat transfer surface by feedback circuits. To examine the validity in the operation of the developed heating surface, preliminary pool boiling experiments from a downward-facing surface were conducted on ground by using FC72. The local heat flux change characterized by the heat transfer enhancement due to the microlayer evaporation and the heat transfer deterioration by the extending dry patch were detected corresponding to the liquid-vapor behaviors underneath a coalesced bubble observed directly through the glass substrate. Microgravity boiling experiments by parabolic flights campaign are planned using the heating surface developed.

1. Introduction

Nucleate boiling is an efficient mode of heat transfer due to the latent heat transport during liquid evaporation. Investigation of mechanisms in nucleate boiling is important for the clarification of two-phase phenomena in heated systems, and the results are valid for the design of high-performance cold plates and two-phase thermal management systems in space. To establish the database for the design of high-performance thermal management systems, experiments in orbit on flow boiling heat transfer and two-phase flow are desired, which are performed under a new concept of a common two-phase flow loop with interchangeable test sections as shown in Figure 1. Not only to establish the database but to clarify the mechanisms of heat transfer in boiling of various systems on ground, the test sections of different types are employed.

In microgravity nucleate boiling, the structure of vapor bubble is similar to that on ground, but vapor bubbles generated are not detached from the surface or detached at very low frequency, which results in the bubble growth to become a large size on the heating surface. In such a situation, behaviors of liquid microlayer underneath vapor bubble dominate the heat transfer also in microgravity nucleate boiling. The model of heat transfer around a single bubble in nucleate boiling was analyzed by Stephan-Hammer using the concept of Wayner et al. Distribution of liquid microlayer underneath vapor bubble is unsteady and its thickness varies along local positions on the heating surface. Hence, to investigate the relation between the microlayer behaviors and local heat transfer characteristics is a key to solve a problems on the mechanisms of nucleate boiling in microgravity.

In the present study, a transparent heating surface, as shown in Fig. 2, was developed for the measurement of local heat transfer characteristics, where local heat transfer coefficients are related directly to the behaviors of liquid microlayer underneath vapor bubbles. Preliminary pool boiling experiments from downward-facing surface were conducted on ground using FC72. Microgravity boiling experiments by parabolic flights campaign are planned by using the developed heating surface.

2. Transparent Heating Surface

A transparent substrate of heating surface with dimensions of 76 mm in diameter and 2 mm in thickness is made of sapphire glass to realize the observation of liquid-vapor behaviors from underneath. The heating surface has 88 pairs of temperature sensors and mini-heaters coated directly on the liquid side and on the rear side, respectively. The arrangement of temperature sensors and mini-heaters is shown in Figure 2, and their specification is summarized in Table 1.

The present heating surface with effective heating area of 40mm in diameter located in the center is quite enlarged from the surface developed by Kim et al. with a size of 2.7mm×2.7mm in order to cover the entire base area of large generated bubbles normally encountered in microgravity. The substrate of present heating surface is transparent which arrows to relate the observed liquid-vapor behaviors underneath bubbles directly to the measured local heat transfer characteristics. Because of the limitation in the number of independent electrical circuits controlling the individual heater powers, the size of heaters is also enlarged for the present heating surface to occupy the effective heating area.
Temperature sensors are operated as resistance thermometers and they are made by platinum thin films with an electric resistance of around 800 Ω. The linearity between the electric resistance of temperature sensor and temperature was obtained. Mini-heaters are made of gold and their electric resistances are around 350 Ω. They are heated individually by the electric circuits and controlled by

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**Fig. 1** Concept of a common two-phase flow loop with interchangeable test sections proposed for the experiments in orbit.

**Fig. 2** Schematic of transparent heating surface.
Because of high thermal conductivity of sapphire glass substrate ($\lambda=41.8\,\text{W/mK}$), the surface temperatures can be controlled with high response by inputted power to the individual mini-heaters. The maximum error of temperature measurement is around 2K caused by the accuracy of temperature-electric resistance curves calibrated. The maximum error of heated power, evaluated directly from voltage and electric current supply to individual mini-heaters, is less than 1%.

Table 1 Specifications of temperature sensors and mini-heaters.

<table>
<thead>
<tr>
<th></th>
<th>Temperature sensor</th>
<th>Mini-heater</th>
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<tbody>
<tr>
<td>Materials</td>
<td>Pt</td>
<td>Au</td>
</tr>
<tr>
<td>Size</td>
<td>1.3 mm $\times$ 1.3 mm</td>
<td>3 mm $\times$ 3 mm</td>
</tr>
<tr>
<td>Thickness</td>
<td>0.1 $\mu$m</td>
<td>0.04 $\mu$m</td>
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3. Preliminary experiments on ground

3.1 Surface temperature control

To realize a uniform and constant surface temperature as an ideal and simple boundary condition, the feedback system using analog circuit shown in Figure 3 is introduced to all 88 pairs of a temperature sensor and a mini-heater. The voltage $E_h$ proportional to the difference between desired temperature $T_{\text{desired}}$ and local surface temperature $T_s$ is supplied to the mini-heater on the rear side.

3.2 Experimental conditions and methods

To check the validity of surface temperature control systems and the operation of developed heating surface, preliminary experiments were conducted on ground. Test fluid is Fluorinert FC72 with saturation temperature $T_{\text{sat}}=55.6\,^\circ\text{C}$ at 0.1 MPa. The bubble size is too small, however, on ground to obtain good resolution of local heat transfer characteristics by using the array of sensors and heaters developed for large bubble sizes observed in microgravity. Therefore, the bubble growth on a heating surface facing downwards was realized as shown in Figure 4 in the preliminary experiments. Through the transparent glass substrate liquid-vapor behaviors and a LED light synchronized with the initiation of DC power supply are monitored and recorded to obtain the bubble growth rates. The instantaneous local heat transfer data is related to the distribution of liquid and vapor phases changing with time elapsed.

3.3 Experimental results

One of results for constant surface temperature control is shown in Figures 5 and 6, where the transition of surface temperature $T_s$ and heater power input $Q_{\text{in}}$ at three different elements #2-15, #4-8 and #4-10 are indicated in relation to the location of a growing bubble. The surface temperatures are almost kept constant remaining offset values from the desired temperature at 58.7°C, which is corresponding to the different heat loss amounts depending on the individual sensor locations. When heat loss from the sensor is larger, the temperature has a larger deviation (offset) from the desired temperature to generate a larger power under the proportional control system adopted here, and vice versa. The element #2-15, for example, power consumption is smaller than other two elements due to the smaller heat loss. It is obvious that the power input from the mini-heaters take peak values instantaneously just after the bubble contact periphery pass over the relevant temperature sensors. To clarify this result in more detail, the relation between the distance $x$ from the bubble contact periphery and the instance of peak power input is examined as shown in Figure 7, where $x$ is negative (before bubble passage) or positive (after bubble passage) depending on the bubble behavior (see Figure 8). At the elements #2-15, #4-8 and #4-10, it is clear that the peak power input $Q_{\text{in,peak}}$ from the mini-heater occurs just after the passage of bubble contact periphery when the sensor is covered by microlayer. The peak power input $Q_{\text{in,peak}}$ depends partly on the temperature offset in the present control system additionally to the enhanced heat transfer during the passage of bubble contact periphery. The lower value of $Q_{\text{in,peak}}$ for #2-15 than others seems to be caused by the smaller temperature offset because the behaviors of the passing bubble are quite similar for all three elements checked here.

Both of the heat transfer enhancement due to microlayer evaporation and the heat transfer deterioration by the extending dry patches are detected corresponding to the liquid-vapor behaviors underneath an attached bubble.

4. Planning of aircraft experiments

Outline of experimental setup for microgravity
boiling experiments by aircraft is shown in Figure 9. The boiling vessel has a metal bellows to replace the vapor volume before the initiation of boiling to avoid the interference with the generated bubbles from the heating surface. The bellows is used also for the removal of residual bubbles generated in the previous test run, where pressurizing inner gas of bellows increases the pressure of two-phase mixture and promotes the condensation of gas phase.

Experiments under low pressure conditions are performed by the combination of bellows behaviors and the operation of vacuum pump. The core part of the experimental system is composed of a boiling vessel, regulation system for the boiling vessel, air bath, measurement and control units for temperature sensors and mini-heaters, and observation system. All components of experimental apparatus are integrated in racks.
Through the aircraft experiments, effects of gravity on bubble growth rates and resulting transition of heat transfer rate are clarified. The analysis is conducted based on a concept of co-existed trends of heat transfer enhancement and deterioration depending on the distribution of microlayer and dry patches underneath a single bubble. Observed bubble growth rates in microgravity are compared with the existing classical model developed under an assumption of uniform temperature fields.

5. Conclusions
(i) A transparent heating surface was developed for the clarification of mechanisms of nucleate boiling under microgravity conditions.
(ii) To examine the validity of the developed heating surface, preliminary experiments were conducted on ground. Enhancement or deterioration of heat transfer was detected corresponding directly to the microlayer behaviors underneath an attached bubble.
(iii) For microgravity boiling experiments by parabolic flights campaign, an experimental apparatus was designed using the developed transparent heating surface with arrays of sensors and mini-heaters.

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