Experimental study of boiling initiation on a smooth heating surface

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ABSTRACT

In the present study, we pay attention back to the first step of the bubble process, nucleation. Classically, bubble nucleation on a conventional heating surface was supported by the activation of trapped vapor on the micro cavity of the heating surface. Without the trapped vapor on a heating surface, bubble nucleation has been predicted at high superheat condition. In saturated water under atmospheric condition, the predicted superheat for bubble nucleation is approximately 200°C. According to the recent experimental reports, however, bubble nucleated at comparatively low superheat (~ 10°C) on smooth heating surfaces free from the trapped vapors. To explain the bubble nucleation at low superheat on a smooth surface without trapped vapor, the thermal potential gradient produced by a thermal boundary layer from the heating surface was incorporated in the nucleation model. The potential gradient accelerates the bubble nucleation kinetics and thus bubble nucleation occurs at comparatively low superheat on the smooth surface. Consequently, the induced bubble nucleus in the potential gradient would initiate boiling, when the nucleus reaches thermal-equilibrium condition. In the current study experimental investigation was conducted, and it is expected to improve basic understanding of bubble nucleation mechanism by being connected to the concept of the potential gradient bubble nucleation model.

KEYWORDS
Bubble nucleation, smooth surface, vapor-trap, potential gradient.

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1. INTRODUCTION

In a nuclear reactor, boiling is a key physical processes to determine the efficiency and the safety margin of the power plant. Therefore, for enhancement of safety and improvement of efficiency of the plants, nuclear power plants require good boiling performance that can be guaranteed by high-level understanding of boiling phenomenon. The understanding allows to improve models in thermal-hydraulic analysis to design reactors for the plant efficiency improvement and the plant safety.

Bubble nucleation is a familiar behavior in daily life. In general, water boils at near 100 °C on an ordinary surface under atmospheric condition. However, heterogeneous nucleation of vapor bubble without any foreign assistances such as non-condensable gas and gas trapped rough surface will occur above 300 °C [1, 2]. Therefore, classically, bubble nucleation on a conventional heating surface was supported by the activation of trapped vapor on the micro cavity of the heating surface [3, 4]. The existence of the micro cavity on a conventional heating surface was essential to predict bubble nucleation.

Recently the surface-modification technique employing micro/nanostructure control has opened a new chapter in boiling. It makes possible scrutinizing the fundamental mechanisms and the effects of key parameters including, surface characteristics (cavity, wettability, contact angles etc.). According to these recent studies, bubble nucleation occurred at very low temperature (~110 °C) even if on smooth surfaces free from trapped vapor [5-8].

To describe such bubble nucleation without trapped vapor, some possibilities have been considered in recent research work [9-12]. One of them is 'nanobubble' [9, 10]. The existence of nanobubble is conjectured to provide a seed vapor for creating bubble. However, the nanobubble hypothesis is only supported on hydrophobic surfaces, since only hydrophobic surfaces can have nanobubble. Therefore, it could not support boiling nucleation on conventional metal or oxidized surfaces which have hydrophilic characteristic. The other discussed hypothesis for the bubble nucleation at low superheat is the activation of micro-defects as nucleation sites in boiling [11, 12]. It is based on the limitation of the surface fabrication technique which was used to make the 'smooth heating' sample. However, to create a large number of bubbles in this way, a fabricated surface should have as many micron defects as activated sites. However, the presence of so many micron defects was not intended or ensured. Thus, there is a continuing debate on the mechanism of bubble nucleation on a smooth heating surface without trapped vapor.

Very recently, Jo et al.[13] focused on the thermal potential gradient produced by a thermal boundary layer from the heating surface. Higher temperature on a heating surface compared with bulk liquid temperature would induce higher Gibbs potential adjacent the heating surface. It means that potential gradient would be formed along the temperature profile on a heating surface. The potential gradient would accelerate the bubble nucleation kinetics and thus bubble nucleation could occur at comparatively low superheat on the smooth surface. Consequently, the induced bubble nucleus in the potential gradient would initiate bubble generation, when the nucleus reaches thermal-equilibrium condition. Based on this nucleation model, Jo et al.[13] could predict bubble nucleation at low superheats on smooth surfaces and could describe the variation of superheats required for bubble nucleation on different wettability heating surfaces.

In the present study, we conducted experimental investigation which is expected to support the potential gradient nucleation model. By manipulating the heating area, we tried to control the thickness of the thermal boundary layer, and then the effect was evaluated. And we discussed how the variation of the thermal boundary layer formed on a heating surface could affect bubble nucleation physics.

2. Experimental setup and heating surface

This experiment was conducted in a pool boiling facility with distilled water under atmospheric pressure saturated condition. To evaluate the effect of thickness variation of thermal boundary layer, the actual heating area was manipulated from 150 to 0.05 mm^2. Detail surface information is shown in Table A1 (Appendix A). For incorporating the effect of the heating surface wettability, hydrophilic and hydrophobic heating surfaces were prepared.

2.1. Pool boiling facility.

Pool boiling experiment was conducted in a rectangular aluminum pool. Two visualization windows were installed to check the bubble nucleation on heating surfaces. Saturated condition of distilled water was maintained by two components: an immersion heater fixed on a side wall of the pool and a reflux condenser installed on a lid of the pool. The immersion heater supplied heat to water and the power of supplied heat was controlled by a PID controller. Evaporated vapor by the immersion heater was condensed in the reflux condenser and it kept constant water level during the experiment. The pool boiling system was opened to atmospheric pressure through the reflux condenser. Fig. 1(a) is the schematic of the pool boiling facility.

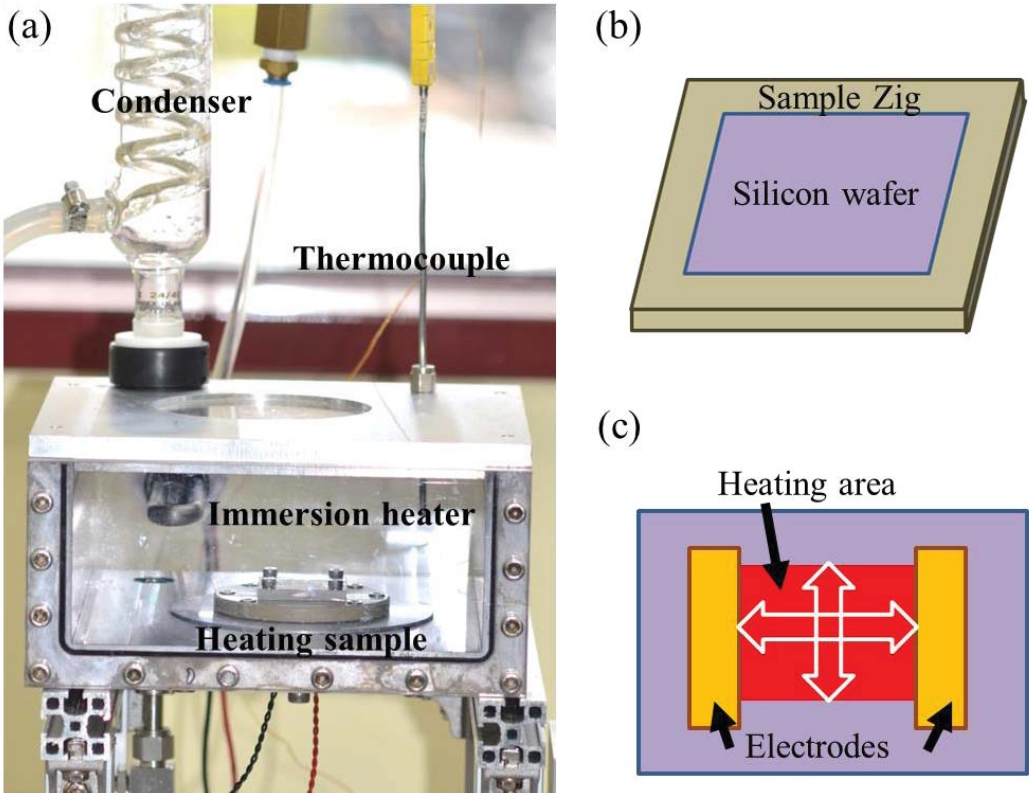

Figure 1. (a) Schematic of pool boiling facility, (b) sample part, and (c) the bottom side of silicon wafer.

2.2. Heating surface.

Silicon wafers were used for all heating surfaces. The silicon wafers possess sub-micron roughness. The wettability of heating surface was controlled in the same way proved in previous report [14]: one is oxidizing process for a hydrophilic surface and the other one is Teflon thin layer coating method for a hydrophobic surface. After these treatments, hydrophilic (~ $\theta = 54^{o}$) and hydrophobic (~$\theta = 120^{o}$) surfaces could be obtained. The surface roughness (Ra) of oxidation layer and Teflon coated layer were less than 10 nm. The nanoscale roughness is definitely smaller order than the critical cavity size for vapor trapping, the minimum size that could be formed in stable and could begin to grow. For Joule heating method, a thin platinum layer (1200Å) with adhesion titanium layer (120 Å) was deposited on the other side (bottom side) of the silicon wafer as a heating element. The area of the platinum thin layer was manipulated from 150 to 0.05 mm^2. Since MEMS technique was used to make heating area, the heating could be manipulated precisely. For wire connection to the heating element, two electrodes were made of gold thin layer (1000 Å) with titanium adhesion layer (100 Å). All thin metal layers were deposited by E-beam evaporator. And, soldering made connection between the electrode and wires. The wires were used to supply electric power and were used to measure the voltage and current across the heating element. The sample assembly and schematic of the heating part are shown in Fig. 1(b) and (c).

2.3. Experimental procedure.

All main experiments were conducted after degassing procedure for 2 hours. Supplied heat flux was evaluated with the fabricated heating area of the platinum layer, the measured voltage and current across the platinum thin layer. Until observing bubble nucleation on a heating surface, the heat flux was adjusted step-wise. If the heating surface had hysteresis, we re-decreased the heat flux till the superheats at which an already-activated bubble vanished. And then, we re-increased the heat flux. When it was confirmed that the vanishing point corresponded to the re-bubble nucleation superheat without hysteresis effect, the vanishing point was regarded as the nucleation superheat on the heating surface in the present study.

The superheats of heating surface were obtained with the calibration charts which include the electric resistance changes of the samples under varied temperature conditions. For the calibration charts, the electric resistances of all heating samples were measured through connected wires in convection oven which can maintain constant temperature. The reliability of calibration chart was confirmed by comparing the calibration chart before and after the experiment.

As described in previous, four wires were connected on the electrode part with well-spread solder. The soldering made thick solder layer (> 1mm) on the electrode part and it significantly reduces the electric resistance of the electrode part compared with that of the heating area part. It indicates that the resistance of the heating area will dominantly determine the measured resistance through the wires. Therefore, it can give the temperature information of the heating area part. The maximum uncertainty in the superheat measurement was less than 1.7 ^{o}C.

3. Experimental results and discussion.

Fig. 2 shows ONB experimental results on different heating areas and different wettabilities. Interestingly, the large heating surface required low superheat for bubble nucleation. As the heating area decreased, the required superheat increased. The hydrophilic surface with the smallest heating area required almost 65 ^{o}C superheat for bubble nucleation and it corresponds to 6 times larger than the required superheat on the largest heating surface. For the hydrophobic surfaces, required superheats were comparatively lower than superheats for the hydrophilic surfaces. However, the general tendency was also decreasing as the heating area increased. The smallest hydrophobic heating surface required ~16 ^{o}C. The required superheat for the smallest hydrophobic surface was lower than that for the smallest hydrophilic surface, but it was 3.6 times larger than that on the largest hydrophobic heating surface.

Through this experiment, it is pointed out that the required superheat for bubble nucleation increases as the heating area decreases. However, the exact superheat for bubble nucleation is depending on the wettability of the heating surface. It suggests that some significant factor on bubble nucleation is influenced by the change of heating area. And, it can be supposed that the important factor is also related with the heating surface wettability. In this study, based on the nucleation model incorporating the effect of the potential gradient on bubble nucleation, it was supposed that the important factor for bubble nucleation is the thickness of the thermal boundary layer. In the potential gradient nucleation model, the thickness of the thermal boundary layer determines how large area (or how many particles) would be affected by the induced potential gradient. Therefore it is conjectured that the change of heating area affects the thickness of the thermal boundary layer and affects the bubble nucleation kinetics. As a consequence of that, the required superheats on the different heating areas would be changed.

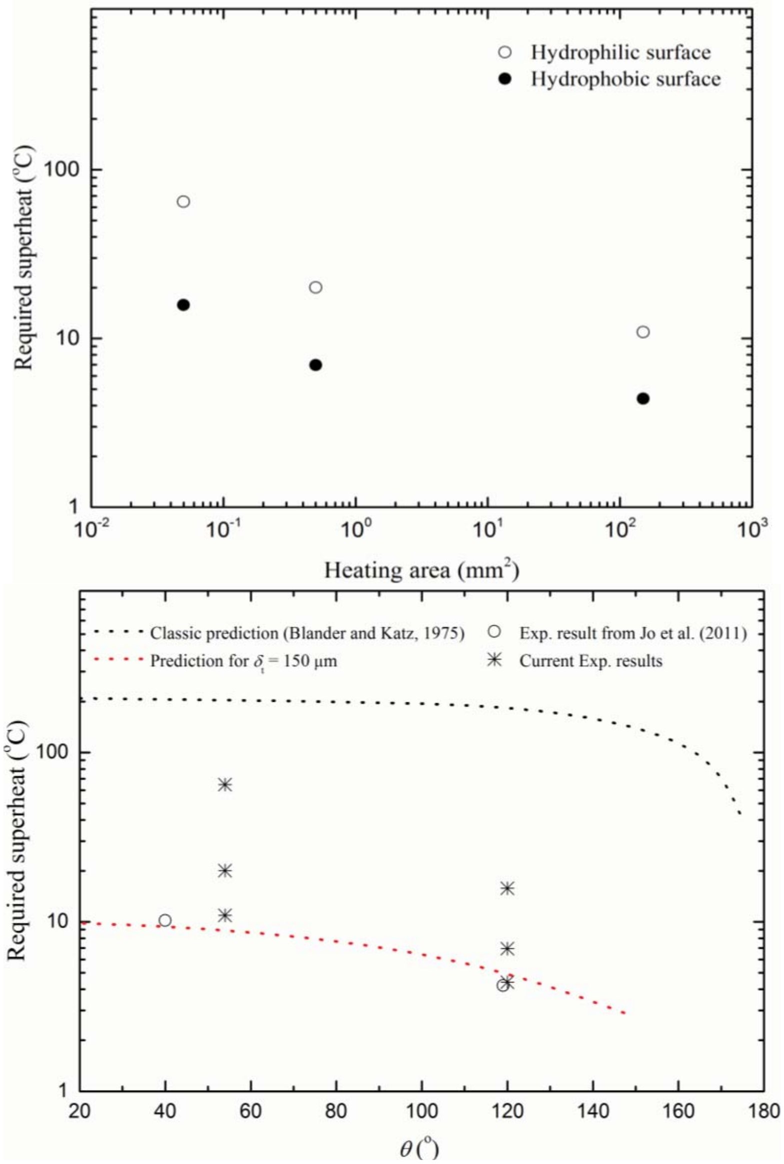

Figure 2. ONB experimental results with varied heating area.

In the classic heterogeneous nucleation model, only kinetic motion was incorporated without considering the heating area effect or any thermally induced condition, such as the thermal boundary layer or temperature distribution of working fluid. Therefore, when we considered the classic nucleation model in the view of the heating area effect, the classic nucleation model could be regarded as the model developed for infinitesimally small heating area. The infinitesimally small heating indicates a conceptual surface which transfers heat from the surface to working fluid but does not affect temperature distribution of working fluid. Therefore, it could be assumed as a uniform temperature condition for working fluid which was applied in the classic nucleation model. In other words, we can hypothesize that the kinetic motion for the classic boiling model condition is accepted for an infinitesimally small heating surface or uniform temperature condition of working fluid. From this point of view, very high superheat for bubble nucleation predicted in the classic heterogeneous nucleation is corresponding to the reported experimental trend in this study. As the heating area increases, however, it seems that the formation of the thermal boundary layer contributes more to the nucleation mechanism than does the general kinetic motion incorporated in the classical nucleation model. Therefore the thickness of the thermal boundary layer is an important parameter. However, determining the precise thickness of thermal boundary layer on a heating surface with numerical simulation is challenging thing. It will require many technical improvements and huge computational load so that continuous efforts will be made for our further research work. Instead of that, in the current study, the change of the thermal boundary layer on small heating surfaces was conjectured based on known information. Conventionally, the thickness of the thermal boundary layer on a macro heater (> 100 mm^2) is assumed as 100 μm. It indicates that the heat diffusion length from a heating surface is definitely shorter than the characteristic length of the heating area. Therefore, as the heating area changes, the influenced area of working fluid will be changed. And the thickness of the thermal boundary layer will be also varied. On a micro heater, the heat diffusion length is estimated in micron- or nano-scale.

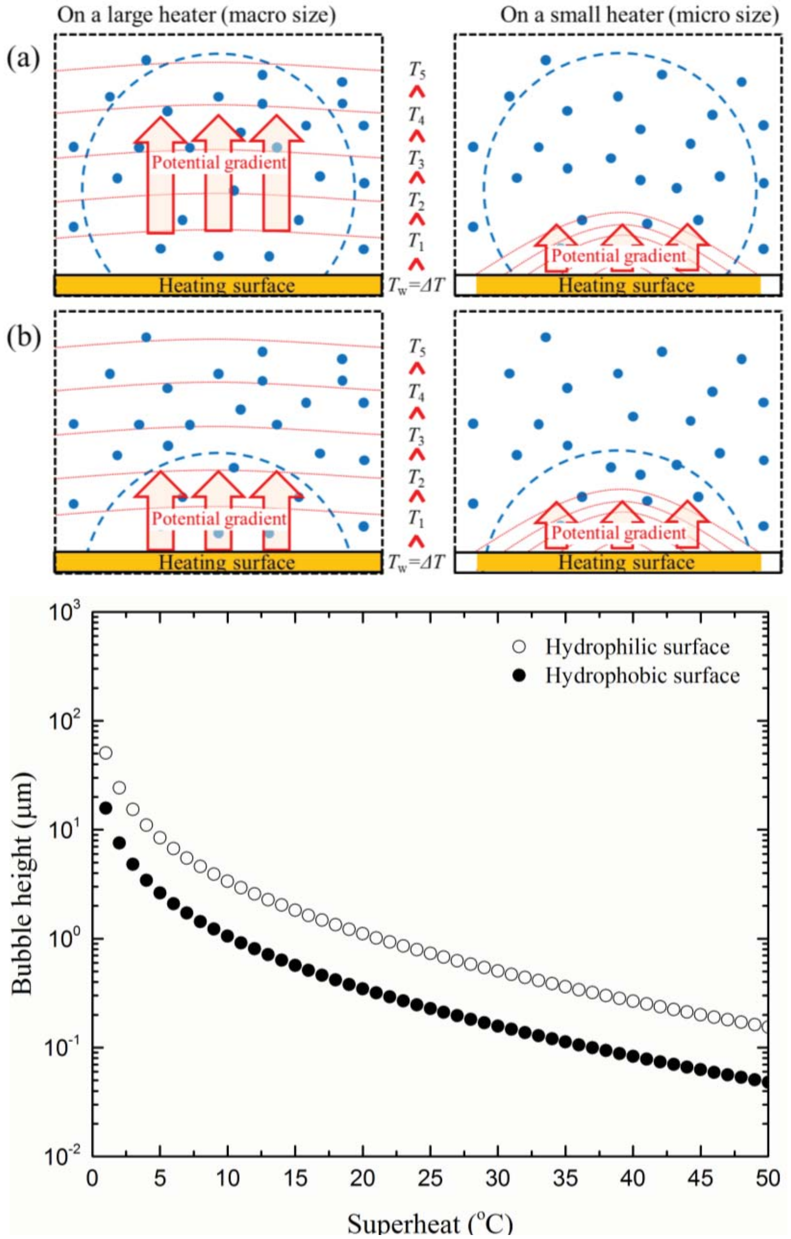

Figure 3. The effect of heating area on different wetting surfaces.

In the thermal boundary layer, liquid particles would be influenced by the potential gradient. Therefore, if the thickness of the thermal boundary layer decreases, the size of influenced area would be smaller than the critical size (micron- or nano-scale as shown in Fig. 3) for bubble nucleation. In other words, a small heating area requires higher temperature condition for bubble nucleation to induce more vigorous kinetics because decreasing heating area would dilute the effect of the induced potential gradient on bubble nucleation physics.

Fig. 3 shows the effect of heating area on different wetting surfaces. The variation of the thermal boundary layer thickness is definitely related with the surface wettability because the different wettabilities require different heights for the same critical size. The critical size of nucleation is independent of the heating surface wettability. However, different contact angles of the heating surfaces made different heights for the top position of the critical nucleus, and the top position of the critical nucleus could affect bubble nucleation criterion. It is related with the thermo-stable criterion. On a hydrophobic surface, the height of nucleus at the same critical size is closer than that on a hydrophilic surface. Therefore, even though the heating area decreases, the suppression effect by decreasing thermal boundary layer will not be significant compared with that on a hydrophilic surface, as shown in Fig. 3(b).

4. CONCLUSIONS

In the present study, the effects of heating area and surface wettability on bubble nucleation were evaluated. On the large (macro-size) heating area, the required superheat was lower than that on the small (micro-size) heating area. The decreasing heating area was suspected to form the thin thermal boundary layer, and it might dilute the effect of the potential gradient which contributes more to the nucleation mechanism than does the general kinetic motion incorporated in the classical nucleation model. The detail tendency of required superheat was depending on their wettability, due to the different bubble top heights of the nucleus on different wetting surfaces. Even if this experimental investigation has some limitations, it gives insight to improve understanding of boiling nucleation based on the potential gradient nucleation model. In future work, this study will be extended by improving experimental setup to include heat loss of the small heater and by analyzing numerical simulation for temperature profile on a heating surface. It is expected to contribute to not only improving understanding of phase change physics but also enhancing the reliability of the safety components in nuclear power plant systems.

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APPENDIX A

The platinum thin heating layer has rectangular heating area, and each side of the rectangular was controlled to manipulate the heating area. Detail information is shown in Table AI.

Table AI. Sample information

Case	The length of the longer side (mm)	The length of the shorter side (mm)	Total heating area (mm^2)
Case 1	15	10	150
Case 2	1	0.5	0.5
Case 3	1	0.05	0.05

Initially, all heating areas were designed for different conditions, but the lengths of the longer side in case 2 and 3 were made in same size. Fig. AI shows the experimental results as the each side of the heater changes.

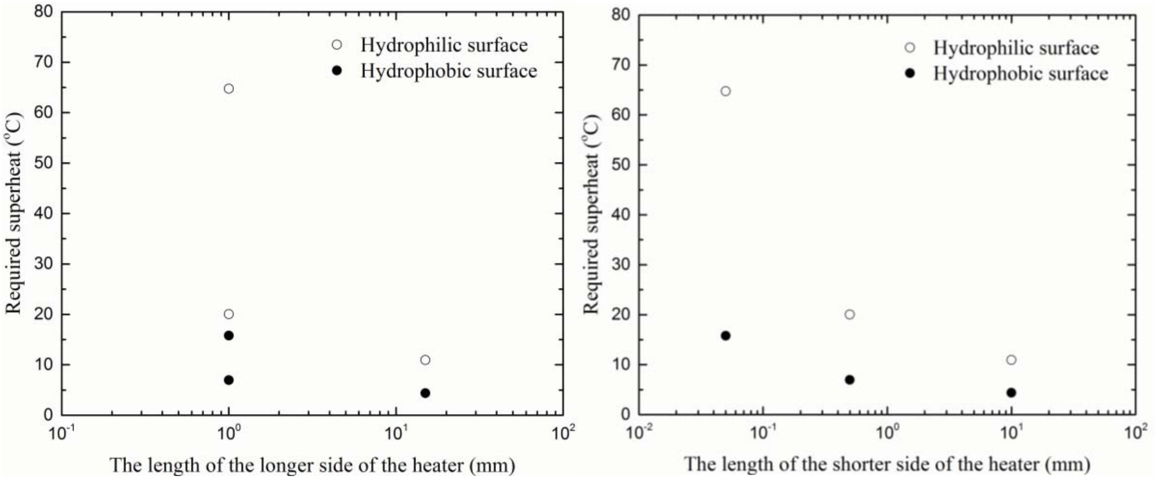

Figure A1. ONB experimental results with varied heating area.