Onset of Nucleate Boiling for Downward Flow in Narrow Rectangular Channel under Low Pressure

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ABSTRACT

Bubble nucleation itself is not important for nuclear reactor safety at all, but it can be led to critical thermal-hydraulic events such as OFI (Onset of Fluid Instability) or CHF (Critical Heat Flux) easily as research reactor operates under atmospheric condition. Thus, the ONB (Onset of Nucleate Boiling) margin for normal operation in research reactor is recommended. In IAEA report 'IAEA-TECDOC-233', ONB margin for research reactor is recommended as well. Though ONB margin in research reactor is emphasized for these kinds of reasons, only few experiments were performed for downward flow direction in narrow rectangular channel. In addition, several existing ONB prediction correlations have arguments for the applicability to flow boiling condition in the narrow rectangular channel because most of them are developed based on Hsu's model which is the model developed in pool boiling case. In the study, ONB experiments for various inlet temperature condition and mass flux condition were performed as increasing heat flux step by step. Based on experiment data, the effect of inlet temperature and mass flux to wall superheat and heat flux at ONB was investigated. Also, existing ONB prediction correlations were evaluated for predicting wall superheat and heat flux at ONB based on the experiment data. Then, new ONB prediction correlation was developed for better-evaluating and was compared with other correlations.

KEYWORDS

ONB, ONSET OF NUCLEATE BOILING, BUBBLE NUCLEATION

1. INTRODUCTION

Generally, nuclear reactors can be divided into two types; commercial reactor and research reactor. Neutron source served from research reactor is used for many industries such as neutron scattering. Some research reactors such as the Jordan Research & Training Reactor (JRTR) have three characteristics. First, they operate under atmospheric pressure. Second, they use the nuclear fuel plate. Third, they use downward flow to remove the heat of the fuel plate.

However, one of the precautions of using downward flow under low pressure is that fluid behavior can change much faster than under high pressure. Bubble nucleation itself is not important for nuclear reactor safety at all, but it can be led to critical thermal-hydraulic events such as onset of fluid instability (OFI) or critical heat flux (CHF) easily. Also, bubble nucleation would be avoided to maintain the steady normal operation. The IAEA also recommends for research reactors to have enough ONB margin to maintain a normal operation state in 'IAEA-TECDOC-233' (1980) [1].

Though ONB in research reactors is emphasized for these reasons, there is insufficient ONB data for downward flow condition either ONB prediction correlation for downward flow as well. In addition, most past researches on ONB did not consider the geometry, inlet temperature and mass flux effect on ONB as the models were developed based on the Hsu's model.

In Hsu (1962) [2], the uniform bulk temperature T_∞ was assumed in the pool. After that, the ONB prediction correlation was developed by using one-dimensional transient conduction equation and linear temperature profile as shown in Fig.1. Thus, arguments about the applicability of the models to ONB criteria still remained because Hsu's model didn't consider the flow condition with varying bulk temperature.

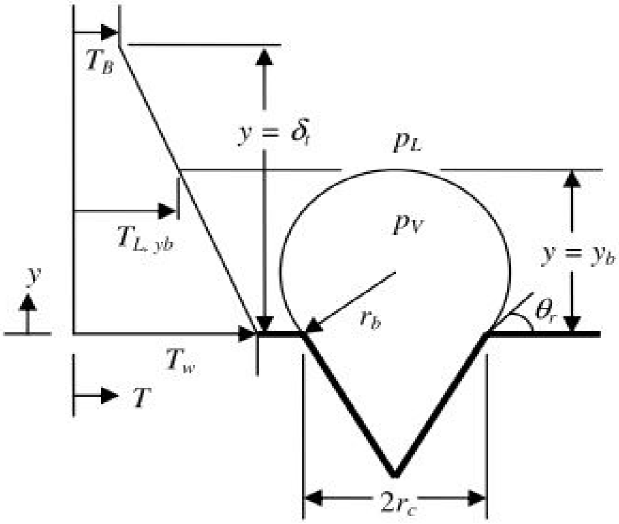

Fig. 1 Temperature profile around a nucleating bubble [3]

Bergles and Rohsenow (1964) [4] extended Hsu's criterion to flow boiling in the tube, then prediction correlation was developed graphically with the experiment data performed in tube condition. Sato and Matsumura (1964) [5] also extended Hsu's criterion and compared it with experiment data carried out in the rectangular channel. Jens and Lottes (1951) [6], Thom and Fallon (1965) [7] investigated the effect of heat flux on wall superheat at ONB. Hino and Ueda (1985) [8] performed ONB experiment with Fluorocarbon R-113 liquid in annular tube and insisted that mass flux and inlet temperature has no effect on ONB. The reported superheat data in the study was much higher than 'Bergles and Rohsenow' expectation. Sudo et al. (1986) [9] performed ONB experiment in narrow rectangular channel which is similar with JRR-3 (Japan Research Reactor) design for downward and upflow. Based on the experiment data, effect of mass flux and inlet temperature on ONB was investigated and 'Bergles and Rohsenow' correlation was recommended for conservative prediction. Also, they argued that the ONB for upward flow and downward flow may not be different. Kandlikar (1997) [10] studied bubble growth charactersitics under flow condition by using flow rate, surface temperature, and inlet subcooling to establish the nucleation cavity size and range of active cavities. Hapke et al. (2000) [11] performed ONB experiments in vertical cylindrical tube. In the study, measured heat transfer coefficient was used to investigate ONB. Qu and Mudawar (2002) [12] studied boiling heat transfer in horizontal rectangular channel. They suggested mechanistic model to predict ONB in microchannel. Liu et al. (2005) [13] also insisted that Hsu's model which was developed for pool boiling is not appropriate for flow boiling. Then, they conducted ONB experiments in horizontal michrochannel and compared data with existing correlations. In addition, new correlation was developed from superheat equation for bubble nucleus. Su et al. (2005) [14] investigated diameter effect on ONB and insisted that boiling incipience heat flux is independent of system pressure. Wu et al. (2010) [15] conducted a study on ONB with various tube diameter and gap size in annular tube. They found that the boiling incipience heat flux at annular tube is much lower than that in conventional channels. Hong et al. (2012) [16] performed ONB experiments in narrow rectangular channel for upward flow and found that existing ONB prediction correlations for conventional channels are not suitable for narrow rectangular channel. Wang et al. (2014) [17] conducted experiments in narrow rectangular channel for upward flow with three different ONB judging criteria and compared it with exiting ONB prediction correlations. Consequently, they founded that the Thom correlation can be used to predict ONB in narrow rectangular channel. Recent study, Forrest et al. (2016) [18], compared several ONB determination methods to investigate the differences that may occurred according to different determination method. They insisted that ONB determination by channel pressure drop and bubble visualization is not adequate because channel pressure drop is quite small so that may subject to large uncertainty. Also, channel pressure drop detects the global pressure drop in the channel which may be affected by geometry such as edge effect, not local pressure drop. Bubble visualization is not appropriate as well based on current technology to permit visual detection. They argued that much higher heat flux in required to permit visual detection of bubble with current technology. With these reasons, they found that the ONB determination using temperature is expected to be most reliable.

As being explained above, it is still controversial that existing ONB prediction correlation could be applied to rectangular channel. Also, as the only ONB experimental data for downward flow is Sudo’s case, it needs to generate more data for downward flow and investigate the applicability of existing correlations to it. Thus, in the present work, the existing ONB prediction correlations was estimated based on the experiment data for the rectangular channel with downward flow. These data and estimated correlations would be helpful for understanding ONB phenomena and setting safety margin in research reactor operation.

2. EXPERIMENT SETUP

2.1. Experimental loop

The experimental loop is installed at Korea Advanced Institute of Science and Technology (KAIST) as shown in Fig.2. The experimental loop is composed of the test section, an open pool, a heat exchanger, a centrifugal pump (Grundfos CRN 10-17), an electromagnetic flow meter (Toshiba GF 630/LF 600), a surge tank, a pre-heater (1000W), and piping. Thermocouples in the pre-heater are connected to proportional-integral-derivative (PID) system to control the power of pre-heater in the feedback process. Experiment procedure follows these steps; ① In the experiment, water is injected or emitted by the drain line installed on the surge tank. ② The water in the surge tank goes to a pre-heater for conditioning to the test section inlet temperature. ③ The pre-heated water flows through the DO sensor to measure the dissolved oxygen concentration of the water. ④ Flow then enters the test section where it is heated by two plate heaters. ⑤ The outlet of test section is connected to an open pool to maintain the atmospheric pressure. ⑥ Flow is cooled by a heat exchanger before passing through the circulation pump and flow meter, and finally returning to the surge tank.

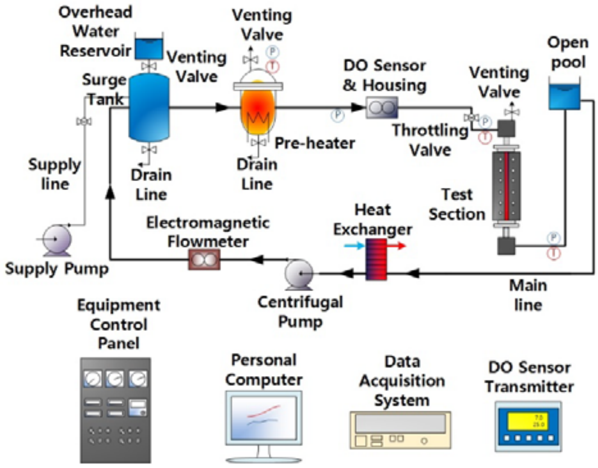

Fig. 2 Experimental loop installed in KAIST

2.2. Test section

The experiment was performed in a 350 mm heated length narrow rectangular channel (entire section is heated) with deionized (DI) water. In the test section, the channel width and gap are 40 mm and 2.35 mm, respectively, as shown in Fig.3. Polycarbonate transparent windows are installed at the front side and back side so the water flow in the rectangular channel could be observed directly. The heater width is 30 mm which is made of SUS304 plate. Copper electrodes installed both sides in the rectangular channel are connected to 150 kW (50V/3000A) DC power supply system with copper cables. The distance between the electrodes installed upper side and bottom side is same as heated length, 350 mm. Six thermocouples (Omega Engineering K-type) are installed at the back of the heaters along the axial direction. Also, in Fig.4, pressure transducer (Keller PA-21Y/10bar) and thermocouples are installed in the inlet and outlet of test section to measure the water pressure and temperature. As the ONB is local phenomena which is affected by local bulk temperature mainly, the temperature data from thermocouples installed near the exit was used for data analyzing. Thermocouples attached to outside heater are connected to data acquisition system (Agilent 34972A) with personal computer. Experiments were controlled by the equipment control panel and monitored through the computer. All the measured data are recored in 0.660s time interval. To handle the effect of conduction of the heater itself, the measured wall temperature was calibrated by calibration experiments.

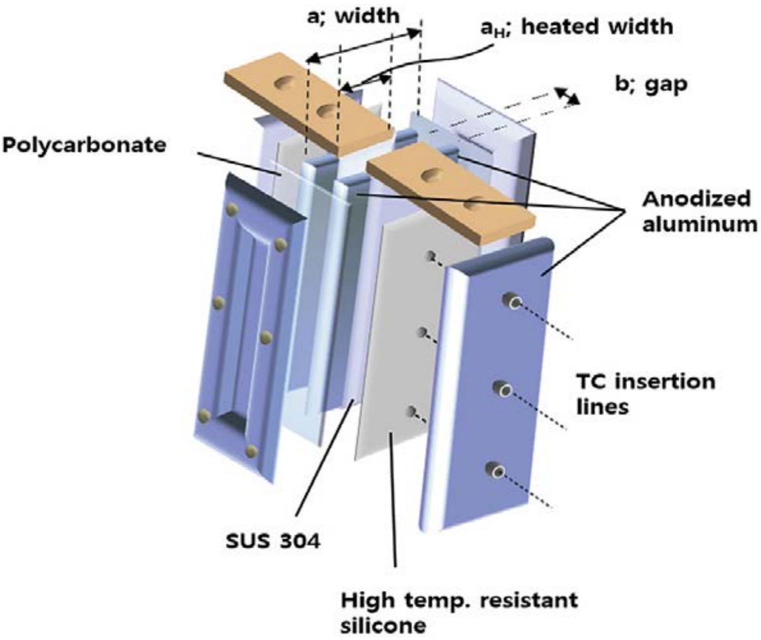

Fig. 3 3-D cut-view of test section [19]

Table 1. Detail sizes of test section (units : mm)

b	a	a_h	L_h	D_e	Heater thickness
2.35	40	30	350	4.44	2

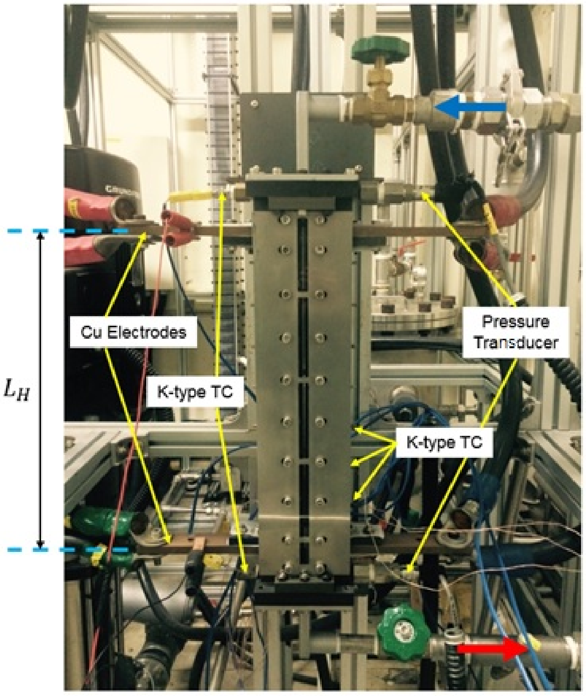

Fig. 4 Image of test section

ONB experiments were performed with varying inlet temperature and mass flux. In the experiments, inlet temperature condition is from 25°C to 45°C, mass flux condition is from $800\ \mathrm{kg/m^2}s$ to $1200\ \mathrm{kg/m^2}s$ under atmospheric pressure as shown in Table 2.

Table 2. Test matrix of the experiment

Flow direction	Mass flux ($\mathrm{kg/m^2}s$)	Inlet temperature (°C)	Pressure (bar)
Downward	800, 1000, 1200	25, 35, 45	Atmospheric

3. EXPERIMENTAL PROCEDURE

ONB phenomena is very sensitive to dissolved gas in the water and entrapped gas in the loop. Thus, degassing process should be performed before the experiments to eliminate the effect of dissolved gas and entrapped gas. To get rid of entrapped gas in the test section, the heater in the test section was heated up to 110°C for 20 minutes.

To investigate the effect of dissolved gas in the water, water is pre-heated at various temperature with mass flux $1500\ kg/m^2s$ for 30 minutes to lower the gas solubility of the water. The vaporized gas could be emitted by open pool or venting valves installed on surge tank and pre-heater. After heating at each temperature, DO (dissolved oxygen) concentration was measured by DO sensor in the loop. Measured DO concentration is about 4.9, 3.7, 3.2, 2.2, and 1.9 ppm for differnet temperature case. Assuming that the DO concentration maintains constant for a while, test experiments were conducted for each DO concentration to figure out the effect of DO concentration on ONB. It is found that wall superheat at ONB measured increased from high DO concentration to low DO concentration and wall superheat at ONB seemed to be saturated from 2.2 ppm. Thus, following ONB experiments were performed under 2.2 ppm condition.

After that, mass flux in controlled to meet the test matrix in single-phase liquid region and inlet temperature is controlled by pre-heater. For the fixed mass flux and inlet temperature, power applied to the heater in the test section is increased step-by-step.

4. RESULT AND DISCUSSION

4.1. ONB determination

For single-phase heat transfer, heater temperature increases linearly as the heat flux applied to the heater increases. Until the inside wall temperature reaches the saturation temperature of liquid, nucleate boiling cannot be occurred under steady flow condition. When the liquid temperature near the wall exceeds saturation temperature, bubbles could be generated on the wall. As bubbles being generated on the wall, heat transfer between liquid and heater increases hugely.

As bubble generates and heat transfer between liquid and heater increases, it is able to identify ONB point through several ways. In general, there are three main methods to identify ONB point; first, bubble visualization by high-speed camera, second, pressure drop increment in the test section, third, heater temperature deviation from single-phase flow to two-phase flow using thermocouples or IR (Infra-Red) camera.

As explained above, ONB determination using heater temperature would be the most appropriate method among several methods. In narrow rectangular channel, it is hard to measure the heater temperature and ONB occurrence using IR camera because gap is too narrow to look front side of heater. Thus, method using inside heater temperature is recommended for set the ONB criteria. Although it is able to judge ONB comparing heat transfer coefficient with single-phase heat transfer correlation, single-phase heat transfer correlation itself has error range based on its development that can lead quite huge error when judge ONB based on its performance. Thus, deviation change that occurred in the transition from single-phase flow to two-phase flow in the boiling curve could be used to figure out ONB point.

Black circles in Fig.5, gradient in boiling curve shows the point that heat transfer coefficient deviates drastically after bubble generates. Until now, previous studies determined ONB point just as the point which gradient suddenly changes from single-phase heat transfer in boiling curve as without any quantified criteria. Based on experimental data, gradients were calculated from the experiment beginning and gradient change at each point was calculated.

For example, black circle in mass flux $800\ \mathrm{kg/m^2}s$ case, gradient change was figured out with the averaged gradient of the beginning to black circle and gradient of black circle to next data. For all experimental cases, gradient changes were calculated with .

Then, gradient changes were used to quantify the gradient change at ONB point and it was found that noticeable change in gradient showed more than 42% in all the experiment cases. Thus, 42% gradient change using averaged gradient to following gradient at each point was set as the quantified criteria for determining ONB point.

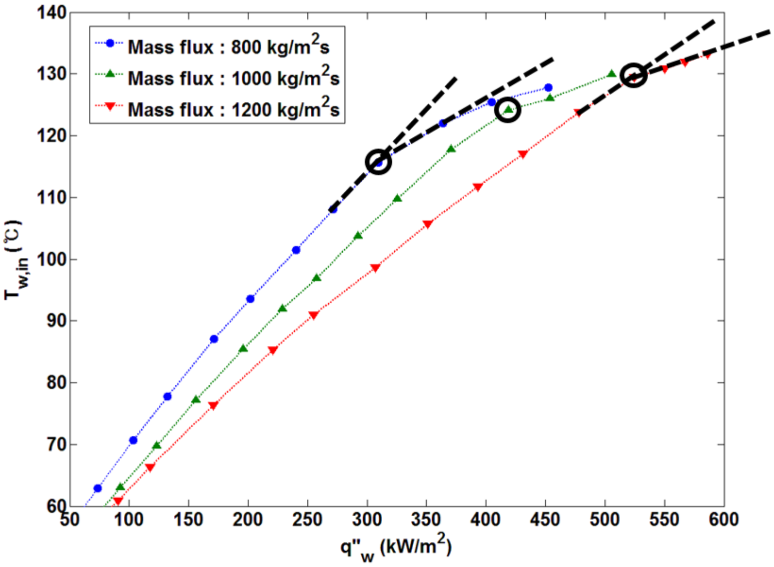

Fig. 5 Gradient deviation at ONB in boiling curve from single-phase to two-phase

4.2. Parametric trends on ONB

In the Fig.6, effect of various mass flux condition for ONB data is shown. According to the data, heat flux at ONB increases as mass flux increases from blue points to red points obviously. Thus, it could be figured out that more heat flux is required to reach bubble nucleation for higher mass flux condition because higher mass flux enhances the heat transfer between liquid and heater. In addition, wall superheat at ONB increases as mass flux increases as well. It could be interpreted as higher temperature difference is needed to generate bubble due to enhanced heat transfer for higher mass flux condition. This trend is also reported by Basu et al. (2002) [20] and Hong et al. (2012) [16].

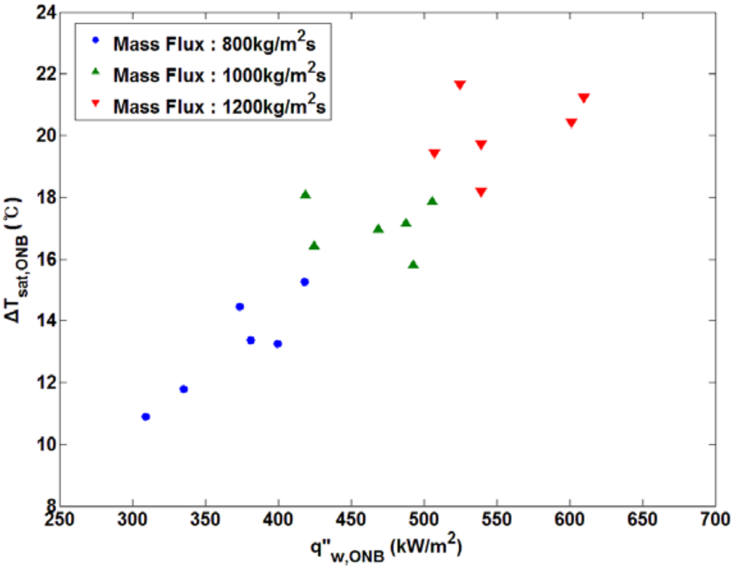

Fig. 6 Effect of mass flux on ONB

In the Fig.7, ONB data for various inlet temperature condition are reported. Based on the data, heat flux at ONB decreases as inlet temperature increases from blue points to red points. The reason is that as higher inlet temperature reduces required heat flux to reach bubble nucleation, less heat flux in needed. For low mass flux condition ($800\ \mathrm{kg/m^2}s$), wall superheat at ONB decreases as inlet temperature increases from blue points to red points. On the contrary, significant tendency of inlet temperature on ONB wall superheat was not found for relatively higher mass flux conditions. For the test section, length is long enough compared to equivalent diameter to develop thermally fully developed condition. So, there would be no change in thermal boundary layer for different mass flux conditions. In detail, however, superheated layer could be developed near the heater surface in bubble nucleation process and certain superheated layer thickness determined by surface roughness can be regared as threshold value for bubble nucleation. Superheated layer thickness is affected by inlet temperature, mass flux, and heat flux applied to heater; superheated layer thickness increases with increasing inlet temperature, increasing heat flux, and decreasing mass flux. From the experimental results, it can be figured out that mass flux and heat flux have dominant effects to determine superheated layer thickness compared to inlet temperature. Thus, for low mass flux condition, high inlet temperature increased superheated layer thickness and it led wall superheat to decrease. On the contrary, inlet temperature effects on wall superheat were neglected for relatively higher mass flux condition. This kind of result showed difference compared to the tendency noted by Hong et al. (2012) [16].

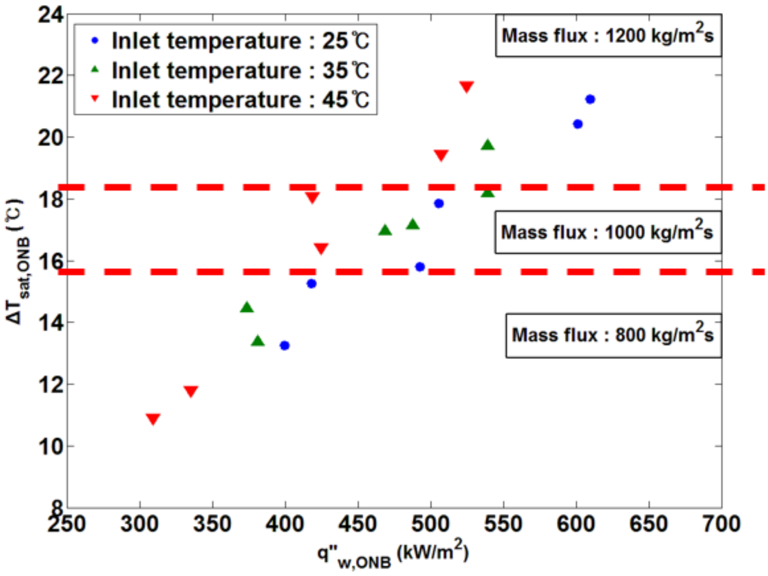

Fig. 7 Effect of inlet temperature on ONB

4.3. Comparison with existing correlations

Many ONB prediction correlations have been developed. Among them, six correlations were selected to predict wall superheat at ONB with provided heat flux in the experiments. Comparison between experimental data and existing correlations (Sato and Matsumura (1964) [5], Bergles and Rohsenow (1964) [4], Jens and Lottes (1951) [6], Thom and Fallon (1965) [7], Hong et al. (2012) [16], and Liu et al. (2005) [13]) is shown in Fig.11. These correlations are listed in Table.3; Hong et al. (2012) was developed based on experimental data in rectangular channel and the others were developed based on tube experimental data. In Fig.8, it is found that existing correlations predict wall superheat quite differently from low heat flux to high heat flux. Among them, Thom and Fallon’s correlation predicted the experimental data well respectively compared to experimental results and Hong et al. (2012) predicted it quite lower than others.

Table 3. Existing ONB prediction correlations

Author	**Correlation**
Sato and Matsumura (1964)	$\Delta T_{sat,ONB} = \sqrt{\frac{8 * \sigma * q''_w * T_{sat}}{h_{fg} * k_f * \rho_g}}$

Bergles and Rohsenow (1964)	$\Delta T_{sat,ONB} = \frac{5}{9} * \left(\frac{q''_w}{1082 * P^{1.156}}\right)^{\frac{p^{0.0234}}{2.16}}$
Jens and Lottes (1951)	$\Delta T_{sat,ONB} = 25 * \left(\frac{q''_w}{1000}\right)^{0.25} * e^{-\frac{P}{6.2}}$
Thom and Fallon (1965)	$\Delta T_{sat,ONB} = 22.65 * \left(\frac{q''_w}{1000}\right)^{0.5} * e^{-\frac{P}{8.7}}$
Hong et al. (2012)	$\Delta T_{sat,ONB} = 0.05 * T_{Sat} * Re^{0.156} * \left(\frac{\rho_g}{\rho_f}\right)^{-0.413} * q^{*1.321}$ ($Re = \frac{GH}{\mu_f}$, $q^* = \frac{q''_w}{Gh_{fg}}$, H : gap size)
Liu et al. (2005)	$\Delta T_{sat,ONB} = 2 * \sqrt{\frac{2 * \sigma * C * q''_w * T_{sat}}{h_{fg} * k_f * \rho_g}} + \frac{2 * \sigma * C * q''_w}{h_{fg} * k_f * \rho_g}$ ($C = 1 + cos\theta$)

(units : T in K, P in bar, θ in degree, q''_w in $\mathrm{kW/m^2}$, G in $\mathrm{kg/m^2s}$)

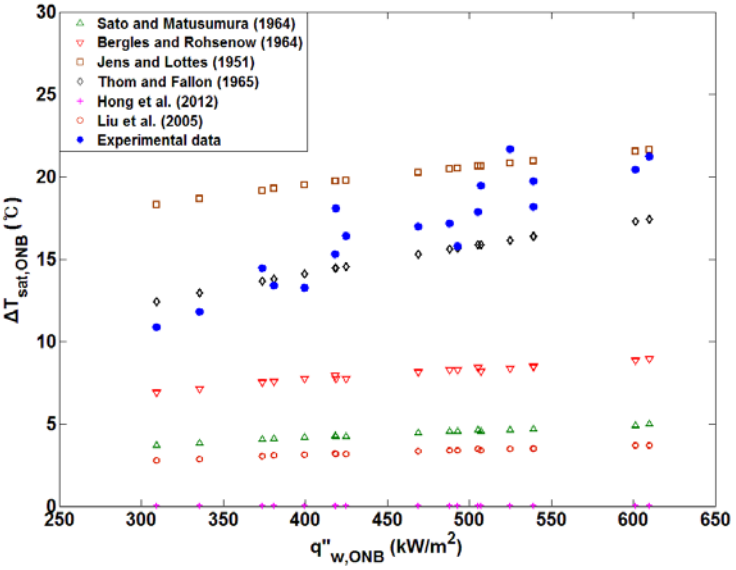

Fig. 8 Comparison between experimental data and predicted values

4.4. Experimental correlation development

By analyzing parametric trends, it was determined that key parameters related to ONB are wall superheat ($\Delta T_{sat,ONB}$), heat flux (q''_w), mass flux, and inlet temperature. Therefore, $\Delta T_{sat,ONB}$, q''_w, D_e, mass flux, and inlet temperature are the main parameters and are used to develop an empirical correlation.

For applicability of the correlation to an extended range of data, Sudo's ONB data for downward flow were gathered by a digitizing method. In Sudo et al. (1986), experiments covered a range of mass flux, G, varying from $370 - 1500\ kg/m^2s$ and, inlet temperature, T_i, varying from $15 - 72°C$. Based on extended ONB database which includes Sudo's experimental data, a new empirical correlation was developed as follows. The following dimensionless parameters are developed and are used for the correlation.

Reynolds number (Re) is defined to consider mass flux and geometry as

$$Re = \frac{GD_e}{\mu_f} \tag{1}$$

Boiling number (Bo) is defined to consider heat flux and mass flux as

$$Bo = \frac{q''_w}{Gh_{fg}} \tag{2}$$

Dimensionless inlet temperature is defined as

$$T_i^* = \frac{T_{sat} - T_i}{T_{sat}} \tag{3}$$

Dimensionless wall superheat is defined as

$$\Delta T_{sat}^* = \frac{\Delta T_{sat,ONB}}{T_{sat}} = \frac{T_{w,ONB} - T_{sat}}{T_{sat}} \tag{4}$$

With developed dimensionless parameters, empirical correlation for ONB prediction is developed as (5).

$$\Delta T_{sat}^* = 1.677 * Bo^{0.569} * Re^{0.264} * T_i^{*0.042} \tag{5}$$

In Fig. 9(a) and Fig. 9(b), the performance of the developed correlation for wall superheat and heat flux is compared with other correlations. The graphs reveal that the newly developed correlation achieved better performance to predict wall superheat and heat flux than the other correlations. The prediction error for wall superheat ranges from -29.68% to 40.07%. The prediction error for heat flux ranges from -45.68% to 85.57%. The RMS errors are 19.13% and 32.94%, respectively.

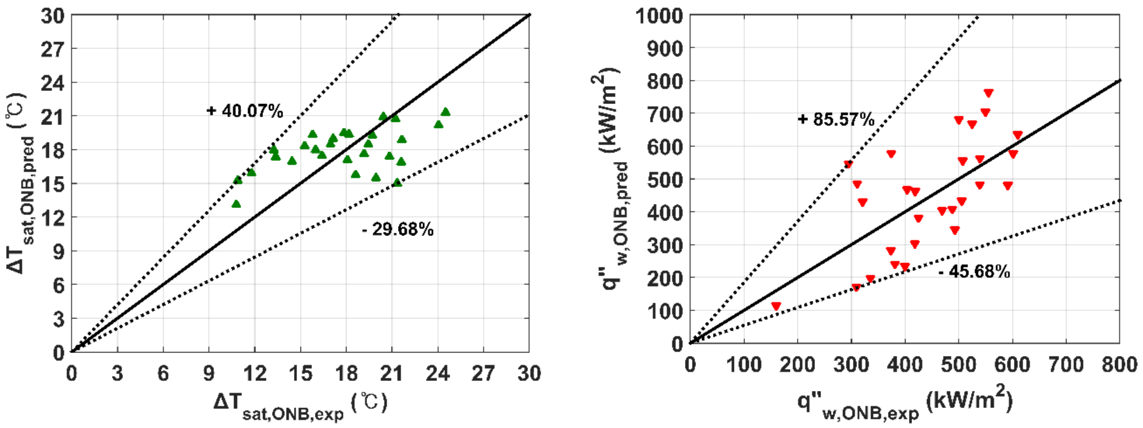

Fig. 9 Comparison between predicted and measured data
(a) for wall superheat (left) (b) for heat flux (right)

5. CONCLUSIONS

In the study, ONB experiments were performed for downward flow in narrow rectangular channel with quantified ONB determination criteria. With the experiments data, effects of wall superheat and heat flux were investigated and new empirical correlation was developed including Sudo's experiment data. Conclusions were summarized as follows.

(1) Based on the data from single-phase to two-phase flow, 42% gradient change (empirical value) was set as quantified ONB criteria for noticeably change in boiling curve.
(2) As mass flux increases, both wall superheat and heat flux at ONB increased. With the inlet temperature, heat flux at ONB decreased as inlet temperature increases. For low mass flux condition, wall superheat decreased as inlet temperature increases. However, no clear

relationship between inlet temperature and wall superheat for high mass flux conditions was found as mass flux and heat flux has dominant effect on wall superheat at ONB.

(3) Among several ONB prediction correlations, all of correlations showed quite huge differences compared to the experimental data. However, Thom and Fallon's correlation predicted well with experimental data repectively.

(4) For an extended database including Sudo's ONB experiments for downward flow by digitizing, a new correlation to predict ONB was developed. It achieved better performance for predicting wall superheat and heat flux at ONB than existing correlations. However, it still has limitation that prediction error is quite large to find out exact ONB point at given condition.

NOMENCLATURE (IF NEEDED)

a	channel width (mm)
a_h	heated width (mm)
b	channel gap size (mm)
D_e	hydraulic equivalent diameter (mm)
G	mass flux (kg/m^2s)
L_h	heated length (mm)
ΔT_{sat}	wall superheat (= inside wall temperature – saturation temperature) (℃)
ΔT_w	temperature difference between inside and outside of heater (℃)
q''	heat flux (kW/m^2)

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