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Onset of Nucleate Boiling in Rectangular Channels under Low Pressure

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1. Introduction

Nuclear reactors can be divided into two types; commercial reactor and research reactor. Radiation from research reactors is used for many industries. Due to that characteristic of research reactors, as many people work around research reactor, the design with conservative safety margin for research reactor is more sensitive issue.

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 lead 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) [6].

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 [5].

In Hsu’s model, the uniform bulk temperature T_∞ is 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.

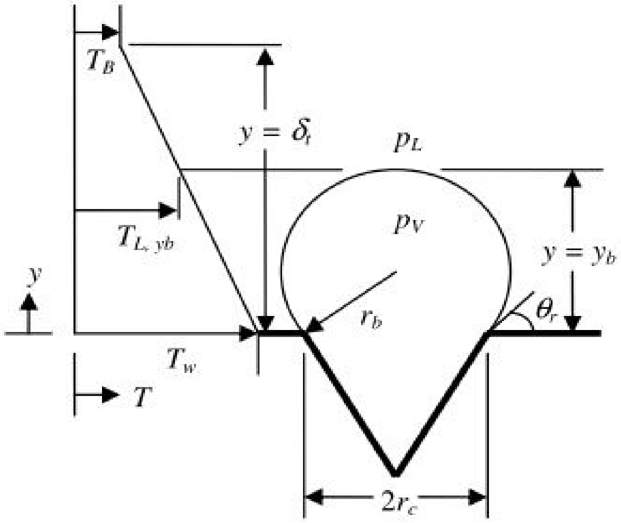

Figure 1. Temperature profile around a nucleating bubble [8]

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.

Also some researches, e.g., Liu et al. [10] and Hong et al. [4] note that the existing ONB correlations were not suitable for the narrow rectangular channel. Sudo et al. [12] performed only few ONB experiments in rectangular channel with downward flow.

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 Set

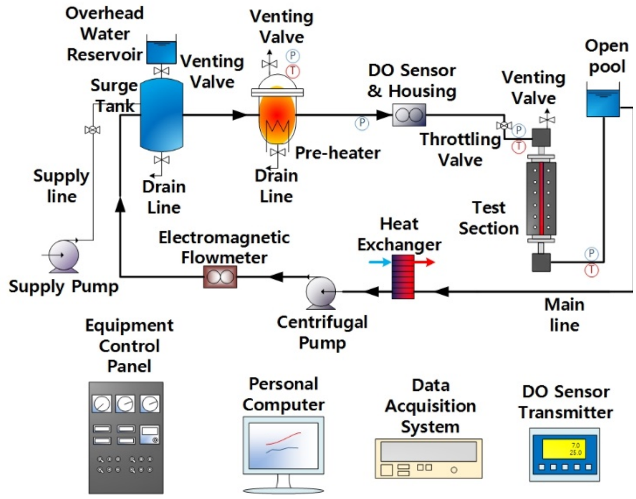

Figure 2. Experimental loop installed at KAIST

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, an electromagnetic flow meter, a surge tank, a pre-heater, and piping. In the experiment, water is injected or emitted by the drain line installed on the surge tank. The water in the surge tank goes to a pre-heater for conditioning to the test section inlet temperature. The pre-heated water flows through the DO sensor to measure the dissolved oxygen concentration of the water. Flow then enters the test section where it is heated by two plate heaters. The outlet of test section is connected to an open pool to maintain the atmospheric pressure. Flow is cooled by a heat exchanger before passing through the circulation pump and flow meter, and finally returning to the surge tank.

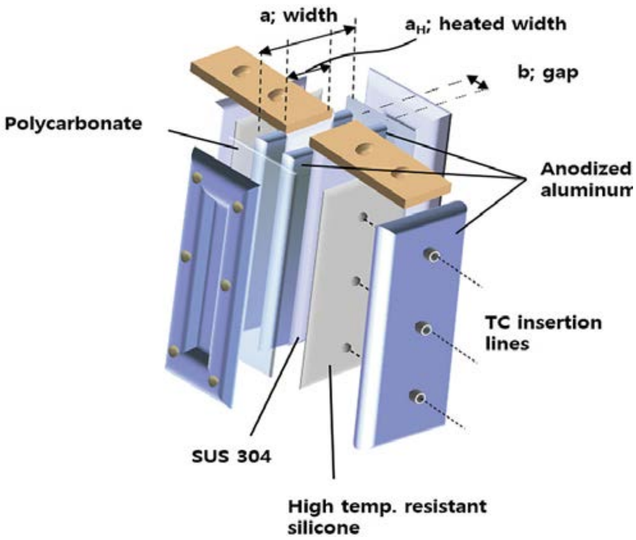

Figure 3. 3-D cut view of test section [9]

The experiment was performed in a 350 mm length narrow rectangular channel (entire section is heated) as shown in Fig.3. In the test section, the channel width and gap are 40 mm and 2.35 mm, respectively, as shown in Fig.2. The heater width is 30 mm. Six thermocouples are installed at the back of the heaters along the axial direction. As the ONB is local phenomena which is affected by local bulk temperature mainly, the temperature data from TC installed near the exit was used for data analyzing. To handle the effect of conduction of the heater itself, the measured wall temperature was calibrated after the experiments.

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 $1200\,\mathrm{kg/m^2}s$ as shown in Table 1.

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

Table 1. Test matrix of the experiment

3. Results

In general, for single phase heat transfer, wall temperature increases linearly as the heat flux on the wall increases. Until the wall temperature reaches the saturation temperature T_{sat} of liquid, nucleate boiling cannot be occurred under steady flow conditions. When the water temperature near wall exceeds the saturation temperature and reaches enough amount of superheat, bubbles can be generated on the wall surface. As the bubbles are generated on the wall, the heat transfer at the wall surface is enhanced and the relationship between heat flux and wall temperature becomes different. Thus, the occurrence of ONB could be identified by the deviation change from single phase behavior in wall temperature versus heat flux.

To figure out when ONB occurs, the measured wall temperature under 90°C were considered as single phase and used for fitting single-phase heat transfer correlation. Commonly used single phase heat transfer correlation, Dittus & Boelter (1930) [3] correlation, and single phase heat transfer correlation developed based on the rectangular channel data, Jo et al (2014) [7], were used for evaluating single phase experimental data as shown in Fig.4. Dittus & Boelter (1930) correlation shows 21.99% RMSE and Jo et al. (2014) shows 9.64% RMSE. Thus, for conservative manner, Jo et al (2014) was used to evaluate single phase heat transfer. And the point including uncertainty beside the range was chosen as ONB point as shown in Figure 4.

As the Jo et al. (2014) errors as large as -19.20% to 30.19%, the Nussel number range was set to 30.19% to define the single phase heat transfer and two phase heat transfer. With this criterion, ONB is determined as shown in Fig.5 which is the point out of range.

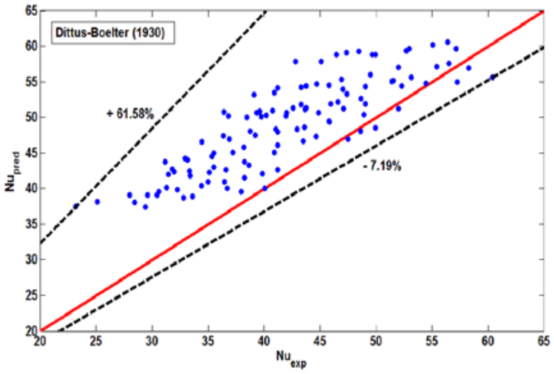

Figure 4-A. Single phase heat trnasfer data evaluated with Dittus & Boelter (1930)

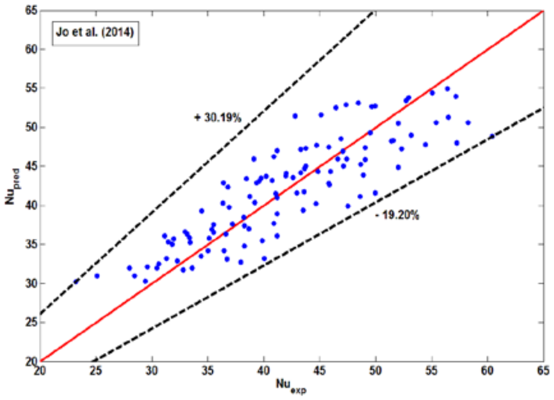

Figure 4-B. Single phase heat trnasfer data evaluated with Jo et al. (2014)

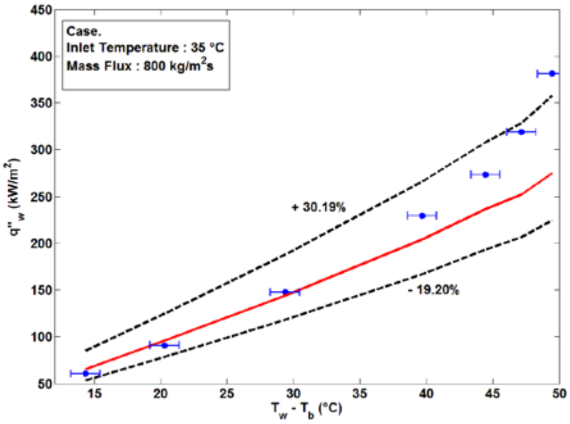

Figure 5-A. Example of ONB determination criterion

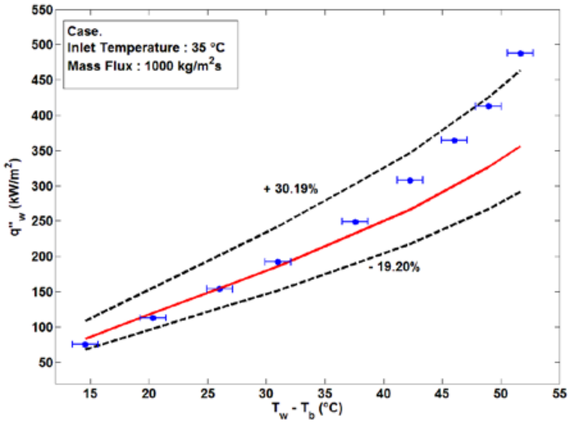

Figure 5-B. Example of ONB determination criterion

In the Fig.6, the required heat flux for ONB increases as mass flux increases. Increasing mass flux increases the heat transfer in the test section; thus, more heat flux is required for reaching ONB for higher mass flux condition. Thus, superheats calculated by existing correlations for fixed pressure condition increase as heat flux increases. However, experimental superheats at ONB of became smaller for higher mass flux condition. This is due to saturation temperature increment as mass flux increment cause pressure increment in the system. The superheat at ONB considering pressure effect is shown as Fig.8. Considering the effect of pressure on superheat, the range and tendency of experimental data is similar with other correlations.

In the Fig.7, heat flux on ONB decreases and wall superheat on ONB increases as inlet temperature increases. The reason is that for higher inlet temperature, the temperature difference between the inlet temperature and saturation temperature is small. Thus, less energy is needed to reach the bubble nucleation temperature for higher inlet temperature condition.

Existing correlations errors about at least 80% to predict heat flux or wall superheat at ONB as shown in Table 2 based on the experimental data.

In Fig. 6, 7 and 8, it is found that heat flux, pressure, and inlet temperature are related to ONB superheats closely.

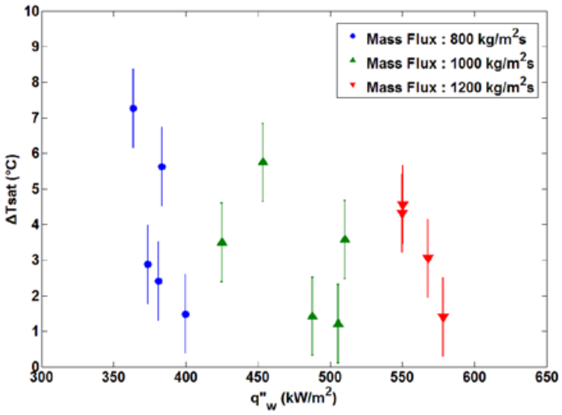

Figure 6. Effect of mass flux on ONB superheat

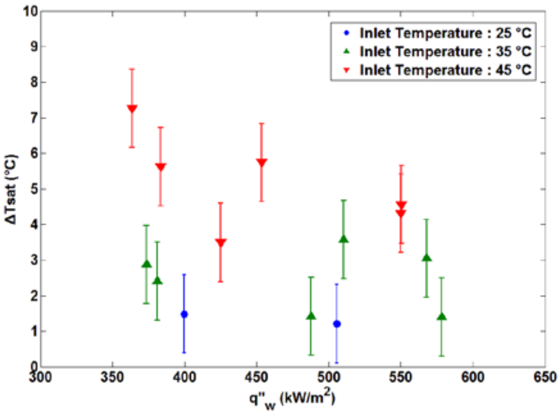

Figure 7. Effect of inlet temperature on ONB superheat

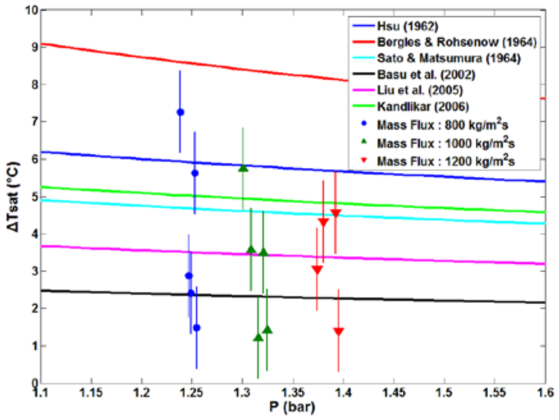

Figure 8. Effect of pressure on ONB superheat

RMSE (%)	**Hsu et al.** [5]	**Bergles & Rohsenow** [2]	**Sato & Matsumura** [11]
ΔT_{sat}	180.92	292.22	129.74
q''_w	73.06	81.18	89.33
RMSE (%)	**Basu et al.** [1]	**Liu et al.** [10]	**Kandlikar** [8]
ΔT_{sat}	54.19	84.90	143.49
q''_w	410.56	81.23	89.14

Table 2. ONB heat flux, wall superheat prediction performance

4. Conclusion

In this study, new methodology to define ONB point based on the heat transfer coefficient difference between single phase heat transfer and two phase heat transfer using single phase heat transfer correlation.

In addition, several existing ONB prediction correlations based on the Hsu's model showed large error with experimental data. It can support that not only heat flux and wall superheat, but also the local parameters should be figured into ONB prediction. Thus, it can support that the existing ONB prediction correlations are not suitable for predict ONB in rectangular channel and new correlation is needed to this condition.

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