High-Speed Detection of Onset of Nucleate Boiling of DI Water at Stainless Steel Heater Confined in Narrow Rectangular Vertical Channel

Junkyu Han, Yongjae I, Sung Joong Kim*
Department of Nuclear Engineering, Hanyang University
17 Haengdang-dong, Seongdong-gu, Seoul, 133-791, Republic of Korea
**Corresponding author: sungjkim@hanyang.ac.kr*

1. Introduction

Onset of Nucleate Boiling (ONB) is the criterion which is one of operational conditions. In the publication, IAEA Safety Standards guide achieving the highest level of safety for their Research Reactors (RRs). In operational conditions at Section of Safety of Research Reactor in IAEA Safety Standards, there are five items: Safety limits, Safety system settings, Limiting conditions for safe operation, Surveillance requirements and Administrative requirements. ONB is included in Safety System Settings (SSS). Limiting Safety System Settings (LSSS) are some range parameters in SSS (Fig. 1).

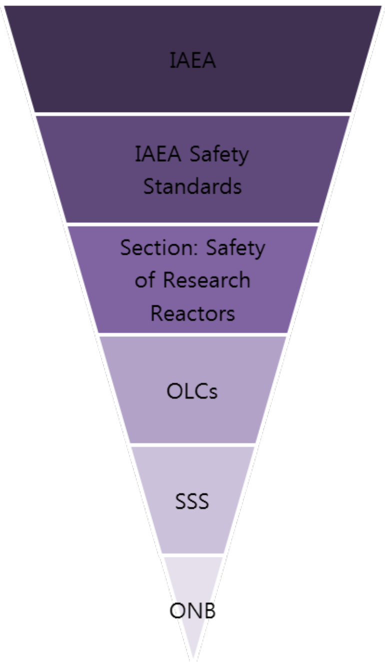

Fig. 1. Diagram of relation between IAEA and ONB

It has 31 parameters and the parameters about ONB have seven particulars. In other words

1) Temperatures of fuel cladding of Fuel channel coolant,
2) Temperature of reactor coolant,
3) Rate of change of temperature of reactor coolant,
4) Pressure of the reactor coolant system,
5) Water level in reactor vessel or pressurizer,
6) Reactor coolant flow,
7) Rate of change of reactor coolant flow.

Based on the seven particulars, the ONB can be a criterion of a safety standard at RRs (Fig. 2).

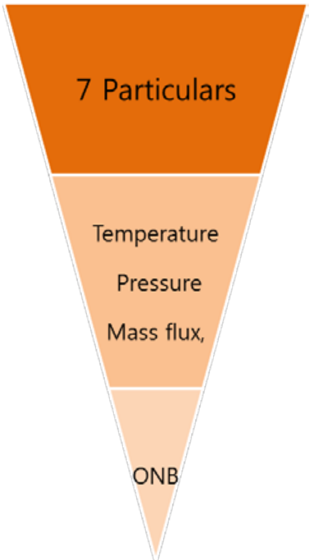

Fig. 2. Diagram of relation between 7 particulars and ONB

A flow loop facility (HYU ONB loop) was designed and constructed to investigate the ONB heat flux with DI water flowing in the narrow rectangular channel. Particulars are related to temperature, pressure and mass flux at ONB. To measure the bubble occurrence, experimental instrument is constructed using K-type Thermocouples, pressure gage and turbine flowmeter. Keeping inlet experimental conditions, a heat exchanger chills the heated water from a test chamber.

In this study, prediction of ONB heat flux in a vertical rectangular channel is performed using the superposition method by Bergles - Rosenhow (B-R) ONB correlation. Also Petukhov - Gnielinski (P-G) single-phase correlation was introduced in replace of Dittus - Boelter (D-B) correlation in Bergle - Rosenhow correlation as Petukhov - Gnielinski correlation is more optimized for analysis of narrow rectangular channel. So those correlations are used for predicting the bubble occurrence and compared with experiment values.

The objective of this study is, therefore, to obtain experimental ONB heat flux data within the operating conditions of research reactors utilizing rectangular flow geometries. The study of onset of nucleate boiling separated two parts, theoretical approach and experimental approach. The test section is designed to make a same condition of RRs for experimental approach. Numerical analysis about ONB was used for theoretical approach.

2. Experimental Description

2.1 Description of ONB flow chamber

The flow chamber was designed to simulate the narrow rectangular flow geometries having some similarities with flow channels of RRs (Fig. 3).

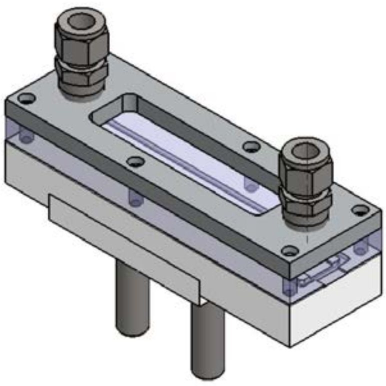

Fig. 3. 3D drawing of ONB flow chamber

The material of the chamber body is PEEK for heat isolation. The entrance and exit are 1/2˝ tube. The rectangular flow channel is 15 mm width and 1.1 mm height. This boundary reflects a part area of MITR (Fig. 4).

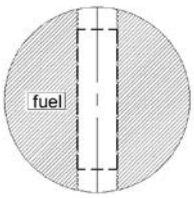

Fig. 4. Reflected waterways of MITR core

The temperature is measured by thermocouples from backside of heater. For having more precise measurement of temperature, the thermocouples touched the most probability spot of operating ONB (Fig. 5).

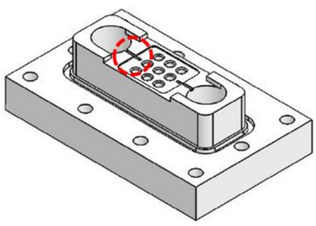

Fig. 5. The place of setting thermocouples

The heater is plate type. It is designed to consider the thermal expansion. Due to the narrow channel, if there is bowing effect, the channel could be blocked (Table 1).

Table 1. Heater dimension

Dimension (m)	Value
Length	0.035
Width	0.015
Thick	0.002

The boiling heat transfer is affected by surface conditions; roughness, wettability and porosity. For measuring the surface conditions, wettability (Table 2) and roughness were measured.

Table 2. Wettability measurement of heater

Test ID	SS-01	SS-02	SS-03
picture			
Angle [°]	85.5	85.1	85.4

The average contact angle of upside center is 85.33° at the range. In each test, the height from a tip to heater is same.

For getting uniform roughness, sand grit paper and silicon carbide (SiC) grit paper with water was used, starting with 1000 grit and repeating with finer grit sizes up to 4000.

To measure the roughness, Atomic Force Microscope (AFM) is used with non-contact cantilever with PPP-NCHR-10. The rms roughness (Rq) is 16.803 nm and the difference RP-P between the lowest and highest points on the surface is 76.93 nm (Fig. 6).

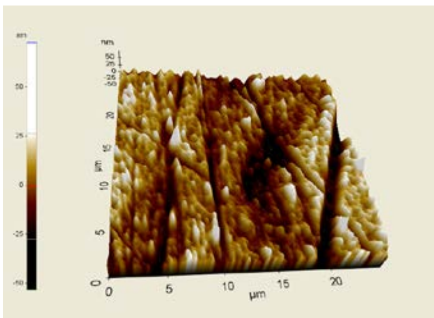

Fig. 6. The roughness of heater

2.2 Flow Loop Design and Experimental Procedures

Figure 6 shows a schematic of the flow loop for ONB observation. Several experimental components are installed in the loop. The flow rate is measured by a turbine flow meter calibrated by OMEGA. Two pressure transducers are installed to measure the inlet and outlet pressure of flowing water. Two thermocouples are installed at the inlet and outlet of the test section to measure of the flowing water temperature. The inlet temperature is controlled using the secondary side valve of the heat exchanger. The front side of the test section is set up with the visualization system, which has a high speed camera to observe a bubble occurrence.

As an experiment starts, the test samples in the test section are heated up electrically through the copper electrodes with a maximum current of 1200 A. The heated water flows to the high capacity 4-pass shell-and-tube heat exchanger, and the cooled water heads back to the pump.

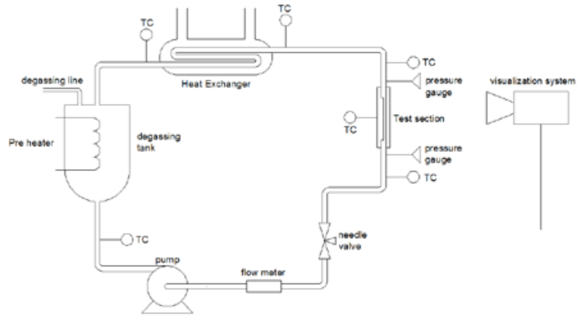

Fig. 6. Schematic of ONB loop

2.3 Visualization System

In order to capture the first inception of a bubble, a high speed camera system was introduced. It consists of Phantom v7.3 camera (800 x 600 at 6,688 fps), AF micro nikkor 105mm 1:2.8 D lens, Phantom camera control software, MBA100PN tripod, and four 750W lamp light with compacted grass reflector.

3. Numerical analysis for ONB Prediction

For our analysis, there are three correlations used in this study using MATLAB

A correlation for heat flux prediction at ONB
- Bergles - Rohsenow correlation (1)

$$q''_{ONB} = 1082 P^{1.156}\left[1.8\left(T_w - T_{sat}\right)\right]^{2.16/P^{0.0234}} \quad (1)$$

Correlations for flow conditions:
- Dittus - Boelter correlation (2)

$$q''_{Dittus} = 0.023\frac{k}{D_e}\mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.4}(T_{wall} - T_{fluid}) \quad (2)$$

- Petukhov - Gnielinski correlation (3)

$$q''_{Petukhov} = \frac{k}{D_e}\times\frac{(f/8)(\mathrm{Re}-1000)\mathrm{Pr}}{1+12.7(f/8)^{1/2}\left(\mathrm{Pr}^{2/3}-1\right)}\left(T_{wall} - T_{fluid}\right) \quad (3)$$

To progress the prediction using the correlations, the parameters should be determined. Considering operation conditions of the effective research reactor, Reynolds number is set up by 2400 kg/m^{2}sec and properties of water fluid. To have more accuracy, the solution error is 0.0005% (Table 3).

Table 3. Prediction parameters

Experimental parameter	Value
Pressure (Pa)	101325
Re	11487.84
mass flux (kg/m^{2}sec)	2398.78
Pr	2.66
inlet temperature (℃)	67
hydraulic diameter (m)	2.05×10^{-3}
k (W/m·K)	0.66
Error (%)	0.0005
μf (N·s/m^2)	4.67×10^{-4}

Figure 7 shows the results of prediction using MATLAB program. The black line is the B-R, red is D-B and blue is P-G correlation under the conditions. The interactions of two correlations which are B-R & D-B, or B-R & P-G become the predicted values.

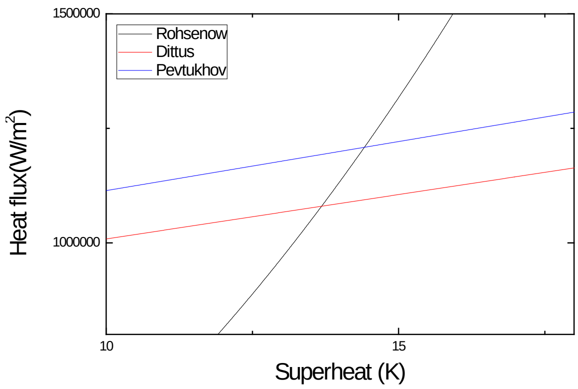

Fig 7. D-B, P-G and B-R correlations at the conditions

Table 4. Heat flux and Temperature for prediction

correlation	q'' (kW/m^2)	T_{wall_out} (K)
B-R & D-B	1,080	386.83
B-R & P-G	1,209	387.56

Under the assumption of no heat loss into the PEEK insulator, T_{wall} is obtained with the local surface temperature T_{wall_out} of heating plate measured on the PEEK insulator side, the electric power supply q to the heater thermal conductivity k of heater and thickness S, width W and length L of heater as follows Eqs.(4):

$$T_{wall} = T_{wall\_out} - \frac{qS^2}{2kWL} \quad (4)$$

4. Results and Discussion

4.1. Result of ONB heat flux and temperature

In order to compare the prediction values with the experimental data, four tests were carried out under the constant inlet temperature of 332.15K and atmospheric pressure. Each test has different flow conditions in Reynolds number of 11098.76, 11145.12, 11271.27 and 11303.41. Table 5 shows the heat fluxes, heater outside temperatures (T_{wall_out}), and the heating surface temperatures (T_{wall}) at the ONB occurrence.

Table 5. Experiment result

No.	Experiment q" (kW/m^2)	Experiment T_{wall_out} (K)	Experiment T_{wall} (K)
1	917	389.35	389.23
2	876	387.49	387.37
3	892	387.93	387.81
4	885	388.56	388.44

Figure 8 shows the experimental data with the theoretical lines, which are Dittus – Boelter, Petukhov – Gnielinski and Rohsenow correlations.As shown, the obtained wall temperatures were higher than the predicted values.
Moreover, as the coolant velocity increases, the higher wall temperatures were achieved.

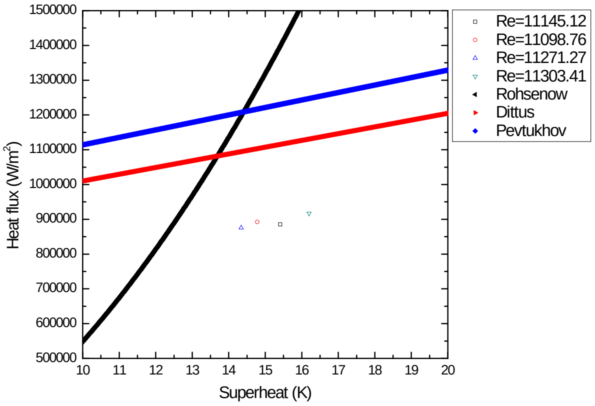

Fig. 8. Experiment result at Re = 11145.12, 11098.76, 11271.27, 11303.41 fluid temperature = 332.15℃ with D-B, P-G and B-R correlations

Table 6 shows the prediction with B-R and D-B correlation (R-D), and B-R and P-G correlation. Heat flux predicted by R-D is lower than R-P predicted heat flux, and superheat is also lower 0.7℃ approximately.

Table 6. Prediction at experiment condition

No.	q"(R-D) (kW/m^2)	q"(R-P) (kW/m^2)	T_{wall} (R-D) (K)	T_{wall} (R-P) (K)
1	1,063	1,187	386.65	387.36
2	1,038	1,159	386.51	387.20
3	1,024	1,141	386.42	387.10
4	1,028	1,146	386.44	387.13

As the criteria frequency of bubble departure is 450ms, Table 7 shows the difference between experiment data and prediction. The differences make us know that the heat flux by experiment is lower than both predictions, and wall temperatures are higher than both predictions.

Table 7. The difference between Experiment result and Prediction

No.	Δq" (R-D) (kW/m^2)	Δq"(R-P) (kW/m^2)	ΔT_{wall} (R-D) (K)	ΔT_{wall} (R-P) (K)
1	146	270	2.58	1.87
2	163	284	0.86	0.17
3	131	249	1.39	0.71
4	143	261	2	1.31

4.2 High speed detection of ONB heat flux

ONB phenomenon is determined by visualization using high speed camera. The criteria of determination using visualization is two things,

First, to consider the fully developed flow, bubble is placed at the center line of a heater.

The frequency of bubble departure is approximately 450ms.

Fig. 9. shows a bubble departure phenomenon using high speed camera.

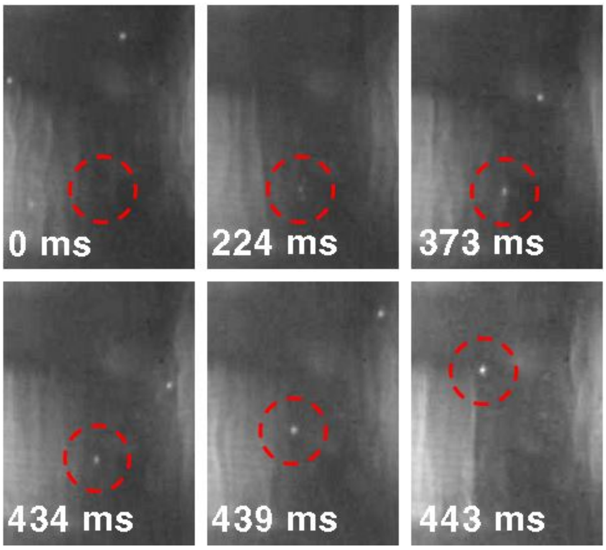

Fig. 9. Bubble operation under the criteria at Re=11098.76

5. Conclusions

Major findings from this study can be summarized as followings:

(a) The ONB heat flux was predicted using B-R, D-B and P-G correlation. It is observed that the ONB heat flux increases with mass flux.

(b) In addition to the prediction, the ONB heat flux was measured experimentally. The experimental results are higher heat flux and temperature compared by two predictions at the bubble departure frequency of 450ms.

(c) Visualization of the ONB heat flux suggests that incipience of boiling appears earlier. Need to make sure the visual criteria of determination about ONB.

(4) Although the heat flux condition of 900kW/m^2sec have ONB occurrence, the bubbles are nearly no affect to waterway and blocking.

Acknowledgements

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REFERENCES

[1] A. E. Bergles and W. M. Rohsenow, The determination of Forced-convection Surface-boiling Heat Transfer, Heat Transfer, Vol.86, pp. 365-372, 1964.
[2] F. W. Dittus and L. M. K. Boelter, Heat Transfer in Automobile Radiators of the Tubular Type, California University of California press, Berkeley, Vol.2, pp. 443-461, 1930.
[3] V. Gnielinski, New Equations for Heat and Mass Transfer in Turbulent Pipe and Channel Flow, International Chemical Engineering, Vol.16, No.2, pp. 359-368, 1976.
[4] Y. Sudo, K. Miyata, H. Ikawa, and M. Kaminaga, Experimental Study of Incipient Nucleate Boiling in Narrow Vertical Rectangular Channel Simulating Subchannel of Upgraded JRR-3, Nuclear Science and Technology, Vol.23, pp. 73-82, 1986.
[5] M. G. Kang, Variation of local Pool Boiling Heat Transfer Coefficient on 3-Degree Inclined Tube Surface, Nuclear Engineering and Technology, Vol.45, pp. 911-920, 2013.
[6] S. J. Kim, T. McKrell, J. Buongiorno, and L. W. Hu, Experimental Study of Flow Critical Heat Flux in Alumina-water, Zinc-oxide-water, and Diamond-water Nanofluids, Heat Transfer, Vol.131, pp. 1-7, 2009.
[7] H. W. Coleman and W. G. Steele, Experimentation and Uncertainty Analysis for Engineers, 2nd Edition, John Wiley & Sons, New York, 1999.