# Experimental study on the Onset of Nucleate Boiling in a narrow rectangular channel under transversely non-uniform heating

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## 1. Introduction

The Onset of Nucleate Boiling (ONB) is one of the most important parameters in research reactors because the ONB determines an operating condition. Most of research reactors use plate-type nuclear fuel, and coolant channel is narrow rectangular shape. Many researchers have investigated the ONB in a narrow rectangular channel. All previous investigations were performed under uniform heating condition. However, transversely non-uniform heating is encountered in the plate-type fuel research reactor. The power released from the edge of plate-type fuel is higher than the middle of plate-type fuel [1]. Al-Yahia et al. [2] investigated the effect of transverse power distribution on the subcoold boiling in a narrow channel. They found different thermal-hydraulic characteristic between non-uniform and uniform power distribution. Thus, non-uniform heating must be considered in research reactors which use the plate-type fuel. The objective of this experimental study is to find the effect of transversely non-uniform heating on the ONB.

## 2. Experimental method

### *2.1. Experiment facility and procedure*

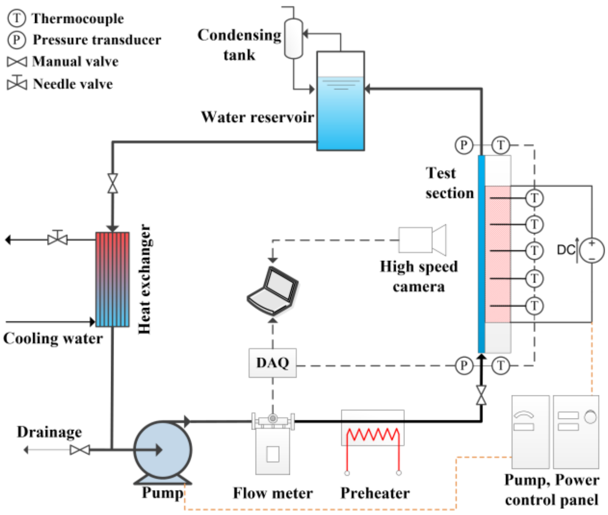


Fig.1. Schematic drawing of experimental facility

A schematic drawing of experimental facility is shown in Fig. 1. Demineralized water circulates by the pump and mass flow rate is measured by the Coriolis flow meter. The Preheater and heat exchanger are used to set desired inlet temperature. DC power is supplied to the test section and controlled by the power control panel. The K-Type thermocouple and the pressure transducer are installed at the inlet and outlet of test section. All measured data is collected to the data acquisition system. Bubbles behavior is recorded by high speed camera from the front of test section in which one side is heated and the other side is window.

Two test sections are used, one is uniformly heated and the other is non-uniformly heated. The cross-section view of test sections is shown in Fig. 2. The difference between two test sections is the heating block. In non-uniformly heated test section, air gap is inside of the heating black. The air gap causes more heat flux to releases from the edge of surface. The K-type thermocouples are installed in the edge and middle of heating block to check transverse distribution of heat flux and wall temperature. Fig. 3 shows the detail location of thermocouples.

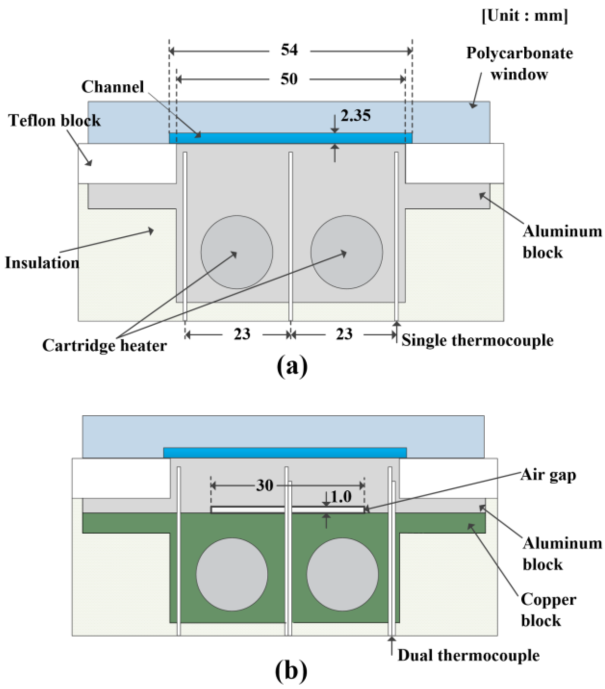


Fig. 2. Cross-section view of (a) uniformly and (b) non-uniformly heated test section

Before the ONB experiment, degassing is performed for 40 min at the liquid inlet temperature of 80 °C and the wall temperature of 110 °C. After degassing, the mass flow rate and inlet temperature are set to desired value. The power is increased step by step, and all measurements are collected at the steady state. This process is repeated until many bubbles appear through the high speed camera. Experiments are performed under various mass flow rate and inlet subcooling conditions, as shown in Table I.

Table I: Test condition

| Parameter | Range |
|---|---|
| Mass flow rate | 0.015~0.12 $kg/s$ |
| Inlet subcooling | 35~65 ℃ |
| Heat flux | 50~550 $kW/m^2$ |
| Pressure | 1~1.2 bar |

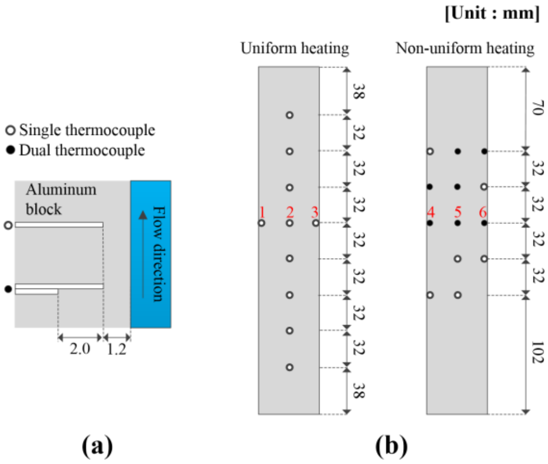


Fig. 3. Location of thermocouple (a) from the surface and (b) axial location

*2.2. Data reduction*

Thermal power ( $Q_{th}$ ) supplied to the flow in the narrow channel is calculated as follow

$$Q_{th} = \dot{m}C_P(T_{out} - T_{in}) \quad (1)$$

where $\dot{m}$ is the mass flow rate, $C_P$ is the specific heat of liquid, $T_{out}$ and $T_{in}$ is the liquid outlet and inlet temperature, respectively. In case of uniformly heated test section, the heat flux is calculated as follow

$$q'' = Q_{th}/(WL) \quad (2)$$

where $WL$ is the area of heated surface. In case of non-uniformly heated test section, the heat flux is calculated as follow

$$q'' = k\frac{\Delta T_{dual}}{\delta_{dual}} \quad (3)$$

where $k$ is the thermal conductivity of the aluminum block, $\Delta T_{dual}$ is the difference of temperature readings in the dual thermocouple, and $\delta_{dual}$ is the distance between thermocouples in the dual thermocouple, 2 mm. The wall temperature is calculated as follow

$$T_w = T_{TC} - \delta\frac{q''}{k} \quad (4)$$

where $T_{TC}$ is the thermocouple reading which is away from the heated surface as $\delta$, 1.2 mm.

## 3. Results and discussion

*3.1. Heat flux and wall temperature distribution*

In case of uniform heating, TC1, TC2, and TC3, shown in Fig. 3b, are selected to calculate the heat flux and wall temperature. The readings of these thermocouples have around 1 ℃ difference, and it is assumed that the heat flux and wall temperature are uniform in the transverse direction. In case of non-uniform heating, TC4, TC5, and TC6 are selected, show in Fig. 3b. The readings of TC4 and TC6 have around 0.5 ℃ difference. Thus, it is assumed that heat flux and wall temperature are symmetric with respect to the middle of heated surface. Fig. 4 shows the heat flux and wall temperature distribution under non-uniform and uniform heating at the same test condition. The mark in Fig. 4 is the experiment result, and CFX result is added to show the distribution of heat flux and wall temperature. Both distributions show the same trend.

*3.2. Thermal power at ONB*

Before the ONB, the wall temperature increases linearly with the thermal power. After the ONB, the increase rate of wall temperature is decreased due to the increase of the heat transfer coefficient. Thus, to find the variation of the increase rate of wall temperature is used to determine the thermal power at ONB. Fig. 5

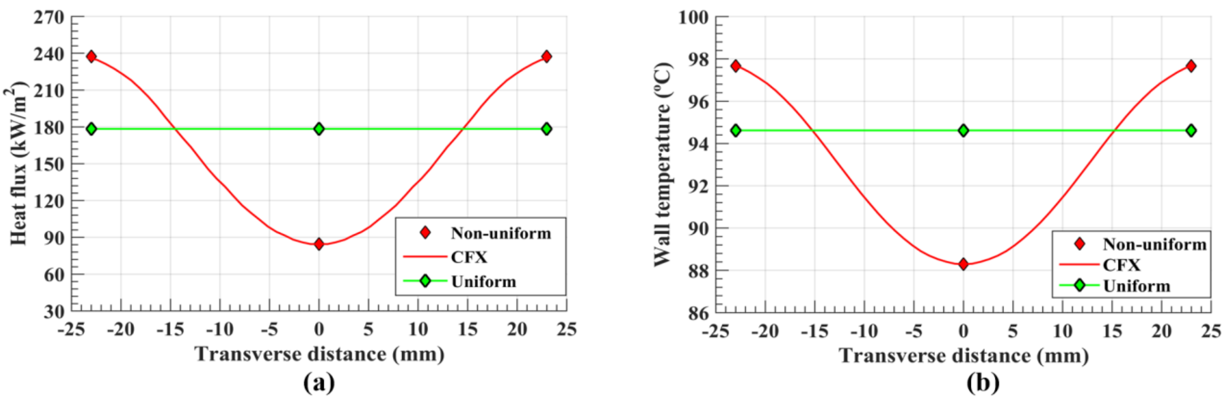


Fig.4. Transverse distribution of (a) heat flux and (b) wall temperature (Test condition: $Q_{th}$ =2.7 $kW$, $\dot{m}$ =0.08 $kg/s$, $T_{in}$ =40 ℃ )

shows the variation of wall temperature with thermal power under non-uniform and uniform heating. The wall temperature under non-uniform heating is value at TC4 and it under uniform heating is value at TC2. At the same test condition, the thermal power at ONB under non-uniform heating is lower compared to the result under uniform heating. On the other hand, the wall temperature at ONB shows similar results under both heating conditions. A certain amount of wall superheat is required for the ONB, and it depends on the system conditions such as mass flow rate, liquid subcooling, pressure and geometry of channel [3,4,5]. Since the test conditions under both heating conditions are same, the wall superheat for ONB is not affected by the heat flux distribution. However, non-uniform heating causes the high local wall temperature at the relatively low thermal power. In this study, the thermal power at ONB under non-uniform heating is decreased around 22% compared to uniform heating condition, as shown in Fig. 6.

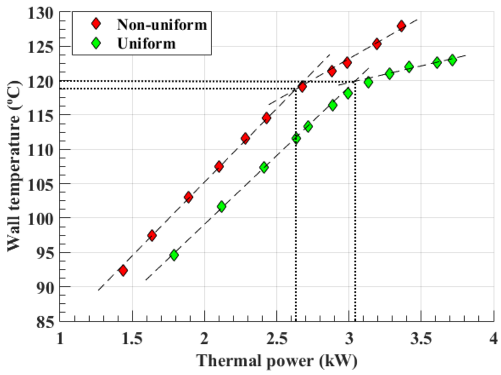

Fig. 5. The variation of wall temperature with increasing thermal power ( $\dot{m}$ =0.06 $kg/s$ , $T_{in}$ =50 ℃ )

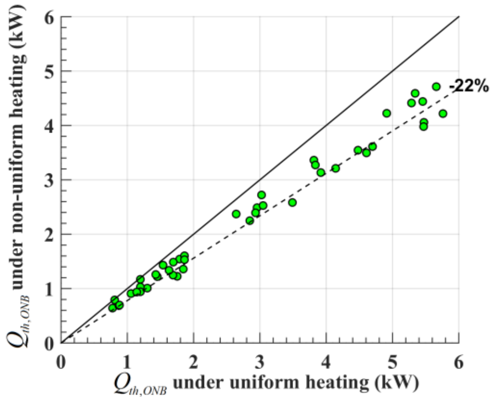

Fig. 6. Comparison of thermal power at ONB under non-uniform and uniform heating

*3.3. Heat flux at ONB*

The heat flux at ONB is determined in the same way as the thermal power at ONB. The variation of wall temperature with heat flux is shown in Fig. 7. The heat flux and wall temperature under non-uniform heating are values at TC4, and the wall temperature under uniform heating is value at TC2. The heat flux at ONB shows the similar results under both heating conditions, as shown in Fig. 8. Boiling incipience is depends on the local condition. Therefore, under the same test condition, the local heat flux at ONB is not affected by the heat flux distribution.

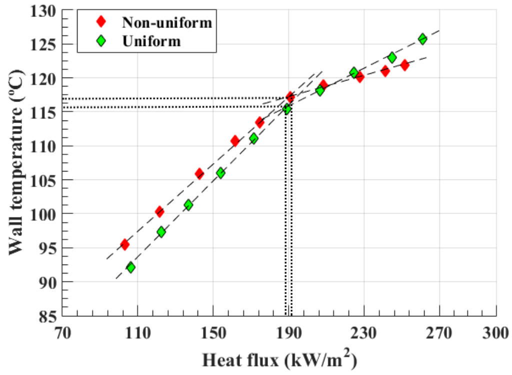

Fig. 7. The variation of wall temperature with increasing heat flux ( $\dot{m}$ =0.06 $kg/s$ , $T_{in}$ =60 ℃ )

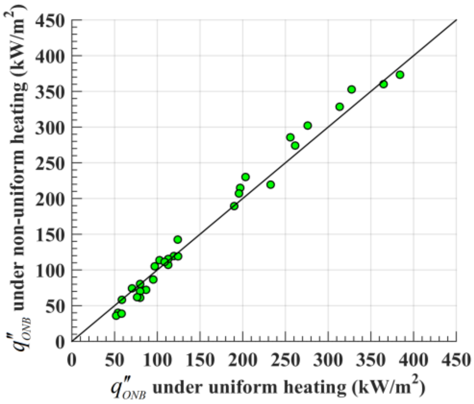

Fig. 8. Comparison of heat flux at ONB under non-uniform and uniform heating

Hong et al. [3], Al-Yahia and Jo [5] developed a correlation to predict the ONB in vertical narrow rectangular channel. The present results are comparable to the Al-Yahia and Jo correlation and comparable to the Hong et al. correlation in $q'' \geq 300\ kW/m^2$ range, as shown in Fig. 9. The difference between the results of non-uniform heating case and the correlations is similar to that of uniform heating case.

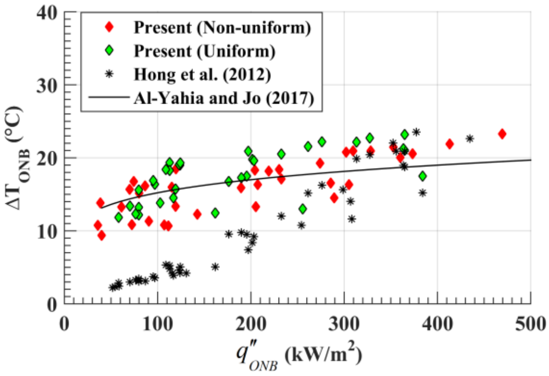

Fig. 9. Comparison between present data and correlations

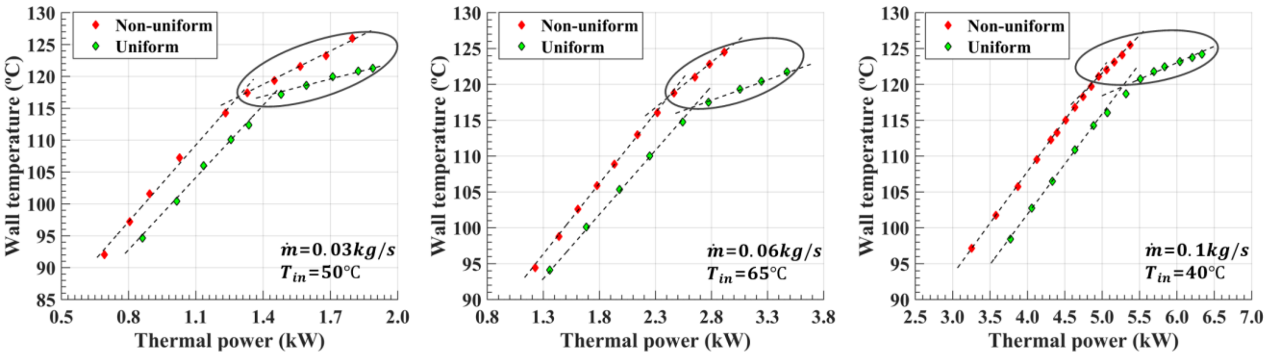


Fig. 10. Difference of the wall temperature variation under non-uniform and uniform heating

*3.4. Difference of the wall temperature variation*

Fig. 10 shows the increase of wall temperature with thermal power under various test conditions. Before the ONB, the slope of wall temperature versus the thermal power under both heating conditions is same. After the ONB, this slope under non-uniform heating is higher than the one under uniform heating. It can be said that the boiling heat transfer under non-uniform heating is less compared to uniform heating condition. Fig. 11 shows the bubble images under both heating conditions. In the case of uniform heating, boiling occurs in the whole transverse direction. In the case of non-uniform heating, boiling only occurs near the edge of surface, and the flow at the middle of surface is the single-phase flow. As a result, the contribution of boiling heat transfer is low, and the increase of wall temperature with thermal power is high under non-uniform heating.

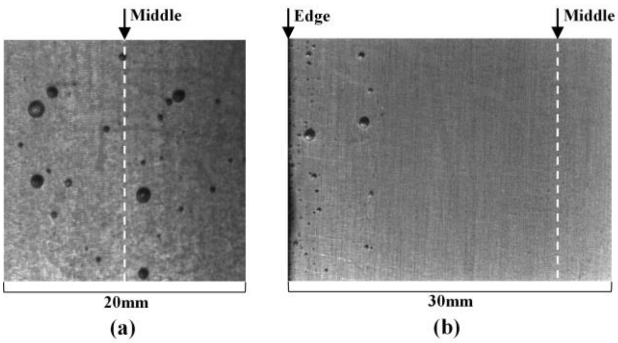


Fig. 11. Bubble image under (a) uniform and (b) non-uniform heating (Test condition : $Q_{th} = 1.7kW,\ \dot{m} = 0.03kg/s,\ T_{in} = 50°C$)

## 4. Conclusion

The effect of transversely non-uniform heating on the ONB in a narrow rectangular channel is studied. The experiments under non-uniform and uniform heating are performed, and the results are compared. The thermal power at ONB is decreased under non-uniform heating. Since the non-uniform heating causes the local high heat flux and wall temperature, ONB occurs at relatively low thermal power compared to uniform heating condition. The local heat flux and wall temperature at ONB under non-uniform heating are similar with the results of uniform heating condition. Since bubble generation is depends on the local condition, under the same system condition, the non-uniform heating has no effect on the local heat flux and wall temperature at ONB. After ONB, it is found that the wall temperature variation with thermal power under non-uniform and uniform heating is different. Under the same test condition, non-uniform heating produces the smaller boiling area in the transverse direction, compared to uniform heating condition. Therefore, in the subcooled boiling region, the non-uniform heating causes the higher increase of wall temperature.

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