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

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ABSTRACT

Onset of Nucleate Boiling (ONB) in a narrow rectangular channel was experimentally studied under transversely non-uniform and uniform heating conditions. The experiment was performed under various mass fluxes and inlet subcooling conditions. The behavior of the bubbles was recorded using a high-speed camera, and was analyzed using an image processing technique. In the case of uniform heat flux, the wall temperature was uniformly distributed in the transverse direction. In the case of non-uniform heat flux, the wall temperature had the lowest value in the middle of the heated surface, and increased along the transverse direction toward the edges. At the same mass flux and inlet subcooling temperature, the thermal power at the ONB under non-uniform heat flux was lower than that under uniform heat flux. However, the local heat flux and wall temperature at the ONB were similar at both heating conditions. In the subcooled boiling region, it was found that the boiling heat transfer under non-uniform heat flux was lower than that under uniform heat flux. Additionally, the slope of the wall temperature-thermal power curve after the ONB was higher in the non-uniform heat flux case. Using the results elicited from image processing, the evaporation and quenching heat transfers were evaluated to analyze the differences in boiling heat transfers. The boiling heat transfer was less affected by evaporation and quenching in the case of non-uniform heat flux.

1. Introduction

Flow boiling in narrow channels is encountered in many engineering applications, such as compact heat exchangers, microelectronics, once-through steam generators, and nuclear reactors. Since boiling significantly enhances the heat transfer, many researchers have studied boiling phenomena in narrow channels [1–6]. The Onset of Nucleate Boiling (ONB) is considered as one of the important characteristics of boiling heat transfer. As the single-phase flow is changed to two-phase flow, the characteristics of heat transfer and pressure drop are changed, thereby affecting the performance of the system.

The distribution of heat flux significantly influences the boiling incipience in the flow channel. However, there are many engineering applications that are associated with non-uniform power distribution, such as the case of nuclear reactors. Nemitallah et al. [7] studied the boiling behavior of fuel under different heat flux profiles in the axial direction. They found that the ONB occurs at the locations of high heat flux. Al-Yahia et al. [8] investigated the effect of transverse power distribution on the ONB location in a narrow rectangular channel using CFX and TMAP codes. Different thermal-hydraulic behaviors were observed between non-uniform and uniform heating conditions. The transversely non-uniform heating is important in the channels which have a narrow rectangular cross-section, mainly in plate-type fuel research reactors. Miller and Ozaltun [9] found that the power released from the edges was higher than that from the middle of the fuel because of the self-shielding effect. Jo and Seo [10] investigated the effect of transverse power distribution on temperature of the plate-type fuel research reactors using the Monte Carlo N-Particle (MCNP) code. The cladding temperature distribution in the transverse direction had the same trend as the power distribution. Because of this, transversely non-uniform heating should be considered in a narrow rectangular channel.

Sudo et al. [11] investigated the ONB in the vertical narrow rectangular channel. They reported an error of 1 K superheat at the ONB between their experimental results and the correlation of Bergles and Roshenow [12]. There was no effect by the flow direction (upward and downward) on the ONB. Hong et al. [13] investigated the effect of rolling motion on the ONB in the narrow rectangular channel. They developed an ONB correlation involving the effects of pressure, mass flux, and the gap size of a narrow rectangular channel. Wang et al. [14] determined the ONB in the narrow rectangular channel by using four judging criteria, and reported that there were no significant differences among these criteria. The effect of mass flux, inlet subcooling, and

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Nomenclature

A_a	area fraction influenced by bubbles
A_b	area influenced by bubbles [m^2]
A_{heated}	heated surface area [m^2]
A_{image}	image processing area [m^2]
a	bubble influence factor
C_P	specific heat [kj/kg·K]
D	departure diameter [mm]
D_e	equivalent bubble diameter [mm]
f	departure frequency [1/s]
G	mass flux [kg/m^2·s]
H	gap size of narrow channel [mm]
h_{fg}	latent heat of vaporization [kj/kg]
h_q	quenching heat transfer coefficient [W/m^2·K]
k	thermal conductivity [W/m·K]
N	number of nucleation sites
N_a	nucleation site density [sites/m^2]
$\dot{m}$	mass flow rate [kg/s]
p	pressure [bar]
Q	heat transfer rate [W]
Q_{th}	thermal power [W]
q''	heat flux [W/m^2]
R	uncertainty of derived parameter
T	temperature [°C]
t_g	growth time [s]
t_w	waiting time [s]
X	uncertainty of measured parameter

Greek symbols

α	thermal diffusivity [J/m^3·K]
δ_1	distance between thermocouple and surface [mm]
δ_2	distance between thermocouples [mm]
ρ	density [kg/m^3]

Subscripts

avg	average
bulk	bulk fluid
c	convection
e	evaporation
f	liquid
g	gas
in	inlet of test section
non	non-uniform heating
ONB	Onset of Nucleate Boiling
out	outlet of test section
q	quenching
TC	thermocouple
uni	uniform heating
w	wall

pressure on the ONB was also investigated, and the correlation of Thom et al. [15] expressed in Eq. (1) was recommended for the prediction of the ONB.

$$\Delta T_{w,ONB} = 22.65\left(\frac{q''_{ONB}}{10^6}\right)^{0.5}\exp\left(-\frac{p}{8.7}\right) \tag{1}$$

Al-Yahia and Jo [16] investigated the effect of mass flux and inlet subcooling on the ONB in the narrow rectangular channel. The same effect of mass flux and inlet subcooling on the ONB was observed in the CFX results. They assessed the existing correlations, and the correlation of Jens and Lottes [17] expressed in Eq. (2) was comparable to the experimental results.

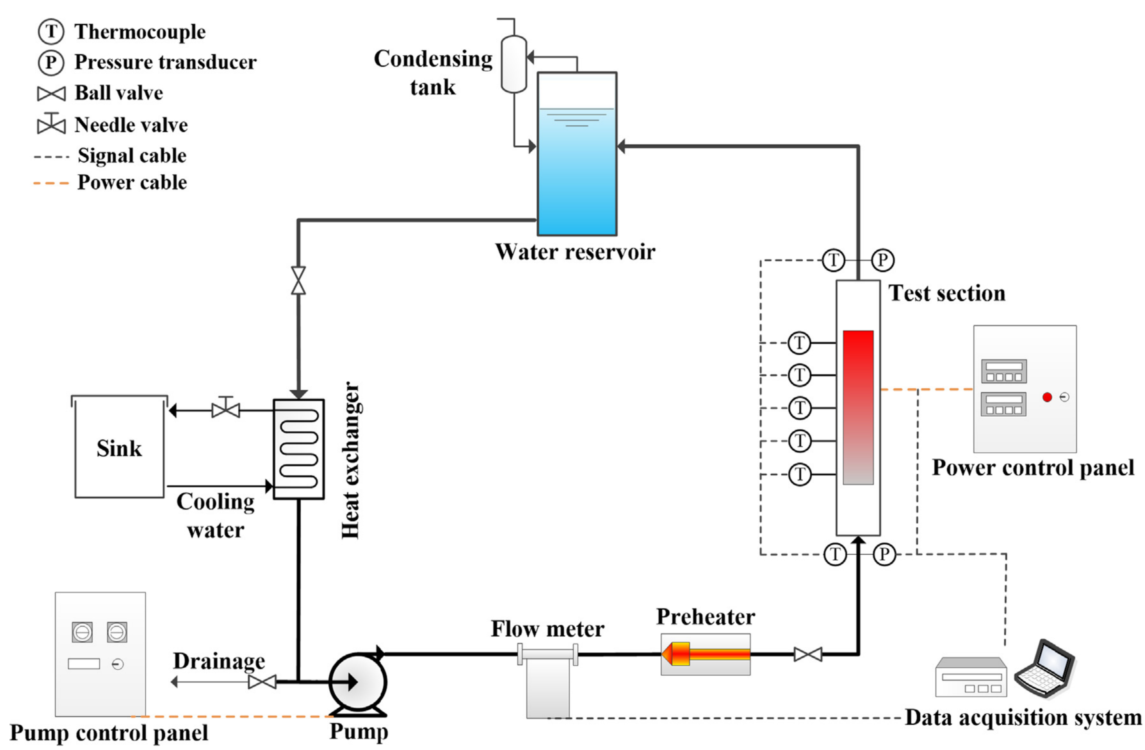

Fig. 1. Schematic drawing of the experimental loop.