Experimental investigation of ONB incipience measurement and bubble behavior under the natural circulation in the narrow rectangular channel

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1. Introduction

The natural circulation (NC) [1, 2] is utilized in various engineering fields such as nuclear industry due to enhancement of reliability of system. The ONB incipience and bubble behavior of NC condition is much more affected than that of the forced circulation due to lower flow rate in the sub-cooled region. In the sub-cooled boiling [3], the ONB incipience and bubble behavior affected system performance by changing the characteristics of pressure drop and heat transfer. Therefore, it is important to investigate the ONB incipience and bubble behavior. This research work investigates the ONB incipience with respect to location of the heater. Also, other parameters such as bubble departure diameter, bubble departure frequency and bubble sliding velocity are analyzed using the image processing technique to study the bubble behavior. The existing correlations used to predict the ONB incipience and bubble departure diameter are compared with the experimental results.

2. Experimental facility and test condition

The experimental facility consists of primary and secondary system. The primary system consisted of test section, water reservoir and heat exchanger. The flow path was formed to keep the primary system steady state whereas the flow rate in secondary system was controlled by controlling the needle valve. The experiment was performed at steady state inlet temperature of 35℃.

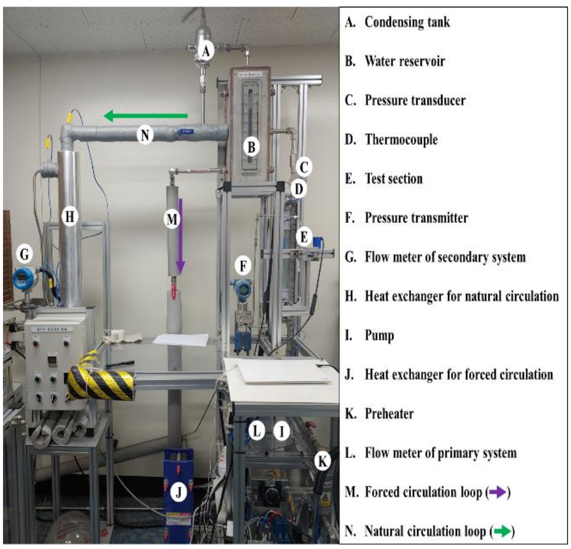


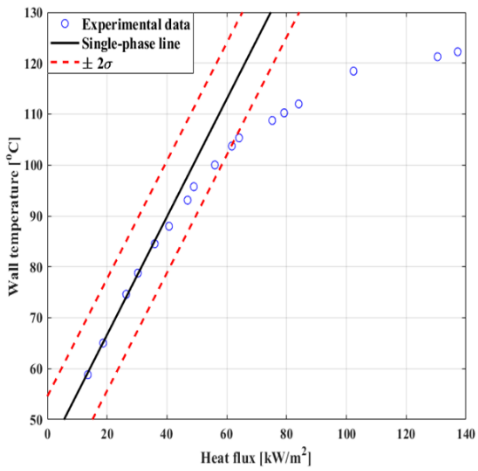
Fig. 1. Experimental facility.

3. Result & Discussions

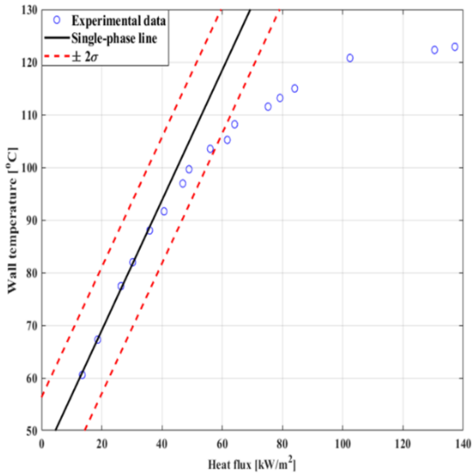
NC experiment was performed for inlet temperature of 35 ℃ under the steady state condition. The ONB incipience was predicted by using statistical method with respect to location of the heater. Three different locations of the heater are named TC4, TC6 and TC10 such that TC4 is the lowest and TC10 is the highest location. Also, various bubble behavior parameters were analyzed using image processing and relationship between bubble behavior and superheated thermal boundary layer was investigated.

3.1 ONB measurement

ONB incipience was measured using heat flux versus wall temperature curve. The existing method [4], intersection point between single- and two-phase line, predicted ONB incipience as virtual point and ONB wall temperature was over-predicted. But the proposed statistical method predicted ONB wall temperature as experimental data and it was predicted lower than the existing method. The ONB incipience was determined to be a point out of linearity. If the experimental data is out of $\pm 2\,\sigma$ line, the first point was ONB incipience.
The heat flux at the ONB incipience decreased as the location of the heater changed from TC4 to TC6. This is because of increase in the bulk liquid temperature with change in heater location. The heat flux at the ONB incipience was also affected by increase of the NC flow rate.



(a)



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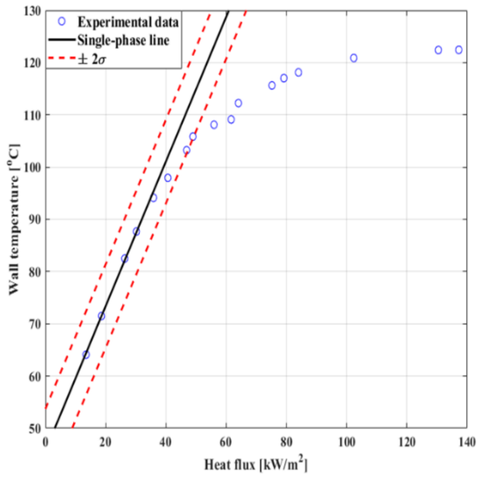

(c)

Fig. 2. ONB incipience with location (a) TC 4 (b) TC 6 and (c) TC 10.

3.2 Bubble departure diameter with location

The bubble that was generated from the activated cavity increased in size by absorbing energy from the heated surface in the form of evaporation energy. The bubble diameter reached its maximum value before the bubble detached from the heated surface thus losing energy to the surrounding subcooled liquid region in the form of condensation energy. The maximum diameter up to which the bubble grows is called the bubble departure diameter. In general, when the bubble departs from a nucleation site, the shape of bubble is spherical. But bubble departure shape was ellipsoid due to narrow gap between channels in the present study. To obtain the bubble departure diameter, the shape transformation was required from ellipsoid to spherical. To transform the shape, the ellipsoid equation was used which is given as:

$$\frac{x^2}{a^2}+\frac{y^2}{b^2}+\frac{z^2}{c^2}=1 \quad (a=b>c) \tag{1}$$

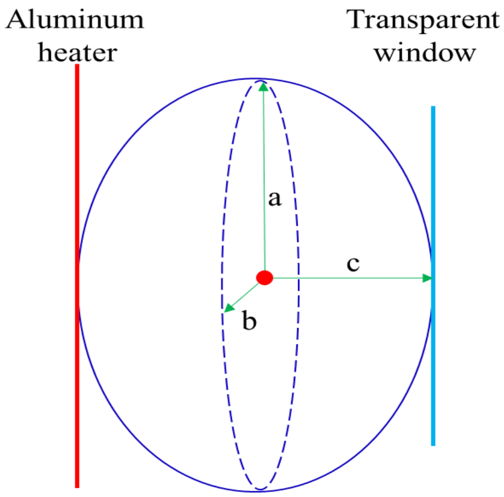

Fig. 3. Bubble shape in the narrow rectangular channel under the NC condition

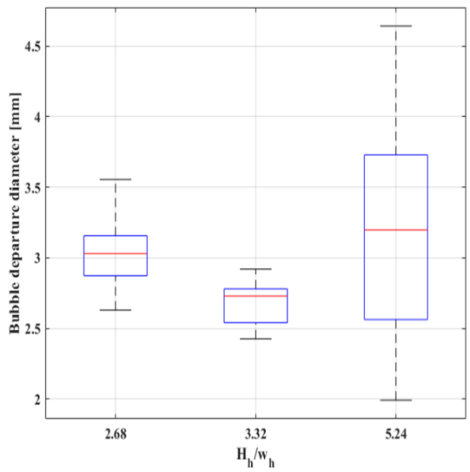

Fig. 4. The Deformed bubble departure diameter with location of heater

To obtain the spherical equation, diameters of x, y and z axis must be same. Diameters of all directions were averaged such that a = b = c. The volumes of both ellipsoid and sphere were calculated to evaluate the shape transformation. The calculated error between both volumes was about 0.36 %. The average deformed bubble departure diameter was maximum for TC 10 and minimum for TC 6. The size of bubble departure diameter was affected by ONB wall temperature. When the ONB wall temperature was higher, the bubble departure diameter increased since the energy delivered to the bubble increased.

3.3 Bubble departure frequency with location

The quenching heat flux occurs when sub-cooled liquid fills the empty space after the bubble departs from the nucleation site. Also, the quenching heat flux reformed thermal boundary layer [5]. The quenching heat flux equation is expressed as follows:

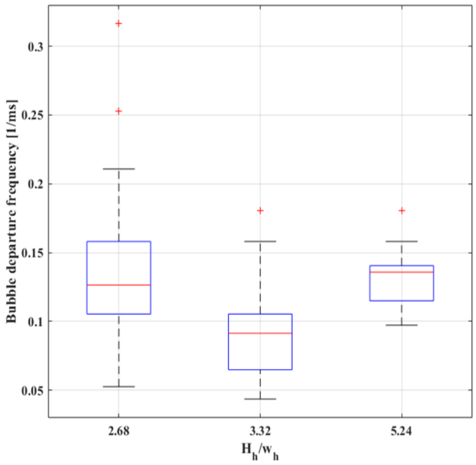

Fig. 5. The bubble departure frequency with location of heater

$$q_e'' = h_q A_f (T_w - T_{bulk}), \tag{2}$$

where h_q is quenching heat transfer coefficient, A_F is the area fraction influenced by bubbles. The quenching heat transfer coefficient is expressed by Rohsenow as

$$h_q = 2k_f f \sqrt{\frac{t_w}{\pi \alpha_f}}, \tag{3}$$

where k_f is thermal conductivity of liquid, f is departure frequency, α_f is thermal diffusivity of liquid and t_w is waiting time. Since the quenching heat transfer coefficient is function of departure frequency and waiting time and quenching heat flux affects the thermal boundary, the bubble departure frequency will be affected by quenching heat flux. The bubble departure frequency is the inverse of the sum of growth time (t_g) and waiting time (t_w). The waiting time and growth time were measured from single nucleation site. In the region where ONB incipience occurs, quenching heat transfer coefficient is largest at TC 10. When the quenching heat transfer coefficient is higher, the thermal boundary layer is quickly reformed. Therefore, the waiting time at TC 10 was the smallest.

3.4 Bubble sliding velocity with location

Bubble sliding motion is affected by buoyancy force (F_b), quasi steady drag force (F_{qs}), added mass force (F_{growth}) due to the liquid flow, surface tension (F_s) according to the study of Xu [6]. The bubble which departs from heated surface moves in both x and y directions. Therefore, bubble sliding velocity was calculated for both directions. When the bubble sliding velocity increased, the buoyancy forced increased and drag force, added mass force and surface tension in the wall decreased.

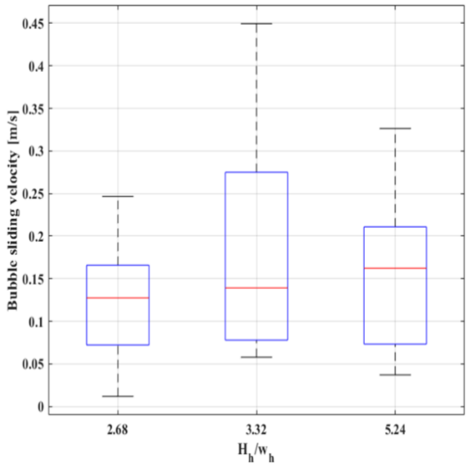

Fig. 6. The bubble sliding velocity with location of heater

3.5 Prediction of ONB incipience and bubble departure diameter

Existing correlations were used to predict the ONB incipience and bubble departure diameter under the NC conditions as shown in Table 1 and 2. NC experiments were performed 3 times for the inlet temperature of 35°C. The Jens and Lottes' correlation predicted ONB incipience within error of $\pm 33\ \%$. But the results for bubble departure diameter showed a large error. Therefore, a new correlation is required to predict the bubble departure diameter under the NC in the narrow rectangular channel.

Table I. The existing correlations to predict the ONB incipience

Reference	Correlation $(\Delta T_{w,ONB})$
Jens and Lottes (1951) [7]	$25\left[\frac{q''_{ONB}}{10^6}\right]^{0.25} exp\left(-\frac{P}{6.2}\right)$
Bergles and Rohsenow (1964) [8]	$22.65\left[\frac{q''_{ONB}}{10^6}\right]^{0.5} exp\left(-\frac{P}{8.7}\right)$
Thom and Fallon (1965) [9]	$\frac{5}{9}\left[\frac{q''_{ONB}}{1082P^{1.156}}\right]^{\frac{P^{0.0234}}{2.16}}$

Table II. The existing correlations to predict the bubble departure diameter

Reference	Correlation (D_b)
Kocamustafaogullari (1983) [10]	$2.64 \times 10^{-5}\sqrt{\frac{\sigma}{g(\rho_l-\rho_v)}}\left(\frac{\rho_l-\rho_v}{\rho_v}\right)^{0.9}$
Van stralen and Zijl (1978) [11]	$2.63\left[\frac{Ja^2\alpha_l^2}{g}\right]^{\frac{1}{3}}\left[1+\left(\frac{2\pi}{3Ja}\right)^{\frac{1}{2}}\right]^{\frac{1}{4}}$
Stephan wenzel (1993) [12]	$0.25\left[1+\left(\frac{Ja}{Pr}\right)^2\frac{100000}{Ar}\right]^{0.5}\sqrt{\frac{2\sigma}{g(\rho_l-\rho_v)}}$

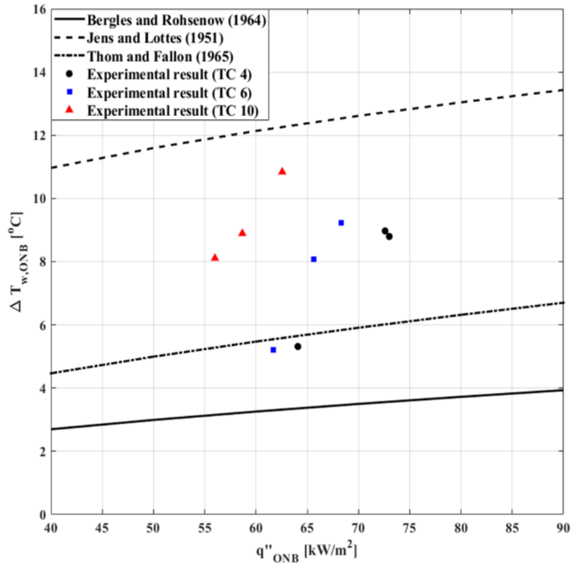

Fig. 7. The prediction of ONB incipience

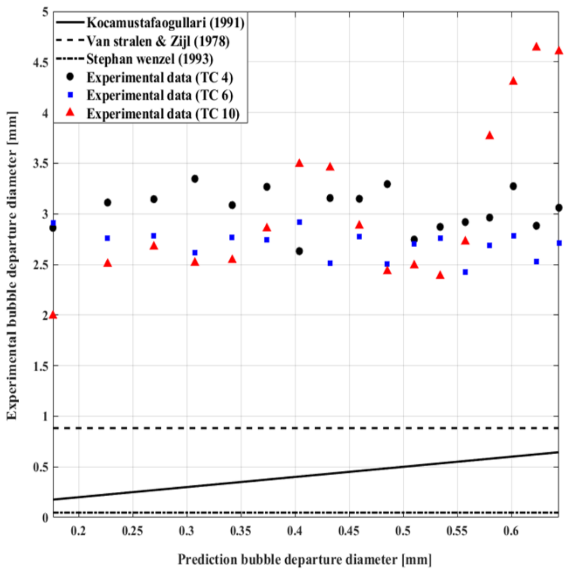

Fig. 8. The prediction of bubble departure diameter

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