Experimental Validation of Bubble Departure and Lift-off Diameter Models under the Low Heat Flux and Low Flow Velocity Conditions

Yun-Je Cho[a,b*], Heung-June Chung[b], Goon-Cherl Park[a]
[a]*Seoul National University, Department of Nuclear Engineering*
San 56-1, Shillim-dong, Kwanak-Gu, Seoul, 151-742, Korea E-mail
[b]*Thermal-Hydraulic Safety Research Division, Korea Atomic Energy Institute*
1045 Daedeokdaero, Yuseong, Daejon, Korea
[*]*Corresponding author: yjcho@kaeri.re.kr*

1. Introduction

Bubble departure and lift-off diameters are important parameters to predict the evaporation heat flux at a heated wall. In particular, the boiling in the water pool-type reactor cavity cooling system (WPT-RCCS) of HTGR [1] occurs at a vertical wall under the condition of natural convection with low wall heat flux. Even though the bubble diameter detaching from the heated wall depends on both the wall heat flux and flow condition, most correlations for bubble departure and lift-off diameters were developed under the high heat flux and high flow velocity conditions. Therefore, in order to estimate the bubble diameters under the low heat flux and low flow velocity conditions, it is needed to validate the applicability of existing correlations using the experimental data acquired under the similar conditions.

2. Literature Review

The correlations of bubble departure diameter developed on horizontal heated surface such as Zuber, Zeng, Cole, and Kutateladze's correlations are not appropriate to predict the bubble diameter on vertical surface since it is well known that the inclination of heated surface affects the bubble behavior and heat transfer near wall [2]. Although Unal's correlation is widely used for its wide applicable ranges, the range of heat flux is too high; the minimum heat flux in applicable range is 470 kW/m^2 but the heat flux from the cavity wall of the WPT-RCCS is lower than 10 kW/m^2.

The bubble lift-off diameter also plays an important role in determining the evaporation heat flux at low pressure. Sateesh found that the heat transfer due to the sliding effect is more than 50% of total heat transfer at 5K of wall superheat. Since the effect of bubble sliding is significant at low pressure and at low wall superheat, the bubble lift-off diameter should be used instead of the bubble departure diameter. Therefore, it is required to develop the bubble departure and lift-off diameter models which are applicable to the condition of low wall heat flux and low flow velocity.

3. Wall Boiling Experiment

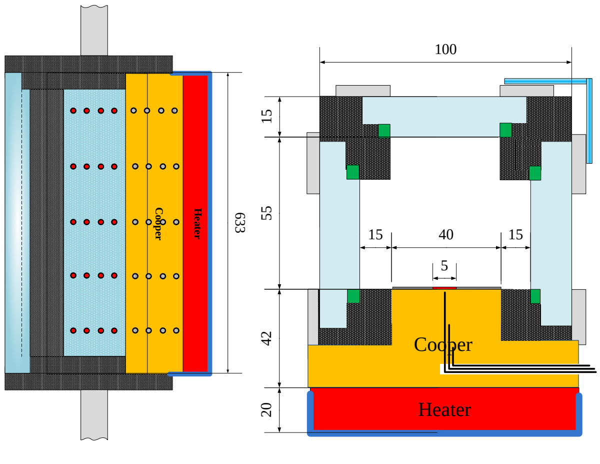
Cho [3] developed the new models for the bubble departure and lift-off diameters from the force balance equations acting on a bubble at active nucleate site as follows,

$$D_d = 2\left(\frac{6\sin\theta_m \sigma \dfrac{\theta_d}{\pi^2-\theta_d^2}\left[\sin(\theta_m+\theta_d)+\sin(\theta_m-\theta_d)\right]}{g\Delta\rho}\right)^{0.5} \quad (1)$$

$$D_l = D_d\left(1+2.073\, Lo^{-0.505}\right)^{0.5} \quad (2)$$

where, $Lo = C_{sl}\left(r_d u_r / G_b^{\,2}\right)^2$, θ_m, θ_d and C_{sd} are lift-off number, mean contact angle, difference of contact angle and shear lift coefficient, respectively. The departure diameter model is strongly dependant on the bubble contact angle while the lift-off diameter model is expressed in terms of the lift-off number, which represents the relative magnitude between the shear lift force and the growth force. The lift-off diameter showed exponentially decreasing behavior with the lift-off number.

In order to validate the existing correlations and Cho's model of bubble departure and lift-off diameters, the wall boiling (WABO) experiments were performed under the conditions of the low heat flux and the low flow velocity at atmospheric pressure as follows: $Ja_e \le 20$, 2750W/m^2 ≤ heat flux ≤ 6570 W/m^2, 0.02m/s ≤ mean flow velocity ≤ 0.05m/s, 2.0 K ≤ degree of inlet subcooling ≤ 11.8 K, and $20^o \le$ contact angle $\le 60^o$.



(a) Side view (b) Top view
Fig. 1. Schematic diagram of WABO test channel

Figure 1 shows the schematic diagrams of test channel of WABO experimental apparatus. The digital images of bubbles were taken by a high speed camera from the departure to lift-off of bubble. Through the digital image processing, the images were converted into the information of bubble diameter and velocity. From the experimental results, Cho suggested the bubble growth constant and contact angle for the use of the developed model under the condition of low wall heat flux and low flow velocity.

4. Comparative Analysis

4.1. Bubble departure diameter

The Cho's departure diameter model was compared with the experimental data and existing correlations of bubble departure diameter developed by Cole, Unal, Kocamustafaogullari, Farajisarir, and Basu [4] as shown in Fig. 2. The correlations of Cole, Kocamustafaogullari, Farajirir, and Basu were consistentely overestimated the departure diameter. Especially, since the Farajirir's correlation shows that the order of magnitude is higher than the experimental data by 10^2, the calculation result by Farajirir's correlation was excluded from the Fig. 2. It is presumed that the reason for the overestimation is mainly responsible for the applicable range of each correlation. Most of correlations have been developed under the much higher heat flux and flow velocity conditions than the range of WABO experiments except Cole's correlation, which have been developed for pool boiling condition. Thus, the correlations generally overestimate the departure diameter when the low Jacob number, wall superheat in other term, is applied. On the other hand, Unal's model shows similar order of magnitude with the experiment but it generally underestimated the departure diameter.

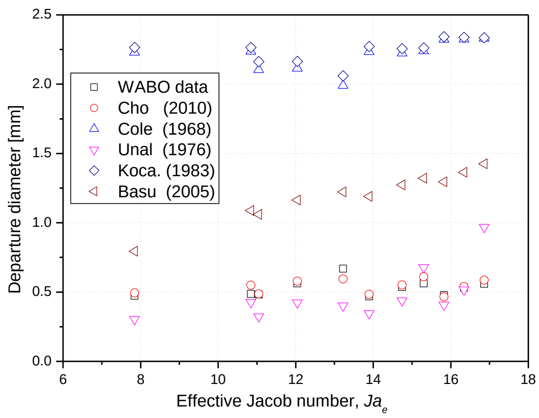


Fig. 2. Comparison of departure diameter with existing correlations

4.2. Bubble lift-off diameter

For the model of bubble lift-off diameter, three correlations of Cho, Bae and Basu were compared. The comparison result for the model of bubble lift-off diameter is depicted in Fig. 3. The predicted lift-off diameter by Cho's model shows good agreement with the experimental data. However, Basu's correlation significantly overestimated the experimental data although it partially predicted the increasing trend with the Jacob number at fixed velocity condition. Meanwhile, the Bae's correlation shows similar trend with the experimental data but it overestimated when the degree of subcooling is low.

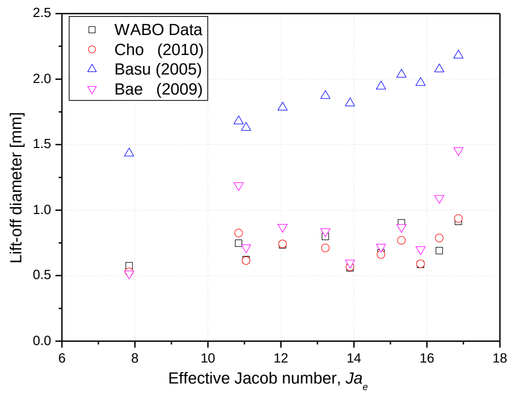


Fig. 3. Comparison of lift-off diameter with existing correlations

5. Conclusions

The existing correlations developed under the conditions of high wall heat flux, forced convection, or horizontal pool boiling generally overestimated the bubble departure and lift-off diameters at the vertically heated wall with low heat flux. On the other hand, Cho's model properly predicted the bubble diameters measured in the WABO experiments within the maximum error range of 15%. Therefore, for the prediction of the wall boiling in the pool of the WPT-RCCS and other water pools such as the water cooling panel of RCCS in HTR-10, Cho's model is recommended with proper experimental parameters including the bubble growth constant and contact angle.

REFERENCES

[1] H.K. Cho, Y.J. Cho, M.O. Kim and G.C. Park, "Experiments on a Water Pool-Type Reactor Cavity Cooling System in a High-Temperature Gas-Cooled Reactor," Nuclear Technology, Vol. 159, pp. 39-58, 2007.

[2] G. Sateesh, S.K. Das, A.R. Balakrishnan, "Analysis of Pool Boiling Heat Transfer: Effect of Bubbles Sliding on the Heating Surface," Int. J. Heat Mass Transfer, Vol. 48, pp. 1543–1553, 2005.

[3] Y.J. Cho, "Experimental Assessment of the Water Pool-Type Reactor Cavity Cooling System with Development of Bubble Diameter Models in the MARS code," Ph.D. thesis, Seoul National University, 2010.

[4] N. Basu, G.R. Warrier, and V.K. Dhir, "Wall Heat Flux Partitioning During Subcooled Flow Boiling: Part 1-Model Development," J. Heat Transfer, Vol. 127, pp. 131-140, 2005.