Transactions of the Korean Nuclear Society Virtual Spring Meeting
July 9-10, 2020

The effect of sliding large bubbles on nucleate boiling of subcooled water flowing in a slightly inclined channel subjected to upper heated surface

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1. Introduction

There are many experimental works on nucleate boiling heat transfer showing either negative or positive effect of liquid in subcooled state on efficiency of heat transfer. Such efficiency can be quantified as a heat transfer coefficient which is a proportionality between the imposed heat flux and temperature gradient along the interface of heated material and fluid. Still change in boiling heat transfer coefficient with variation of subcooling is difficult to well understand, accordingly regarded as one of the most complex phenomena in phase change area.

Several studies showed that a boiling curve was shifted toward a higher wall-superheat as subcooling increases [1,2]. On the other hand, the other studies observed that increase in subcooling can enhance the convective heat transfer [3,4], as a result, the boiling curve was shifted toward a lower wall-superheat. It is interesting to note that the aforementioned studies reported conflicting results. This may arise from the complex nature of the physical mechanism through which subcooled liquid affects bubble size, nucleation frequency, and bubble dynamics related to bubble growth and collapse.

Here, characteristics of the boiling curve under a subcooled condition have been interrogated if a heater surface faces downward. It is expected that boiling curves with various degree of subcooling would merge into a virtual asymptote, even under an intermediate heat flux level, because bubble behavior in a downward-facing heater is quite similar to that in the fully-developed boiling region. Along the downward-facing heater, there would be a more active bubble coalescence process due to both increased thermal boundary layer thickness and a corresponding increase in nucleate site density. The active coalescence process leads to the formation of a large vapor mass even at low heat flux and wall-superheat. If the heater size is large enough, we can observe a sliding motion of the large vapor mass along a heater surface.

However, if a downward-facing heater surface, subcooled water, and low flow rate are taken into account all at once, only some experimental data on boiling curves are available in the literature. It can be concluded that at downward-facing heater boiling, the influence of subcooling is still unclear and therefore a more thorough investigation should be conducted to improve the prediction capability for subcooled nucleate boiling heat transfer. Detailed research content can be found in the paper of Jeong and Kim [5].

2. Experimental apparatus

In order to achieve a stable formation of large vapor slug and its sliding motion, length and width of heater were determined as 216 mm and 108 mm, respectively. Figs. 1 and 2 present the sectional view of the test section and the forced convective water boiling loop, respectively.

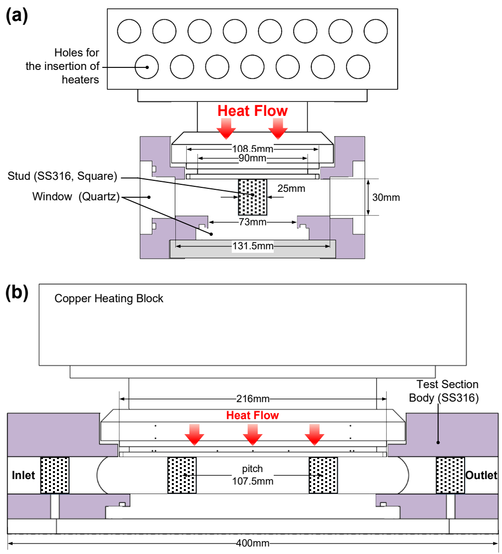

Fig. 1. Sectional views of the test section; stud structures were eliminated in this study.

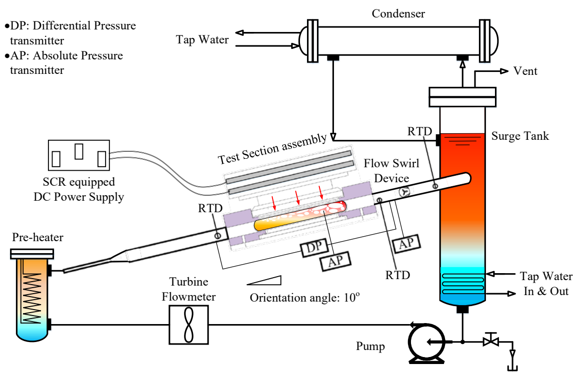

Fig. 2. Simplified schematic of the boiling loop.

The test section contains a copper heating block which is a heat source. Tangential plane of the heater surface in contact with water is inclined 10 degree from the horizontal, and the heater surface faces downward.

Local heat flux and temperature gradient were calculated using a three-point backward space Taylor series approximation. Many thermocouples were installed in the heater block by drilling micro-holes. The absolute uncertainty of the surface temperature was calculated as ± 0.6K.

3. Results

3.1 Repeatability test

In this study, the boiling heat transfer coefficient (BHTC) was defined based on local parameters, such as local heat flux, local surface temperature measured at the most downstream section of heater, where the sliding large bubbles appear most stably. The BHTC was defined as a time-averaged value of the raw data obtained during 1 minute. In order to ensure reproducibility of experiments, boiling curves were obtained at a specific thermal-hydraulic condition. As shown in Fig. 3, the reproducibility was confirmed even though the boiling curves were measured on different dates.

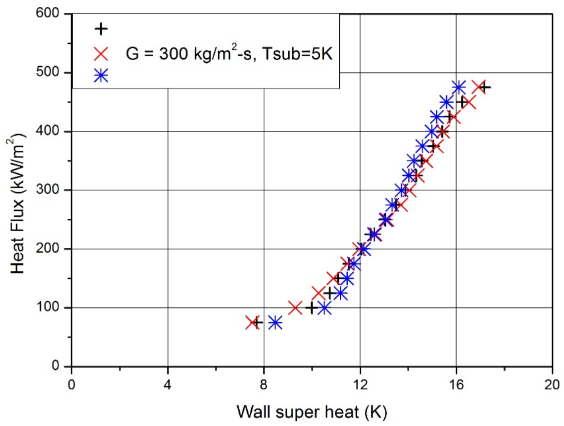

Fig. 3. Reproducibility of boiling curves.

3.2 Weak dependency on flow velocity

By employing a high-speed camera, it can be observed that nucleated bubbles slide along the heater surface by buoyancy, which pushed them up to the surface and allowed to grow by merging with neighboring bubbles. As reported by Nishikawa and Fujita (1990), Rouge (1997), and Qiu and Dhir (2002), a thin liquid layer seems to exist underneath the large sliding bubble. According to the observation by this author with the naked eye, it was confirmed that the color of the heat transfer surface slightly changed in the state of shining strong light, and this is due to the difference in refractive index due to the formation and disappearance of the thin liquid layer. It is apparent that if mass flux is reduced, large bubbles would be generated more frequently due to increased amounts of heat from the heater surface to the fluid. Accordingly, the contribution of evaporative heat transfer becomes larger. In terms of overall heat transfer, even though a decrease in bulk flow velocity deteriorates the convective heat transfer, a reduction in velocity may only slightly affects the boiling heat transfer.

Prospect on weak dependence of flow velocity on boiling curve was well matched with the experimental results, presented in Fig. 4. Note that, for the downward-facing inclined heater, the sliding characteristics of the large bubble can enhance the convective heat transfer and therefore make substantial contribution to the total convective heat transfer.

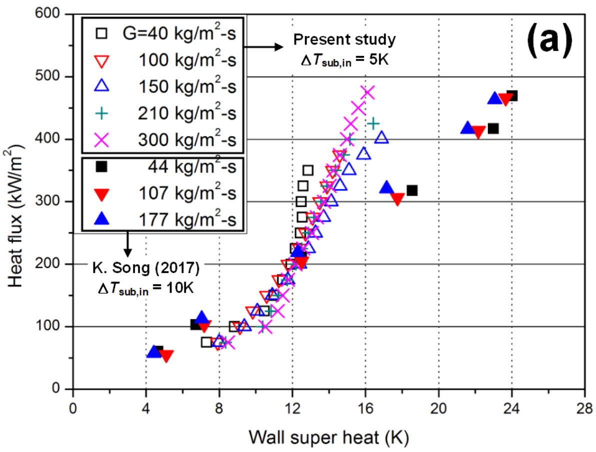

Fig. 4. 3D drawing of the boiling loop.

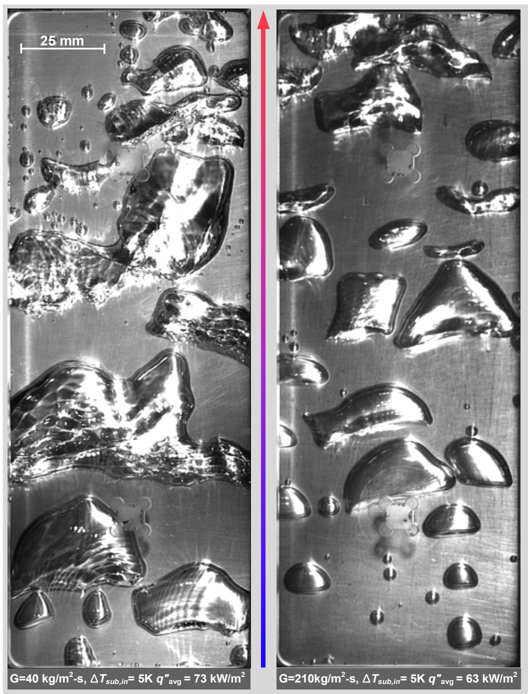

Fig. 5. Captured bubble behavior; heat flux ~70 kW/m^2.

As shown in Fig. 5, even at heat flux conditions below 70 kW/m^2, a bubble grows rapidly after its departure via merge with neighbors along its path. Then, the enlarged bubble slides up along the surface. It was clearly observed that the liquid flowing near the heater surface was significantly disturbed by the bubble-sweeping process, which generated large amounts of turbulence around and behind the sliding bubble. According to previous works by Bayazit et al. (2003) and Donnelly et al. (2012), it is expected that the turbulent motion induced by the sliding bubble would enhance the convective heat transfer to a level approximately three times that of natural convection level even at small size of the bubble. Also, Fig. 5 clearly showed that increase of bulk velocity inevitably leads to formation of smaller bubbles, the corresponding small volume of bubble brings about lower bubble velocity owing to decreased buoyancy force. For convenience sake, the total rate of heat transfer at the slightly inclined horizontal surface facing downward can be regarded as sum of followings. Evaporative heat transfer, convective heat transfer 1: originated from the sliding characteristic of bubble, convective heat transfer 2: excluding influence of the sliding bubble. In summary, the enhancement of convective heat transfer 2 due to increased flow velocity can compensate for the deterioration of the evaporative heat transfer. In this way, the apparent independence of boiling curve and flow velocity can be explained.

3.3 Heavy dependency on degree of subcooling

Figures 6 and 7 presents the subcooled boiling curves for water at different flow velocities. The boiling curves under pool boiling conditions were plotted in Fig. 6 and compared with the experimental data from previous works.

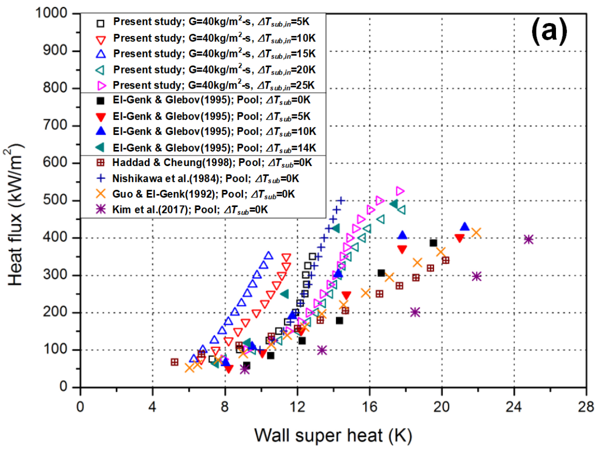

Fig. 6. Subcooling effect on boiling curves at low mass flux or pool boiling condition.

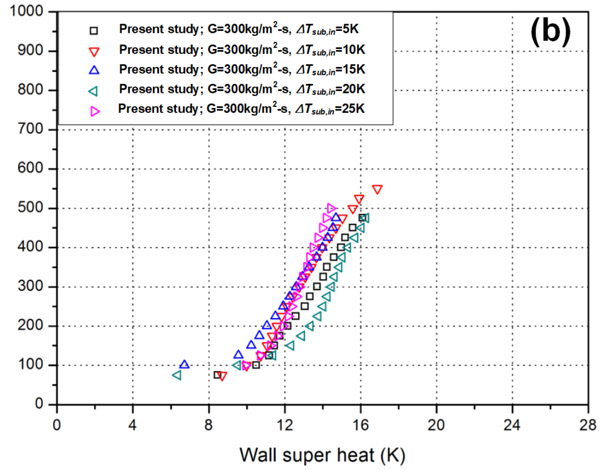

Fig. 7. Subcooling effect on boiling curves at high mass flux.

In addition, under flow boiling condition, the boiling curves of various degrees of liquid subcooling were plotted in Fig. 7. Compared to the flow boiling case, Fig. 6 showed that boiling curve of pool boiling condition is heavily dependent on degree of subcooling. The data of El-Genk and Glebov (1995) quantitatively agree with the present data. The consistent trend is that the boiling curves shift upward from the saturated state with liquid subcooling to 15 K.

However, it is noteworthy that beyond 15 K subcooling, boiling curves experience an abrupt and large downward shift with an increase of subcooling, showing negligible difference between boiling curves at subcooling of 20 and 25 K. Such abrupt decrease of NBHT beyond a specific subcooling of 15 K may be come from change in bubble behavior and a corresponding change in enhancement of convective heat transfer by sliding motion of a large bubble. Bubble behavior along a heater surface was visually examined by comparing videos recorded at different degrees of subcooling 15 and 20 K under a same heat flux level of 165 kW/m^2. Difference in bubble behavior was clearly observed. While most of a heater surface was covered by small isolated bubbles and infrequent appearances of large bubbles at 20 K subcooling, larger sliding bubbles appeared frequently at 15 K subcooling. This visual observation provides a reasonable evidence for the abrupt and large downward shift.

The boiling curve of Kim et al. (2017) was shifted toward a higher wall superheat most severely compared to the others. This discrepancy may arise from an inherent feature of their experimental apparatus. That feature utilizes a mirror-polished silicon wafer plate as a main heater, and therefore the cavity mouth radius and corresponding roughness on the heater surface were very small. According to Webb and Kim (2005), the required conditions for boiling nucleation on a surface was defined as shown in Eq. (1).

$$T_{wall} - T_{sat} = \frac{q''r_c}{k_l} + \frac{2\sigma_l}{nr_c} \quad \text{Eq. (1)}$$

where r_c is the cavity mouth radius and n is the slope of the vapor pressure curve. The first term of right hand side in Eq. (1) is not significantly affected by the r_c because q'' is very large. Therefore, the decrease in r_c would increase the wall superheat. In this way, the shift toward the higher superheat observed in the boiling curve of Kim et al. (2017) can be explained. Furthermore, experimental study of Jabardo et al. (2009) clearly showed that the boiling heat transfer coefficient deteriorated with a decrease of the surface roughness measured by the arithmetical mean deviation of the profile.

All the experimental results obtained in the present work in various operating conditions of $5 < \Delta T_{sub,in} < 25$ K, $40 < G < 300$ kg/m^2-s, and $75 < q'' < 550$ kW/m^2 are presented in Fig. 8, which displays the wall heat flux versus the wall-superheat, $T_w - T_{sat}$. Based on most of the whole results, in which the data for the subcooling 10 and 15 K at a mass flux of 40 kg/m^2-s were excluded, a correlation could be developed as following:

$$q'' = 0.321\Delta T_{sat}^{2.62} \quad where \ \ \Delta T_{sat} = T_{wall} - T_{sat} \quad \text{Eq. (2)}$$

where q'' is the wall heat flux for nucleate boiling heat transfer, having a unit of kW/m^2. Most of the whole data are laid within ±30% of the correlation except in the case of mass flux of 40 kg/m^2-s and inlet subcooling of 10 and 15 K. In the exceptional case, quite higher heat flux could be imposed on the wall for a given wall super-heat compared to that of the correlation and experimental data.

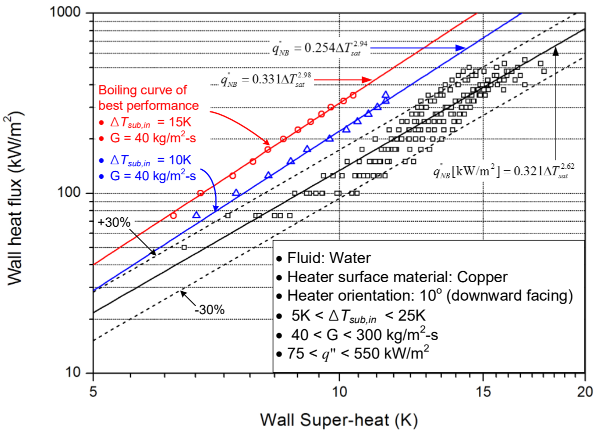

Fig. 8. Entire results on nucleate boiling heat transfer.

4. Conclusions

In this study, bubble dynamics was investigated with the help of high-speed camera to determine the influence of subcooling and flow velocity on the boiling curve with a 10° inclined downward-facing heater. A non-linear relation between liquid subcooling and nucleate boiling heat transfer coefficient was revealed under the pool boiling condition, showing the best performance at a subcooling of 15 K. Enhancement may be attributed to frequent appearance of sliding large bubbles even at subcooled state. This is because, formation of such sliding bubbles are favorable for evaporative heat transfer at the liquid sublayer and convective heat transfer via creation of a lot of turbulence near the heater surface.

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