

Experimental Investigation of Heater Length and Orientation Effects on Critical Heat Flux in Downward-Facing Pool Boiling

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1. Introduction

i-SMR (innovative Small Modular Reactor) is an integral pressurized water reactor type currently under development in the Republic of Korea. Due to its integral design, IVR-ERVC (In-Vessel Retention External Reactor Vessel Cooling) of i-SMR is conducted under pool boiling conditions. Unlike flow boiling, pool boiling is characterized by negligible liquid mass flux; consequently, bubble motion is governed almost exclusively by buoyancy.

This buoyancy-dominated behavior is particularly pronounced on downward-facing inclined surfaces, where bubbles slide along the heated wall in response to the buoyancy component parallel to inclination. Accordingly, bubble dynamics in downward-facing pool boiling manifest as two distinct modes—rising (longitudinal migration) and spreading (lateral growth). The dominance of these modes is primarily determined by the local surface inclination angle. For instance, Lu et al. [1] experimentally demonstrated that bubbles exhibit spreading motion at the bottom region of 3D hemispherical surface (low inclined orientation) under pool boiling conditions, whereas they tend to rise along the surface in the upper region (higher inclination angles) (See Fig.2).

As the complexity of fabricating an entire 3D hemispherical surface, research typically employs flat plate heaters oriented at specific angles. However, most previous studies have utilized relatively small heater sizes compared to the actual dimensions of an RPV lower head. On such limited surface, bubbles often escape prematurely upon reaching the edge of the heater, which may prevent the full development of bubble dynamics such as coalescence and extensive rising motion that would occur on a larger scale.

Therefore, the objective of this study is to provide the experimental CHF data using longer heaters to ensure sufficient space for bubble growth and rising motion.

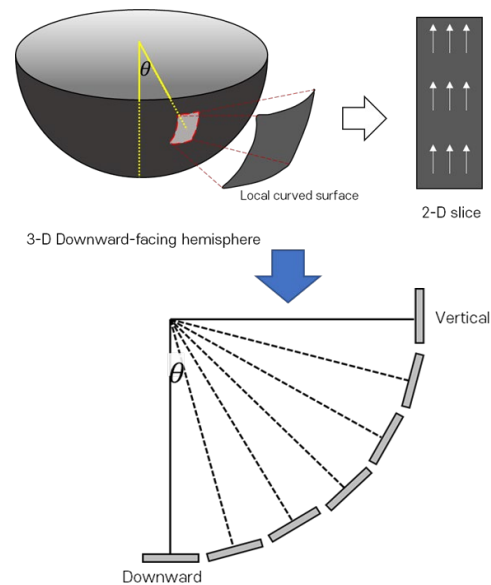


Fig. 1. Simulation methodology for the local surface of 3D downward-facing hemisphere

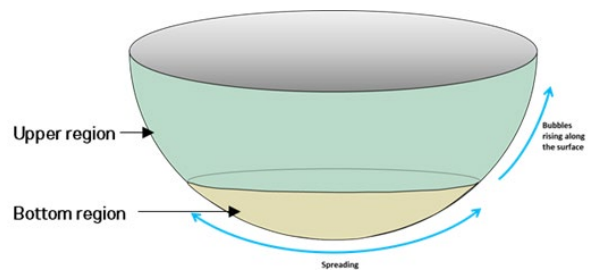


Fig. 2. Two bubble modes on hemispheric surface: rising and spreading

2. Experimental Method

To examine the effect of length on rising-bubble behavior, three heaters with different lengths were fabricated. The tested inclination angles and heater dimensions are summarized in Table 1.

The overall experimental loop is illustrated in Fig 3. The heaters were installed at a fixed inclination angle inside a test pool with an inner diameter of 550 mm and

a height of 850 mm. The imposed heat flux was generated using the Joule heating method. All heaters were polished with the same condition using #1200 grit sandpaper. Silicon rubbers and Bakelite were attached to the rear side of the heater to provide thermal insulation and prevent liquid ingress (See Fig.4).

To ensure the mechanical integrity of the test section under high-temperature and boiling conditions, the test section was rigidly assembled using bolts and nuts. The specific cross-section of the test section is illustrated in Fig 2.

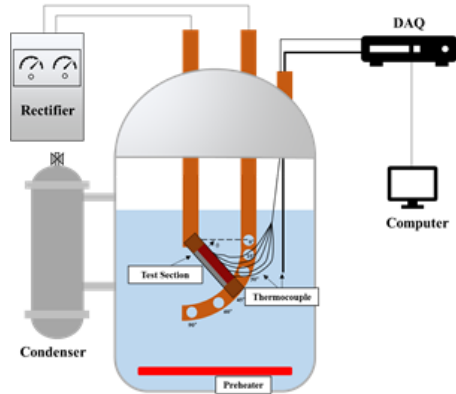


Fig. 3. Schematic of test loop

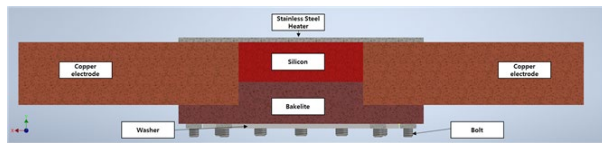


Fig. 4. Cross-sectional schematic of the test section

Table 1: Test matrix of present experiments

Material	Stainless Steel 304
Width (mm)	50.8
Length (mm)	50.8, 100, 200
Thickness (mm)	2.0
Orientation (°)	15 – 90 (vertical)

3. Results and Discussion

Fig. 5 presents the measured CHF values from the present experiments. For inclination angle between 15° and 90°, excluding 15° and 90°, no significant variation in CHF with heater length was observed. At an inclination angle of 15°, where the 200 mm heater exhibited a higher CHF value compared to the 100 mm and 50.8 mm heaters. This phenomenon is likely due to the lateral escape behavior of the bubbles. At this surface orientation, bubbles sliding along the heated surface tend to reach the lateral edges and depart before they can form a continuous vapor film. This lateral escape may delay the onset of CHF in the 200 mm heater, resulting in a higher measured value than in the shorter heater where such dynamics might be less pronounced. For the 200 mm heater at an inclination angle of 90°, the CHF values showed decreasing trend.

A similar behavior was reported in the experimental studies by Theofanous et al. [2] and Kam et al. [3]. Kam et al. attributed this trend to the effect of liquid supply direction on CHF. Since slightly inclined surfaces can provide more liquid supply conditions than a vertical surface, CHF may deteriorate at the vertical orientation.

In general, previous studies [4] have suggested that an increase in heating surface length leads to a larger heating area and higher bubble generation rates. This promotes more frequent bubble coalescence, resulting in an increase in the maximum bubble growth size. However, in the present experiments, the length effect was not consistently observed under all conditions. In particular, the negligible change in CHF when the heater length was increased to 200 mm suggests that bubbles coalescence and upward bubble motion had already developed sufficiently within 200 mm length.

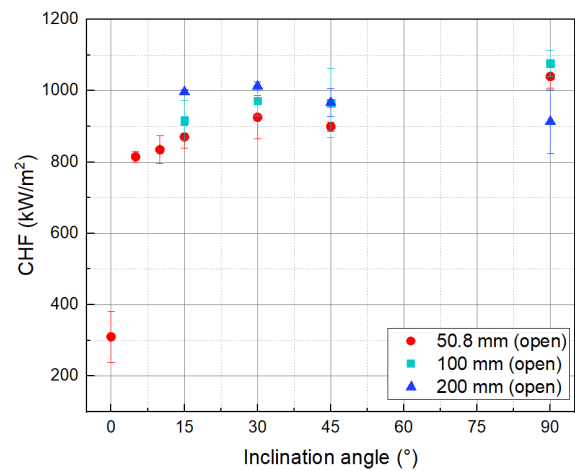


Fig. 5. Measured CHF data

In Fig. 6, the boiling curves obtained from all length conditions indicate that the heat transfer performance is most efficient in the vertical orientation. The heat flux values in the boiling curves for vertical conditions were higher than those for all other inclined downward-facing orientations. This cooling performance in the vertical position can be attributed to the unimpeded motion of bubbles. Unlike downward-facing inclined surfaces, where the heater surface acts as a physical barrier that blocks or traps the vapor bubbles against the wall, the vertical orientation allows buoyancy to effectively drive bubbles away from the surface. This rapid bubble removal enhances the quenching effect and liquid replenishment, leading to more effective heat transfer compared to lower inclination angles.

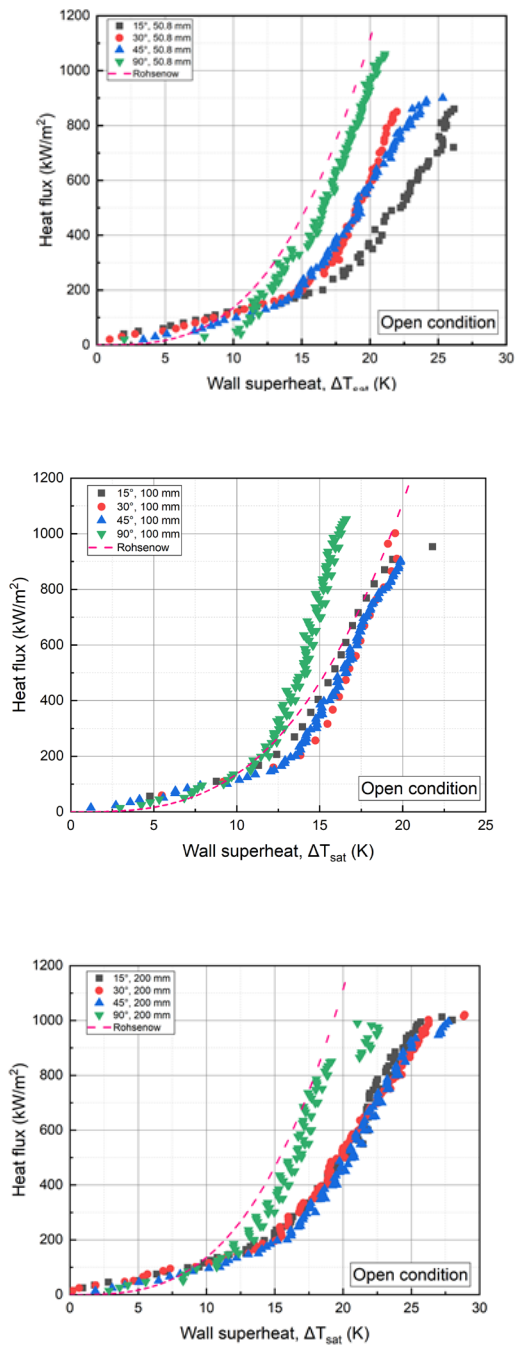


Fig. 6. Boiling curves for present experiments (Upper: 50.8 mm, middle: 100 mm, bottom: 200 mm)

4. Conclusion

In this study, CHF experiments were conducted to simulate the bubble rising motion and heat transfer characteristics on the lower head of RPV under pool boiling conditions. Using 50.8 mm, 100 mm, and 200 mm length heaters, there was no significant length effect on CHF. This result indicates that the influence of heater length on CHF reaches a saturation point beyond 100 mm. For local downward-facing boiling

simulations, this finding suggests that a heater length of approximately 100 mm may be enough to represent the developed bubble behavior relevant to CHF occurrence.

Furthermore, we confirm that the bottom region of the RPV—where the inclination angle is at its minimum—will be the most thermally vulnerable area. This region is expected to exhibit the lowest CHF and the poorest heat transfer performance due to the stagnation and spreading of vapor bubbles, which are less likely to be removed by buoyancy compared to the upper, more steeply inclined regions.

These results provide critical insights for the safety analysis of IVR-ERVC systems in i-SMRs, highlighting the necessity of focused thermal management on the lower-most section of the reactor vessel where bubble escape is most restricted.

5. Acknowledgement

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