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Experimental Observation of Bubble Behavior and CHF on a Downward-Facing Surface in Pool Boiling

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1. Introduction

In-vessel retention external reactor vessel cooling (IVR-ERVC) is a severe accident management strategy designed to maintain the integrity of the reactor pressure vessel (RPV) and prevent the leakage of radioactive materials. IVR-ERVC achieves this by cooling the outer wall surface of the RPV to remove residual decay heat from corium. To evaluate the feasibility of IVR-ERVC, critical heat flux (CHF) on the RPV wall surface is a key safety margin factor.

Additionally, cooling must occur within the nucleate boiling region, ensuring that the heat flux on the RPV wall does not exceed CHF. Proper cooling is essential to prevent meting of the RPV wall due to decay heat from corium, making the investigation of boiling heat transfer on the RPV surface important for successful IVR-ERVC.

Since the RPV lower head has a hemispherical downward-facing surface, bubble formation on the RPV is influenced by buoyancy, which varies with the inclination angle of the surface. Bubble accumulation and bubble departure motion affect CHF and heat transfer. Therefore, many previous experimental studies were conducted downward-facing CHF experiments using 2-D slice plate heater. At the 2-D slice surface, the bubble can departure from not only vertical direction but also the lateral edge. This delayed CHF occurrence lead to an abrupt increase in CHF at a specific inclination angle, known as the "transition angle" [1].

However, while a 3D hemispherical surface has a continuous curvature, a 2D slice surface has a fixed inclination angle. Therefore, the transition angle is believed to result from the geometrical difference between 3D and 2D surfaces, which affect bubble behavior and CHF.

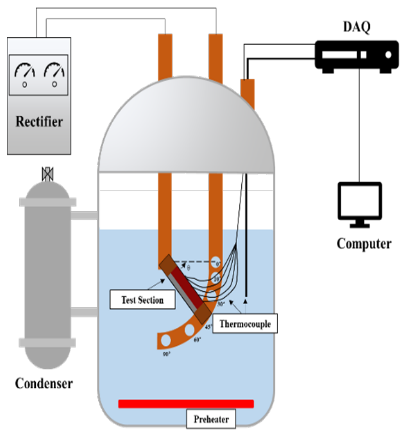
In this study, pool boiling experiments were conducted using a stainless steel plate to investigate bubble departure on 2D surface under the closing the lateral sides condition and open periphery condition.

2.Experiments

2.1 Experimental Apparatus

The experimnetal apparatus used in this study was illustrated in Fig. 1, top: Boiling pool, condenser, preheater, test section, thermocouple , data acquisition (DAQ), and a rectifier. The boiling pool has an inner diameter of 550 mm, a height of 850 mm, a thickness of 8 mm, and a total capacity of 0.3 M3. It was desinged to minimize the effects of bubble behavior and fluid circulation on CHF at the heater surface. A condenser is connected with the boiling pool to maintain the water level of pool. During boiling experiments, preheater control the temperature of pool to maintain the satureated temperature. The heating area of stainless steel plate test section has 50.8 mm x 50.8 mm size as shown in Fig 2. The test section where the heated and CHF occurred, is connected with copper electrodes to heat by joule heating. The inclination angel of tese section can be adjusted at 0° (downward), 5°, 10°, 15°, 30°, 45°, and 90° (vertical). A high-speed camera was used to observe and shoot the boiling phenomeon on the stainless steel plate.

Total six thermocouples were used in this experiments. Five thermocouples measrue the tempertuare of stainless steel plate heater. One thermocouple measures the temperatrue of pool. To get the parameter; voltage, resistance, current and temperature were saved by DAQ. These data were saved at the computer.



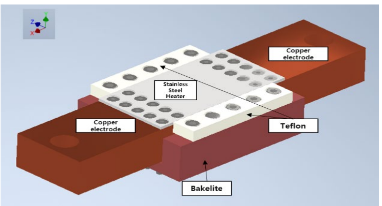


Fig. 1. Schematic of the experimental apparatus (top) and test section (bottom)

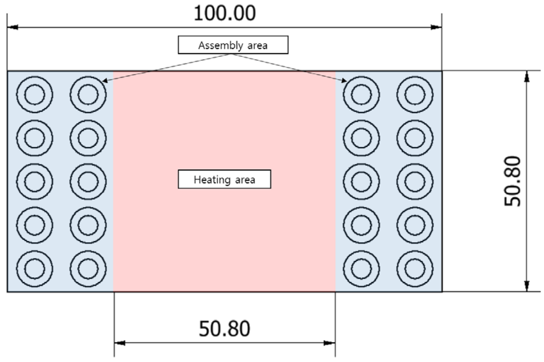


Fig. 2. Schematic of the stainless steel plate

2.2 Experimental methodology

To investigate the effect of bubble departure motions on CHF, experiments were conducted under two conditions: closed-sides condition and open periphery condition. The closed-sides condition was designed to mimic bubble motion on a 3D surface. On a 3D surface, bubbles generates across the entire surface, and as they grow and coalesce, they are blocked to departure from lateral direction by lateral bubbles. Therefore, they hardly depart laterally. Instead, they are driven upward along the surface by buoyancy. To replicate this behavior on a 2D slice surface, the closed-sides condition was implemented by blocking the lateral sides, preventing bubbles from escaping in the lateral direction, as they would on a 3D surface.

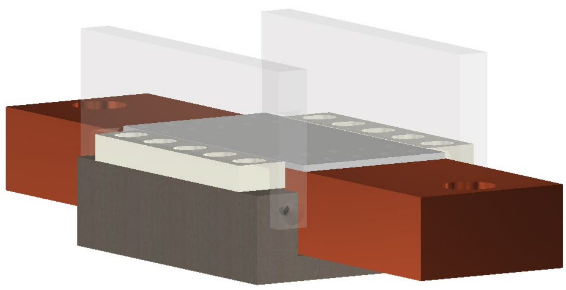


Fig 3. The test section with polycarbonate walls under closed-side condition

For the closed-sides condition, two polycarbonate guide walls 110 mm in length and 30 mm in height were installed along the lateral sides of the test section, as shown in Fig 3.

The boiling experiments were conducted in this study, the experimental procedures were carried out as follows:

- Polishing surface of stainless steel plate with SiC 120# and 1200# sandpaper.
- Cleaning up surface with acetone
- Connecting thermocouples and voltage lines to stainless steel plate
- Assembling two copper electrode blocks and stainless steel plate
- Connecting test section to electrode
- Turning on pre-heater to maintain the saturated temperature of pool
- Turning on power supply and DAQ
- Increasing current and monitoring temperature and resistance
- Turn off the power supply if the resistance increases abruptly due to CHF occurrence

3. Results and Discussion

Fig. 4 shows the comparison of CHF data between the closed-sides condition and the open periphery condition. At all inclination angles, CHF in the closed-sides condition was lower than in the open periphery condition. While a significant increase and the appearance of transition angle was observed at 5° in the open periphery condition due to bubble lateral departure as illustrated in Fig. 5, a sharp increase was not observed at 5° in the closed-sides condition.

In Fig 6., bubbles generated from the heated surface coalesced with adjacent bubbles, forming a slug bubble layer. Since the lateral sides were blocked by polycarbonate guide walls, the slugs could not depart laterally, leading to a thicker accumulation of bubbles on the surface. This increased bubble stagnation induced earlier CHF occurrence, as heat transfer was inhibited by the growing vapor layer.

In the closed-sides condition, the transition angle occurred at 10° rather than 5°. A notable observation in this condition was the "backflow" motion, which is believed to be responsible for the CHF value at 10° being higher than at 15°. As the part of bubble layer detached from the surface due to back flow, CHF occurrence was delayed. This shift is attributed to backflow, where the heavier, lower part of the bubbles pushes back and detaches as observed in Fig. 7. In Fig. 7, the blue-shaded region indicates where accumulated bubbles formed a slug, which subsequently split into two, leading to backflow. This phenomenon was observed due to the blocked lateral sides, which prevented bubbles from departing through the lateral direction. As the slug continued to grow and became heavier, the drag force acting on the slug exceeded the buoyancy force, preventing it from rising and causing it to split into two. According to Brusstar [2], on an inclined downward-facing surface, buoyancy forces cause vapor bubbles to rise along the surface, while drag forces resist their ascent, as shown in Fig. 7 (bottom). This interaction is believed to induce backflow in present experimental observation, splitting the bubbles into lower and upper parts. Since buoyancy force increases with inclination angle, backflow was no longer observed at higher inclination angles.

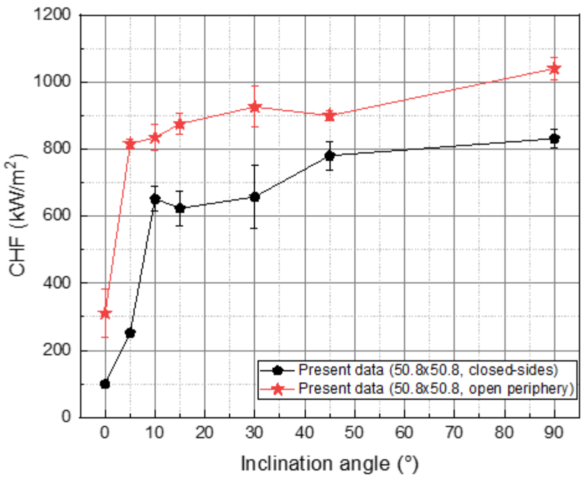


Fig. 4. CHF comparison between two conditions: closed-side and open-periphery

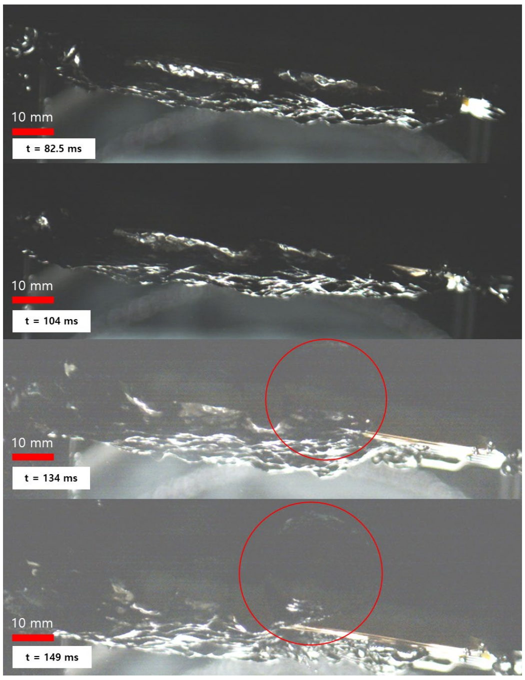


Fig. 5. The high-speed image of the lateral bubble departure motion at 5 ° (250 kW/m^2)

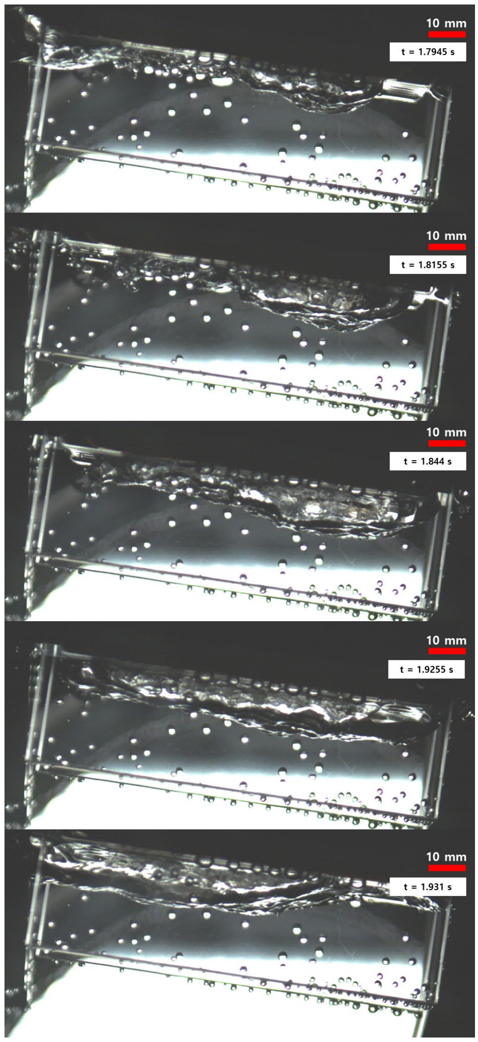
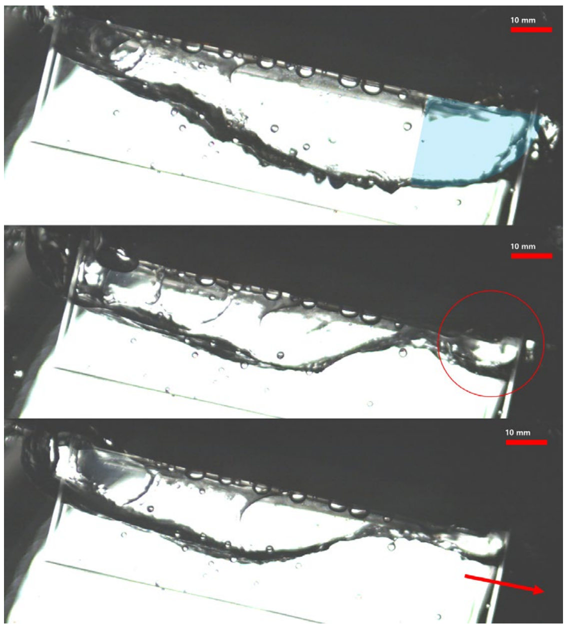


Fig. 6. The high-speed image of the sliding bubble motion at 5° at 250 kW/m^2 under closed-sides condition



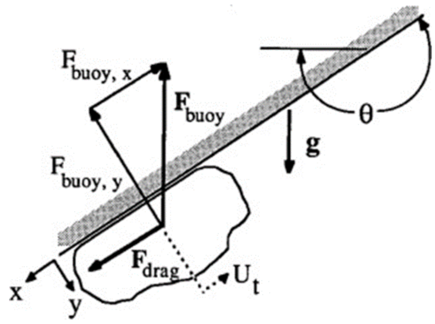


Fig. 6. The high-speed camera image of slugs under the closed-side condition near CHF (650 kW/m^2) (top) and interaction forces acting on bubble from Brusstar et al. (bottom)

4. Conclusion

In this study, pool boiling CHF experiments were conducted to investigate bubble departure dynamics using a stainless steel plate under two conditions: open periphery and closed-sides. In the open periphery condition, coalesced bubbles were observed to depart both laterally and in the upward direction, leading to the appearance of the transition angle at 5°. However, in the closed-sides condition, where lateral bubble departure was restricted, an abrupt increase in CHF was not observed at the same inclination angle as in the open periphery condition.

These findings suggest that the closed-sides condition significantly alters CHF behavior by preventing lateral bubble departure, which results in earlier CHF occurrence and the presence of backflow at intermediate inclination angles. In contrast, in the open periphery condition, lateral departure enhances heat transfer efficiency, delaying CHF and causing a lower transition angle at 5°.

As the inclination angle increases toward the vertical, the effect of lateral departure weakens due to the increasing influence of buoyancy force. Backflow was observed at 10°, where the buoyancy force was insufficient to lift the growing bubbles upward, causing them to push back and detach. However, this backflow phenomenon is unlikely to occur on a 3D surface, where the curvature is continuous and uniform. This suggests that backflow is a limitation of 2D slice surfaces, highlighting the geometrical constraints of 2D experimental models.

5. Acknowledgement

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