Experimental Investigation of CHF on Downward-Facing Plates with Micro-Porous Structure

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1. Introduction

In-Vessel Retention (IVR) combined with External Reactor Vessel Cooling (ERVC) has been considered one of the key severe accident management strategies in advanced light water reactors. In this strategy, the molten core material is retained inside the reactor pressure vessel while the outer vessel wall is cooled by external boiling, and the critical heat flux (CHF) directly determines the feasibility of vessel integrity [1].

Under ERVC conditions, the boiling surface is predominantly downward-facing, and CHF decreases significantly compared to upward-facing configurations due to vapor accumulation beneath the surface. Numerous studies have reported that CHF decreases as the inclination angle increases toward 180° because buoyancy-assisted bubble departure is suppressed and vapor coalescence is enhanced [2-4]. Therefore, understanding the CHF behavior under downward inclination is essential for evaluating IVR cooling capability.

The definition of the inclination angle (θ) and the corresponding surface orientations are shown in Fig. 1. The angle is measured from the upward-facing surface (0°) to the downward-facing surface (180°), with 90° indicating the vertical configuration. This geometrical variation directly affects bubble departure and vapor accumulation, thereby influencing CHF behavior under ERVC conditions.

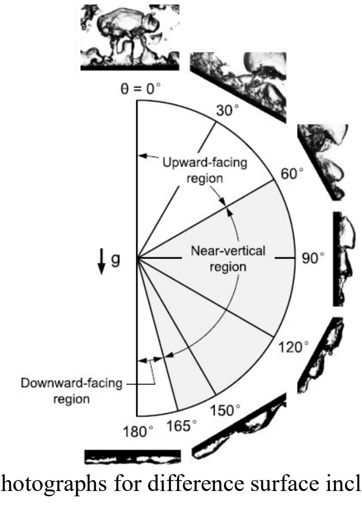

Fig. 1. Photographs for difference surface inclination [3].

To enhance CHF, various surface-modification techniques have been investigated, including micro/nano-structured surfaces, porous coatings, surface roughness control, and extended surfaces such as ribs [5]. Among them, electro-deposited micro-porous structures (MPS) have shown significant CHF enhancement under horizontal configurations. The CHF increased by approximately 60% compared to the plain surface without MPS [6]. The enhancement mechanisms include increased active nucleation site density, improved bubble departure characteristics, and capillary-driven liquid supply through interconnected pore networks [7].

However, most existing studies were conducted under upward-facing or horizontal conditions, and there is a lack of research regarding the applicability of MPS under downward-facing inclined plates relevant to IVR-ERVC conditions. Therefore, this study aims to investigate the effect of micro-porous structures on the critical current density (CCD), which is analogous to CHF, under downward-facing inclined plates.

2. Theoretical Backgrounds

2.1 Analogy between CHF and CCD

Direct CHF experiments under severe accident conditions involve high thermal loads and operational risks, making systematic parametric studies challenging [8, 9]. As an alternative, the hydrogen-evolving electrolysis system has been widely adopted to simulate boiling-like gas generation phenomena [10].

During water electrolysis, hydrogen gas evolves from the cathode surface after applying cell potential. As applied potential increases, the current density increases with intensified hydrogen generation and eventually reaches a limiting value when a continuous hydrogen film forms on the cathode surface, blocking ionic transport. This limiting condition is referred to as the CCD [6].

The CCD is considered analogous to CHF because both phenomena correspond to a transition from efficient phase-change transport to a vapor/gas film regime that significantly deteriorates transport performance. Previous studies have validated this analogy under various parameters including mass flux, surface inclination, and channel geometry [1, 11].

2.2 Inclination Effect on Downward-Facing Surfaces

For upward-facing surfaces, buoyancy assists bubble departure, enhancing liquid rewetting and delaying dryout [3]. However, when the surface inclination exceeds 90°, buoyancy acts to retain vapor beneath the surface, resulting in increased vapor coalescence and reduced liquid accessibility [2]. The effective buoyancy component normal to the surface decreases, while the tangential component increases with increasing inclination angle. This reduction in the normal buoyancy force promotes vapor retention beneath the surface, leading to earlier vapor blanket formation and lower critical conditions. Consequently, both CHF and CCD decrease as the surface approaches 180° (downward-horizontal configuration) [12].

2.3 Enhancement mechanisms of micro-porous structures

Micro-porous structures enhance critical conditions through several mechanisms. First, micro-scale cavities increase active nucleation site density, promoting distributed vapor generation across the surface. Second, porous morphology modifies bubble growth and departure behavior, suppressing large bubble coalescence. Third, interconnected pore networks induce capillary-driven liquid replenishment toward the heated surface. Finally, vapor escape through pore-connected channels reduces large-scale vapor blanket formation [6]. Under upward-facing conditions, these mechanisms have been reported to significantly enhance CHF performance [2, 12]. However, although such enhancement under upward-facing configurations is well documented, studies addressing the effectiveness of micro-porous structures under downward-facing orientations remain very limited, and systematic investigation under such adverse inclination conditions has scarcely been reported.

3. Experimental setup

3.1 Copper electro-deposition setup

Figure 2 shows a schematic image of experimental apparatus and electrical circuit for the electro deposition. 0.8 M $CuSO_4$ and 1.5 M H_2SO_4 solutions are used. The cathode where the electro-deposition occurs was a 10 mm diameter disk. And a cylindrical copper was used as the counter electrode (anode). Prior to the deposition, the cathode was cleaned by DI water and isopropyl alcohol (IPA). The current was modulated directly on power supply (DW INSTEK GEP112178). After then, the micro-porous deposited surface was washed by DI water and dehydrated using a heat gun.

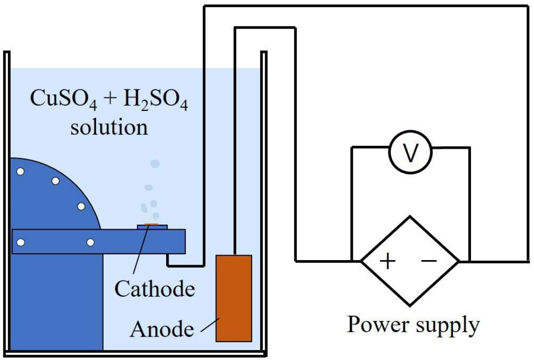

Fig. 2. Schematic diagram of the water electrolysis system for copper electro deposition.

Table 1 shows the test matrix for the CCD measurements and the electro-deposition conditions of the micro-porous structure. The CCD tests were conducted at three inclination angles, 120°, 150°, and 180°, for both plain surfaces and surfaces with MPS.

Table 1. Test matrix for inclination angle and electro deposition.

Surface	**Inclination angle θ (°)**		
Plain	120, 150,180		
MPS			
Electro deposition conditions		Current density (kA/m^2)	Deposition time (s)
	1st step	30	15
	2nd step	1	500

For the fabrication of MPS, a two-step electro-deposition process was employed, with each step playing a distinct role in forming the final structure. In the first step, a relatively high current density of 30 kA/m^2 was applied for 15 s to rapidly generate an initial porous layer. As shown in Figure 3, hydrogen evolution and copper deposition occur simultaneously during this stage, and the vigorous bubble generation acts as a dynamic template, creating micro-scale voids and a roughened surface morphology. In the second step, a lower current density of 1 kA/m^2 was maintained for 500 s to further develop the structure. Under this milder condition, dendritic copper clusters grow and interconnect, forming a stable micro-porous network with re-entrant features. Through this sequential process, a highly roughened and interconnected MPS layer is established. Identical deposition conditions were applied to all samples to ensure consistent surface morphology throughout the experiments.

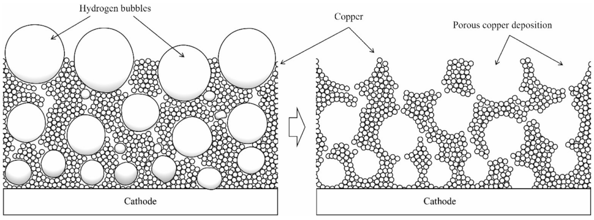

Fig. 3. Formation of the micro-porous structure during the 1st step electrodeposition [6].

3.2 Water electrolysis CCD experiments setup

Figure 4 is a schematic diagram of the experimental rig for water electrolysis. The 1.5 M H_2SO_4 solution was used for working fluid. The plain and electro-deposited 10 mm diameter copper surfaces were used as cathodes where hydrogen evolution occurred. And 100×200 mm rectangular copper was used for the anode. The electric potential was applied using DC power supply (Keysight N8965) and the voltage and current data were recorded by data acquisition (DAQ) system.

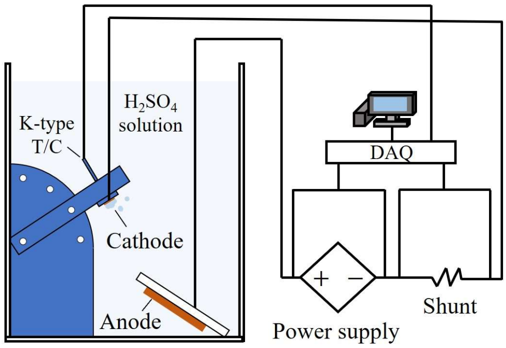

Fig. 4. Schematic diagram of the experimental rig for water electrolysis.

The test section was designed to allow controlled variation of the surface inclination. For temperature measurement, a thermocouple was inserted through the rear of the cathode and positioned near the heating surface. We confirmed that it did not extend beyond the heating surface while ensuring accurate temperature monitoring.

4. Results and discussions

4.1 Inclination Effect on Plain Surface

For the plain surface, Fig. 5 shows that the maximum current density clearly decreases as the inclination angle increases from 120° to 180°. The peak value of I-V curve is regarded as the CCD and at 120° exhibits the biggest, followed by 150°, while the lowest value is observed at 180°. This trend indicates that downward-facing inclination strongly promotes hydrogen accumulation beneath the cathode surface. As the inclination angle approaches 180°, buoyancy acts to retain gas near the surface rather than assisting detachment. Consequently, bubble coalescence occurs more readily, leading to earlier gas-film formation and lower limiting current density.

In addition, the onset of saturation occurs at lower voltages for larger inclination angles, suggesting that gas blanketing becomes dominant at earlier stages under more adverse orientations. The steep reduction at 180° demonstrates that the downward-horizontal configuration represents the most severe condition for gas removal, consistent with the CHF degradation mechanism in downward-facing boiling.

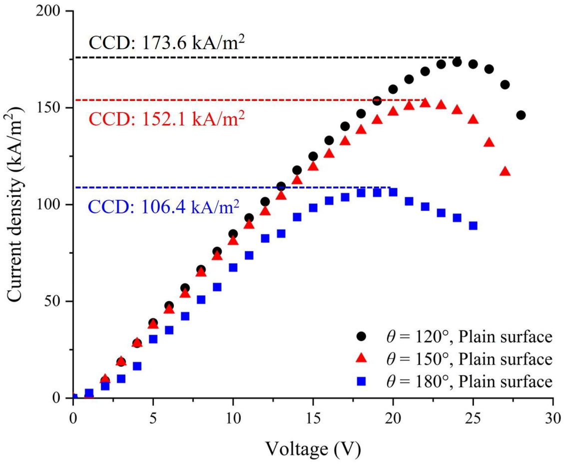

Fig. 5. Experimental data plain surface at downward facing region.

4.2 Effect of Micro-Porous Structure

Figure 6 shows that the overall shape of the I–V curves remain similar and CCD decreases as the inclination angle increases. This indicated that the inclination effect is still valid with micro porous structure.

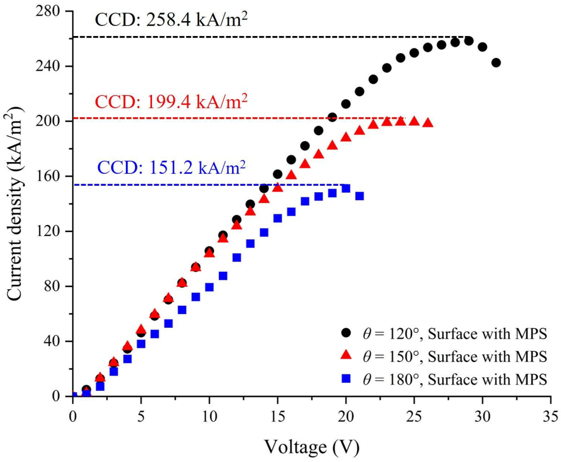

Fig. 6. Experimental data with micro-porous structures at downward facing region.

However, the magnitude of current density is significantly higher at all inclination angles as can confirmed on Fig. 7. It shows the CCD values for both plain and MPS surfaces. The CCD values for MPS surfaces are markedly elevated compared to the plain surface for 120°, 150°, and 180°. Specifically, the CCD increased by approximately 48.9% at 120°, 31.2% at 150°, and 42.1% at 180° with the application of the micro-porous structure.

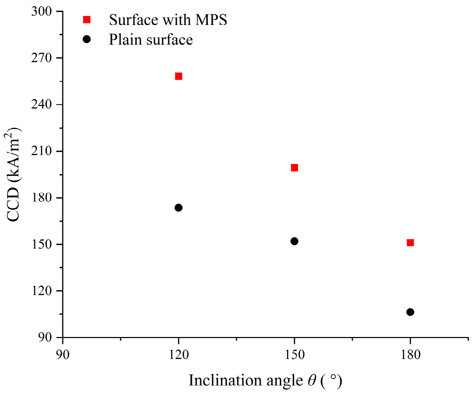

Fig. 7. CCD reduction trend about micro-porous structures.

The enhancement is attributed to the micro-porous structure, which provides interconnected pore channels and dendritic morphology. These features facilitate hydrogen escape through preferential pathways while simultaneously promoting capillary-driven liquid supply toward the cathode surface. As a result, bubble accumulation is delayed and a higher voltage is required before a continuous gas film forms.

Notably, even at 180°, where buoyancy-assisted gas removal is minimal, the MPS surface maintains substantially higher CCD compared to the plain surface. This indicates that capillary wicking and distributed ~~gas~~ bubble generation partially compensate for the adverse inclination effect.

5. Conclusions

While significant enhancements in CCD and CHF using micro-porous structures have been reported for the upward-facing inclination, it remains unexplored in the downward-facing inclination. This study experimentally investigated the effect of micro-porous structures on the under downward-facing inclined configurations using a hydrogen-evolving electrolysis system.

For the plain surface, CCD decreased significantly as the inclination angle increased from 120° to 180°. The downward-horizontal configuration (180°) exhibited the lowest CCD due to suppressed buoyancy-assisted gas removal and enhanced hydrogen accumulation beneath the surface.

The micro-porous structure did not change the trend that the CCD decreased as the inclination angle increased. However, compared to the plain surface, micro-porous significantly increased the CCD. The CCD values measured on the micro-porous structure were observed to be, on average, 40.7% higher than those measured on the plain surface. The porous structure promoted capillary-driven liquid replenishment and provided preferential bubble escape pathways, thereby delaying gas-film formation and increasing the limiting current density.

Overall, MPS significantly improves the critical condition under downward-facing configurations but does not completely overcome the geometric limitation associated with suppressed buoyancy. These results provide important implications for enhancing thermal margins in IVR-ERVC applications and offer insight into optimizing hydrogen-evolving electrolysis systems operating under restricted orientations.

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