Influence of micro-porous structure and inclination on critical current density in water electrolysis

2026. 05. 07

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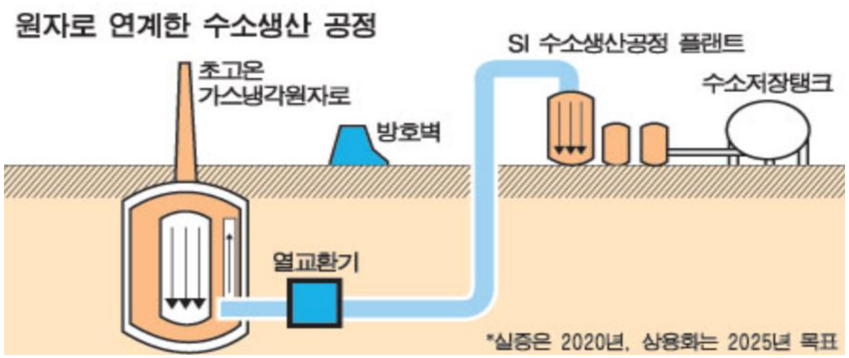
Backgrounds

Importance of hydrogen production efficiency

- Nuclear reactor heat → water electrolysis → enabling hydrogen production



[Nuclear hydrogen production process]

- Efficiency is directly linked to production rate
  - ➢ Higher efficiency → more hydrogen at same input

- System performance limitation is limited by critical current density (CCD)

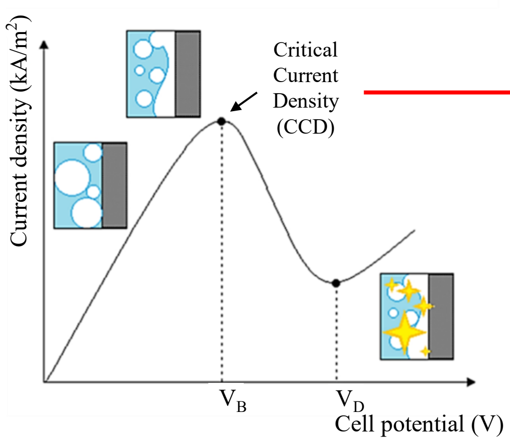
  - ➢ Improving hydrogen production rate is essential

CCD – CHF Analogy

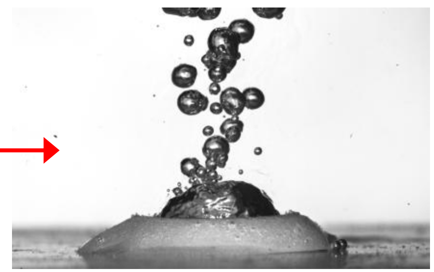
- CHF in boiling system and CCD in hydrogen evolving system have analogous relation

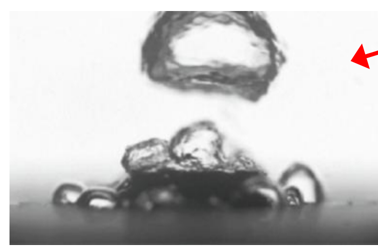
Hydrogen reduction (Mass transfer)
Current density
Cell potential difference
Critical Current Density (CCD)

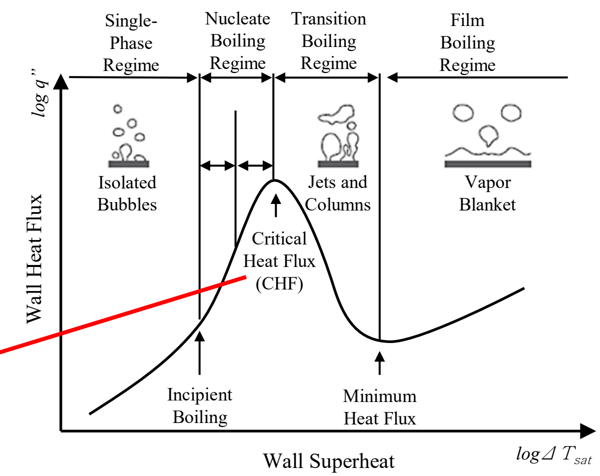
Boiling (Heat transfer)
Heat flux
Wall superheat
Critical Heat Flux (CHF)



(a) I-V curve in a water electrolysis



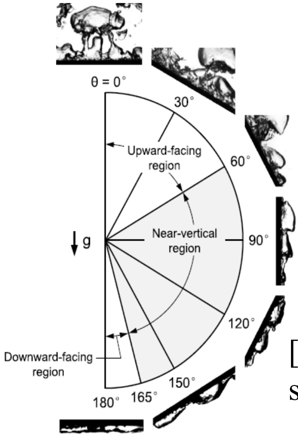




(b) Boiling curve in a water subcooled boiling

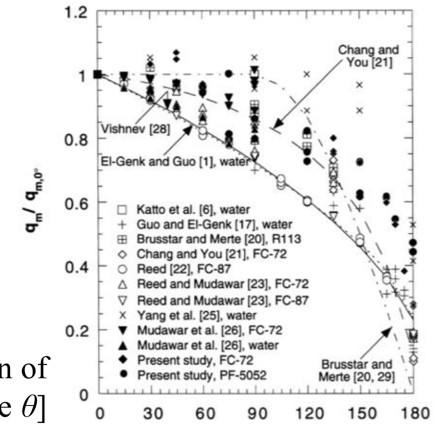
Influence of inclination on the CHF

- As the inclination angle increases toward 180°, the critical condition decreases because:
  - ✓ Buoyancy-assisted **bubble departure is suppressed**
  - ✓ Vapor is retained beneath the surface more easily
  - ✓ **Bubble coalescence** is enhanced
  - ✓ Earlier **vapor blanket formation** occurs



[Photographs for difference surface inclination]

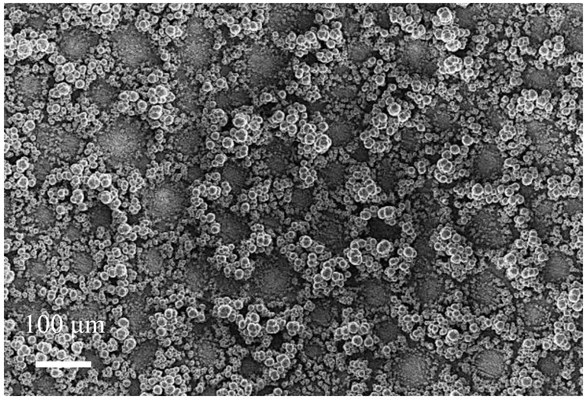
Downward-horizontal condition (180°)
→ the worst-case orientation for CHF/CCD



[CHF function of inclination angle θ]

Enhancement mechanisms of micro-porous structures

- Micro-porous structure (MPS) is a surface modification technique fabricated by electro deposition



[SEM image of MPS]

- MPS improves boiling heat transfer through:
  - ✓ Active nucleation site density ↑
  - ✓ Bubble departure frequency ↑
  - ✓ Capillary-driven liquid supply (wicking) ↑
  - ✓ Formation of vapor escape pathways through pores

→ These mechanisms **delay dry-out and vapor blanket formation**, which **leads to CHF enhancement**

Objective

Objectives

- Investigate CCD behavior in water electrolysis considering both MPS and surface inclination
- Analyze the inclination effect on gas bubble dynamics from upward to downward configurations
- Evaluate the effectiveness of MPS in enhancing electrolysis performance

Experimental setup

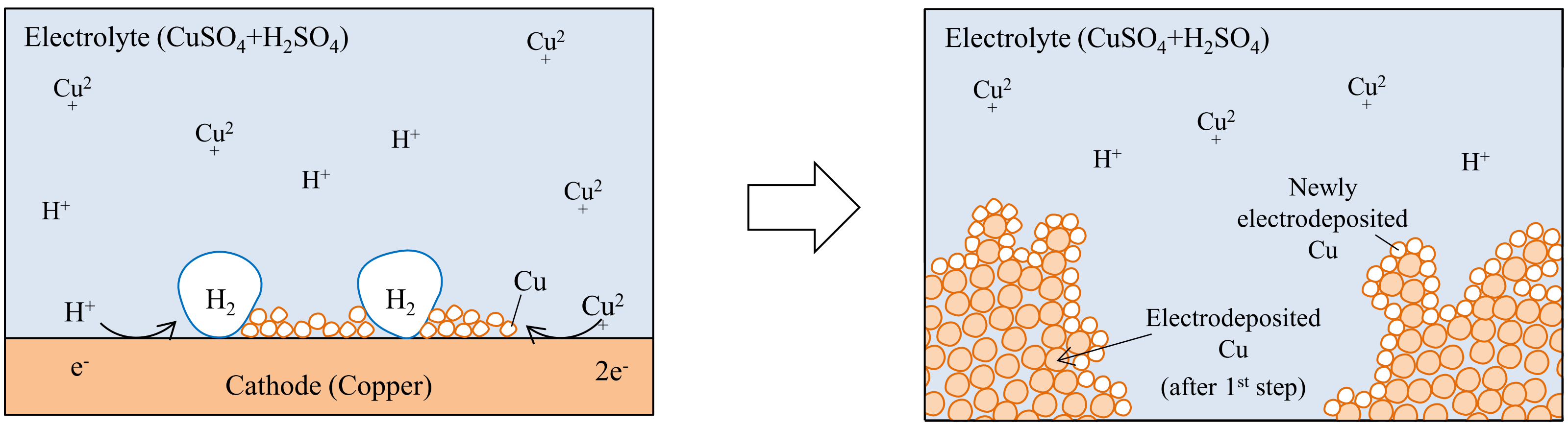
Surface modification – Two step method

Step 1

Voltage is higher than cell potential of
Copper precipitation ($Cu^{2+} + 2e^- \rightarrow Cu$)
& Hydrogen reduction ($2H^+ + 2e^- \rightarrow H_2$)

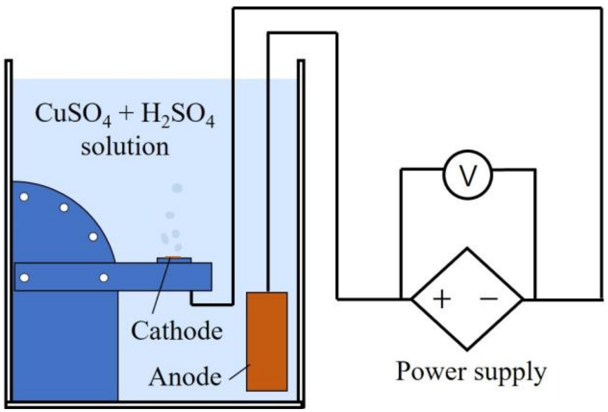
Step 2

Voltage is higher than copper precipitation cell potential
($Cu^{2+} + 2e^- \rightarrow Cu$)
& lower than hydrogen reduction cell potential
($2H^+ + 2e^- \rightarrow H_2$)

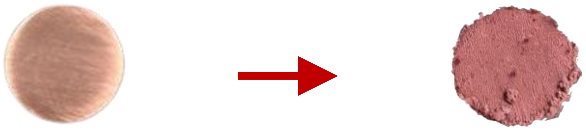


Copper electro-deposition setup

- 0.8 M $CuSO_4$ + 1.5 M H_2SO_4 solution was used for the electrodeposition of copper micro-porous on the cathode
- Disk cathode with 10 mm diameter was placed horizontally for homogeneous deposition



[Schematic diagram of the water electrolysis system for copper electro deposition]

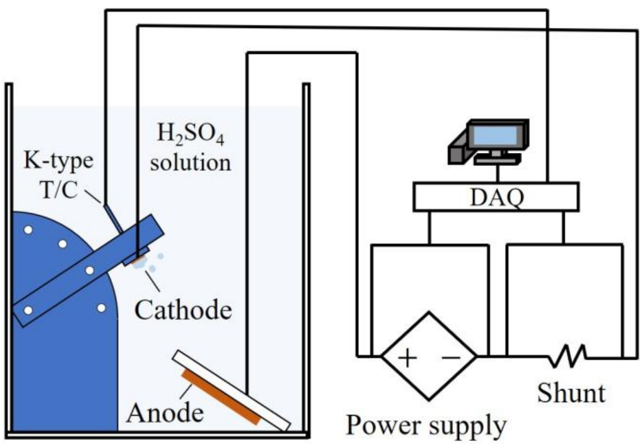


[Test matrix for copper electro-deposition]

		Current density (kA/m^2)	Deposition time (s)
Electro deposition	1st step	30	15
	2nd step	1	500

Water electrolysis CCD experiments setup

- 1.5 M H_2SO_4 solution was used as the working fluid for the CCD experiments
- A 10 mm copper cathode and a 100 × 200 mm copper anode were used in the electrolysis cell
- The test section allowed controlled variation of the surface inclination



[Schematic diagram of the experimental system for water electrolysis]

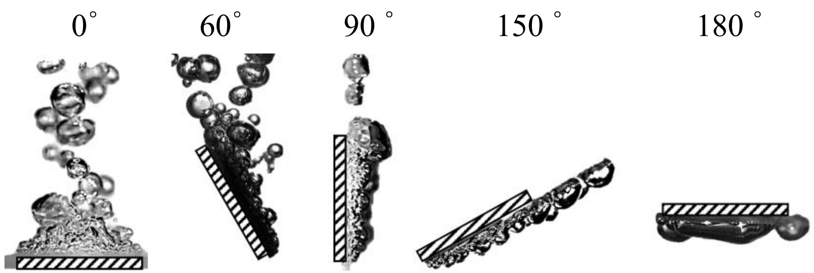
[Test matrix for inclination angle and electro deposition]

	Inclination angle θ (°)		
Plain	**0, 30, 60, 90, 120, 150, 180**		
MPS			
Electro deposition		Current density (kA/m^2)	Deposition time (s)
	1st step	30	15
	2nd step	1	500

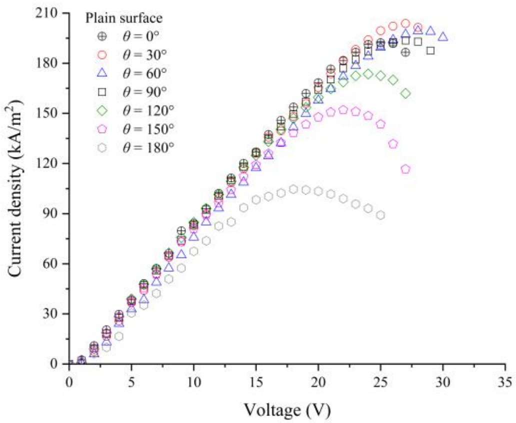
Results and discussion

Effect of inclination on CCD with plain surface

- **CCD decreases as the inclination angle increases**
  - ➢ Bubble merger increases as the inclination angle increases



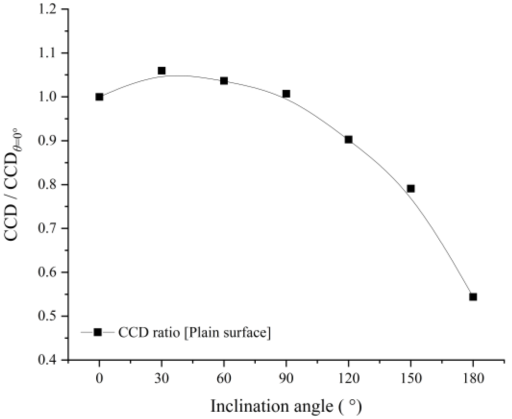
[Bubble behavior at various angles]



[I-V curve for plain surface]

- ***θ* = 180° shows the lowest normalized CCD** among all tested orientations

[Visual observation at 180° orientation]

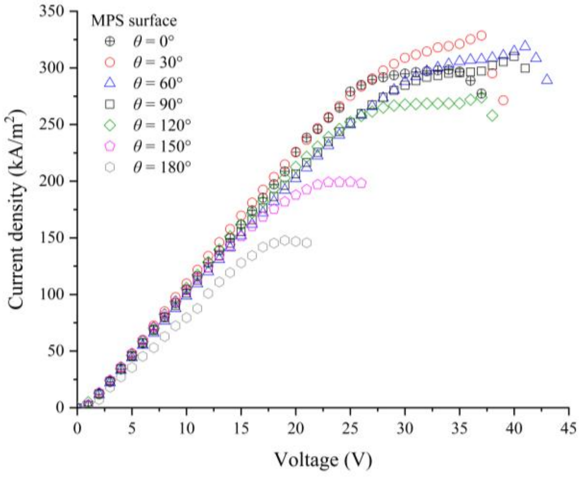


[Normalized CCD of plain surface]

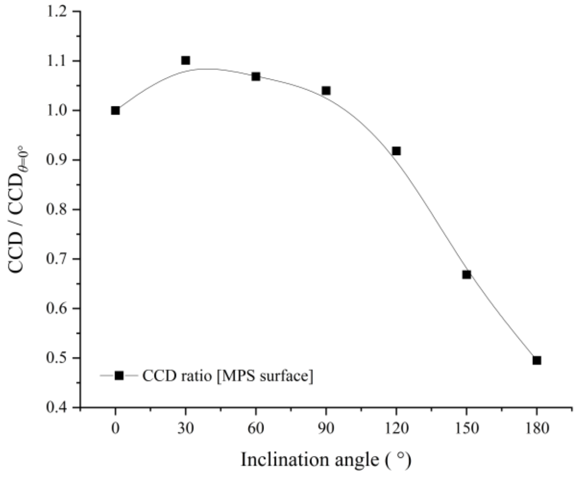
Effect of inclination on CCD with MPS surface

- **CCD on the cathode with MPS also decreases as the inclination angle increases**
  - ➢ Inclination effect remain even with MPS

- The normalized CCD trend of the MPS surface shows a **steeper decrease** compared to the plain surface

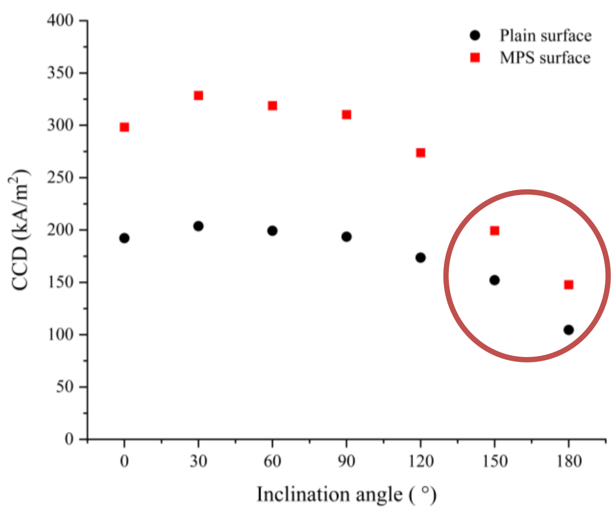


[I-V curve for MPS surface]



[Normalized CCD of MPS surface]

Bubble dynamic determining CCD



[CCD values of plain & MPS surface]

- **CCD decreasing trend** with increasing inclination angle
  - ➢ Suppressed buoyancy-assisted bubble departure
  - ➢ Enhanced **hydrogen accumulation** beneath the surface
  - ➢ More frequent **bubble coalescence**
  - ➢ Earlier gas-film formation
    → Lower CCD

- At 180° (downward-horizontal)
  - ➢ Bubble departure is strongly restricted
    → Minimum CCD observed

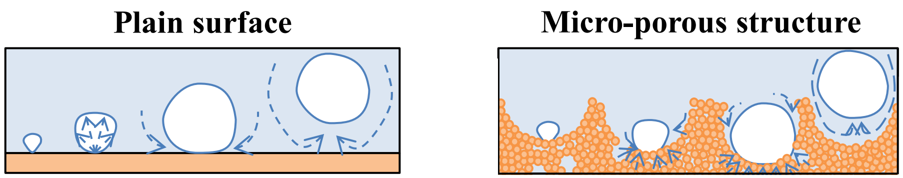
- Sharp CCD decrease near 150°
  - ➢ Transition region → Rapid increase in bubble retention and coalescence

Effect of micro-porous structure (1/2)

MPS CCD increased mechanism

① **Capillary wicking**

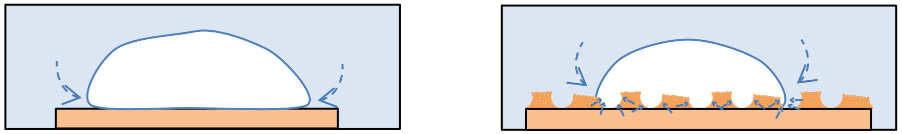
- Increase liquid supply through the porous structure
  - → Restrain dry spot
  - → Increase bubble growth efficiency



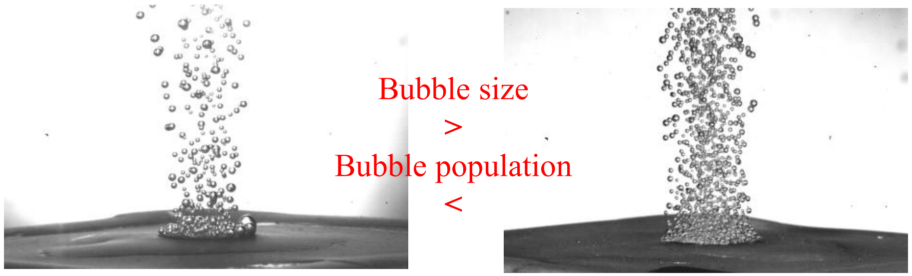
[At single bubble growth]

② **Increased nucleation site**

- Increase electrical energy which consumed to the hydrogen reduction



[At film growth]



[Photograph of bubble growth (Park et al., 2024)]

Effect of micro-porous structure (2/2)

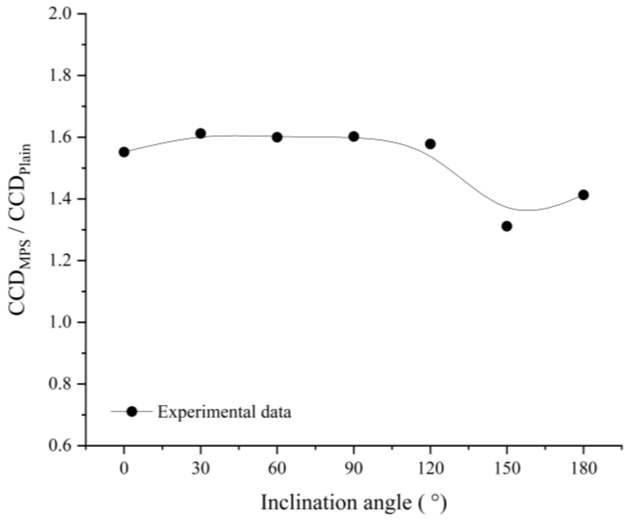
- MPS increased the CCD up to 61%

✓ **<u>0° ~ 120°</u> :**

→ Enhancement is stable, maintaining a high and uniform level (1.55–1.6 times)

✓ **<u>150° ~ 180°</u> :**

→ Performance **slightly fluctuates** due to increased vapor retention effects



[CCD enhancement by MPS surface]

Conclusion

- CCD decreases with inclination due to deteriorated bubble removal
  - 180° shows the lowest CCD
  - This trend is observed consistently for both plain and MPS surfaces

- MPS surface significantly enhanced CCD across all inclination angles compared to the plain surface
  - Enhancement CCD (up to ~61%) driven by capillary wicking and increased nucleation site density

- Hydrogen production is strongly influenced by surface structure and inclination; therefore, further studies are required for its application to reactor systems

Thank you for your attention