Experimental Investigation on Augmentation of Critical Current Density in Alkaline Water Electrolysis using Shroud Structure

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1. Introduction

Hydrogen production is a promising technology to attain global carbon neutrality [1]. Among various production methods, pink hydrogen generated using surplus electricity from nuclear power has drawn attention as a clean energy source with minimal carbon emissions and a stable power supply. One of the primary methods to store hydrogen is using a water electrolysis. However, hydrogen bubble adhesion on the cathode surface causes over-potential and in turn it limits the maximum hydrogen production rate [2] in a certain high current and cell potential condition. To overcome these limitations, previous research in chemical engineering has focused on improving electrode efficiency by applying electrochemical parameters such as catalysts and working temperature.

However, studies regarding the hydrodynamic parameters applicable to the electrolysis system are hardly available. Park and Chung [3, 4] have been demonstrating the similarity of the hydrodynamic behavior between the boiling and the hydrogen evolving system based on the analogy concept.

Previous studies have attempted to enhance the critical heat flux (CHF) by increasing surface hydrophilicity [5] or implementing surface wicking [6]. Zhang and Wang [7] explored an alternative method by improving surface rewetting through vapor flow control using a shroud. The work confirmed that installing a shroud above the surface induced the chimney effect, resulting in the augmentation of CHF by up to 83% when the Bond number was ~ 1.

In this study, critical current density (CCD) was measured using an alkaline water electrolysis system by employing a shroud. The behaviors of hydrogen bubbles were visualized and analyzed using a high-speed camera.

2. Background

CHF and CCD are phenomena that occur in a heat transfer device and a water electrolysis, respectively. In a pool boiling system, the CHF limits the heat flux when the vapor attached to the surface working as a thermal insulator. Similarly, in a water electrolysis system, the CCD represents the critical point at which partial hydrogen film forms on the electrode surface. Fig. 1 and Fig. 2 show that there are similar N-shaped curves including the limits; the CHF and CCD.

In particular, there is a strong similarity between the two systems in that the temperature and heat flux at boiling correspond to the voltage and current density in water electrolysis. In other words, just as in CHF, vapor bubbles formed on the superheated surface the heat transfer, hydrogen bubbles formed on the electrode surface affect the electrode reaction. In both systems, when certain critical conditions are exceeded, a film (vapor film or hydrogen film) forms and it impairs the transfer rate significantly.

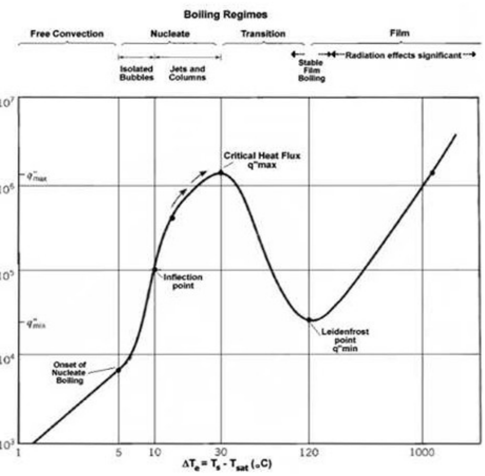


Fig. 1. Boiling curve [8]

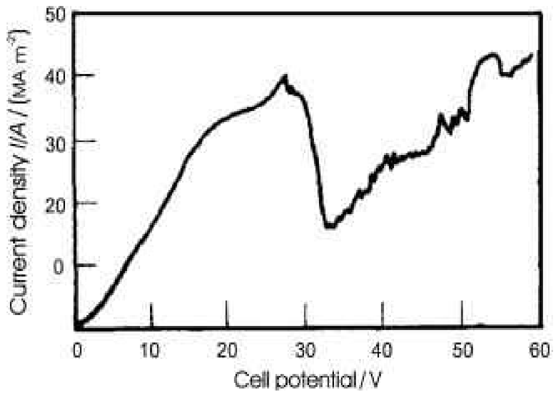


Fig. 2. Cell potential Current density curve [9]

3. Experimental setup

To measure the critical current density of the water electrolysis system, a 10 mm diameter nickel as the cathode and a 56 mm diameter nickel as the anode were used. A 1.94 M KOH solution was used as the electrolyte, and a Keysight N8952A power supply was applied to apply voltage to the system. A data acquisition unit (DAQ, NI9225) was used for voltage and current measurements, and a 0.1 mΩ shunt resistor was used to measure the current.

The shroud was made of acryl for visibility and corrosion resistance, and it is a hollow cylindrical structure similar to a straw, with an inner diameter of 10 mm and a height of 60 mm. And an additional device was designed to adjust the gap between the electrode and the shroud. In addition, a high-speed camera (Phantom Lab 1116GMono, Vision Research) was used to capture the behavior of the hydrogen bubbles.

Zhang and Wang [7] reported that the peak of CHF was measured when the Bond number is close to unity, when the capillary length and the size of the gap become similar. Based on the existing work, we expected that the critical current density would also have a maximum value when the bond number approaches unity.

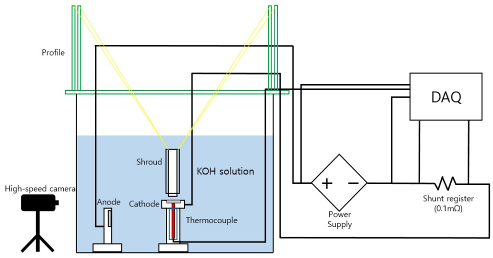


Fig. 3. Circuit Design for Critical Current Density

Fig. 4. Shape of shroud

Table 1. Test matrix and the characterization of shroud surface

Parameters	Cases		
	#1	**#2**	**#3**
Shroud length, L (mm)	60		
Shroud inner diameter, D (mm)	10		
Gap, s (mm)	w/o	2.5	3.1
Bond number	0	0.81	1.24

4. Results and discussion

Fig. 4 shows the electrical data recorded for Case #1 (without shroud), where the measured CCD was 126.225 kA/m². Initially, the current tends to increase as the voltage increases, and then current density decreases rapidly after the CCD point similar to the CHF. The CCD value obtained by Park and Chung [10] using the H_2SO_4 aqueous solution-copper system was about 179.320 kA/m^2. It is inferred that the higher CCD measured in the H_2SO_4 aqueous solution-copper electrolysis system is due to the differences in cathode material, roughness, and electrical conductivity of the aqueous solution.

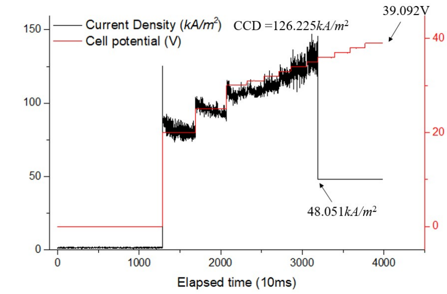
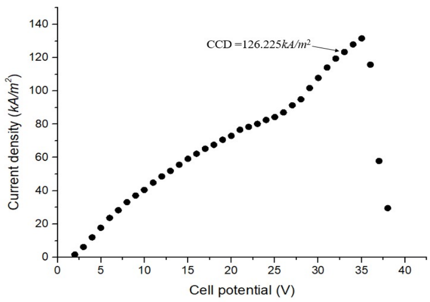
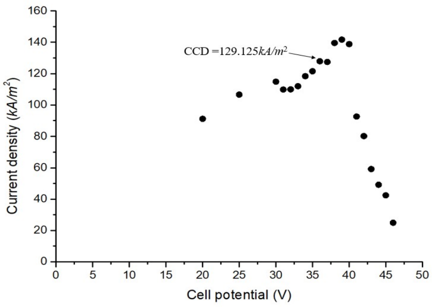


Fig. 4. Changes in voltage, current density over time when controlling voltage without shroud

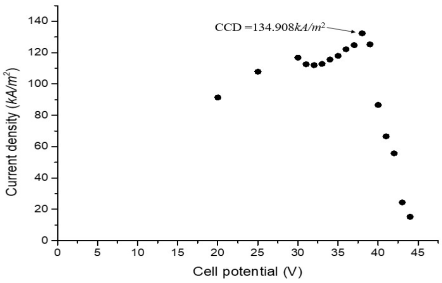
Fig. 5 shows the V-I curves for all the cases. There is an initial tendency for the current density to increase with increasing voltage, followed by a sharp decrease in current density similar to the CHF.



(a) w/o shroud



(b) gap: 2.5mm



(c) gap: 3.1mm

Fig. 5. V-I curves of case #1, #2 and #3

Fig. 6. shows the variation of the CCD value with gap. The CCD increases by 2.3% and 6.4% for gaps of 2.5 mm and 3.1 mm, respectively, when the bond number is relatively close to 1.

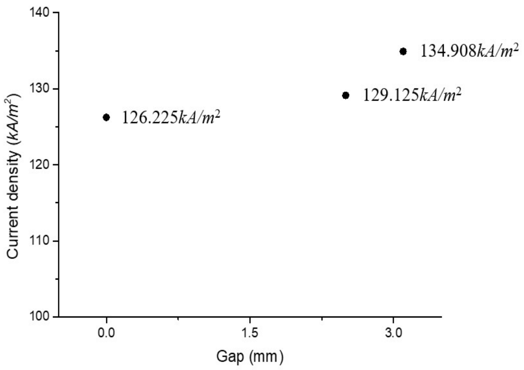


Fig. 6. CCD with and without shroud and gap variation

Fig. 7 and Fig. 8 show the bubble behavior without and with the shroud. Fig. 7 shows the bubble behavior at the CCD point with the voltage controlled (without the shroud). Fig. 8 shows the change in bubble behavior with the shroud when the time point 50 ms after the CCD point is reached is set to 0 ms. We observed that the size of the bubble just above the surface is relatively small in case of shroud installation compared to Fig. 7. Moreover, descending hydrogen bubbles, which are indicated by the black circles were captured as shown in Fig. 8 (a) to (c). These two distinct phenomena might have been caused by the liquid backflow from the top of the shroud due to the chimney effect as the generated hydrogen clots were accelerated inside the shroud. Hence, it is postulated that the augmentation of CCD was due to the enhanced surface wetting resulting from the liquid backflow.

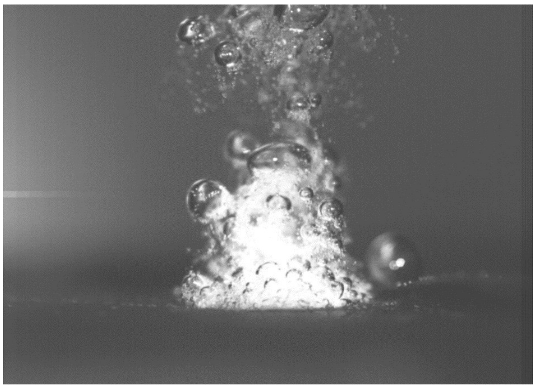
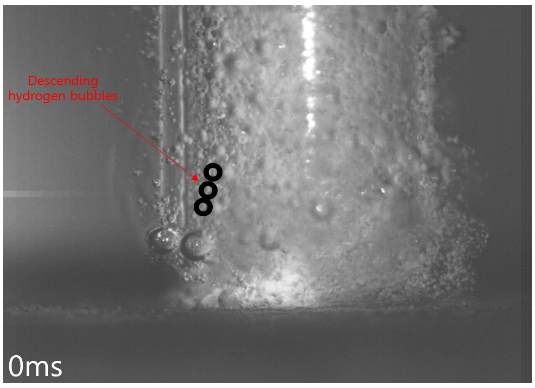
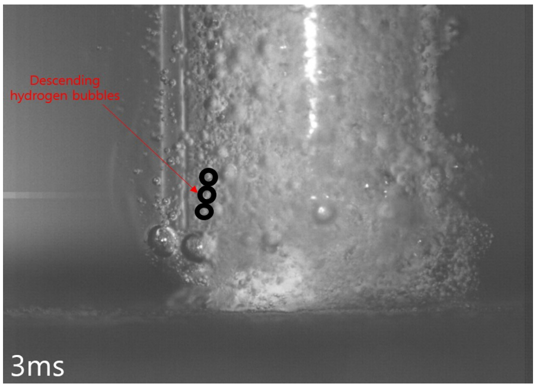


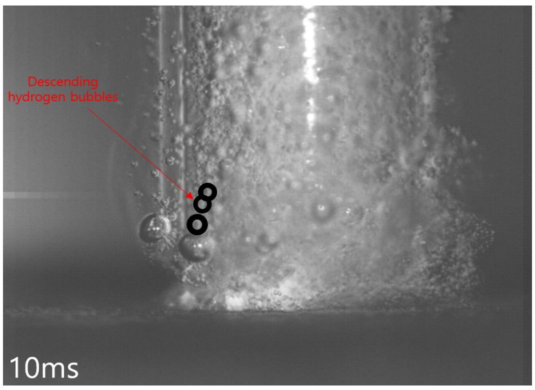
Fig. 7. Bubble behavior without shroud



(a) 0 ms



(b) 3 ms



(c) 10 ms

Fig. 8. Bubble behavior using shroud

5. Conclusion

The critical current density (CCD) of the water electrolysis system was measured by controlling the voltage using a KOH aqueous solution-nickel electrolysis system. The method similar to that used in the boiling heat transfer system was applied to enhance the CCD using the shroud structure.

The CCD measured in the KOH aqueous solution-nickel system was 126.225 kA/m². The chimney effect caused by the shroud delays the hydrogen film formation resulting in the augmentation of the CCD by up to 6.4%. It can be inferred that the liquid backflow enhanced the surface rewetting as hydrogen bubble clots accelerated inside the shroud. The hydraulic factors of the water electrolysis system revealed in this study are expected to be utilized as design factors to improve the hydrogen production efficiency of next-generation water electrolysis systems. Since the present work is limited to the lack of experimental case (size of gap), future work should be performed varying the gap size and shroud length to clarify the explanation proposed in this work.

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