

Measurements of critical current density in alkaline electrolysis varying inclination and vertical length of cathode

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1. Introduction

Small Modular Reactors (SMRs) are emerging as next-generation nuclear reactors, highlighted by their advantages in mass production and shortened construction periods. In particular, to achieve the modularization and miniaturization of components, SMRs adopt Helical Coil Steam Generators (HCSGs) to replace shell-and-tube type steam generators. As the working fluid in an HCSG passes through helical tube geometries and undergoes phase change, the two-phase flow regime would be affected significantly by centrifugal forces.

It is expected that the secondary flow caused by the centrifugal force in the helical channels reduces the validity of straight-tube-based flow regime maps. Furthermore, density wave oscillations and flow-induced vibrations affect the flow stability and the structural integrity of the helical tubes. Additionally, the high-temperature and high-pressure conditions of experimental facilities limit the direct observation of internal boiling phenomena and bubble behavior. Therefore, a novel experimental methodology is required to visualize two-phase flow phenomena inside the HCSG.

Our research group firstly proposes the experimental methodology using electrochemical reactions to simulate the two-phase flow generated by boiling heat transfer. Previous studies have confirmed that the hydrodynamic behavior of hydrogen bubbles generated by water electrolysis is similar to that of vapor generated by boiling heat transfer [1-2]. Critical Heat Flux (CHF) is a phenomenon which deteriorates heat transfer significantly, representing the operation limit of a boiling system due to a vapor film acting as thermal insulator. Similar phenomenon in the water electrolysis, Critical Current Density (CCD) occurs at a certain high hydrogen generation rate mode, which deteriorates mass transfer significantly, and it represents the operation limit caused by a partial hydrogen film acting as an electric insulator.

The ultimate goal of this method is to construct a two-phase flow regime map applicable to HCSGs. Therefore, it is essential to identify the operational limit of the electrochemical system to design a cathode acting as a diabatic wall. Although actual HCSGs feature complex curved geometries, electrodes were utilized in this study to independently isolate and investigate the fundamental local effects of vertical length and inclination angle, excluding complex curvature effects. This work employs

a 10 wt% KOH solution and nickel electrodes varying the cathode lengths and inclination angles.

2. Background

2.1. Analogy between boiling and water electrolysis

Based on the analogy concept between boiling and water electrolysis, the superheat and heat flux correspond to the cell potential and current density, respectively. In water electrolysis, as the applied voltage increases and the current density rises, a larger volume of hydrogen bubbles generated at the cathode surface coalesces into unstable film. This film disturbs the rewetting of the electrolyte on the electrode surface, resulting in a sharp increase in electrical resistance, which decreases the current density. This hydrodynamical mechanism is analogous to that of boiling system when the CHF occurred.

2.2. Influence of geometric parameters on CHF/CCD

Different bubble behaviors are expected along the circular surface due to its unique geometry. To better understand the complex phenomena inside a circular tube, it is important to investigate the local influence of geometric parameters, such as the vertical length and inclination.

Zhang et al. [3] conducted boiling experiments on downward-facing heated surfaces with varying inclination angles and lengths. They confirmed that as the inclination approaches the vertical, buoyancy-driven bubble departure is promoted, leading to an increase in the CHF.

Ohk et al. [4] conducted water electrolysis experiments on a downward-facing cathode with varying inclination angles. They confirmed that as the inclination approaches the horizontal, buoyancy promotes bubble coalescence, leading to a decrease in the CCD. Park et al. [5] observed that the CCD decreases as the vertical length of the cathode increases while maintaining a fixed width.

However, existing studies have been limited to investigating a single variable, either the inclination angle or the vertical length. Therefore, this study simultaneously varies both the inclination angle and the vertical length of rectangular electrodes.

3. Experimental setup

Fig. 1 illustrates the definition of the geometric parameters for the cathode used in this study, specifying the width (W), length (L), and inclination angle (θ). Fig. 2 illustrates the experimental setup and electrical circuit for the two-electrode alkaline electrolysis system. A cathode was exposed on both sides and fixed to an inclination control device, which was installed at top of an open-top acrylic tank filled with a 10 wt% potassium hydroxide aqueous solution. Nickel sheet ($t = 0.1$ mm) was used as the cathode, as detailed in Table I. A nickel plate (100×100 mm, $t = 1$ mm) was used as the anode. The experiments were conducted at room temperature and atmospheric pressure, voltage and current were applied by a DC power supply and measured by a DAQ system. Also, the hydrogen bubble behavior was recorded by a high-speed camera at 100 fps.

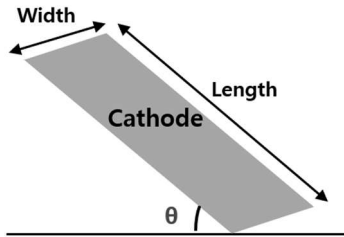


Fig. 1. Definition of geometric parameters for the cathode

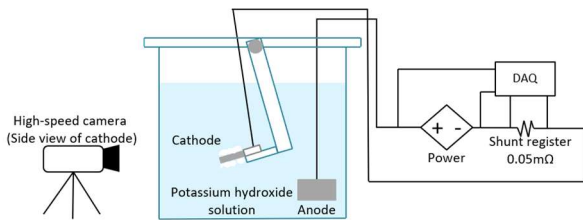


Fig. 2. Schematic diagram of the experimental setup for cathode inclination.

Table I: Test matrix for cathode to investigate the effects of inclination angle and length.

Case	W (mm)	L (mm)	Inclined angle (deg)
1	10	10	0, 45, 90
2	10	5	

4. Results and discussion

Fig. 3 presents a representative case of the experiments and the measured cell potential and current density over time to identify the CCD. As the cell potential was increased stepwise, the current density initially rose while maintaining a stable oscillation amplitude. However, as the cell potential continued to increase, the fluctuation of the current density became significantly severe. The CCD was identified as the point where the average current density reached its highest value just before the onset of these massive fluctuations.

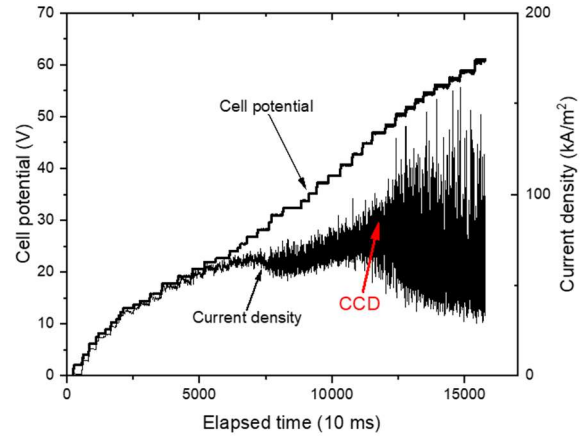


Fig. 3. Identification of CCD in alkaline water electrolysis (Case 1 at 90°).

Fig. 4 shows a tendency for the CCD values as the inclination increases. At all the inclination cases, case 1 was lower than that of case 2. This is due to the larger cathode area (longer vertical length) of case 1. Longer vertical length increases the surface rewetting resistance distance, causing an reduction in the CCD. Decreasing trend of the CCD with respect to the area and vertical length is consistent with the results of Park et al. [5].

Existing studies regarding CHF have reported two geometric effects. Regarding the inclination effect, it is shown that the CHF gradually decreases in upward-facing surfaces as the surface becomes vertical, while a decreasing trend of the CHF is observed in downward-facing surfaces as the surface becomes horizontal. Regarding the length effect, it is evident that a shorter bubble escape length on the heated surface results in a higher CHF. Since the present work measured the CCD using a double-sided surface, these two conflicting phenomena are expected to occur simultaneously. In case 1, the influence of the upward-facing side appears to predominantly governs the overall system, as evidenced by the decreasing trend of the CCD as the surface becomes vertical. Similarly, case 2 generally exhibits a similar decreasing trend with increasing inclination. However, the 90° condition deviates from this tendency, which was conducted at the last stage in the experimental series seemed to be damaged to the surface sealing.

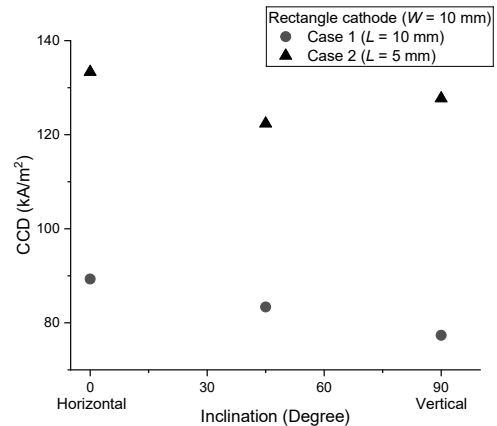


Fig. 4. Effects of inclination angle on the CCD of double-sided cathodes.

Fig. 5 shows a photograph of bubbles taken near the CCD point, indicating the formation of a partial film on the cathode surface. As indicated by the red arrows in the figure, the coalesced hydrogen gas films are observed covering specific local areas, which shows the visual evidence of the partial film formation.

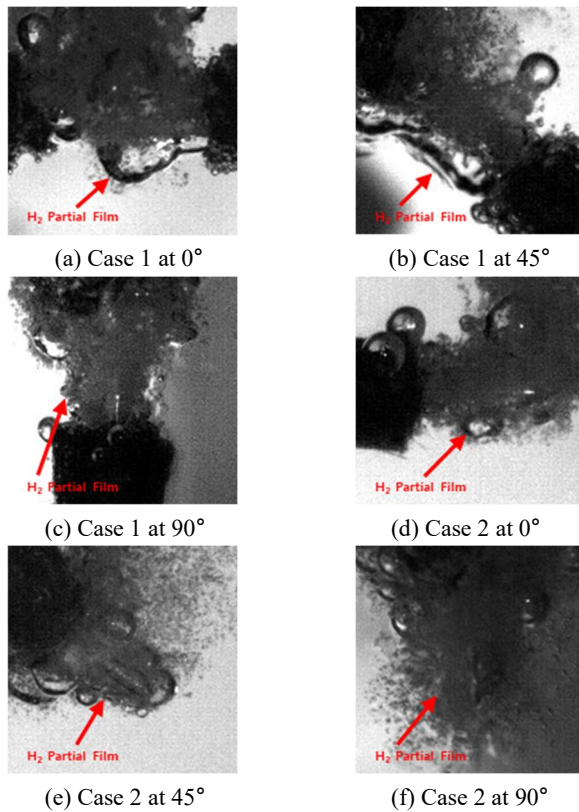


Fig. 5. In-situ observation of hydrogen bubble behavior near CCD.

5. Conclusion

The effects of the vertical length and the inclination angle of double-sided rectangular cathodes on the CCD and bubble behavior were investigated to specify the operation limits of the cathode.

The key findings demonstrate that regarding the vertical length, a shorter cathode (case 2) resulted in a higher CCD compared to the longer cathode (case 1). This improvement is attributed to the reduced rewetting resistance distance and the smaller cathode area. Furthermore, regarding the inclination angle, the CCD of double-sided electrodes appears to be predominantly governed by the upward-facing surface within the limited range of experimental conditions.

Ultimately, the insights obtained from this study will serve as valuable preliminary indicators for designing two-phase flow experimental facilities and using electrochemical methods to simulate two-phase flow regimes applicable to the HCSG.

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