

Original Article

DOI 10.1007/s12206-026-0628-8

Keywords:

- Water electrolysis
- Bubble
- Hydrogen
- Electrodeposition

Correspondence to:

Gihun Son
gihun@sogang.ac.kr

Citation:

Bae, S., Son, G. (2026). Experimental study on hydrogen bubble growth and detachment on surface-modified electrodes. *Journal of Mechanical Science and Technology* 40 (7) (2026) 5175–5184.
<https://doi.org/10.1007/s12206-026-0628-8>

Received January 23rd, 2026

Revised March 5th, 2026

Accepted March 12th, 2026

† Recommended by Editor
No-cheol Park

Experimental study on hydrogen bubble growth and detachment on surface-modified electrodes

Sungjae Bae and Gihun Son

Research Institute for Smart Design & Manufacturing Technology, Department of Mechanical Engineering, Sogang University, 35 Baekbeom-ro, Mapo-gu, Seoul 04107, South Korea

Abstract Hydrogen bubble behavior strongly affects the performance of alkaline water electrolysis, particularly at high current densities. This study experimentally investigates the influence of electrode surface modification on hydrogen bubble dynamics using nickel wire cathodes. The electrode surfaces were modified via electrodeposition at different deposition current densities, resulting in distinct surface morphologies. The non-coated electrode exhibited bubble behavior that varied with electrolysis current density, whereas the surface-modified electrodes predominantly showed dispersed bubble generation over a wide operating range, indicating an increased density of active nucleation sites. The hydrogen bubble generation volume rate increased monotonically with current density for all electrodes, while bubble size and residence time were strongly dependent on the surface condition. Cell voltage and energy conversion efficiency were governed by bubble surface coverage and detachment characteristics. Moderate surface modification reduced voltage losses and mitigated efficiency degradation, whereas excessive modification led to increased electrical losses. These results demonstrate that optimizing electrode surface morphology is essential for enhancing the performance of alkaline water electrolysis systems.

1. Introduction

Hydrogen has attracted significant attention as a sustainable energy carrier because of its high gravimetric energy density and carbon-free utilization [1]. Sharshir et al. [2] described alkaline water electrolysis as a highly developed and economically competitive technology for large-scale green hydrogen production, enabled using non-precious metal electrodes. Zeng and Zhang [3] further emphasized that AWE is particularly suited for industrial applications because of its robustness and operational simplicity.

During alkaline water electrolysis, gas bubbles inevitably nucleate, grow, and detach from electrode surfaces, and this gas evolution process plays a crucial role in determining electrolysis performance. Janssen and Hoogland [4] showed that gas bubbles generated during electrolysis lead to an effective thickening of the diffusion layer, resulting in increased mass transport resistance. Janssen and Barendrecht [5] further showed that gas evolution at electrodes substantially alters mass-transfer characteristics, particularly under conditions of high gas generation rates.

As the applied current density increases, bubble generation becomes more intense, and bubble coverage on the electrode surface increases accordingly. Zhang and Zeng [6] experimentally demonstrated that bubble behavior directly affects the cell voltage in AWE, reporting that the presence of bubbles increases both ohmic and concentration overpotentials. Boissonneau and Byrne [7] further reported that bubble-induced free convection and gas holdup significantly modify transport processes in electrochemical cells, leading to efficiency degradation under high-rate operating conditions.

Recent studies have shown that the efficiency of alkaline electrolyzers does not increase monotonically with current density due to bubble-related losses. Angulo et al. [8] demonstrated that,

beyond a critical operating condition, the electrolysis process transitions from a reaction-limited regime to a bubble-dynamics-limited regime, in which increased bubble coverage and prolonged bubble residence times significantly reduce energy conversion efficiency despite higher hydrogen production rates. Ursúa et al. [9] similarly reported that high-current-density operation in practical water electrolysis systems often leads to efficiency deterioration owing to insufficient gas removal and increased transport resistance near the electrode surface.

Accordingly, considerable efforts have been devoted to improving electrolysis efficiency by mitigating bubble-related losses. Kwon et al. [10] experimentally demonstrated that enhanced hydrogen bubble removal in AWE reduces cell voltage and improves energy efficiency, highlighting the importance of bubble behavior control for AWE performance. In addition, the influence of gas-liquid two-phase flow on electrolysis efficiency has been reported in related water electrolysis systems, indicating that gas evolution and phase interactions play a critical role in determining overall cell performance [11].

Because bubble growth, merging, and detachment determine the degree of surface coverage at high current densities, effective regulation of bubble behavior is crucial for reducing efficiency losses. Park et al. [12] reported that the bubble coverage of gas-evolving electrodes strongly depends on electrode surface conditions, demonstrating that surface properties directly influence bubble detachment frequency and surface coverage. These results indicate that electrode surface characteristics play a decisive role in regulating bubble dynamics and, consequently, electrolysis performance under high-rate operation.

Despite these findings, most previous studies have focused on external operating conditions or system-level optimizations, while the direct influence of electrode surface characteristics on bubble dynamics and efficiency degradation has not been sufficiently clarified. In particular, a systematic understanding of how surface modification alters bubble growth behavior and shifts the onset of non-monotonic efficiency trends with increasing current density remains limited.

In this study, hydrogen bubble dynamics during AWE are systematically investigated over a wide range of current densities. Bubble behavior on non-coated electrodes is first analyzed to identify characteristic bubble growth modes and their relationship with efficiency degradation. Subsequently, surface-modified electrodes are examined to elucidate how electrode surface characteristics regulate bubble dynamics and delay the onset of efficiency deterioration. By directly linking bubble behavior, surface effects, and efficiency trends, this work aims to provide physical insight into bubble-induced performance limitations and to propose surface engineering strategies for improving AWE efficiency under high-current-density operation.

2. Materials and methods

Hydrogen bubble dynamics during alkaline water electrolysis are investigated through two sequential experimental stages. First, electrodeposition is performed to fabricate nickel

electrodes with controlled surface morphologies under well-defined deposition conditions. Second, hydrogen bubble generation experiments are conducted using the prepared electrodes to directly observe bubble growth and detachment behavior during electrolysis. These two stages are designed to clearly separate electrode surface preparation from electrochemical bubble observation. The detailed experimental methodology is presented in the subsections that follow.

2.1 Electrodeposition setup for surface modification

A schematic of the experimental setup used for electrodeposition is depicted in Fig. 1. Electrodeposition experiments are conducted using a dedicated electrochemical setup to modify the surface of nickel wire electrodes. An aqueous solution containing $\text{NiSO}_4 \cdot 6\text{H}_2\text{O}$ (Samchun Chemicals, Pyeongtaek, Korea) is used as the nickel source. A 1.0 M $\text{NiSO}_4 \cdot 6\text{H}_2\text{O}$ electrolyte was formulated and thoroughly mixed using a magnetic stirring system (MSH-20D, Daihan Scientific, Daegu, Korea) with magnetic beads. Boric acid (H_3BO_3 , Samchun Chemicals, Pyeongtaek, Korea) is added as a buffering agent, and its concentration is adjusted to 0.6 M. The electrolyte temperature is maintained at 25 °C throughout all electrodeposition experiments.

A nickel wire with a diameter of 100 μm is used as the cathode substrate. The side surface of the wire is insulated with epoxy to ensure that the electrodeposition occurs only on the top surface. A platinum mesh with dimensions of 1 × 1 cm is employed as the anode. Both electrodes are immersed vertically in the electrolyte, and the inter-electrode distance is fixed at 2.5 cm to maintain a stable electric field during deposition.

Electrodeposition is performed under galvanostatic control using a potentiostat (SP-240, BioLogic, Seyssinet-Pariset, France). The deposition current density, J_{ed} is set to 700 A/m^2 , 1500 A/m^2 , and 3000 A/m^2 , depending on the target surface morphology. For all cases, the deposition time is fixed at 30 min. This electrodeposition setup is used exclusively for surface modification of the nickel wire electrodes prior to the hydrogen bubble generation experiments.

2.2 Preparation of surface-modified electrodes

Using the electrodeposition setup described in Sec. 2.1, nickel

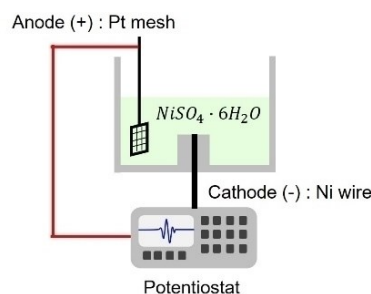


Fig. 1. Schematic of electrodeposition experimental setup.

wire electrodes with modified surface morphologies are prepared. These electrodes are hereafter referred to as surface-modified electrodes, while nickel wire electrodes used without electrodeposition are referred to as non-coated electrodes.

After electrodeposition, the electrodes are removed from the electrolyte, rinsed thoroughly with deionized water to eliminate residual salts, and dried under ambient conditions. No additional post-treatment is applied prior to subsequent experiments.

The surface morphology of the non-coated and surface-modified electrodes was characterized by scanning electron microscopy (SEM; JSM-7100 F, JEOL, Tokyo, Japan). SEM observations are used to qualitatively assess changes in surface roughness and microstructural features induced by electrodeposition at different deposition current densities.

The prepared electrodes are then used directly as cathodes in the hydrogen bubble generation experiments described in Secs. 2.3-2.7.

2.3 Electrochemical system for hydrogen bubble generation

A schematic of the experimental setup used for hydrogen bubble generation experiments is depicted in Fig. 2.

The electrodes prepared in Sec. 2.2 are mounted as the cathode in this system. A nickel wire with a diameter of 100 μm is used as the cathode, and its exposed active length is defined by epoxy insulation to maintain a constant electrochemically active area during electrolysis.

A coiled nickel wire is employed as the anode. The cathode and anode are arranged concentric inside a custom-designed electrochemical acrylic cell with dimensions of 50 x 50 x 50 mm. The radial distance between the electrodes is fixed at 5 mm to ensure a stable and reproducible current distribution.

The cell configuration allows unobstructed front-view observation of the cathode region without interfering with electrochemical operation. This electrochemical system is used exclusively for hydrogen bubble generation and visualization experiments and is separate from the electrodeposition setup described in Sec. 2.1.

2.4 Electrolysis conditions

Hydrogen bubble generation experiments are performed under galvanostatic conditions using a potentiostat. An aqueous solution containing potassium hydroxide (KOH; Sigma Aldrich,

St. Louis, MO, USA) is used as the electrolyte. The KOH concentration is fixed at 1.0 M and the solution is prepared using a magnetic stirrer with magnetic beads. The electrolyte temperature is maintained at 25 $^{\circ}\text{C}$ throughout all experiments, and the electrolyte volume is kept constant to ensure consistent operating conditions.

During electrolysis, no external flow is imposed and the electrolyte remains quiescent. Using the electrochemical system described in Sec. 2.3, the applied current density is systematically varied over a wide range to investigate hydrogen bubble behavior under different operating regimes. For each current density condition, experiments are repeated to confirm reproducibility. For each experimental run, a newly prepared electrolyte solution was used to ensure consistent conditions within the electrochemical cell.

The cell voltage is continuously recorded during electrolysis and is subsequently used to evaluate the energy-based performance metrics described in Sec. 2.7.

2.5 High-speed visualization of hydrogen bubble dynamics

Hydrogen bubble nucleation, growth, coalescence, and detachment at the cathode surface are visualized using a high-speed imaging system. A high-speed camera (VEO 410, Phantom, Wayne, NJ, USA) is positioned to observe the cathode region through the transparent wall of the electrochemical cell described in Sec. 2.3. A long-distance lens is attached to the camera to achieve sufficient spatial resolution for imaging the 100 μm -diameter nickel wire cathode.

The magnification of the optical system is adjusted using a zoom lens (Optem Zoom 70XL, Optem Fusion, Waltham, MA, US) depending on the observation scale. Uniform backlighting is provided by an LED lamp (Cyclops 1, Suwon, Korea) placed opposite the camera to enhance the contrast between hydrogen bubbles and the surrounding electrolyte. The optical axis is carefully aligned to minimize image distortion and to maintain consistent focus on the cathode surface.

Image sequences are recorded at a frame rate of 100 fps with a spatial resolution of 512 x 512 pixels. The frame rate was selected based on the characteristic time scales of hydrogen bubble growth and detachment during water electrolysis. Even under high current density conditions, where gas evolution becomes intense, the bubble residence time remains significantly longer than the 10 ms inter-frame interval, enabling reliable tracking of the bubble interface and accurate measurement of the detachment diameter (D_{detach}). The recorded images are stored for subsequent frame-by-frame analysis to extract quantitative information on hydrogen bubble behavior under different electrolysis conditions.

2.6 Bubble detachment parameters

Based on the high-speed visualization described in Sec. 2.5, hydrogen bubble detachment behavior is quantified using two

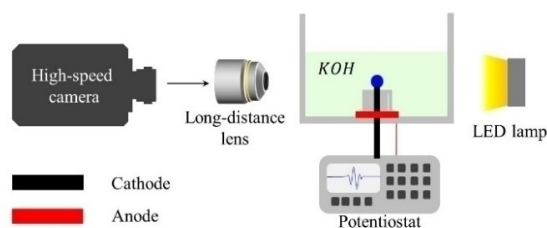


Fig. 2. Schematic of hydrogen bubble generation experimental setup.

parameters: the detachment diameter (D_{detach}) and the detachment time (t_{detach}). These parameters are defined to characterize bubble growth and release from the cathode surface under different electrolysis condition.

The detachment time t_{detach} is defined as the time interval between the onset of observable bubble growth at a nucleation site and the moment when the bubble completely detaches from the cathode surface. The onset of bubble growth is identified as the first frame in which a bubble becomes distinguishable from the electrode surface.

The detachment diameter D_{detach} is defined as the equivalent bubble diameter measured immediately prior to detachment. The equivalent diameter is calculated from the projected bubble area obtained from image analysis, assuming axisymmetric bubble geometry. The projected area is processed and measured using ImageJ software.

These detachment parameters are applied consistently to both non-coated and surface-modified electrodes and form the basis for subsequent evaluation of hydrogen generation efficiency described in Sec. 2.7.

2.7 Definition of efficiency metrics

The hydrogen generation performance is evaluated using the energy conversion efficiency, which quantifies the fraction of electrical energy converted into the chemical energy of produced hydrogen. The energy conversion efficiency η_E is defined as

$$\eta_E = \frac{\dot{E}_{H_2}}{\dot{E}_{\text{elec}}} \times 100 = \frac{\dot{n}_{\text{measured}} \cdot HHV}{VI} \times 100 [\%] \quad (1)$$

where $\dot{n}_{\text{measured}}$ is the experimentally measured hydrogen molar production rate, HHV is the higher heating value of hydrogen, taken as 285.8 kJ/mol, V is the measured cell voltage during electrolysis and I is the applied current.

3. Results

3.1 Surface morphology of electrodeposited electrodes

Fig. 3 presents SEM images of nickel wire cathode surfaces before and after electrodeposition at different deposition current densities J_{ed} . To ensure the statistical validity of the morphological characterization, SEM observations were conducted on at least three different sampled regions for each electrode condition. All images used for quantitative analysis were acquired at a consistent magnification of x3000 to allow for direct comparison of surface features. Table 1 presents the quantitative image analysis results obtained using ImageJ software, which enables objective characterization of the crack-branching morphology. The quantitative metrics reported in Table 1 correspond to the mean values derived from these multiple observations.

As J_{ed} increased from 700 to 1500 A/m², the branching degree

Table 1. Quantitative morphological metrics of the electrodeposited electrodes obtained via ImageJ analysis.

J_{ed}	Crack density	Branching degree
700 A/m ²	8.5 %	3.4 nodes/100 μm^2
1500 A/m ²	14.2 %	8.2 nodes/100 μm^2
3000 A/m ²	19.8 %	1.6 nodes/100 μm^2

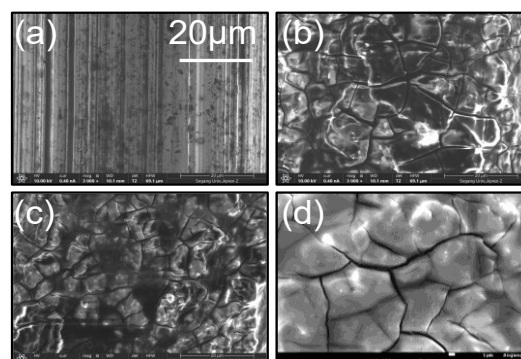


Fig. 3. SEM images of nickel wire cathode surfaces with and without surface modification. The non-coated electrode is shown in (a); while surface-modified electrodes prepared by electrodeposition at J_{ed} = (b) 700; (c) 1500; (d) 3000 A/m² are presented. All images were acquired at a magnification of x3000.

(defined as the density of junction nodes) reached its maximum value of 8.2 nodes/100 μm^2 , while the mean crack length significantly decreased to 10.8 μm . This indicates that the primary cracks observed at lower current densities were subdivided into a dense network of micro-cracks, thereby providing a high density of active nucleation sites.

Interestingly, at the highest deposition current density of J_{ed} = 3000 A/m², the crack density reached its peak of 19.8 % due to the formation of wider cracks. However, the branching degree decreased to 1.6 nodes/100 μm^2 , as the surface morphology transitioned into coarse structures consisting of large plate-like domains separated by wide cracks. This reduction in structural complexity suggests that crack coalescence and surface fragmentation at 3000 A/m² simplify the interconnected crack network, which may lead to prolonged bubble residence times and increased electrical losses.

Overall, the SEM observations indicate that the surface morphology does not evolve monotonically with increasing deposition current density. Instead, the electrode surface transitions from a finely cracked and relatively uniform structure at lower current density, through a highly branched and heterogeneous crack network at intermediate current density, to a coarse morphology composed of large domains separated by wide cracks at the highest current density.

3.2 Hydrogen bubble behavior on non-coated electrodes

Fig. 4 compares the experimentally measured hydrogen generation volume rate obtained in this study with previously rep-

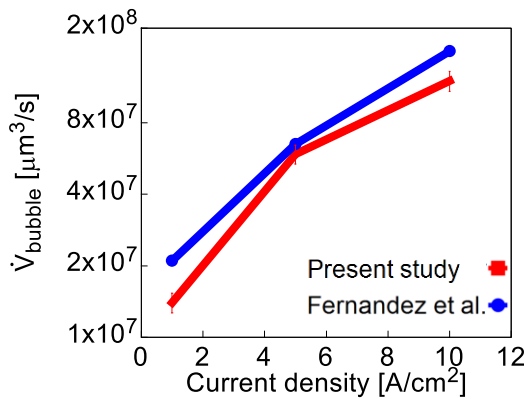


Fig. 4. Comparison of the present experimental data with previously reported results [13]. The error bar represents the standard deviation.

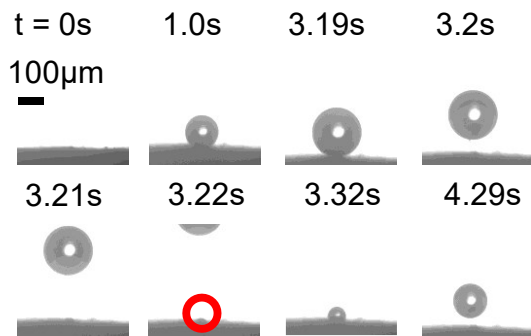


Fig. 5. Hydrogen bubble growth and detachment at $J_{bg} = 1 \text{ A}/\text{cm}^2$, in the isolated single-bubble mode (mode 1).

orted results by Fernandez et al. [13]. Close agreement is observed over the investigated current density range, indicating that the present experimental setup and measurement methodology reliably capture hydrogen bubble growth and detachment behavior on non-coated electrodes. Based on this validation, detailed observations of hydrogen bubble dynamics are discussed below.

Fig. 5 presents a time-resolved sequence of hydrogen bubble growth and detachment on a non-coated nickel wire cathode operating in the isolated single-bubble mode (mode 1) at a bubble generation current density of $J_{bg} = 1 \text{ A}/\text{cm}^2$. In this mode, a single bubble nucleates at the electrode surface, grows steadily, and detaches without interference from neighboring bubbles. Following detachment, a finite time interval is observed before the next bubble nucleates at the same site, indicating that bubble generation and detachment occur sequentially.

Fig. 6 presents representative side-view images of mode 1 observed at different current densities. Despite variations in current density, the bubbles remain confined within a narrow vertical column above the electrode surface. No lateral dispersion of bubbles is observed, and bubble motion is primarily governed by buoyancy in the vertical direction. This columnar confinement indicates that hydrogen bubble generation is localized at a limited number of active sites, resulting in spatially isolated bubble growth.

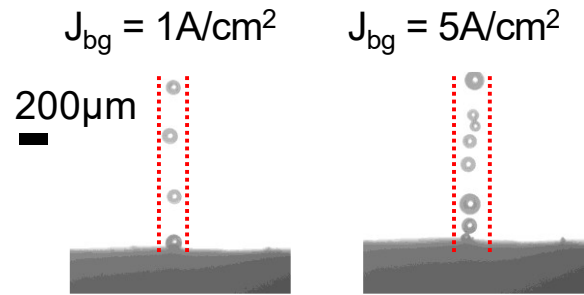


Fig. 6. Representative images of hydrogen bubble behavior in mode 1 at $J_{bg} = 1$ and $5 \text{ A}/\text{cm}^2$.

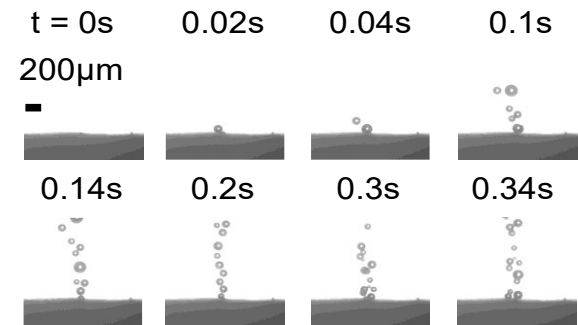


Fig. 7. Hydrogen bubble growth and detachment at $J_{bg} = 6 \text{ A}/\text{cm}^2$, in the dispersed multi-bubble mode (mode 2).

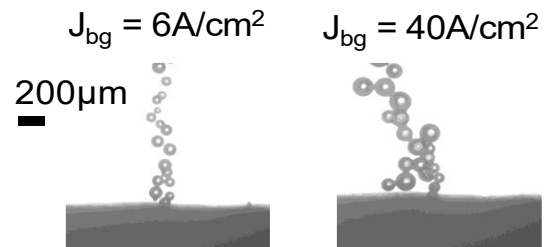


Fig. 8. Representative images of hydrogen bubble behavior in mode 2 at $J_{bg} = 6$ and $40 \text{ A}/\text{cm}^2$.

As the J_{bg} increases further, the bubble behavior transitions to a dispersed multi-bubble mode (mode 2), as illustrated in the time-resolved images shown in Fig. 7. In this mode, multiple bubbles nucleate in close proximity and grow simultaneously before detaching. Unlike mode 1, new bubbles are generated before previously formed bubbles detach, leading to temporal overlap between bubble growth and detachment events.

Fig. 8 shows mode 2 behavior at different current densities. In contrast to mode 1, where bubble generation is temporally and spatially isolated, mode 2 is characterized by the simultaneous presence of multiple bubbles at similar horizontal levels above the electrode surface. Multiple bubbles nucleate and grow in parallel prior to detachment, resulting in a dispersed multi-bubble configuration in which individual bubbles coexist at comparable heights.

The transition from mode 1 to mode 2 is analogous to the nucleate boiling, in which an increase in heat flux activates addi-

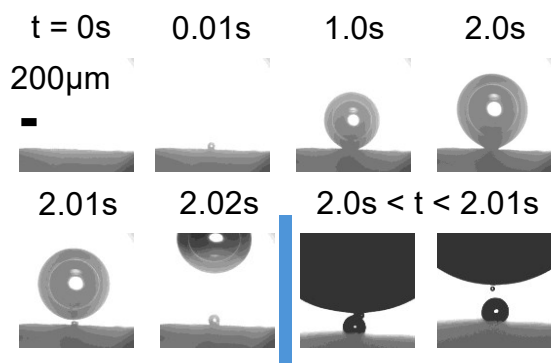


Fig. 9. Hydrogen bubble growth and detachment at $J_{bg} = 90 \text{ A/cm}^2$, in the coalesced large bubble mode (mode 3).

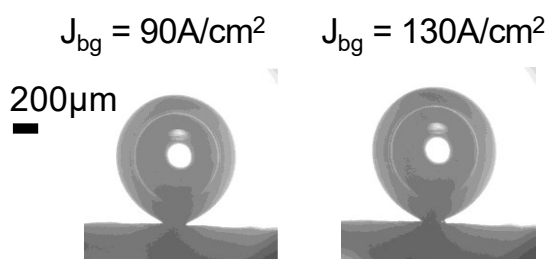


Fig. 10. Representative images of hydrogen bubble behavior in mode 3 at $J_{bg} = 90$ and 130 A/cm^2 .

tional nucleation sites. Similarly, in the present electrolysis system, increasing the current density promotes the activation of multiple bubble nucleation sites, resulting in concurrent bubble generation and overlapping growth dynamics.

At higher J_{bg} , the bubble behavior further transitions to the coalesced large-bubble mode (mode 3), as illustrated by the time-resolved images in Fig. 9. Although the transition between mode 2 and mode 3 occurs gradually with increasing current density, an operational criterion was adopted to distinguish the two regimes. Mode 2 is defined as the regime where multiple bubbles coexist and detach individually without forming a dominant merged bubble. In contrast, mode 3 is identified when repeated bubble coalescence occurs prior to detachment, resulting in the formation of a single large bubble within the bubble column. In this mode, bubbles generated within the column coalesce extensively before detachment, forming a single large bubble. Notably, the images following the blue vertical line show that new bubbles are already present beneath the growing bubble immediately prior to detachment. This behavior contrasts with Mode 1, in which a distinct waiting time exists between bubble detachment and subsequent nucleation.

Fig. 10 shows mode 3 behavior observed at different current densities. As the current density increases, the bubble column becomes denser, and repeated merging events lead to the formation of large bubbles that maintain an approximately spherical shape prior to detachment. While the overall structure resembles the vapor column observed in boiling phenomena, an important distinction exists. In contrast to boiling, where rapid

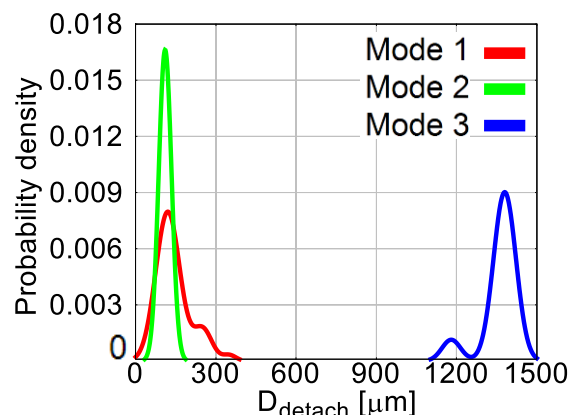


Fig. 11. Probability density functions (PDFs) of D_{detach} for mode 1, mode 2, and mode 3.

phase change often produces elongated or irregular vapor structures, the relatively slower rate of electrochemical gas generation allows bubbles in mode 3 to retain a near-spherical geometry during growth and coalescence.

Overall, the transition from mode 1 to mode 2 is associated with an increase in the number of active nucleation sites, resulting in simultaneous bubble generation analogous to nucleate boiling. The subsequent transition from mode 2 to mode 3 is governed by enhanced bubble merging within the column, leading to the formation of large, coalesced bubbles. Despite similarities to boiling-induced vapor columns, the electrochemical nature of hydrogen evolution gives rise to distinct bubble shapes and dynamics.

To further validate the transition between bubble evolution regimes, the probability density functions (PDFs) of the detachment diameter D_{detach} were analyzed (Fig. 11). As the system transitions from mode 1 to mode 2, the PDF peak shifts toward smaller diameters, with the mean value decreasing from $147.2 \mu\text{m}$ to $110.9 \mu\text{m}$. In addition, mode 2 exhibits a sharper and narrower distribution, indicating more uniform bubble detachment. This reduction in bubble size, despite the higher current density, can be attributed to the increased density of active nucleation sites, which distributes gas evolution more uniformly across the electrode surface.

In contrast, mode 3 shows a pronounced shift toward much larger detachment diameters, with the mean value increasing to $1361.3 \mu\text{m}$. The distribution is centered around a large-bubble peak with occasional smaller contributions, reflecting a transition to a coalescence-dominated regime. In this regime, the high gas-generation rate promotes frequent bubble merging, leading to the formation of large stochastic bubbles that increase surface coverage and may contribute to higher voltage losses.

3.3 Hydrogen bubble behavior on surface-modified electrodes

Fig. 12 compares hydrogen bubble behavior on nickel wire cathodes coated at different deposition current densities under

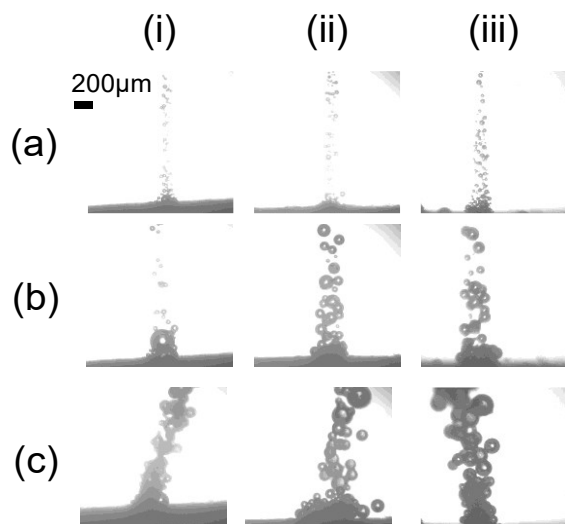


Fig. 12. Comparison of hydrogen bubble behavior on nickel wire cathodes with different surface conditions under increasing applied current density J_{bg} . Rows (a) – (c) correspond to $J_{bg} = 1, 6$, and 90 A/cm^2 . Columns (i) – (iii) represent electrodes prepared by electrodeposition at $J_{ed} = 700, 1500$ and 3000 A/m^2 .

increasing J_{bg} . For reference, bubble behavior on non-coated electrodes was previously classified into three distinct modes (mode 1–3) as a function of J_{bg} , as described in Sec. 3.2. In contrast, the surface-modified electrodes predominantly exhibit bubble behavior resembling the dispersed multi-bubble mode (mode 2) over the entire investigated current density range.

At $J_{bg} = 1 \text{ A/cm}^2$, bubbles formed on the coated electrodes already appear in a dispersed configuration, with multiple bubbles nucleating and growing simultaneously near the electrode surface. This behavior differs markedly from that observed on the non-coated electrode, where isolated single-bubble growth (mode 1) dominates at comparable current densities.

As J_{bg} increases to 6 and 90 A/cm^2 , the coated electrodes continue to display multi-bubble behavior, characterized by an increasing bubble population and frequent bubble-bubble interactions. However, no clear transition to either a fully isolated single-bubble mode or a strongly coalesced large-bubble mode, both as observed on the non-coated surface, is evident.

The absence of mode 1-like behavior on the surface-modified electrodes indicates that electrodeposition significantly alters the bubble nucleation characteristics. The increased surface roughness and crack networks generated during electrodeposition provide a higher density of active nucleation sites, thereby promoting simultaneous bubble nucleation even at relatively low current densities. Consequently, bubble behavior on the coated electrodes remains to mode 2 across a wide range of J_{bg} , rather than exhibiting distinct mode transitions as observed for the non-coated electrode.

Before discussing the electrochemical performance, the tested operating conditions and the corresponding bubble evolution modes are summarized in Table 2 for clarity.

Fig. 13 presents the variation of D_{detach} and t_{detach} as a function

Table 2. Summary of experimental conditions and the corresponding bubble evolution modes for each electrode.

$J_{bg} [\text{A/cm}^2]$	0 – 5	6 – 70	70 – 90
Non-coated	Mode 1	Mode 2	Mode 3
$J_{ed} = 700 \text{ A/m}^2$	Mode 2		
$J_{ed} = 1500 \text{ A/m}^2$			
$J_{ed} = 3000 \text{ A/m}^2$			

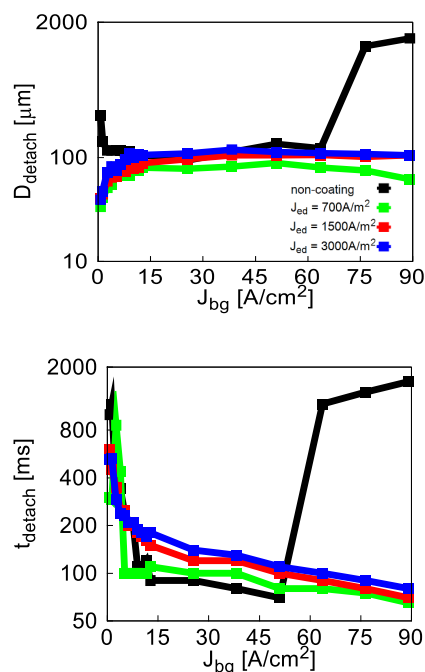


Fig. 13. D_{detach} and t_{detach} as functions of J_{bg} at various J_{ed} .

of J_{bg} for the non-coated and surface-modified electrodes. The detachment diameter increases gradually with increasing J_{bg} for all electrode conditions due to the enhanced hydrogen generation rate.

However, a clear difference is observed depending on the electrode surface condition. For the non-coated electrode, D_{detach} increases sharply at high current densities, accompanied by a significant increase in t_{detach} . This behavior reflects a transition from the dispersed multi-bubble mode to the coalesced large-bubble mode, in which repeated bubble merging leads to the formation of large bubbles with prolonged residence times.

In contrast, the surface-modified electrodes maintain relatively small and stable detachment diameters over a wide range of J_{bg} , while the detachment time gradually decreases with increasing current density. This behavior can be attributed to the increased density of active nucleation sites produced by electrodeposition, which promotes frequent bubble generation and suppresses excessive bubble coalescence.

These results quantitatively demonstrate that electrode surface modification significantly alters bubble detachment dynamics and plays a critical role in regulating gas evolution behavior during alkaline water electrolysis.

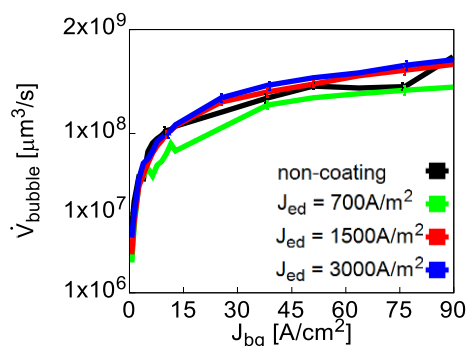


Fig. 14. Variation of $\dot{V}_{\text{bubble}}$ as functions of J_{bg} .

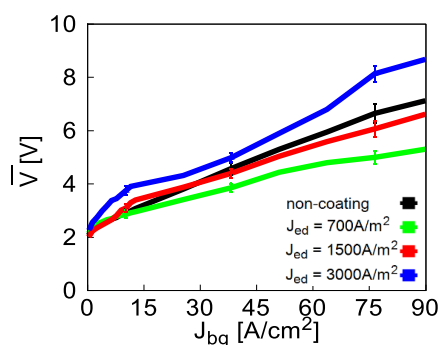


Fig. 15. Variation of $\bar{V}$ as functions of J_{bg} .

Fig. 14 illustrates the variation in the hydrogen bubble generation volume rate $\dot{V}_{\text{bubble}}$ as a function of J_{bg} for both non-coated and surface-modified electrodes. The volumetric rate was determined by integrating the individual volumes of detached bubbles, calculated from their measured D_{detach} , over the recorded time sequence. This parameter provides a quantitative measure of the hydrogen gas evolution rate and enables correlation between the electrode surface morphology and the gas transport characteristics of the system. In all cases, $\dot{V}_{\text{bubble}}$ increases monotonically with increasing current density, reflecting enhanced hydrogen evolution at higher electrolysis rates.

Compared with the non-coated electrode, the electrode coated at $J_{\text{ed}} = 700 \text{ A/m}^2$ exhibits a lower bubble generation volume rate over a wide range of J_{bg} . Although a larger number of bubbles detach from the electrode surface under this coating condition, the individual bubbles are relatively small. Consequently, the cumulative gas volume released per unit time is reduced, resulting in a lower measured $\dot{V}_{\text{bubble}}$ despite the high frequency of bubble detachment events.

In contrast, electrodes coated at higher deposition current densities ($J_{\text{ed}} = 1500$ and 3000 A/m^2) produce larger bubbles upon detachment, leading to bubble generation volume rates that are comparable to or exceed those of the non-coated electrode. These results indicate that the coating conditions influence not only the frequency of bubble detachment but also the characteristic bubble size, and that these two factors together govern the overall gas release rate.

Fig. 15 presents the variation in the average cell voltage as a

function of J_{bg} for non-coated and surface-modified electrodes. The total cell voltage consists of activation, ohmic, and concentration overpotentials, all of which are strongly influenced by the gas evolution behavior at the electrode interface. At higher current densities, increased bubble coverage produces a surface masking effect, which restricts the available active sites and increases the local current density, thereby increasing the activation overpotential. Simultaneously, the accumulation of gas near the interface can hinder ionic conduction and mass transport, leading to increases in both ohmic resistance and concentration overpotential. Although the qualitative influence of bubble evolution on these voltage components is discussed here, a rigorous quantitative decomposition requires advanced electrochemical techniques such as in-situ impedance spectroscopy and remains a subject for future investigation.

For all electrodes, the cell voltage increases monotonically with increasing current density, reflecting enhanced electrochemical and transport losses under more demanding operating conditions. Compared with the non-coated electrode, the electrodes coated at $J_{\text{ed}} = 700$ and 1500 A/m^2 exhibit lower average cell voltages over a wide range of current densities. Under these coating conditions, hydrogen bubbles are generated in a dispersed manner as relatively small bubbles that detach frequently from the electrode surface. Such bubble behavior limits prolonged surface coverage and promotes rapid re-exposure of the electrode to the electrolyte, thereby reducing gas-induced electrical losses and leading to a lower average cell voltage.

In contrast, the electrode coated at $J_{\text{ed}} = 3000 \text{ A/m}^2$ shows higher cell voltages than the non-coated electrode, particularly at elevated current densities. Although hydrogen bubbles are actively generated, they tend to grow larger and remain in contact with the electrode surface for longer durations. This increased bubble residence time leads to greater surface coverage and additional resistance to charge transfer, resulting in a higher average cell voltage despite the high rate of gas evolution.

Overall, these results indicate that the cell voltage is governed not by the nominal classification of bubble behavior, but by the size, residence time, and surface coverage characteristics of hydrogen bubbles, all of which are strongly influenced by the electrode surface condition.

3.4 Effect of electrode surface modification on efficiency

Fig. 16 shows the variation in the energy conversion efficiency η_E as a function of J_{bg} for non-coated and surface-modified nickel wire cathodes. For all electrode conditions, η_E decreases with increasing current density, reflecting the combined effects of increased cell voltage and enhanced electrochemical losses at high operating currents.

At low current densities, the non-coated electrode exhibits the highest energy conversion efficiency among the investigated cases. Under these conditions, hydrogen bubbles are generated discretely and detach individually from the electrode surface, resulting in relatively low electrical losses and a high

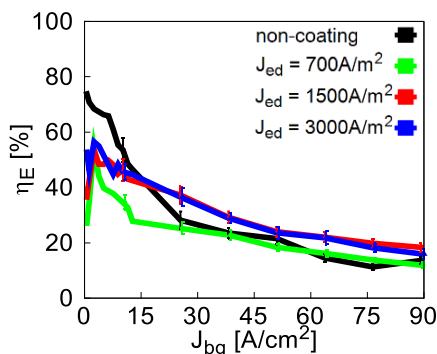


Fig. 16. Variation of η_E with J_{bg} for non-coated and surface-modified nickel wire cathodes.

fraction of the supplied electrical energy being converted into chemical energy.

As the current density increases, however, the efficiency of the non-coated electrode decreases rapidly. This decline is associated with the formation of larger bubbles and extended surface coverage, which increase electrical resistance and contribute to additional voltage losses. Consequently, the efficiency advantage of the non-coated electrode diminishes at moderate to high current densities.

In contrast, the surface-modified electrodes exhibit a more gradual decrease in η_E with increasing J_{bg} . In particular, electrodes coated at $J_{ed} = 1500$ and 3000 A/m² maintain higher energy conversion efficiencies than the non-coated electrode over a wide range of current densities. This behavior is attributed to the formation of dispersed hydrogen bubbles with reduced residence times on the electrode surface, which mitigates prolonged gas coverage and suppresses excessive voltage increases under high-current operation.

Among the surface-modified electrodes, the electrode coated at $J_{ed} = 700$ A/m² shows the lowest efficiency over most of the investigated range. Although frequent bubble detachment is observed for this condition, the detached bubbles are relatively small, leading to a lower effective hydrogen gas release per unit time and, consequently, a reduced energy conversion efficiency.

At the highest deposition current density of $J_{ed} = 3000$ A/m², the efficiency does not improve further despite enhanced bubble generation. The formation of larger bubbles and the presence of thicker surface layers contribute to increased electrical losses, resulting in efficiency values comparable to or slightly lower than those obtained at $J_{ed} = 1500$ A/m².

The comparable energy conversion efficiencies observed at $J_{ed} = 1500$ and 3000 A/m² can be explained by the interplay between gas evolution kinetics and voltage losses. At 1500 A/m², the highly branched morphology facilitates rapid bubble detachment and minimizes the voltage penalty associated with surface masking. In contrast, at 3000 A/m², although the volumetric hydrogen generation rate is further enhanced by the aggressive surface modification, the increased bubble residence time leads to a higher cell voltage. As a result, the efficiency gain from enhanced hydrogen production is partially offset by the elevated

electrical energy consumption. These results suggest that $J_{ed} = 1500$ A/m² represents an optimal balance between bubble detachment dynamics and energy efficiency for the present electrode system.

Overall, these results demonstrate that electrode surface modification significantly influences energy conversion efficiency, particularly under moderate to high current density conditions. Rather than monotonically improving efficiency, surface modification introduces competing effects associated with bubble size, detachment behavior, and electrical resistance. These findings highlight the importance of optimizing surface modification conditions to achieve improved electrolysis performance over a practical operating range.

4. Conclusions

This study systematically investigated the effects of electrode surface modification on hydrogen bubble behavior and electrolysis performance using nickel wire cathodes. Electrodeposition carried out at different deposition current densities produced distinct surface morphologies, characterized by non-monotonic variations in crack structure and surface heterogeneity.

On the non-coated electrode, hydrogen bubble behavior varied markedly with the applied current density, whereas surface-modified electrodes predominantly exhibited dispersed bubble generation over a wide operating range. Surface modification increased the number density of active nucleation sites, resulting in more frequent bubble generation and altered bubble size and residence time characteristics.

For all electrodes, the hydrogen bubble generation volume rate increased with current density, while the cell voltage and energy conversion efficiency were strongly governed by bubble size, surface coverage, and bubble residence time. Moderate surface modification effectively reduced voltage losses and mitigated efficiency degradation at elevated current densities, whereas excessive surface modification led to increased electrical losses, offsetting the benefits of enhanced bubble generation.

Overall, these results demonstrate that electrode surface modification plays a critical role in controlling hydrogen bubble dynamics and electrolysis efficiency. Rather than maximizing the extent of surface modification, optimizing the resulting surface morphology, rather than maximizing surface modification, is essential for improving the performance of alkaline water electrolysis under practical operating conditions.

Acknowledgments

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (RS-2024-00350110).

Conflict of interest

The authors declare no conflict of interest.

References

- [1] J. O. Abe, A. P. I. Popoola, E. Ajenifuja and O. M. Popoola, Hydrogen energy, economy and storage: Review and recommendation, *International Journal of Hydrogen Energy*, 44 (2019) 15072-15086.
- [2] S. W. Sharshir, A. Joseph, M. M. Elsayad, A. A. Tareemi, A. W. Kandeal and M. R. Elkadeem, A review of recent advances in alkaline electrolyzer for green hydrogen production: Performance improvement and applications, *International Journal of Hydrogen Energy*, 49 (2023) 458-488.
- [3] K. Zeng and D. Zhang, Recent progress in alkaline water electrolysis for hydrogen production and applications, *Progress in Energy and Combustion Science*, 36 (2010) 307-326.
- [4] L. J. J. Janssen and J. G. Hoogland, The effect of electrolytically evolved gas bubbles on the thickness of the diffusion layer, *Electrochimica Acta*, 15 (1970) 1013-1023.
- [5] L. J. J. Janssen and E. Barendrecht, The effect of electrolytic gas evolution on mass transfer at electrodes, *Electrochimica Acta*, 24 (1979) 693-700.
- [6] D. Zhang and K. Zeng, Evaluating the behavior of electrolytic gas bubbles and their effect on the cell voltage in alkaline water electrolysis, *Industrial & Engineering Chemistry Research*, 51 (2012) 13825-13832.
- [7] P. Boissonneau and P. Byrne, An experimental investigation of bubble-induced free convection in a small electrochemical cell, *Journal of Applied Electrochemistry*, 30 (2000) 767-775.
- [8] A. Angulo, P. van der Linde, H. Gardeniers, M. Modestino and D. F. Rivas, Influence of bubbles on the energy conversion efficiency of electrochemical reactors, *Joule*, 4 (2020) 555-579.
- [9] A. Ursua, L. M. Gandía and P. Sanchis, Hydrogen production from water electrolysis: Current status and future trends, *Proceedings of the IEEE*, 100 (2012) 410-426.
- [10] S. Kwon, S. Bae and G. Son, Experimental study of ultrasound-assisted alkaline water electrolysis for hydrogen production, *Journal of Mechanical Science and Technology*, 39 (2025) 663-669.
- [11] S. K. Kim and S. Y. Jung, The effect of two-phase flows on PEM water electrolysis cell performance, *Journal of Mechanical Science and Technology*, 38 (2024) 3933-3939.
- [12] S. Park, A. Bashkatov, J. J. J. Eggebeen, S. Lee, D. Lohse, D. Krug and M. T. M. Koper, Combined effects of electrode morphology and electrolyte composition on single H₂ gas bubble detachment during hydrogen evolution reaction, *Nanoscale*, 17 (2025) 10020-10034.
- [13] D. Fernandez, M. Martine, A. Meagher, M. E. Mobius and J. M. D. Coey, Stabilizing effect of a magnetic field on a gas bubble produced at a microelectrode, *Electrochemistry Communications*, 18 (2012) 28-32.



Sungjae Bae received his B.S. degrees in mechanical engineering from Sogang University in 2024. He is currently a master student of Mechanical Engineering at Sogang University in Seoul, Korea. Bae's research interests include microfluidics and multiphase dynamics with phase change.



Gihun Son received his B.S. and M.S. degrees in Mechanical Engineering from Seoul National University in 1986 and 1988, respectively, and his Ph.D. degree in mechanical engineering from UCLA in 1996. Dr. Son is currently a Professor of mechanical engineering at Sogang University, Korea. His research interests include heat transfer, multiphase flows and power plants.