

Effects of coalescence inhibition on multi-bubble detachment dynamics during water splitting

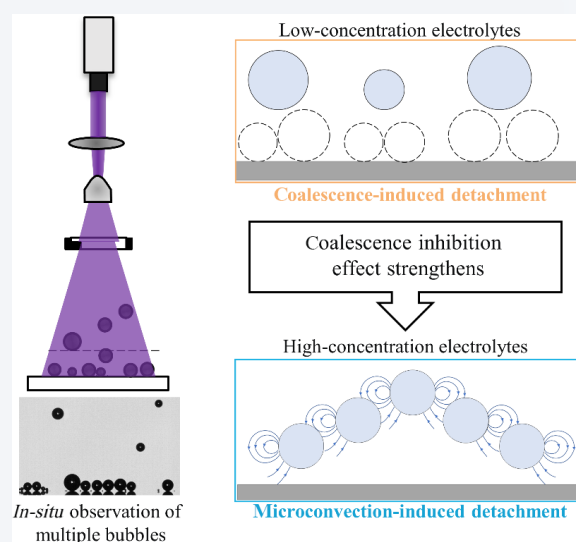
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ABSTRACT: Promoting bubble detachment is crucial for enhancing the efficiency of water splitting reactions. However, the existing detachment theories, derived from single- or dual-bubble scenarios, fail to fully explain the multi-bubble detachment characteristics under practical application conditions. In this work, multi-bubble detachment characteristics are investigated during photoelectrochemical water splitting on a TiO_2 nanorod array photoelectrode by varying the current density and the electrolyte concentration. We find that, in addition to the bubble coalescence, micro-convection from adjacent bubble detachment also significantly affects the bubble detachment radius. During the evolution of multiple bubbles, the coalescence inhibition related to the electrolyte concentration alters the detachment mode by changing mutual bubble interactions, leading to different relationship between the average detachment radius and current density. Specifically, in a low-concentration electrolyte, bubble detachment is governed by coalescence-induced detachment, whereas in a high-concentration electrolyte, enhanced coalescence inhibition promotes a transition to microconvection-induced detachment.



In-situ observation of multiple bubbles

KEYWORDS: bubble detachment, water splitting, bubble coalescence, coalescence inhibition

1 Introduction

Water splitting, including electrochemical and photoelectrochemical (PEC) water splitting, has attracted substantial research attention as a promising strategy to convert renewable solar/electrical energy into green hydrogen without carbon emissions [1–5]. However, as a typical gas-evolving reaction, its efficiency is significantly limited by bubble adhesion on electrode surfaces. These bubbles reduce the reaction area [6], obstruct ion

transport channels [7], and cause additional optical losses [8], leading to decreased reaction efficiency [9–12]. Therefore, a detailed understanding of bubble detachment mechanisms is essential for developing efficient strategies to eliminate bubbles from electrode surfaces, thereby facilitating the large-scale application of water splitting reactions.

In practical water splitting applications, high-concentration electrolytes and high current densities are employed to enhance efficiency [2, 13–15]. For instance, industrial alkaline water electrolysis typically operates with current densities of 100–500 mA/cm^2 and 5 M KOH/NaOH electrolytes [13]. Under these conditions, the high bubble nucleation density leads to the simultaneous evolution of multiple bubbles. Existing experimental observations primarily rely on tracking the upward motion of bubbles after detachment [16–19]. Experimental studies reveal two

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key characteristics of multi-bubble detachment under such conditions: first, a broad distribution of detachment radii, and second, an increase in the average detachment radius with rising current density. For instance, Ikeda et al. [19] reported that on a nickel rectangular wire electrode in 2 M KOH at 200 mA/cm², bubble detachment radii ranged from below 10 μm to over 100 μm, while the average detachment radius grew from 60 to 150 μm as current density increased from 50 to 1000 mA/cm².

Currently, two primary mechanisms have been proposed to describe bubble detachment: buoyancy-driven detachment (BDD) and coalescence-induced detachment (CID). However, neither mechanism can fully explain these two observed multi-bubble detachment characteristics. The BDD mechanism, derived from the force balance of an isolated bubble, predicts a constant single bubble detachment radius [20–22], $R_{\text{d, single}}$, which contradicts the first multi-bubble detachment characteristic. However, the solutal Marangoni force, recently recognized as a key factor influencing bubble detachment in the BDD mechanism [23], increases with current density, thereby providing a convincing explanation for the second multi-bubble detachment characteristic. The CID mechanism originates from the observation that two adjacent bubbles, each smaller than the $R_{\text{d, single}}$, coalesce and subsequently detach from the electrode surface [24, 25]. The detachment radius is predicted to scale with the nucleation site spacing S [26, 27]. Iwata et al. [28] proposed a theoretical framework that links CID mechanism to nucleation site distribution, suggesting that the bubble detachment radius follows a Rayleigh distribution, which serves as a typical broad distribution function to mathematically account for the highly disperse sizes of bubble populations. This statistical signature is highly consistent with the first observed multi-bubble detachment characteristic. However, their model also establishes a $-1/2$ power-law scaling between the average detachment radius and the nucleation site density. Since the nucleation site density scales with current density [29], this prediction contradicts the second experimental observation.

This pronounced discrepancy between classical theoretical models and experimental observations strongly suggests that certain critical physicochemical factors governing multi-bubble behavior under practical conditions remain overlooked. Crucially, while CID mechanism emphasizes the spatial distribution of bubbles, it largely oversimplifies the underlying interfacial physicochemical dynamics that control bubble coalescence, particularly in high-concentration environments. In industrial processes such as mineral processing, this concentration-dependent inhibition of bubble coalescence has been extensively investigated [30, 31]. Within specific electrolyte concentrations, the bubble coalescence time increases as the electrolyte concentration rises; once a certain threshold—termed the critical coalescence concentration—is reached, bubble coalescence is completely inhibited. Furthermore, the varying anti-coalescence efficacy among different electrolytes is governed by ion-specific effects [32, 33]. Liu et al. [34] demonstrated that the solutal Marangoni stress induced by nanoscale interfacial transport successfully explains this bubble coalescence inhibition. Recently, Park et al. [35] discovered that the microbubble coalescence efficiency during the electrocatalytic water-splitting reaction follows an anion-dependent Hofmeister series, with coalescence being consistently suppressed in the presence of alkali metal cations. The lack of integration of such electrolyte-dependent interfacial transport processes into the existing multi-bubble detachment framework indicates a critical gap in our current understanding of

how coalescence inhibition shapes multi-bubble detachment characteristics.

Direct observation of multi-bubble detachment behavior from the electrode surface is hindered by mutual occlusion among bubbles, which significantly impedes the understanding of multi-bubble detachment mechanisms. In this work, we overcame this limitation by controlling the reaction area that directly observed the entire process from the detachment of bubbles from the electrode to their ascent in the electrolyte. We report that bubble coalescence inhibition, governed by electrolyte concentration, greatly influences the detachment characteristics of multiple bubbles. With changes in the electrolyte concentration, we observed a significant alteration of the dependence of the average detachment radius on current density. To understand this phenomenon, we investigated the influence of mutual bubble interactions on the bubble detachment radius and the multi-bubble detachment mode under different electrolyte concentrations. Both coalescence and micro-convective induced attraction alter the bubble detachment radius. With increasing electrolyte concentration, the inhibition of bubble coalescence intensifies while the micro-convective induced attraction interaction strengthens, driving a transition in the multi-bubble detachment mode from coalescence-dominated to buoyancy-dominated. This change in the multi-bubble detachment mode leads to variations in the dependence of the average bubble detachment radius on current density. This study reveals the profound influence of coalescence inhibition on multi-bubble detachment characteristics, thereby clarifying how distinct bubble-bubble interactions dictate the collective detachment dynamics during water splitting.

2 Results and discussion

2.1 Multi-bubble detachment characteristics

To investigate the multi-bubble detachment characteristic during the oxygen evolution reaction (OER), the size of the reaction area was controlled by adjusting the spot profile of a monochromatic laser (NovaPro, wavelength is 375 nm). The original elliptical spot (major axis 3.2 mm, minor axis 1.5 mm) was transformed into a rectangular spot (140 μm wide, 3.5 mm long, Fig. 1(a)) using a convex lens and a prism, resulting in uniform distribution along the length and a Gaussian profile along the width. To visualize the multibubble detachment process, a high-speed camera (Photron SAZ) was positioned on the side, with illumination provided by an LED light source filtered through a 450 nm filter. Figure 1(b) shows a typical image of multiple bubble evolution near and above the electrode. The space above the electrode may be divided into two regions: the evolution region (within ≤ 300 μm of the electrode), where bubbles nucleate, grow, coalesce, and detach; and the rising region, where detached bubbles rise in the electrolyte (see Video S1 in the Electronic Supplementary Material (ESM)). We developed an image processing algorithm that captures both the detachment radius and the detachment mode by tracking the complete evolution of bubbles from nucleation to detachment (see Note S1 in the ESM). To ensure the reliability of our experimental statistics, a comprehensive uncertainty analysis regarding the bubble detachment radius has been provided in Note S4 in the ESM. The detachment modes are classified into two types based on whether bubble detachment is triggered by coalescence: non-coalescence-induced detachment (NCID) mode (Fig. 1(c)) and CID mode (Fig. 1(d)).

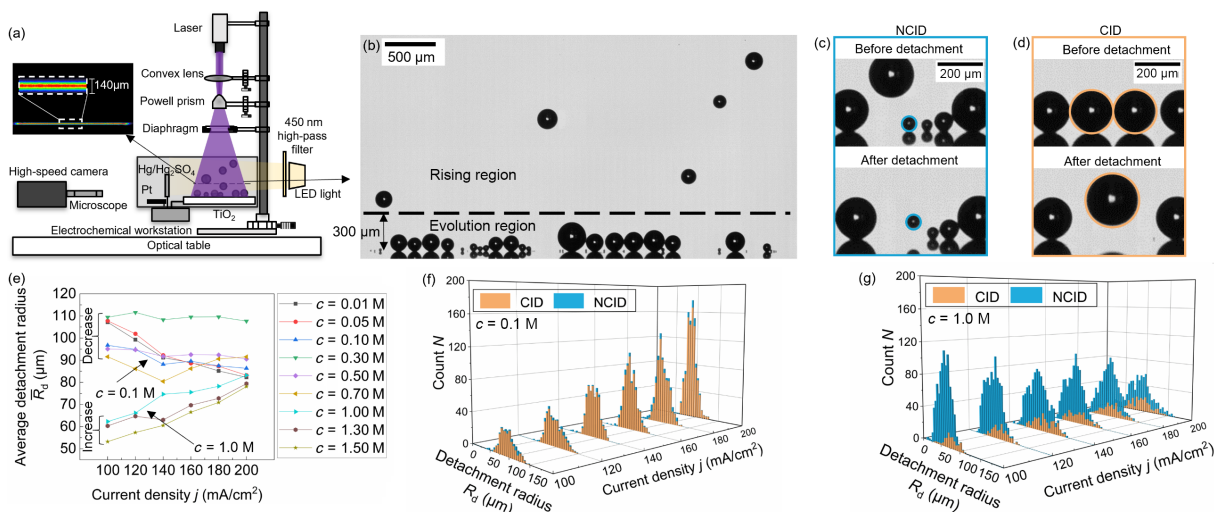


Figure 1 Multi-bubble detachment characteristics in PEC water splitting. (a) Schematic of the experimental setup. (b) A representative image of the evolution of multiple bubbles, scale bar is 500 μm . (c) and (d) Snapshots of bubble detachment before and after the detachment driven by NCID (c) and CID (d) mode, scale bar is 200 μm . (e) Average bubble detachment radius $\bar{R}_d$ as a function of current density j at electrolyte concentration c . (f) and (g) Bubble detachment radius distribution as a function of current density at electrolyte concentrations of $c = 0.1$ M (f) and 1.0 M (g), respectively. Yellow denotes CID mode, while blue represents NCID mode.

The TiO_2 nanorod array deployed as the working electrode plays two critical, active roles that inherently dictate the bubble dynamics and the subsequent transition of detachment modes. First, the nanoscale morphology of the TiO_2 nanorods fundamentally alters the surface wettability, yielding a superhydrophilic characteristic where the bubble contact angle drops to as low as 15° . As established by Iwata et al. [28], the phenomenon of CID can only be successfully activated when the contact angle is suppressed below a critical threshold of 30° . Second, the nanostructured array electrode provides a highly favorable spatial distribution of bubble nucleation sites. According to classic bubble nucleation kinetics, bubbles preferentially nucleate within surface depressions or micro-cavities. Here, the well-ordered nanorods ensure a highly uniform matrix of potential nucleation coordinates.

Figure 1(e) shows the dependence of the average bubble detachment radius on the current density at different electrolyte concentrations. The bubble detachment radii were statistically determined by capturing bubbles in the rising region over a 100-second reaction period (with the corresponding uncertainty analysis provided in Note S6 in the ESM). As the electrolyte concentration varies, the dependence of the average bubble detachment radius on current density exhibits two distinct and opposite trends: the average detachment radius decreases monotonically with increasing current density at lower concentrations (0.01–0.5 M), whereas it increases monotonically at higher concentrations (1.0–1.5 M). At an intermediate concentration of 0.7 M, the average detachment radius exhibits a non-monotonic trend—first increasing and then decreasing with current density—signaling a transition regimen governed by the competition between different detachment modes.

To elucidate the origin of this discrepancy, we selected bubbles detached at concentrations of $c = 0.1$ M and $c = 1.0$ M as representative cases and further characterized their detachment modes. As depicted in Fig. 1(f), at $c = 0.1$ M, bubble detachment is dominated by the CID mode. Increasing the current density results in a smaller average bubble detachment radius and a narrower size distribution, which is consistent with CID theory, which dictates that both the average and maximum bubble detachment radii

decrease as the nucleation site density increases. In contrast, at $c = 1.0$ M (Fig. 1(g)), the NCID mode becomes prevalent. Here, increasing the current density leads to larger average detachment radii and broader size distributions. This behavior completely opposes the predictions of classic CID theory and simultaneously deviates from traditional BDD theory, thereby confirming the dominance of a distinct, concentration-dependent detachment mechanism. These observations suggest the emergence of a previously unreported detachment mechanism under high electrolyte concentrations. Moreover, and most importantly, the underlying reason why this detachment mechanism is suppressed or remains non-dominant under lower concentration conditions (e.g., $c = 0.1$ M) requires further clarification.

2.2 The influence of mutual bubble interactions on the bubble detachment radius

To gain insight into how complex multi-bubble detachment characteristics arise, we investigated mutual bubble interactions and their effects on the bubble detachment radius. By adjusting the laser spot pattern on the electrode surface, we generated two distinct bubble configurations during the experiments: an isolated bubble, a dual-bubble system with tunable S.

First, we investigated the detachment characteristics of an isolated bubble. As shown in Fig. 2(a), the primary forces acting on it during growth are buoyancy F_b , the thermal Marangoni force F_{MT} , and the solutal Marangoni force F_{MC} . Regarding oxygen bubbles, the presence of solutal Marangoni force during water electrolysis was recently confirmed directly through experiments by Babich et al. [36]. Figure 2(b) shows the variation trends of different forces during bubble growth. Bubble detachment via the BDD mode occurs when the net force F_{net} , $F_{\text{net}} = F_b - F_{MT} - F_{MC}$, becomes zero (Fig. 2(b)). The bubble evolution exhibits periodic behavior, with the detachment radius fluctuating within a small 7 range around a specific value (see Video S2 in the ESM). Through force balance analysis, the expression for the bubble detachment radius $R_{\text{d, single}}$ can be obtained (see Note S2 in the ESM).

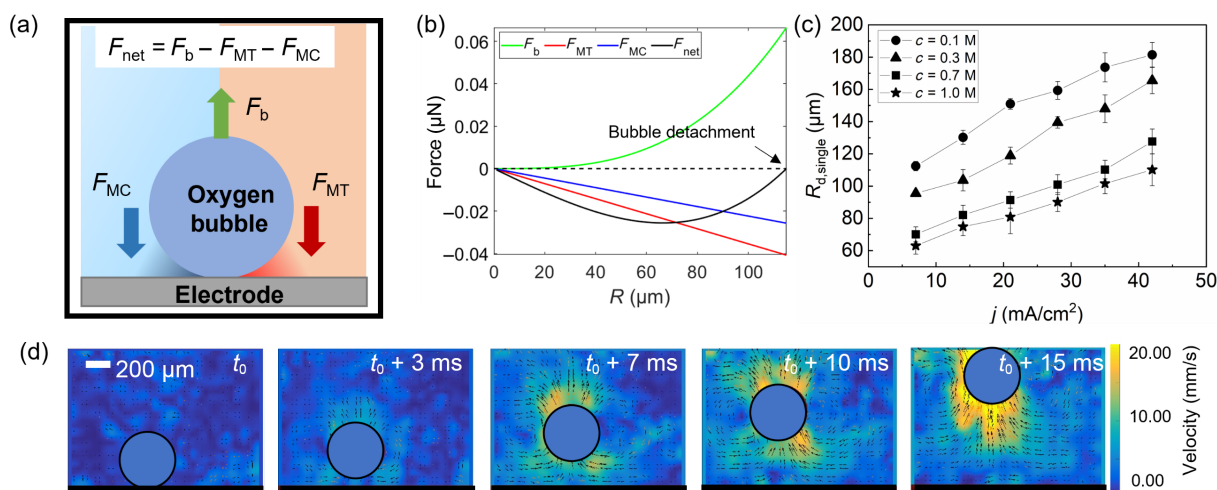


Figure 2 Detachment characteristics of an isolated bubble. (a) Force analysis of an isolated bubble during growth. (b) Force variations corresponding to different bubble radii. (c) Detachment radius R_d as a function of current density j under different electrolyte concentrations. (d) PIV measurements of an isolated bubble detachment via BDD mode.

$$R_{d,\text{single}} = \sqrt{\frac{3}{4} \frac{|\sigma_T| \Delta T + |\sigma_c| \Delta C}{(\rho_L - \rho_g)g}} \quad (1)$$

where σ_T is the rate of change of surface tension with temperature, ΔT is the temperature difference between the bottom and the top of the bubble, σ_c is the rate of change of surface tension with the localized electrolyte concentration. ΔC signifies the electrolyte concentration difference between the bubble base and its apex. The solutal Marangoni force is predominantly driven by localized electrolyte concentration changes (i.e., proton production and subsequent ionic redistribution to maintain electro-neutrality during the oxygen evolution reaction). As shown in Fig. 2(c), $R_{d,\text{single}}$ decreases with increasing electrolyte concentration and increases with higher current density. Particle image velocimetry (PIV) measurements results show that after detachment, the bubble forms vortex structures on both sides during its ascent, influencing the surrounding electrolyte flow (Fig. 2(d), see also Video S3 in the ESM).

Next, we investigated the interactions between adjacent bubbles. At a current density of 100 mA/cm² and an electrolyte concentration of 1.0 M, two bubbles with unequal single-bubble detachment radii and growth times were generated on the electrode surface by adjusting the laser spot size ($R_{d,\text{single}}^A = 138.4 \mu\text{m}$, $T_{d,\text{single}}^A = 17.7 \text{ s}$, $R_{d,\text{single}}^B = 153.1 \mu\text{m}$, and $T_{d,\text{single}}^B = 20.3 \text{ s}$) (Fig. 3(a)).

As the nucleation site spacing S increased, four distinct modes of bubble interaction were observed (Fig. 3(b) and Video S4 in the ESM), i.e., coalescence without detachment (Fig. 3(b)(i)), CID (Fig. 3(b)(ii)), synchronous detachment mode (Fig. 3(b)(iii)), and independent detachment modes (Fig. 3(b)(iv)), ultimately leading to different detachment characteristics. Meanwhile, the distinct detachment modes also exert a significant influence on the transient voltage profiles, as systematically detailed in Note S5 in the ESM.

Both the coalescence without detachment and CID modes occur when two bubbles undergo coalescence. In the coalescence without detachment mode (Fig. 3(b)(i)), the merged bubble formed by the coalescence of two bubbles first bounces and then reattaches to the electrode surface. Eventually, the bubble detaches through the BDD mode, and the coalescence interaction does not change its detachment radius. In contrast, in the CID mode (Fig. 3(b)(ii)), the merged bubble continues moving upward without returning to the

electrode. The transition between these two modes depends on whether the kinetic energy converted from the energy released during coalescence is sufficient to propel the merged bubble away from the electrode surface. A detailed energy analysis has been thoroughly discussed in Refs. [25–27].

Both the synchronous detachment mode and independent detachment mode occur in the absence of direct contact between two bubbles. Since $T_{d,\text{single}}^A < T_{d,\text{single}}^B$, bubble B has not yet reached single bubble detachment radius $R_{d,\text{single}}^B$ when bubble A detaches and remains in the growth stage. Finally, both bubble A and bubble B were detached through the BDD mode, as shown in the independent detachment mode (Fig. 3(b)(iv)). In contrast, in the synchronous detachment mode (Fig. 3(b)(iii)), bubble B detaches 40 ms after the detachment of bubble A, with an actual detachment radius $R_{d,\text{single}}^B$ of 145.9 μm , which is smaller than the $R_{d,\text{single}}^B$.

To further investigate the influence of the aforementioned four bubble–bubble interaction modes on the bubble detachment radius, Fig. 3(c) presents the variation of the bubble detachment radius with the S . Firstly, Mode I and Mode IV do not alter the $R_{d,\text{single}}$. In Mode I, the merged bubble continues to grow until it reaches the $R_{d,\text{single}}$ before detaching. Due to the close proximity of the two laser spots and their combined thermal effect on the merged bubble, the $R_{d,\text{single}}$ decreases as S increases [27]. Secondly, both Mode II and Mode III modify the $R_{d,\text{single}}$, and their ranges of influence are constrained by the S . When the spacing is in the range $160 \mu\text{m} < S < 270 \mu\text{m}$, bubble detachment is governed by coalescence, and the detachment radius increases with S . Within the range $270 \mu\text{m} < S < 360 \mu\text{m}$, the detachment radius of Bubble B is smaller than the $R_{d,\text{single}}^B$, but the difference remains independent of S .

To investigate the physical mechanism underlying the premature detachment of bubble B in the synchronous detachment mode, we leveraged PIV flow fields (Video S5 in the ESM) to quantitatively calculate the transient vertical pressure drop force (F_{py}) exerted on bubble B, which is induced by the localized microconvection generated during detachment process of bubble A. For a rigorous extraction of this hydrodynamic force—while avoiding the severe optical noise and reflections typically present directly at the gas–liquid interface—we invoked the control volume momentum integral approach [37, 38]. As illustrated in Fig. 4(a), a circular control volume (CV) of radius R_{CV} was defined in the two-

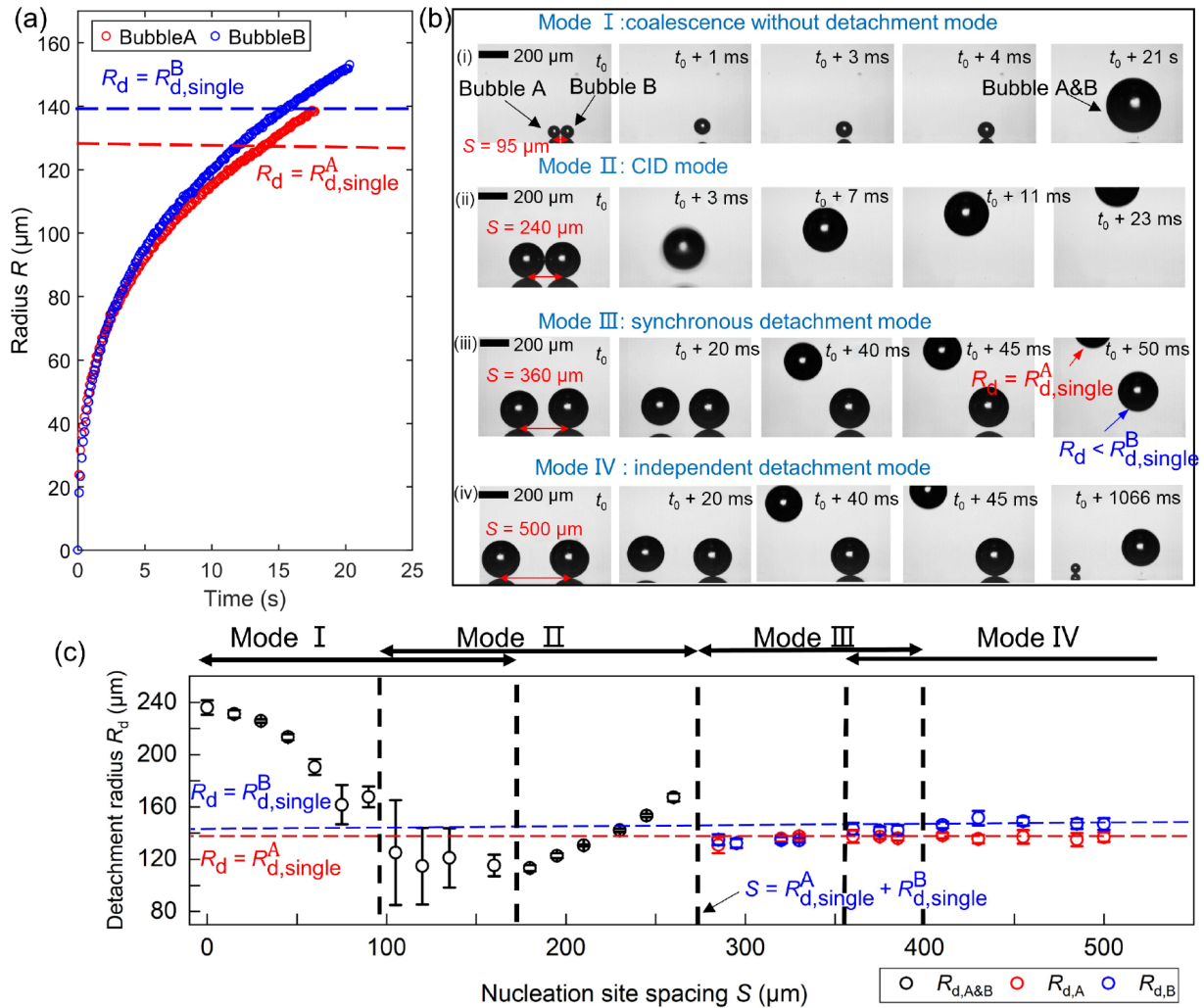


Figure 3 Bubble-bubble interactions and their effects on bubble detachment radius under the condition of a current density of 100 mA/cm^2 and an electrolyte concentration of 1.0 M . (a) The curve of dual-bubble radius variation during a growth cycle. (b) Modes of bubble-bubble interactions. (i) Coalescence without detachment mode: the merged bubble detaches via the BDD mechanism. (ii) CID mode. (iii) Synchronous detachment mode: Bubble A detaches via the BDD mechanism, while bubble B synchronously detaches from bubble A before reaching the single bubble detachment radii $R_{d,\text{single}}^B$. (iv) Independent detachment mode: Both bubbles detach independently via the BDD mechanism. (c) Detachment radius as a function of nucleation site spacing.

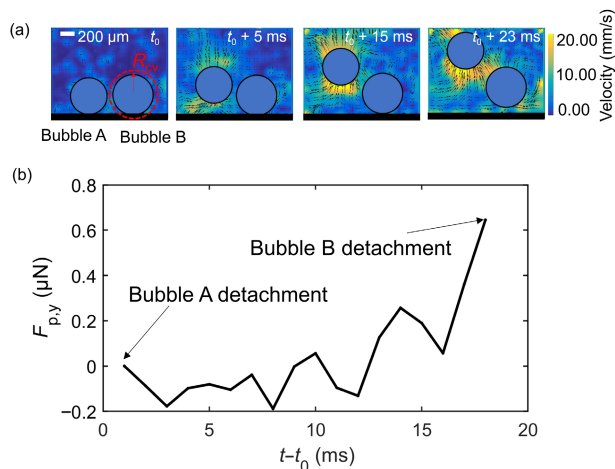


Figure 4 (a) PIV measurements of bubble detachment under synchronous detachment mode. (b) Transient vertical pressure drop force ($F_{p,y}$) exerted on bubble B, obtained at each respective moment during bubble A's detachment process.

dimensional (2D)-PIV plane to completely encapsulate the growing bubble.

Integrating over the fluid domain within this CV and projecting the linear momentum conservation onto the y -axis (vertical direction) yields

$$F_y = \oint_{\Omega} \rho \nu (\mathbf{u} \cdot \mathbf{n}) ds \quad (2)$$

where F_y is the total vertical hydrodynamic force component acting on the control volume; Ω denotes the boundary of the defined circular control volume; ρ represents the fluid density; ν is the vertical velocity component (along the y -axis); $\mathbf{u}$ is the fluid velocity vector; and $\mathbf{n}$ is the outward unit normal vector to the control surface Ω and ds is the differential line element along the 2D control surface. As the bubble A rises, the vertical forces on the right bubble are mainly governed by thermal Marangoni, solutal Marangoni, and vertical pressure drop forces. Given the minimal change in bubble radius during the ascent, the fluctuations in both Marangoni forces are negligible. Therefore, the lateral pressure force on the bubble can be derived using the following expression

$$F_{py}(t) = F_y(t) - F_y(t_0) \quad (3)$$

Figure 4(b) illustrates the temporal evolution of the measured F_{py} . As bubble A begins its ascent, the F_{py} exerted on bubble B undergoes a fluctuating transition, dropping initially before undergoing a sharp escalation. At $t - t_0 = 18$ ms, F_{py} reaches its peak value of $0.65 \mu\text{N}$. This value is numerically equivalent to the buoyancy force of a bubble with a radius of $250.5 \mu\text{m}$, thereby instantly triggering the detachment process. Consequently, bubble B detaches as long as the criterion $F_{py} + F_{B,net} \geq 0$ is satisfied, regardless of whether its radius has reached the $R_{d,single}^B$. Given that this process is driven by the localized microconvection from the neighboring bubble, we term this mechanism microconvection-induced detachment (MID), which serves as a new form of NCID distinct from BDD. Concurrently, this specific bubble–bubble interaction is defined as microconvection-induced attraction.

Two types of bubble interactions influence the detachment radius: coalescence and microconvection-induced attraction. For the CID (Fig. 5(a)), the detachment radius $R_{d,CID}$ depends only on the nucleation site spacing S and the radii of the smaller (R_s) and larger (R_L) bubbles before coalescence, assuming surface tension is neglected (see Note S3 in the ESM for detailed derivation)

$$R_{d,CID} = \frac{S}{2} \cdot \left(\frac{R_L}{R_s} \right)^{1/2} \cdot \left(1 + \left(\frac{R_L}{R_s} \right)^3 \right)^{1/3} \quad (4)$$

For the MID, the detachment radius $R_{d,MID}$, which is systematically smaller than the $R_{d,single}$, is strictly coupled to the instantaneous magnitude of F_{py} (Fig. 5(c)). Because the nucleation site spacing, the phase lag between adjacent nucleation events, the required F_{py} for lifting the bubbles varies drastically across different sites. This hydrodynamic fluctuation inherently broadens the radius of prematurely detached bubbles, thereby providing a robust, physics-based mechanistic explanation for the broad size distribution characteristics of NCID bubbles observed in Fig. 1(g).

To establish a unified boundary differentiating CID and NCID, a further detailed analysis was performed on the non-coalescence induced detachment. Two distinct non-coalescence detachment modes exist, namely, BDD and CID. For the BDD mode, the detachment radius is strictly governed by the F_{net} (Fig. 5(b)). In contrast, for the MID mode, the detachment radius is dictated by the coupled summation of F_{net} and F_{py} (Fig. 5(c)). Consequently, BDD can be rationalized as a special, limiting case of MID where F_{py} remains constantly at zero.

In multi-bubble scenarios, each individual bubble possesses a

unique theoretical detachment radius ($R_{d,theory}$), which is determined by the equilibrium criterion $F_{net} + F_{py} = 0$. Remarkably, distinct from the constant $R_{d,single}$ observed in an isolated bubble case, the magnitude of $R_{d,theory}$ varies dynamically in response to the ambient flow field. Accordingly, for two adjacent bubbles (designated as bubble A and bubble B), the critical separation distance (S_{cr}) demarcating the transition between CID and non-NCID modes is mathematically formulated as

$$S_{cr} = R_{d,theory}^A + R_{d,theory}^B \quad (5)$$

when $S > S_{cr}$, the bubbles undergo non-coalescence detachment; conversely, when $S \leq S_{cr}$, coalescence detachment takes place.

In dual-bubble scenarios, this critical boundary simplifies to the summation of the $R_{d,single}$ of both adjacent bubbles: $S_{cr} = R_{d,single}^A + R_{d,single}^B$.

In the second set of dual-bubble experiments, we investigated the effect of coalescence inhibition on the CID mode. The current density was set to 100 mA/cm^2 , the nucleation site spacing was fixed at $200 \mu\text{m}$, and the electrolyte concentrations were configured to 0.05, 0.1, 0.3, 0.5, 0.7, and 1.0 M, respectively. Figure 6(a)(i) displays a complete dual-bubble evolution cycle under the condition of electrolyte concentration is 1.0 M (see Video S6 in the ESM). The bubble growth process can be clearly divided into two distinct stages: the inflation stage and the contact stage. The inflation stage spans from bubble nucleation ($t = 0$ s) to the moment when the two bubbles come into contact ($t = 10.456$ s). The contact stage covers the period from initial contact until bubble detachment ($t = 13.864$ s). The bubble radius evolution curve indicates that bubbles follow the same growth law during both the inflation and contact stages (Fig. 6(a)(ii)). Figure 6(b) shows how the bubble contact time varies with electrolyte concentration, with all results averaged over more than six CID events. The contact time increases rapidly as the concentration rises from 0.05 to 0.5 M, and then plateaus between 0.5 and 1.0 M (Fig. 6(b)). During the approach and collision of two bubbles, the intervening electrolyte solution drains out, forming a nanometer-scale thin liquid film. Crucially, due to the preferential surface-bulk partition of the solute, the thinning of the film generates a pronounced radial electrolyte concentration gradient within the interaction region. This concentration inhomogeneity gives rise to a solutal Marangoni stress that acts in direct opposition to film drainage [34]. As the bulk electrolyte concentration increases, the generated Marangoni stress is significantly enhanced, which abruptly decelerates the film thinning rate. Macroscopically, this manifests as a substantial extension of the bubble contact/coalescence time within the lower concentration regime

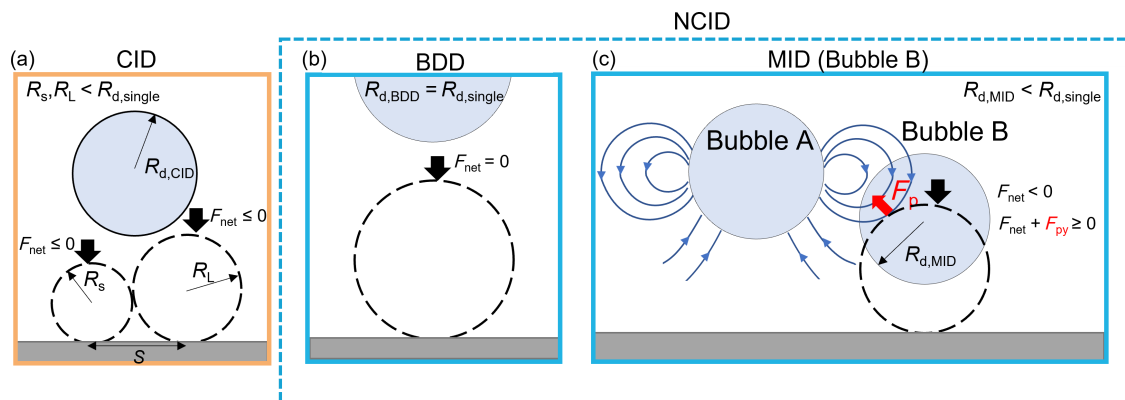


Figure 5 Schematic of the bubble detachment mechanism. (a) CID mechanism. (b) BDD mechanism. (c) MID mechanism.

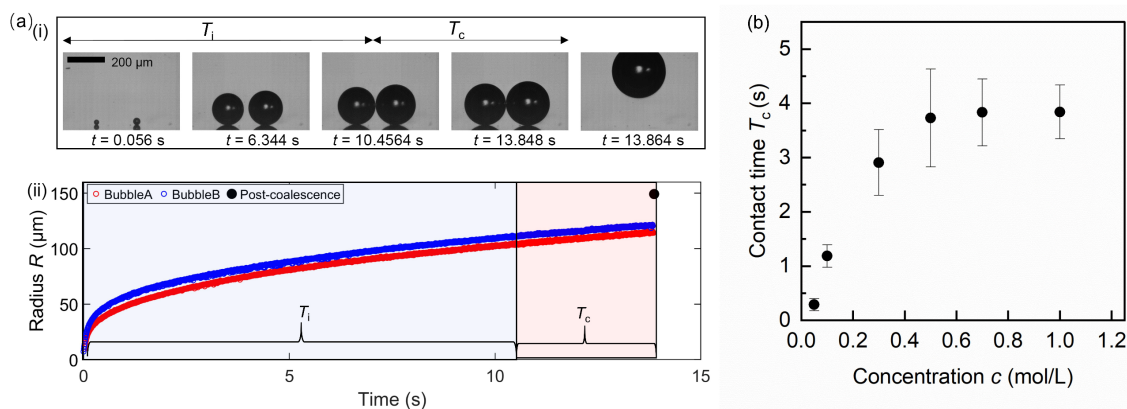


Figure 6 Effect of coalescence inhibition on CID. (a) Snapshots of the bubble evolution sequence (i) and corresponding bubble radius variation (ii) over time at an electrolyte concentration of 1.0 M. (b) Contact time T_c as a function of electrolyte concentration c .

(e.g., from 0.01 to 0.5 M). However, once the concentration surpasses the critical coalescence concentration, the ionic adsorption at the gas–liquid interface and the resulting Marangoni stress reach a state of physical saturation. Beyond this threshold (0.5 M), the maximum achievable surface tension gradient within the draining film encounters a thermodynamic upper limit, failing to provide additional hydrodynamic resistance. Consequently, further increases in electrolyte concentration cause the bubble contact time to plateau.

2.3 The influence of electrolyte concentration on the multi-bubble detachment

Based on the experimental results described above, we conclude that both bubble coalescence and the micro-convective induced attraction can alter the detachment radius of an isolated bubble. However, as electrolyte concentration increases and coalescence inhibition is enhanced, the extent to which these interactions influence multi-bubble detachment characteristics requires further investigation.

The bubble coverage, denoted as Θ , is defined as the ratio of the area occupied by adhered bubbles to the total reaction area [39, 40]. It is calculated as

$$\Theta = \frac{\sum_{i=1}^{N_E} \pi(r_i \sin \alpha)^2}{A_{\text{laser spot}}} \quad (6)$$

where N_E represents the number of bubbles adhered to the electrode surface, r_i is the radius of the i^{th} bubble, α is the contact angle between the bubble and the electrode (taken as 15° in this study), and $A_{\text{laser spot}}$ denotes the area of the laser spot. The value of bubble coverage reflects the evolution of multiple bubbles and exhibits synchronous variation with the voltage changes. Specifically, an increase in bubble coverage is caused by bubble nucleation and growth, whereas a decrease is caused by bubble detachment.

Figure 7(a) shows the temporal evolution of bubble coverage under a current density of 140 mA/cm² and electrolyte concentrations of 0.1, 0.3, and 1.0 M (see Videos S7 and S8 in the ESM). The average value of the coverage increases significantly with higher electrolyte concentration. This can be explained through the images presented in Figs. 7(b) and 7(c), which depict bubble dynamics over one evolution cycle under each concentration. In these figures, bubble detachment modes are color-coded: Yellow indicates CID, and blue represents NCID.

As shown in Fig. 7(b), when $c = 0.1$ M, a multi-bubble evolution cycle can be divided into two stages: the aggregation stage (Figs. 7(b)(i) and 7(b)(ii)) and the detachment stage (Figs. 7(b)(ii)–7(b)(v)). At the initial moment (Fig. 7(b)(i)), the value of bubble coverage is relatively low, and bubbles are dispersed and growing on the electrode surface. As the reaction proceeds, existing bubbles continue to expand while new bubbles nucleate and grow in bubble-free regions, resulting in a gradual increase in overall bubble coverage (see Note S8 in the ESM for the deconstruction of bubble coverage growth). The maximum value of bubble coverage is reached when the first pair of adjacent bubbles detach by CID mode (Fig. 7(b)(ii)). As the number of CID events in a bubble gradually increases, bubble coverage continues to decrease until the bubbles are no longer in contact with each other (Figure 7(b)(v)). Due to the short duration of bubble coalescence, the formation of multiple interconnected bubbles remains uncommon even at maximum bubble coverage. As a result, the influence of micro-convective induced attraction on multi-bubble detachment is limited.

At $c = 0.3$ M, the bubble contact time increased significantly. During the contact process, the continued growth of existing bubbles and the nucleation of new bubbles resulted in a higher bubble coverage compared to the case at $c = 0.1$ M. When bubble coverage reached its maximum, multiple bubbles came into contact with each other (Fig. 7(c)(ii)), which provides the conditions for the occurrence of MID. As shown in Figs. 7(c)(ii)–7(c)(v), following a CID event, adjacent bubbles detached successively via the MID mode within tens of microseconds, and the results further reveal that MID exhibits a transitive characteristic.

This phenomenon explains why NCID bubbles exhibit a widely distributed characteristic. At $c = 1.0$ M, coexistence of both CID and MID detachment modes was observed, similar to the behavior under the $c = 0.3$ M condition (Fig. 7(d)). In addition, under the condition of $c = 1.0$ M, we also observed the first bubble detaching via the BDD mode, followed by subsequent bubbles detaching sequentially via the MID mode due to micro-convective interactions (see Fig. S1 in the ESM). It should be noted that although the transition to MID is initiated at $c = 0.3$ M, its occurrence frequency is relatively low compared to the dominant pairwise CID mode. Consequently, the average detachment radius at $c = 0.3$ M still follows the downstream trend of CID theory, decreasing with increasing current density due to the reduction in average nucleation site spacing. At $c = 1.0$ M, the coexistence of both CID and MID detachment modes was also observed.

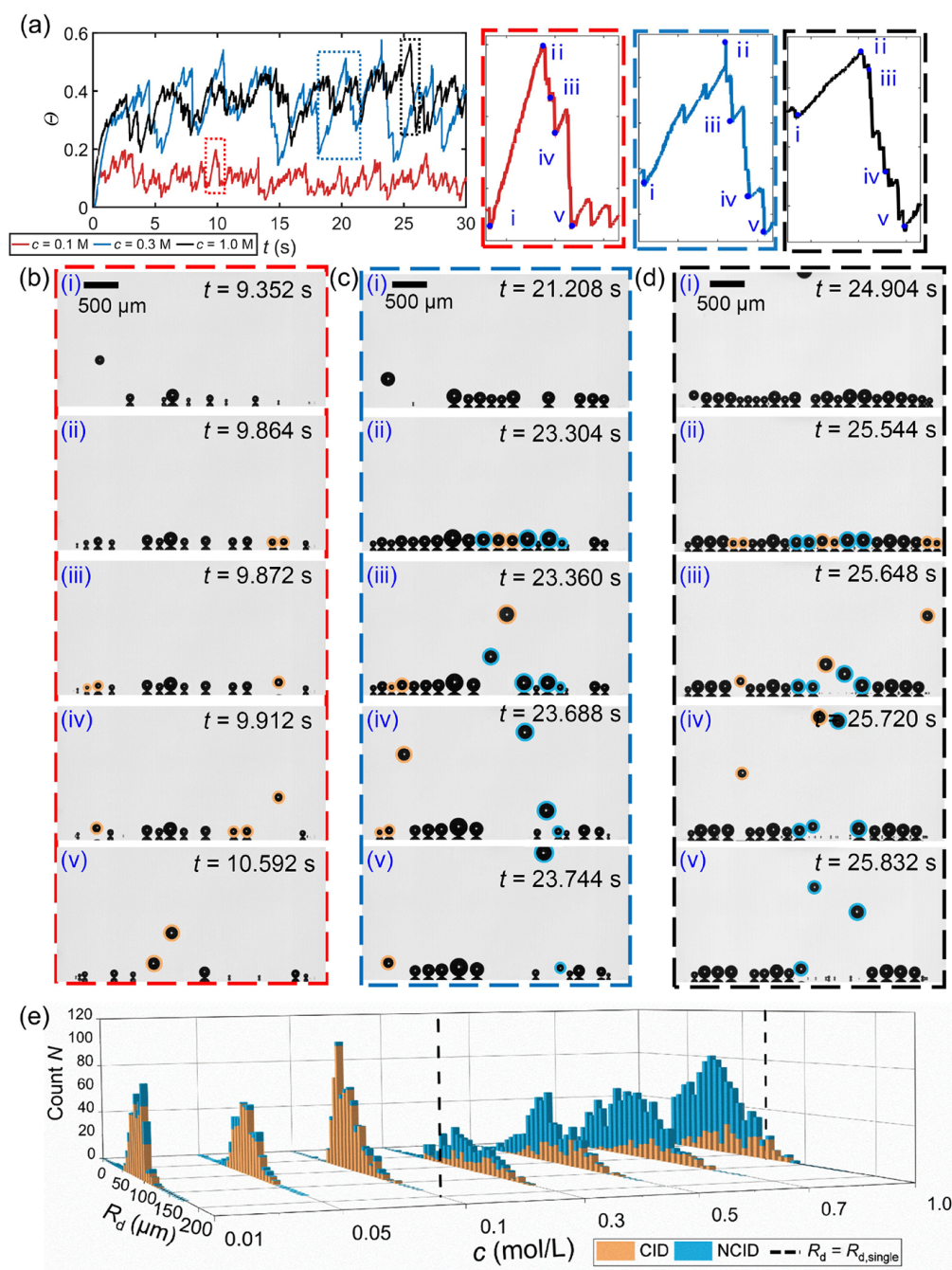


Figure 7 Coalescence inhibition alters multi-bubble detachment modes by regulating bubble-bubble interactions. (a) Bubble coverage [39, 40] versus time at a current density of $140 \text{ mA}/\text{cm}^2$ for electrolyte concentrations of 0.1 and 0.3 M. Inset shows a magnified view of the selected region. (b) Bubble evolution at 0.1 M: (i) dispersed bubble growth at relatively low coverage; (ii) maximum bubble coverage and onset of CID; (iii) and (iv) successive CID events; and (v) reduced bubble coverage after detachment. (c) Bubble evolution at 0.3 M: (i) bubble growth and aggregation; (ii) maximum bubble coverage with multiple neighboring bubbles in contact; (iii) initiation of detachment by CID; (iv) successive MID events triggered by the preceding detachment; and (v) reduced bubble coverage after the detachment cascade. (d) Bubble evolution at 1.0 M: (i) high bubble coverage before detachment; (ii) onset of bubble detachment; (iii) and (iv) successive detachment involving CID and MID; and (v) reduced bubble coverage after successive detachment. (e) Distribution characteristics of bubble detachment radius as a function of electrolyte concentration at $140 \text{ mA}/\text{cm}^2$.

However, distinct from the $c = 0.3 \text{ M}$ condition, the prolonged contact time and enhanced microconvective attraction at $c = 1.0 \text{ M}$ allow MID to become prevalent with increasing current density, ultimately reversing the macro-trend into a monotonic increase. Regarding the triggering threshold, MID cascades extensively emerge when the electrolyte concentration exceeds 0.3 M , driven by spatial crowding within the bubble population. This strongly signals

the existence of a critical bubble coverage θ_c required to activate the MID mechanism, which is determined to be approximately 0.3 in this work.

Figure 7(e) presents the distribution of bubble detachment radii measured at a current density of $140 \text{ mA}/\text{cm}^2$ under various electrolyte concentrations. Below an electrolyte concentration of 0.1 M , coalescence inhibition exerts negligible influence on the

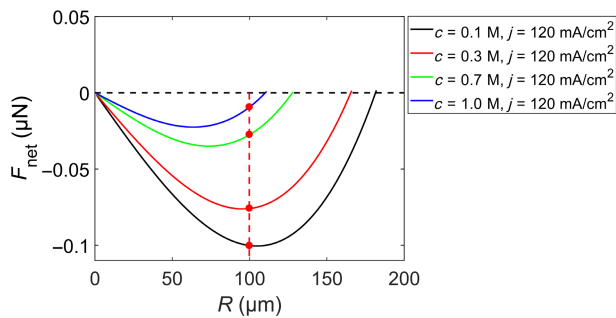


Figure 8 Curves of the net force F_{net} acting on an isolated bubble versus its radius under different concentration conditions. The vertical coordinate of the intersection point between the red dashed line and the curve represents the force F_{py} required for bubble detachment under micro-convective attraction interaction at a radius of 100 μm .

mode of bubble detachment, with bubbles primarily detaching through pairwise CID. Above this critical concentration, however, the coalescence contact time prolongs as concentration increases, accompanied by a reduction in the $R_{\text{d, single}}$. As shown in Fig. 8, under the same bubble radius condition, a higher electrolyte concentration results in a smaller pressure difference force F_{py} required for MID detachment. These dual effects promote the occurrence of MID, leading to a progressive decrease in the proportion of CID.

An increase in electrolyte concentration does not merely coalescence inhibition; rather, it simultaneously modulates multiple interfacial and transport-related factors, including mitigating surface tension gradients [23], enhancing mass transfer rates [41], and elevating bubble nucleation frequency. First, an increase in concentration leads to a more uniform localized ionic distribution, thereby smoothing the concentration gradients around the growing bubbles. As a consequence, the local solutal Marangoni force acting on the bubbles is substantially weakened, which significantly lowers the critical pressure difference required to trigger the MID pathway. Then, the elevated mass transfer rate under higher concentration conditions shortens the transient time required for bubbles to grow from initial nucleation to mutual contact. This rapid growth dynamics dramatically increases the statistical probability of multiple neighboring bubbles consecutively undergoing the MID process. Finally, the increase in bubble nucleation frequency effectively reduces the average spatial distance between neighboring active nucleation sites. This suppresses the conventional buoyancy-driven detachment pathway, thereby forcing a higher proportion of bubbles to participate in the MID process. In summary, while electrolyte-concentration-dependent coalescence inhibition acts as the primary mechanical driver for the detachment mode transition, it operates in tandem with these closely coupled adjustments in

interfacial forces and transport phenomena.

To elucidate the occurrence fractions and evolutionary trends of each mechanism as a function of current density and electrolyte concentration, the CID fraction was calculated as follows

$$c_{\text{CID}} = N_{\text{CID}} / (N_{\text{CID}} + N_{\text{NCID}}) \quad (7)$$

where N_{CID} and N_{NCID} represent the quantities of bubbles for CID and NCID, respectively. Figure 9(a) depicts the evolutionary trends of the c_{CID} under varying current densities and electrolyte concentrations. Specifically, the CID fraction decreases as the electrolyte concentration rises; this is because the concentration-induced coalescence inhibition reduces the inter-bubble distance, which enhances the F_{py} produced by shedding bubbles. Concurrently, the higher concentration weakens the concentration Marangoni force, both facilitating the MID mode. Conversely, the CID fraction scales up with increasing current density due to dual factors: First, when $c < 0.3$ M, a higher current density diminishes the nucleation site spacing, shortening the time needed for coalescence. Second, for $c > 0.3$ M, the current-induced intensification of the concentration Marangoni force and the distance-induced attenuation of F_{py} work in tandem. This synergistic combination increases the theoretical detachment radius, posing a higher deterministic threshold for MID.

The mechanistic phase diagram of electrolyte concentration versus current density is presented in Fig. 9(b). In this phase diagram, concentration serves as the x -axis and current density as the y -axis. To ensure statistical rigor, a specific detachment mode is defined as “dominant” under a given operating condition when the number fraction of bubbles detaching via this mode exceeds a 50% threshold. As illustrated in the diagram, the BDD regime dominates under low concentration and low current density conditions. In this region, active nucleation sites are sparse, and the hydrodynamic interactions between neighboring bubbles are characteristically weak. As the current density escalates, the spatial proximity and interaction between bubbles strengthen. Consequently, when the electrolyte concentration remains below 0.3 M, CID mechanism assumes dominance. Conversely, when the concentration exceeds 0.3 M, the inhibitory effect on bubble coalescence intensifies, shifting the system into a regime dominated by MID.

Mechanistically, the onset of MID is sequentially dependent on the prior occurrence of CID. Therefore, the threshold where the BDD model remains perfectly applicable directly maps to the physical boundary condition where CID is completely suppressed. This geometric criterion is mathematically fulfilled when the neighboring active nucleation sites spacing (S_n) is greater than the sum of their respective theoretical detachment radii: $S_n > R_{\text{d, single}}$.

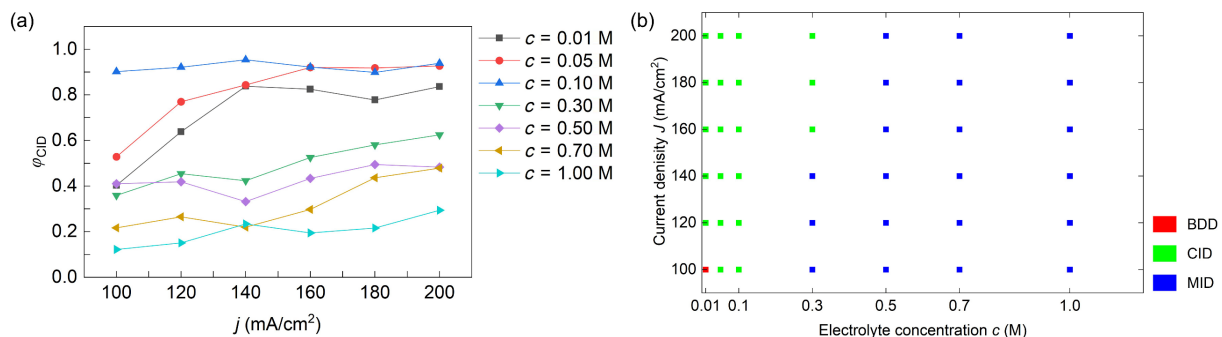


Figure 9 (a) Fraction of CID bubble c_{CID} as a function of current density j at electrolyte concentration c . (b) Mechanistic phase diagram of bubble detachment regimes as a function of electrolyte concentration and current density.

Under this spatial boundary condition, growing bubbles can never physically overlap or touch each other throughout their entire lifetimes on the electrode.

To clarify the concentration discrepancy between the contact time plateau (0.5 M, Fig. 6(b)) and the average detachment radius $\bar{R}_d$ trend reversal (0.7 M, Fig. 1(e)), a multi-mechanism competition mode is considered. The macroscopic statistical mean radius ($\bar{R}_d$) is non-linearly determined by the weighted contributions of coexisting modes

$$\bar{R}_d = c_{\text{CID}} \bar{R}_{d,\text{CID}} + (1 - c_{\text{CID}}) \bar{R}_{d,\text{NCID}} \quad (8)$$

where $\bar{R}_{d,\text{CID}}$ and $\bar{R}_{d,\text{NCID}}$ (encompassing MID and BDD) are their respective average detachment radii. Mechanistically, although the individual contact time stabilizes beyond 0.5 M, the aseline of $\bar{R}_{d,\text{CID}}$ remains constrained by the nucleation site spacing, which continuously scales up and forces $\bar{R}_{d,\text{CID}}$ to decrease. Concurrently, elevated concentrations systematically promote the MID pathway, altering c_{CID} and suppressing the majoritarian advantage of the CID mode. Therefore, the collective interplay of nucleation site spacing, c_{CID} and $\bar{R}_{d,\text{NCID}}$ continues to evolve, delaying the macroscopic trend reversal of $\bar{R}_d$ until 0.7 M.

2.4 Factors influencing the dependence of the average bubble detachment radius on the current density

To elucidate the dominant factors governing the dependence of the average bubble detachment radius on current density under different concentration conditions, a comparative analysis was conducted using data from electrolyte concentrations of 0.1 and 1.0 M.

At an electrolyte concentration of 0.1 M, the $\bar{R}_d$ decreases with current density, and the primary mode of bubble detachment is CID. Based on the preceding analysis, it can be concluded that the average CID bubble radius $\bar{R}_{d,\text{CID}}$ is primarily influenced by two factors: the critical condition for CID and the nucleation sites spacing (Eq. (7)). Figures 10(a) and 10(b) present the distributions

of the bubble detachment radius obtained at current densities of 100 and 180 mA/cm², respectively. With increasing current density, the minimum bubble size remains around 60 μm , while the maximum size decreases significantly.

Figures 10(c) and 10(d) present the phase diagrams of bubble coalescence results obtained at current densities of 100 and 180 mA/cm², respectively. These diagrams incorporate experimental data for both coalescence without detachment mode and CID mode. CID consistently occurs to the right of the equivalent nucleation site spacing line at $S = 105 \mu\text{m}$, which explains why the detachment radius is constrained to a minimum value of approximately 60 μm . Additionally, the critical curve is independent of the current density, as the concentration boundary layer is too thin to significantly influence the ascent motion of bubbles after coalescence [42]. Consequently, with increasing current density, the bubble nucleation site density increases (Fig. 10(e)), and the average nucleation site spacing $\bar{S}$ decreases (see Fig. 10(f)), leading to a reduction in $\bar{R}_{d,\text{CID}}$. Additionally, since the range of multi-bubble detachment radii is significantly smaller than $R_{d,\text{single}}$, the $\bar{R}_d$ remains independent of $R_{d,\text{single}}$.

At an electrolyte concentration of 1.0 M, the average bubble detachment radius increases with current density, and bubble detachment occurs through a combination of NCID and CID mode (Figs. 11(a) and 11(b)). Next, we analyze the characteristics of bubble distributions for the two modes. For the CID mode, the critical curve remains consistent with that under the condition of $c = 0.1 \text{ M}$. The range of R_L is constrained by the $R_{d,\text{single}}$ (Figs. 11(c) and 11(d)). As the current density increases, the $R_{d,\text{single}}$ increases, leading to a wider range of CID bubbles and an increase in the $\bar{R}_{d,\text{CID}}$. Although the increase in current density reduces the average nucleation site spacing $\bar{S}$, its influence on the detachment radius remains negligible due to coalescence inhibition (see Fig. 11(e)). For the NCID mode, the detachment radius can be as small as 10 μm , while the maximum detachment radius is limited by the $R_{d,\text{single}}$. Both $R_{d,\text{single}}$ and the detachment-radius distribution range expand with increasing current density. As For bubbles whose detachment is influenced by micro-convective induced attraction interaction, a

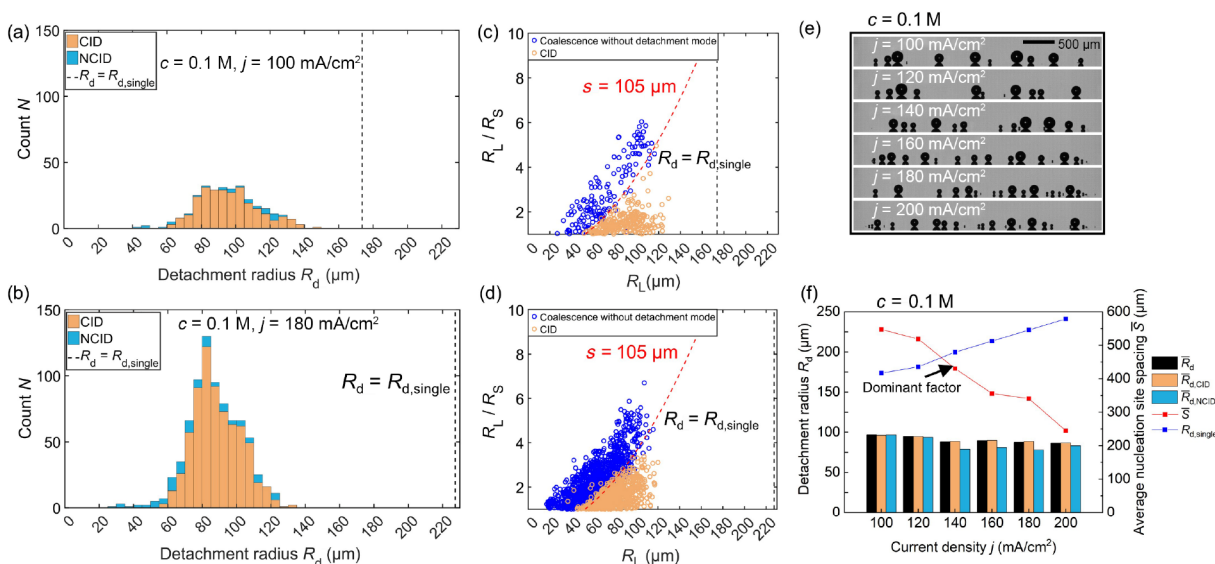


Figure 10 Dominant factors influencing the relationship between average bubble detachment radius and current density at a concentration of 0.1 M. (a) and (b) Bubble detachment radius distributions (a) $j = 100 \text{ mA/cm}^2$; (b) $j = 180 \text{ mA/cm}^2$. (c) and (d) Bubble coalescence phase diagrams. (e) $c = 1.0 \text{ M}$, $j = 100 \text{ mA/cm}^2$; (d) 1.0 M, 180 mA/cm². (e) Bubble images at maximum bubble coverage under different current densities. (f) Variations of the average detachment radius $\bar{R}_d$, the average CID bubble radius $\bar{R}_{d,\text{CID}}$, the average NCID bubble radius $\bar{R}_{d,\text{NCID}}$, the average detachment radius $\bar{R}_d$, average nucleation site spacing $\bar{S}$, and $R_{d,\text{single}}$ with current density j . R_L denotes the radius of the larger bubble prior to coalescence, and R_S denotes the radius of the smaller bubble prior to coalescence.

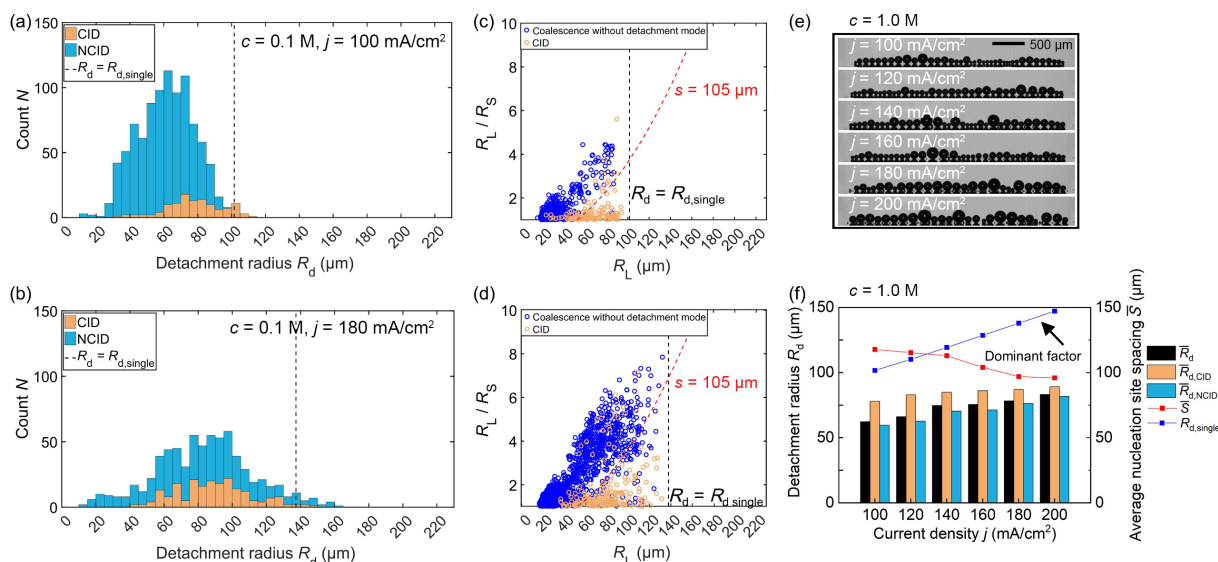


Figure 11 Dominant factors influencing the relationship between average bubble detachment radius and current density at a concentration of 1.0 M. (a) and (b) Bubble detachment radius distributions (a) $j = 100 \text{ mA/cm}^2$; (b) $j = 180 \text{ mA/cm}^2$. (c) and (d) Bubble coalescence phase diagrams. (c) $j = 100 \text{ mA/cm}^2$; (d) $j = 180 \text{ mA/cm}^2$. (e) Bubble images at maximum bubble coverage under different current densities. (f) Variations of the average detachment radius $\bar{R}_d$, the average CID bubble radius $\bar{R}_{d,CID}$, the average NCID bubble radius $\bar{R}_{d,NCID}$, the average detachment radius $\bar{R}_d$, average nucleation site spacing $\bar{S}$, and $R_{d,single}$ with current density j . R_L denotes the radius of the larger bubble prior to coalescence, and R_S denotes the radius of the smaller bubble prior to coalescence.

larger radius is required to initiate NCID as current density increases under identical flow field conditions (see Fig. S2 in the ESM). This results in an increase in the $\bar{R}_{d,BDD}$. In summary, the $\bar{R}_d$ increases with current density, primarily influenced by the $R_{d,single}$ (see Fig. 11(f)).

As shown in Fig. 12, the dimensionless average detachment radius $\bar{R}_d/R_{d,single}$ increases monotonically with the dimensionless average nucleation site spacing $\bar{S}/R_{d,single}$, with all values remaining strictly below 1. Crucially, under identical $\bar{S}/R_{d,single}$, the $\bar{R}_d/R_{d,single}$ at $c = 0.1 \text{ M}$ is systematically lower than that at $c = 1.0 \text{ M}$. This indicates that the CID-dominated multi-bubble process exhibits superior bubble evacuation efficiency and gas evolution performance compared to the MID-dominated counterpart.

3 Conclusions

This study investigated the multi-bubble detachment characteristics on TiO_2 photoelectrodes under various electrolyte concentrations

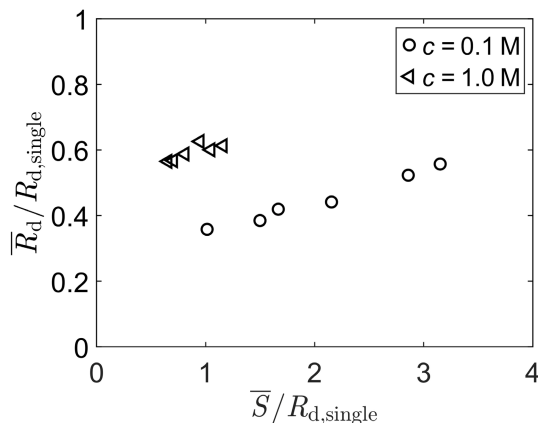


Figure 12 Relationship between the dimensionless average detachment radius $\bar{R}_d/R_{d,single}$ and the dimensionless average nucleation site spacing $\bar{S}/R_{d,single}$ under $c = 0.1 \text{ M}$ and $c = 1.0 \text{ M}$ conditions.

and current conditions during photoelectrochemical water splitting. By confining the reaction to an elongated area via a linear laser pattern, we enabled *in situ* observation of the multi-bubble evolution process. Our results demonstrated that as electrolyte concentration increased, the propensity for bubble detachment shifted from coalescence-induced detachment mode to non-coalescence-induced detachment mode. Consequently, the correlation between the average bubble detachment radius and current density transitioned from positive to negative. We revealed that the competition between bubble coalescence and micro-convective induced attraction governs the multi-bubble detachment process. This competition is modulated by electrolyte concentration through coalescence inhibition effects. At low concentrations, weak coalescence inhibition allows coalescence to dominate, with the average nucleation spacing dictating the average bubble detachment radius. In contrast, at high concentrations, strong coalescence inhibition enables micro-convective induced attraction to prevail, whereby the single bubble detachment radius determines the average bubble detachment radius. Thus, the correlation between the average detachment radius and current density is fundamentally governed by the electrolyte concentration. Finally, we explicitly clarify the applicability boundaries and limitations of the present work. Although this study successfully elucidates the multi-bubble detachment dynamics influenced by bubble–bubble interactions on a superhydrophilic electrode under quiescent, neutral conditions, practical industrial operations usually involve concentrated KOH electrolytes and forced circulation. The intensive external fluid shear may suppress the spatial packing required for microconvection-induced detachment, while the shifted wettability alters the critical bubble coverage threshold. Therefore, the proposed MID mechanism is expected to function as a dominant localized pathway primarily within hydrodynamic stagnation zones, rough micro-grooves, or porous catalyst substrates under high current densities where local gas accumulation overwhelms convective removal.

4 Methods

4.1 Chemicals

The electrolyte was composed of Na_2SO_4 and Milli-Q water ($\geq 18.2 \text{ M}\Omega\text{-cm}$).

4.2 Fabrication of TiO_2 electrode

The TiO_2 nanorod electrode was synthesized via a hydrothermal method. Figure 13 presents scanning electron microscopy (SEM) images of the fabricated electrodes. Fluorine-doped tin oxide (FTO) glass substrates were first ultrasonically cleaned in acetone, ethanol, and deionized water for 30 min each to remove surface contaminants. Subsequently, a seed layer was spin-coated onto the substrate at 4000 rpm for 20 s using a spin coater. The seed layer solution was prepared by sequentially adding 153 μL of acetylacetone, 1700 μL of tetrabutyl titanate, and 90 μL of ultrapure water into anhydrous ethanol, followed by diluting the mixture to a total volume of 100 mL with additional anhydrous ethanol. After spin-coating, the substrates were dried on a hotplate at 100 $^\circ\text{C}$ for

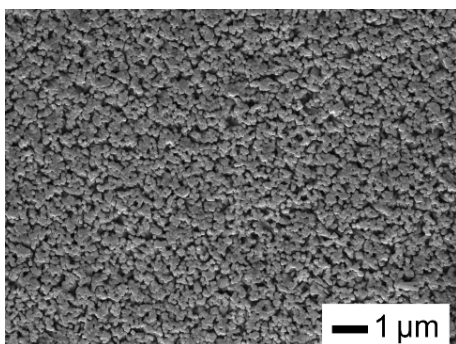


Figure 13 SEM image of TiO_2 nanorod array electrode.

10 min and then calcined in a muffle furnace at 500 $^\circ\text{C}$ for 2 h. The seeded conductive glass was then placed in a hydrothermal autoclave along with the precursor solution for hydrothermal reaction at 160 $^\circ\text{C}$ for 2 h. The precursor solution was composed of concentrated hydrochloric acid, ultrapure water, and 0.05 M tetrabutyl titanate in a volume ratio of 30:30:1. After the reaction, the samples were annealed in the muffle furnace at 400 $^\circ\text{C}$ for 30 min.

4.3 PEC water splitting experiment

The experiments were performed in a three-electrode electrochemical cell that has a transparent glass window at the side. A TiO_2 nanorod electrode was placed facing upwards to study the freely detachable O_2 gas bubble. The platinum electrode and the $\text{Hg}/\text{Hg}_2\text{SO}_4$ electrode were used as a CE and a RE, respectively. The electrochemical measurements were carried out with a potentiostat (ModuLab XM ECS, Solartron Analytical). Before the experiment, nitrogen gas was purged through the Na_2SO_4 solution for 15 min to remove dissolved gases and the TiO_2 electrode was irradiated under a Xenon lamp for 2 h to achieve a stable superhydrophilic state. Oxygen bubbles were visualized by the highspeed camera (Photron SAZ) from the side.

4.4 Bubble *in situ* observation system

In situ multi-bubble observation experiments were conducted under electrolyte concentrations of 0.01, 0.05, 0.1, 0.3, 0.5, 0.7, 1.0, 1.3, and 1.5 M, and at constant current densities of 100, 120, 140, 160, 180, and 200 mA/cm^2 . The discussion on the rate-determining regimes of the photoelectrochemical system can be found in Note S7 in the ESM.

The single-bubble generation setup employs by focusing a single laser beam through a convex lens, an elliptical spot with a major axis of 115 μm was obtained (Fig. 14(a)). After the reaction

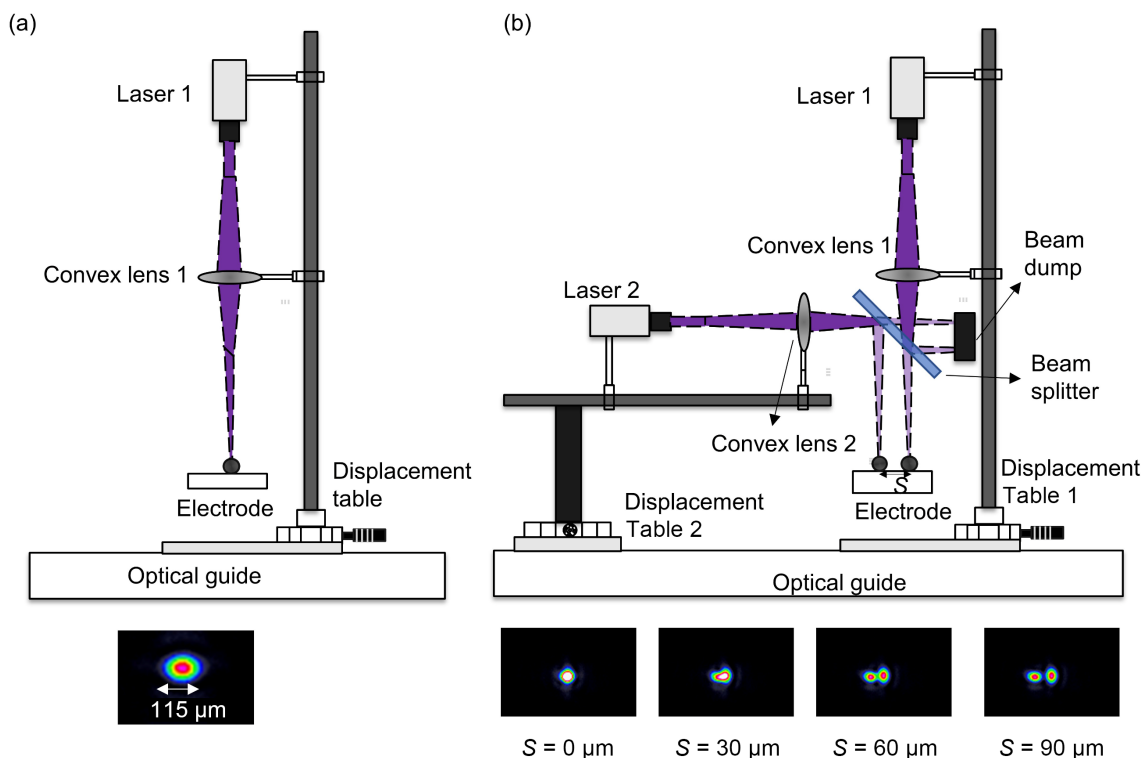


Figure 14 Schematic diagram of the bubble generation setup and spot morphology. (a) Single bubble. (b) Double bubbles.

commenced, a single bubble was generated at the center. The frame rate and the spatial resolution of the high-speed camera were 125 fps and about 4 $\mu\text{m}/\text{pixel}$, respectively.

The double-bubble generation setup employs a bubble spacing control system consisting of vertically and horizontally arranged precision translation stages (Fig. 14(b)). A beam splitter directs two focused laser beams vertically onto the photoelectrode surface to form two spots. The positions of these spots are adjustable via the translation stages, enabling control of the nucleation point spacing with a precision of 10 μm . The bubble detachment radius is regulated by laser power. The frame rate and the spatial resolution of the high-speed camera were 1000 fps and about 2 $\mu\text{m}/\text{pixel}$, respectively.

4.5 Particle image velocimetry experiment

For the PIV measurement, fluorescent particles (Thermo Scientific, Fluoro-Max Orange, 0.86 μm in diameter) were added to the 1.0 mol/L Na_2SO_4 electrolyte at particle concentration of 20 $\mu\text{g}/\text{mL}$. These particles were excited by a 532 nm sheet laser source, with the laser beam adjusted to a size larger than the bubble radius to ensure a sufficiently large illumination area, as shown in Fig. 15. The laser power used in the measurement was 4.32 W. A high-speed camera (Photron SAZ) equipped with a 10 $\times$ objective lens was then employed to record images at a frame rate of 1 kfps. The PIVlab toolbox in MATLAB was utilized to process the images and obtain the flow field of the images.

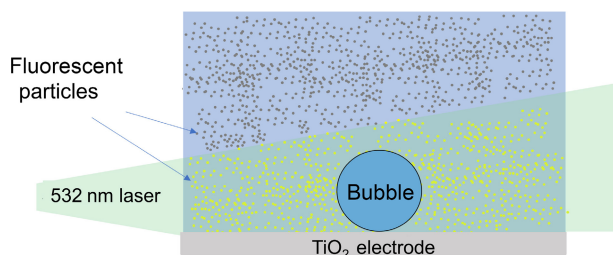


Figure 15 Schematic diagram of the PIV measurement.

Electronic Supplementary Material: Supplementary material (supplementary notes, figures, and videos on image processing, theoretical analysis, uncertainty evaluation, bubble evolution, and PIV measurements) is available in the online version of this article at <https://doi.org/10.26599/NR.2026.94909078>.

Data availability

All data needed to support the conclusions in the paper are presented in the manuscript and the Electronic Supplementary Material. Additional data related to this paper may be requested from the corresponding author upon request.

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Declaration of competing interest

All the contributing authors report no conflict of interests in this work.

Author contribution statement

B. Z.: Data curation, project administration, validation, writing manuscript, experimental design. Y. C. W.: Data curation, project administration, validation, writing manuscript, experimental design. Y. Y. F.: Experimental design. C. H. Z.: Experimental design. R. W. D.: Experimental design. J. X. Z.: Experimental design. B. S. L.: Experimental design. S. R. W.: Experimental design. Q. Y. Z.: Project administration, writing manuscript. L. J. G.: Project administration, funding acquisition, project administration, writing manuscript, experimental design. All the authors have approved the final manuscript.

Use of AI statement

During the preparation of this work, the authors used ChatGPT (OpenAI) for language editing and proofreading. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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