

Influencing mechanism of buoyancy-induced micro-deformation on bubble horizontal transport along conical surfaces

Xiang Gao¹, Hong-Yang Ning¹, Yun-Yun Song¹, Patrick Verdin², Fu-Jian Zhang^{1, a)}, Zhong-Qiang Zhang^{1, a)}

¹ School of Mechanical Engineering, Jiangsu University, Zhenjiang 212013, PR China

² Faculty of Engineering and Applied Science, Cranfield University, Cranfield, MK43 0AL, UK

^{a)} Author to whom correspondence should be addressed:

zhangfj@ujs.edu.cn; zhangzq@ujs.edu.cn.

Abstract: Superhydrophobic conical surfaces exhibit significant potential in microfluidic manipulation and interfacial engineering due to their unique wettability and geometric constraints. However, previous studies have focused on steady-state bubble transport capacity on cone surfaces, overlooking the critical role of bubble morphology evolution in dynamic performance. Herein, a fluorinated silica nanoparticle suspension was synthesized and applied via spray-coating technology onto additively manufactured conical substrates, achieving simultaneous superhydrophobicity (water contact angle $> 150^\circ$) and exceptional bubble adhesion characteristics. Four stages of bubble transport on these surfaces were identified: (I) bubble-cone contact, (II) deformation and spreading, (III) maximum deformation and transition, and (IV) stable transportation. A comparative analysis of bubble transport morphology across conical surfaces reveals that the transition stages (II and III), marked by maximum deformation and interfacial instability, play a pivotal role in determining overall transport efficiency. These observations were validated by COMSOL simulations, which showed consistent deformation times and revealed how bubble morphology influences migration velocity and pressure distribution. Notably, the double-cone structure enhanced transport efficiency by 62% over the single-cone design by simultaneously suppressing vertical bubble deformation and enhancing interfacial fluidity during the transition stages. Increasing the surface contact angle can enhance bubble transport velocity, whereas an increase in fluid viscosity slightly reduces the velocity. Simulations also show that cone arrangement strongly affects bubble transport, with vertical double-cones fastest and 30° configurations slowest. These findings offer practical insights for optimizing microfluidic devices and bubble collection systems, such as gas-liquid separators or microreactors, requiring precise hydrodynamic control.

1. Introduction:

In recent years, the transport behavior of bubbles, including their morphological changes and transport characteristics, has become a significant research focus due to its crucial impact on the efficiency and reliability of applications such as methane fuel bubble capture [1], microfluidic devices [2, 3], and gas evolution reactions [4]. The morphology of bubbles during transport is influenced by various physical factors, such as surface tension, fluid dynamics, and thermodynamic conditions [5, 6]. These factors not only determine the stability of the bubbles but also directly affect their velocity and transport efficiency. While previous studies have provided initial insights into bubble formation [7], stability [8, 9], and basic transport behaviors [10-12], limited research has explored the relationship between changes in bubble morphology and its transport efficiency. Furthermore, the dynamic modeling and experimental validation of bubble behavior remain incomplete. Therefore, studying how the evolution of bubble shape influences its migration velocity on conical surfaces is of paramount importance for elucidating the underlying mechanisms of bubble dynamics and for providing a theoretical foundation for the optimization of microfluidic devices and related engineering applications.

While previous studies have mainly examined bubbles on flat or mildly curved surfaces driven by surface tension gradients and inertial forces, unpinned bubbles on these surfaces demonstrate spontaneous transport [13-15]. Surfaces featuring micro/nanopores coated with lubricants, exhibiting sponge-like structures and superhydrophobic properties, are particularly suitable for bubble manipulation in aquatic environments. The geometric characteristics of these surfaces guide bubble transport through sustained adhesion, enabling continuous directional movement [16]. Moreover, incorporating asymmetric interface structures on the surface allows for precise control over the directional transport of individual bubbles [17]. Numerous studies have demonstrated that the unique multi-level microstructure of cactus spines generates Laplace pressure and surface energy gradients, which act as synergistic driving forces for the directional transport of bubbles [18-20]. However, conical surfaces introduce additional complexities due to their varying curvatures, which alter the force distribution on the bubble. Shape transformations, such as elongation, deformation, or detachment, can significantly influence the translational velocity of bubbles [21, 22]. The interaction between the bubble's volume and surface curvature further complicates these effects [4]. Recent research has underscored the role of surface shape and curvature in inducing diverse bubble transport patterns, which in turn impact both velocity and transport efficiency [23, 24]. On conical

surfaces, variations in curvature lead to a nonuniform distribution of contact angles and surface energy, causing complex, shape-dependent changes in bubble morphology [25]. On the other hand, the variation in bubble morphology is of considerable importance in several fields, including multiphase fluid dynamics [26, 27], chemical reaction engineering [28], environmental science [29-31] and food science [32]. On superhydrophobic surfaces, bubble shape is influenced by the radius of the superhydrophobic circle (SBC). As the SBC radius decreases, the bubble transitions from a flattened sphere to a more spherical shape [33]. Furthermore, bubble shape and dynamics are notably affected by the orientation of the surface. On upward-facing hydrophobic surfaces, hydrostatic pressure acts against the base of the bubble, leading to more compact shapes and limiting its spreading. In contrast, on downward-facing surfaces, higher hydrostatic pressure at the apex causes the bubble to spread more, increasing its contact area with the surface and reducing its height [34]. Viscosity and surface tension also play critical roles in determining the rising velocity and morphological characteristics of bubbles. As viscosity increases, both the equilibrium velocity and shape factor decrease, while the drag coefficient of the bubble initially decreases and then increases with rising Reynolds number. Conversely, higher surface tension results in higher equilibrium velocity and smaller shape factors [35]. Although some studies have explored how bubble morphology influences the transport efficiency during free rise, the specific relationship between shape evolution and transport velocity on conical surfaces remains poorly understood.

Herein, we achieved superhydrophobicity and enhanced bubble adhesion by coating a suspension of fluorinated silica nanoparticles onto the surface of a 3D-printed cone. The dynamic interactions between bubbles and conical surfaces were systematically investigated, with a focus on the critical role of morphological evolution during transport. COMSOL simulations further confirmed that the double-cone structure reduces transport time by 62% compared to the single-cone structure, due to suppressed vertical bubble deformation and enhanced interfacial fluidity. This study not only elucidates the mechanistic relationship between geometric constraints and bubble dynamics but also offers a design framework for optimizing microfluidic devices requiring precise control over hydrodynamic transport.

2. Results and Discussion:

2.1 Preparation and characterization of superhydrophobic cones.

Materials: Hydrophilic silica nanoparticles with diameters of 10 - 20 nm were procured from

National Medicines Co., Ltd. Tetraethoxysilane (TEOS, 99.99%) and 1H,1H,2H,2H-perfluorodecyltriethoxysilane (PFDTES, 97%) were sourced from McLean reagent and Shanghai Tengzhun Biotechnology Co., Ltd., respectively. Polyvinylidene fluoride (PVDF, 42wt.%) was supplied by Dongguan Zhanyang Polymer Materials Co., Ltd. Ammonia solution (25 - 28wt.%), absolute ethanol, hydrochloric acid (HCl), and sodium hydroxide (NaOH) were acquired from Aladdin Industrial Corporation.

Sample characterization: The water contact angle (WCA) was measured using a contact angle goniometer (SL250, KINO, USA). A high-speed camera (VEO 710, Phantom, USA) was employed to capture real-time dynamic images of bubble transport on the conical surface. The bubble volume was controlled via a microinjection pump (Pump 11 Elite Glucose Clamp Pumps, Harvard Apparatus, USA).

The preparation of the fluorinated SiO₂ nanoparticle suspension: 1.0 mL of TEOS and 1.2 g of nano-silica nanoparticles (10 - 20 nm) were dispersed in 44 mL of anhydrous ethanol and 6 mL of ammonia solution. The mixture was magnetically stirred at room temperature for 1 hour. Then, 0.8 mL of PFDTES and 4 g of PVDF were added to the suspension. The mixture was first subjected to ultrasonic stirring for 30 minutes to break up particle agglomerates, followed by an additional 60 minutes of magnetic stirring to ensure homogeneity (Figure 1a(I)). The cavitation effect induced by ultrasound generated intense localized shear forces and shock waves, effectively dispersing the superhydrophobic fluorinated SiO₂ nanoparticles and promoting their uniform distribution in the solvent [36].

The 3D-printed conical structures were sonicated in anhydrous ethanol for 10 minutes and then dried at 333.15 K to remove any residual surface resin. The conical structures were vertically mounted on a glass slide for ease of surface spray coating. A spray gun was used to apply a 0.2 MPa to the surface of the conical structures from a distance of 0.1 m. The samples were left at room temperature for 5 minutes and then cured at 333.15 K for 15 minutes after spraying, resulting in superhydrophobic conical structures. The inset in Figure 1a(II) shows the droplet spreading on the untreated surface, exhibiting a WCA of $47.5 \pm 0.3^\circ$, whereas the surface sprayed with the fluorinated SiO₂ nanoparticle suspension achieves superhydrophobicity with a WCA of $150.5 \pm 0.5^\circ$. Then, an underwater bubble adsorption test was conducted on the coating. When the rising bubble approaches and contacts the coated surface, it initially ruptures and subsequently spreads across the surface (29

ms), ultimately forming a thin gas film (92 ms). The resulting bubble contact angle (BCA) is approximately 0° , indicating strong bubble adsorption by the coating (Figure 1b). This behavior highlights the critical role of the hierarchical micro/nano structure and low surface-energy groups (Figure S1, Supporting Information), as demonstrated in our previous work [36], in facilitating bubble adsorption and promoting stable gas-film formation.

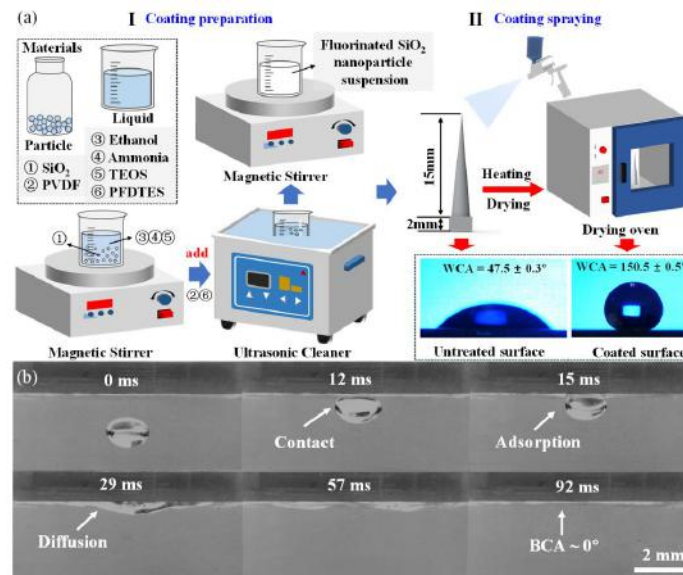


Figure 1 (a) Preparation and characterization of superhydrophobic coatings. (b) Snapshot of bubble adsorption on superhydrophobic coating surface.

Experimental setup: Figure 2 provides a schematic diagram of the experimental setup used to record the transport of bubbles with different volumes on the conical surface. To ensure a constant air flow rate, a microinjection pump (Pump 11 Elite Glucose Clamp Pumps, Harvard Apparatus, USA) was used. The needle connected to the pump can be replaced to generate bubbles of different volumes. The bubble formation process was recorded from the side of the cone using a high-speed camera (VEO 710, Phantom, USA) with a resolution of 1200×800 pixels, and the pixel size of the imaging system was $15 \mu\text{m}/\text{pixel}$. To enhance image contrast, an 88W light source was used, as shown in Figure 2. To capture the dynamic morphological changes of the bubbles on the conical surface, the shutter speed was set to 5000 fps. The acquired images were then processed to extract

bubble characteristics. The bubble average velocity was determined by measuring the time interval between the moment when the bubble first contacted the conical surface and the moment when it contacted the cone base. The bubble displacement was determined by tracking the contact point between the bubble and the cone surface from high-speed images, and the measurement uncertainty due to pixel resolution and thresholding during image analysis was estimated to be within $\pm 1 - 2$ pixels ($\pm 15 - 30 \mu\text{m}$).

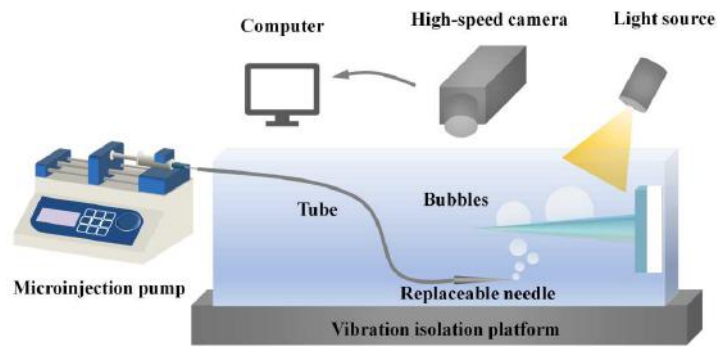


Figure 2 Schematic diagram of the experimental setup.

2.2 The effect of bubble size and cone angle on the transport velocity of bubbles on conical surfaces.

The transport of bubbles on conical surfaces has long been a subject of interest among researchers. However, the morphological changes that occur during their transport on such surfaces have received little attention. Figure 3a illustrates the time-dependent dynamic evolution of a $5 \mu\text{L}$ bubble as it moves along a conical surface. Initially, the bubble contacts the cone surface while retaining a nearly spherical shape (0 ms). Slight deformation occurs due to the interplay of surface tension and the local curvature of the cone (1 ms). Subsequently, a significant morphological shift takes place, with the bubble briefly elongating and forming a cap-like structure (highlighted in the red dashed region), marking a transition phase influenced by buoyancy and wetting forces (11.2 ms). The bubble spreads and shifts along the conical surface over time (23.4 - 45 ms), driven by interfacial forces and hydrodynamic effects. Finally, the bubble reaches the base of the cone at 69.6 ms. The relationship between bubble average velocity (v_a) and cone angle α for different bubble volumes is shown in Figure 3b. As the apex angle α increases from 4° to 7° , both $5 \mu\text{L}$ and $25 \mu\text{L}$ bubbles demonstrate a monotonic increase in average velocity, with the smaller $5 \mu\text{L}$ bubbles

exhibiting consistently higher velocities than their 25 μL counterparts under identical conditions. This result suggests that as the cone angle increases, the influence of buoyancy and surface tension effects enhances bubble transport. The greater mobility of smaller bubbles may be attributed to their reduced buoyancy force and stronger interactions with the surface. For the larger bubble (25 μL), a significant shape transformation occurs at $t = 45.4$ ms, forming a highly deformed structure (red dashed region), indicating a stronger interaction between the bubble and the surface. Compared to the 5 μL bubble, the deformation of the 25 μL bubble is more pronounced, and the time required to reach a distinct cap-like structure is considerably longer (Figure 3c). These findings indicate that cone geometry plays a crucial role in bubble dynamics, affecting both velocity and surface interaction.

As mentioned above, the average velocity of bubble transport on the conical surface is closely related to its deformation. Therefore, the relationship between the time required for the bubble to reach its maximum deformation and the cone angle was investigated. The Figure 3d illustrates that the time required for bubbles of 5 μL and 25 μL to reach maximum deformation decreases as the cone apex angle increases. For 5 μL bubbles, the deformation time remains relatively short (approximately 10 - 12 ms) with minimal variation across different cone angles, indicating lower resistance to deformation and faster adaptation to conical surfaces. These findings were further corroborated by our subsequent experiments with 2.5 μL bubbles (Figure S2, Supporting Information). In contrast, the deformation time for the 25 μL bubble significantly decreases from about 47.5 ms at $\alpha = 4^\circ$ to around 28.2 ms at $\alpha = 7^\circ$. Although larger bubbles deform more slowly due to increased inertia and internal resistance, the enhanced buoyancy force acting along the surface at higher apex angles accelerates their deformation (the inset in Figure 3d). Based on the findings above, it is essential to reduce the deformation time of bubbles (particularly larger ones) to improve their average velocity on conical surfaces.

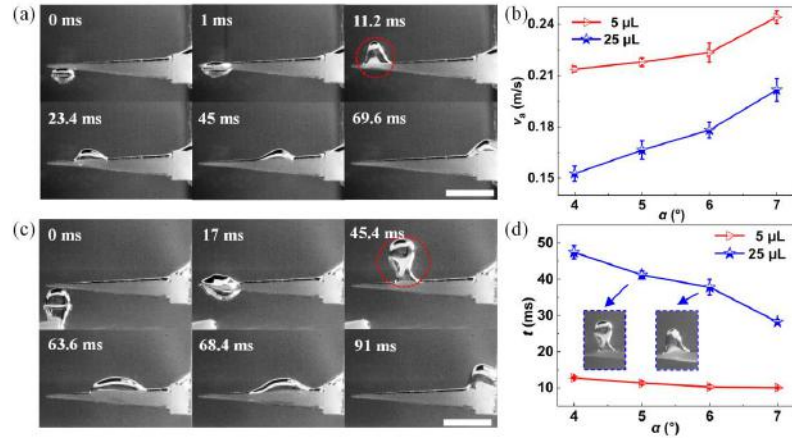


Figure 3 (a) Snapshot of the transport of a 5 μL bubble on a conical surface with an apex angle of 5° . (b) Average velocities of bubbles with different volumes on conical surfaces with apex angles of 4° , 5° , 6° , and 7° . (c) Snapshot of the transport of a 25 μL bubble on a conical surface with an apex angle of 5° . (d) Time required for bubbles of different volumes to reach maximum deformation on conical surfaces with different angles. Scale bar: 5 mm.

2.3 Effect of double-cone and triple-cone structures on the bubble average velocity.

An effective strategy to further enhance bubble velocity is to employ double-cone or multi-cone geometries. Such designs significantly enhance buoyancy-driven deformation, enabling bubbles to quickly adapt to the surface shape, thereby forming curved gas-liquid interfaces on conical surfaces and ultimately increasing bubble velocities [37]. As shown in Figure 4a, a rising microbubble (5 μL) deforms upon contacting a biconical structure. Under buoyancy and inertia, it ascends the conical surface while elongating from spherical to elliptical (9.8 ms), without contacting the upper cone. Surface tension and geometric confinement then guide the bubble downward (22.4 - 57 ms), culminating in a stable curved meniscus at the conical base. This hydrodynamic process culminates in bubble stabilization at the conical apex, where interfacial energy minimization results in the formation of a characteristic meniscus-shaped gas-liquid interface. Comparatively, upper cone contact during large bubble transport on double-cone and triple cones reduces deformation time and increases average velocity (Figure 4b and c). As shown in Figure 4d, compared to the single-cone structure, the double-cone and triple-cone structure can enhance bubble average velocity. However, the difference in velocity between the double-cone and triple-cone structure is negligible, as the

bubble movement on the triple-cone structure closely resembles that on the double-cone structure. Significantly, with increased bubble release distance, the bubbles detach from the lower cone of the tri-cone structure and establish contact with the uppermost cone. Subsequently, they undergo interfacial diffusion between the upper and middle cones before being transported toward the cone base, demonstrating a novel cone-cone transport mechanism (Figure S3, Supporting Information). For a 5 μL bubble, the double-cone structure enhances the average velocity by approximately 10%. This enhancement arises because, upon immersion of the double-cone structure in water, surface tension establishes an initial curved gas-liquid interface at the base (blue dotted circle in Figure 4a). As the bubble traverses the cone and reaches the base, it interacts with this pre-existing gas film, thereby accelerating its movement. This phenomenon has been corroborated in our prior research [38]. In the double-cone structure, the stretching of a 25 μL bubble during its ascent is constrained by the upper cone (as indicated by the red dashed circle in Figure 4b). This constraint not only reduces the deformation time of the bubble but also leads to the formation of a curved gas film between the cones due to pressure differences, thereby increasing the average velocity of the bubble along the cone surface. Furthermore, an initial gas film is present at the cone base (as shown by the blue dashed circle in Figure 4b), which further enhances bubble transport. Consequently, the double-cone structure increases the velocity of large bubbles by 20%, an improvement significantly greater than that observed for small bubbles.

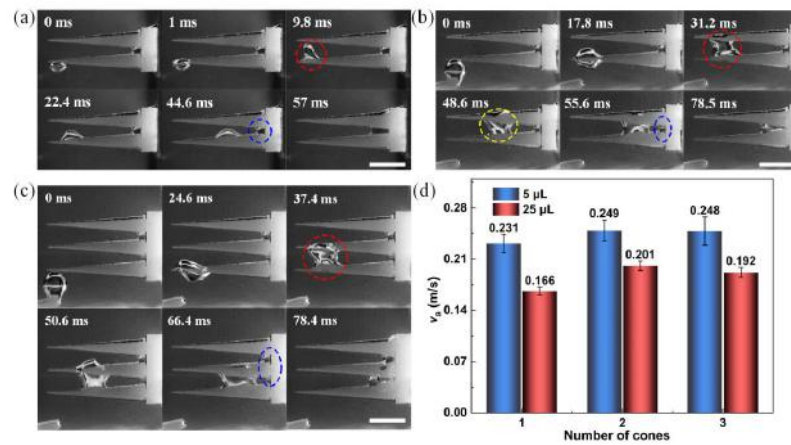


Figure 4 Snapshots of bubble transport on a double-cone surface with an apex angle of 5° for bubble volumes of (a) 5 μL and (b) 25 μL . (c) Snapshot of the transport of a 25 μL bubble on a triple-cone

surface with an apex angle of 5° . (d) Average velocity of bubbles with different volumes on surfaces with varying numbers of cones. Scale bar: 5 mm.

2.4 Theoretical analysis of bubble transportation stages on a conical surface

As shown in Figure 5, bubble transportation on the conical surface occurs in four stages: (I) the bubble-cone contact stage; (II) deformation and spreading stage; (III) maximum deformation and transition stage; (IV) stable transportation stage.

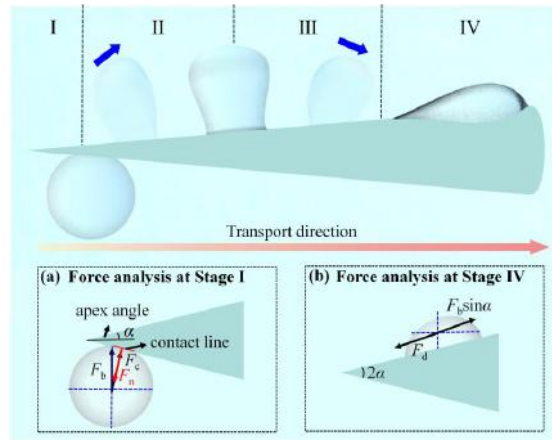


Figure 5 The schematic diagram of bubbles at different transport stages on the conical surface. The illustration shows the main forces and parameters. (a) and (b) are schematic diagrams of the force analysis of bubbles in the first and fourth stages, respectively.

In the bubble-cone contact stage, the bubble first contacts the conical surface, forming a three-phase contact line (gas-liquid-solid) with a small contact area and a specific contact angle. Surface tension at the gas-liquid interface dominates, maintaining the bubble in a nearly spherical shape by minimizing its surface energy. Under static equilibrium conditions, the upward buoyancy force is balanced collectively by the capillary force resulting from surface tension and the normal supporting force from the solid cone surface (Figure 5(a)). The static equilibrium in the vertical direction is given by [4]:

$$F_b = F_c + F_n \cos \alpha. \quad (1)$$

Where $F_b = (\rho_l - \rho_g)Vg$ is the buoyancy force (ρ_l and ρ_g are the liquid and gas densities, V is the bubble volume, and g is gravitational acceleration), $F_c = \sigma L \sin \theta$ is the vertical component of the

capillary force (L is the contact line length, θ is the contact angle and σ is surface tension coefficient), and F_n is the normal force. At this stage the behavior of bubble is primarily governed by the balance of these forces, with minimal deformation.

During the deformation and spreading stage, the bubble deforms and spreads along the conical surface, increasing its contact area and transitioning from a nearly spherical shape to an elongated form. The conical geometry imposes a lateral constraint, forcing the bubble to adapt its shape, while surface tension resists this deformation. The pressure difference across the gas-liquid interface, governed by the Young-Laplace equation, drives the deformation:

$$\Delta P = \sigma \left(\frac{1}{R_1} + \frac{1}{R_2} \right). \quad (2)$$

where R_1 and R_2 are the principal radii of curvature. As the bubble elongates, the radii change, altering the pressure difference and facilitating the spreading process. The characteristic deformation time is influenced by inertial and capillary effects [39]:

$$t_d \sim \sqrt{\frac{\rho_l r^3}{\sigma}}. \quad (3)$$

Here, r represents the characteristic radius of the bubble. Smaller bubbles, with a reduced r , exhibit a shorter deformation time t_d . Moreover, their higher surface-to-volume ratio amplifies the relative effect of surface tension, increasing their resistance to deformation. In contrast, larger bubbles with increased r exhibit more pronounced deformation. Their lower surface-to-volume ratio leads to a smaller pressure difference (owing to larger R_1 and R_2), resulting in a prolonged deformation time [40]. Meanwhile, a larger cone angle α creates a steeper surface, which limits the bubble vertical stretching more quickly. This compels the bubble to elongate along the conical surface at a faster rate, reducing the effective length scale of deformation and thereby shortening the deformation time. Conversely, a smaller α permits the bubble to deform over a greater distance, extending the duration of the deformation process (Figure 3d). The double-cone structure consists of two conical surfaces, with the bubble rising in the narrow space between them. The upper cone restricts vertical stretching of bubbles, while the lower cone guides initial contact and expansion of bubbles. For larger bubbles, their low surface-to-volume ratio leads to greater deformation, and the double-cone structure accelerates this process by quickly limiting vertical expansion. During the deformation and expansion stage, the bubble stretches along the conical surface, transitioning from a near-spherical to an elongated shape. The upper cone (shown by the red dashed circle in Figure 4b) curbs vertical

stretching, forcing faster deformation along the surface. This geometric constraint reduces the effective length scale of deformation, shortening the deformation time.

In the maximum deformation and transition stage, the bubble achieves its greatest elongation (as indicated by the red dashed circle in Figure 3c) and starts to shift toward transportation along the conical surface. Within a double-cone structure, the bubble develops into a curved gas film between the cones (yellow dashed circle in Figure 4b), propelled by pressure differences across the interface. The pressure difference across this gas film is expressed as:

$$\Delta P_{\text{gas film}} = \sigma \left(\frac{1}{R_{\text{film}}} \right). \quad (4)$$

Here, R_{film} denotes the curvature radius of the gas film. This pressure difference accelerates the bubble transport, while the double-cone structure boosts the bubble velocity by shortening the deformation time and enabling quicker transportation.

In the stable transportation stage, the bubble travels steadily along the conical surface, gradually regaining a more compact shape. Buoyancy drives the transport, while fluid drag opposes it (Figure 5(b)). The force acting on the bubble can be given by [21]:

$$F_d = 6\pi\mu rv. \quad (5)$$

Here, μ represents the liquid viscosity, and v denotes the velocity. During the stable transportation stage, buoyancy equilibrates with drag: $F_b \sin \alpha \approx F_d$

$$v \sim \frac{(\rho_l - \rho_g)gr^2}{\mu}. \quad (6)$$

From the equation, we can observe that due to the positive correlation between v and r^2 , larger bubbles exhibit a higher stable velocity. However, smaller bubbles, owing to their shorter deformation time, reach this stage earlier, enabling them to arrive at the cone base more quickly, which aligns with our experimental data.

Overall, the transportation dynamics of a bubble on a conical surface are governed by the combined effects of bubble volume, cone angle, and the conical structure itself, which collectively influence the deformation time, transition to transportation, and final velocity.

2.5 The finite element simulation of bubble transport on a conical surface

Numerical simulations are instrumental in understanding the transport characteristics of bubbles on conical surfaces. In this study, a model was developed using COMSOL software to investigate the transport state of bubbles on a superhydrophobic conical surface, with specific model

parameters shown in Figure 6. It is assumed that the bubble is at rest at time $t = 0$. The Cartesian coordinate system (x, y, z) is used to model the fluid dynamics. Gravity acts in the negative z -direction. The upper boundary of the computational domain is set as an open boundary, while the remaining walls are subjected to free-slip and no-penetration conditions. The contact angle on the cone surface is set to 150° , and the volume of the bubble is approximately $25 \mu\text{L}$, consistent with experimental data.

Figure 6c verifies mesh independence by comparing the time evolution of the instantaneous bubble velocity v_i for two fine mesh densities (3,434,389 and 3,604,466 cells). A coarse mesh (904,423 cells) caused severe bubble distortion or disappearance due to its inability to resolve surface tension and curvature at the gas-liquid interface (Figure S4, Supporting Information). Only with a sufficiently refined mesh could the bubble remain stable and exhibit realistic rising and attachment behavior. The close agreement between the two fine-mesh curves indicates that further refinement produces negligible changes in rise time and deformation, confirming the accuracy and reliability of the selected mesh.

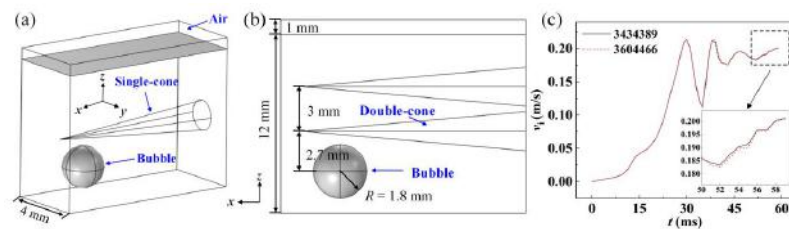


Figure 6 Specific models and parameters used in the COMSOL simulation: (a) single-cone structure; (b) double-cone structure. (c) Verification of mesh independence, with time on the x-axis and instantaneous bubble velocity on the y-axis.

The transport behavior of a $25 \mu\text{L}$ bubble on a superhydrophobic conical surface with an apex angle of 5° was first investigated (Figure 7a). At the initial contact stage (0 ms), simulation showed the bubble as a spherical shape with a diameter of approximately 1.8 mm, positioned at the tip of the conical surface, indicating negligible interaction with the surface. By 10.5 ms in the simulation, the bubble exhibited slight deformation, signaling the onset of surface interaction. At the maximum deformation and transition stage, exhibited pronounced teardrop shapes with evident necking. These results confirm the high fidelity of the simulation in reproducing the maximum deformation of

bubbles. For the double-cone structure, the bubble exhibited a similar evolutionary pattern but under distinct geometric constraints. Initial contact ($t = 10.5\text{ms}$) and early deformation ($t = 26\text{ms}$) aligned with experimental observations. However, the narrower cone angle induced faster lateral spreading, causing the bubble to contact the upper cone at $t = 34.5\text{ms}$. Subsequently, a curved gas-liquid interface formed between the two cones, which caused the bubbles to accelerate toward the cone base (Figure 7b). By $t = 86\text{ms}$, the bubble stabilized into a thin, elongated layer along the twin cones, consistent with the experimental trend of stabilization.

The instantaneous velocity (v_i) of the bubble on the single-cone structure reveals its dynamic behavior: initially, the bubble ascends under buoyancy, then accelerates upon contacting the cone due to surface adhesion, promoting rapid spreading. The v_i was characterized by the maximum velocity in the flow field region around the bubble. Subsequently, its velocity gradually decreases as the bubble undergoes maximum deformation, followed by a brief velocity increase during shape recovery before stabilizing for steady transport. For the double-cone structures, the bubble exhibits similar initial transport as on the single cone. Then, its velocity surges sharply due to enhanced surface adhesion when the bubble contacts the upper cone. During surface spreading, the velocity oscillates while decreasing but remains consistently higher than on a single cone. Finally, it accelerates through the inter-cone gap toward the cone base (Figure 7c).

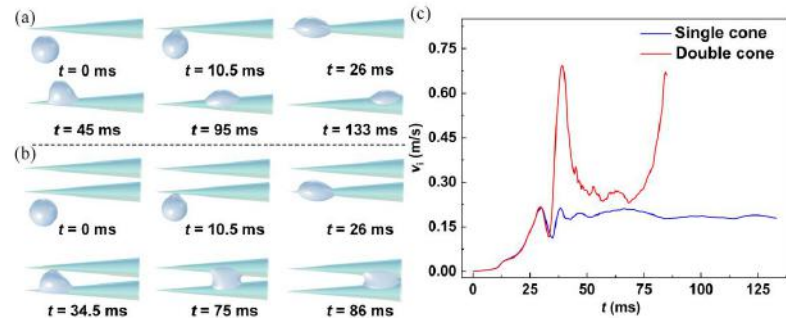


Figure 7 Simulated snapshots of key time points for bubble motion on the single-cone (a) and double-cone (b) structures. (c) The instantaneous velocity of a $25\mu\text{L}$ bubble versus time on single-cone and double-cone structures.

Figure 8 illustrates distinct fluid dynamic behaviors between single-cone and double-cone structures through velocity contour plots. At $t = 45\text{ms}$, the fluid under single-cone conditions

exhibits pronounced asymmetry in velocity distribution (Figure 8a). The left interface (cyan region) shows a peak velocity of 0.2 m/s, while the right side forms a low-velocity zone (<0.1 m/s, blue) due to contact line pinning. This asymmetry is driven by the Laplace pressure gradient induced by the curvature gradient of the single cone. When the bubble transitions to the stable transport phase ($t = 95 - 133$ ms), the velocity field on the cone surface becomes more uniform, stabilizing at a velocity of 0.2 m/s until reaching the cone base. In contrast, the double-cone structure (Figure 8b) demonstrates higher transport efficiency. At $t = 34.5$ ms, when the bubble contacts the upper cone, its velocity becomes more stable. By $t = 75$ ms, the curved gas-liquid interface formed between the double cones generates localized high-speed regions (>0.3 m/s, yellow), which accelerate bubble migration toward the cone base. This geometric constraint suppresses vertical elongation deformation, as evidenced by the improved symmetry of the velocity field compared to the single-cone case. At $t = 86$ ms, the bubble rapidly stabilizes under the combined effects of the Laplace pressure gradient and interfacial energy minimization between the double cones, achieving complete transport to the cone base 62% faster than in the single-cone structure.

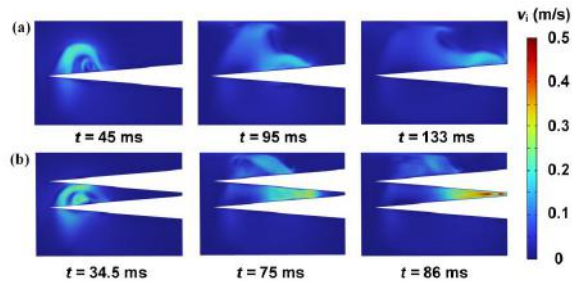


Figure 8 Velocity field visualization of bubble dynamics during the deformation-to-stabilization transition. (a) single cone structure; (b) double-cone structure.

The pressure distribution dynamics during bubble evolution on single and double-cone surfaces are illustrated in Figures 9a and 9b, which compare simulated pressure fields across six key time points. For the single cone structure, the pressure gradient evolves gradually, with localized high-pressure regions (red) emerging near the contact line between $t = 26$ ms and $t = 45$ ms, corresponding to the onset of significant deformation (Figure 9a). The continuous pressure fluctuations demonstrate the bubble's non-equilibrium state, with a residual pressure of ~ 120 Pa still observable near the conical base at $t = 133$ ms. In contrast, the double-cone structure exhibits

accelerated pressure equalization due to geometric confinement. At $t = 34.5$ ms, a distinct high-pressure zone forms between the double cones (Figure 9b). The symmetric pressure distribution at $t = 75$ ms contrasts with the persistent asymmetry in the single-cone structure at $t = 95$ ms, where residual high-pressure regions near the apex indicate incomplete equilibrium. On the single cone, the continuous increase in pressure indicates that surface bubbles are still in the stage from maximum deformation to stable transport (30 ms - 75 ms), whereas on the double cone, the gradual decrease in pressure within this range suggests that the bubbles rapidly reach a stable state, suppressing vertical deformation. However, when the bubble rapidly reaches the cone base ($t = 86$ ms) between the double-cone structure, it generates a transient pressure of up to 300 Pa on the conical surface, which then rapidly decays until stabilizing (Figure 9c). These results correlate with the observed stabilization trends, where the double-cone geometry reduces steady-state formation time compared to the single cone, underscoring the critical role of curvature gradients in modulating pressure-driven transport.

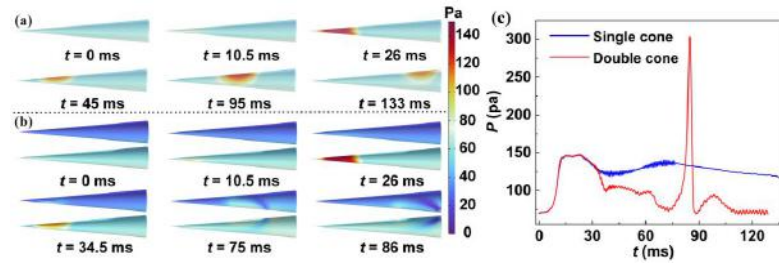


Figure 9 Instantaneous surface pressure distribution on the cone structure. (a) single-cone structure; (b) double-cone structure. (c) The relationship between instantaneous surface pressure and time for both single-cone and double-cone structures.

To better understand the factors influencing bubble transport on conical surfaces, the effects of surface wettability and fluid viscosity were examined (Figure 10a and 10b). Surface wettability was represented by the contact angle θ , while the fluid viscosity μ was varied between 0.5×10^{-3} and $2 \times 10^{-3} \text{ Pa}\cdot\text{s}$. In both geometries, the average bubble velocity v_a increased with θ , as larger contact angles reduce contact area and contact-line pinning, enabling the capillary driving force to act more efficiently [41]. The double-cone geometry consistently produced higher v_a values than the single-cone. In contrast, v_a decreased slightly with increasing μ due to greater viscous dissipation, though the double-cone maintained a clear advantage under all simulation conditions. The experimental

average velocity for the single-cone structure was higher than the simulated value, primarily because the simulation assumed an idealized smooth superhydrophobic surface and neglected the presence of surface gas films in the actual cones. These gas films can greatly reduce the hydrodynamic drag on the bubbles, thereby accelerating their transport [38]. In contrast, for the double-cone structure, the acceleration effect is predominantly governed by the geometric guidance provided by the interconnected conical surfaces (Figure 8b). As a result, the influence of surface gas films is markedly diminished, leading to a close agreement between the experimental velocity (0.208 m/s) and the simulated value (0.199 m/s). This high degree of consistency further validates the effectiveness and reliability of our simulation approach.

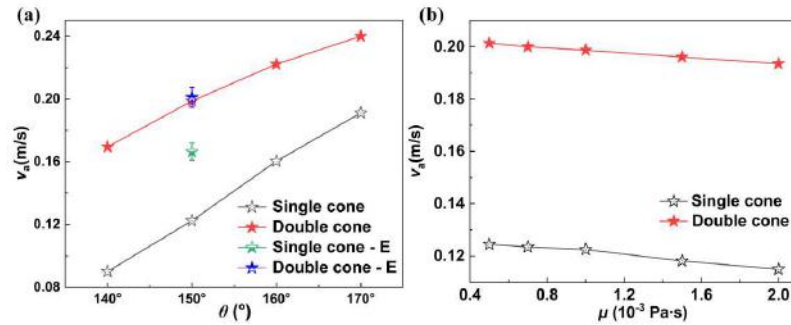


Figure 10 Variation of the average bubble velocity on single- and double-cone surfaces with (a) contact angle and (b) liquid viscosity. The green and light blue colors represent the v_a of bubbles in the experiments on single- and double-cone surfaces with a contact angle of 150°.

The elongated bubbles exhibited asymmetry relative to the central axis of the cone. Therefore, it is of considerable interest to investigate how placing additional cone surfaces at different positions in three-dimensional space influences bubble transport. To this end, we constructed and analyzed off-axis cone arrangements, including double-cone configurations with horizontal, 30° inclined, and 60° inclined arrangements, as well as a triple-cone array with a triangular apex arrangement (Inset in Figure 11a). The results show that bubbles achieved the highest average transport velocity on vertically aligned double-cone surfaces, followed by the horizontal and 60° arrangements; the triple-cone configuration with an equilateral triangular arrangement ranked third, while the 30° inclined arrangement yielded the slowest transport (Figure 11a). The reduced performance of the 30° configuration is attributed to the larger horizontal offset between cones, which forces bubbles

to undergo greater lateral displacement before making contact, thereby prolonging the contact time. In contrast, the 60° arrangement positions the second cone closer to the bubble's vertical ascent path, where the combined effects of buoyancy and flow guidance facilitate faster contact (Figure 11b). The triple-cone configuration exhibited slower transport than the vertical double-cone due to its longer and more complex path, along with increased resistance from multiple surface contacts—the vertical double-cone, in comparison, provides a direct, well-guided pathway with minimal resistance. These simulations elucidate the mechanisms by which lateral offsets and triangular apex arrangements influence bubble deformation and transport pathways, offering a unique perspective for the manipulation of bubble motion.

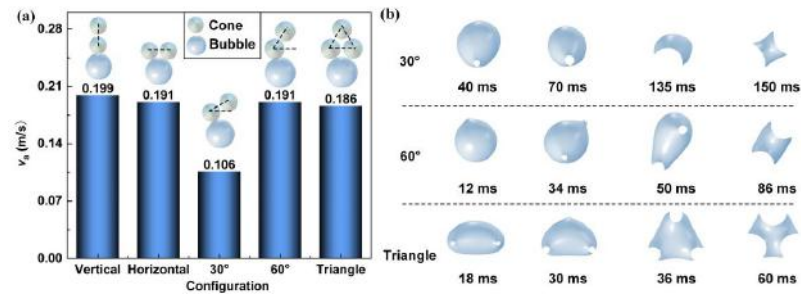


Figure 11 (a) Average bubble transport velocity on cone surfaces with different configurations. Insets are schematic illustration of different cone arrangement models. (b) Morphological changes of bubbles on cone surfaces with different configurations.

3. Conclusions:

In summary, a suspension of fluorinated silica nanoparticles was prepared and spray-coated onto conical surfaces to achieve superhydrophobicity and enhanced bubble adhesion on the conical substrates. The results demonstrate that the transport velocity of bubbles on conical surfaces increases with increasing apex angles, while larger bubbles exhibit lower velocities compared to smaller ones. Concurrently, the time for bubbles to reach maximum deformation decreases as the apex angles increase, with smaller bubbles achieving this much faster than larger ones. This observation fundamentally explains why smaller bubbles attain higher transport velocities on conical surfaces. The introduction of a double-cone structure facilitates faster completion of bubble deformation and transition to stable transport, thereby enhancing the transport velocity. Specifically,

the curved interface formed between the double-cone structures, along with the initial gas film at the cone bottom, collectively accelerates bubble transport towards the cone base. Ultimately, COMSOL simulations not only validated the experimental observations but also provided mechanistic insights into the dual role of double-cone structure in stabilizing and accelerating bubble transport, achieved through detailed analyses of instantaneous surface pressure and velocity fields. Meanwhile, the simulations also revealed that increasing the surface contact angle enhances bubble transport velocity, whereas increasing fluid viscosity slightly decreases it. Furthermore, the results demonstrate that lateral offsets and triangular apex arrangements significantly affect bubble deformation and transport, with vertically aligned double-cones achieving the fastest transport and 30° inclined configurations the slowest. These computational findings confirm that geometric confinement and interfacial pressure redistribution in double-cone architectures are decisive factors for efficient bubble manipulation, having become indispensable in the development of advanced microfluidic systems and subaquatic gas-capture technologies.

ABBREVIATIONS

SBC	Superhydrophobic circle
WCA	water contact angle
BCA	bubble contact angle

NOMENCLATURE

α	Conical apex angle (°)
v_a	bubble average velocity (m/s)
v_i	bubble instantaneous velocity (m/s)
F_b	buoyancy force (N)
F_c	vertical component of the capillary force (N)
V	bubble volume (L)
ρ_l, ρ_g	liquid and gas densities (kg/m ³)
L	contact line length (m)
θ	contact angle (°)
F_n	normal force (N)
ΔP	pressure difference across the gas-liquid interface (Pa)
t_d	characteristic deformation time (s)
r	characteristic radius of the bubble (m)
σ	surface tension coefficient (mN/m)
R_1, R_2	principal radii of curvature (m)
F_d	fluid drags (N)
μ	liquid viscosity (mPa s)

SUPPLEMENTARY MATERIAL

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See the supplementary material for more details of the SEM images of superhydrophobic surfaces(S1), Snapshot of the transport of a 2.5 μL bubble on a conical surface with a 5° apex angle (S2), Snapshot of the transport of a 25 μL bubble on a triple-cone surface with a 5° apex angle (long release distance) (S3), Simulation snapshots of bubbles on a single cone under a coarse mesh (904,423 cells) (S4).

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Xiang Gao: Conceptualization (equal); Data curation (equal); Investigation (equal); Resources (equal); Software (equal); Writing - original draft (equal). **Hong-Yang Ning:** Methodology (equal); Software (equal); Supervision (equal). **Yun-Yun Song:** Resources (equal); Software (equal); Supervision (equal); Visualization (equal); Writing - review & editing (equal). **Verdin Patrick:** Resources (equal); Software (equal); Supervision (equal); Visualization (equal). **Fu-Jian Zhang:** Formal analysis (equal); Methodology (equal); Validation (equal); Visualization (equal). **Zhong-Qiang Zhang:** Data curation (equal); Investigation (equal); Software (equal); Validation (equal).

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Supporting Information

Influencing mechanism of buoyancy-induced micro-deformation on bubble horizontal transport along conical surfaces

Xiang Gao¹, Hong-Yang Ning¹, Yun-Yun Song¹, Patrick Verdin², Fu-Jian Zhang^{1, a)}, Zhong-Qiang Zhang^{1, a)}

¹ School of Mechanical Engineering, Jiangsu University, Zhenjiang 212013, PR China

² Faculty of Engineering and Applied Science, Cranfield University, Cranfield, MK43 0AL, UK

^{a)} Author to whom correspondence should be addressed: zhangfj@ujs.edu.cn and zhangzq@ujs.edu.cn.

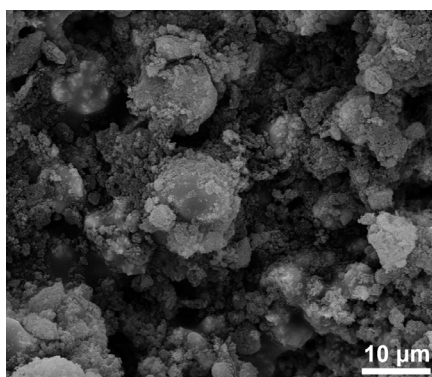


Figure S1 SEM images of superhydrophobic surfaces

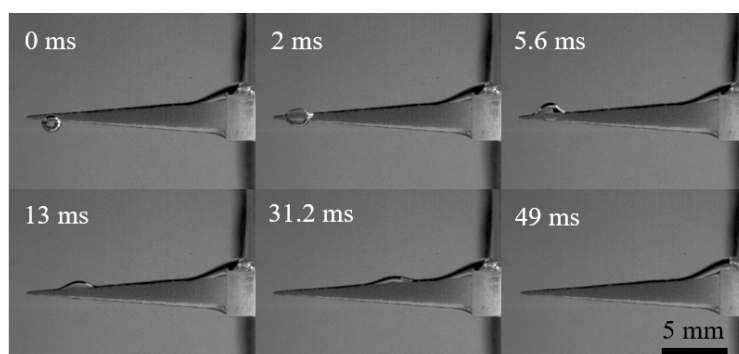


Figure S2 Snapshot of the transport of a 2.5 μL bubble on a conical surface with a 5° apex angle.

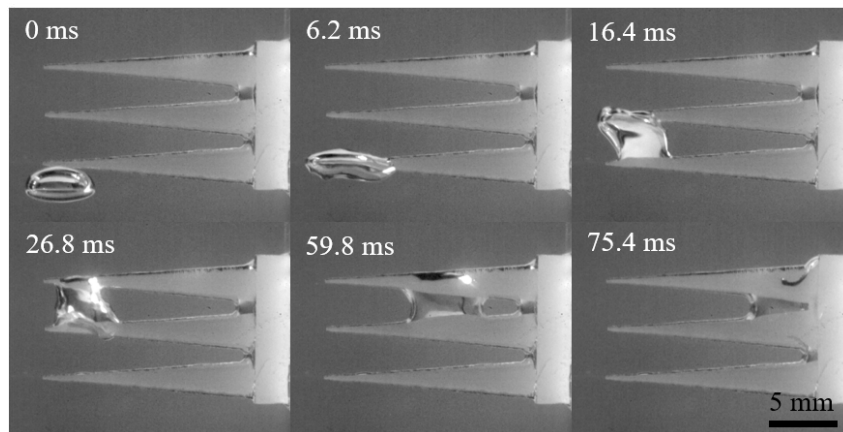


Figure S3 Snapshot of the transport of a 25 μL bubble on a triple-cone surface with a 5° apex angle (long release distance).

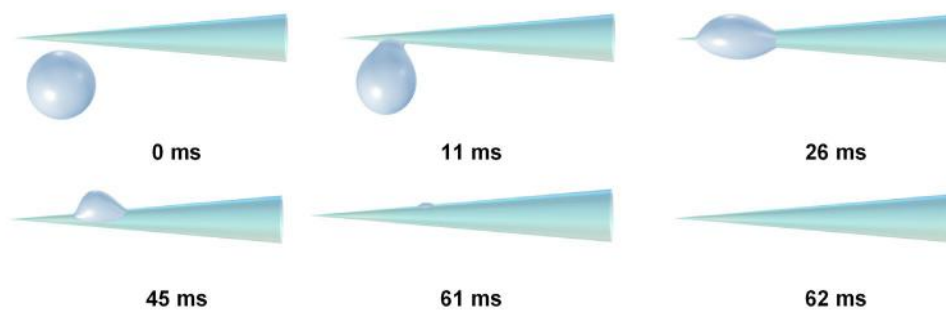


Figure S4 Simulation snapshots of bubbles on a single cone under a coarse mesh (904,423 cells).



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