Capturing Bubbles and Preventing Foam Using Aerophilic Surfaces

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Bubbles are common in nature and the ability to capture them is advantageous in many industrial applications. Here, the authors propose how surfaces can be designed to capture rising bubbles in a liquid column upon contact. When a rising bubble approaches a horizontal surface, the thin liquid film separating the bubble and the surface needs to be drained for the bubble to be captured by the surface. The authors design aerophilic surfaces that can efficiently drain liquid films upon bubble contact, and show how their ability to catch bubbles relates to their texture parameters. The authors develop a physical model, based on surface slip length and liquid properties, to determine when the film would drain. Then they use these findings to design a plastron encased surface comprising textures across three length scales, which enables capture upon contact and a reduction of two orders of magnitude in capture time relative to a flat surface. Finally, the authors use these principles to create an easily scalable device that passively captures a rising flow of bubbles in a surfactant rich solution. This technology can be utilized to prevent foam from forming in bioreactors and fermentation tanks and eliminate the use of antifoaming agents.

1. Introduction

Bubbles are ubiquitous in our everyday lives and in many industrial applications. The ability to capture bubbles in a controlled manner could have an impact on a wide variety of fields such as energy, biomedicine, desalination, as well as many others. Methane for example is the second largest contributor to global warming and has 25 times the global warming potential of carbon dioxide.\[1,2\] Its release rate from wetlands and freshwater sources due to ebullition was shown to correlate to temperature rise in various places across the world.\[3,4\] Capturing methane bubbles before they are released to the environment could have a significant environmental impact and could potentially serve as an additional source of energy. Another example is foam buildup, which is a common challenge across a wide range of industries such as paper, coatings, water treatment, food and beverage, agrochemical, biochemical, and others.\[5,6\] Capturing gas bubbles as they rise through the bulk of a bioreactor for example could passively prevent foam from forming and mitigate associated adverse effects such as cell death\[7,8\] and reduced product yield.\[9\] Controlled bubble capturing can also improve pool boiling by allowing for faster replenishment of bubbles on the heat transfer surface and thereby improving the performance of heat exchangers and desalination plants.\[10,11\]

In order to capture bubbles we use aerophilic surfaces, which are class of surfaces that are sufficiently non-wetting so that they can sustain an air layer between their features when submerged. This layer is called a plastron and it is used by insects and spiders for underwater respiration.\[12–14\] and can be utilized to introduce slip\[15\] and reduce drag in various applications.\[16–18\] It is important to note that the requirement for a surface to be aerophilic is more restrictive than for it to be superhydrophobic and that the two terms are not always interchangeable.\[19\] Plastron stability over time also depends on the geometrical and chemical properties of the surface.\[20–22\] There have been promising studies that demonstrated the use of both natural and artificial aerophilic surfaces to capture bubbles.\[23–27\] yet the relationship between surface parameters and the dynamics of bubble capturing remains elusive. This relationship is important in many practical applications, as bubbles are not gently deposited but rather impact onto surfaces. These impacting bubbles often bounce off the surface multiple times before they are arrested, thereby increasing the probability of their escape without being captured by the surface. Thus, minimizing the time it takes for an aerophilic surface to capture bubbles is critical. To the best of our knowledge, prior studies have not established the quantitative measures and physical mechanisms underlying dynamic capture of bubbles and have not demonstrated the design rules to achieve bubble capture upon initial impact by aerophilic surfaces. Furthermore, the use of these surfaces has been demonstrated only in pure liquids whereas many practical applications require bubble capturing in surfactant rich solutions.

In this work we study the impact of bubbles on aerophilic surfaces in various liquids. We define a quantitative measure of the ability of an aerophilic surface to capture bubbles, and create a theoretical framework to analyze the underlying dynamics of bubble capturing. We use this framework to establish design...
guidelines for aerophilic surfaces with enhanced bubble capturing ability, and show how the addition of nano-textured macroscale features can reduce the capture time by an order of magnitude compared to other aerophilic surfaces. We then use these findings to create multiscale aerophilic surfaces and incorporate them in a device that can be submerged into surfactant rich solutions, capture bubbles in bulk, and prevent foam from forming.

2. Results

2.1. Capturing Bubbles

To analyze the effect of surface parameters on bubble capture we use a submerged needle to release bubbles onto a leveled surface at varying distances as shown in Figure 1a, where \( R \) is the instantaneous distance of the bubble centroid from the surface. The bubble diameter is chosen to maximize its terminal velocity, \( U_{\text{term}} \) [28]. We record the impact using a high speed camera and reconstruct the bubble trajectory by tracking its centroid as can be seen in Figure 1b (see Section 4). As the bubble approaches a flat surface its velocity reduces from its terminal value due to the presence of the surface. When the velocity reaches negative values, the bubble starts to move away from the surface and regains its spherical shape to complete a single bounce. With each bounce, the energy of the system is dissipated until it rests on the thin liquid film separating it from the surface. This film drains until it reaches a critical value at which it ruptures and the surface captures the bubble [29–31]. We define the time from the initial deceleration from terminal velocity to the point at which the surface captures the bubble as \( t_{\text{capt}} \).

We examine the influence of surface parameters on the capture time by performing bubble impact experiments on hydrophobic surfaces with different texture morphologies (see Section 4). Specifically, we compare a flat hydrophobic surface to hydrophobic surfaces with micro- and nanotextures as shown in Figure 1c–e, and the respective dependence of velocity versus time is shown in Figure 1i. After the bubble is captured, its shape is governed by the surface coverage of the plastron (Figure 1f–h). Plastron surface coverage also influences the bubble capture time as can be seen from Figure 1i,j. Specifically, capture time on a nano-textured surface is a fraction of the corresponding value on a flat hydrophobic surface as the nano-textured surface captures the bubble during its second bounce. To understand the fundamental principles governing bubble capture and the dependence of capture time on plastron coverage, we examine the drainage dynamics of the thin liquid film separating the bubble and plastron.

2.2. Dynamics of Film Drainage

To analyze the drainage dynamics we model the film as a cylinder with diameter \( D_b \), the basal diameter of the bubble, and thickness \( h \), which is the spatial average of the varying film thickness across the basal area of the bubble (Supporting Information). We use a hydrodynamic drainage model to derive an expression for the time it takes the film to drain to the critical thickness \( h_{cr} \) at which the film breaks (see Supporting Information)

\[
t_{d} \sim \frac{\mu \frac{D_b^2}{h}}{P_{\text{film}} h^2}
\]

\[
\tilde{h}^2 = \begin{cases} \frac{h_{cr}}{\beta} & \beta = 0 \\ \frac{h_{cr}}{\beta} & \beta > h_{cr} \\ \end{cases}
\]

where \( \mu \) is the viscosity, \( P_{\text{film}} \) is the equivalent pressure in the film (Supporting Information), and \( \beta \) is the slip length (the case of \( 0 < \beta < h_{cr} \) can be solved numerically and is not discussed here as \( \beta > h_{cr} \) for all plastron sustaining samples used in this work) [15]. If the bubble is sufficiently slow so that \( U < \sqrt{\frac{D_b}{\rho}} \) (\( U \) is the bubble velocity, \( D_b \) is the undeformed bubble diameter and \( g \) is the acceleration due to gravity) the equivalent pressure in the film is the result of buoyancy and deceleration of the bubble (see Supporting Information) [30]

\[
P_{\text{film}} = \frac{2 \Delta \rho g D_b^3}{3} \left( 1 - C_m \frac{dU}{dt} / g \right) \left( \frac{D_b}{D_b} \right)^3
\]

where \( \Delta \rho \) is the density difference and \( C_m \) is the coefficient of added mass. The force dominating pressure buildup in the film as well as its drainage is dictated by the ratio \( (-C_m dU/dt) / g \). When this ratio is greater than unity, film drainage is governed by the bubble’s deceleration and the system is in the inertial drainage regime. When this ratio is smaller than unity, we find that film drainage is governed by buoyancy and the system is in the buoyant drainage regime.

In order to calculate this ratio we perform bubble impact experiments on samples with varying plastron coverage. Specifically we use samples decorated with square microposts of size \( a = 10 \mu m \) and varying wall-to-wall pitch \( h = 5, 10, \mu m \), and a sample with 50 \( \mu m \) pyramidal structures with submicron textures on their walls which we denote as a “low \( \phi \) surface” (\( \phi \) is the ratio of emerged surface area to projected surface area, see Supporting Information). We also use a flat hydrophobic sample that does not sustain a plastron. We extract the bubble velocity profile for impacts on each of the samples and calculate the deceleration to gravity ratio for each bounce on each of the surfaces. As shown in Figure 2a, this ratio does not change between samples, as the bubble deceleration is similar for all surfaces. We then use these values to get the ratio \( (-C_m dU/dt) / g \) shown in Figure 2b and find that in the first couple of bounces the deceleration of the bubble dominates buoyancy so that the system is in the inertial drainage regime. However, as the bubble’s energy is dissipated with each bounce the deceleration to buoyancy ratio decreases and from the fifth bounce the system transitions into a buoyant drainage regime. Note that except for the low \( \phi \) surface, the system always enters the buoyant drainage. In the case of a low \( \phi \) surface, the bubble is captured in the inertial regime during its second bounce on the surface.

For both the inertial and the buoyant drainage regimes, bubble capturing is governed by drainage of the liquid film separating the bubble and the surface as illustrated in Figure 2c. In the inertial drainage regime, film drainage is limited by the bubble residence time on the surface during an impact.
If during this time the film reaches the critical film thickness, then the bubble will be captured by the surface. If during this time the film does not reach the critical film thickness, then the bubble will bounce away. In the buoyant drainage regime, on the other hand (after the fifth bounce) the bubble resides on the thin liquid film until it is captured.
To understand the relationship between surface properties and capture regime we first need to find the critical thickness $h_{cr}$ at which the liquid film separating the bubble and the surface drains. To fulfill that purpose, we perform buoyant drainage experiments, in which we release a bubble close to a surface, and measure the time until the bubble is captured and the triple contact line is established. In these experiments, we vary bubble diameter, liquid viscosity, and surface parameters and measure the capture time $t_b$ as shown in Figure 2d (the subscript b is to emphasize that during each of these experiments the system is in the buoyant drainage regime). We apply the drainage time analysis presented in Equations (1) and (2) to derive an expression for the capture time $t_b$ and use linear regression to find

$$t_b \sim \mu \times (\Delta \rho g)^{1/2} \times \left(\frac{D_b}{D}\right)^{3/2} \times \left(\frac{D_b^2}{h_b^2}\right)^{1/2}$$

(see Supporting Information) and use linear regression to find

**Figure 2.** Thin film drainage dynamics. a) Bubble centroid position normalized by bubble radius ($\bar{R} = 2R/D$, represented by a solid line) and bubble velocity normalized by its terminal velocity ($\bar{U} = U/U_{term}$, represented by a dashed line) as a function of time during an impact on a surface. We consider drainage to occur when the bubble centroid is less than one radius away from the surface, and a bounce as a finite period of time during which the film is draining. The five bounces of the bubble are highlighted and numbered. We approximate the deceleration of the bubble during a bounce by a constant as shown here in red. b) Bubble deceleration to buoyancy ratio for four different surfaces. The drainage is dominated by inertia during the three first bounces and by buoyancy for the later ones. On the low $\varphi$ surface, the film ruptures at the second bounce in the inertial regime. c) Illustration of film drainage. The film is considered to be flat with an equivalent thickness $h$ and a basal area $\pi D_b^2/4$. A no-slip boundary condition is used for a flat hydrophobic surface, while a slip length boundary condition is used for the plastron containing surfaces. d) Capture time $t_b$ of bubbles with different diameters released close to the surface in solutions of different viscosities. The capture time increases with liquid viscosity, and decreases substantially when the bubble is impacting the low $\varphi$ surface regardless of bubble size or liquid viscosity. e) Scaled data for capture time using the flat film model. The solid line is obtained by linear regression with a fitting parameter $h_{cr} = 5 \mu m$. The slope of the linear regression is 0.73. The legend was changed so that the surfaces are represented by the associated value of slip length $\beta$. f) Ratio of the minimum equivalent thickness $h_{min}$ reached during each bounce and $h_{cr}$. The minimal thickness is lower than the critical thickness only for low $\varphi$ surface and it is the only surface that is able to capture bubbles in the inertial regime. Furthermore, the model predicts that the capture occurs at the second bounce as observed. The minimum film thickness reached during the first bounce on the other samples is in the order of 50 $\mu m$. 

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an equivalent critical film thickness of $h_{cr} = 5 \, \mu m$ as shown in Figure 2e.

We then use this value to assess whether the bubble can be captured during one of its bounces in the inertial drainage regime. Specifically, we compare the critical film thickness to the minimal film thickness achieved in each of the bubble’s bounces in the inertial drainage regime (see Supporting Information). As can be seen in Figure 2f, on the micro-textured surfaces as well as for a flat hydrophobic surface, the minimal film thickness to which the film drains in each of the bounces is larger than the critical film thickness and the bubble is not captured in the inertial drainage regime. In contrast, the low $\varphi$ surface captures the bubble within the second bounce as the film drains past the critical value as shown in Figure 2b. The capture time on the low $\varphi$ surface is substantially shorter than on the other surfaces as it is reduced from hundreds of milliseconds on the flat surface to tens of milliseconds.

### 2.3. Enhanced Capturing

To reduce the capture time even further we aim to drain the film during the first impact of the bubble and before it bounces away from the surface. To achieve this we created a high slip length surface comprising macrotextures in the form of localized protrusions with a conformal plastron as shown in Figure 3a,b. We use laser scanning confocal microscopy (see Section 4) to confirm the presence of this continuous microlayer across the surface as shown in Figure 3c. The size of these protrusions is chosen to be an order of magnitude greater than the minimal equivalent film thickness achieved during the bubble's first bounce (see Supporting Information). As shown in Figure 3d, the bubble is captured by the surface upon initial impact without bouncing away from the surface. As can be seen in Figure 3e, the corresponding capture time is a mere few milliseconds, which is an order of magnitude reduction relative to other areas of the sample. Interestingly, as long as the basal area of the bubble comes into contact with the protrusion the capture time of a bubble is agnostic to its lateral location relative to the protrusion, as shown in Figure 3f. This is also true in the case of surfactant solutions. However, in this case the efficacy region of the protrusion is smaller since bubbles in surfactant solutions are stiffer, slower, and thus have a smaller basal area upon impact.

To conclude, we were able to reduce the capture time of a bubble by a hydrophobic surface by two orders of magnitude from hundreds of milliseconds to a mere few milliseconds. A first order of magnitude reduction (hundreds of milliseconds to tens of milliseconds) was achieved by changing the textures of the sample so that its slip length is substantially larger than the critical film thickness. An additional reduction in order of magnitude (tens of milliseconds to a few milliseconds) was achieved by preventing the bubble from bouncing away from the surface using plastron protrusions as shown in Figure 3g.

![Figure 3. Enhanced drainage. a) Illustration of a bubble with horizontal radius $R$ approaching a protrusion at a lateral distance $W$ to the bubble centroid. b) SEM image of the protrusion. Scale bar is 100 $\mu m$. c) Laser scanning confocal microscope image of a submerged surface showing a plastron protrusion of 168 $\mu m$. d) Frame sequence of a bubble impacting a protrusion (see video S5, Supporting Information). Film breakage and establishment of the triple contact line occurs on top of the protrusion. Scale bar is 1 mm. e) Velocity profile of an impact on (solid line) and off (dashed line) the protrusion normalized by the terminal velocity. When the bubble impacts the protrusion, the capture occurs during the initial impact. f) Normalized capture time as a function of the normalized lateral distance $W/R$ for water (● 72 mN m$^{-1}$) and surfactant solution (○ 45 mN m$^{-1}$). The capture time is normalized by the average value away from the protrusion($W/R \geq 1$). The capture time on the protrusion is independent of the lateral distance and is an order of magnitude lower than the capture time away from the protrusion. g) Capture time for impacts at terminal velocity on a flat hydrophobic surface (left), low $\varphi$ surface (middle), and on a protrusion (right). By combining high slip length and plastron protrusion, a two orders of magnitude reduction of the contact time is achieved.](image-url)
2.4. Foam Prevention

We use the principles developed in the previous sections to prevent foam formation by catching bubbles as they rise through the bulk of the solution as illustrated in Figure 4a. In bioreactors and fermentation tanks, there is a tradeoff between introducing gas by ebullition and the foam that is generated as a result. To prevent the foam, antifoaming additives (defoamers) are added to the broth to break the foam in a controlled manner. These defoamers then need to be filtered and bioassays that insure their removal need to be introduced to the process. Apart from the additional costs that defoamers introduce, breakage of the foam gives rise to large shear stresses within the foam lamella that can cause trapped cells to denature. We construct a device that contains a multiscale surface comprising porous stainless steel plate and a stainless steel mesh that are rendered superhydrophobic so that the contact angle of a water droplet on these surfaces is greater than 160° (see Section 4). The porous stainless steel plate effectively acts as a high slip length surface while the mesh is chosen so that the wire diameter is similar to the size of the protrusion shown in the previous section. Furthermore, the distance between two adjacent wires in the mesh is on the order of a typical bubble diameter to ensure impact of incoming bubbles on at least one of the protruded elements. As shown in Figure 4b the porous plate and the mesh are sandwiched between two 3D printed parts, an enclosure and a cover, as well as an O-ring seal to create a sealed device. The device is connected to a tube which provides a continuous gaseous pathway between the environment and the porous mesh when the device is submerged.

We use this device in a foaming solution (see Section 4) after a stable foam layer has been formed. After the device is submerged into the solution it disrupts the balance between bubbles rising into the foamy layer and foam breakage by continuously collecting gas from bubbles that would otherwise add to the foamy layer. Consequently, the foam layer decreases until it is finally reduced to a fraction of its initial size. In contrast when a flat hydrophilic (see Section 4) is used instead of the porous stainless steel plate and the mesh it does not reduce the foam thickness as shown in Figure 4e–g and Video S6, Supporting Information.

Figure 4. Foam prevention. a) Illustration of the experimental setup where bubbles are generated using a sparger. The detail shows the multiscale aerophilic stainless steel surface, which enables a continuous gaseous pathway from the surface on which the bubbles impact to the outer environment. b) Exploded view of the device components. c) An image of the operational parts of the device, which include the porous plate and the mesh. Scale bar is 1 mm. d) SEM image of the porous mesh. Scale bar is 50 µm. e) Foam thickness as a function of time. At t = 0, the device is immersed into the solution where bubbles are rising. The foam thickness then decreases to reach a plateau in 10 min. A control experiment is performed using a flat hydrophilic plate instead of the porous plate and the mesh. The control has no effect on the foam thickness over time. f,g) After 10 min the foamy layer reduced to a residual thickness of 1 cm (see video S6, Supporting Information).
3. Summary and Discussion

In this work, we have shown how the ability of aerophilic surfaces to captures impacting bubbles depends on the structure of their micro and nanotextures. A bubble is captured after the thin liquid film separating it from the plastron is drained to a critical value. The thin film's spatiotemporal evolution can be described more accurately by the Stokes–Reynolds model that takes into account the dimple shape of the water–bubble interface.\cite{32,33} However, by taking the average position of this surface, and without neglecting its curvature, we can derive a scaling law that describes the attachment dynamics and highlights the dependency of capture time and surface parameters such as the slip length. This model also allows us to achieve a value for the equivalent critical thickness of the film, $h_{cr}$, which is on the order of values that have been achieved using the Stokes–Reynolds model.\cite{30}

The drainage of this film is due to pressure buildup which is driven by two forces: the deceleration of the bubble and buoyancy. When the deceleration of the bubble is smaller than the gravitational acceleration $g$, the system is in the buoyant drainage regime. In this regime, the pressure in the film is due to buoyancy and it drains the film until the critical film thickness is reached and the bubble is captured. When the deceleration of the bubble is larger than the gravitational acceleration $g$, the system is in the inertial drainage regime. In this regime, the pressure in the film is due to bubble deceleration and it is larger than the pressure in the buoyant drainage regime. However, this pressure acts for a limited time, which is the residence time of the bubble on the surface during a bounce. If during this time film thickness reaches the critical value, the bubble will be captured by the surface. Otherwise, the bubble will bounce away.

To catch bubbles efficiently, the slip length of an aerophilic surface needs to be substantially larger than the critical film thickness (a few microns). By using a surface with low solid fraction and large slip length (tens to hundreds of microns), drainage time can be reduced by up to an order of magnitude and a bubble can be captured during the inertial drainage regime. Capture time can be minimized further by an additional order of magnitude when the surface has local plastron protrusions in addition to high slip length. These protrusions can catch bubbles during their first bounce provided that they are larger than the thickness to which the film drains during the bubble's first bounce. Overall, we have shown that capture time can be reduced by two orders of magnitude from hundreds of milliseconds to only a few milliseconds by increasing slip length beyond the critical thickness and introducing large plastron protrusions.

Finally, we use these principles and design guidelines to create a submerged bubble-catching device, which is based upon an aerophilic surface with sub millimetric protrusions. This device is passive and can be retrofitted to existing reactors to prevent foam formation by capturing bubbles as they rise through the bulk. Furthermore, this method is environmental friendly as it can replace the use of antifoaming agents, which are a popular method for foam mitigation. As the performance of the device is dependent only on the existence and stability of a plastron, this design can be extended to other applications such as capturing methane bubbles from wetlands, and removing vapor from heat transfer surfaces in boiling applications.

4. Experimental Section

**Experiment Setup:** Single bubbles were generated using a syringe pump (Pump 11 Elite by Harvard Apparatus) with a 3 mL syringe (by BD) connected to a j-shaped needle of various gauges to generate bubbles of different diameters (gauges 20, 25, 26, and 30 by McMaster) under a constant flow rate of 20 µm s\(^{-1}\). The sample was placed on a colorimeter cell (by Starna Cell) which was placed onto a two-axis goniometer stage (by Thorlabs) leveled to 0.0° on roll and yaw. To allow impact on predetermined locations on the sample, the needle was connected to a 3-axis stage (XYZ stage by Thorlabs). For impacts in the buoyant regime, the needle’s tip was placed at the minimal distance ensuring bubble detachment without touching the sample. For impacts at terminal velocity, the needle’s tip was ≈25 mm away from the sample. The bubble’s terminal velocity was verified by comparing to known values.\cite{30}

**Samples:** The textured silicon surfaces used in this study were prepared by a standard photolithography process. The resulting micro-posts had a square geometry with width $a = 10 \, \mu m$ and varying pitch $b = 5, 10 \, \mu m$. The low $\varphi$ surface was prepared using a 1064 nm Nd:YAG laser (TYMKA ElectroX) which was used to ablate a flat silicon surface in a controlled pattern. The resulting texture consisted of closely packed and reproducible pyramidal features spaced ≈50 µm apart and 50 µm deep that were covered with submicron features. The samples were then cleaned in an oxygen plasma chamber (PDC-32G-2 by Harrick Plasma) at 200 mTorr for 20 min and treated with a low-energy silane octadeicylchlororosilane (advancing and receding contact angle of water on a flat surface in the presence of air were $\theta_{w(s),adv} = 109.4^\circ \pm 0.5$ and $\theta_{w(s),rec} = 100.1^\circ \pm 1.1$, or perfluoroocylchlororosilane ($\theta_{w(s),adv} = 112.4^\circ \pm 0.7$ and $\theta_{w(s),rec} = 93.4^\circ \pm 3.3$). Both were purchased from Sigma-Aldrich and used without modification. The nano-textured samples were obtained by spraying hydrophobic nanometric silicon particles (Glaco by Soft 99) onto flat silicon wafers. The foam prevention device was prepared by sandwiching a porous stainless steel plate (20 µm grade by Wald Krause Engineering) and a mesh (0.7 mm opening, 0.16 mm wire diameter by McMaster) between two custom 3D printed parts and an O-ring seal (McMaster). These surfaces were rendered superhydrophobic by functionalization with fluorophosphoric acid (Sigma-Aldrich) and by adding a layer of hydrophobic nanoparticles by spray coating (Neverwet by Rust-Oleum).

**Fluids:** Mixtures of DI water (18.2 MΩ cm from Milli-Q Integral System by Millipore) and Glycerol (Sigma-Aldrich) of different viscosities were obtained by mixing the appropriated quantities during 12 h with a magnetic stirrer at 220 rpm. The device was placed in a foaming solution of Tween 80 (by Sigma-Aldrich) in water at a concentration of 0.012 m$\text{w}$ (twice the CMC, surface tension 45 mN m$^{-1}$) into which bubbles were introduced using a sparger (5 µm grade media by Wald Krause Engineering) connected to house air.

**Dynamic Analysis:** The dynamics of single bubble impact were recorded using high-speed photography (Fastcam SA1.1 and S55 by Photron) and a high magnification lens (x12 by Navitar) at up to 40 000 frames per second. Image analysis was performed using imageJ. The performance of the foam preventing device was recorded with an optical camera (D800 with a 70–180 mm lens, both by Nikon).

**Procedures:** Contact angles and surface tension were measured using a Goniometer (Model 500 by Ramé-Hart). The advancing and receding angles were taken as an average of at least three measurement on different locations on the surface. The advancing angle was measured by adding water to a 5 µL water droplet at a rate of 4.2 nL s\(^{-1}\) while measuring the diameter of the triple contact line. When the diameter started to increase, the measured contact angle was taken as the advancing contact angle. Similarly, for the receding contact angle, water was extracted from the droplet at a rate of 6.7 nL s\(^{-1}\) and the receding
was used. The sample was immersed in a 0.05 mg L $^{-1}$ water-immersion lens microscope (LSM 880 by Carl Zeiss) with a x$	imes$20 water-immersion lens was used. The sample was immersed in a 0.05 mg L $^{-1}$ solution of Rhodamine B (by Sigma-Aldrich) in water. A 514 nm wavelength laser was used to excite the Rhodamine B to receive an image for the wetted system, Dr. J. Bales and the MIT Edgerton Center for use of the high-speed camera, Dr. D. Richardson and the Harvard Center for Biological Imaging for use of the laser confocal scanning microscope, and Dr. D. Soto and Prof. S. Dash for the helpful discussions.

**Supporting Information**

Supporting Information is available from the Wiley Online Library or from the author.

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**Conflict of Interest**

The authors declare no conflict of interest.

**Author Contributions**

L.R. and T.E. contributed equally to this work. L.R., T.E., and K.K.V. designed the research. L.R. and T.E. performed the research. L.R., T.E., and K.K.V. analyzed the data and wrote the manuscript.

**Keywords**

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