## Surfactant Exchanges between Deformed Soap Films

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The effective viscosity of liquid foams is controlled by Marangoni forces and therefore by the transport of surfactants. Direct tracking of the latter during foam deformation is out of reach. Besides, the competition between diffusion and convection on the interfaces and in the bulk of complex assemblies of thin films and menisci is still an open problem. These shortcomings severely limit our understanding of foam rheology and stability. In this Letter, we use a comprehensive characterization of in-plane flows in an elementary foam during imposed deformation to determine indirectly the flux of surfactants from a film to its first neighbor. We show that the meniscus connecting the films, despite its potential role as a surfactant reservoir, is not involved in surfactant transport. This information has been identified as a key missing piece in local foam viscosity models of the literature.

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As many other complex fluids, liquid foams are viscoelasto-plastic materials whose rheological behavior is well described by a Herschel-Bulkley model [1]. However, predicting the parameters of this phenomenological law is still a challenge. Notably, the Herschel-Bulkley exponent, close to 1/2, may be explained either by the local description of the flow [2], or by a mean field theory based on the generic elastoplastic properties of athermal systems [3–5]. Liquid foams offer the unique opportunity to question these predictions, as both the plasticity field [6] and the local structure are experimentally accessible. Focusing on this second approach, previous experiments have been performed where a few foam films connected to a common meniscus are being deformed, defining the scale of what is called an elementary foam [7–10].

When a foam film is stretched or compressed, the surfactant population of its interfaces is diluted or concentrated, and the surface tension  $\gamma$  changes. The local subphase is too thin to provide or accept enough surfactants to relax toward equilibrium, and a Gibbs elasticity  $E = A(\partial \gamma / \partial A)$  can be defined, with *A* the film area [11]. However, the interfaces can relax through surfactant exchanges with the exterior, at the edges of the film. This relaxation process provides the internal timescale of the material, and is thus a key process to predict the foam effective viscosity [12].

At its boundary, a film is in contact with a meniscus, shared with two other films. On the generic example shown in Fig. 1, the horizontal film is compressed and its two neighbors are stretched. The compressed film shares the interfaces  $I_1$  and  $I_2$  with its neighbors and its surfactants can easily escape by flowing over the meniscus, convected by a Marangoni flow driven by the surface tension difference between the films. However the interface  $I_3$  cannot follow the motion of both  $I_2$  and  $I_1$  without being locally

stretched, which hinders the relaxation toward equilibrium: this is reminiscent of the geometric frustration encountered in granular stacking [13]. As already predicted in [14], the key to fully determine the foam local relaxation timescale is knowing the origin of the surfactants covering this frustrated interface. The Fig. 1(b) illustrates two possible limiting cases: (i) a transverse flux of surfactant from the other interface, or (ii) bulk diffusion from the meniscus. All the state-of-the-art models of elementary foam deformation [7–10] had to make hypotheses on this transport process to predict the relaxation rate of the films, which



FIG. 1. (a) Schematic view of the experimental setup. (b) Two limit scenarios for the surfactant transport induced by the deformation. The red and dark red surfactants are on the top and bottom interfaces of the horizontal film at t = 0. At final time, they are on the left and the interface  $I_3$  is covered either by the red surfactant having crossed the film [scenario (i), as actually measured] or by the blue surfactants coming from the meniscus [scenario (ii), which will be invalidated].

remains a fitting parameter, in the absence of experimental evidence to justify the choice.

In a preliminary work [15], the velocity field on both sides of a meniscus has been measured, during the deformation shown in Fig. 1. On the stretched side, the velocity is directed toward the film and drives some liquid out of the meniscus by viscous shear [16]. This extracted film is thicker than the film initially present, and has a well-defined boundary which was tracked to determine the velocity. On the compressed side, the velocity is directed toward the meniscus and was measured by tracking photobleached spots. However, the amount of surfactant carried by the flow depends on the film deformation state (stretched or compressed), so no quantitative surfactant mass balance could be achieved in [15].

In this Letter, we measure simultaneously the local velocity and the film deformation states, on both sides of a meniscus, during the deformation. For different foaming solutions, having a Gibbs elasticity in the range [5-10] mN/m, a mass balance around the meniscus allows us to conclude that the meniscus does not provide nor absorb any surfactants. In the experimentally accessible time range, and for the investigated deformation rates, we thus provide a clear experimental answer to this long-standing question.

An isometric view of the elementary foam used in our study is shown in Fig. 1(a), where light blue represents the three liquid films denoted as the top, bottom, and horizontal films. The meniscus they share will be called the free meniscus, by contrast with the menisci hung on the solid frames, on the three other edges of the films. The lateral edges are supported by a fixed solid frame, respecting the angle of 120° between the films. The external edge of each film is supported by a mobile frame [in dark gray in Fig. 1(a)] of length  $L_z = 45$  mm along the z direction. Each one is controlled by a piezomotor and moves in the plane of its film. We will impose a compression to the horizontal film, of length  $L^-(t)$ , and the same extension to the top and bottom films, of length  $L^+(t)$ . Both lengths are measured in the (x, y) plane.

The solution used is made with deionized water to which we add sodium dodecyl sulfate (SDS, concentration  $c_s = 5.6$  g/L, i.e., 2.4 CMC), fluorescein (0.8 g/L) and dodecanol (DOH, concentration  $c_d$ ). The reference surface tension is measured with a pendant drop method, yielding  $\gamma_0 = 37 - 34 - 33$  mN/m (for, respectively,  $c_d = 15 - 35 - 50$  mg/L), and the viscosity is assumed to be the same as pure water  $\eta = 10^{-3}$  Pa s. These solutions mainly differ by their Gibbs modulus, respectively, E = 5-8-10 mN/m, as measured in [17].

The frame is first bathed in the soapy solution and the motors are then moved during a preparatory phase, beginning at  $t_p = -4$  s and ending at t = 0 s, to produce a well defined initial state (see the Supplemental Material [18], which includes Refs. [19,20]). At t = -1 s, the motors stop



FIG. 2. Scheme of the elementary foam before (a) and after (b) the main deformation. The notation  $\pm$  indicates the stretched (+) and compressed (-) films. Their different parts are denoted (c) for central, (e) for external, and ( $\Sigma$ ) close to the free meniscus, as they belong to the system  $\Sigma$ , shown in red.

and the horizontal film is hit with a cyan laser to create two rows of photobleached circular spots of radii  $\sim 100 \mu m$ , acting as passive tracers in the film. Two cameras with filters are positioned around the setup, monitoring the fluorescent light emitted by the horizontal and top films.

The radius of curvature *R* of the free meniscus is measured with a subsidiary close-up camera, from which we get  $R = 0.39 \pm 0.02$  mm, and the thickness profile of the horizontal film is measured using a hyperspectral camera [18]. During the preparatory phase, the horizontal film is stretched, inducing a film extraction at both edges of the film initially present. These extracted films have a thickness around  $h \simeq 0.5 \mu m$  while the preexisting film has a thickness of the order of 0.3  $\mu m$ , leading to the initial thickness profiles schematized in Fig. 2(a).

At t = 0, we start deforming the three films as shown in Fig. 2: the horizontal film length  $L^-$  goes from 10 to 5 mm, whereas the top and bottom ones  $L^+$  go from 10 to 15 mm, all at  $U_{def} = 10 - 20 - 35 - 50$  mm/s.

The top film can be decomposed into three parts, clearly distinguishable on the images. Its central part  $L_c^+(t)$  is the part of the film present at t = 0. Afterward, it is bounded by two growing extracted films of length  $L_{\Sigma}^+(t)$  and  $L_e^+(t)$ , respectively, on the free meniscus and external sides. The total film length, imposed by the motor motion, is thus  $L^+ = L_{\Sigma}^+ + L_c^+ + L_e^+$  [see Fig. 2(b)]. Similarly, the horizontal film  $L^- = L_{\Sigma}^- + L_c^- + L_e^-$  is decomposed into the central part  $L_c^-$ , present at  $t_p = -4$  s, and the films extracted during the preparatory phase, whose lengths  $L_{\Sigma}^{-}(t)$  and  $L_{e}^{-}(t)$  decrease during the main deformation. The size of the different pieces of film are measured as long as their boundaries remain straight, i.e., during typically 0.1 s, using image processing discussed in the Supplemental Material [18] (see Fig. 3). The time evolution of  $L_{\Sigma}^+$ ,  $L_{\Sigma}^-$  and  $L_c^-$  are represented in Fig. 4(a).

We define  $\sigma = 2\gamma$  the tension in a given film as twice the surface tension. This quantity is uniform along a



FIG. 3. Experimental images from both cameras cropped around their respective ROI, shown in Fig. 1. (a) and (c) Horizontal film during the deformation at t = 0 (a) and t = 0.15 s (c), with  $U_{def} = 20$  mm/s; the vertical bars localize the edge of the free meniscus (black), the edge of the central film (red and blue) and the center  $x_m$  of the free meniscus (green). The black circles highlight two photobleached dots. (b) and (d) Top film during the deformation at t = 0 (b) and t = 0.15 (d), with  $U_{def} = 50$  mm/s; the red vertical bar is the edge of the central film, coinciding at t = 0 with the edge of the free meniscus (black line).

single film [7,10], and the force balance on the free meniscus, projected on the horizontal axis x, reads, neglecting its inertia as well as pressure and gravity forces,  $\sigma^{-}(t) = 2\sigma^{+}(t)\cos\theta(t)$ . The semiangle  $\theta(t)$  between the top and bottom films (see Fig. 2) can be deduced from the meniscus position  $x_m$  [see Figs. 3(a) and 3(c) and [10]]. The resulting tension ratio is shown in Figs. 4(c), 4(d) and quantifies the Marangoni stress that sets the interfaces in motion, thus allowing the surfactant transfers between films.

For  $t < t_p = -4$  s, the tension ratio is stable which indicates that tensions in all films are equal. This is our reference state at which  $\sigma^+ = \sigma^- = 2\gamma_0$  and  $\theta = \pi/3$ . The tension ratio increases as  $L^-$  is slowly stretched during the preparatory phase and then relaxes when the motors are at rest. Note that, at t = 0, this first relaxation is still going on and  $\sigma^-/\sigma^+ > 1$ . The tension ratio then suddenly decreases during the main deformation, and crosses the point  $\sigma^-/\sigma^+ = 1$  at a time denoted  $t = t^*$  (see Fig. 4), before reaching its minimal value, at the end of the motor motion. Afterward, the tension ratio tends to relax to one, its equilibrium value.

From these tension and length measurements, we will be able to quantify the surfactant exchanges from one film to another.

The surfactant diffusion in the direction parallel to the film occurs on the time scale  $\tau_{\parallel}^d \sim \ell^2/D \sim 10$  s, with  $D \sim 10^{-9} \,\mathrm{m}^2/\mathrm{s}$  the surfactant diffusivity, and  $\ell \simeq 100 \,\mu\mathrm{m}$  the typical distance for thickness variations. The Poiseuille flows induced by these thickness heterogeneities scale as  $v_{\parallel}^p \sim \gamma_0 h^3/\eta \ell^3 \sim 10^{-5} \,\mathrm{m/s}$  (with respect to the interface),



FIG. 4. Experimental data for  $c_d = 50 \text{ mg/L}$  and  $U_{def} = 50 \text{ mm/s}$ , averaged over 4 experiments. The root mean square is shown in shaded area (when larger than the symbol size). (a) Lengths, (b) deformation states, and (c) tension ratio. The time range where all quantities can be measured simultaneously is the gray shaded area in (a),(b). The tension ratio for the velocities  $U_{def} = 10 - 20 - 35 - 50 \text{ mm/s}$  (from light to dark greens) are shown in (d).

which leads to the typical time  $\tau_{\parallel}^p = \ell / v_{\parallel}^p \sim 10^2$  s. Our experimental time  $\tau_{\exp} \sim 10^{-1}$  s is much smaller, so these parallel transport mechanisms are negligible. Especially, both surfactant and water fluxes are negligible across the boundary between the central and extracted films.

In the transverse direction, the diffusion time scales as  $\tau_{\perp}^d \sim h^2/D \sim 10^{-3}$  s, much lower than  $\tau_{exp}$ . The bulk and interface concentrations are thus at equilibrium at each point of the films. The SDS concentration is large enough to remain above the CMC even in the stretched film, so it has no contribution to the tension change. The dodecanol is much less soluble and its characteristic length  $h_{\Gamma} = \Gamma/c_d$ , with  $\Gamma$  and  $c_d$  the interface and bulk dodecanol concentrations, is of the order of 400 µm [10]. As  $h_{\Gamma} \gg h$ , the amount of dodecanol in the bulk of a thin film element is negligible, and any variation of film area leads to a variation of  $\Gamma$  which cannot be compensated by exchange with the bulk. However,  $h_{\Gamma} \approx R$  and the meniscus contains a significant amount of dodecanol.

Thus, we assume DOH is the only surfactant to contribute to the film tension variations observed in Figs. 4(c) and 4(d), and it is the species we track when quantifying the surfactant exchanges during the deformation. In this respect we define  $\Gamma_0$  the reference surface excess of DOH associated with the reference tension  $\sigma_0$ . Note that, as the tensions  $\sigma^-(\Gamma^-)$  and  $\sigma^+(\Gamma^+)$  are homogeneous in each film, the concentrations  $\Gamma^-$  and  $\Gamma^+$  are homogeneous too.

In the following, we work with the system  $\Sigma$  represented in red in Fig. 2, and defined for t > 0. It encompasses the free meniscus, the piece of film  $L_{\Sigma^-}$  in the horizontal film and the two pieces of film  $L_{\Sigma^+}$ , in the top and bottom films. As soon as  $L_{\Sigma^+}$  is visible,  $\Sigma$  has measurable boundaries, across which the surfactant fluxes are negligible:  $\Sigma$  is a well-defined closed system in which the quantity of DOH is conserved.

Importantly, the photobleached spots allow us to check the absence of any compression or dilation in the z direction. The spots are observable between t = -0.4and t = 0.1 s and during this time range the distance between two spots in the row [see Fig. 3(a)] varies by less than  $2\%(\pm 2)$ . It means that the quantities N used below to build the mass conservation law can be defined per unit length in the z direction.

Let us denote  $N_{\Sigma}$  the total quantity of dodecanol in  $\Sigma$ . In the limit  $h_{\Gamma} \gg h$ , we have  $N_{\Sigma} = 2N_{\Sigma}^{-} + 4N_{\Sigma}^{+} + N_{m}$  with  $N_{m}$  the quantity of DOH in the meniscus (interface and bulk) and  $N_{\Sigma}^{\pm} = \Gamma^{\pm}L_{\Sigma}^{\pm}$  the quantity of DOH on each interface of  $L_{\Sigma}^{\pm}$ . The surfactant contribution of the meniscus will be deduced from the conservation of  $N_{\Sigma}$  with time.

This requires to have an experimental access to the dodecanol concentrations  $\Gamma^{\pm}$  on the interfaces of  $L_{\Sigma}^{\pm}$ . However, we will take advantage of the concentration uniformity to determine them in the central part of each film, where they are more easily accessible.

In the horizontal film,  $L_c^-$  forms a well-defined closed system. Indeed, from  $t_p = -4$  s to later times, it remains separated from the menisci by the extracted films  $L_{\Sigma}^$ and  $L_e^-$ , and has therefore trackable boundaries, impermeable to surfactants. The amount  $\Gamma^- L_c^-$  of DOH on its interfaces is thus conserved. At  $t = t_p$ ,  $\Gamma^- = \Gamma_0$  so we get  $\Gamma^-(t) = \Gamma_0 L_c^-(t_p)/L_c^-(t)$ .

The situation in the stretched film is more subtle as, at times t < 0, its boundaries are in contact with the menisci and it is thus able to lose surfactants in an undetectable way. At t > 0, the top and bottom films are stretched, and the extracted films  $L_{\Sigma}^+$  and  $L_e^+$  begin to grow, even if their sizes are not immediately measurable. The quantity  $\Gamma^+ L_c^+$  is thus conserved at t > 0, but not before. The reference value is obtained at the time  $t^*$ , at which we have, by definition,  $\sigma^+(t^*) = \sigma^-(t^*)$  and, consequently,  $\Gamma^-(t^*) = \Gamma^+(t^*)$ . We thus get  $\Gamma^+(t) = \Gamma^-(t^*)L_c^+(t^*)/L_c^+(t)$ .

We define  $L_{c,0}^+$  as the reference length that the closed system  $L_c^+$  would have once relaxed toward  $\Gamma_0$ , and we get from the previous relation  $L_{c,0}^+ = \Gamma^-(t^*)L_c^+(t^*)/\Gamma_0$ . Similarly, for  $L_c^-$ , we set  $L_{c,0}^- = L_c^-(t_p)$ , and we define the film deformations as  $\varepsilon^{\pm} = L_c^{\pm}(t)/L_{c,0}^{\pm} - 1$ . These quantities are shown in Figs. 4(a) and 4(b). As expected, both films are prestretched at t = 0, because of the preparatory phase. During the main deformation, the horizontal film is compressed and the lateral films are stretched. The small discontinuity observed in  $\varepsilon^+$  is due to the measurement of



FIG. 5. Amount of dodecanol  $N_{\Sigma}^{+}(t)/\Gamma_{0}$  extracted by each of the four stretched film interfaces as a function of the amount  $(N_{\Sigma}^{-}(0) - N_{\Sigma}^{-}(t))/\Gamma_{0}$  evacuated by each of the two compressed film interfaces (normalized by  $\Gamma_{0}$ ). Each curve stands for one chemistry  $c_{d}$  at one  $U_{def}$  and is an average over 4 experiments. From lightest to darkest colors:  $U_{def} = 10 - 20 - 35 - 50$  mm/s.

 $L_{\Sigma}^+$ , which has been set to 0 as long as it is not distinguishable from the meniscus and suddenly jumps to a finite size when measurable [see Fig. 4(a)].

The amount of surfactant on each interface, once rescaled by  $\Gamma_0$ , can now be expressed as a function of the various measurable lengths:

$$\frac{N_{\Sigma}^{-}(t)}{\Gamma_{0}} = \frac{L_{c}^{-}(t_{p})}{L_{c}^{-}(t)} L_{\Sigma}^{-}(t); \qquad \frac{N_{\Sigma}^{+}(t)}{\Gamma_{0}} = \frac{L_{c}^{+}(t^{*})L_{c}^{-}(t_{p})}{L_{c}^{-}(t^{*})L_{c}^{+}(t)} L_{\Sigma}^{+}(t).$$
(1)

The DOH conservation in  $\Sigma$  between the times 0 and t finally imposes, using  $N_{\Sigma}^{+}(0) = 0$ ,

$$N_{\Sigma}^{+}(t) = \frac{1}{2} (N_{\Sigma}^{-}(0) - N_{\Sigma}^{-}(t)) + \frac{1}{4} (N_{m}(0) - N_{m}(t)).$$
(2)

The quantities  $N_{\Sigma}^{+}(t)$ , entering each of the four stretched interfaces, and  $(N_{\Sigma}^{-}(0) - N_{\Sigma}^{-}(t))$  leaving each of the two compressed interfaces, are compared in Fig. 5. For all the velocities and all the concentrations, on the time range where all quantities can be measured simultaneously [as shown in Figs. 4(a) and 4(b)], the measurements are compatible with a slope 1/2. Using Eq. (2), this means that the meniscus does not contribute significantly to the surfactant exchanges, in line with the scenario (i). The scenario (ii), in contrast, assumes that the meniscus provides the surfactants needed on interface  $I_3$  so that  $N_m(0) - N_m(t) = 2N_{\Sigma}^+$ , leading, from Eq. (2), to the slope 1 shown in Fig. 5, which can be ruled out.

The meniscus is thus a large but unused reservoir of surfactant. This important experimental result is the first direct characterization of surfactant transport induced by foam deformation.

We systematically impose the deformation  $\delta L^+ = \delta L^-$ , which is symmetric for the elementary foam, yet not specific at the local scale of the free meniscus. In fact, the deformation near the free meniscus is also influenced by the film extraction at the external meniscus, where we measure  $L_{e}^{+} \neq L_{e}^{-}$ , as well as a variation with velocity. Generality is ensured by the fact that we explored a range of non-symmetric deformations, all of which involve an increase in the total interface area. While globally compressive cases remain to be investigated experimentally, they are expected to yield similar results, at least in the linear regime, where compressions and expansions are governed by similar transport rules. We therefore argue that the absence of meniscus contributions in the surfactant mass balance established in this study is relevant to a broad class of deformations. However, different processes may be observed if the films are thin enough to be governed by the disjoining pressure, of if the film size becomes smaller than the dynamical length scales appearing in the vicinity of the meniscus [10].

Our experimental determination of surfactant transfer is an important piece of information needed to close the different models of local flows in liquid foams [2,7,8,10]. Notably, this sets the free parameter of the model developed in [10] which predicts the effective viscoelasticity of an elementary foam. This opens the way for rheological models for macroscopic liquid foams with physical local building blocks, and provides local-scale data to validate and calibrate numerical models of foam flow [21–23].

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- R. Höhler and S. Cohen-Addad, Rheology of liquid foam, J. Phys. Condens. Matter 17, R1041 (2005).
- [2] N. D. Denkov, S. Tcholakova, K. Golemanov, K. P. Ananthapadmanabhan, and A. Lips, Viscous friction in foams and concentrated emulsions under steady shear, Phys. Rev. Lett. **100**, 138301 (2008).
- [3] P. Hébraud and F. Lequeux, Mode-coupling theory for the pasty rheology of soft glassy materials, Phys. Rev. Lett. 81, 2934 (1998).
- [4] J. Lin, E. Lerner, A. Rosso, and M. Wyart, Scaling description of the yielding transition in soft amorphous solids at zero temperature, Proc. Natl. Acad. Sci. U.S.A. 111, 14382 (2014).
- [5] C. Liu, E. E. Ferrero, F. Puosi, J.-L. Barrat, and K. Martens, Driving rate dependence of avalanche statistics and shapes at the yielding transition, Phys. Rev. Lett. **116**, 065501 (2016).

- [6] B. Dollet, A. Scagliarini, and M. Sbragaglia, Twodimensional plastic flow of foams and emulsions in a channel: Experiments and lattice Boltzmann simulations, J. Fluid Mech. **766**, 556 (2015).
- [7] M. Durand and H. A. Stone, Relaxation time of the topological *T*1 process in a two-dimensional foam, Phys. Rev. Lett. **97**, 226101 (2006).
- [8] S. Besson, G. Debrégeas, S. Cohen-Addad, and R. Höhler, Dissipation in a sheared foam: From bubble adhesion to foam rheology, Phys. Rev. Lett. **101**, 214504 (2008).
- [9] A. L. Biance, S. Cohen-Addad, and R. Höhler, Topological transition dynamics in a strained bubble cluster, Soft Matter 5, 4672 (2009).
- [10] A. Bussonnière and I. Cantat, Local origin of the viscoelasticity of a millimetric elementary foam, J. Fluid Mech. 922, A25 (2021).
- [11] A. Prins, C. Arcuri, and M. van den Tempel, Elasticity of thin liquid films, J. Colloid Interface Sci. 24, 84 (1967).
- [12] L. Bocquet, A. Colin, and A. Ajdari, Kinetic theory of plastic flow in soft glassy materials, Phys. Rev. Lett. 103, 036001 (2009).
- [13] R. M. Baram, H. J. Herrmann, and N. Rivier, Space-filling bearings in three dimensions, Phys. Rev. Lett. 92, 044301 (2004).
- [14] S. Besson and G. Debrégeas, Statics and dynamics of adhesion between two soap bubbles, Eur. Phys. J. E 24, 109 (2007).
- [15] A. Bussonnière, E. Shabalina, X. Ah-Thon, M. Le Fur, and I. Cantat, Dynamical coupling between connected foam films: Interface transfer across the menisci, Phys. Rev. Lett. 124, 018001 (2020).
- [16] K. J. Mysels, K. Shinoda, and S. Frankel, Soap Films: Study of Their Thinning and a Bibliography (Pergamon, New-York, 1959).
- [17] R. Poryles, T. Lenavetier, E. Schaub, A. Bussonnière, A. Saint-Jalmes, and I. Cantat, Non linear elasticity of foam films made of SDS/dodecanol mixtures, Soft Matter 18, 2046 (2022).
- [18] See Supplemental Material at http://link.aps.org/ supplemental/10.1103/PhysRevLett.134.168201 for experimental and data processing details.
- [19] E. Shabalina, A. Bérut, M. Cavelier, A. Saint-Jalmes, and I. Cantat, Rayleigh-Taylor-like instability in a foam film, Phys. Rev. Fluids 4, 124001 (2019).
- [20] C. Trégouët and I. Cantat, Instability of the one-dimensional thickness profile at the edge of a horizontal foam film and its plateau border, Phys. Rev. Fluids **6**, 114005 (2021).
- [21] R. I. Saye and J. A. Sethian, Multiscale modeling of membrane rearrangement, drainage, and rupture in evolving foams, Science 340, 720 (2013).
- [22] A. Titta, M. Le Merrer, F. Detcheverry, P. D. M. Spelt, and A.-L. Biance, Level-set simulations of a 2d topological rearrangement in a bubble assembly: Effects of surfactant properties, J. Fluid Mech. 838, 222 (2018).
- [23] P. Heiss-Synak, A. Kalinov, M. Strugaru, A. Etemadi, H. Yang, and C. Wojtan, Multi-material mesh-based surface tracking with implicit topology changes, ACM Trans. Graph. 43, 1 (2024).