Gallery of Fluid Motion

Breaking waves: To foam or not to foam?

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Breaking waves entrain air bubbles that rise to the surface [1,2]. In clean fresh water, the bubbles disappear as they coalesce with each other or with the atmosphere. Yet in seawater, the bubbles cluster up on the surface and appear as foam. The reason is that surfactants and electrolytes [3–5] found in seawater prevent or delay coalescence as they stabilize the thin liquid films separating the bubbles. In this work, we show how prevention of coalescence changes the behavior of bubbles entrained by breaking waves. We compare two limiting cases, with and without coalescence, on a series of volume-of-fluid simulations of increasing complexity.

Conventional volume-of-fluid simulations correspond to the first case, bubbles always coalesce at a distance below one computational cell since the method is unable to describe multiple interfaces in the same cell. For coalescence prevention, we use an implementation [6] of the multimarker volume-of-fluid method [7,8] that removes its dependence on the number of bubbles and makes it applicable to systems with thousands of noncoalescing bubbles. The source code of our solver *Aphros*, documentation, and examples of simulations are available on GitHub [9] https://github.com/cselab/aphros.

The simplest setup is the forced collision of two bubbles shown in Fig. 1. The bubbles, initially separated, move towards each other under the force applied to the outer sides. Coalescence, if allowed, starts with a neck propagating along the surface of the newly formed bubble. Our simulations [10,11] describe this process in close agreement with experimental data [12]. Without coalescence, the bubbles deform and eventually repulse.

Now we consider a column of bubbles generated by a periodic source, under the surface of water. With coalescence, each bubble rises towards the surface, and rapidly bursts creating radial capillary waves. Without coalescence, in Fig. 2, the bubbles cluster up on the surface. This clustering is driven by buoyancy since each bubble creates an elevation that attracts other bubbles. We obtain the same cluster of bubbles experimentally. In a tank of soapy water, we generate small bubbles of about 2 mm in diameter by injecting air at a fixed pressure through a thin tube.

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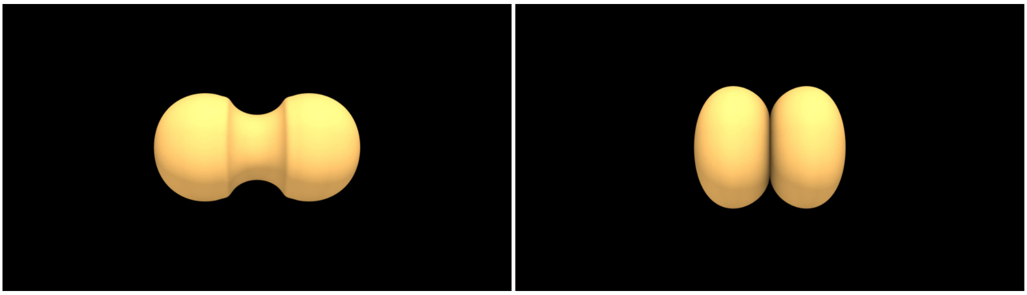

FIG. 1. Collision of two bubbles with coalescence (left) and without coalescence (right).

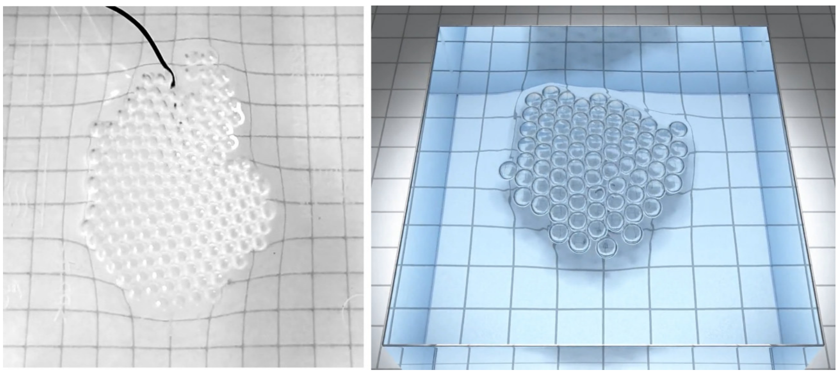

FIG. 2. Cluster of bubbles generated by a periodic source: experiment in water with surfactant (left) and simulation without coalescence (right). The square cells are 4 mm wide.

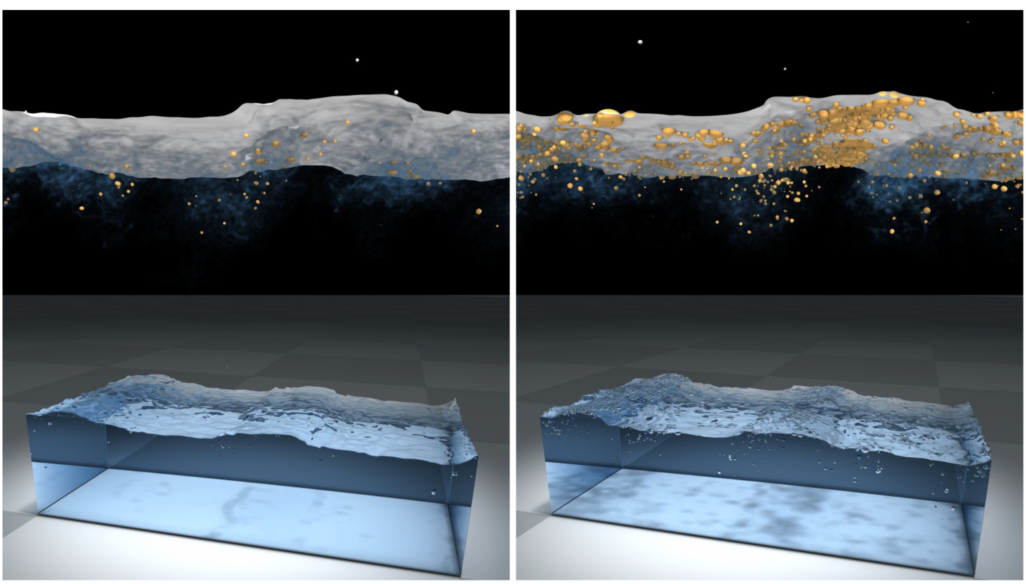

FIG. 3. Bubbles generated by breaking waves with coalescence (left) and without coalescence (right). Bubbles highlighted with orange (top) and rendering using path tracing (bottom).

Finally, we consider a breaking wave using initial conditions [13] with a steepness $\varepsilon = 0.65$ and a wavelength of 27 cm. The wave captures a tube of air that is then divided into small bubbles. A snapshot is shown in Fig. 3. As expected, with coalescence the bubbles reach the surface and disappear. Prevention of coalescence makes the bubbles cluster up as foam.

We have illustrated the two limiting cases of coalescence prevention. However, depending on the flow conditions and the concentration of surfactants, bubbles can undergo partial coalescence. For example, foam on seawater decays over time. Future work will deal with such intermediate cases.

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