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Gallery of Fluid Motion

Birth of microbubbles in turbulent breaking waves

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Microbubbles have been observed in large-scale two-phase flows like breaking waves [1,2], seafaring vessel wakes [3,4], and raindrops impacting liquid pools [5,6]. These microbubbles rise slowly [3,7] and reside for a long time in oceans, thereby influencing interfacial transport [1,8], surface reflectance [4,9,10], and acoustic wave propagation [3,11]. Researchers have measured the distribution of bubble sizes in laboratory breaking waves, including Deane and Stokes [2] and Blenkinsopp and Chaplin [12], who measured bubbles with sizes of 0.1–10 mm. Microbubbles with sizes of 10–100 μm, however, were difficult to characterize due to resolution limitations [13]. These microbubbles are hypothesized to form when liquid interfaces collide and entrap thin gas films, which subsequently rupture and retract. Here, the stages involved in this postulated mechanism are outlined, from large to progressively smaller scales.

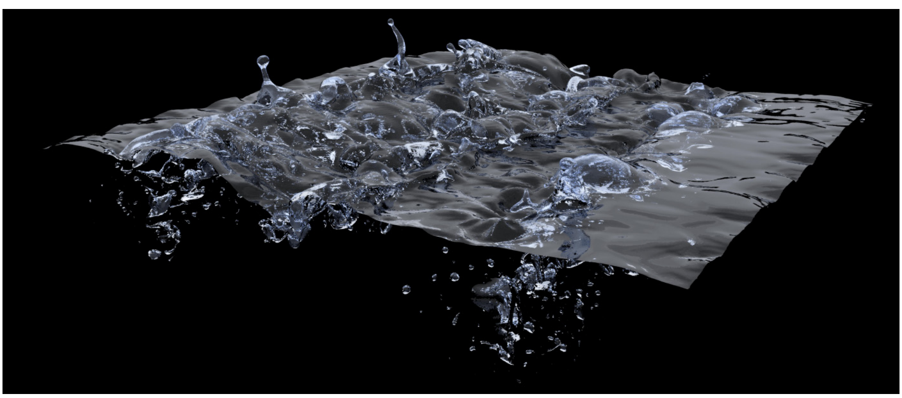

FIG. 1. Snapshot of the side view of the simulated breaking wave, shortly after the wave has broken.

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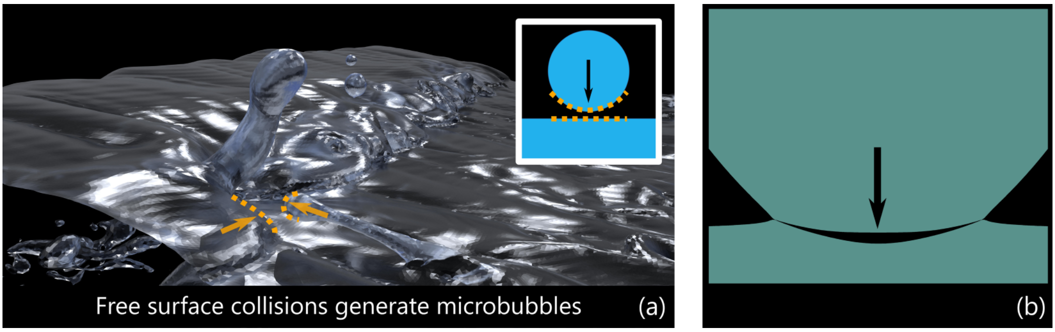

FIG. 2. (a) Close-up view of an imminent collision between interfaces after the wave has broken. Inset: Schematic illustrating the drop-pool model problem. The imminent collision (dashed lines, main image) may be mapped to drop impact on a deep liquid pool (dashed lines, inset). (b) Simulation snapshot depicting drop-pool impact and the ensuing air film entrapment.

To investigate the large scales, a geometric volume-of-fluid-based incompressible two-phase solver with consistent mass and momentum advection [14,15] was used to simulate a 27-cm-long breaking Stokes water wave in air [16,17] with a minimum grid size of 0.6 mm, as depicted in Fig. 1. The simulation revealed that turbulent breaking waves entrain large gas cavities that break up into smaller bubbles. Collisions between interfaces that may trap thin gas films and generate microbubbles were also observed. These films and microbubbles cannot be resolved by this simulation.

The impact of a drop on a deep liquid pool is a suitable model problem for studying how collisions between two arbitrarily curved interfaces may lead to microbubble entrainment, as suggested in Fig. 2(a). This is motivated by the observation of Mesler entrainment of microbubbles in drop-pool impact experiments [18–20], which revealed that these microbubbles are remnants of a thin gas film sandwiched between the colliding interfaces. Simulations employing the boundary integral method (similar to [21,22]) were performed to capture the film geometry. A simulated water-air impact event with an impact velocity of 0.5 m/s and a drop diameter of 1.3 mm is depicted in Fig. 2(b).

Experiments [20] have shown that once the entrapped gas film ruptures and retracts, transverse edge instabilities will trigger microbubble shedding. Three-dimensional simulations of retracting thin gas films performed using a conservative diffuse interface method developed by Mirjalili *et al.* [23] also capture this. Retraction of a 2-μm-thick air film in water is shown in Fig. 3. Microbubbles with diameters of 30–40 μm were shed due to these instabilities [24].

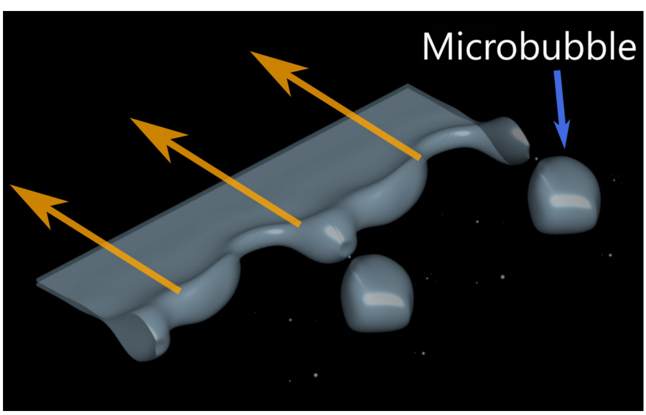

FIG. 3. Simulation snapshot depicting the formation of microbubbles due to the retraction of a thin air film. The large arrows indicate the direction of retraction of the rim of the film.

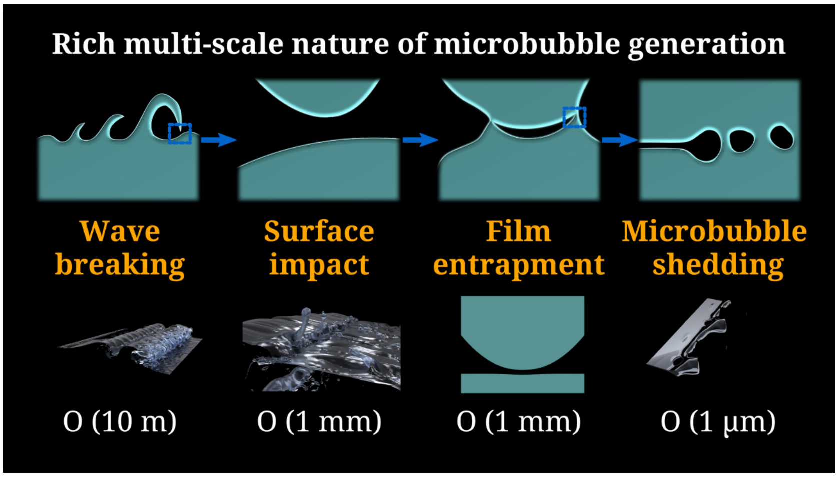

FIG. 4. Schematic describing the various stages in the potential pathway for microbubble formation in breaking waves described in this work, along with the characteristic length scales associated with each stage. The top row comprises sketches of each stage, while the bottom row comprises snapshots of simulations that were performed in this work.

This work outlines a potential pathway for microbubble formation in breaking waves, which is summarized in Fig. 4. Preliminary application of a collision detection algorithm [16] to the wave simulation suggests up to hundreds of microbubble-producing collisions may occur every second, thus creating up to a million microbubbles per cubic meter every second. The sheer number of expected microbubbles, which cannot be resolved in large-scale simulations and require additional modeling, motivates further study of their formation and evolution.

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