FLUID DYNAMICS

Getting the drops in

When a bubble bursts at a liquid–gas interface, a portion of gas is released from the liquid. Now, another, counterintuitive process is reported: rapid motion generated by bubble-bursting transports oil droplets from the surface into the interior of a volume of water.

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Efficient exchange between two different phases in contact, such as between a liquid and a gas (pictured), is important for natural and industrial processes. For example, approximately 90 gigatonnes of carbon are exchanged between the atmosphere and the oceans each year; this has important consequences for climate modelling[1]. As is demonstrated in the simple case of beating an egg, finding efficient routes to transport one phase (air) into the other (liquid) is equally important for smaller-scale, man-made systems.

Purely molecular processes such as diffusion are often slow. Higher efficiency can be realized through macroscopic transport: entraining drops and bubbles with small size (but with large surface-to-volume ratio) into the continuous phase. However, such entrainment is not simple to achieve: the air–water interface must neatly envelop the intruder phase to prevent the air from escaping. This non-generic character of entrainment has been illustrated beautifully by analysing the sound produced by raindrops impacting on a water surface[2]: only drops of a particular size succeed in producing a cavity that closes. This results in the entrainment of bubbles of only a limited size range, producing a narrow peak in the sound spectrum.

General pathways to entrainment are actively sought. It has been proposed that small-scale, singular structures may serve as entryways into the other phase. Namely, the surface of a viscous liquid folds into a narrow cusp when stirred, which allows a thin sheet of air to enter into the liquid if the stirring is sufficiently strong[3]. The crucial point is that such singular structures are a generic feature of driven flows, so that conditions for entrainment don't depend on the particulars of how the process is driven. In addition, singularities serve to focus the flow into small-scale features, providing a natural explanation for the small size of some of the entrained bubbles, such as those resulting from the beating of an egg.

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The mechanism described above works sufficiently well for viscous fluids, but fails for water. Now, as they report in *Nature Physics*, Jie Feng and colleagues[4] have made an important step forward by discovering a route to entrainment that does the job for water: entraining tiny, 100 nm-radius oil drops. As a starting point, the team took a beaker of water covered by a thin film of oil, similar to what may be encountered after an oil spill. After releasing air bubbles from under the water for dozens of hours, the originally transparent water became hazy, indicative of the presence of small oil drops that scatter light. But how does the bursting of bubbles at an oil–water interface lead to transport of oil into the water, and how is the extremely small drop size achieved?

Looking at frames from a high-speed movie — taken with a side-view from beneath the surface of the water — provides the answer to the first question[4]. The thin film of liquid covering the top of a bubble, having risen to the surface, ruptures and creates a violent downward motion along the surface of the cavity formed by the bubble. Then, a strong localized perturbation of the cavity is seen, associated with fluid flow into the bulk of the liquid, which transports oil droplets with it; in the end, a cloud of small droplets is left behind.

Theoretical calculations[5] indicate that transport into the bulk is the result of a so-called boundary-layer flow, which is confined to a very small region close to the surface of the cavity. It is a curious property of flow near a free surface that fluid elements always rotate in a direction opposite to the direction of curvature of the cavity itself. As a result, fluid elements always leave the boundary layer with a trajectory perpendicular to the surface[6], ensuring efficient entrainment into the bulk of the liquid. By cleverly placing small solid particles at the oil–water interface, Feng *et al.*[4] have provided direct evidence for such an entrainment mechanism and found that it is fairly insensitive to the nature or size of objects being transported into the water.

The small size of the oil droplets that Feng and colleagues[4] were able to generate, on the other hand, is governed by chemistry. Adding surfactant to the water, the oil–water system is pushed into a curious hybrid state in which small lenses of oil coexist with a microscopically thin layer of oil that has spread over the surface of the water. This state is the result of molecular interactions having the opposite effect at small (atomic) distances from what is favoured at longer distances of around 100 nm. As a result, the size of the lenses is on the order of 100 nm, which by volume conservation sets the size of the resulting oil droplets. The combination of chemical and hydrodynamic pathways leads to an extremely efficient way to disperse oil into a water phase.

Much remains to be done to fully understand the pathways discovered and described by Feng and co-workers. For example, the nature of the boundary layers near a free surface (such as between air and water) is largely unexplored. This and other aspects of the reported work provide fascinating opportunities for future scientific enquiry. ❐

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References
1. Falkowski, P. *et al. Science* **290,** 291–296 (2000).
2. Prosperetti, A. & Oguz., H. N. *Annu. Rev. Fluid Mech.* **25,** 577–602 (1993).
3. Eggers, J. *Phys. Rev. Lett.* **86,** 4290–4293 (2001).
4. Feng, J. *et al. Nature Phys.* http://dx.doi.org/10.1038/nphys3003 (2014).
5. Boulton-Stone, J. M. & Blake, J. R. *J. Fluid Mech.* **254,** 437–466 (1993).
6. Sébilleau, J., Limat, L. & Eggers, J. *J. Fluid Mech.* **633,** 137–145 (2009).

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