Pressure unites two regimes of fluid breakup

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Bubbles of xenon near the gas's critical point are so dense that they behave like drops of water, not bubbles of air.

When a water droplet falls from a leaky faucet, it dangles from a narrow conical filament of water that lengthens and narrows before it finally breaks. So-called droplet pinch-off has been extensively studied,[1] both theoretically and experimentally—in part due to its applicability to processes such as ink-jet printing but also because of its interest to mathematical physicists (see PHYSICS TODAY, September 1997, page 11). It was long thought that the reverse setup—a bubble of air released from an underwater nozzle—would behave in much the same way. But that turns out not to be the case: Bubbles and droplets differ qualitatively in both the shape of the pinch-off region and the time dependence of the process.[2]

Now, Justin Burton and Peter Taborek of the University of California, Irvine, have produced both bubble-like and droplet-like behavior in a single continuously variable system: xenon bubbles in liquid water over a range of pressures (and hence xenon densities).[3] They've thus been able to observe the transition between bubble and droplet pinch-off, which has previously eluded both theoretical and experimental treatment. And they've found that the boundary between the bubble and droplet regimes is sharp.

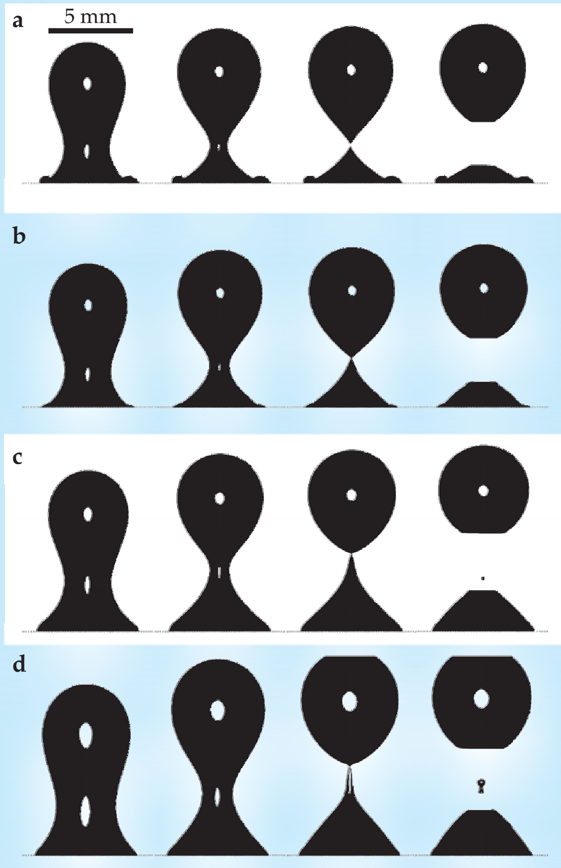

Figure 1. Time-sequence photographs of xenon bubbles released from an underwater nozzle. **(a)** At a pressure below 1 atmosphere, the ratio D of the xenon density to water density is 0.0007, and the xenon bubble looks like an air bubble, with the neck of the pinch-off region displaying top-to-bottom symmetry. When the pressure is increased so that **(b)** $D = 0.05$ and **(c)** $D = 0.2$, the asymmetry of the pinch-off region is increasingly more pronounced. **(d)** At a pressure of 68 atmospheres, $D = 0.7$, and the xenon bubble looks like an upside-down water droplet, with a pronounced neck at the instant before pinch off. The system is illuminated from behind, causing the xenon to appear black on a light-colored background. The spots in the middle of the images are optical artifacts due to lensing. (Adapted from ref. 3.)

The pinch-off of liquid droplets is driven by surface tension and opposed by either the liquid's viscosity or its inertia. When the inertial contribution dominates the viscous one, as it does in water droplets at length scales of more than a few nanometers, viscosity does not matter at all. For water and other inviscid (or low-viscosity) fluids, the width w at the neck of the pinch-off region depends only on surface tension γ, density ρ, and time t—and must therefore be proportional to $(\gamma t^2/\rho)^{1/3}$, because no other combination of those three quantities has units of length. That dimensional-analysis argument is borne out by experiments, which have verified that $w \sim t^{2/3}$, where $t = 0$ at the moment the droplet breaks away, so w decreases as t becomes less negative.

For water droplets in air or air bubbles in water, the surface tension at the air–water interface is the same. The surface-tension mechanism might therefore be expected to also produce a scaling exponent of ⅔ for bubble pinch-off. But it doesn't, because there is another mechanism that works faster. Surface tension helps to start the pinch-off process, but once it gets going, it's driven by the pressure difference between the air bubble and the surrounding water. Theory predicts a scaling exponent of ½, but with a slowly converging logarithmic correction. As a result, over the time scales probed by experiments, the exponent appears to be about 0.57.

The two air–water systems are special cases of one inviscid fluid breaking up inside another. The continuum of possibilities can be parameterized by D, the ratio of the inner fluid's density to the outer fluid's—for bubbles, D is nearly zero, and for droplets, nearly infinite. When $D = 1$, theory predicts droplet-like behavior,[4] so the boundary between the bubble and droplet regimes must occur at $D < 1$. In 2003 David Leppinen and John Lister, then both at the University of Cambridge in the UK, simulated inviscid pinch-off over a range of D values.[5] For $D > 0.16$, their simulations followed the droplet-like surface-tension mechanism. For smaller values of D, the mechanism was the same, but the simulated fluids were subject to instabilities that produced jagged fractal-like shapes in the fluid interface.

An experimental search for the bubble–droplet transition requires at least one fluid whose density can be continuously varied over a wide range. Liquids don't fit the bill. And most gases require dangerously high pressures to reach the necessary densities—if they don't condense into liquids first. Xenon is suitable because its critical point lies at around 17 °C, which means that at room temperature it does not undergo a gas–liquid phase transition, and its density increases faster under pressure than an ideal gas's would. At 68 atmospheres—the highest practical pressure for the experiment, since above that pressure xenon forms a solid clathrate with water—xenon is 70% as dense as water, whereas an ideal gas with xenon's mass would be just 36% as dense as water.

Housing the bubbles

Burton and Taborek built their own high-pressure xenon source from which they could bubble the gas into a stainless steel cell filled with water. But taking highly magnified pictures of the xenon formations under such large pressures was a challenge. The camera needed to sit within 2 cm of the bubbles and yet remain outside the cell. So the researchers fitted their cell with two parallel sapphire windows—one for illuminating the bubbles and the other for imaging them—which could withstand the pressure but were less than a centimeter thick.

The available range of densities from $D \approx 0$ to $D = 0.7$ allowed the researchers to observe both bubble-like and droplet-like pinch-off behavior, as shown in figure 1. "We were initially hoping to see evidence of the instabilities that were predicted in the numerical simulations," says Burton. But the droplet profiles they observed, as far as they could tell, were perfectly smooth. The researchers speculate that perhaps the instabilities were damped out by viscous effects on the small but nonzero viscous length scales of xenon and water.

The shapes of the pinch-off regions appeared to vary continuously from the symmetric profile of the bubble-like regime to the tapered filament of the droplet-like regime. But the scaling exponent that describes the neck width as a function of time was another story, as shown in figure 2. "You might expect to see a smooth, linear transition from 0.57 to ⅔," explains Burton. "But that's not the case." To the researchers' surprise, what they saw instead was a nearly constant value of 0.57 for low values of D, a nearly constant value of 0.66 for high values of D, and an abrupt transition near $D = 0.25$.

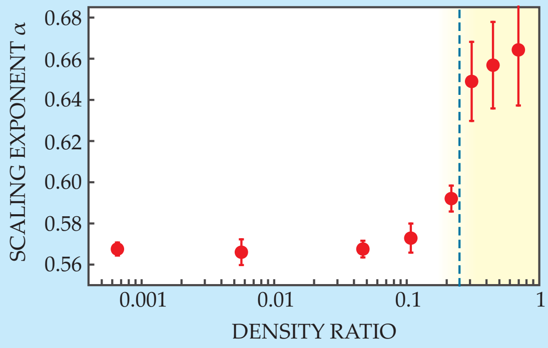

Figure 2. The scaling exponent α describes the pinch-off neck width w as a function of time t: w is proportional to t^{α}. In the experiments on xenon bubbles in water, when the xenon-to-water density ratio was less than about 0.25, $\alpha = 0.57$, the same as for air bubbles in water. At higher density ratios, $\alpha = ⅔$, the same as for water droplets in air. The error bars are much larger in the droplet-like regime because the xenon bubble sometimes obscures the narrowest point of the pinch-off region. Even subject to that limitation, the sharp boundary between bubble-like and droplet-like scaling is evident. (Adapted from ref. 3.)

Theoretical understanding of Burton and Taborek's results—why the transition is so sharp and why it occurs at $D = 0.25$—has yet to come. Burton and Taborek themselves are now working on numerical simulations to help them understand what they've seen. But they're also looking experimentally at droplet and bubble formation in electrically charged fluids and non-Newtonian fluids—further exploring the zoo of pinch-off possibilities.

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physics update

These items, with supplementary material, first appeared at http://www.physicstoday.org.

Measuring soil moisture with cosmic-ray neutrons. Through its influence on evaporation rates, humidity levels, and other factors, the moisture content of soil has a significant impact on weather. Accurate measurements of that content, though important for meteorological, hydrological, and ecological forecasting, are difficult to make. Extrapolating point measurements to larger areas is inaccurate, and satellite-based remote-sensing methods are hindered by ground cover, surface roughness, and other limitations. A team from the University of Arizona and the Southwest Watershed Research Center in Tucson has shown that just above the ground surface, so-called fast neutrons with energies on the order of an MeV are quantifiably correlated with soil moisture and thus provide a noninvasive means for measuring the average moisture levels over regions several hundred meters wide and tens of centimeters deep. The neutrons are generated by cosmic rays. Upon collision with atmospheric nuclei, cosmic rays create showers of high-energy secondary particles, and those that reach Earth's surface can penetrate it, collide with nuclei there, and produce among their debris fast neutrons, some of which escape back into the atmosphere. Marek Zreda and colleagues discovered that hydrogen, mostly found in water, dominates soil's ability to moderate fast neutrons and that a strong inverse correlation, independent of soil chemistry, exists between moisture content and the intensity of the fast neutrons that escape out of the ground. The team demonstrated that with an independent measurement of the moisture