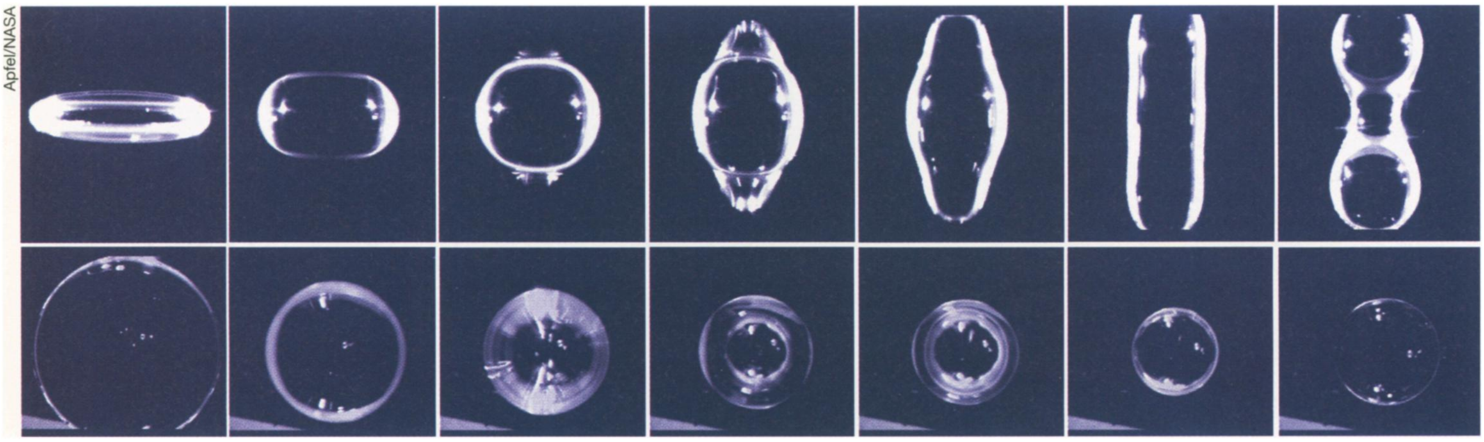
Dancing Droplets

Studying liquids in microgravity yields applications for Earth and space

By PAUL SMAGLIK

On her last space shuttle ride, Kathryn C. Thornton spent a lot of time pummeling droplets of water and other liquids. An engineer at the University of Virginia in Charlottesville, Thornton compressed the golf-ball-sized drops until they were as flat as pancakes. She spun them fast enough to rip the droplets into pieces. She squeezed them rhythmically until they shook like blobs of gelatin.

Studying droplets is a standard scientific technique for investigating phenomena ranging from the deformation of atomic nuclei to the explosion of stars. Experiments in space reported at a meeting earlier this year could yield such earthbound applications as improved transplantion of human cells and new techniques for controlling oil spills. Understanding of droplet physics could also ease routine space-based tasks like moving coolants through tiny tubes, filtering waste, and removing excess heat from electrical equipment.


Apfel/NASA

After being squeezed flat by sound waves, a drop of water enhanced with the surfactant Triton X-100 oscillates between a disk shape and a cigar shape (top sequence, side view) but maintains its symmetry (bottom sequence, top view) in an experiment aboard a 1995 mission of the space shuttle Columbia. The drop is 2.33 centimeters in diameter.

During her 1995 shuttle flight, though, Thornton didn't have time to consider the implications of her work. She just wanted to find a way to make the droplets behave.

In her experiments, Thornton didn't jiggle the droplets with her hands; instead, she used three intersecting sound waves to manipulate them.

The drops didn't always act as she expected. Sometimes, droplets expanded beyond her control and then imploded. Other times, drop formation was blocked by bubbles that, not shackled by gravity, crawled back up the drop injector. Perhaps most surprising, drops that Thornton had been squeezing would sometimes continue to flatten after she had released them.

Those sorts of novelties help to justify conducting these experiments in space, says Taylor G. Wang, a physicist at Vanderbilt University in Nashville, Tenn. In 1985, Wang joined the crew of the Challenger and was one of the first scientists to do droplet research in space. More recently, he developed some of the experiments that Thornton performed on her Columbia flight.

Wang and other researchers routinely perform these types of experiments on Earth, but they have to pound much smaller droplets with much stronger sound waves in order to suspend the liquid against the force of Earth's gravity. The smaller size makes it more difficult for physicists to measure a droplet as they make it dance.

To escape gravity, scientists have also tried creating temporarily weightless environments, for example in the bellies of diving planes, but then they have only seconds in which to conduct their experiments.

Wang prefers the microgravity conditions in space, even though researchers must compete for a limited amount of time on the few shuttle flights each year. In space, he says, "you can take a much longer time to look at an experiment."

His three experiments aboard the 1995 Columbia mission bore out this inclination, Wang reported in February at a NASA microgravity research conference in Washington, D.C. In one test, Thornton and other astronauts spun drops at increasing rates to determine when they would split in two. In another experiment, they injected a bubble of air into a liquid drop and made the bubble bounce inside of the droplet before coming to a rest in the center. In a third, they investigated how a drop behaves when placed inside a larger drop of a different liquid.

All three experiments showed that some physical theories devised to account for earthbound experimental data need slight numerical adjustments because they don't fully account for gravity's influence, Wang says.

In another set of experiments on the same flight, the near-zero-gravity environment allowed shuttle scientists to literally push drops of water to the limit.

Robert E. Apfel, a mechanical engineer at Yale University, designed a new test to measure "magical little droplets" containing compounds called surfactants, which are used as cleansers and mixing agents. Minuscule amounts of a surfactant—in this case 1 part per 10,000—dramatically change the properties of a liquid.

The surfactants in his experiments decrease surface tension by weakening the attraction between molecules on the outside of the water droplets. This effect creates a more elastic outer surface. The surfactants also increase surface viscosity, the friction between a liquid's molecules near the surface. With increased viscosity, the surface becomes syrupy.

Surfactants play a wide range of roles in industry. Chemical engineers want to find ways of designing new surfactants to tackle specific jobs. "The science of surfactants has been one of trial and error, rather than predicting how the surfactants will act based on their properties," Apfel says.

Part of the trick in designing improved surfactants will be to find better ways of measuring their properties. On Earth, scientists have trouble monitoring the effect of surfactants on moving liquids, such as during mixing. Because shuttle scientists can work with larger droplets, they can use video cameras to record data.

The astronauts have put surfactant-laced drops through their paces. They squeezed the drops and released them in different ways, all the while recording the action on camera.

The extent to which the astronauts could squeeze the drops surprised Apfel. "We did not expect to be able to flatten our drops into the shape of a pancake," he says.

He was also pleasantly surprised at the way the super-squeezed drops reacted after the astronauts abruptly released the pressure. The drops assumed a variety of symmetrical shapes as they oscillated between a disk shape and a cigar shape. Drops without the surfactant shattered under the same conditions.

The results provide a benchmark for understanding the surfactant's properties. "If your theory is not consistent with these observations, then it is wrong," Apfel says.

Back on Earth, Kathleen J. Stebe, a chemical engineer at Johns Hopkins University in Baltimore, attacks surfactants from a different angle.

Surfactant molecules have water-attracting parts and water-repelling parts. Mixed into a liquid, surfactants rush to the surface and arrange themselves so their water-repelling parts stick out of the droplet and their water-attracting parts cling to the inside. Stebe studies the speed at which this process happens.

Controlling that speed, called the mass transfer rate, may allow scientists to determine how quickly fluids flow. Surfactants with a slow mass transfer rate inhibit a liquid's flow because their sluggish motion causes uneven tensions in the fluid's moving surface. Adding surfactants with a fast mass transfer rate speeds the flow because their quick alignment on the surface rapidly eliminates those stresses.

"I'm doing all my work earthbound with the hope of understanding these things in general," Stebe says. "But they are of particular importance in space."

In space, gravity can't be relied upon to move wastes, coolants, fuel, and other fluids. Her research could help astronauts use surfactants to stimulate the flow of fluids aboard spacecraft.

It could also allow engineers on Earth to control the fluids flowing through the tiny conduits that cool miniature electronic parts. "On Earth, gravity becomes less and less important" as things get smaller, Stebe says, so manipulating surface tension could have big applications in small places.

Scientists could also control surface tension—and bubble behavior in space—by changing temperatures in a liquid. "Bubbles will swim toward the warmer parts," says R. Shankar Subramanian, a chemical engineer at Clarkson University in Potsdam, N.Y.

The mechanisms causing that movement are as complex as the forces that propel a swimmer through the water. Heating a drop of liquid containing a bubble reduces the surface tension on the warmer side of the bubble. The difference in surface tension between the warm and cool sides of the bubble creates a force that causes fluid to circulate around the bubble toward its cooler side.

"This is just like a swimmer reaching out and pushing the water toward her," says Subramanian. "By reaction, the bubble is propelled in the opposite direction, just like the swimmer."

A trio of Johns Hopkins researchers is now trying out earthbound experiments that may fly on future shuttle missions. The scientists are testing ways of moving bubbles and droplets.

In space, bubbles that result from boiling a liquid stay in place, getting bigger and bigger instead of moving away from the heat.

Cila Herman plans to move bubbles with electricity. By inserting electrodes into a pool of liquid, she hopes to generate an electric field that can replace the gravity-driven buoyancy of bubbles in water on Earth.

Hasan N. Oguz proposes a way to dislodge and move bubbles by shooting a stream of liquid at the site of bubble formation.

Andrea Prosperetti plans to use sound waves to dislodge these bubbles. If he and his colleague, Eugene Trinh at the Jet Propulsion Lab in Pasadena, Calif., are successful, astronauts may be able to use bubbles and sound waves to cool down hot objects or electronic equipment.

These lines of research may strike some as fanciful, but Thornton can tell from experience that controlling bubbles is a major hurdle for engineers planning future missions in space.

"It's easy to get rid of bubbles on Earth," the former NASA astronaut says. "It's not so easy in microgravity."