Shuttle Liquids

Taking coffee-cup mathematics into orbit

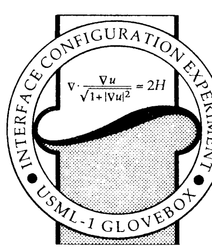
By IVARS PETERSON

It's morning. An inviting cup of hot coffee awaits. The dark, aromatic liquid sits undisturbed in its vessel, displaying a reassuringly placid, nearly flat surface.

Take away gravity, and a liquid's behavior enters a strange, largely unexplored realm. Surprises lie in store for an unwary imbiber aboard the space shuttle or a future space station orbiting Earth.

Studies of the mathematical equations defining the shapes of liquid surfaces in the absence of gravity suggest that, depending on the container's shape, a liquid may develop a curiously curved surface that reproduces in miniature the sweeping contours of a ski slope that ends in a shallow hollow. In certain containers, the liquid may actually creep along the vessel's walls until it dribbles out.

But this is theory. How well does the mathematics of low-gravity liquid surfaces correspond to physical reality?



In late June, mathematicians Paul Concus of the Lawrence Berkeley (Calif.) Laboratory and Robert Finn of Stanford University, along with mechanical engineer Mark M. Weislogel of NASA's Lewis Research Center in Cleveland, arrived at the Marshall Space Flight Center in Huntsville, Ala., hoping to obtain at least a partial answer to this question.

"We were looking for some sort of confirmation of our unusual mathematical predictions," Concus says.

The occasion was the launch on June 25 of space shuttle Columbia, carrying into orbit the U.S. Microgravity Laboratory. Among the experiments on board, ranging from crystal growth to flame propagation, one concerned the geometry of liquid surfaces in "exotic," or unusually shaped, containers.

"It's a very valuable area of study for the space program," Weislogel says. For example, engineers need to understand how fluids, such as liquid fuels stored in tanks, behave in various low-gravity situations. Experiments in space test whether mathematical theory accounts adequately for the main features of liquid surface behavior.

"In space travel, the stabilizing effect of gravity, which leads to the free surface configurations to which we have all become accustomed in our daily lives, is no longer present," Concus and Finn write in the March SIAM NEWS. "The behavior that we must learn to expect certainly will be at first strikingly (and in some ways disconcertingly) at variance with our everyday experience."

Concus and Finn began their collaboration more than 20 years ago, when Concus came to Finn with a mathematical problem related to the calculation of surface shapes. "It just happened that from a completely different, entirely mathematical point of view, I had become interested in precisely those equations," Finn says. "We've been working together ever since."

At the heart of their work lies the mathematical problem of finding the shape of a surface when a given volume of liquid partly fills a container of a certain geometry. What happens hinges on a quantity known as the "contact angle" — the angle at which the liquid meets the container's inner surface. This angle, in turn, depends upon the type of liquid being used and the material from which the container is made.

Such problems are so complicated that even today, engineers have useful, precise answers for only a few simple shapes: cylinders and spheres. That leaves lots of geometries available for further investigation.

Over the years, Concus and Finn have mathematically auditioned a wide variety of container shapes, discovering a host of peculiar liquid-surface behaviors — especially when gravity is left out of the equations. For instance, a surprising prediction that liquids can flow in sharp-cornered containers was confirmed by photographs of a free-falling, liquid-containing vessel with a hexagonal cross section.

One of the strangest examples they encountered involves a cylindrical container with a bulge encircling its waist (see diagram). The curvature of the bulge is such that, for a given contact angle and a certain fluid volume, solutions of the appropriate equation provide an infinite number of symmetric surface-shape possibilities, each with the same surface energy.

But Concus and Finn also realized that all of these symmetric surface configurations are unstable. Liquids confined by this particular geometry can contort their surfaces into asymmetric shapes that have a lower energy than the symmetric configurations the mathematicians had already found.

"That was surprising and unexpected," Finn says.

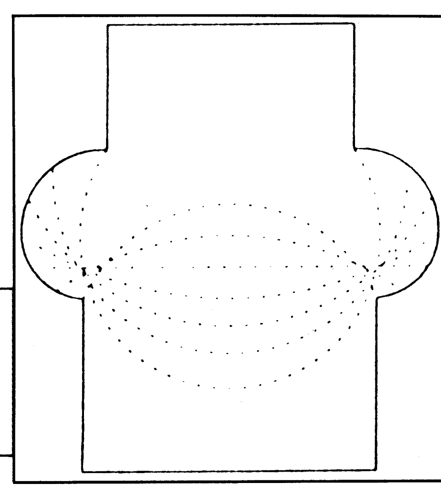
Known solutions of the equation, however, provided little guidance for identifying the lowest-energy asymmetric shape, and computer simulations suggested three possibilities.

"We didn't know which one, if any, it would be," Finn says. Perhaps an experiment in space, where the effects of gravity could be minimized for extended periods of time, would provide guidance on how to proceed with their studies.

Weislogel found the predictions intriguing. "When Concus and Finn started describing their neat ideas, I said to myself: I'm going to build this thing and test it," he recalls.

But translating a mathematical ideal into physical reality proved no simple matter. Getting the right geometry while keeping the interior as smooth as possible required the use of a special, computer-controlled lathe with a diamond blade to hollow out the interior of a block of acrylic plastic.

"The container had to be very precise, but the shape was one that wasn't easily



Cross section of an "exotic" cylindrical container featuring a radial bulge that permits an infinite number of surface shapes (dotted lines) having the same contact angle and energy.

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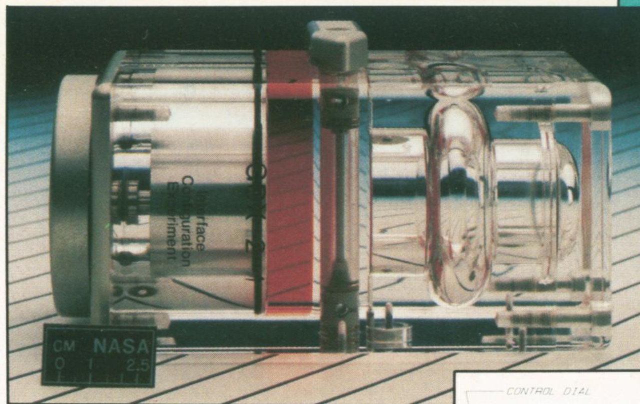
made," Weislogel says. He also had to devise a foolproof scheme for delivering exactly the right volume of liquid into the container every time the experiment was done.

To avoid optical distortions caused by the bending of light as it passes from one medium to another, Weislogel also had to hunt for a liquid having the same refractive index as acrylic plastic. His final choice of a custom-blended mixture of various hydrocarbons did the trick, enabling him to measure surface features directly from photographs of the experiment.

But now he had to make sure that this concocted liquid met the container's inner surface at the correct contact angle (55°). The choice of a special coating for the container's interior surfaces solved that problem.

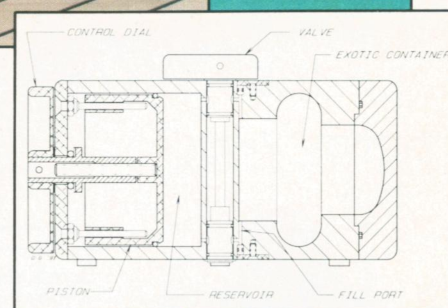
"It wasn't easy to find all these materials," Weislogel admits.

The researchers ended up with four containers for their shuttle experiments. Two vessels contained the special fluid, lightly dyed red to make it more visible, and two others held distilled water, dyed blue.



Illustrations: NASA Lewis Research Center

One of four special vessels for exploring the possible surface configurations of a liquid in a low-gravity environment, this container has a reservoir holding a certain volume of a hydrocarbon mixture (dyed red).



The "interface configuration experiment" of Concus, Finn, and Weislogel went on board the space shuttle as a one of a suite of 16 experiments to be performed in the glovebox, an airtight enclosure furnished by the European Space Agency and specifically designed for handling fluids and potentially hazardous materials.

So there were Concus, Finn, and Weislogel, sitting in the control room in Huntsville on June 28, watching shuttle payload specialist Lawrence J. DeLucas getting ready to do their experiment.

"There was a lot of tension," Finn says. "We didn't actually know what was going to happen."

But one glitch after another delayed the denouement. Initially, the researchers couldn't communicate with DeLucas because the line was tied up by another group relaying instructions for its experiment. The magnets holding an elevated, movable platform, or labjack, to the glovebox proved too weak, so the labjack (used to position a vessel in view of two video cameras to record the experiment) had to be taped down. Then it had to be moved into a better position and taped again. There was also a lighting problem, and a video camera had been installed upside down.

"All that took time," Weislogel says. "It put us nearly half an hour behind schedule."

Finally, DeLucas turned the crank that slowly pushed the red liquid from its reservoir into the container. At first, the liquid stayed pinned to the sharp edge where the container's waistline bulge starts, but a few energetic taps freed the liquid, and it slipped into the bulge and came to rest with a clearly asymmetric surface. The liquid, in effect, stretched itself from the "bottom" edge of the bulge to its "top" edge, spanning the container's circumference to create a surface resembling the contours of a spoon.

"This looked a lot like one of the numerical solutions we had gotten," Concus says.

This particular configuration was stable enough to resist DeLucas' attempts to dislodge it in the hope of seeing whether the liquid could readily assume other configurations. "With little taps, it just wouldn't budge, so it was really quite stable," Concus says. "We were happy to see that it kind of did what we thought it would do."

"There was a great sense of relief and victory," Finn adds.

On the following day, DeLucas performed the same experiment using the vessels containing distilled water. A few days later, the shuttle crew managed to squeeze in an extra, unscheduled run requested by Weislogel and his colleagues. This time, mission specialist Carl J. Meade repeated the first experiment in the laboratory area at a workbench rather than in the glovebox. In this way, the researchers could obtain much sharper, brighter photographs of the liquid's behavior.

In the glovebox, "the quality of the video, the precision of the focus, and the lighting were just not ideal," Weislogel says. "Out on the workbench, the quality was tremendous."

How close was the real thing to the computer simulation? The researchers won't know in detail until they analyze the images captured by the video cameras monitoring the experiments.

"We got two views of the surface shapes that formed in the glovebox," Weislogel says. "We can reconstruct the surface from those views and get a pretty good idea of [how] its shape compared with the numerical solution." That sounds straightforward, but the steps involved are both complicated and time-consuming.

"We'll be able to plot the interface shape in three dimensions," Weislogel says. "Then we can calculate energies and contact angles to see what parts of the theory are validated."

This analysis, when completed, should provide some indication of whether a theoretical approach based on such parameters as contact angle can in fact predict the shape of a liquid surface in a container of a given geometry. If it works, researchers will have a relatively simple means of calculating the behavior of fluids in a space environment.

In addition, the results may well suggest new experiments. Meanwhile, Concus and Finn have a long list of possibilities for future shuttle experiments.

"We try to find geometries with particularly interesting effects – where things will happen that are strikingly different from what normally comes up," Finn says. "If we get another chance, I wouldn't mind trying a few of our other choices."

"It's awfully time-consuming. There's a lot of paperwork. There's training. There are meetings. There are engineering details," Concus says. "But you get it in your blood."

Finn, who had started out as an engineer, remarks: "I thought I had escaped all that physical reality that I didn't want to have anything to do with, but now it's more fun. I think mathematics should get motivational input from outside – from the rest of science. Otherwise mathematics dies out." □