

Leidenfrost drops are on a roll

A 250-year-old effect still has some surprises in store.

The Leidenfrost effect is at once familiar and mysterious. The heart of the effect is easy enough to observe and understand: Sprinkle a liquid on a hot surface and the drops skitter around frictionlessly, levitated by a thin cushion of their own vapor. Although the drops evaporate eventually, the insulation of the vapor keeps them liquid for tens of seconds or more.

Beyond that simple picture, it gets a lot more complicated. The aerodynamics of the vapor, hydrodynamics of the liquid, and continual flux of heat and mass between the two phases are all tremendously difficult to understand in detail, and a number of seemingly elementary questions remain unanswered. In particular, there's little physical understanding of what determines the Leidenfrost point—the minimum surface temperature, typically many tens of degrees above a liquid's boiling point, required for the drop to levitate.

The richness of Leidenfrost physics, combined with the absence of friction between the drops and the surface, means that the drops can behave in strange and surprising ways. In 2006 Heiner Linke and colleagues discovered the Leidenfrost ratchet (see *PHYSICS TODAY*, June 2006, page 17): When the surface is etched with a series of parallel sawtooth grooves, the levitating drops spontaneously creep in the direction perpendicular to the grooves.¹ And they do so even when they're given an initial velocity in the opposite direction or when the surface is tilted so they must flow uphill.

Now Ambre Bouillant, her PhD adviser David Quéré, and their colleagues at ESPCI Paris have discovered what may be the strangest and most surprising result to date. Rather than looking at a variation on the Leidenfrost theme, they investigated the basic setting: a liquid drop placed on a flat, solid surface. They found that drops initially at rest self-

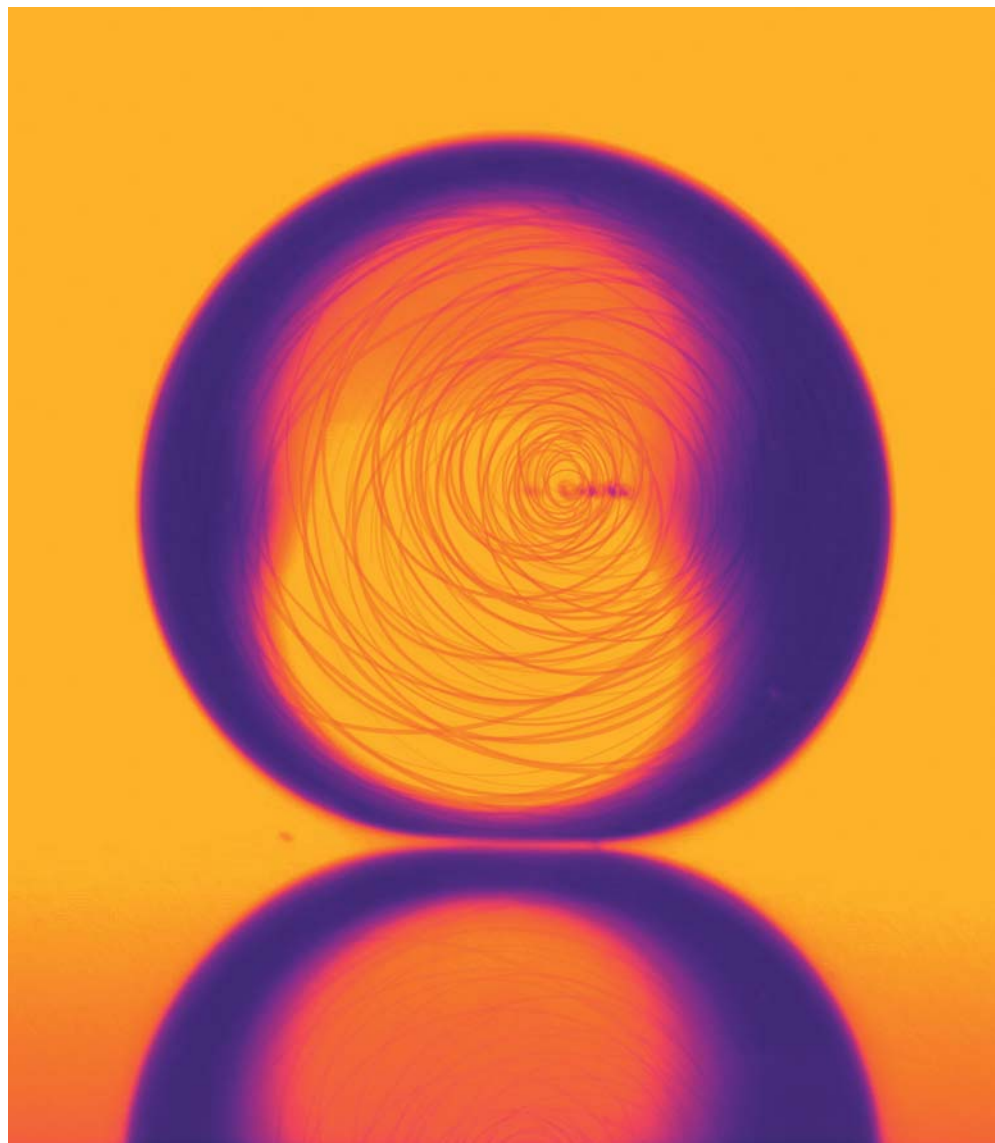


FIGURE 1. FLUID FLOW IN A LEIDENFROST DROP. A relatively large drop can host a large number of swirling vortices, and the overall flow isn't biased in any particular direction. A smaller drop, like the one shown here, can accommodate just one vortex; the uniform circulation is the basis for self-propulsion. (Courtesy of Ambre Bouillant, Célia Boutilier, and David Quéré.)

propel and roll like wheels—no surface texturing required.² The only catch is that the drop must be of just the right size: large enough that its base is slightly indented when it rests above the hot surface, but not so large that it loses its overall spherical shape and flattens into a

pancake-like puddle. For water drops, that means having a radius between 0.7 mm and 1.3 mm.

Rolling on air

Johann Gottlob Leidenfrost first wrote about his namesake effect in 1756, but

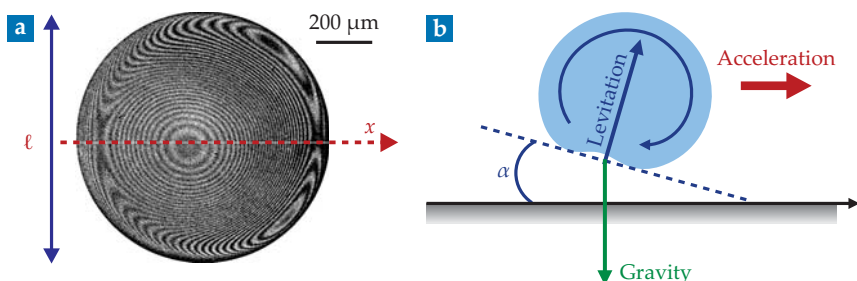


FIGURE 2. FROM SPINNING TO ROLLING. An interferometric image (a) of the bottom of a Leidenfrost drop shows the drop tipped slightly forward in the direction of motion x . The width ℓ of the contact region is about a third of the drop's diameter. As shown schematically (b), tipping the drop by an angle α tilts the levitation force vector by the same angle and produces a net forward acceleration. Both α and the thickness of the vapor film are exaggerated for visibility. (Adapted from ref. 2.)

until now, no one noticed the self-propulsion on flat surfaces. That's largely because freely moving drops on flat surfaces have so rarely been studied. Most of the time, researchers immobilize the drops, either with a needle or by placing them on curved surfaces, to keep them from drifting away due to air currents, a slight tilt of the table, or other extraneous forces.

Quéré has worked extensively on the dynamics of liquids on surfaces, and he's no stranger to the Leidenfrost effect. Among other work on the topic, he and colleagues showed that Linke and colleagues' ratchet experiment still worked when the liquid drops were replaced by small chips of a sublimating solid.³ The ratcheting mechanism, therefore, was not related to groove-induced deformation, as some thought it might be.

One day a student asked him if the liquid flowed inside a Leidenfrost drop. "The answer had to be, obviously, yes," he says: As vapor forms and escapes from between the liquid and the hot surface, it exerts a drag force on the drop's outer layer, which generates internal fluid flow. "But I was unable to say more, so we decided to look at it."

He and Bouillant seeded some water with tracer particles—hollow, micron-scale glass spheres with nearly the same density as water—and with a high-speed video camera tracked the particles' motion in immobilized Leidenfrost drops. In large, flat drops, the researchers saw multiple swirling vortices, as shown on the cover of this issue, indicative of a mostly symmetric flow of vapor escaping in all directions from under the drop. "It was the common case of boring

research where you find what you expect," says Quéré. But as the drops slowly evaporated, a surprising thing happened. When a drop's radius shrank below 1.3 mm, it could no longer accommodate more than one vortex. The symmetry of the balanced flow was spontaneously broken, and the entire drop mass started circulating in the same direction like a rotating wheel, as shown in figure 1.

Full tilt

The immobilized drops turned like wheels, but would they roll like wheels when freed? In principle, they wouldn't have to. Wheels on a road are propelled forward by friction, but no frictional contact connects a Leidenfrost drop and its substrate. Perhaps the drops would just whirl in place like tires on a slick sheet of ice.

The next step, then, was to let them move freely on a flat surface. When placed initially at rest, large, flat drops all ambled off in the same direction—not because they were self-propelling but because the surface wasn't perfectly level: Their rate of acceleration corresponded to an incline of a few tenths of a milliradian. The smaller, spherical drops, on the other hand, also took off in straight-line trajectories, but at a much faster clip and in seemingly random directions. Closer investigation showed that each drop was indeed moving in the direction that corresponded to the wheel's rotation.

To identify the cause of the self-propulsion, the researchers looked at the drops from below. They replaced the hot substrate with a transparent material

and interferometrically imaged the contours of the underside of the liquid, as shown in figure 2a. They found that the drops tipped forward slightly, by an angle α of typically a few milliradians, in the direction of rotation. The sketch in figure 2b shows the possible consequence of that tipping: The force of levitation tilts forward by the same angle, resulting in a net forward acceleration a , the same as would be experienced by a drop rolling down a slope of angle α .

That picture yields a testable hypothesis: $a = g \sin \alpha$, where g is the acceleration due to gravity. Experimental intricacies made it difficult to measure a and α simultaneously, but the few times the researchers managed it, they found quantitative agreement with the predicted relationship, which suggests that they have the correct explanation for the self-propulsion. Still, the simple story glosses over a lot of details, and Quéré hopes to put his theoretical understanding on firmer footing. "We have a scenario, but is it true?" he asks. "To check our interpretation, we would need careful analytical calculations, and we would need sophisticated numerical simulations."

A more complete theory could also help to predict α . Experiments so far suggest that α depends strongly on the drop size and, for water, is maximized for drops around 1 mm in radius. But there's no clear model for what functional form that dependence should have, and even drops of the same size can exhibit widely different values of α .

The self-propulsion effect is striking, but is it good for anything? As a first step, Quéré and colleagues have been exploring ways to use surface topography or temperature gradients to steer the drops in desired directions. "It might also be possible to exploit the effect to carry something," says Quéré. "If you somehow invent a wheel, you can be tempted to put a car on it and see what happens."

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References

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