A heat-seeking slingshot: Liquid droplets show ability to cool extremely hot surfaces

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Turn on a skillet and let it heat up until it is well above the boiling point of water. Then sprinkle a teaspoon of water on the skillet and watch. Water droplets will bounce up, form spheres and scurry across the surface.

What you have just observed is an example of the Leidenfrost effect, named for Johann Gottlob Leidenfrost, an 18th-century German physician and scientist. The phenomenon occurs when a liquid, upon approaching an object that is much hotter than the liquid's boiling point, produces a vapor which insulates the liquid from the surface of the object.

This repulsive force, say scientists, has two consequences. It prevents droplets of the liquid from making physical contact with the surface, causing them instead to hover over the surface. And it causes the droplets to boil off more slowly than they would on a surface with a lower temperature that is still above the liquid's boiling point.

Researchers in Hong Kong and at Lehigh University recently demonstrated that it is possible to exploit the Leidenfrost effect to control the direction and destination of liquid droplets on a surface and thus to cool it more efficiently. They achieved this by lithographically patterning a surface with microscale features that convert excess surface tension into a kinetic energy that propels droplets to "hot spots" on the surface.

The discovery, say Zuankai Wang of the City University of Hong Kong and Manoj Chaudhury of Lehigh, has the potential to improve technologies that involve microfluidics, heat transfer, heat exchange, micro-heat exchange, water management and thermal management.

"Many applications, such as power plant reactors, require the management and control of the movement of water droplets at very high temperatures," says Wang, an associate professor of mechanical and biomedical engineering at City University. "Typically, the cooling of extremely hot surfaces has been accomplished with spray cooling. You spray a lot of water droplets onto a surface and as they boil, they take away the heat.

"At a high temperature, however, this doesn't work because the Leidenfrost effect prevents the droplets from making sufficient contact with the surface to cool it. Thus it takes too long to cool a surface by boiling off water."

Wang, Chaudhury and their colleagues reported their results today (Feb. 1) in *Nature Physics*, a journal of Nature magazine, in an article titled "Directional transport of high-temperature Janus droplets mediated by structural topography." The article's lead author is Jing Li, a Ph.D. candidate in the department of mechanical and biomedical engineering at City University.

Contrasting topographies

Scientists in the last 20 years have learned to control the movement of liquid droplets on a solid surface by breaking the wetting symmetry that results from the impact of a droplet on a surface. They have accomplished this by harnessing gradients of surface energy and by utilizing light, temperature, electric force and mechanical vibration.

Chaudhury, the Franklin J. Howes Jr. Distinguished Professor of Chemical and Biomolecular Engineering at Lehigh, for example, has published articles with his students in Science and Langmuir describing their successful efforts to direct the movement of water droplets on surfaces.

But scientists have not yet achieved this control on surfaces heated to Leidenfrost temperatures and above, or on surfaces with extremely hot local spots.

Two years ago, Wang came up with the idea of creating topographical contrasts on a silicon wafer by etching the wafer surface with micropillars and arranging the pillars in zones that vary according to the density of the pillars and the contact angle of the pillars with the surface.

"The Leidenfrost Effect has been extensively studied for drag reduction, while the presence of the undesired vapor layer also prevents efficient heat transfer," says Wang. "Thus, we came up with the idea of creating an asymmetric surface to control droplet motion at high temperatures."

In their *Nature Physics* article, the researchers reported that their experiments, which were conducted in Hong Kong, showed that "judicious control of the structural topography and operating temperature range of the solid substrate" served to break the wetting symmetry of droplets.

The group also reported a "new physical phenomenon in which two concurrent wetting states—Leidenfrost and contact-boiling—can be designed in a single droplet [heated] above its boiling point."

The droplet, the researchers wrote in *Nature Physics*, "exhibits a contrasting (or Janus) thermal state with a lower contact angle in the boiling region, but a higher angle in the Leidenfrost region." This contrast generates "a gradient of curvature, and thus a gradient of Laplace pressure."

"As the [droplet's] viscous dissipation is minimal," the researchers wrote, "the resulting excess surface energy of the droplet is converted to kinetic energy, naturally causing it to dislodge from the surface and take flight into the air. The droplet eventually gets deposited in the contact-boiling region."

A similar phenomenon in nature

The researchers liken this phenomenon to the action of a slingshot and note that something similar occurs with a filamentous mushroom called Basidiomycota. Each spore of the fungus is part hydrophobic, with a shape like a thin film, and part hydrophilic, with a shape like a sphere. When the two regions make contact, they coalesce, and the tension between hydrophobic and hydrophilic regions creates a force that carries the entire spore into the air.

"This is a chemical effect that nature produces," says Shuhuai Yao, an associate professor of mechanical and aerospace engineering at the Hong Kong University of Science and Technology. "At the point of coalescence, there is an asymmetry but the desire for symmetry causes a transitory state and generates a force that propels the spore."

The contrasting topographies of the micropillars on Wang's silicon wafer create a similar phenomenon. At a high temperature, as one part of the droplet is boiling and one is non-boiling, an asymmetry is created. But as with the Basidiomycota, the natural tendency toward symmetry creates the slingshot effect that propels the droplet.

There is, however, a critical difference between the two phenomena, the researchers say. While nature makes no effort to guide a spore but instead merely to release it, a droplet on a bio-inspired surface can be targeted to a specific place and made to land on a hot spot and boil off.

More information: Jing Li et al. Directional transport of high-temperature Janus droplets mediated by structural topography, *Nature Physics* (2016). DOI: 10.1038/NPHYS3643

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