Discovery of mini 'water hammer' effect could lead to materials that water really hates

February 8 2011

Researchers from Northwestern University and the Massachusetts Institute of Technology (MIT) have studied individual water droplets and discovered a miniature version of the "water hammer," an effect that produces the familiar radiator pipe clanging in older buildings.

In piping systems, the water hammer occurs when fluid is forced to stop abruptly, causing huge pressure spikes that can rupture pipe walls. Now, for the first time, the researchers have observed this force on the scale of microns: such pressure spikes can move through a water droplet, causing it to be impaled on textured superhydrophobic surfaces, even when deposited gently.

This insight of how droplets get stuck on surfaces could lead to the design of more effective superhydrophobic, or highly water-repellant, surfaces for condensers in desalination and steam power plants, de-icing for aircraft engines and wind turbine blades, low-drag surfaces in pipes and even raincoats. In certain cases, improved surfaces could improve energy efficiency on many orders of magnitude. (About half of all electricity generated in the world comes from steam turbines.)

The research is published by the journal Physical Review Letters.

"We want to design surface textures that will cause the water to really hate those surfaces," said Neelesh A. Patankar, associate professor of mechanical engineering at Northwestern's McCormick School of Engineering and Applied Science. "Improving current hydrophobic materials could result in a 60 percent drag reduction in some applications, for example."

Patankar collaborated with Kripa K. Varanasi, the d'Arbeloff Assistant Professor of Mechanical Engineering at MIT. The two are co-corresponding authors of the paper. Patankar initiated this study in which he and Varanasi led the analytical work, and the experiments were conducted at MIT in Varanasi's lab. Other co-authors are MIT mechanical engineering graduate students Hyuk-Min Kwon and Adam Paxson.

In designing superhydrophobic surfaces, one goal is to produce surfaces much like the natural lotus leaf. Water droplets on these leaves bead up and roll off easily, taking any dirt with them. Contrary to what one might think, the surface of the leaves is rough, not smooth. The droplets sit on microscopic bumps, as if resting on a bed of nails.

"If a water droplet impales the grooves of this bumpy texture, it becomes stuck instead of rolling off," Patankar said. "Such transitions are well known for small static droplets. Our study shows that the impalement of water is very sensitive to the dynamic 'water hammer' effect, which was not expected."

To show this, the researchers imaged millimeter-scale water droplets gently deposited onto rough superhydrophobic surfaces. (The surfaces were made of silicon posts, with spacing from post edge to post edge ranging from 40 to 100 microns, depending on the experiment.) Since these drops were on the millimeter scale and being deposited gently, prior understanding was to assume that gravitational force is not strong enough to push the water into the roughness grooves. The Northwestern and MIT researchers are the first to show this is not true.

They observed that as a droplet settles down on the surface (due to the drop's own weight) there is a rapid deceleration in the drop that produces a brief burst of high pressure, sending a wave through the droplet. The droplet is consequently pinned on the rough surface. That's the powerful mini water hammer effect at work.

By understanding the underlying physics of this transition, the study reveals that there is actually a window of droplet sizes that avoid impalement. Although focused on drop deposition, this idea is quite general and applies to any scenario where the water velocity is changing on a short (less than a millisecond) time scale. This insight can lead to the design of more robust superhydrophobic surfaces that can resist water impalement even under the dynamic conditions typical in industrial setups.

"One way to reduce impalement is to design a surface texture that results in a surface that sustains extremely high pressures," Patankar said. "It is the length scale of the roughness that is important." To resist impalement, the height of a bump and the distance between bumps need to be just right. Hundreds of nanometer scale roughness can lead to robust surfaces.

"Our ultimate goal," he added, "is the invention of textured surfaces such that a liquid in contact with it will, at least partially, vaporize next to the surface -- or sustain air pockets -- and self-lubricate. This is similar to how an ice skater glides on ice due to a cushion of thin lubricating liquid film between the skates and the ice. A critical step is to learn how to resist impalement of water on the roughness. Our work on water hammer-induced impalement is a crucial advance toward that goal of ultra-slippery vapor stabilizing surfaces."

More information: The paper is titled "Rapid Deceleration-driven Wetting Transition During Pendant Drop Deposition on Superhydrophobic Surfaces." prl.aps.org/abstract/PRL/v106/i3/e036102

Provided by Northwestern University