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Materials science

Droplets leap into action

What could cause a water droplet to start bouncing on a surface? A study reveals that a combination of evaporation and a highly water-repellent surface induces droplet bouncing when ambient pressure is reduced. See Letter P.82

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On page 82 of this issue, Schutzius *et al.*[1] report a remarkable phenomenon: at low pressure, droplets of water resting on an extremely water-repellent surface spontaneously jump and bounce. In some cases, the height of each bounce can increase, like a gymnast jumping on a trampoline. The findings add to our understanding of how droplet–surface interactions can prevent the accumulation of water or ice on surfaces.

Ice accretion on surfaces is a big problem in cold regions, particularly for aviation, shipping, or off-shore industries[2]. Strategies to minimize ice adhesion include using either smooth surfaces or highly water-repellent (superhydrophobic) surfaces. Superhydrophobic surfaces are covered with tiny protrusions that have low interfacial energy, which minimizes their attraction to liquids.

A water or ice droplet resting on a superhydrophobic surface sits on top of the protrusions, so that the main part of the droplet's underside is separated from the surface's substrate by a thin layer of air[3]. The low contact area between the water or ice and the protrusions ensures low ice adhesion. However, the remaining adhesion is usually still sufficiently strong to keep ice in place. Furthermore, because the volume of water increases during freezing, water droplets can expand into the space between protrusions upon freezing, increasing both the contact area and adhesion of the resulting ice.

So how can low pressure cause droplets on a superhydrophobic surface to start trampolining? Schutzius and co-workers propose that two effects need to be considered. First, as noted above, the surface reduces the droplets' adhesion. Such low adhesion has previously been shown to cause droplet jumping when two droplets merge, because the surface energy (which quantifies the disruption of intermolecular bonds that occurs in a liquid when a surface is formed) released by the merging can easily overcome the adhesion energy[4]. The second effect is evaporation. When water evaporates in still air, the rate of evaporation is limited by diffusion. Reducing the pressure of the surrounding gas increases the diffusion of the water vapour molecules, and thus the rate of evaporation.

In Schutzius' and colleagues' study, gas and water vapour are rapidly pumped away from the experimental chamber. A film of water vapour therefore remains only in the gap between the droplets' underside and the surface's substrate, because escape of the water vapour from this region is inefficient. An overpressure therefore builds up in the gap — that is, the pressure in the gap becomes higher than that of the surrounding atmosphere.

The authors argue that the droplet jumps once the force induced by the overpressure on the droplet overcomes gravity and adhesion. The gravitational force on droplets of 1 millimetre radius is about tenfold lower than the adhesive force, so less than 10% of the total overpressure needed to cause jumping is used to overcome gravity. But, gravity is, of course, required for the droplet to fall back to the surface.

When droplets land back on the surface, they first spread and their kinetic energy is transformed into surface energy. This spreading is followed by retraction back into an almost spherical droplet, during which process the surface energy transforms back into kinetic energy and the droplet bounces up again. For millimetre-sized droplets, spreading and retraction takes several milliseconds[5,6].

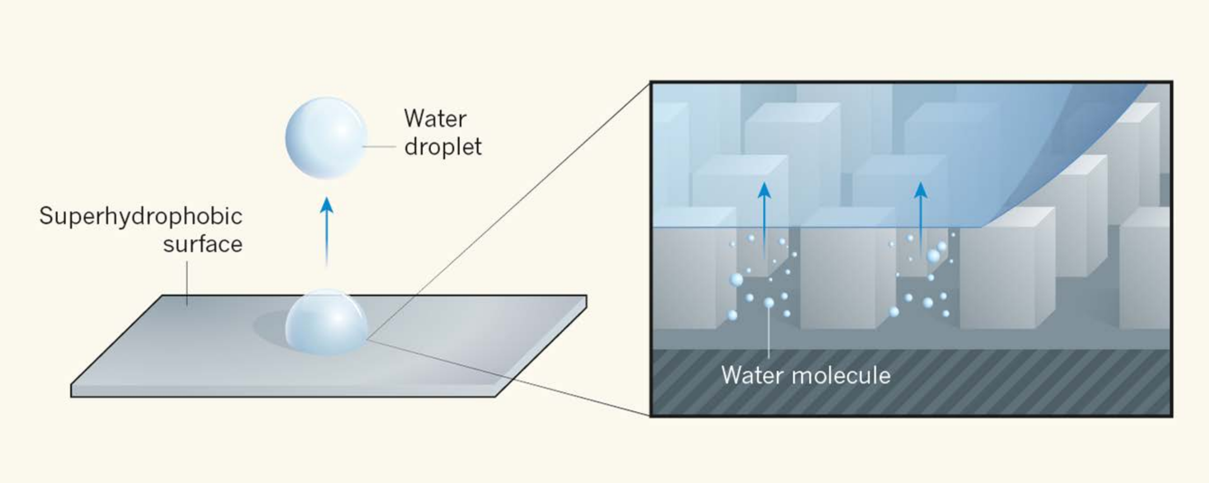

Figure 1 | Mechanism of droplet trampolining. Schutzius *et al.*[1] report that, in a low-pressure environment, water or ice droplets placed on superhydrophobic surfaces (which are covered with micrometre-sized hydrophobic protrusions) can spontaneously jump and bounce. The authors propose that, when a droplet is in contact with the surface, water-vapour molecules from the droplet escape more slowly from the gap beneath the droplet's underside than they do from elsewhere. The pressure in the gap therefore becomes larger than ambient pressure, generating a force (arrows) that lifts the droplet up. (Inset adapted from ref. 9.)

By calculating the volume of water vapour that can pass through the gap between the underside of the droplet and the surface's substrate per unit of time, the authors show that overpressure builds up beneath the droplet about ten times faster than the typical contact time of a droplet with the surface. The overpressure induces an upward force on the droplet that adds to the force caused by the conversion of surface energy to kinetic energy when the droplet retracts. This additional force can increase the height of the droplet's bounces, until a maximum height is reached after a few rebounds.

At sufficiently low ambient pressure, the temperature in the droplet can fall below its freezing point because of cooling caused by evaporation[7]. Schutzius *et al*. report that jumping can also be triggered by freezing of such supercooled water droplets — the latent heat released upon freezing causes a sudden overpressure and the droplet jumps off the substrate.

Droplet trampolining resembles the Leidenfrost phenomenon, which can be observed when water is spilled on a hot frying pan. A liquid droplet in close contact with a hot, solid surface gives rise to a vapour layer beneath the droplet; this vapour keeps the liquid from making direct physical contact with the surface. Typically, the droplet immediately starts to hover and move around, but the onset of trampolining can be fine-tuned by adjusting the time at which the system is de-pressurized. Another difference is that the Leidenfrost effect is caused by an imposed temperature difference between the droplet and surface, whereas droplet trampolining is caused by a pressure difference generated by the droplet itself.

Inertia and viscous dissipation (the conversion of a fluid's surface and kinetic energy into internal energy) typically dominate the rebound of a droplet from a superhydrophobic surface, so that forces exerted on the droplet's lower surface can be ignored. By contrast, trampolining results from a uniformly increasing force acting on the droplet's lower surface. A force also acts on a droplet's lower surface during pancake bouncing[8] — a phenomenon that occurs when droplets collide with superhydrophobic surfaces made from an array of submillimetre-spaced, tapered protrusions.

During pancake bouncing, droplets hitting the surface penetrate substantially into the array, whereby kinetic energy is transferred to interfacial energy. This process is followed by upward motion of the droplet out of the array through capillary action, during which the interfacial energy is transformed back into kinetic energy. The droplets then bounce off the surface in a pancake-like shape.

Both the trampolining and pancake-bouncing mechanisms reduce the contact time of bouncing droplets compared to bouncing on a normal surface[6]. However, unlike pancake bouncing, droplet trampolining is expected to occur for a large variety of surface topographies, as long as the air layer in the gap beneath the droplet is kept thin (at least a hundred times less than the droplet diameter at a pressure of about 0.05 bar). If the gap is too large, water vapour would escape too quickly from the gap and the overpressure within the textured surface would not be high enough.

Although Schutzius and colleagues' observations are fascinating, reducing atmospheric pressure is not a practical method for preventing icing in outdoor areas. And even for smaller areas, a lot of energy is consumed to reduce the ambient pressure. Furthermore, evaporation eventually causes the droplets to become so small that they come to rest and freeze — although bouncing has not been maintained indefinitely in any drop-impact experiments.

Nevertheless, the authors have vividly illustrated that simple experiments can yield unexpected and surprising results. Applying underpressure to a system is the most common method to enhance evaporation, commonly used in chemical and technical labs. Who would have guessed that it could produce such spectacular dynamics?

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