When being outside in nature in the presence of cold, windy, and rainy weather, most of us will have wondered: How do birds keep themselves warm? Not only does the wind imply a thinner thermal boundary layer over bodies, favoring heat loss, but, in addition, the impacting raindrops add considerably to the cooling, directly taking heat away, as most of us will have experienced, when being outside and unprotected in a heavy shower. Birds are better off in such a situation: To partly protect them against the heat loss from impacting rain droplets, evolution has equipped them with feathers, which have a hierarchical superhydrophobic structure. As Kim et al. (1) show, one function of this structure is to minimize the contact time between falling drops and the bird, in order to minimize the net heat transfer. In addition to droplet impact experiments on feathers, the authors studied droplet impact on butterflies and leaves, which also possess hierarchical superhydrophobic structures, as well as on such structures that were manufactured in a controlled way.

The water-repellent character of superhydrophobic leaves—the so-called lotus effect—has been well studied ever since the pioneering work of Barthlott and Neinhuis (2). However, the focus of this line of research has been on gentle droplet deposition on the superhydrophobic structures, and not on droplet impact with large inertia \( \rho U^2 \) compared to the capillary confinement by surface tension forces \( \gamma / R \); in other words, previous work has not focused on large Weber numbers \( We = \rho U^2 R / \gamma \), where \( U \) denotes the impact velocity, \( R \) is the droplet radius, and \( \rho \) and \( \gamma \) are the density and surface tension of the liquid, respectively. In contrast, the focus of the droplet impact experiments by Kim et al. (1) on hierarchical superhydrophobic structures is on the large \( We \) regime.

One of the first studies on large Weber number drop impact on micro- and nanostructured superhydrophobic surfaces was by Tsai et al. (3), who found a transition from bouncing to splashing with increasing \( We \). For the structures they employed, this transition occurred around \( We_c \approx 120 \). Thanks to their ability to manufacture transparent hierarchical superhydrophobic structures and thus allow for bottom views, Kim et al. (1) can now elucidate the nature of this transition.

For their hierarchical superhydrophobic structures, beyond \( We_c \approx 150 \), they find a transition toward considerably reduced contact times of the droplets (see figure 5C of ref. 1). In that large Weber number regime \( We > We_c \), the contact time becomes much smaller than the capillary time \( \tau \approx 2.3 \sqrt{\rho R^3 / \gamma} \), which is otherwise an excellent estimate (4) for the contact time when \( We < We_c \), independent of \( U \). In addition, Kim et al. (1) find that, for \( We > We_c \), the contact time decreases with further increasing \( We \).

In the experiments by Kim et al. (1), the transition between the two \( We \) regimes only occurs for impacts on hierarchical superhydrophobic structures, and not for impacts on a smooth surface. Compare the bottom view snapshots for the drop impact for \( We = 680 > We_c \) on a smooth surface (figure 2A of ref. 1 at 1.9 ms) with that on the hierarchical superhydrophobic structures (figure 2C of ref. 1 at 4.2 ms): While, in the former case, a stable sheet is seen, which, after maximal extension, pulls back, in the latter case, the hierarchical structures of the surface break the sheet up through the nucleation of characteristic holes, which quickly expand. Such hole opening dynamics in a liquid sheet has been associated with the names Taylor and Culick (5, 6) and the opening speed—the so-called Taylor–Culick velocity \( \sqrt{2 \gamma / \rho h} \)—diverges when the thickness \( h \) of the liquid sheet vanishes.

In the Kim et al. (1) experiments, the emergence of the holes can only happen provided 1) the sheet is thin enough, that is, for large enough spreading, implying a large enough \( We \), and 2) that there is a large enough distortion on the liquid sheet, which here is provided by the roughness of the surface on which the impact takes place. To rationalize these findings, the authors provide an analysis invoking capillary waves interacting with the distorted landscape of the solid surface, resulting in a simple hole nucleation criterion: For given surface roughness amplitude \( \epsilon \), the critical

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\text{Double threshold behavior for breakup of liquid sheets}
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impact velocity is \( U_c \approx \frac{\sqrt{\gamma \rho}}{\rho_e} \), independent of the droplet radius \( R \), implying \( We_c \approx R/e \), independent of the type of liquid. This analysis accounts for the experimentally observed double threshold behavior for sheet breakup: 1) strong enough driving and 2) large enough distortions.

The sheet breakup mechanism studied by Kim et al. (1) typifies a whole class of sheet breakups occurring in nature and technology. For example, the liquid sheet breakup occurring after a flying liquid drop was hit by a strong laser pulse (7) shows quite some similarity; see Fig. 1A. Again, a double threshold behavior is found: 1) The Weber number must be larger than a critical Weber number \( We_c \approx 170 \); see ref. 7, and 2) the distortions must be sufficiently large, here provided by spatial inhomogeneities of the laser pulse.

A situation which is even closer to that of Kim et al. (1) is the one of droplet impact on a superheated surface, leading to the so-called Leidenfrost effect, where the droplet floats on its own vapor (12). Again, there are two regimes: For the static Leidenfrost effect (12), the drop is gently deposited on the superheated surface (i.e., very low impact velocity) and then hoovers around, slowly evaporating. Also for the dynamic Leidenfrost phenomenon (13), where the droplet impacts a superheated surface, it remains intact, provided the impact velocity is not too large. However, beyond a critical impact Weber number \( We_c \), the droplet spreads so much over the superheated surface (without touching it) that the liquid sheet becomes so thin that holes emerge and grow (14, 15). This regime is called the film-splash regime; the critical Weber number \( We_c \), beyond which it occurs depends on the surface temperature and is of the order of 100 to 200; see figure 5 of ref. 14. A typical case for the film breakage in the film-splash regime of the dynamic Leidenfrost phenomenon is shown in Fig. 1B, which resembles figure 2C (at 4.2 ms) of ref. 1. Presumably, the liquid vapor under the film provides enough distortions to the liquid film so that it can eventually break for \( We > We_c \). What could contribute to these distortions are local vapor bubbles bursting, among other possible causes; see below. So also here, a double threshold behavior may be in place.

The combined effects of surface structure and superheating on the disintegration of the emerging liquid sheet were also studied (16, 17): Thanks to the massive production of vapor under the liquid sheet at the rough and hot surface, a strong radially outward flow develops which helps the sheet to radially spread, leading to much earlier sheet breakage, both as compared to the rough and cold case (1, 3) and to the smooth and hot case (14).

Again, in all these cases, two conditions must be fulfilled for the liquid sheet to break: 1) The inertial driving of the sheet must be strong enough as compared to the surface tension keeping the liquid together, that is, the Weber number must be large enough, and 2) there must be a large enough initial distortion.

But what do we know for all these cases about the actual film breakage mechanism? The criterion found by Kim et al. (1) for when a sheet breaks—a coincidence of length scales (the sheet thickness \( h \) versus the surface corrugation amplitude \( e \)—is very valuable, but it does not say anything on the very piercing mechanism per se: The sheet thinned at the extreme could well coat the surface grooves without breaking, so that the hole nucleation mechanism remains to be elucidated.

There are, in fact, many ways in which a liquid sheet, or film, may puncture (see the review in ref. 18). A hole will have expanded provided its diameter is larger than the sheet thickness (6); otherwise it heals. But the causes of hole nucleation are diverse. 1) Extremely thin films are sensitive to thermal fluctuations. This thermally activated puncture may thus, at most, apply to films with thickness of order of \( h \sim \sqrt{k_B T} / \pi \approx 10^{-10} \) m in water, like Newton black films. 2) Very thin films, with thickness of the order of a few tens of nanometers, are sensitive to van der Waals forces and puncture under the driving force of the disjoining pressure \( \propto h^{-3} \). 3) External forcings may perturb the film to rupture. The collision with a sharp solid object with a radius of curvature \( e \) smaller than the film thickness, like in the Kim et al. (1) experiments, leads to puncture, as well as the mechanical action of a concentrated air jet, of a focused laser beam, or of a spark vaporizing the liquid. The stimuli may also result from an instability, like the application of a pressure gradient, or pressure difference across a film. The corresponding acceleration may lead to film thickness modulations through a Rayleigh–Taylor mechanism (7, 9, 19), ultimately causing its puncture. The same phenomenon is responsible for the crumpling of liquid bells, and the formation of transverse indentations at the edge of flapping liquid sheets (20, 21); it may affect films with thicknesses in the micron to tens of microns range (Fig. 1A and C). 4) Internal flaws and defects like solid hydrophobic particles introduced into a film can, when their size compares with the film thickness, lead to its rupture as they force the two interfaces of the film to pinch at the surface of the particle. Immiscible oil droplets (11, 22) and bubbles (10) also act as efficient hole nucleation sites in water films (Fig. 1D).
5) Chemical and temperature inhomogeneities at the surface of a liquid translate into inhomogeneities of surface tension. The corresponding Marangoni surface stress is communicated to the bulk of the liquid by viscosity in a way, when the liquid is shallow like in films, which can be dramatic (23). When the film sits in a transverse temperature gradient, or when surface tension is locally lowered by an impurity (Fig. 1E), the tangential flow digging the film is amplified, leading to rupture (18). Applications are numerous, including boiling (24), surface cleaning (25), or the stability of surface bubbles (26). 6) Finally, kinematic thinning, which results from initial inhomogeneities of the liquid interstitial velocity, an effect that may be involved in the Kim et al. (1) observations, and which is characteristic of thick, turbulent films, also provokes rupture in finite time (27). Most of these six mechanisms of hole nucleation have a double threshold behavior in common.

In a broader context, we note that the double threshold feature of an instability—in the work of Kim et al. (1) for the spreading liquid sheet, for which both the Weber number and the distortion must be large enough for the instability and breakage to occur—is rather common in fluid dynamics in general. Other better-known examples are pipe flow or other shear flows where both the Reynolds number and the initial distortion must be large enough for the flow to become turbulent (28, 29) and where the instability is associated with the interplay between nonnormality and nonlinearity of the flow (30, 31), or viscoelastic polymer flows where both the Weissenberg number and the initial distortion must be large enough (32). We speculate that the theoretical concepts successfully applied to explore the instabilities of these flows may also be beneficial to better understand the breakage of thin liquid sheets.

Finally, we suggest an application perspective for the work by Kim et al. (1). In most cooling facilities, the contact between the cooling liquid and the surface to be cooled should be maximal, in order to ensure the best heat transfer. However, a further increase in the heat flux can result in a discontinuous and large increase of the wall temperature, which is appropriately called “burn-out” or boiling crisis (33). The reason for this behavior lies in the massive formation of vapor bubbles which strongly reduce the direct contact between the liquid and the superheated surface [similarly as in the Leidenfrost state (12)] and thus overheat the surface, potentially leading to its destruction. However, in the opposite case, namely, in applications in which a surface is supposed to stay warm and thermally isolated despite being exposed to droplets and spray, the results of Kim et al. (1) teach us that micro- and nanostructuring the surface can be helpful for minimizing the contact time and thus the heat transfer. Their estimates provide guidelines as to the roughness length scale that is sufficient to achieve this. That this strategy can work has, in fact, been proved by birds who happily sit or fly in a cold rainshower without freezing, protected by their hierarchically microstructured and nanostructured feathers.

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