News & views

Fluid dynamics

Hot surfaces cooled by isolating steam from spray

James C. Bird

An innovative microstructure design distributes water to rapidly cool a hot surface without interference from the steam that is created in the process. This approach could enable safer and more efficient power generation. See p.568

A few droplets of water sprinkled on a hot frying pan will quickly boil away. Yet the same droplets on a much hotter pan will instead remain intact by floating on their own insulating vapour – a phenomenon referred to as the Leidenfrost effect[1]. Eye-catching though it might be, this behaviour can have dire consequences in applications that require intense water cooling, including nuclear power plants, in which inefficient cooling due to the Leidenfrost effect can lead to nuclear meltdown. On page 568, Jiang *et al.*[2] report a surface design capable of inhibiting this effect, to allow spray cooling at temperatures exceeding 1,100 °C, which is 600 °C higher than alternative strategies have achieved.

Vaporizing water into steam requires a substantial amount of latent energy, which is the energy released or absorbed during a change in phase. When this latent energy is absorbed from a hot object such as a frying pan, the object's surface cools rapidly, and this effect is exploited in many applications that fall into one of two categories. The goal is either to quickly return a heated object to its original temperature – for example, when red-hot metals are hardened through rapid cooling – or to prevent an object from overheating.

In situations ranging from advanced electronics to nuclear reactors, overheating can occur when the rate of cooling is insufficient to overcome the rate at which heat is generated internally. Although latent-energy absorption provides a remarkable cooling mechanism, there is a risk of a rapid, uncontrolled rise in temperature if the Leidenfrost effect is triggered. Therefore, internal heat generation needs to be maintained below a critical level, often at the expense of efficiency or performance.

When an object is surrounded by air at room temperature, the rate at which it cools increases as the temperature of its surface increases. By contrast, when the object is surrounded by water, the rate of cooling increases, decreases and then increases again as the surface temperature rises[3] (Fig. 1a). This phenomenon occurs because of the Leidenfrost effect. The cooling rate drops when the surface is hot enough to vaporize sufficient steam to create an insulating gap between the liquid and the surface, and is restored to its previous level only once the surface temperature exceeds approximately 1,100 °C. Consequently, if the surface temperature is forced to rise above the critical level at which the cooling rate begins to decrease, then the surface temperature becomes unstable and increases uncontrollably in a process known as the boiling crisis.

To increase the range of temperatures at which cooling rates remain high, researchers have explored strategies to raise the temperature at which the Leidenfrost effect sets in. Much of this effort, including the work by Jiang and colleagues, has focused on cooling with water droplets, because spray cooling with water is an established technique, and because visualizing the droplets offers a simple way to identify the Leidenfrost point. At temperatures below this point, a droplet boils frenetically, which makes its surface visibly uneven. Above the Leidenfrost point, the surface of the droplet is smooth as it skims

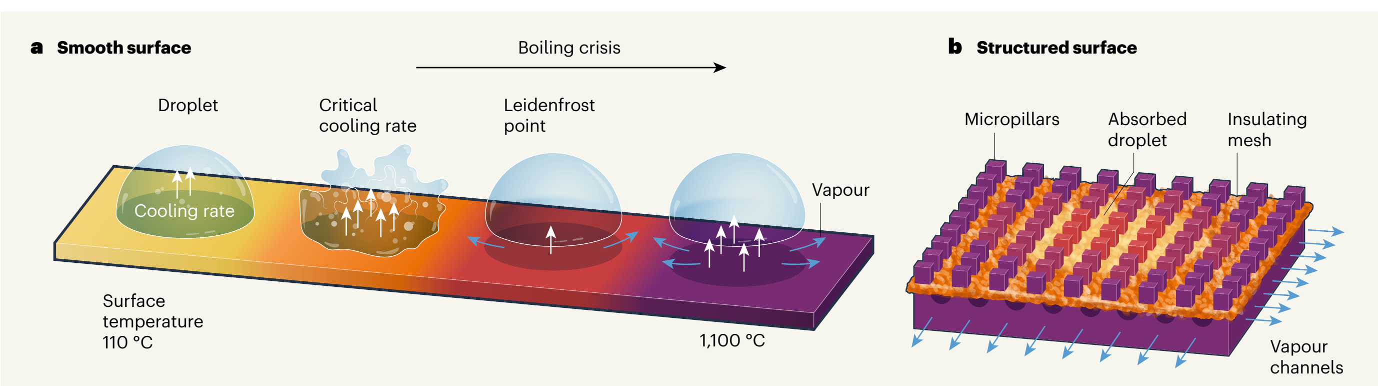

Figure 1 | Suppressing the Leidenfrost effect to enable spray cooling. a, A water droplet in contact with a hot, smooth surface cools at a rate (illustrated by the number of white arrows) that depends on the temperature of the surface. As this temperature increases, the cooling rate initially increases and then decreases, before increasing again. This behaviour can lead to a boiling crisis in which the surface temperature increases uncontrollably to more than 1,000 °C. The sudden decrease in cooling rate occurs because the droplet's own vapour insulates it from the hot surface, a phenomenon known as the Leidenfrost effect. **b**, Jiang *et al.*[2] designed a structured surface that inhibits the Leidenfrost effect over a wide range of surface temperatures. The surface has steel micropillars interspersed with an insulating silicon dioxide mesh, which absorbs the water droplet and draws it towards the micropillars, where it vaporizes. The vapour then escapes through channels underneath the mesh. The insulating properties of the mesh bring its temperature below the Leidenfrost point.

the hot surface. Furthermore, the cooling rate can be calculated from the time it takes the drop to evaporate.

Previous studies have raised the Leidenfrost temperature by incorporating hierarchical structures into the surface to be cooled. Such structures combine nanometre-sized features designed to draw (or wick) liquid to the hot surface with sparse, micrometre-sized textures that act as vents to prevent vapour from lifting the droplet[4,5]. This combination can raise the Leidenfrost temperature by hundreds of degrees, yet as the surface temperature increases, the amount of vapour produced also increases, and this can disrupt the process of drawing liquid to the surface. Designs that decouple the venting and wicking help[5], but at sufficiently high surface temperatures, the vapour accumulates in the wicking region, limiting performance.

To engineer a surface design that achieves high cooling rates at record-high temperatures, Jiang and colleagues fused an insulating mesh between thermally conductive micropillars (Fig. 1b). The mesh is made from silicon dioxide fibres that absorb water droplets and draw them towards the steel micropillars, where the liquid vaporizes. The vapour then escapes through U-shaped channels lying beneath the mesh.

Architecturally, this design is similar to the hierarchical structures developed previously[5]. However, a key difference is that heat conducts quickly between the steel base and pillars, but slowly in the mesh membrane. This mismatch is crucial, because it means that the vapour is generated where the pillars and mesh meet, where it cannot interfere with the absorption of liquid by the mesh. Indeed, Jiang and colleagues demonstrated that, when they removed this feature by making both the membrane and pillars thermally conductive, the surface was effectively cooled to temperatures of up to 500 °C — consistent with the limits of previous designs[4,5] — but not beyond this point.

By introducing the mismatch in conductivity, Jiang and colleagues showed that their surface could be spray cooled from ultrahot temperatures in excess of 1,100 °C. This value is particularly relevant, because 1,100 °C is around the temperature at which a material undergoing the boiling crisis recovers the ability to cool in response to internally generated heat. This achievement indicates that the surface might avoid the boiling crisis, rather than merely delaying it. The authors also demonstrated that their design could be applied to curved and flexible surfaces, opening up the possibility of retrofitting existing heat exchangers and pipes.

Finally, Jiang *et al.* combined mechanistic modelling with numerous systematic experiments, enabling them to form and verify predictions for the parameters of their design. This is the most influential contribution of the study, because it provides in-depth understanding of how these parameters affect the cooling rate, and can therefore guide future improvements.

Increasing the peak cooling rate would be one such improvement. The team's modelling suggests that this could be achieved by increasing the mesh pore size (to draw the liquid to the pillars more quickly) and deepening the channels (to speed up the removal of the excess vapour). In applications for which overheating is a concern, it would also be preferable to have the cooling rate increase sharply with temperature instead of remaining constant, as it does in the current design. Small modifications, such as a non-uniform mesh or channels of varying depth, might enable such a sharp increase by passively adjusting the flow of water and steam as the temperature increases.

Taken together, Jiang *et al.* have demonstrated an innovative approach and a clear understanding of their system, both of which are certain to inspire future cooling strategies.

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Archaeology

A grave matter of ancient kinship in Neolithic Britain

Neil Carlin

An investigation into the nature of genetic connections between individuals interred in the same chambers of an ancient tomb in Britain about 5,700 years ago sheds light on kinship in an early society. **See p.584**

Archaeologists have long suggested that the placement of human remains in tombs during the Stone Age of northwestern Europe reflects one of the ways in which kinship was created and negotiated. Biological descent is presumed to have played a part, but relatively few cases of close genetic relationships have previously been uncovered from these tombs. This is partly because only a couple of studies have investigated the genetic lineage of multiple burials from the same site. Now, an innovative study of a chambered tomb at Hazleton North in southwestern Britain has analysed the genomes of 35 out of at least 41 people, including 22 adults, buried there over the course of a century. On page 584, Fowler *et al.*[1] reveal notable information about the social relationships between these individuals, who lived around 5,700 years ago. The authors' findings provide a uniquely high-resolution, multigenerational and spatio-temporal analysis of the connections between the people who were interred together in the monument.

"All those who were descended from two particular maternal lineages were found in one chamber."

Hazleton North was constructed between approximately 3695 and 3650 BC by an early farming community, at least a century after the start of the Neolithic period in Ireland and Britain[2]. The Neolithic period was accompanied by numerous technological, cultural and social changes, such as the construction of megalithic monuments at various sites on these islands, and the introduction of cattle and cereals from continental Europe[3]. The earliest evidence for such Neolithic practices coincides with the arrival to these islands of people with distinctive genetic signatures found in continental Europe. This is where, in the case of the Hazleton North tomb, the ancestors of the deceased individuals predominantly came from.

Our knowledge of these kinds of broad-scale genetic changes in a population stems from the work of archaeogeneticists. Much of this type of analysis focuses on using ancient DNA from relatively few individuals to identify