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Maths, Physics & Chemistry

Leidenfrost reinvents the wheel

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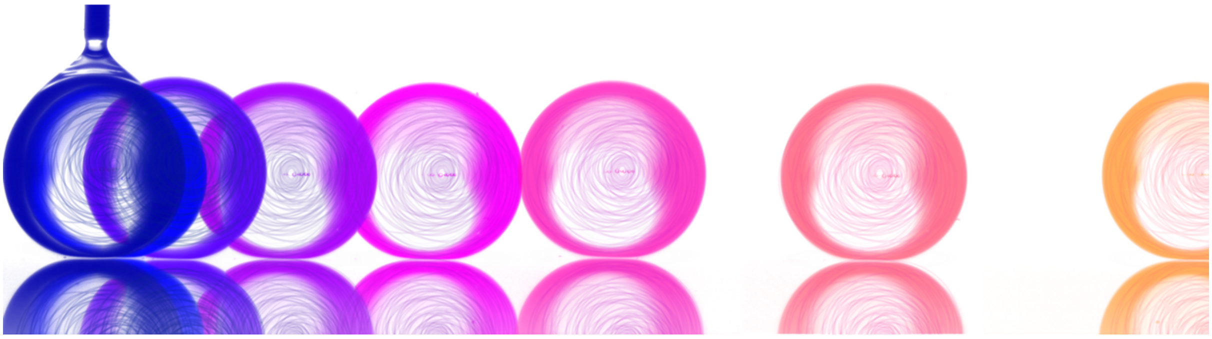
ABSTRACT

Placed on hot solids, water does not only levitate, it also self-propels!



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We often test the temperature of our frying pans by throwing a few droplets of water: if they skate over the hot surface, it is time to cook our pancakes! Water mobility indeed arises above a well-defined temperature, as described in 1756 by Johan Leidenfrost in the chapter XV of his Tractatus de aquae communis nonnullis qualitatibus – one of the last scientific treatises written in Latin. Above this temperature (typically, 200°C), a vapor film forms on which water levitates, instead of contacting its substrate. Levitation has many consequences, such as an absence of boiling (bubbles generally stem from solid/liquid interfaces), a slow evaporation (vapor is a good insulator) and a frictionless mobility (drops then are kinds of hovercrafts).

This mobility leads us to trap the liquid to study it. Leidenfrost, for instance, placed water in hot spoons, which allowed him to evidence with the naked eye the underlying vapor cushion. Even simpler, you can pin water with a thin needle and observe its evaporation and its paradoxical tendency to (slowly) sink inside the vapor – a smaller drop being at a higher pressure, as we learnt from Laplace. But the elusive nature of Leidenfrost drops can also be exploited: placed on hot ratchets by previous research, liquids were observed to self-propel. The vapor flow beneath water being rectified by the ratchet, it entrains the levitating liquid by viscosity – clearly a weak force, yet sufficient to provide quick motions in such frictionless situations.

It is natural that research first focused on the vapor cushion, the hallmark of the Leidenfrost phenomenon – but we decided to complement these studies by observing what happens inside the liquid itself. To that end, a large drop containing tracers is trapped and tracers are simply tracked as water evaporates. Not surprisingly, we observe motions, caused both by the vapor flow (that drags liquid) and by temperature differences between the (hot) bottom and the (colder) top of the drops. But much more unexpectedly, these motions switch from symmetric (counter-rotative vortices) to fully asymmetric (solid-like rotation), when the drop size decreases from a few millimeters to about one millimeter, that is, when its shape initially flattened by gravity becomes quasi-spherical: the liquid cell then cannot accommodate pairs of vortices so that Leidenfrost has no other option than reinventing the wheel!

Wheels convert rotation into translation by taking advantage of friction on roads or rails, but Leidenfrost wheels are rotating above vapor… However, despite the absence of contact, we observed that as soon as the needle is withdrawn from water, drops do move in the direction we could have (naively) expected from rotation. Hence a revelation and an interrogation: Leidenfrost drops are ultra-mobile not because they are frictionless, but because they have a hidden engine in their body! Yet how can a wheel operate without contacting its substrate?

It is always interesting to vary our point of view on mysterious things. While side views reveal inner rotation, while top views show that drop trajectories take place in random directions, the secret of contactless wheels was unlocked by bottom views. Using transparent substrates, we found that the drop base is slightly tilted, which yields a horizontal component to the levitating pressure, in the direction anticipated from the rotation. Why? Because, we think, the rotating water entrains air, which, once combined with the escaping vapor flow, leads to pressure differences between the opposite sides of the base – producing the tilt and thus, so to speak, an endless slope along which water falls down…

Therefore the legendary mobility of Leidenfrost drops turns out to be sui generis: drops do not stay where they are placed because aerodynamics and hydrodynamics conspire to entrain them, which achieves an original heat engine where the liquid takes heat from its substrate and takes it away. Our findings might allow us to design new kinds of self-propelling devices: for instance, a levitating liquid on a hot substrate with a temperature gradient might have its base tilted as well, due to the dependency of the vapor thickness on temperature, and thus be propelled to the cold – emphasizing the richness and diversity of situations where phase change is combined with mobility.