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RESEARCH ARTICLE

Fundamental Mechanics and Emerging Applications of the Leidenfrost Effect

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ABSTRACT: The Leidenfrost effect has captivated researchers since J. G. Leidenfrost first reported the phenomenon over 250 years ago. Today, the Leidenfrost effect has been extensively studied for its role in engineered systems, including power plants, rockets, and manufacturing processes. Liquid droplets encountering superheated surfaces boil rapidly, forming a vapor film. This vapor insulates the remaining bulk of the droplet, inhibits further boiling, and counterbalances droplet weight, causing levitation. This review examines the phenomenon's core principles, covering droplet levitation mechanics, vapor layer behavior, and advanced microfluidic transport methods. Dynamics of the Leidenfrost effect on substrates of varying wettability, especially superhydrophobic substrates, are covered. Methods to suppress the Leidenfrost effect, from altering surface texture to inducing electric fields, are explored. Non-Newtonian droplet interactions with superheated substrates are analyzed, and reasons for renewed interest in these liquids are highlighted. We then compile and describe existing and emerging aerospace, marine engineering, thermal energy systems, material science, and cryogenics applications. These use cases are achieved through tailored modifications of parameters such as wettability, surface topology, and porosity. Such multiplicity in possible applications demonstrates the versatility of the Leidenfrost effect.

KEYWORDS: Leidenfrost Effect, Droplets, Vapor Film, Levitation, Surface Structure.

Introduction

The Leidenfrost effect, first described by Johann Gottlob Leidenfrost in 1756,[1] is the phenomenon observed during stable film boiling. Droplets form and are heated so rapidly after encountering substrates exceeding the liquid's boiling point that they only undergo a partial phase change. Vapor from the droplets forms a film, cushioning droplets and inhibiting further boiling.[2] Pressure from the vapor counterbalances droplet weight, which levitates, as shown in **Figure 1a**.[3] This can be easily observed at home in the kitchen. When a pan is sufficiently heated to approximately 473K, the water drizzles onto the surface and forms droplets. These droplets begin to levitate, moving on the pan's surface rather than quickly boiling away.[2]

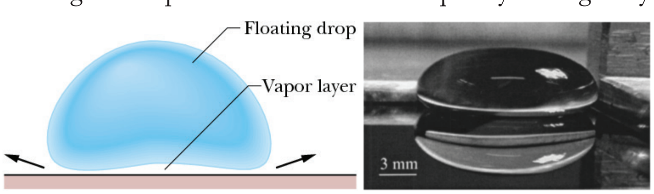


Figure 1a Figure 1b

Figure 1: (a) Leidenfrost droplets levitating on its vapor layer when dropped on a substrate dramatically exceeding the liquid's boiling point. It is reproduced from Walker, 2000.[4] **(b)** Large droplet flattened by gravity, resulting in non-spherical shape and reproduced from Biance *et al*.[2] under license.

The Leidenfrost point or Leidenfrost temperature (TL) is the temperature at which the Leidenfrost effect occurs. Still, it may also refer to the temperature at which the droplet has the longest lifespan. Heat flux through the vapor layer is lower due to vapor layer's poor thermal conductivity, and thus, it acts as an insulator between the hot surface and the droplet. Additionally, the vapor layer isolates the droplet from the heating substrate, and this lack of contact prevents bubbles from being nucleated. These factors increase droplet lifetime by a factor of approximately 500. Significantly reduced heat flux discontinues boiling, and the droplet slowly evaporates.[2]

The Leidenfrost temperature indicates the onset of stable film boiling (point C in **Figure 2**) between a given solid-liquid pair; therefore, factors affecting the minimum film boiling temperature will also influence the Leidenfrost temperature. The minimum film boiling temperature depends on heat flux, and a critical parameter in this relationship is surface tension.[5] In the bulk of a droplet, cohesive forces attract all internal molecules equally, resulting in no directional/net force. However, due to greater cohesion with liquid molecules than adhesion with air molecules, a net force tangential to the interface develops at liquid-air interfaces. Acting with forces of cohesion amongst internal molecules, this tangential force causes the droplets to shrink to the minimum surface area when at rest and levitating.[6]

Capillary length (λ) is the droplet's radius when the force of gravity balances the surface tension of the droplet and is calculated as $\lambda=\sqrt{\sigma/\rho g}$, where σ is the surface tension, ρ is the liquid density, and g is the gravitational acceleration. Droplets with a radius smaller than the capillary length form spherical shapes with a flattened base, as surface tension dominates. In contrast, droplets with a radius larger than the capillary length are flattened by gravity into a puddle, as shown in **Figure 1b**.[2] Capillary length influences the shape, stability, and heat transfer efficiency of a Leidenfrost droplet. Smaller spherical droplets maintain a more stable vapor cushion, whereas larger, flattened droplets exhibit thinner and less stable films.

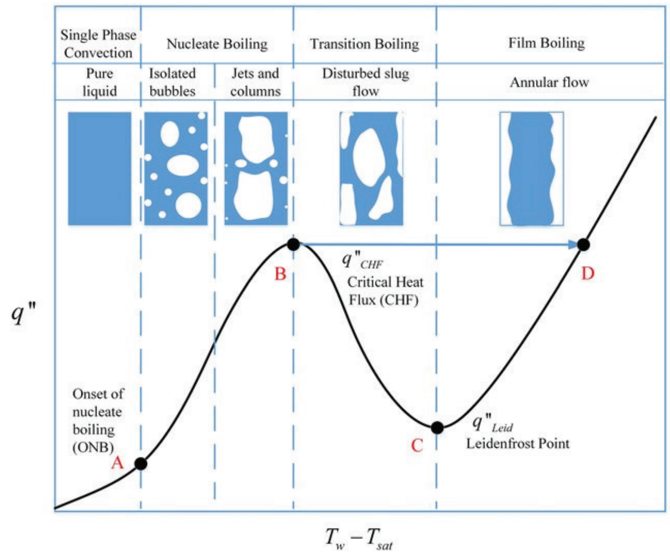


Figure 2: A typical boiling curve shows nucleate and film boiling with maximum heat flux (q") at point B (Critical Heat Flux). Beyond this, heat flux drops to the Leidenfrost point (C) and then rises again, leading to slow droplet evaporation. It is reproduced from Hu *et al.*[7] as per terms CC BY 4.0.

Discussion

Leidenfrost phenomena at Solid-Liquid Interfaces:

Since Leidenfrost droplets float on a layer of their vapor, they do not wet the surface of the solid substrate.[2] Wettability is the tendency of a surface to retain strong contact with a solid surface.[8–11] Material wettability is determined using contact angles. The contact angle is a function of the surface energy of a material and liquid contact angle and is typically experimentally determined. The contact angle is the angle between the tangent to the solid surface and the tangent to the liquid–fluid interface at the contact line between the three phases.[12] Angles of 150 degrees or greater indicate superhydrophobic behavior or high repellency, while angles of 20 degrees or less indicate superhydrophilic behavior or high affinity. Angles of 0 degrees indicate the formation of a film, with droplets coating the surface, while angles of 180 degrees indicate no contact with the surface.[3]

The thickness of the vapor film underneath Leidenfrost droplets is a function of heat transfer, droplet size, and time. As the vapor film becomes less stable, droplets sink lower and become quasi-spherical while evaporating.[2] Leidenfrost droplets are mobile and move chaotically due to the vapor film underneath them. This disordered, random movement can easily be controlled with, for example, external airflow or a pressure gradient. However, small droplets (radii on the order of 1 mm) at rest on a horizontal surface will begin to rotate and propel themselves, independent of external forces and without asymmetry.[13]

Recent research reveals the droplets undergo self-initiated and repeated vertical propulsion. Droplets oscillate in place and then undergo successive jumps that increase the height until a constant maximum is achieved.[14] This trampolining, shown in **Figure 3a**, occurs because any Leidenfrost droplet system consists of a denser fluid (liquid droplet) on top of a less dense, draining fluid (vapor cushion). Thus, equilibrium depends on the draining fluid's pressure balance and droplet weight. Since any real physical system cannot be shielded from even the smallest perturbations, the draining vapor pressure is altered by perturbations, which changes the vapor layers' thickness and provides the impetus for trampolining.[14]

Larger droplets (radii greater than 1.5 mm) do not self-propel, instead following a unique, fixed path as expected for non-adhesive liquids. This is because the droplet's weight flattens its bases, and the main cause of propulsion is the production of isotropic vapor. To mobilize larger droplets, a ratchet may be created using a substrate with an asymmetric microtextured surface, as shown in **Figure 3b**.[13] Teeth with millimetric width and heights of around 150 micrometers have experimentally been shown to successfully create a ratchet that channels vapor flow, propelling the droplet against the ratchet teeth.[13] Teeth create anisotropic vapor flow by causing a sudden contraction in the fluid channel for the approaching vapor.[15] Fluid flow is asymmetric when entering or emerging from a sudden contraction. Thus, it escapes primarily along the smallest sloped texture and exerts a force on the droplet, propelling it in the opposite direction.[16,17]

Figure 3a

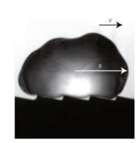


Figure 3b

Figure 3: **(a)** A water droplet is in motion when deposited on a surface above the Leidenfrost point. Z_c is the droplet's centroid position, and d is the height gained by the droplet during jumps, a phenomenon known as Leidenfrost droplet trampolining. The scale bar represents 1 mm. The figure is reproduced from Graeber *et al.* as per terms CC BY 4.0. **(b)** Droplet moving along a ratchet. Teeth are 150 micrometers in height, and channel vapor to propel the droplet with velocity *v*. The scale bar represents 3 mm. The figure is reproduced from Lagubeau *et al.* under license.

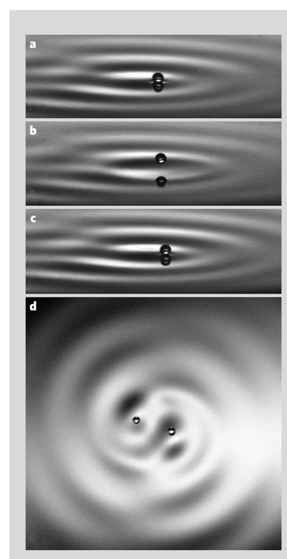


Figure 4: Walking and Orbiting Droplets. It is reproduced from Couder *et al.*[18] CC BY 4.0.

Droplets levitating above a vapor layer are not limited to volatile liquids on heated substrates. Viscous droplets can levitate, bounce, and even traverse on the surface of a liquid bath, as shown in **Figure 4**. Coalescence of the bath and droplet is inhibited by vertical oscillation of the system at the correct amplitude and frequency. When upward surface acceleration exceeds the downward acceleration of gravity, small droplets begin to lift off the bath. A thin air film separates the droplet and bath; the air drains slowly when oscillation ceases.[18,19]

Solid or liquid surfaces translating tangentially can also facilitate levitation because air is entrained between the translating plane and the liquid droplet. Air is dragged along the surface, and its film thickness is determined by balancing viscous effects (favoring entrainment) with capillary action (opposing entrainment). At high velocity, viscous effects exceed capillary forces, and an air film settles into dynamic equilibrium above the surface.

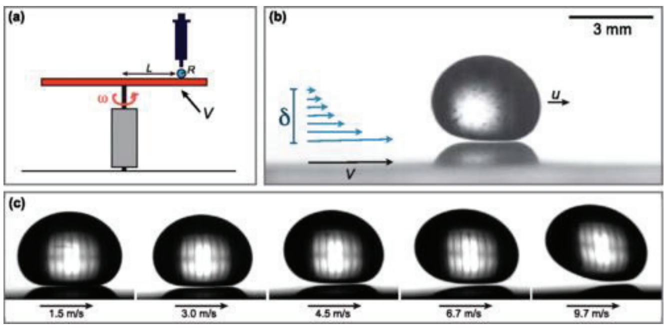


Figure 5: Rotating plate and droplet levitation. **(a)** Schematic of the experimental setup: a droplet of silicone oil with radius R (1.24 mm) is deposited on a disk rotating at an angular velocity ω. Velocity under the droplet is denoted by V. **(b)** Levitation is observed. Due to the plate motion, the droplet drifts at a velocity u <<V. **(c)** As the plate velocity V increases from 1.5 m/s to 9.7 m/s, the gap thickness also increases. It is reproduced from Gauthier *et al*.[20] under license.

Drag and lift from the film balance droplet weight. Film thickness, and thus the height of levitation, increases with velocity as greater viscous forces entrain more air, as shown in **Figure 5**.[20–23]

Suppression and Elimination of the Leidenfrost Effect:

The Leidenfrost effect, which occurs at the Leidenfrost temperature, represents a state of poor heat transfer because the vapor layer between droplets and superheated surfaces acts as a thermal barrier. This phenomenon severely limits cooling performance in systems that require efficient thermal management, such as high-temperature power generation, spray cooling in industrial settings, electronics/photonics, reactors, and spacecraft.[24] Suppressing the Leidenfrost effect (i.e., increasing the Leidenfrost temperature), is a topic of considerable research interest. Two broad strategies have been explored in the literature to address this challenge, with practical examples discussed in the application section.

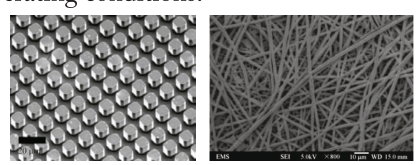
- ***Surface Engineering to Enhance Heat Transfer:***

Engineered surface structures are devised to disrupt the liquid-vapor interface by increasing the roughness, porosity, or wettability, thereby suppressing the Leidenfrost effect. Talari *et al*. categorize these surfaces into two main types: *pillar structures*, which modify surface roughness, and *porous structures*, which tailor surface porosity. The wettability of these engineered surfaces can be further augmented to make them superhydrophilic. Enhancing these physical properties has been shown to effectively suppress the Leidenfrost effect.[25]

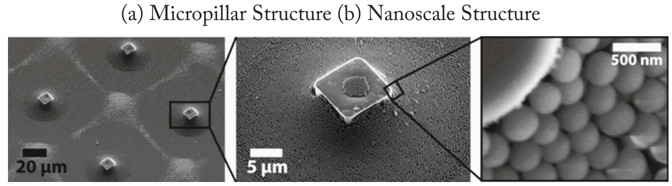
Micropillars, as shown in **Figure 6a**, are protruding structures that can penetrate the vapor film and thereby alter the Leidenfrost temperature. Kwon *et al*. observed an increase in the Leidenfrost temperature with sparser pillar spacing.[26] Tran *et al*. reported that taller pillars could reduce Leidenfrost temperature. These findings suggest that the Leidenfrost temperature can either increase or decrease depending on the specific geometry of the micropillars, including their height, width, and interspacing.[25]

Nanoscale structured surfaces, as shown in **Figure 6b**, are typically composed of carbon nanofibers, silicon nanowires, or zirconium nanotubes, and offer high surface area and porosity.[25] This enhances capillary wicking, promotes superhydrophilic wetting, and initiates heterogeneous nucleation of bubbles which disrupts the formation of stable vapor films.[27] Collectively, these features contribute to a significant increase in Leidenfrost temperature.

The most effective surfaces are *hierarchical structures*, as shown in **Figure 6c**, that deploy nanomembranes assembled on top of micropillar structures.[25] These multiscale structures capitalize on the liquid-spreading and wicking effects of nanoporous coatings, reroute vapor flow, and ensure droplets remain in contact with substrates even at high temperatures, up to 843 K.[24] By leveraging both mechanisms, hierarchical surfaces have demonstrated significant increases in Leidenfrost temperature, and improved heat transfer across a wide range of operating conditions.[25]



(a) Micropillar Structure (b) Nanoscale Structure



(c) Hierarchical Structure

Figure 6: **(a)** Micropillar structure with patterned micropillar arrays, adapted with permission from Kwon *et al*. **(b)** SEM images of the polymer nanofiber mat and the single nanofibers, reproduced under license from Talari *et al*. **(c)** Micro-nano hierarchical surface structure with micropillar array coated with nanoparticles, adapted with permission from Kwon *et al*.

In addition to these structures, another approach that draws inspiration from geological formations is the speleothem-inspired copper/nickel surfaces, developed by Rozati *et al*., with heterogeneous porosity and embedded nickel strands, where synergistic wicking rewets porous nucleation sites, delays dry out, and enhances heat transfer performance.[28]

Applying a coating to engineered surface structures can also make them superhydrophobic, which, in turn, lowers the Leidenfrost temperature – a desirable outcome in certain applications. This effect results from reduced adhesion energy per unit area and smaller liquid-solid contact area, due to in-

DOI: 10.36838/v7i6.14

terfacial entrapment of air.[3,29] For practical applications of this phenomenon, refer to 'Superhydrophobicity' in the Application section.

- ***The Electro-Leidenfrost Effect:***

Another method of modifying the Leidenfrost temperature involves inducing a DC electric field between a droplet and its substrate, which causes a proportionate reduction in asymmetry and thickness of the vapor film, which can suppress the Leidenfrost effect. The interplay of destabilizing electrostatic forces, stabilizing capillary forces, and evaporation defines a critical voltage, beyond which the formation of a vapor layer is suppressed as droplets are electrostatically attracted to the surface and begin to boil.[30–32] The critical voltage required to suppress the Leidenfrost effect increases with surface temperature. Droplets colliding with superheated substrates in an electric field also have greater spreading radius and contact time due to the electrostatic forces experienced by the droplets.[33]

However, nanoparticle deposition, micro-nano hierarchical structures, DC fields, and many other suppressing methods do not fully eliminate the vapor layer formation; instead, they attract the droplet and compress the underlying vapor. The magnitude of the electrostatic force is the defining factor in the effectiveness of electrostatic suppression. This limitation can be circumvented by electrically inducing air discharge around the three-phase line of contact of the droplet. Solid surface free energy increases, which works with the electrostatic force attracting the droplet, significantly reducing the contact angle and ensuring the droplet goes from a superhydrophobic to a superhydrophilic state. Reduced contact angle allows greater contact area between droplet and substrate, which, in turn, leads to more heat flux.[34]

Interestingly, if an AC field is used instead of a DC field, suppression of the Leidenfrost effect can be negated entirely due to high-frequency waveforms. Studies into electrowetting-induced droplet motion show a drastic decrease in actuation force past a particular threshold frequency.[35–38] In this case, high AC frequencies can counter the influence of the applied voltage and cease suppressing the Leidenfrost state. Critical voltages are proportional to the AC frequencies required to counter their suppressive effect since higher frequencies cause the electric field to penetrate further into the droplet. Deeper penetration simultaneously reduces the overall field strength and concentration of electric field lines in the vapor layer, acting to decrease the electrostatic force attracting droplets to the surface. At sufficiently high frequencies, an electrically conducting droplet behaves like an electrically insulating droplet, entirely negating electrostatic suppression of the Leidenfrost effect.[32,35–38]

In the case of vertical electric fields, the electrostatic force on droplets can induce bouncing. Droplets in strong vertical electric fields begin to bounce progressively higher, overcoming gravitational attraction. For evaporating droplets, the charge on the droplet decreases as it slowly evaporates since the charge in a constant electric field is proportional to the droplet surface area, which reduces as the droplet evaporates. Electro-capillary instability in the vapor film facilitates droplet energy jumps; when electrical surface forces exceed gravitational forces on the droplet, they escape the substrate.[39]

Electric fields also suppress the formation of vapor layers on liquid surfaces. Still, instead of squeezing out the vapor layer and forcing droplets into contact with the surface, liquid droplets completely penetrate the underlying liquid surface and form a film. The critical voltage for suppressing vapor formation on liquid surfaces is significantly lower than for solid surfaces.[40]

Non-Newtonian Droplet Interactions:

Interest in non-Newtonian fluids has grown in recent years. A Newtonian fluid follows Newton's Law of Viscosity. At a constant temperature and pressure, and in simple shear, shear stress is proportional to the deformation rate (local strain rate), and that proportionality factor is dynamic viscosity.[41–45] In other words, the viscosity is unaffected by shear stress. A non-Newtonian fluid is one whose viscosity is variable and dependent upon stress. For example, tomato ketchup in a bottle becomes runnier (less viscous) when shaken and thus is a non-Newtonian fluid. Shaking causes the walls of the bottle to exert force on the ketchup, changing its viscosity. Examples include blood, melted butter, toothpaste, paint, molten lava, and magma. Renewed interest in non-Newtonian fluids in the context of heat transfer and the Leidenfrost effect stems from numerous advantages over other fluids. They do not suffer from adverse effects such as agglomeration and sedimentation of particles, which is common amongst nanofluids.[46] Non-Newtonian fluids offer other advantages, like fine-tuning heat transfer characteristics by varying polymer concentrations and/or adding nanoparticles.[47] Shojaeian *et al.* dissolved polymeric additives in water to increase the shear-dependence of viscosity. It showed equilibrium surface tension reduces dramatically past a specific concentration while the contact angle increases to a maximum at that same concentration, demonstrating a lower wettability than water.[46] Soltani *et al*. prepared non-Newtonian solutions of carboxy methyl cellulose in water. It showed lower pool boiling heat transfer coefficients for higher concentrations of CMC that the addition of nanoparticles can counter.[47]

Impact dynamics also differ for non-Newtonian droplets. Newtonian droplets, like water, impact with superheated substrates and undergo rapid contact boiling. Vapor bubbles are generated between the droplet and substrate, which burst vigorously and cause secondary atomization of minuscule droplets. The atomization phenomenon is characteristic of explosive boiling phase change, with vertical ligaments/filaments emanating from the bulk portion of the droplet, subsequently fragmenting and spawning smaller droplets that separate and rebound off the substrate themselves. At similar temperatures, non-Newtonian droplets do not display any secondary atomization. Filament formation and capillary-driven filament thinning increase local strain rates, raising extensional viscosity and arresting filament break-up, suppressing the effect.[48–50] Non-Newtonian droplets also display reduced spreading diameter and rebound height compared to similar Newtonian droplets.[51]

To accurately observe the Leidenfrost point for non-Newtonian droplets, top layer temperature at the onset of droplets bouncing back from the substrate due to levitation on a vapor cushion may be measured. Mishra *et al*.[52] have shown the effectiveness of polymer droplets in delaying the onset of bouncing phenomena and thus raising the Leidenfrost point. This raising of the Leidenfrost point has been shown to increase with the concentration of polyacrylamide (PAAM) in solution, up to 500 ppm. The mechanics behind this are understood after the impact of droplets and just before they completely separate from the substrate. A filamentous structure forms, but unlike those discussed previously, these filaments emanate far enough to connect the bulk portion of the droplet to the substrate, as shown in **Figure 7**. This enhances heat transfer to the droplet, prevents the droplet from bouncing back, and delays the onset of the Leidenfrost phenomenon until much higher temperatures occur. The longer-lasting filament structure, key to increasing the Leidenfrost point in this case, exists only because of the increased extensional viscosity of non-Newtonian fluids, as discussed above.[52]

Figure 7: 500 ppm PAAM solution released from a height of 2.9 cm onto a surface at 295°C. Reproduced from Soumya *et al*.[52]

Leidenfrost Phenomenon in Microgravity:

Microgravity conditions are those where gravitational forces are negligible, such as those found in deep spay or aboard the International Space Station (ISS). The defining limit of microgravity is when a gravitational force generates an acceleration that is one-millionth the strength of gravity on Earth, 9.81 m/s2. As body forces acting on the bulk of the liquid become negligibly small, capillary forces of liquids become dominant, which changes fluid dynamics since, unlike gravitational forces, which are proportional to volume, surface forces are proportional to the surface area, geometry, and wettability.[53] Droplets in microgravity need to be much larger for the gravitational forces on them to balance the dominant surface forces. Thus, capillary length increases to the order of meters. Microgravity also changes boiling heat transfer, with gravitational acceleration influencing the size, growth, and coalescence rate of bubbles formed during nucleate boiling.

This is primarily because buoyancy forces in microgravity are negligibly small due to the lack of gravitational forces, which hinders the liberation of formed bubbles in boiling. Under microgravity conditions, bubbles formed in nucleate boiling are mainly circular, and stronger surface tension delays coalescence. In addition, the lack of buoyancy prevents these bubbles from being carried away from the boiling surface, causing an overall reduction in the heat transfer coefficient.[54] The Leidenfrost effect is also affected where it's enhanced under microgravity conditions, causing it to occur over larger length scales. Droplets of ethanol with diameters exceeding 2.5mm have been shown to display the Leidenfrost effect in drop tower-simulated microgravity conditions.[55]

Under microgravity, the Marangoni effect and capillary forces influence fluid behavior.[54] The Marangoni effect is a phenomenon where mass transfers along a gas-liquid interface due to gradients in surface tension.[56,57] Gradients in temperature, voltage, and fluid concentration all create gradients in surface tension.[58] Higher surface tension causes fluid to pull more strongly on surrounding molecules, resulting in tangential stress at the interface. Tangential stress jumps at the interface are compensated for by viscous stresses in the two fluids, which causes both of them to be carried away by their viscosity, generating Marangoni flows. Due to the surface tension gradient, fluid near the interface moves from areas of low surface tension to areas where it is higher.[58] This allows droplets to be separated from solid substrates and transported with little friction.[57] When heated droplets are introduced to a cold substrate, a temperature gradient forms, and Marangoni flows bring a film of air underneath the droplet, which levitates.[20] Facilitating droplet levitation via the Marangoni effect in microgravity takes advantage of the dominant surface forces and allows easier transport in space.

■ Applications

Applications of the Leidenfrost effect are wide-ranging and include applying or suppressing the phenomenon in various engineered systems. As mentioned previously, the most common use of the Leidenfrost phenomenon in industry is suppressing the Leidenfrost effect. The Leidenfrost point, the temperature at which the heat flux between liquid and substrate is the lowest, is influenced by the liquid's impingement density and the substrate's porosity, topology, and wettability.[59] Adjusting these parameters can increase the Leidenfrost point, suppress the formation of an insulating vapor layer, and delay the onset of film boiling, thus increasing the temperature range of effective heat dissipation.

Applying Leidenfrost Suppression:

Jiang *et al*. demonstrated an increase in the Leidenfrost point by developing thermal armors that hindered the Leidenfrost effect and preserved heat transfer up to temperatures of 1150°C.[60] A flexible structure consisting of steel pillars, an embedded insulating membrane that wicks the liquid, and U-shaped vapor evacuation channels was developed. Efficient cooling is achieved by preventing the formation of a vapor film, ensuring coolant is spread over the maximum surface area, and removing heat via steel pillars. Flexibility allows the material to be attached to other substrates, enabling improved heat transfer characteristics and using various liquid coolants in high-temperature systems otherwise prohibited by insufficient cooling. Implications of such technology extend to nuclear reactors, power generators, steel quenching, manufacturing, electronics/photonics, and spacecraft.[60]

Leidenfrost suppression technology may also help keep thermal systems like boilers, condensers, and heat exchangers clean by lowering the Leidenfrost point. Systems like the aforementioned ones suffer from the deposition of contaminating particles on heat exchange surfaces, impeding heat transfer. Such sticky fouling media can neither be removed

DOI: 10.36838/v7i6.14

by cold droplets nor Leidenfrost droplets, as the vapor layer prevents direct contact with the fouling particles in the latter case. Superhydrophobic surface structures, which suppress vapor layer formation while allowing the droplet to self-purge in a controlled manner, adequately address these challenges.[61]

Huang *et al*. demonstrated self-cleaning through controlled levitation and self-purging Leidenfrost droplets at 130 ˚C on an engineered surface with fin-like micropillar arrays exhibiting superhydrophobic properties. At initiation, droplets thoroughly wet a rough surface and attach to the contaminant.[61] Micropillars significantly enhance heat transfer to the droplet instead of flat surfaces at elevated temperatures, creating a superheated environment that promotes inertia-controlled bubble growth. As the bubbles grow, contaminants are dislodged from the surface into the droplet. The momentum from the droplet-bubble interactions eventually triggers droplet levitation at 130 ˚C, much lower than the traditional Leidenfrost point of ~250 ˚C, allowing the droplet to roll off and leave the surface clean.[61]

Applying Vapor Layer Insulation and Superhydrophobicity:

Another novel application takes advantage of the insulating properties of the Leidenfrost vapor layer but not for heat dissipation. Consider a solid object moving through a fluid. The object is being accelerated by a force that does work on the object, and a portion of the total work is wasted in overcoming hydrodynamic drag. Vakarelski *et al*. demonstrated that the Leidenfrost vapor layer can reduce the drag on a heated sphere moving in a liquid.[62] However, when substrate temperature falls below the Leidenfrost point, the vapor layer collapses, increasing drag. Textured superhydrophobic surfaces stabilize and suppress the collapse, allowing the vapor to gradually dissipate as the surface cools, without entering the nucleate boiling phase.[62]

Vakarelski *et al*. further demonstrated that a steel ball preheated to 400˚C forms a teardrop-shaped gas cavity when dropped into a 95˚C water bath, enabling nearly frictionless motion at a constant velocity.[63] These sphere-in-cavity structures experience a tenth of the drag a solid object of the same dimension would experience. A superhydrophobic sphere achieved the same result at room temperature without preheating, highlighting its potential for aeronautical and marine applications.[63]

Applying Leidenfrost Droplet Mobility:

Leidenfrost droplets are highly mobile, which unlocks a slew of valuable applications. One of these comes from the inverse Leidenfrost effect, which involves a droplet levitating on a vapor layer from a liquid bath, not from the droplet itself. Gauthier *et al*. demonstrate how ethanol droplets on a cryogenic bath of liquid-nitrogen levitate on a vapor layer generated by evaporation of the bath at room temperature.[64] Contrary to droplet dynamics in the Leidenfrost effect, droplets on cryogenic baths glide along a rectilinear path, bouncing close to the edges of the container. These droplets also remain self-propelled in the bath, even after cooling down to the temperature of the bath. This motion occurs due to asymmetry in the vapor layer, arising from a difference in thickness between the front and back of the droplet, causing the droplet to self-propel. Initially, at rest, the droplets accelerate within a few seconds before eventually slowing down over a longer time scale.[64] This spontaneous self-propulsion in straight lines lasts for tens of minutes and continues even after the droplet has cooled down to the temperature of the bath. Such phenomena may have many medical applications, like non-contact transport for stem cells, embryos, or proteins.

An innovative solution was proposed to NASA that combined the self-cleaning and self-transporting properties of Leidenfrost droplets to improve wastewater recovery in space. Rasheed *et al*. proposed the first omni-gravity nanophotonic heating and Leidenfrost-driven, fouling-free water recovery system.[55] Nanophotonic heating is initiated by exposing nanoparticles to infrared light-emitting diodes, elevating localized temperatures, and effectively inactivating microbes in wastewater. Treated wastewater is then deposited on a substrate with temperatures higher than its Leidenfrost point, causing droplets to form and begin levitating. The Leidenfrost effect is enhanced under microgravity, thus significantly increasing the droplet lifetime and allowing them to be circulated using bulk air flows, resulting in the complete non-contact distillation of wastewater.[55]

A frontier space application of the Leidenfrost effect is a Leidenfrost sublimation engine. Controlling the chaotic, low-friction, self-propelled nature of Leidenfrost droplet motion was first shown by Linke *et al*. using a hot ratcheted surface, where droplets moved in the directions of the ridges.[65] When ridges or ratchets are arranged in a circular pattern, forming a ring shape, Leidenfrost droplets exhibit continuous circular motion. Building on these principles, Wells *et al*. presented an experimental proof-of-concept for a sublimation heat engine that leverages the Leidenfrost effect to convert temperature differences into rotational motion.[66] A block of dry ice (solid CO_2) is placed on a hot turbine-like surface with a temperature above the Leidenfrost point of dry ice. This induces the Leidenfrost phenomenon, causing the dry ice to levitate and rotate. The turbine geometry, temperature, and dry ice load size determine the rotation speed. Attaching a frame with eight neodymium magnets to the dry ice rotor and lowering an induction coil to the rotating assembly creates a simple electric generator that converts kinetic energy into electrical energy, generating an alternating current.[66] This concept has practical applications for energy harvesting in challenging environments, such as deep drilling or outer space exploration, where high-temperature differences and resources like ice or dry ice are readily available.

Challenges in Practical Implementation of the Leidenfrost Effect:

Use cases in diverse applications, such as drag reduction, vapor-layer-mediated thermal insulation, and high-temperature cooling via suppression of the vapor layer, are emerging, as discussed above. However, the implementation of these approaches remains constrained by challenges in scalability and durability.

Conventional surface modification techniques, such as sandblasting, particle coating, and salt deposition, often affect multiple surface parameters simultaneously and are limited in their ability to isolate individual contributions that influence the Leidenfrost point.[25] To address these constraints, engineered micro- and nanostructured surfaces have emerged as a more controlled alternative. However, the key challenge now lies in identifying the optimal combination of structural parameters, such as height, spacing, shape, and porosity, for a given substrate–liquid–application triad. This design–function matching remains largely empirical, requiring further experimental and computational studies to establish predictive frameworks.

Superhydrophobic surfaces often suffer from poor mechanical durability due to the fragility of surface textures. Even minor abrasion can degrade the topography and chemistry, leading to a loss of non-wettability.[67] Developing surfaces that can withstand structural forces while retaining their geometric features or incorporating self-healing capabilities will be key to achieving abrasion-resistant textures and improving mechanical durability.[67]

To transition from controlled experimental setups to real-world applications, it is essential to establish standardized evaluation metrics for benchmarking Leidenfrost performance across varying conditions.

Conclusion

Droplets floating on an insulating film of their vapor, held in shape by surface tension, have proved more versatile than the relatively basic mechanics underpinning their behavior may indicate. The non-contact Leidenfrost state means droplets do not wet the surface, revealing the key to one method of increasing Leidenfrost temperature: increasing wettability. This method has become a common way to suppress the

Leidenfrost effect, with nanoparticle deposition and micro-nano hierarchical structures showing the most promise for application in the industry like those developed by Jiang *et al*.[60] A field of research with great potential is applying DC electric fields and induced air discharge to suppress the Leidenfrost effect in medium- and small-scale scenarios. Due to ongoing academic and scientific research, the Leidenfrost effect has demonstrated substantial potential in recent years. As material science and microfluidics evolve, insights into the Leidenfrost effect contribute to developing advanced materials and more efficient thermal management systems. The phenomenon plays a critical role in manufacturing processes requiring cooling and precision in material properties. As space exploration advances, the Leidenfrost effect could become instrumental in developing new manufacturing techniques that overcome the limitations of traditional methods, particularly in microgravity environments where conventional techniques falter due to the absence of gravitational forces. The ability to control and utilize the Leidenfrost effect in these settings opens up opportunities for producing high-quality components and structures that are currently unfeasible. Despite the progress, the potential of the Leidenfrost effect has still not extended into cutting-edge areas such as high-performance electronics, the development of novel cooling systems, HVAC systems, etc. Further, the industrialization of proven scientific applications remains in the nascent stages.

While extended research efforts will deepen our understanding of the phenomenon's underlying mechanisms, prototyping will accelerate commercial adoption, unlocking new technological innovations. This paper aims to draw attention to the transformative potential of the Leidenfrost effect and encourage further exploration to facilitate broader commercial adoption in energy, electronics, medical science, transportation, and engineering systems, both on Earth and in space.

Acknowledgment

I want to acknowledge my mentor, Rawand Rasheed, for his guidance, insights, encouragement, and patience throughout the process.

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DOI: 10.36838/v7i6.14