

Soft Matter

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Lotus-like Effect for Metal Filings Recovery and Particle Removal on Heated Metal Surfaces Using Leidenfrost Water Droplets

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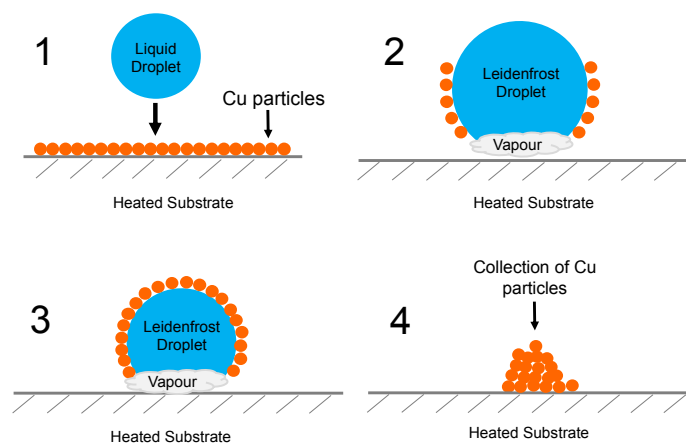
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Abstract A “Lotus-like” effect is applied to demonstrate the ability of the Leidenfrost water droplets to recover Cu particles on a heated Al substrate. Cu particles on the heated surface adhere to the rim of the Leidenfrost droplets and eventually coat the droplets’ surface to form an aggregation. When Fe filings are added to the Cu particles the aggregated mixture can then be collected by the use of a strong rare earth magnet (NdFeB) upon evaporation of the water. We also show the Leidenfrost effect can be effectively utilized to recover both hydrophobic (dust and activated carbon) and hydrophilic (SiO₂ and MgO) particles from heated Al surfaces without any topographical modification or surfactant addition. Our results show that hydrophobic and hydrophilic materials can be collected with > 92% and > 96 % effectiveness on grooved and smooth Al surfaces respectively. Furthermore, we observed no significant differences in the amount of material collected above the Leidenfrost point within the tested temperature range (240 °C vs 340 °C) as well as when replacing the Al with a Cu sheet as the substrate. However, we did observe that the Leidenfrost droplets were able to collect a greater amount of material when the working liquid was water than when the working liquid was ethanol. Our findings show promise in the development of an effective precious coinage metal filings recovery technology for application in the mint industry, as well as the self-cleaning of metallic and semiconductor surfaces where manual cleaning is not amenable.

1 TOC Image



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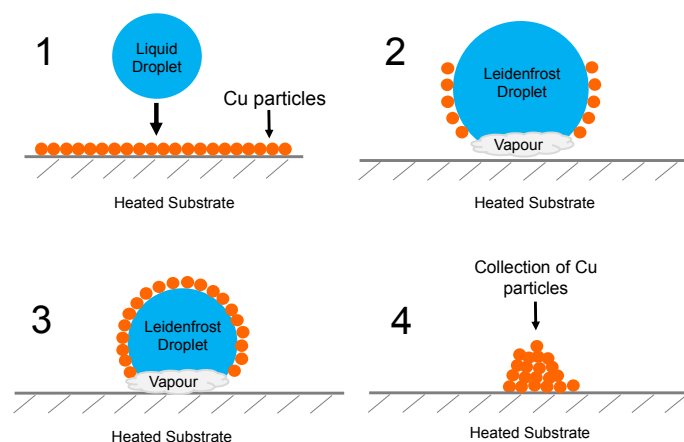
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1 TOC Image



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3 When a liquid droplet contacts a surface that is maintained at a temperature above the
 4 film boiling point of the liquid, the lower section of the droplet vaporizes instantly and results
 5 in the formation of an insulating vapor layer that physically separates the droplet from the
 6 heated surface. The droplet is levitated by a vapor layer film for a limited period of time until
 7 complete vaporization.¹ The Leidenfrost effect is an interfacial phenomenon governed by: (a)
 8 chemical properties (e.g., solution composition and surface free energy), (b) thermophysical
 9 properties (e.g., density, viscosity, and thermal conductivity of liquid/solid interface), and (c)
 10 topography of surface (e.g., hydrophobic/hydrophilic surface, and micro- and nanoscopic
 11 features).^{2,3} In general, hydrophilic surfaces increase while hydrophobic surfaces decrease
 12 the dynamic Leidenfrost temperature, which has been demonstrated to change up to 175 K
 13 through the use of patterned surfaces with varying hydrophobicity.² The dynamic
 14 Leidenfrost temperature is defined as the lowest temperature for which the droplet bounces
 15 off the surface without breaking up or scattering secondary droplets, and at the same time
 16 corresponds to the maximum surface temperature whereby heat transfer can occur most
 17 efficiently.^{2,4} Leidenfrost droplets are influenced by capillary forces in an effort to minimize
 18 the surface energy within the liquid.⁴ In addition, on heated surfaces the vapor layer film also
 19 plays an important role in the droplet's levitation⁴ by becoming thicker for larger droplets,
 20 and past a critical droplet size, it will lead the droplet to undergo a toroidal transformation.⁵

21 The Leidenfrost effect has recently received attention in the scientific community
 22 mainly due to its potential applications in microfluidics⁶⁻⁸ and nanomaterial fabrication,
 23 nanoscale coatings formation, and the design of porous metal foams for plasmonic
 24 applications,⁹ and creation of photonic microgranules.¹⁰ Another important practical
 25 application takes advantage of the Leidenfrost levitation capability to levitate a loaded cart
 26 and propel it across a patterned surface.¹¹ Tailored superhydrophobic surfaces completely

1 suppress the collapse of vapor layer underneath the Leidenfrost droplet, and in the process
2 reduce hydrodynamic drag forces on such heated surfaces.¹² The Leidenfrost effect can also
3 be used as a chemical reactor; water under Leidenfrost conditions catalyzes the chemical
4 reaction without using additional reducing agents or more sophisticated approaches. A
5 notable example is the addition of $\text{Cu}(\text{C}_2\text{H}_3\text{O}_2)$ to aqueous Leidenfrost droplets to produce
6 CuO nanorods, which upon further heating turn into CuO nanograss.⁹ Furthermore, a
7 template-free, droplet-based deposition, and rapid approach to create nanostructures without
8 the use of additional surfactants has been demonstrated using the Leidenfrost effect. Water
9 droplets loaded with bulk powders, resembling liquid marbles at higher temperatures¹³⁻¹⁸,
10 form suspensions of which motion can be manipulated to create nanostructures on the surface,
11 such as cluster chains and wires.¹

12 Heated surfaces with temperatures above the Leidenfrost temperature behave like the
13 lotus leaf surface (Lotus effect) whereby particles are removed from the surface by adhering
14 to spherical water droplets with contact angles near 180° that are moving over the surface
15 almost frictionless and thus ‘cleaning’ it.¹ By heating surfaces to temperatures above the
16 Leidenfrost point, we show the Lotus effect can occur for metallic and ceramic surfaces that
17 do not exhibit lotus-like behavior at sub-Leidenfrost temperatures. In this work, we employ
18 the Leidenfrost phenomenon to demonstrate its excellent ability to recover Cu particles and to
19 remove both hydrophobic and hydrophilic micro- and nano-particles and microfibers from
20 heated Al surfaces without the use of any surfactants or chemical modifications to the metal
21 surface topography. This is the first attempt, to the best of our knowledge, to be reported in
22 scientific literature where the focus of the Leidenfrost phenomenon is *surface cleaning*
23 *application*. We anticipate this technique will pave the way for the development of novel
24 technologies for metal surface cleaning and material recovery in the precious metal
25 processing and mint industries.

26 The Cu powder, MgO powder, Fe filings, activated carbon (AC), and SiO_2 powder
27 were all purchased from Sigma Aldrich and used as received. Dust particles and fibers were
28 collected from the Singapore University of Technology and Design (SUTD) administration
29 office via vacuuming.¹⁹ Dust material collected consisted of mainly fibrous particles, such as
30 paper fibers, lint, and fabrics from carpets and clothing, $\sim 20 \mu\text{m}$ in diameter and $\sim 500 \mu\text{m}$ in
31 length.¹⁹ Al sheets were used as the metallic substrates. Al has a thin, inert, protective and
32 impervious Al_2O_3 coated layer, therefore the surface is already oxidized under ambient
33 conditions. The Al substrates were cleaned using acetone, followed by ethanol and then

1 rinsed with deionized (DI) water before being dried using disposable wipers (Kimwipes,
2 Kimberly Clark) to remove all traces of oil, dirt and impurities.

3 10 mg of Cu, MgO, AC, SiO₂, and dust particles/fibers were deposited separately on
4 heated unscratched Al surfaces for the next three sets of experiments. The Leidenfrost
5 droplets were formed by dispensing water droplets onto these Al substrate surfaces on a
6 hotplate that was heated to a surface temperature of ~ 240 °C. We then measured the masses
7 of the aggregated materials that were formed by the evaporated Leidenfrost droplets.

8 To test the effect of surface morphology on the material collection efficiency by the
9 Leidenfrost droplet, an Al surface was scratched with a box cutter in a grid fashion, with
10 grooved lines ~ 2 mm apart and the depth of the incisions ~ 500 μm, as measured by a
11 profilometer (TI 950 TriboIndenter, Hysitron). We then compared the aggregated mass
12 obtained from the scratched Al surface to that of unscratched Al surface.

13 To test if the Leidenfrost phenomenon was able to collect all of the particles on a
14 heated Al substrate, 5 μl droplets of deionized water were dispensed onto the heated Al
15 substrate using an adjustable micropipette, until all the particles were visibly collected by the
16 droplets into a single mass aggregate. Each 5 μl of deionized water droplet had a starting
17 Leidenfrost diameter of ~ 2 mm.

18 For the following set of experiments, Cu powder was used as the model material to
19 study the Leidenfrost phenomenon collection ability. 50 mg of Cu particles were deposited
20 on unscratched Al substrates and then heated to ~ 240 °C. To test the material collection
21 efficiency of the Leidenfrost droplet as a function of starting liquid droplet volume, water
22 droplets of 5, 10, 15, 20, and 25 μL were dispensed in a single dispensation onto a heated Al
23 substrate using a modified pipette tip. Furthermore, in order to investigate the effect of type
24 of working liquid, we used ethanol droplets with volumes 5 – 25 μL under similar
25 experimental conditions as water.

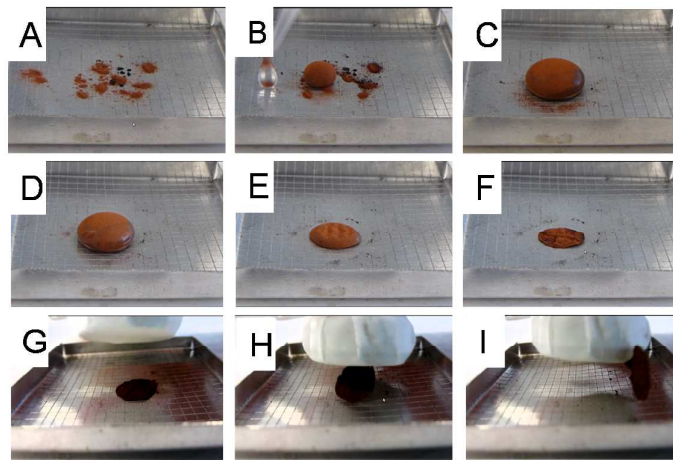
26 To test the effect of temperature on the material collection efficiency, Al substrate
27 was heated to ~340 °C, and the aggregated material was then weighed in the same manner as
28 experiments done at ~ 240 °C on a heated Al substrate.

29 To test the effect of different substrate types on the material collection efficiency, we
30 replaced Al substrate with an unscratched Cu sheet and then heated to ~ 240 °C. Water
31 droplets of 5 – 25 μL were dispensed and the aggregated Cu particles were weighed.

32 In order to investigate the effect of using magnetic force to facilitate the removal of
33 the solid particles aggregated by the Leidenfrost droplet, Fe filings ~10 μm in diameter,

1 Figure S1 in ESI section (Unichem Global, Singapore), were also sprinkled onto Al surfaces.
2 For these magnetic collection experiments we used 10 mg of dust, AC, SiO₂, MgO, or Cu,
3 while Fe was 1, 5, or 10 mg. Dust, AC, SiO₂, MgO and Cu were separately mixed with Fe
4 filings at mass ratios of 1:1, 1:2 and 1:10 (Fe:material), deposited onto a heated Al substrate
5 and tested for the effectiveness of the magnetic removal of the dried aggregates after the
6 evaporation of the Leidenfrost water droplets using a rare-earth (NdFeB) magnet. Each data
7 point is the average of 5 measurements under the exact same experimental conditions, from
8 which we determined the standard deviation. The magnetic properties of the various
9 Fe:material mixtures were measured using a vibrating sample magnetometer (VSM Model
10 1660, ADE Corporation). 10 to 20 mg of the sample powders were placed on a glass
11 coverslip before fixing onto the VSM sample holder. The powders and coverslips were all
12 held together by double sided adhesive tape. The magnetic moment of each sample was
13 measured as the applied field was varied from -10,000 Oe to 10,000 Oe. In order to observe
14 the presence of any hysteresis effect, the magnetic field was applied in a full loop.

15 We investigated the potential of using the Leidenfrost phenomena to recover precious
16 metal filings deposited on metal surfaces. Cu particles were chosen as a model material for
17 our application of the Leidenfrost phenomenon to recover precious coinage metals from coin
18 production waste in mints. Cu particles were scattered together with Fe filings on a heated Al
19 surface, as seen in panel A of Figure 1. The Leidenfrost droplets effectively collected Cu
20 particles from the heated surface (panels B-D). The Cu aggregated into a flat round-shape
21 “pancake” upon water evaporation (panels E-F), which were then recovered via a magnet
22 (panels G-I).

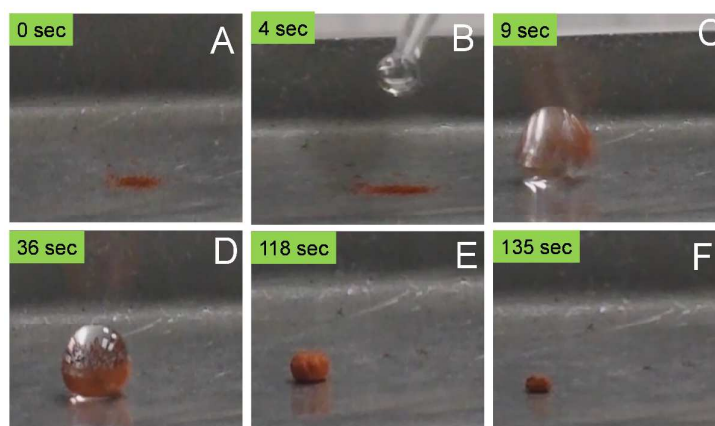


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Figure 1: Panels A-F show the complete surface cleaning process from a mixture of Cu and Fe particles through the Leidenfrost effect, while the use of a rare-earth magnet to remove the dried aggregate from the surface can be observed in panels G-I. Please note that panels G-I represent a different experiment from panels A-F.

1 Our results showed that the Leidenfrost droplets were effective in removing water
2 insoluble particles, such as dust fibers, Fe filings, MgO, SiO₂, and AC particles from heated
3 smooth Al surfaces, as shown in Figures S3-S6, and from heated grooved Al surfaces as
4 displayed in Figure S7 in the ESI section. The removal can be attributed to the greater
5 interaction between the particles and the vapor layer film of the Leidenfrost water droplet
6 forces versus the adhesion forces between the particles and the substrate.²⁰ Our observations
7 suggest a particle collection mechanism whereby hydrophilic and hydrophobic particles are
8 picked up via the vapor layer film and then held initially at the vapor-liquid interface or rim
9 of the Leidenfrost droplet through a combination of intermolecular forces such as van der
10 Waals interactions and capillary action (Cassie-Baxter wetting), as illustrated for liquid
11 marbles.¹⁴ Subsequently, as the water droplet decreases in size, the collected particles move
12 to the periphery along the surface of the droplet. Further decrease in the size of the water
13 droplet leads the material to dry up and aggregate, as shown in Figure 2 and S8 in the ESI
14 section.

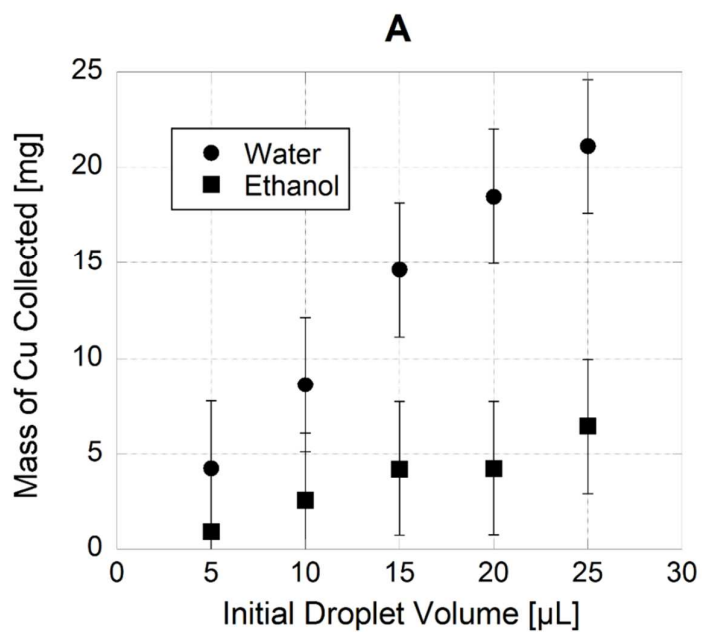
15 Figure 2 illustrates the *surface cleaning application* of the Leidenfrost phenomenon.
16 Panel A shows the placement of ~2 mg of Cu particles on a heated smooth Al surface. In
17 panel B the Leidenfrost droplet formation has been initiated through the use of a micropipette,
18 which in this case dispensed 25 μ L of water. In panel C, the droplet can be observed in the
19 process of picking up the Cu particles in a dynamic process.²¹ At 36 seconds, the collected
20 Cu particles settled at the rim of the Leidenfrost water droplet, as observed in panel D. As
21 the size of the droplet decreases due to water evaporation, the Cu particles engulf the droplet
22 and buckling is observed after 118 seconds, as displayed in panel E. Finally, the aggregated
23 and dried Cu material is observed in panel F.



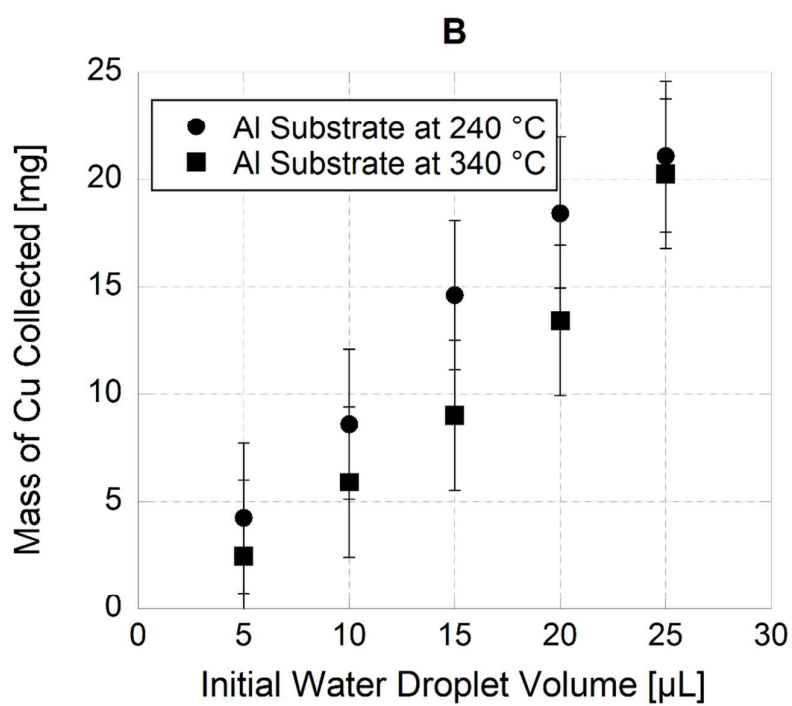
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Figure 2: Time-lapse photographs of the formation of a Leidenfrost droplet and its subsequent surface cleaning effect at various time intervals.

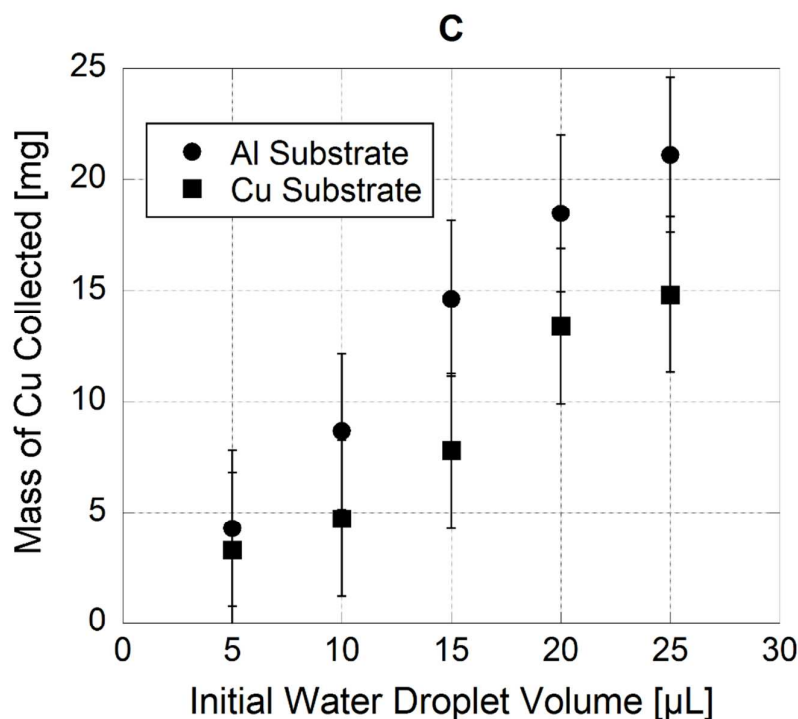
1 According to Abdelaziz et al⁹, fast evaporation of a water droplet placed on a heated
2 Al surface leads to an overheated zone with a temperature gradient and charge separation
3 induced by the self-ionization of water. In their postulate, hydronium ions are lost to the
4 vapor layer film, resulting in an initial increase of metal ions (M^+), followed by an increase in
5 hydroxyl ion concentration (OH^-).⁹ We therefore expect electrostatic forces, which are
6 dependent on the charge separation distance r^{-2} , to be present at the vapor-liquid interface.
7 Leidenfrost dynamics, such as vibration, internal circulation, oscillation and rotation inside
8 the Leidenfrost droplets are complex,⁹ but the random motions of the polar molecules at the
9 interface lead to energetically favorable temporary dipole-dipole interactions, whereby the
10 strength of the attraction falls as r^{-4} , where r represents the intermolecular distance between a
11 water molecule and another polar molecule: for instance, H_2O-MgO , and H_2O-SiO_2
12 interactions.²² The interaction between the permanent dipole moment in a water molecule and
13 a nonpolar molecule gives rise to induced dipole-dipole forces, as is the case in H_2O-AC .
14 Consequently, intermolecular interactions can be attributed to be responsible for keeping the
15 particles adhered to the surface of the Leidenfrost water droplet. Finally, it is important to
16 stress that the surface tension of water plays an important role in the collection mechanism
17 because even though the material accumulates on the surface and coats it, the droplet does not
18 collapse due to the increasing weight.¹⁸ However, the final shape of the particle aggregation
19 is largely dependent on the amount of particles coating the surface of the Leidenfrost droplet.
20 For instance, for a finite amount of material (~ 2 mg), if the initial droplet is large (25 μL), the
21 material will coat only the lower part of the droplet. However, if the droplet is small (5 μL),
22 the material will coat the entire droplet. This comparison is shown in Figure S9 in the ESI.



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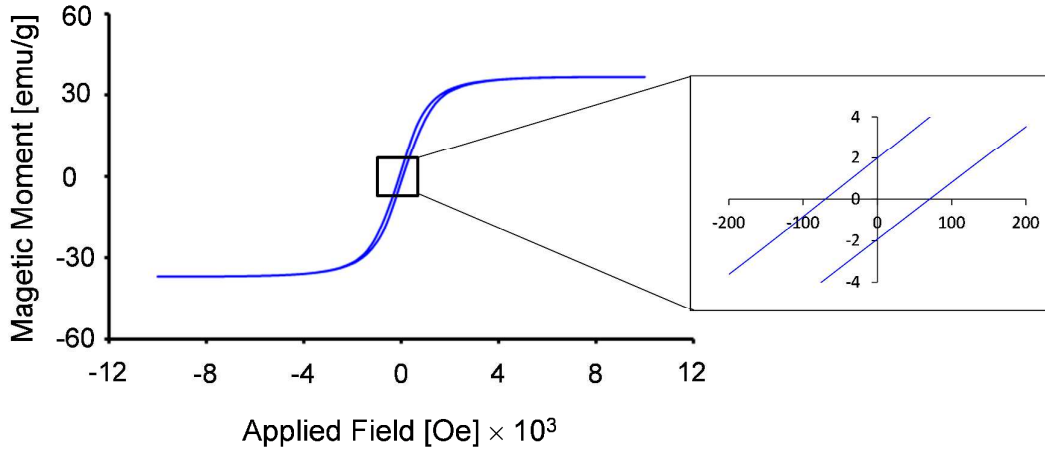
2 Figure 3: Parametric studies on the capability of the Leidenfrost effect to collect Cu particles. (A) displays the
 3 results for water and ethanol as the two different working liquids for Leidenfrost droplets to collect Cu particles
 4 on an Al substrate at 240 °C, (B) shows the influence of substrate surface temperature (240 °C vs. 340 °C) and
 5 (C) the effect of substrate material (Al vs. Cu at 240 °C) on the collection capability of Leidenfrost water
 6 droplets.
 7

8

9 Figure 3 demonstrates the effectiveness of the Leidenfrost droplet to collect Cu
 10 particles. Representative plots of the initial droplet size versus Cu material collected are
 11 presented. Each data point represents the average of 25 mass measurements of the Cu
 12 particles collected using the Leidenfrost effect. The error bars reflect deviations in the
 13 measurements, including measuring errors associated with the sensitivity of the weighing
 14 balance. Initial droplet size refers to the amount of liquid (either water or ethanol) dispensed
 15 through a pipette in a single dispensation. Panel A compares Leidenfrost water droplets
 16 versus Leidenfrost ethanol droplets. The Leidenfrost water droplet is able to collect more Cu
 17 particles on a per unit volume basis compared to ethanol. Our experimental observation
 18 supports our hypothesis that intermolecular interactions play an important role in keeping the
 19 particles adhered to the surface of liquid droplet. In particular, liquid water molecules form
 20 stronger hydrogen bonding, hence stronger capillary forces compared to liquid ethanol
 21 molecules. Panel B indicates that an increase in the surface temperature of about 100 °C
 22 leads to no significant change in the amount of material collected. Finally, panel C shows
 23 that replacing Al for Cu as the heated substrate has no significant effect on the amount of
 material collected. Results in panels B and C hold as long as the temperature remains above

1 the Leidenfrost point because of the formation of an insulating vapor film between the drops
2 and plate.

3 Figure 4 shows the experimentally measured saturation magnetization of a typical Fe-
4 Cu 1:1 composite mixture sample. We observe the presence of magnetic hysteresis loop in
5 the magnetization curve, shown in Figure 4 inset, indicating the ferromagnetic behavior of
6 such composites with saturation magnetization, remanent magnetization, and coercivity
7 values of 36.7 emu/g, 2 emu/g, and 70 Oe, respectively. Since magnetite particles are
8 superparamagnetic at room temperature, the presence of magnetic hysteresis shows that the
9 Fe filings used in our Leidenfrost experiments did not have time to be completely oxidized.
10 Furthermore, pure bulk Fe has a saturation magnetization value of ~ 218 emu/g²³, which is
11 about 5 times larger than the values we obtained for our Fe:dust, Fe:AC, Fe:MgO, Fe:SiO₂
12 and Fe:Cu mixtures. Microparticles and nanoparticles have smaller magnetization values
13 than their corresponding bulk counterpart, which decreases with the reduction in the particle
14 size due to the small particle surface effect and internal crystal disorder.²⁴ Our Fe filings
15 have an average diameter of ~ 10 μm (Figure S1 in ESI).



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17 Figure 4: Magnetization curve of a 1:1 Fe:Cu mixture at room temperature.

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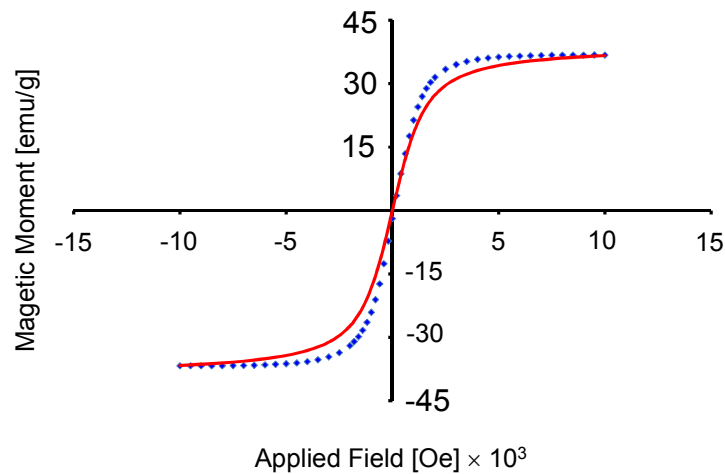
19 We model the magnetization M of the composite mixture of Fe:Cu of uniform
20 diameter d in the direction of an applied magnetic field H with the Langevin function $L(\alpha)$.

$$21 \quad \frac{M}{\phi M_s} = \coth(\alpha) - \frac{1}{\alpha} \equiv L(\alpha) \quad (1)$$

22 where ϕ is the solid volume fraction, M_s is the saturation magnetization of the bulk Fe, and α
23 $= \pi\mu_0 M_s H d^3 / 6kT$, where μ_0 is the vacuum permeability, k is the Boltzmann constant and T is
24 the temperature.^{25, 26}

1 In the case of the series of Leidenfrost experiments with the starting mass ratio of 1:1
 2 (Fe:Cu), we obtain a best-fit solid line derived from equation 1 and this is shown in Figure 5,
 3 when ϕ is ~ 0.30 . The data fit indicates that Fe is more densely packed than Cu in the mixture,
 4 with Fe occupying only 30 % by volume. While the bulk Fe density of 7.87 g/cm^3 is smaller
 5 than the bulk Cu density of 8.96 g/cm^3 ,²² the packing density of Fe filings in our mixtures is
 6 strongly dependent on the applied magnetic field since Cu is diamagnetic. 1:1 (Fe:material)
 7 mass ratio mixtures of dust, AC, MgO and SiO₂ particles show similar ϕ values of 0.30, 0.27,
 8 0.32, and 0.29, respectively, with Fe occupying approximately 30 % by volume.

9



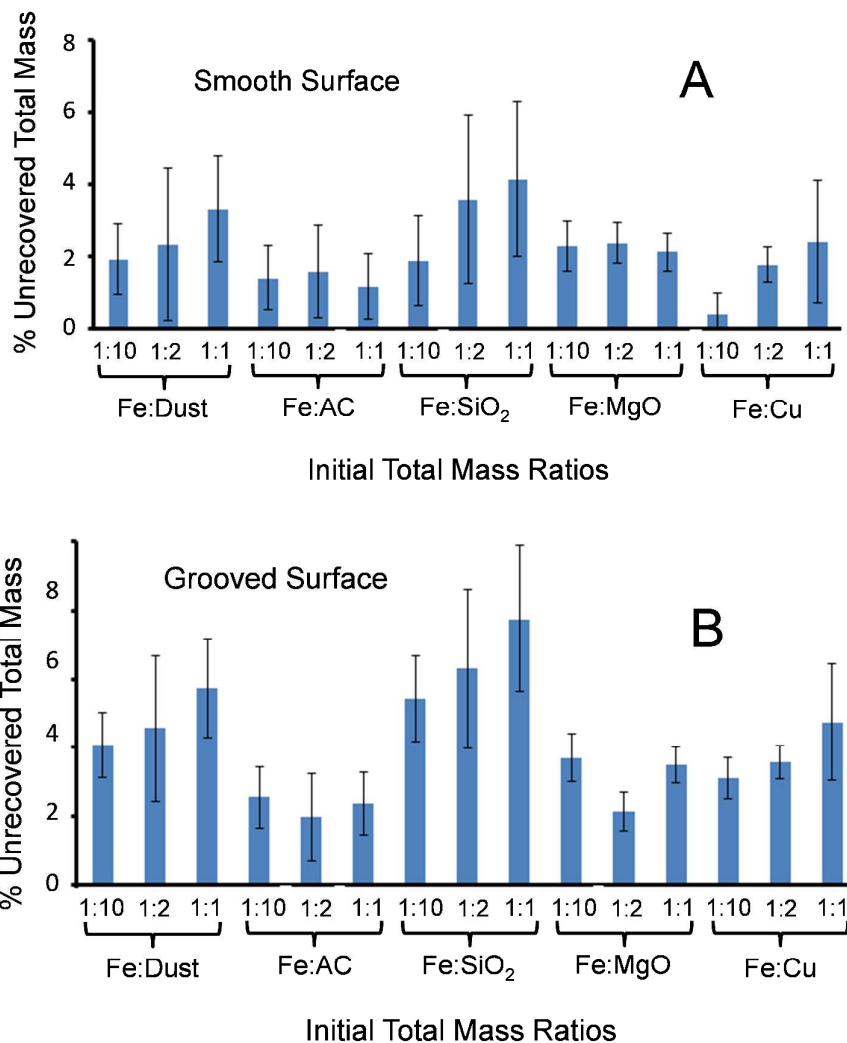
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11 Figure 5: Langevin line of best fit (solid line) of the magnetization curve of a 1:1 mass ratio Fe:Cu mixture
 12 (dotted line).

13

14 The mass percentages of unrecovered dust, AC, SiO₂, MgO, and Cu for both smooth
 15 and grooved surfaces are shown in Figures 6A and 6B respectively. Fe and Cu were mixed in
 16 1:1, 1:2, and 1:10 (Fe:Cu) mass ratios in a smooth heated Al surface and after the Leidenfrost
 17 phenomenon was applied the percentage of unrecovered Cu varied from 2.4 % in 1:1 to 0.4 %
 18 in 1:10 mass ratios. On a grooved surface, the non-removal rate of Cu varied from 5.7 % in
 19 1:1 to 4.1 % in 1:10 mass ratios, which is about 2.4 times larger. On both smooth and
 20 grooved surfaces, the highest non-removal rate belonged to SiO₂ (1:1 SiO₂:Fe mass ratio) at
 21 4.1 % and 7.8 %, respectively. The non-removal rates for the other materials on smooth
 22 surfaces ranged from 1.6 % (activated carbon) to 3.3 % (dust material); while on grooved
 23 surfaces dust particles were also hardest to pick up, with 5.5% remaining on the Al surface.
 24 Although the grooves are > 16 times larger than previous estimates on the vapor layer film
 25 thickness ($\sim 31 \mu\text{m}$),²⁷ there was minimal variation between the smooth and grooved surfaces
 26 with material effective recovery rates of > 90 %. Of particular interest is the fact that the

1 Leidenfrost phenomenon can be applied to the removal of hydrophobic (dust and AC) and
 2 hydrophilic (SiO_2 , MgO) materials. The accuracy of the measured values was dependent on
 3 the accuracy of the mass balance which was listed by the manufacturer (Shimadzu) as \pm
 4 0.01mg, meaning that for a value of 10 mg, there is an instrument error of at most 0.1%.



5

6

7 Figure 6: Average % of unrecovered total mass vs. initial total mass ratios for (A) a smooth surface and (B) a
 8 groove surface. AC refers to activated carbon. Error bars are the result of 5 measurements.

9

10 There are limitations associated with this technique. Firstly, the material to be
 11 aggregated and collected needs to be insoluble in water for the droplets to form at the
 12 Leidenfrost temperature. Soluble salt crystals increase the Leidenfrost transition temperature
 13 by disrupting the minimum vapor film boiling temperature. Since the salt cations and anions
 14 diffuse slowly in aqueous solutions, the salt ionic concentration at the vapor-liquid interface
 15 increases dramatically as the water droplet evaporates. This salt concentration has been

1 estimated to be as high as ~ 30 M; based on Raoult's law, the boiling point elevation should
2 increase in the order of ~ 30 °C.²⁸

3 This most likely explains why we found the Leidenfrost effect to be ineffective in the
4 removal of soluble salts such as NaCl on heated Al surfaces. At the Leidenfrost temperature
5 of 240 °C, the droplets collapsed and rapidly boiled off upon contact with NaCl, leaving
6 behind the solid white crystals, as shown in Figure S10 in ESI section. Electrolytes inhibit
7 bubble merging⁹ and hence a higher temperature is needed to set in motion the Leidenfrost
8 transition. According to a Taylor instability analysis on a Leidenfrost droplet, the minimum
9 vapor film boiling point formation is directly proportional to the saturation temperature, and
10 the square root of the surface tension.²⁷ It is therefore reasonable to expect the addition of
11 soluble salts to raise the Leidenfrost temperature by increasing the minimum vapor film
12 boiling point and decreasing the surface tension of the solution by hindering hydrogen
13 bonding networks in water.⁹

14 Secondly, another limitation is the presence of an insulating particle layer on top of
15 the heated metal surface, which was maintained above the Leidenfrost temperature. We
16 observed that water boils off when the surface has been covered with a layer of Cu particles
17 ~ 2 mm, implying that the Leidenfrost temperature had been raised. This phenomenon is
18 similar to that observed by Aberle et al whereby coated particles to liquid marbles behave as
19 an insulating layer when heated to greater than 200 °C.²⁹ The boiling off process is
20 chronologically displayed in Figure S11 in ESI.

21
22 Finally, the Leidenfrost effect can only be used on heated metal or ceramic surfaces.
23 Wood and many plastics surfaces will combust in air at/above the Leidenfrost temperature.

24 In summary, we showed that the Leidenfrost effect can effectively reconcentrate
25 precious coinage metal filings, which with the addition of Fe filings can be collected using a
26 simple magnet. Furthermore, we demonstrated that the removal of particles using the
27 Leidenfrost effect requires no special surface treatment, while being able to successfully
28 remove both hydrophobic and hydrophilic particles from heated metallic surfaces. Our study
29 is relevant in the development of effective precious coinage metal filings recovery technology
30 for application in the mint industry, as well as in the self-cleaning of metallic and
31 semiconductor surfaces in the semiconductor industry.

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4 Information on particle size (Figure S1 and S2), the removal of hydrophilic material
5 via the Leidenfrost Lotus effect (Figure S3 and S4), the removal of hydrophobic material
6 (Figure S5 and S6), Leidenfrost Lotus effect on grooved surfaces (Figure S7), optical images
7 of the shape of the dried-up aggregations (Figure S8), final geometry of the aggregated
8 material as a function of the initial Leidenfrost droplet size (Figure S9) the failure of the
9 Leidenfrost droplets to form on NaCl (Figure S10) and on a Cu particle layer ~2 mm thick
10 (Figure S11) can be found in the electronic supplemental information (ESI) section.

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