Floating on Air - The Leidenfrost Effect

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Get Wet Image Report

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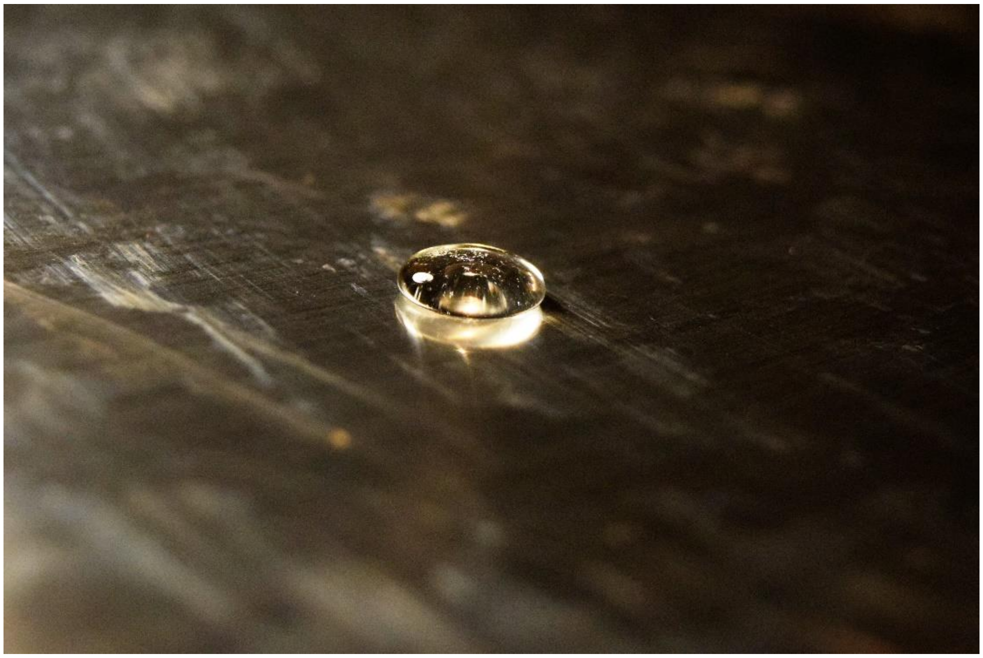

Figure 1: Get Wet Image – Edited

This image was taken for the Get Wet assignment, where I was tasked with taking my first photograph of a fluid flow phenomenon. My focus in this project was to take a photograph of the Leidenfrost Effect – where liquids can float above a hot surface for extended periods of time. This effect is only visible at high temperatures, so it involved working over my kitchen stove, heating a sheet of aluminum and photographing water droplets suspended above the hot surface. The final image for this project was produced on my third session. The original image was taking using my 13 year old Cannon EOS Rebel. Because of the age of the camera, I struggled with adequate lighting and had to open the aperture to f/4.5, high ISO and a slow shutter speed. This resulted in an image with short depth of field, high grain and motion blur. My third set of images was taken with a borrowed Nikon 3300D, which allowed me to capture a detailed image with relative ease compared to my previous attempts.

As mentioned above, the flow phenomenon occurs only on surfaces with high temperatures, and therefore I used an infrared cooktop to heat up a plate of aluminum. This plate gave a flat, adjustable surface (with little distracting texture) that allowed me to reduce the movement of the water droplets. Next, I positioned the camera 90˚ from my light source, lifted slightly above the aluminum plane. The setup for the image is shown in a simple schematic below in Figure 2. Once the plate was heated sufficiently (water no longer boiled upon contact, but instead began to hover) I splashed several drops of water onto the plate and started taking photographs.

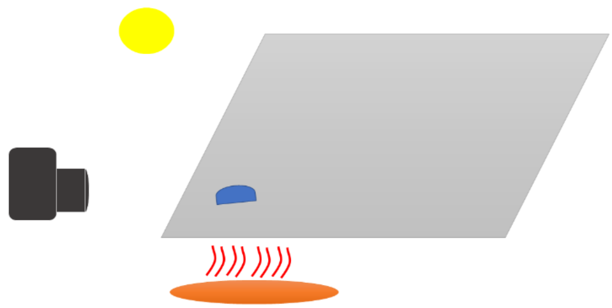

Figure 2: Schematic of fluid flow setup for final image

The water which landed in the middle of the heated section, directly above the burner, began to form into small spherical droplets and quickly move across the plate's surface. The water droplets that sped off of the hottest part of the surface, then collapsed and boiled away. These fast moving drops and boiling around the perimeter can be seen in Figure 3. The remaining droplets, which hovered above the surface of the hot plate settled to the lowest point on the plate and combined to form a larger droplet.

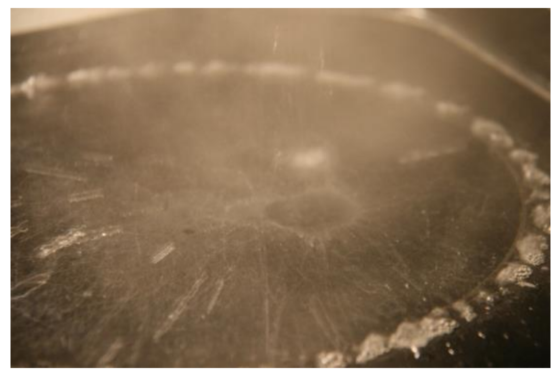

Figure 3: 0.10 second exposure of droplets flying across hot surface – circle measures 7" in diameter

When the water is dropped onto the hot surface, a portion of the water immediately boils. This expansion of liquid into gas propels some of the small drops away from the center. The speed of these drops can be calculated by looking at the length of the streaks compared to the diameter of the burner and factoring in the shutter speed.

$$v = \left(1.5\ in \cdot \frac{7\ in}{8\ in}\right) \Big/ 0.10\ sec \ \rightarrow v = 13.2\ \frac{in}{s} \rightarrow v = 0.34\ \frac{m}{s}$$

One interesting part of the Leidenfrost effect is the fact that a liquid can be suspended over a hot surface for minutes, while the same droplet would boil in seconds on a cooler surface. The longevity of a droplet appears to be related to whether or not the droplet settles in a local minima in the "substrate" that it is suspended over [1]. To make use of this, as I heated the plate I gently bent the corner by approximately 3˚ up, producing a small area for the droplet to settle. As the drop of water settled into this very slight pocket, its movement slowed down, as it glided around the depression with a speed of no more than 1 inch per second. A helpful diagram of the drop levitation is given by P. Brunet:

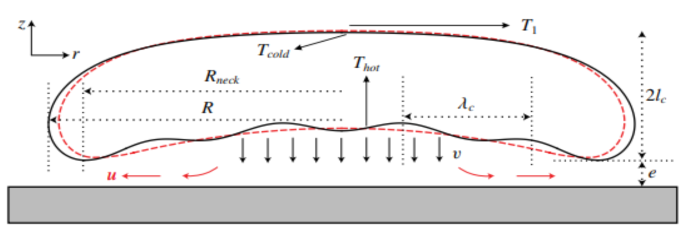

Figure 4: Diagram of Leidenfrost levitation courtesy of [2] vector u shows the radial velocity of superheated steam escaping from under the drop, while v gives the downward velocity of water forming into steam.

This diagram shows the behavior of the droplet as water boils off of the bottom, replacing steam that has flowed out from the sides. The temperature at which the Leidenfrost effect begins to occur is around 300 to 400˚C [3]. Assuming that the bottom surface is at the boiling point (100˚C), the upper surface is at room temperature (25˚C) and the hot surface is at 400˚C, we can look at the density imbalance:

Saturated Temperature	25 ˚C (liquid)	100 ˚C (liquid)	100 ˚C (steam)	400 ˚C (steam)	Air @ STP
v_f or v_g spec. vol (m^3/kg)	0.001003	0.001043	1.6720	3.1027	0.797
ρ (kg/m^3)	997.01	958.78	0.598	0.322	1.255

Table 1: Temperature and density of steam and water at 1 atm [4]

This gives the mean density of the water in the droplet as: $\rho_{water} = 977.9\ kg/m^3$, and mean steam density as $\rho_{steam} = 0.460\ kg/m^3$. In the case of simple buoyancy, the water in the drop would fall below the steam bubble, but in the Leidenfrost Effect, surface tension effects dominate, thus keeping the steam trapped underneath. The mean thickness of the steam layer is 0.009 cm [3] and the bubble photographed is approximately 1 cm in diameter. Taking the layer under the bubble as a uniform cylinder, we get a volume of: $v = 9 \cdot 10^{-5}m \cdot \pi \cdot (5 \cdot 10^{-3}m)^2 \rightarrow v = 7.069 \cdot 10^{-9}\ m^3$ therefore, the net buoyant force on the steam is: $F_{net} = (\rho g V)_{air} - (\rho g V)_{vapor} \rightarrow F_{net} = 5.51 \cdot 10^{-8}\ N$ is the force pushing up on the drop of water above just due to buoyancy. While this force is small, the normal force of the substrate counters the force of gravity pushing against the bubble of water. The result is a slight net force upwards which fights to keep the drop of water suspended above the heat.

Another unique property of the Leidenfrost effect is the reduced friction between the water droplet and the hot substrate. In fact, prototype heat engines have been built using the Leidenfrost Effect to reduce friction. Since shear stress is directly proportional to viscosity in Newtonian fluids:

$$\tau = \mu \frac{d\gamma}{dt} \quad [5]$$

lower viscosity would result in a lower shear stress for the same input force, and therefore less resistance to movement. Below is a table showing the dynamic viscosities of steam and water at their respective average temperatures:

	Water @ 25 ˚C	Steam @ 400 ˚C
$\mu \cdot 10^{-3}\ Pa/s$	0.388	0.024

Table 2: Dynamic viscosities of water and steam [5]

From the table above, we can see that the viscosity of steam is much lower, and therefore is less resistant to shear. This allows the bubbles to slide around with the appearance of zero friction.

The flow visualization technique used in this photograph was index of refraction. This is apparent in Figure 1, because the droplet can only be seen because it bends the light captured by the camera. The use of this technique is made easier by the plainness and reflectivity of the surface that the droplet is suspended above. The polished aluminum (6061-T6 @ 1/8” thick) allows us to see a concentrated bright spot below the bubble, which further emphasizes it in the image. Additionally, it appears that the bubble is acting like a lens to create the bright spot in such a concentrated area underneath. The scene was lit from the left side of the camera using a desk lamp and from above using the light below my microwave. Both of these lights were incandescent, which provided some of the yellow appearance in the image.

The final image was captured with the camera 7" away from the subject with a 34 mm focal length on an 18-55 mm wide angle lens. This photo was taken using a Nikon 3300D DSLR. While the drops were relative stationary, I was getting motion blur with slower shutter speeds. Therefore, I switched to shooting on shutter priority mode and took my final photo with a 1/500 second shutter speed. The automatic settings were: f/4.5, ISO-3200. With an aperture at f/4.5, I had a short depth of field, which was advantageous, because I was able to get the background and foreground to drop out of focus. This short depth of field allowed me to center the focus on the water droplet. The only changes between the final image and the photograph taken by the camera was some simple cropping and the addition of contrast using an S-curve in Gimp.

To me this image feels graceful, which to me feels more in line with the flow phenomena than my previous image did, which felt chaotic. The beauty of the Leidenfrost Effect is how peacefully the water acts under extreme conditions. The careful balance of temperatures required to cause this phenomenon, makes seeing and capturing the effect very rewarding. Showing the behavior of water when this effect is taking place is difficult with a still image, so I tried recording a couple of videos to show the weird behavior better. In the end I went with a still image, because the videos that I recorded didn't quite capture the elegant behavior of a droplet floating above a hot surface. If I were to make changes to this image, I would likely focus on trying to capture the relationship between calm and chaos, where I had a small droplet zooming past the larger more stable drop of water. That image could maybe be done in two separate exposures (on a tripod), which were merged in photoshop after the images were taken.

References

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4. Cengel, Y. & Boles, M. (2015) Thermodynamics an Engineering Approach 905 – 918.
5. Cengel,Y. & Cimbala, J. (2006) Fluid Mechanics: Fundamentals and Applications 47.