MCEN 5151: Flow Visualization

The Leidenfrost Effect

First Team Assignment

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The third assignment for MCEN 5151: Flow Visualization is the first of 3 team projects where experiments are set up by a group of individuals rather than a single person. A major goal of this group setup is that with more manpower, people will be able to do more complicated experiments and achieve more spectacular images or videos. Students are not required to work in their group or in any group at all, but they are expected to help the members of their group with whatever experiment is decided upon by the majority. Initially, our group consisting of Philip Latiff, Michael McCormack, Adam Sokol and myself was planning on capturing slow motion footage of steam explosions. Unfortunately, the high speed camera did not work well with the sunlight, but during our experimentation we discovered an odd fluid effect that occurred when placing the water on a hot plate. This effect is known as the Leidenfrost Effect, and we agreed as a group that it was a very interesting phenomena. I chose to make a video in which water droplets are placed on a super-heated plate. Some droplets were dyed with various colors, others were mixed with oil and the end of the video does display one of the few steam explosions we were able to capture.

To capture the effect, we used a 10"x10" Corning PC-600D hot plate with a temperature range of 5-550ºC. A flat, thin, 13" aluminum pizza tray was placed on the hot plate and the hot plate was turned all the way up to the 550ºC setting. Once the aluminum plate had been sufficiently heated, water droplets (roughly 0.25in in diameter) were dropped onto the plate one at a time using syringes filled with different colored water (red, yellow, blue and green food dyes were used). As the cool water was dropped onto the plate, it cooled the area where it landed, which stifled the effect. Because of this, the syringes were moved as droplets were placed on the plate so that no one area would become too cool for the effect to be visualized. A white plastic plate was utilized as the background for the image. This setup can be seen in **Figure 1** below.

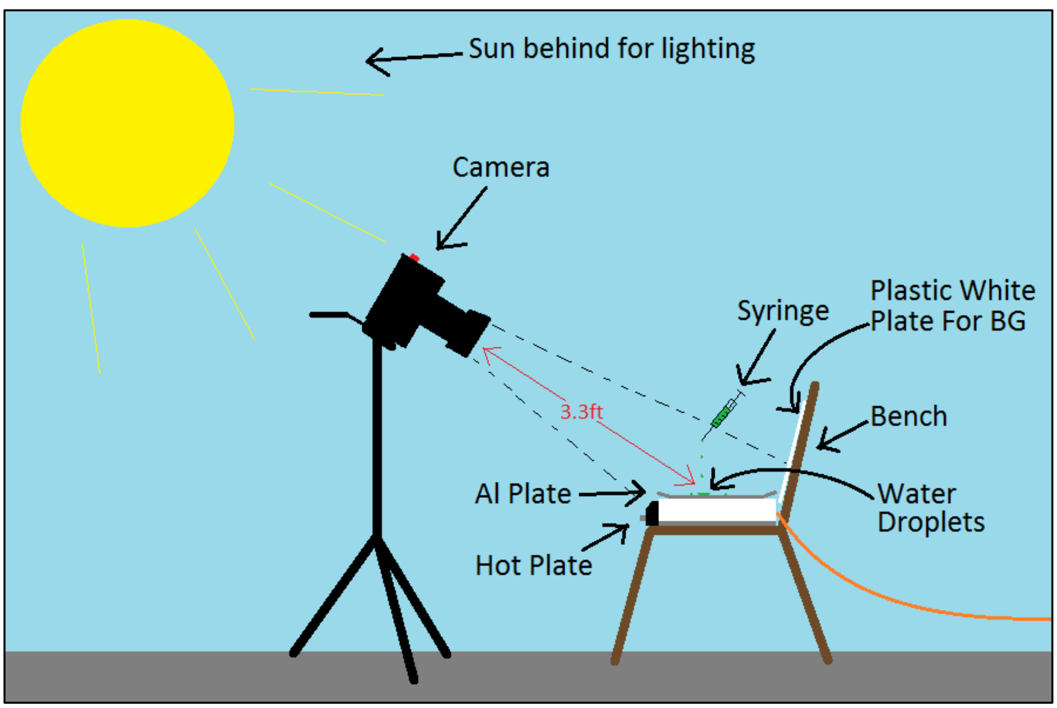

Figure 1: Experimental setup for capturing Leidenfrost Effect (not to scale)

To capture the effect, the hot plate was placed on a 1.5ft high bench and a DSLR camera with relatively high-speed capabilities was placed a horizontal distance of about 2.5ft from the bench. The direct distance from the area of focus on the aluminum plate to the camera lens was 3.3ft (see **Figure 1**). The experiment was done outside and so the sun provided the lighting. The camera was faced away from the sun to avoid lens flare and to get the best lit image. There were clouds present on the day of the experiment, so to avoid shadows and inconsistencies in color, many separate recordings were taken.

Because the hot plate used was set at such a high temperature, it caused a phenomenon called the Leidenfrost Effect, named after Johann Gottlob Leidenfrost, which is a result of fluid (water in this case) coming into contact with a surface at a significantly higher temperature than its boiling point. This is not sufficient though, because the temperature must also be higher than the so called Leidenfrost point of the fluid as well. Depending on the surface material and texture, the amount of liquid and temperature of the droplet, and other variables, the Leidenfrost point can vary. For water, it is generally accepted to be around 200°C.[2, 3] A change in any of these variables can effect this, though. For example, an increase in pressure will cause an increase in the Leidenfrost point (as well as a reduction in evaporation time of the droplet).[2] If pressure is decreased enough, the Leidenfrost point of water can even occur at room temperature.[1]

When a fluid comes into contact with a surface with a temperature above the fluid's Leidenfrost point, the bottom surface of the liquid almost immediately vaporizes and forms a thin film of vapor that acts as a cushion between the liquid and the surface, eliminating solid-liquid contact and giving the "levitating" liquid a unique, frictionless mobility in addition to potential self-propulsion of the droplets.[5] **Figure 2** below illustrates what this looks like. Even though this vapor cushion is less than 0.1 mm thick at the edges (exact height depends on droplet size), the vaporization of the rest of the drop is slowed significantly, allowing it to stay in liquid form on the surface for an extremely long time when compared to a surface at the boiling temperature of the liquid.[3] This is because the bottom surface of the drop will continually evaporate to replenish the film of vapor that is levitating the liquid above the hot surface, preventing the temperature of the bulk (droplet) to increase to a high enough value to vaporize. This leads to droplets with lukewarm temperatures, even though they are on a 500°C surface.

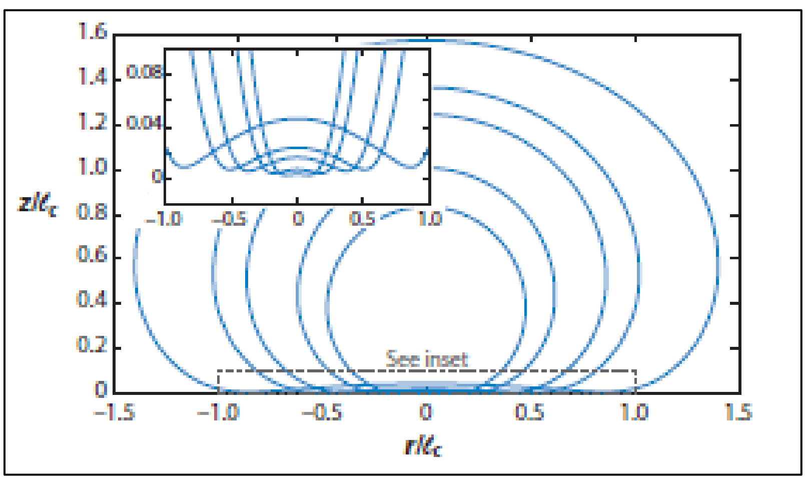

Figure 2: Shape of various sized Leidenfrost drops.[5]

Looking at **Figure 2**, we see an interesting phenomena occurring as the droplet gets larger. From this image, it looks like the larger the drop gets, the flatter it becomes. It is a well-known effect that has been studied by many. From this, we now know that Leidenfrost drops will undergo a transition from quasi-spherical droplets to flattened puddles due to the increased gravitational force as they increase in size.[4] This occurs only in the larger droplets because as mass increases, the gravitational force is able to overcome gravity. A clear visualization of this flattening can be seen in **Figure 3** below. It can also be seen both in the video and in the image on the title page.

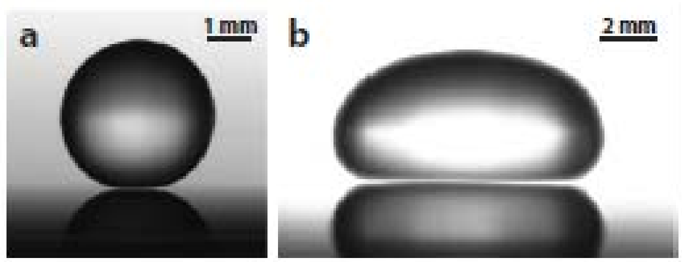

Figure 3: (Left) Smaller, spherical Leidenfrost drop. (Right) Large, flattened Leidenfrost "puddle".[5]

A few interesting situations occurred with our experiment. Firstly, the hot plate was not effective at uniformly heating the aluminum plate above the Leidenfrost point. In fact, the edges of the play did not even reach the boiling point of water (they were actually cool enough to touch for prolonged periods). Because of this, there were different regimes in which the water would behave differently. On the edge of the plate, droplets would spread out and rest at that point indefinitely, as they do on any non-hydrophobic surface at a temperature below their boiling point. If a droplet was placed in a 2 inches wide ring starting roughly 2.5 inches from the center of the plate, the droplets would vaporize (see **Figure 4**). This is because if the temperature is above the boiling point, but not the Leidenfrost point, the water spreads out and conducts heat from the plate at a high rate, which results in the vaporization of the droplet in a short amount of time (3-5 seconds, depending on droplet size).[3] Additionally, if droplets were placed in the same position too many times, the temperature would drop below the Leidenfrost point and cause boiling to occur, which is why the syringes had to be moved around as droplets exited their tips.

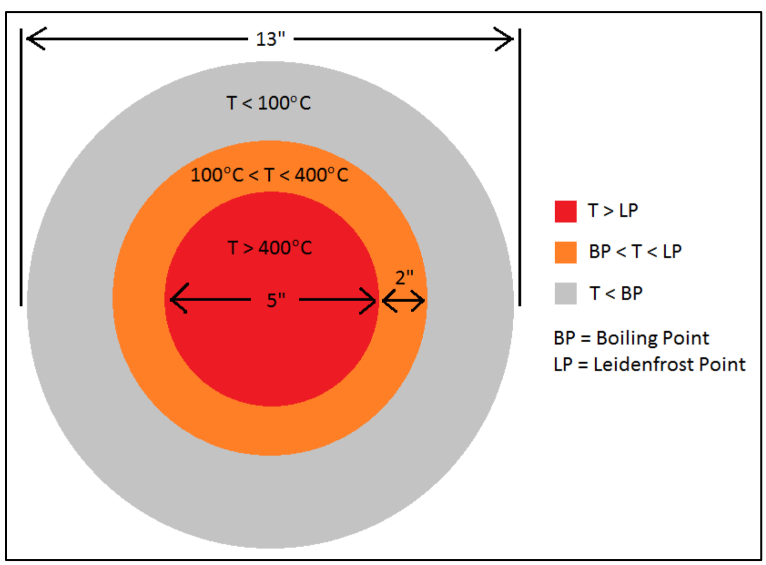

Figure 4: Temperature zones on aluminum plate

In addition to the Leidenfrost effect, our group filmed some steam explosions by super heating oil and dropping water on the surface. This occurs when water is violently boiled, or flash boiled, which causes a large increase in volume as it instantaneously vaporizes, leading to an explosion. The video also depicts a smoking Leidenfrost drop, which was brought about when a droplet of oil was dropped directly on top of a large, flattened Leidenfrost drop. This effect was not the focus of the project, so extreme detail about steam explosions will not be provided.

In order to better visualize the droplets and to add more vibrancy to the video, food coloring was added to many of the droplets. Four colors were used; red, yellow, blue and green. In some clips, red droplets are placed on the plate with blue droplets and when they combine, purple droplets resulted. The camera was placed high up on a tripod and rotated 45° below horizontal. The standard zoom lens was zoomed all the way in so that the highest amount of information could be resolved. As was mentioned before, a white plastic sheet was placed behind the image so the bench was not visible, and the sun was utilized as the only light source.

The video is spatially resolved, with a very high shutter speed compared to the movement speeds of the liquid droplets, which was roughly a foot per second at its fastest. This means that each individual frame contains very little to no motion blur, which can be seen in the screen shot taken from the video on the title page, which contains several droplets, all of which were moving in that frame. The largest point of interest (in my video) is the steam explosion at the end, which takes up the majority of the frame, giving it 0 decades of separation. The smallest point of interest are the little Leidenfrost drops, which were roughly 0.25 inches in diameter after being dropped from the syringe. Once these droplets impacted with the surface, they broke apart, making them even smaller at roughly 0.04 inches (1mm) in diameter. The frame size was 7.5x10 inches (for the still shots), giving us 3 decades of separation in the video. For the handheld portions, which zoomed in and out periodically, the frame size is hard to determine. The size of the puddle in those 2 shots was roughly 1.5 inches across, so that can be used to get an idea of the frame size. We also know that 2 to 3 decades are required to spatially resolve moving fluid, and because our pixel dimensions are 1280x720, which is equivalent to 3 decades, the video is spatially resolved.

The camera settings can be seen in **Table 1** below. The ISO was set at 100 to reduce grain and limit the amount of light reaching the sensor. Because the experiment was done outside at midday, a lot of light was present. This meant a low ISO could be used to achieve higher quality video without sacrificing light. Even with the low ISO, the shutter speed was set at 1/250 because there was still too much light. This gave the video good spatial resolution and low motion blur. The aperture was set at 8.0 to balance these two values and get the best lighting possible. The 28-135mm lens was zoomed all the way in, giving a focal length of 135. The video was shot in 1280x720 resolution with 60 fps (with each frame being exposed for 1/250 seconds).

Table 1: Camera settings

Camera Body	Canon EOS Rebel T2i
Camera Lens	Canon EF 28-135mm IS USM standard zoom
Shutter Speed	1/250
ISO	100
Aperture (f-stop)	8.0
Focal Length	135mm
Pupil Diameter	16.875mm
Pixel Dimensions	1280x720
Frame Rate	24fps (shot in 60fps and slowed in post processing

Post-processing was done in Final Cut Pro X. The first step was to take every clip and convert to 24 frames per second. This gave us 2.5x slow-motion and, because the footage was shot in 60fps, also allowed us to keep everything smooth. One segment was speed up to 160% so that the timing of the events in the clip would work with the music, which is entitled “The Voices”, and was composed by Josh Woodward. The rest of the video was cut to match up with the selected music, and each clip was color matched so that they all appeared the same (this was necessary because clouds inevitable blocked the sun out in some portions of the footage taken). Once the color match was completed, a filter was added to each clip that increased exposure, contrast, brightness and saturation to desirable levels. A “glory” effect was also added in some of the clips to make the droplets shimmer. Ken Burns zooms were placed on various tripod shots to make them more mobile and interesting, and some clips were cropped to eliminate undesirable areas that were either blown out or discolored by the filter. Lastly, a fade to white was used in conjunction with the steam explosion to create a good ending transition.

I feel that this video captures a very interesting fluid phenomenon, and it was an especially good learning experience because we captured the effect on accident, so we spent the duration of the shoot trying to determine what generated the observed effect. This was a good exercise, because it got all of our group thinking about fluid physics and using information we already knew to try and figure out something foreign to us. In the end, our hypothesis turned out to be correct. We also were still able to get some good steam explosions in, and one even made it into my video, so I have no regrets about how the experiment went. If I were to redo this project, there a few things I would change. Firstly, oil would not be introduced until the very end of filming. This is because it caused some discoloration and blackening of the plate, which is not as aesthetically pleasing as a clean plate. I would also use some form of ceramic or a thicker metal plate so that the warping and discoloration effects would not be as apparent (though the warping did create some interesting “jumping” droplet effects). I would also like to have tried out different types of fluid to see how viscosity and density effect the phenomenon, and also a wider range of fluid colors. Lastly, I would come better prepared with a more adequate tripod that would allow better framing. The one we used could only rotate so far, which limited our ability to frame the footage the way we would have liked to (which would not have shown the edges of the aluminum plate). Aside from that, I enjoyed the experiment and found it interesting, and I am proud of the product that was produced.

References

[1] Celestini, Franck, Thomas Frisch, and Yves Pomeau. "Room temperature water Leidenfrost droplets." *Soft Matter* 9.40 (2013): 9535. Print.

[2] Emmerson, George S.. "The effect of pressure and surface material on the leidenfrost point of discrete drops of water." *International Journal of Heat and Mass Transfer* 18.3 (1975): 381-386. Print.

[3] Jearl, Walker. "Boiling and the Leidenfrost Effect." *Cleveland State University.* Print.

[4] Pomeau, Yves, Martine Le Berre, Franck Celestini, and Thomas Frisch. "The Leidenfrost effect: From quasi-spherical droplets to puddles." *Comptes Rendus Mecanique* 340.11-12 (2012): 867-881. Print.

[5] Quéré, David. "Leidenfrost Dynamics."*Annual Review of Fluid Mechanics* 45.1 (2013): 197-215. Print.

CLOUDY ARCTIC BOUNDARY LAYER