IV3 – Leidenfrost Effect in Cast-Iron Pan

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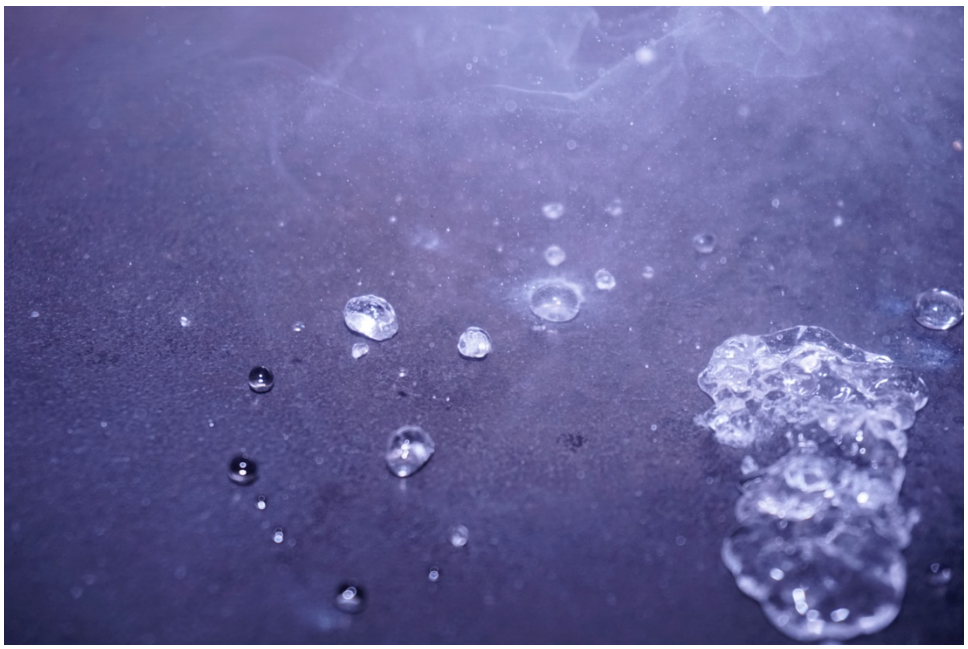

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MCEN 4151 – Flow Visualization

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INTRODUCTION

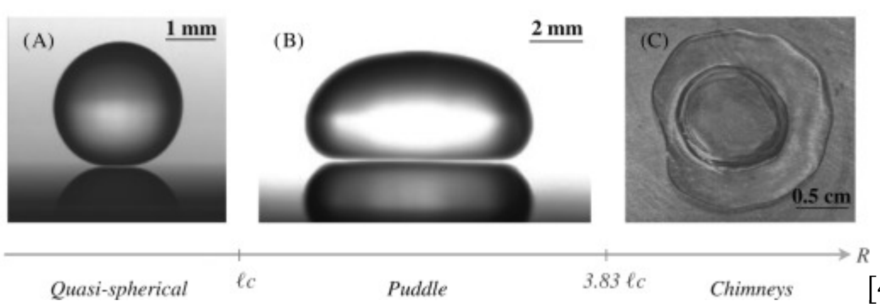
In this report I describe a fluids experiment with the Leidenfrost effect for my Flow Visualization class. The Leidenfrost effect is a name for film boiling, which is what happens when the heat flux between a fluid and a surface reaches a critical value, causing a continuous vapor film to cover the surface and separating the fluid from the surface. In 1756, Leidenfrost observed that water droplets on a hot surface will move around and boil away slowly, suspended on a vapor film [1]. The effect is also possible with cold surfaces, like dry ice, where the warm fluid hitting the dry ice causes it to sublimate, suspending the fluid [2]. My group wanted to observe the Leidenfrost effect ourselves, so we recorded ourselves dropping water onto hot kitchen pans and used our developing photographic skills to capture it.

EXPERIMENTAL SETUP

I decided to use my 10 ¼ inch Lodge cast iron skillet for this experiment. I didn't want to risk damaging a Teflon coated pan by heating it past 260° C[3], even though the Leidenfrost temperature for water is typically below that. My photography equipment consisted of a Sony Alpha a6300 with 16-50mm lens and a video light panel with adjustable brightness and color temperature. To set up the experiment, I used an electric stove to heat the pan up to the point where residual oil smoked off, and I prepared a 3 *mL* syringe with needle to add water to the pan in a controllable manner. Next, I set up my tripod next to the stove so the camera could capture the experiment from the side and slightly above, and I attached a light panel on top of the camera to illuminate the action. Once the pan was hot, I used the syringe to inject a small amount of water to the pan to test for the effect, and after verifying it was indeed hot enough, I added more water and filmed the droplets bead and bounce around the pan.

RESULTS AND ANALYSIS

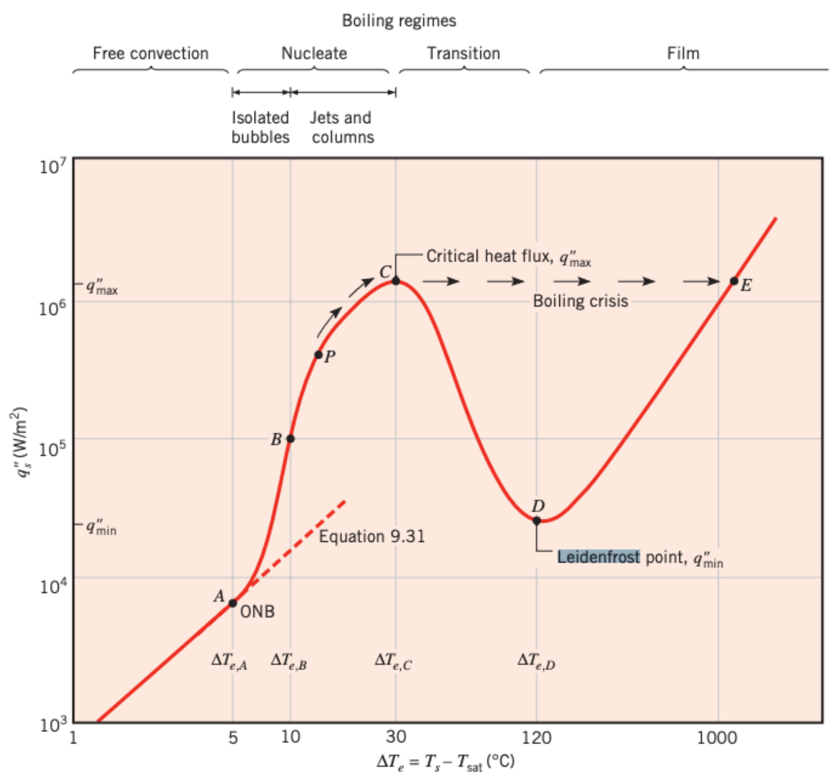
The video I captured illustrates the Leidenfrost effect well, with small spherical water drops bouncing on the pan and refusing to wet the surface. The reason the drops levitate is because the temperature of the surface of the pan is significantly higher than the saturation temperature of the water. This means the water doesn't immediately boil, but rather floats on a layer of its own vapor, as the pressure from the vapor at the bottom of the droplet is sufficient to support its weight, as shown in Figure 1. Without direct contact with the pan the droplet experiences no heat transfer via conduction, meaning the heat flux into it is lower than if the same drop were added to a hot pan at a temperature *below* the Leidenfrost point.



[4]

Figure 1: The Leidenfrost effect will create a spherical shape in small droplets and an oblong shape in larger ones. Notice the gap between the droplets and the surface.

What happens before the Leidenfrost point? There are four stages of boiling: Free convection, Nucleate, Transition, and Film, shown in Figure 2 below. For water, free convection occurs when the temperature of the hot surface is less than 5°C above the saturation temperature. In this region, bubbles are present at the hot surface, and the water's motion is dominated by convective currents. Free convection is the region before point (A) on Figure 2. If the water is further heated, it reaches the onset of nucleate boiling, at point (A), where bubbles nucleate at the hot surface, separate, and float to the top, causing increased mixing throughout the body of water. Still, most of the heat transfer to the water occurs at the hot surface. When the temperature is raised further, individual bubbles merge together forming jets and columns in the boiling water. This merging of individual bubbles inhibits mixing, and the heat flux versus excess temperature experiences a change in behavior. This occurs at point (P) in Figure 2. If the water is heated further still, it reaches the point where so much vapor is being formed that the liquid cannot continuously wet the heated surface. The heat transfer coefficient begins to drop, and a maximum heat flux is achieved. This *critical heat flux* is represented by point (C) in Figure 2 and occurs approximately 30° C in excess of the saturation temperature.



[1]

Figure 2: The Leidenfrost effect occurs at the end of the transitional boiling regime, where the heat flux into the fluid is at a minimum due absence of conduction.

Past point (C), the water experiences transition boiling. Vapor formation is occurring at a rate where the water is only intermittently in contact with the heated surface, and the water can fluctuate between nucleate and film boiling. This region stretches all the way from 30-120° C past the saturation temperature. Finally, we get to point (D) in Figure X, the Leidenfrost point.

Here, the heat flux is at its minimum, and the heated surface is fully covered by a blanket of vapor. Now, the only heat transfer from the hot surface to the water is via radiation and convection through the vapor. This is what we observe in my video, where the water droplets never wet the cast-iron pan and bounce and hover above the surface instead. I was curious what the minimum heat flux might be, so I studied Novak Zuber's derivation of the minimum heat flux for a large horizontal plate, which is given as

$$q''_{min} = C\rho_v h_{fg}\left[\frac{g\sigma(\rho_l - \rho_v)}{(\rho_l + \rho_v)^2}\right]^{1/4} \text{ [1]}, \tag{1}$$

where C is an experimentally determined constant, q''_{min} is the minimal heat flux, h_{fg} is the enthalpy of vaporization, g is the gravitational acceleration, ρ_l is the density of the liquid, ρ_v is the density of vapor in, and σ is the surface tension-liquid-vapor interface.

I used this correlation to calculate a minimum heat flux of 14,612 [W/m^2], which appears to closely match with the predicted q''_{min} on the log scale y-axis in Figure X. If the Leidenfrost effect I observed was occurring at the minimum heat flux, then I would expect the temperature of the pan to be approximately 215 °C, which is 120 degrees above the temperature water boils in Boulder, Colorado [1].

VISUALIZATION TECHNIQUES

No special techniques were required to capture the motion of the water droplets, and I chose not to dye the tap water or alter it in any way. However, I did need ample lighting. To illuminate the setup, I used a Pixel G1s video light panel attached to the top of my camera. I set it to 3700 K and 100% brightness yielding the full power of the light. This 12 W light has proven to work wonderfully for close-range flow visualization experiments in my otherwise dim and drab kitchen.

PHOTOGRAPHIC TECHNIQUES

The camera setup required some tuning to capture the flow appropriately. I used a Sony a6300 Mirrorless digital camera with a 16-50mm lens and set the video resolution to 1920x1080 px, which is retained in my edited video. The camera was placed approximately 5 inches above the pan and 14 inches away from the part of the pan in the camera's field of view. I used an aperture of f/9 to keep a wider envelope of droplets in focus, and an ISO of 1200 to make sure the video was correctly exposed but not grainy. I recorded the bouncing droplets at 60 fps, which I chose not to slow down, and I exported the final version at 30 fps for submission to YouTube. As far as video editing, I made a minor adjustment to the white balance to make the video less yellow and increased the sharpness a small amount, both of which help the video. All editing was done in iMovie, and the original footage is available upon request.

OUTCOMES

I think this is some of my best work of the semester. I've had enough practice to choose my materials, setup my experiment, and document the flow expertly and efficiently. In this case, I am very pleased with the instance of the Leidenfrost effect I have captured, and think this work offers a lot of opportunity for analysis and discussion. My only complaint is with the music, which is a problem I have yet to tackle. For future projects, I'd like to explore beyond the realm of the iMovie built-in soundtracks and see what other kinds of royalty-free music are available. As for the flow itself, I think my analysis would be made easier with quantitative data for the temperature of the hot pan. If I chose to study the Leidenfrost effect further, I will add some sort of thermometer to the bed of the pan and closely assess the transition through the four stages of boiling.

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