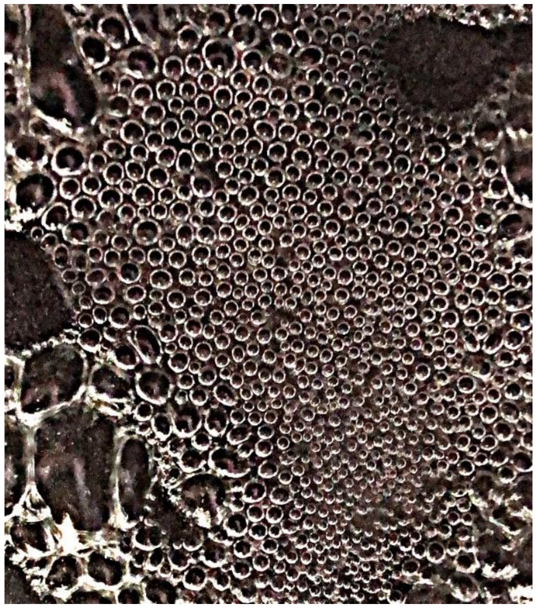
Audrey Viland, Get Wet Report, MCEN 5151-001



The first assignment of the semester, Get Wet, is analogous to students getting their feet wet with photography, or in the case of photography students getting their feet wet with fluid mechanics. The assignment: simply capture a photo that clearly demonstrates a fluid mechanics phenomenon. This description, while purposely vague, proved a harder assignment than previously anticipated. I must have generated 4-5 separate experiments with the expectation that the fluids would behave as I had imagined, however this soon turned out to be incorrect. While cooking, I discovered the Liedenfrost effect, which allows water droplets to scatter across a hot surface in a spherical shape due to air trapped between the surface and the water. I decided to move to a griddle and experiment more with heating water, catching the intermediate boiling stage between the first few air bubble and chaotic boiling.

There is a surprising about of physics surrounding bubbles. In a boiling environment, bubbles appear from water because they are the gaseous stage of water that exists in the liquid [2]. As the molecule heats, the vapor rises since it is less dense than the remainder of the liquid. While at a microscopic level bubbles are not all spherical, they tend to be spherical in nature since the internal fluid is a vapor – exerting a force equally at every point along the film. The heat at the bottom of the pot creates the drive for a physical transformation to a vapor state, and surface tension limits the size of the bubbles [2]. In my experiment, I blew air parallel to the surface of the bubbling water to prevent steam from fogging the lens of my camera. Coincidently, this created another fluid mechanics property: bubble growth limitations. It turns out as I blew across the surface, the larger bubbles broke into several smaller bubbles. This sensation is supported by the physics of a greater temperature differential [3]. As I blew across the top, the ambient air temperature became much cooler, whereas the internal temperature of the bubble remained at a boiling level. This temperature differential limits growth. Bubbles are encouraged to grow if their internal vapor temperature is the same as the outside air since the surface tension will not break [3]. In addition, the shear forces from the forced convection on the outer surface (blowing across the layer) reduce the height to which the bubble can grow [3]. Therefore, a temperature differential and velocity gradient play a significant part in formation and size of the bubbles.

To quantify bubble growth, I turn to the equations governing surface tension and Laplace pressure. One can consider the cutout of a bubble as having a circumference with infinitesimal thickness. This can be expressed as a bubble containing two circumferences with nearly equal radius. Therefore, the change in pressure can be expressed as [1]

$$(P_{in} - P_{out})\pi R^2 = 2 * (2\pi R) * \gamma,$$

where γ represents the surface tension, R is the radius of the bubble, and $P_{in} - P_{out}$ is the pressure difference [1]. In this case, P_{out} is considered the water until the bubble reaches air. As the bubble rises from the bottom of the heat source, it decreases in pressure, creating a larger pressure differential. We can now calculate the pressure difference as [1]

$$\Delta P = \frac{4\gamma}{R} = \frac{4 * (0.0482\,\frac{N}{m})}{(0.002)\;m} = 96.4\;Pa.$$

The equation above represents the fundamental equation relating surface tension to pressure and bubble radius, however other scientist tried to more precisely quantify growth through kinetic energy or through heat diffusion. Rayleigh considered an increase in bubble pressure from inertial forces imposed on the interface of the surrounding liquid through the differential equation below. The equation relates the radius to the density of liquid and vapor, characteristic length of the bubble, and superheat of the bubble radius with respect to the bulk saturation [3].

$$R(t) = \left(\frac{2\rho_v l \Theta_0}{3\rho_l T}\right)^{1/2} t$$

In 1979, Bosnjakovic used a heat balance at the interface of water and water vapor to find a relationship between bubble growth rate and boundary layer thickness [3]. The equation below shows the bubble radius is proportional to the square root of time in a heat-diffusion controlled growth [3].

$$R(t) = \frac{2}{\pi^{\frac{1}{2}}} Ja(at)^{1/2}, where\; Ja = \frac{\rho_l c}{\rho_v l}\Theta_0.$$

These are only a few examples in a plethora of equations derived to demonstrate bubble growth, demonstrating the complexity of this seemingly simple fluid mechanics concept.

When capturing my picture, I wanted to focus on the spherical nature and shape of the bubbles since they grow evenly before bursting. I decided to use the griddle (set at 400 F) because it had a smooth black surface with no distracting surface finishes. Therefore, the eye would not gravitate towards a sparkle in the background. I only added a tablespoon of water to the to reduce the steam coming off the source and to create a thin layer of water, although because of the heat of the griddle the water evaporated quickly. I had to work quickly from pouring the water to capturing the image, with the water only lasting 30 seconds. From the beginning I knew I wanted to focus on smaller bubble formation since it was more controlled than larger bubbles chaotically popping, so an excess amount of water was not needed for this experiment. To reduce the amount of glare on the bubbles, I allowed as much natural light as possible into the room and used an iPhone 5 flashlight from the left end of the griddle (approximately 6 inches away) with a slight angle (5 degrees from the griddle) to add to the intensity. If all lights are turned off and a small flashlight illuminates the image, it creates too much glare and too much attention to the portion of the liquid receiving the light. I wanted equal focus on the small bubbles since the center bubbles are almost all identical in size.

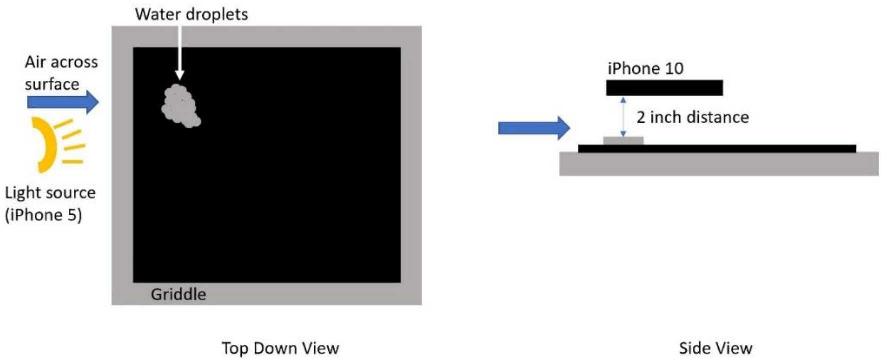


Figure 1: A representation of the original setup

The griddle is an 8”x8” square, however I only used a 1”x1” square to capture the bubbles. The camera was set to a 2-inch distance through a homemade stand. I used the iPhone 10X to capture this image. I found the iPhone 10 camera was very quick to capture small images, whereas my DSLR could not focus as quickly due to bubble burst and reformation. The standard specifications on the iPhone 10 is a shutter speed of 1/25 seconds, ISO 640, aperture f/1.8, and focal length 4.8 mm. The original image was 3024 px x 4032 px, but after cropping the image in photoshop the final image size was 2354 px x 2677 px. The original picture is shown below:

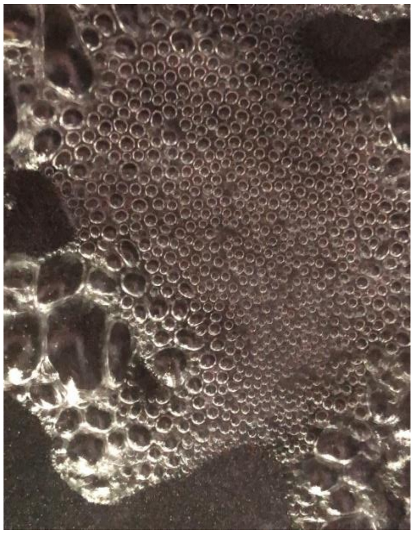


Figure 2: The original image, unedited and uncropped

The image above was cropped to focus on the smaller bubbles. To accentuate the bubble shape, I took advantage of the “unsharp mask” on Photoshop. The settings on amount percent, radius, and threshold were 239%, 27.3 pixels, and 0 pixels, respectively. Apart from cropping and sharpening the image, these were the only modifications I made to the original image. I was very drawn to the bubble shape because of how perfect they looked interrupted. The image was not foamy, and it was not chaotic. In my opinion, it is difficult to tell that the water is even boiling.

After adjusting the image in Photoshop, it speaks more to the spherical nature of the bubbles. It is clear now how densely packed these bubbles are but how they still maintain a strict boundary so as to not merge with surrounding bubbles. I am surprised how clear the image turned out, even before the edits, but I am curious how to increase the resolution. I will lower the ISO and increase the shutter speed as suggested by the comments with an app that manipulates the iPhone speed, but other comments and suggestions are greatly appreciated. I would like to focus on fewer bubbles next time, but that might require more equipment to capture the bubble formation and spacing at that close of a range. Finally, I would like to investigate the use of a high-speed camera to capture the bubble growth and formation. I could use the video footage if it is clear enough, but I am also interested in grabbing still shots from the video to capture a bubble mid burst.

References:

[1] Kundu, P. K., (2016). *Fluid Mechanics, Sixth Edition*. San Diego, CA: Academic Press.

[2] Mistry, N, A. (2014 Jan). Review of Theories on Bubble Formation in Boiling Phenomenon. Veermata Jijabai Technological Institute. Retrieved from https://www.researchgate.net/publication/265209319_Review_of_Theories_on_Bubble_Formation_in_Boiling_Phenomenon

[3] Raykoff, T. (1996 Sep 1). Bubble growth rate and heat transfer suppression in the flow boiling of binary mixtures. Rochester Institute of Technology. Retrieved from https://scholarworks.rit.edu/cgi/viewcontent.cgi?referer=https://www.google.com/&httpsredir=1&article=6877&context=theses