Nathan Sheiko
Flow Visualization
2/10/11

Get Wet – CO_2 Sublimation in Water

The image taken for the "Get Wet" assignment demonstrates the sublimation of solid CO_2 in water. When viewed with the naked eye, the sublimation process produces CO_2 gas bubbles at a rapid rate that obscures the bubble formation process. By taking the image at a high shutter speed, the details of the formation process were clearly shown. The image shows how the gas collects around the solid CO_2 pellet to form bubbles, and how the resulting bubbles move towards the surface of the water.

Figure 1 shows the apparatus used to create the image. A common fish tank with dimensions of 12in x 6in x 8in was filled with water to a depth of 6in. A single solid CO_2 pellet was then place in the center of the tank. The pellet was cylinderical with a length of ~2in and a 0.5in diameter. The camera was placed approxiamtely 12in from the tank, and the image was taken of the pellet and resulting bubbles.

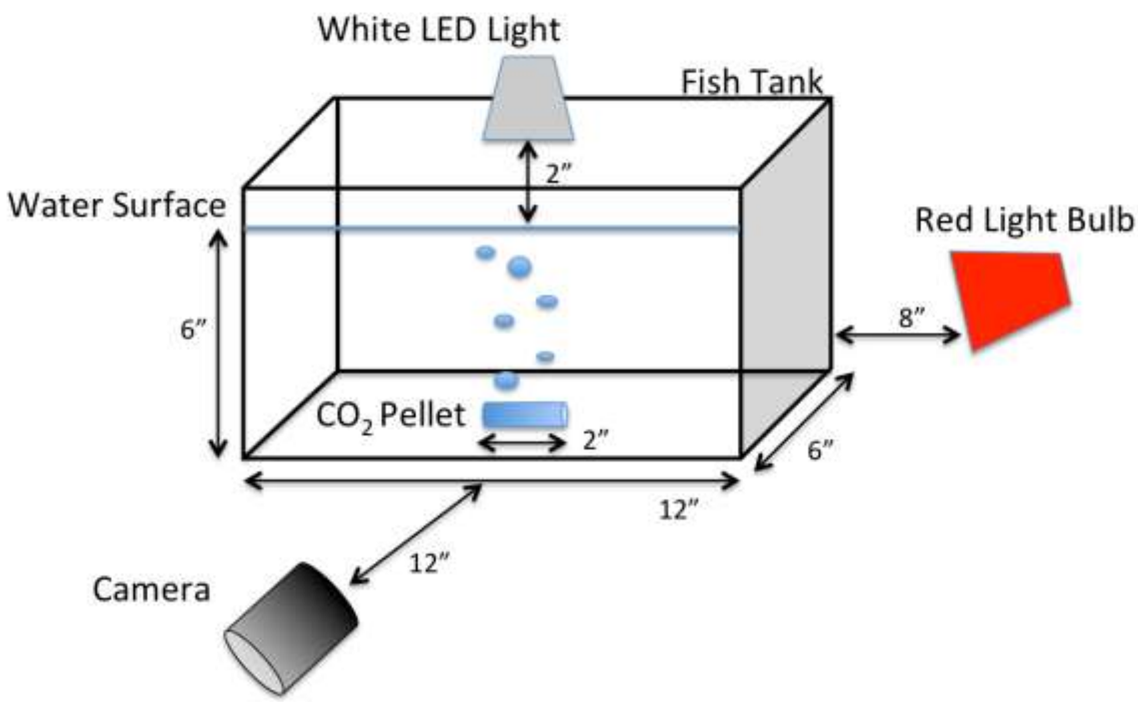

Figure 1: Flow Visualization Apparatus

The image shows the sublimation of solid CO_2 to vapor CO_2. Sublimation occurs when a solid substance passes directly to the vapor phase without first becoming a liquid. From the Pressure-Temperature diagram, the triple-point pressure of CO_2 is 517kPa, or ~5.1 atm.[1] Therefore, when subject to atmospheric pressure of ~1atm, solid CO_2 will always sublimate when exposed to temperatures above its freezing point. The freezing point of CO_2 has been extensively researched and is given by Equation 1, where P is pressure and P_0 is standard atmospheric pressure at sea level (1 atm).[2]

$$t_p = -78.5 + 12.12\left(\frac{P}{P_0} - 1\right) - 6.4\left(\frac{P}{P_0} - 1\right)^2 \quad °C \qquad (1)$$

Using the average atmospheric pressure of Boulder, ~12psi, Equation 1 calculates the freezing point of carbon dioxide as -80.9°C. The water in the fish tank was rather cold at ~10°C, but this was still well above the freezing point, leading to the rapid sublimation observed in the image. As the CO_2 changes to the vapor phase, bubbles form along the top surface of the cylindrical pellet. The image shows a cloudy fog contained within each bubble. The fog is not CO_2, but rather condensed water vapor created by the extremely low sublimation temperature of the carbon dioxide.

The image also shows how the bubbles change shape as they accelerate towards the surface of the fish tank. As the bubbles move upward, they are subject to both buoyancy and drag forces. When the forces reach equilibrium, the bubble will be moving at the terminal velocity, which is a function of both the bubble radius and the temperature of the water. With a pellet length of 2in, the image shows the each bubble is ~1cm in diameter. Using this diameter, Reference 3 has experimentally shown that an air bubble will reach a terminal velocity of ~24cm/s. The bubble is obviously not composed of air in the image, but the velocity of a CO_2 bubble would be similar to air considering the constituent molecules. Using a velocity of 24cm/s and a characteristic length each to the bubble diameter, the Reynolds number of the flow is given by Equation 2.

$$Re = \frac{VL}{\nu} = \frac{.24(.01)}{1.004\times10^{-6}} = 2390 \qquad (2)$$

The CO_2 pellets used in the image were purchase in bulk at General Air Services & Supply Co. in Boulder. The water filling the fish tank was simply tap water without any dyes. The lighting setup for the image is shown in Figure 1. The fish tank was also surrounded by black foam board to provide a clean background. Preliminary images taken with ambient interior lighting gave poor results. The LED was then included to illuminate the bubbles from above, resulting in much brighter images. The red light bulb placed to the right of the fish tank gave the CO_2 pellet an interesting coloring effect.

The image field of view was approximately 4in in width and 6in in height, and the distance from the camera lens was ~12in. A Canon T2i digital camera with a 17-85mm focal length lens was used to take the picture. The focal length for the submitted image was 52mm. The original image was 3456 x 5184 pixels, and the final cropped image was 3264 x 5184 pixels. The aperture was set at f/5.6 with ISO 3200. The shutter speed was the most interesting aspect of the image capture process. About a dozen different shutter speeds were tried to see how they affected the bubble clarity. Overall, shutter speeds below 1/500s resulted in slight motion blur. As the shutter speed was increased, the clarity of the fast moving bubbles increased up to a point. Shutter speeds above 1/1000s did not show any increase in clarity, but they did reduce the amount of light. Therefore, the optimal shutter speed range for the lighting was between 1/500s and 1/1000s. The final image used a shutter speed of 1/640s.

Photoshop was used to slightly modify the original image. The original showed the back edge of the fish tank and slight reflections of the bubbles in the back pane of glass. These blemishes were simply removed using the clone stamp tool. The contrast was also slightly modified to increase the red highlights, but the change is only obvious when swapping between images.

Overall, I was pleased with the final image. My main issue with my image is the focus on the bubbles. After ~300 images, I could not achieve a crisp focus on the bubbles. I tried many different shutter speeds and ISO values to no avail. I would like to learn more about this process and how to improve my macro focus in the future. It was especially difficult considering I was using the rear LCD for manual focus instead of the optical viewfinder. The camera was placed on the table, so I couldn’t twist my head to look through the viewfinder. But the image still managed to show the physics of the sublimation process clearly. I like how the lifecycle of the bubble is shown, starting as a blob on the top of the pellet.

References

[1]Cengel, Yunus A. *Introduction to Thermodynamics and Heat Transfer*. New York: McGraw-Hill, 1997. Print.

[2]Barber, C.R. "The Sublimation Temperature of Carbon Dioxide." *BRIT. J. APPL. PHYS.* 17 (1966): 391-97. Print.

[3]Patro, Ranjan, Ira Leifer, and Peter Bowyer. *Better Bubble Process Modeling : Improved Bubble Hydrodynamics Parameterization*. Tech. Web. 08 Feb. 2011. <http://www.angelfire.com/ri/rpatro/research/Bubble/patroetal.pdf>.