Get Wet – Sublimation of Dry Ice
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Background:
This photograph was taken as the initial individual assignment for the Flow Visualization course offered at the University of Colorado, Boulder campus. The name of the assignment "Get Wet" refers to the nature of the requirements for the assignment; a picture must be taken of fluids (any combination of fluids or fluid phase states) that both demonstrates the phenomenon being observed and is a good picture[1]. The intent of this image was to capture the sublimation phenomenon that occurs when solid carbon dioxide, or dry ice (the term "dry ice" stems from the solid and gas phase properties it exhibits at atmospheric pressure with no liquid phase), is fully submerged in water, and to capture a view that clearly shows or demonstrates what this looks like. To find a suitable viewing angle in which this phenomenon was clearly visible a trial and error method was used.

Experimental Setup:
The setup of this experiment included a variety of simple and common household items. The background setup (Figure 1) consisted of a solid white serving dish (elliptical in shape with a major diameter approximately 2 feet long and minor diameter approximately 8 inches long), and a white paper curtain rising 9 inches from the surface of the dish.

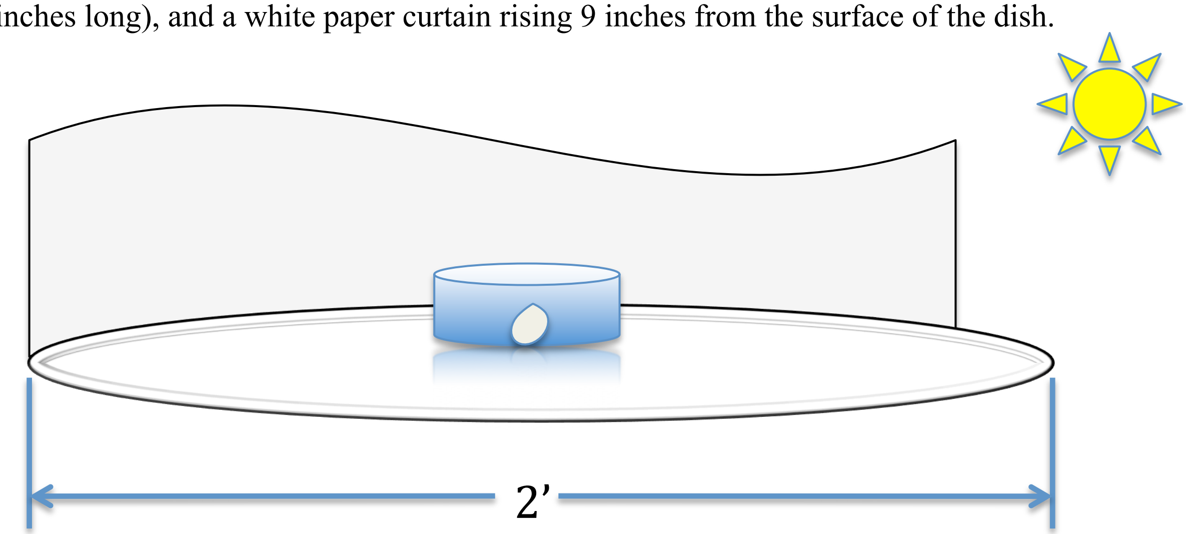

Figure 1 - Experimental Setup

In order to capture the sublimation phenomenon of the fully submerged dry ice, a circular clear glass container was placed on the serving dish and was filled with warm tap water (approximately 25 degrees Celsius). The dimensions of the circular glass container were 3.5 inches tall with a diameter of 6 inches and a wall thickness of .25 inches (Figure 2).

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[1] Hertzberg, Jean. *Initial Assignments.* Spring, 2011.
< http://www.colorado.edu/MCEN/flowvis/course/initialassignments.pdf>

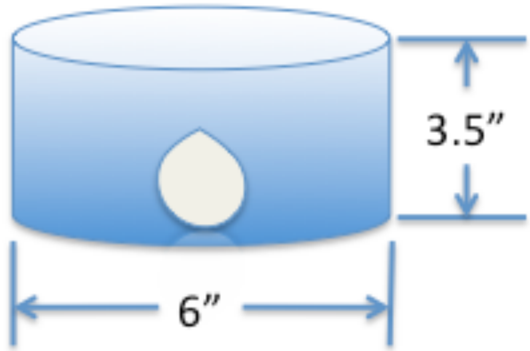

Figure 2 - Glass Container Dimensions

The lighting for this experiment was entirely natural coming from the right-hand side of the setup and reflecting off of the white dish and paper to increase the brightness of the image (Figure 1). A series of burst images were taken 6 inches from front of the container with the following specifications:

1.) Exposure time: 1/1250 second
2.) Focal Length: 10.12 inches
3.) F number: 8.8
4.) ISO Value: 800

The distance the picture was taken at was chosen because it was the closest location that captured the entire phenomenon that was to be observed. As for the other specifications, my “point and shoot” camera chose them automatically. The field of vision on the original photograph was approximately 3 inches. The original photograph (see Appendix A) had a bit of glare and some distracting components that needed to be edited out. The photograph was then edited using Adobe Photoshop; only cropping of components I found distracting were deleted and replaced with a solid black background. A collage of the same pictures with different color enhancements was added to emphasize the bubbles and add an artistic component to the photograph (see Appendix B).

Results – Explanation of the Phenomenon:

The phenomenon captured was the sublimation of solid carbon dioxide in tap water. The image shows a thin film layer of carbon dioxide gas surrounding the solid carbon dioxide (dry ice). At standard atmospheric pressures dry ice only exists in either a solid or gaseous form depending on temperature (Figure 3)[2]. The temperature at which these two phases can coexist at a specific pressure is referred to as the sublimation temperature. If dry ice is subject to a temperature greater than that of its sublimation temperature continual sublimation will occur.

In this scenario as heat is continually transferred from the surrounding tap water to the dry ice, sublimation occurs at a near constant rate assuming a constant bulk tap water temperature. This constant rate of sublimation creates a thin film of carbon dioxide gas over the solid dry ice. As the build up of this gas reaches a critical volume at points near the top of the solid it releases a bubbles of gas that travel to the surface.

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[2] Prof. Shakhashiri. “Chemical of the Week – Carbon Dioxide,” February 06, 2008 <www.Scifun.org>

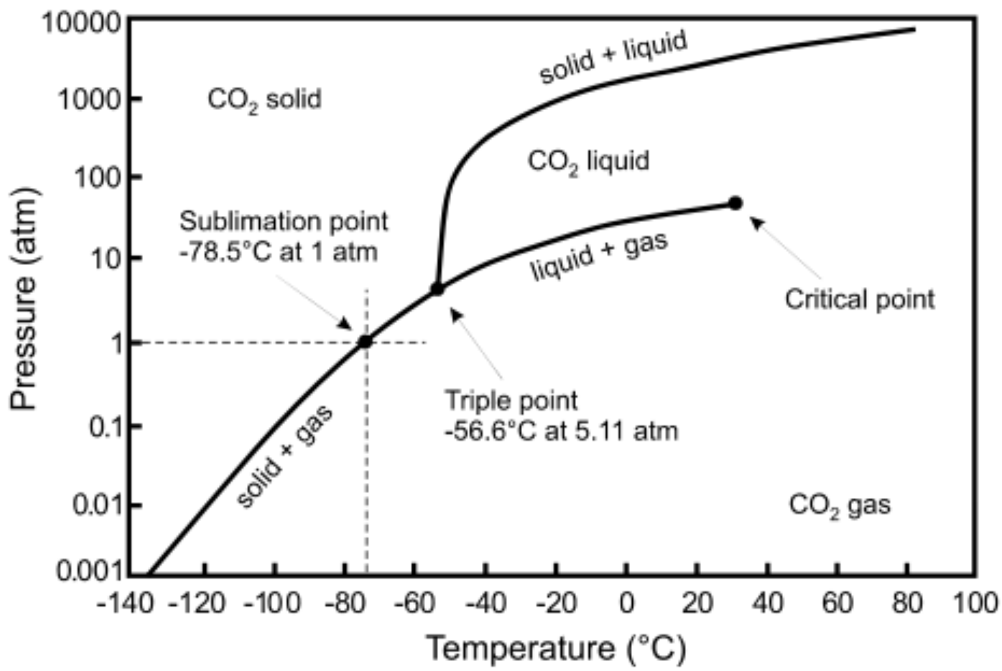

Figure 3 - Pressure - Temperature Phase Diagram for Carbon Dioxide

The temperature at which sublimation occurs for dry ice at pressures near 1 atmosphere (1atm) was investigated by Barber in 1965 and was determined experimentally to be 74.475 degrees Celsius with a an error of +/- .005 degrees Celsius[3]. As the gas is forced into the liquid buoyancy and gravity effects take over and force the bubbles from the dry ice film to the surface of the liquid. Dhir, Castle and Catton determined that the location and size of carbon dioxide bubbles rising from a solid flat slab of dry ice were directly related to the fastest growing Taylor wavelength of the system represented by a liquid boiling off of a flat plate (equivalent to the Taylor wavelength between two inviscid fluids of infinite length). The bubbles would be released in a square grid with a spacing of the Taylor wavelength in a two-dimensional view[4]. This could explain an observation that I made while taking the pictures; I noticed that it seemed like the ripples on the side the dry ice block were originating in the same location each time resulting in a staic looking ripple. Dhir, Castle and Catton were also able to determine the upward rising velocity of the bubble based on the thermal conductivity of carbon dioxide, k_g, the change in temperature, ΔT, density of carbon dioxide at sublimation, δ_g, and the latent heat of sublimation of carbon dioxide, h_{sg}, as shown in Equation 1. The velocity of the bubbles rising from the system described in this paper was estimated using this equation.

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[3] C.R. Barber. "The Sublimation Temperature of Carbon Dioxide," Standards Division, Middlesex National Physical Laboratory, September 30, 1965.

[4] V.K. Dhir, J.N. Castle, Ivan Catton. "Role of Taylor Instability on Sublimation of a Horizontal Slab of Dry Ice," ASME Journal of Heat Transfer Vol. 99, Pg. 412 (1977).

$$V = \frac{k_g\,\Delta T}{\delta_g h_{sg}} = \frac{\left(10.65\frac{\mathrm{mW}}{\mathrm{m\,C}}\right)(158.5\ C)}{\left(2.814\frac{\mathrm{kg}}{\mathrm{m3}}\right)(199.0\frac{\mathrm{kJ}}{\mathrm{kg}})} = 3.01\,\frac{m}{s} \tag{1}$$

The temperature of the carbon dioxide gas initially released due to sublimation is extremely cold (below the condensation temperature of water) and undergoes another heat transfer interaction with the surrounding water and the air at the surface of the water. As a result, the cold carbon dioxide bubbles rise and come into contact with the water and the air heat and energy is transferred out of the warmer components (the water and air) causing the gas to collect water condensate and form the white fog that appears at the surface of the liquid. Once this new gas is released from the liquid surface is descends through the air due to a combination of lower temperature and increase in density from the absorbed water vapor.

Discussion, Conclusion and Future Work:

This image shows the phenomenon of sublimation of solid carbon dioxide very well, and shows the clear boundaries between the fluid, gas and solid as I intended to show. It clearly shows that due to the temperature difference between the water and the dry ice surface that the sublimation temperature is constantly reached creating a nearly constant layer of carbon dioxide gas. There are a few things that I would change or try to highlight if I were to attempt this experiment again; lighting, color and shape of dry ice block. Although the lighting in the picture isn't horrible, it looks as if the gas film on the right side is different from the film on the left. I would like to take the image with the light entering either directly from above or below to try and get a symmetric lighting scheme. The colors of the photo (the one that was not edited using Photoshop) showed good contrast but also emphasized darker elements anywhere in the room. I think a darker background and correct lighting could have produced a much better effect. After reading the study by Dhir, Castle and Catton I would really like to try it out myself and submerge a flat block of dry ice in water to measure and observe the locations of the bubble release. Another extrapolation of this experiment I would like to attempt would be to view how a more viscous fluid like a vegetable oil effects the sublimation of dry ice, and whether the findings in Dhir, Castle and Catton's study hold true in that case as well.

APPENDIX A - Original Photograph (2844 x 2594 Pixels):