Flow Visualization

MCEN 5151, Spring 2011

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Team Project 3

5/4/11

Dry Ice: Sublimating underwater, Forming a Cloud of CO_2, and CO_2 gas spilling over an edge.

Purpose: The objective of this image was to use dry ice as the focus and capture as much physics as possible. This was accomplished by placing a piece of dry ice under water, capturing it sublimating, and having the of gas cloud spill over an edge. Although the set up seams simple it creates an senario in which a lot is happening. First the piece of dry ice is sublimating and forming bubbles. Those bubbles are buoyant and rise to the water's surface where there water's surface tension is not enough force to contain the gas and they burst. The gas originally contained in the bubble then released into the upper area of the container. This gas being denser than air remains contained in the container until CO_2 fills the upper portion of the container. Then the cloud spills over the edge. The image shows this in profile. This set up draws light on to the physics of a cold and denser gas forming, floating, and sinking through other fluids.

Flow Apparatus: The flow apparatus used here was a square acrylic container measuring 3 inches to a side and 5 inches tall. Three sides of the container were opaque while the fourth side was clear. This created a window to see what was happening within the container. A different side was slightly lower than the rest and had a notch removed from its top edge. This directed the flow of the CO_2 gas in a relatively +controlled manner. Figure 1 shows a rough schematic of the container.

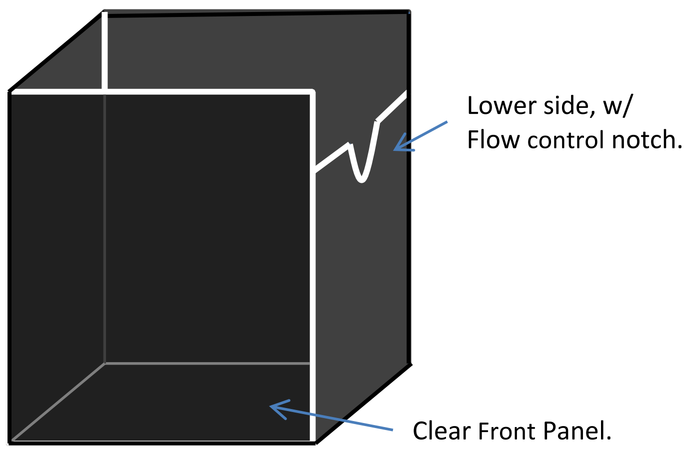

Figure 1, Artistic rendition of the flow apparatus.

Flow:

Background: Dry ice is a common term for the solid form of carbon dioxide (CO_2). At atmospheric pressures and temperatures, dry ice changes straight from solid to gas through a process known as sublimation.[1] This process is described in detail below. Even in gas form CO_2 is still denser than air. [1] Therefore the cloud formed by dry ice sublimation sinks to the lowest confined place. If not confined the CO_2 gas will eventually diffuse into the atmosphere. As the density due of CO_2

decreases, due to the increasing temperature, Brownian motion and diffusion driven gradients take over and spread the gas throughout the atmosphere.

CO_2 Sublimating: CO_2's triple point, seen in the phase diagram (figure 2) is positioned such that for standard pressures found in our atmosphere the material will change directly from solid to gas. This process is called sublimation. This phenomenon can be seen in figure 3, and is highlighted by circle 1. Sublimation is happening across the entire surface area of the piece of dry ice. The reason why it only appears to happen at the top is due to CO_2 buoyancy and the surface tension of the water. This is discussed with greater detail in the next section. The phase diagram below shows that at 1 atm CO_2 is solid below -78.51°C. [2] Above this temperature it is gas. When a material undergoes a phase change no matter if its from solid to liquid, or liquid to gas, or any combination of two of the three. The material undergoes a rapid change of density. Specifically for CO_2 under goes sublimation it goes from a density of $\rho_s = 1562 kg/m^3$to $\rho_g = 2.814 kg/m^3$. [3] This also corresponds to a drastic increase in volume. In fact the change in volume is equal to the inverse ratio of the densities, there for for going from solid to gas the change in volume is: $\frac{\rho_s}{\rho_g} = \frac{V_g}{V_s} = 555$, meaning the volume of solid CO_2 will be 555 times larger as a gas. [1]

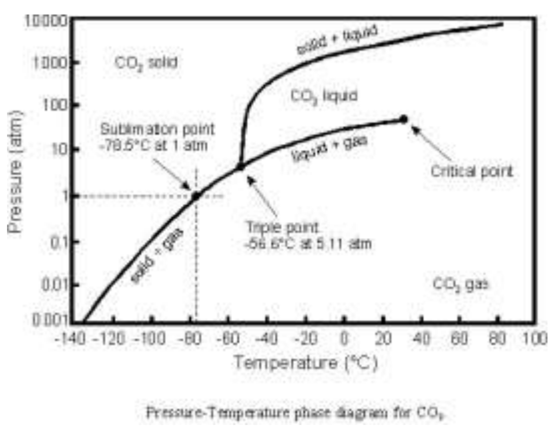

Figure 2, Phase Diagram or CO_2 [2]

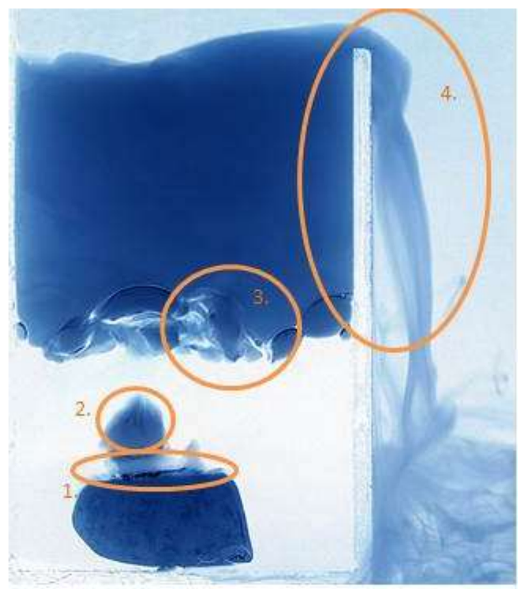

Figure 3, Highlighting different Dynamics.
1. Sublimation, 2.Bubbles of CO2, 3 Bubbles Bursting, 4. Gas spilling

Bubble Rising & Bursting: As discussed above, in standard states found in out atmosphere CO_2 does not melt, its sublimates. [1] This is even true when it is submersed under water (as shown in the image). Therefore the bubbles seen under the water's surface are 100% CO_2. The gas phase of CO_2 is about 500 times less dense than that of H_20. [1] This means there is a tremendous buoyancy force acting on the gas. However we also need to consider the surface tension of the water, which at the surface to the dry ice acts against the buoyancy force. Therefore small bubbles of CO_2 only move along the surface of the dry ice. Only when small bubbles join together to form a large enough bubble will the buoyancy force over power the surface tension. This event is highlighted by circle 2, in figure 3. It is a pretty trivial calculation to determine the approximated buoyancy force on a bubble of CO_2. This calculation is outlined below.

Approximating the bubble volume which is highlighted by circle #2 in figure 3 to be $V_{CO_2} = 3cm^3$ and letting g be equal to the acceleration due to gravity the buoyancy force the gas experiences in water for is:

$$F_{b\ in\ water} = (\rho_w - \rho_{co_2})V_{co_2}g = 0.029N$$

This is a huge force for such a little bubble and causes the bubbles to rise rapidly.

When the bubbles reach the surface of the water the bubbles burst. This is highlighted by circle 3, in figure 3. A bubble burst is caused by the internal pressure of the bubble overcoming the surface tension of the water. Because the bubbles are moving so fast there will be a lot of inertial contributions to the internal pressure. This is because when the bubble reaches the surface, the surface tension wants to stop the bubble propagation immediately. However the gas having some mass will want to keep going. Additionally, there is only a certain size bubble that water can form. The bubble circled in figure 3 by circle 2 is much bigger than this limit.

Cloud spilling: When the bubbles burst the CO_2 is released into the upper cavity of the container. The gas being more dense than air, $\rho_{air} = 1.1\frac{kg}{m^3} < \rho_{co_2} = 2.814\frac{kg}{m^3}$ will remained confined in that cavity until the cavity becomes full. Remember that the volume of gas produced by small amount of dry ice is very large. Therefore the amount of dry ice seen had no trouble filling the upper cavity. When the upper cavity was filled the gas then spilled over the edge. This is highlighted by circle 4 in figure 3. It spilled over because, again, the gas is denser than the air. We can calculate the buoyancy force on a similar volume of CO_2 as above.

$$F_{b\ in\ air} = (\rho_{air} - \rho_{co_2})V_{co_2}g = -5.043x10^{-5}N$$

First notice the negative sign, as anticipated from the image, the CO_2 will sink in the air. Second, notice the magnitude of this buoyancy force compared to that calculated for CO_2 in water. In air it is much smaller. Therefore we can conclude that the gas will sink in air much slower than it will rise in water. This is exactly what was witnessed.

Note, that the sinking of the CO_2 happened soon after sublimation. At this time the gas is cold and very dense. At about 15°C (~60°F) the density is approximately $1.87\frac{kg}{m^3}$. When the gas reaches this density diffusion and Brownian motion dominates over the negative buoyancy force. This is why we don't suffocate at ground level.

Interesting Fact: Earths north and south poles impose a constant magnetic field throughout the planet of. [5] At the poles magnetic fields range from micro- to milli-Teslas. This is unique compared to Mars, which has negligible magnetic poles, and gaseous planets like Jupiter contain have large magnetic field strengths. [5] Mars unlike Earth has no CO_2 at its poles while large gaswours planets have literally tons of CO_2. [5] This raised the question of whether magnetic fields increase the release of CO_2. [5] The study outlined in "Effects of Gradient Magnetic Fields on CO_2 Sublimation in Dry Ice" prove that in fact our poles is increasing the rate of CO_2 production on earth, (and gaseous giants) and directly affecting global warming and climate change. [5]

Visualization Technique: The image setup is as follows. The container was filled just under half with water. It was then placed in front of a black backdrop and underneath a table. This eliminated the excess glare from the above florescent lights. The camera was then positioned and focused on the front of the container. Then a large piece of dry ice was placed in the container so that it was close to the front, clear side of the container. Several camera shots were taken while the dry ice was sublimating. This image was chosen since it showed the most fluid dynamics. Then a lot of photo editing was done. First priority was to fix the image perspective. The container was made to appear square with the camera. Then the image was cropped to focus the viewer's attention on the flow. Colors were then inverted to try to bring out detail the regular image hides. Finally distracting image impurities like dots, lines and other distracting nuances were removed to give the final image seen below. Figure 4 shows the before edit and post edit, pre-edit is on the left, and post-edit is on the right. All editing was done in Adobe PhotoShop. Meta data for the image can be found in Table 1 below. This data corresponds to the camera settings and other original image data for the original image.

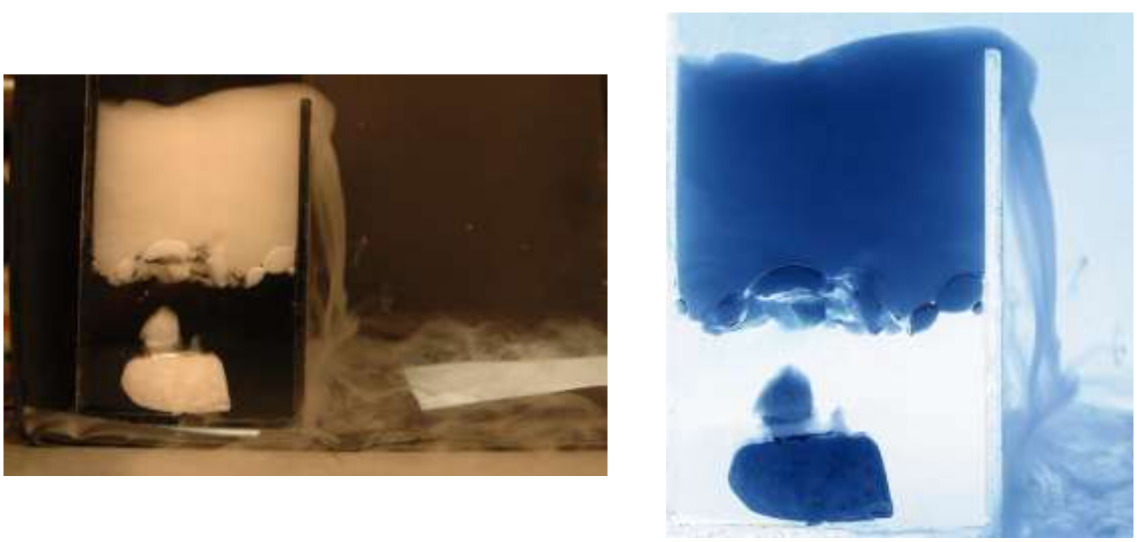

Figure 4, Left, Pre-edited photo. Right, Post-edited photo.

Image & Camera Info

Camera		Nikon D70s
Lens		35.0-80mm, 4/5.0-5.6
Shutter Speed		1/80sec
F-Stop		f/5.0
ISO		900
Focal Length		35mm
Pixel Resolution	x	3008
	y	2000

Table 1, Meta Data

Image: The final image shows a lot happening. The dry ice sublimating, bubbles filled with CO_2 are rising in the water and busting at the surface. The cloud of CO_2 fills the container's top portion. The gas then spills over the edge. As a focus piece of photography I personally found that dry ice to be a very frustrating medium to work with. Phenomenon surrounding dry ice is erratic and often unpredictable this is because there is so much involved. Several tries were taken of different container orientation, dry ice size, and water levels. I was never pleased with the images I captured. However after editing I am very happy with the results. I believe this image to portray the physics of the flow very accurately despite the perspective editing. The perspective change and all other photo editing was done very carefully not to take away or skew any information but to give the clearest and most esthetic image. As a final result I believe the image to be a good composition of a whole bunch of fluid dynamics shown in an artistic yet straight forward manner.

References

[1] X R Zhang, H. Yamagucho, M Masuda, “Study of the CO_2 Solid-Gas Two Phase Flow with Particle Sublimation and iIts Basic Applications,” American Institute of Physics (2008) 978-0-7354-0501-l/08 658-663

[2] Air Liquide, Gas Encyclopaedia, CO_2, http://encyclopedia.airliquide.com/Encyclopedia.asp?GasID=26

[3] Real Science. Theme: Twenty Ten Blog at WordPress.com. http://stevengoddard.wordpress.com/2010/09/05/the-freezing-point-and-the-dew%C2%A0point-part-2/

[4] Engineering ToolBox, Density of Air at 5000ft, Density of water. www.engineeringtoolbox.com.

[5] M. Iwasaka, “Effects of Gradient Magnetic Fields on CO_2 Sublimation in Dry Ice” Journal of Physics: Conference Series **156** (2009) 012029