Dry Ice Vortices

Image-Video 2
MCEN 5151-001: Flow Visualization
University of Colorado Boulder
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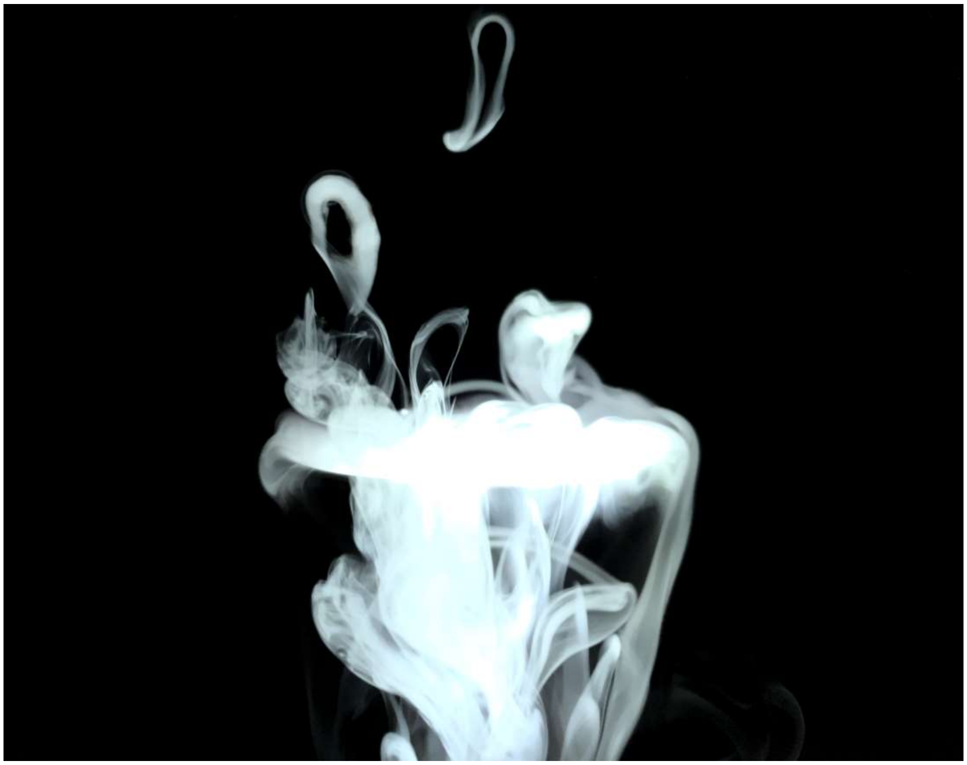

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1. Introduction

This report will outline the setup that enabled this image, discuss the fluid dynamics involved in this image, and describe the visualization and photographic techniques used to take this image. This image was taken for the Image-Video 2 assignment for the "Flow Visualization" course (MCEN 5151) at CU Boulder. The image shows the result of dropping a piece of dry ice into a coffee cup full of room temperature water. Once the dry ice contacted the water, it sank and started to release cold bubbles of carbon dioxide. These bubbles caused water vapor to condense and form the fog that can be seen in the image. Originally, I had only expected to image the fog pouring over the edge of the cup. However, there were the occasional vortex ring that kept jumping out of the cup. Therefore, I decided to try to time my image to capture one of these vortex rings and managed to capture this image.

2. Experimental Setup and Procedure

A diagram of the experimental setup can be seen in **Figure 1**. The coffee cup that the experiment was performed in was placed on a chair, with a black pillowcase on the back of the chair serving as a dark background. A flashlight was held about a foot above the cup to light up the fog. The camera was held to the side of and a little bit above the rim of the coffee cup. The experiment was performed in the following order. First, a piece of dry ice was broken off the main block by scoring with a knife and then hitting the block to break the piece off. Next, the cup was filled with warm tap water and placed on the chair. Then, the piece of dry ice was dropped into the cup. After a short period, the cup filled with fog and the effects pictured in the image began to occur. This is when the image was taken. After a few minutes, the piece of dry ice sublimated to a size where it floated to the surface of the water and very little fog was being created. The piece of dry ice was allowed to fully sublimate, then the cup was emptied of the water (which had noticeably cooled down) and then dried off. The experiment could then be repeated from the beginning.

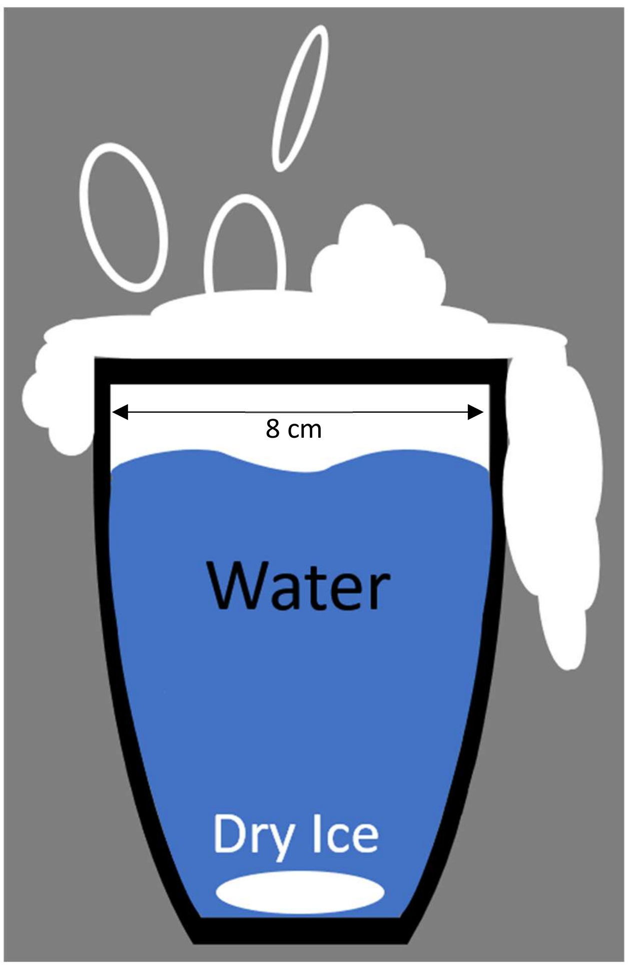

Figure 1 Diagram of the experimental setup.

Gavin Zimmerman assisted me in performing the experiment. He aided in breaking off pieces of the dry ice and held the flashlight above the cup to illuminate the fog.

3. Flow Discussion

An interesting fact of the flow being depicted is that the way in which the fog forms is a common misconception. Many sources that talk about the effect shown in the image say that the fog produced by this flow forms from the cold carbon dioxide gas mixing with the air and causing the water vapor in the air to condense. It is true that the fog forms from water vapor condensing to form a fog, but the water vapor in this fog comes from the water that the carbon dioxide traveled through and not from the air that it mixes with after it leaves the water.[2]

The vortices that can be seen in the image above the cup are a result of "the energy transfer by capillary waves generated at the moment of the [bubble] impact." [3] This means that when the bubble of carbon dioxide and water vapor meets the water/air surface, the interaction between these two surfaces causes the vortex to begin to form at the boundary line. Once the vortex has formed it is free to continue to travel past the surface and into the fluid, which in this case is out of the coffee cup. An interesting note is that these vortices can form in multiples. At a Reynolds number (Re) of <2,000 a single ring forms, at a Re >2,000 two rings form, at a Re >3,000 three rings form, and at a Re >5,000 four rings form.[3] The Reynolds number of a fluid flow is a parameter used to determine certain aspects of a flow. One of the most common ways is using it to determine how likely the flow is laminar or turbulent. The Reynolds number of this fluid flow is:

$$Re = \frac{uL}{\nu} = \frac{(0.32[m/s])(0.02[m])}{8x10^{-6}[m^2/s]} = 800$$

In the equation, Re is the Reynolds number, the number being solved for, u is the velocity of the fluid flow, L is the characteristic length, the size of the flow elements (2 cm is the approximate size of the vortex rings), and ν is the kinematic viscosity, a measure of the viscosity of the fluid (viscosity is a property of the fluid, and is 0.8×10^{-5} for carbon dioxide[1]). The Reynolds number at which a fluid flow transitions from laminar to turbulent can vary a lot. For fluid flow in a pipe, it usually happens around 2000 to 3000. Given that the Reynolds number of the fluid in the image is only several hundred, it should be almost entirely laminar. This is confirmed by looking at the flow in the image and seeing the long smooth flow paths of the fog.

4. Visualization Technique

The fluid flow was caused and visualized using dry ice. The dry ice would cause the fluid to flow by releasing gas through sublimation and the cold carbon dioxide released would cause water vapor to condense and form a fog that would allow the flow to be seen. The dry ice was purchased at King Soopers, but I forget to document the brand that produced the dry ice. The water used was tap water from Boulder, Colorado. The coffee cup used was the cup given out to CU Boulder spring 2020 graduates as a consolation for the graduation ceremony being canceled.

The experiment was lit up by a white LED flashlight held about a foot above the cup. This was done to provide sufficient lighting of the image since the exposure time needed to be dropped to a low value.

5. Photographic Technique

The main issue that arose in taking the image was that the vortices that were being imaged moved quite quickly. This forced the exposure time to be dropped significantly to not have a noticeable amount of motion blur, however this caused a significant darkening of the image. This darkening was countered by pointing a bright flashlight at the flow. This was chosen to counter the darkness because the aperture of the camera being used could not be changed and I did not want to raise the ISO much to avoid having too much noise in the image. The camera was held about 6 inches from the center of the cup, and the camera setting that the image was taken with were:

Camera:	Samsung SM-G960U (Galaxy S9)
Aperture:	f/1.5
Exposure:	1/500
Focal Length:	4 mm
ISO:	400
Width:	4032 pixels
Height:	3024 pixels

The image was edited using Darktable and had 4 edits performed. The first edit was noise reduction, which was done by the built in denoise function with the default settings. The second edit was an adjustment to the RGB curve, so that colors near black were set to pure black. This was done so that the small variations in the background cloth were removed and would not cause any distractions. The third edit was removing two spots in the background that were not black by copying two other parts of the background over top. The fourth edit was a minor cropping of the image, which was done to bring the cup closer to the center of the image. The unedited image of the flow can be seen in Figure 2 in the appendix.

6. Image Commentary

This image showed me a very interesting fluid phenomenon that I did not know existed. The vortex that form when a drop or bubble of fluid meets a boundary layer is an interesting interaction. Thinking back, I have likely seen this when a drop of food coloring is added to a glass of water and a vortex forms to help dissolve the food coloring into the water. I really like how the image turned out. The background ended up as a very consistent black and did not offer any distractions to the rest of the image. I managed to get quite lucky in capturing this image, as the vortices that came out of the cup only lasted for about a second before dissipating. This meant that I had to react quite quickly to determine if it was a vortex coming out of the cup and still capture the image before it dissipated. Most of the flow turned out well and you can see many of the details in it, however the part of the flow that the flashlight was directly illuminated ended up overexposed. Putting some kind of dissipative film in front of the flashlight would have greatly helped with that.

References

[1] Engineers Edge, (28 September 2020) *Kinematic Viscosity Table Chart of Liquids.* https://www.engineersedge.com/fluid_flow/kinematic-viscosity-table.htm

[2] Kuntzleman, T. S., Ford, N., No, J., and Ott, M. E. (2015). *A Molecular Explanation of How the Fog Is Produced when Dry Ice Is Placed in Water*. Journal of Chemical Education. https://doi-org.colorado.idm.oclc.org/10.1021/ed400754n

[3] Lee, J. S., Park, S. J., Lee, J. H., Weon, B. M., Fezzaa, K., and Je, J. H. (2015). *Origin and dynamics of vortex rings in drop splashing*. Nature Communications, 6, 8187. http://dx.doi.org.colorado.idm.oclc.org/10.1038/ncomms9187

[4] Sharp N. (27 June 2016) *Sublimation*. FYFD; https://fyfluiddynamics.com/2016/06/sublimation-is-a-transition-directly-from-a-solid/

Appendix

Figure 2 Unedited image of the flow