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MCEN 5151 Flow Visualization

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Team First Report: Snap-Freezing

I. Context & Purpose

Flow visualization is an observing technique that makes transparent fluid flow patterns more visible by using adjuncts like optical methods or dye tracers. Therefore, flow visualization is not only widely used in scientific analysis, but also important in the artistic field. In the Team First Assignment, Team Snap Peas considered researching a special physical phenomenon called snap-freezing. When pure water in a container is subjected to a cold environment at standard atmospheric pressure, the water sometimes does not freeze when the ambient temperature is below the freezing point, which is 0 °C (32 °F). Such water is known as the super-cooled water. In this case, shaking or impacting the container vigorously may cause the super-cooled water to freeze rapidly in a short period of time. This physics phenomenon is known as snap-freezing. We believed that snap freezing was a brilliant idea for the concept of fluid visualization, as the process of water freezing is visible and the ice structures formed have artistic elements. As part of the team, I decided to use the telephoto lens to record the process of water freezing and the beautiful structure of the ice as clearly as possible. I'd like to thank my teammates, Abhishek Raut and Alexandr Vassilyev. I acknowledge that they provided plenty of help and suggestions during the recording, like equipment setup and moving, and sharing experience about the production of the super-cooled water, etc.

II. Flow Apparatus

Figure 1. Recording scene

Some unopened bottles of distilled water, as pure as possible, were required for this assignment. When the temperature was just below freezing, condensation nuclei were needed for ice to form[1], so pure distilled water was difficult to freeze because it lacked enough heterogeneous impurities or particles to act as condensation.

First, if there were bubbles on the inside surface of the bottles, the remaining air at the bottle mouth was allowed to be absorbed by swirling the bottle. Second, these bottles were gently placed in the freezer and allowed to cool to the freezing point. This usually took about an hour and a half. The bottle was gently removed from the freezer, and placed in front of the camera. Then started recording, and the bottle was shaken vigorously to create bubbles in the water. If the water began to freeze, immediately place the bottle in front of the camera and keep it stationary for the recording. If the water did not freeze, follow the same steps as the first step to remove the air bubbles, then place the bottle back in the freezer for about 15 minutes and resume the attempt.

In order to understand the properties of the water during the moving of water, it is useful to calculate the Reynolds number of water:

$$Re = \frac{V_{avg} D}{v}$$

Where V_{avg} is the average flow velocity, D is the characteristic length of the geometry, and v is the kinematic viscosity of the fluid[2]. In this case, the average flow velocity was estimated to be 1.2 m/s by frame-by-frame analysis of the video: the video was recorded at 30 frames per second, and the water bottle was able to move about 12 cm in three frames, or one tenth of a second, during the shake, implying a velocity of 1.2 meters per second. For the tubular shape of the bottle, the characteristic length was the diameter of the bottle, which is 0.09 m. The kinematic viscosity of water at 0°C is 1.791×10^{-6} m^2/s[3]. Substituting the above values into the Reynolds number formula, the Reynolds number of the water at this point could be estimated to be about 60300. Under most practical conditions, the fluid exhibits a turbulent flow pattern of motion when the Reynolds number is greater than 4000. Therefore, when shaking the bottle, the water easily formed turbulence and involved the remaining air at the mouth of the bottle, creating bubbles under the influence of surface tension. This created condensation nuclei that allowed the water to freeze quickly.

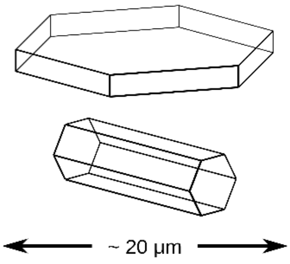

Figure 2. Two different kinds of ice crystals

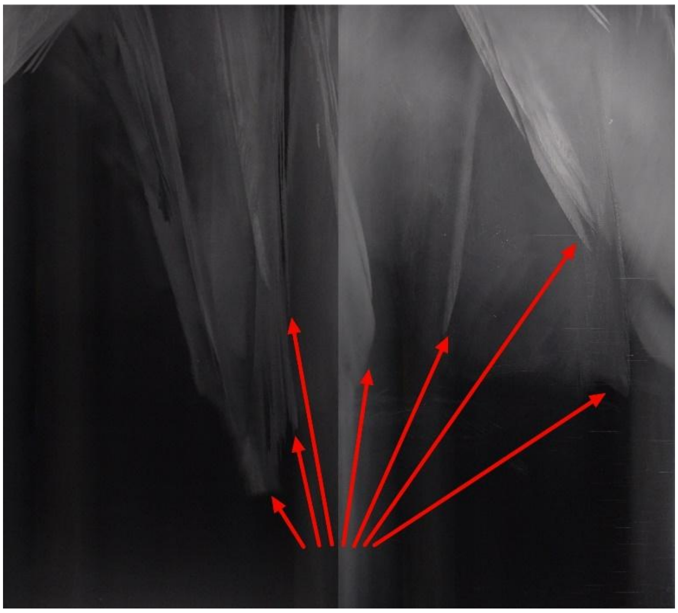

Figure 3. Freezing in single plane

Figure 4. Uniformly freezing

The crystal lattices of ice are hexagonal[4] as shown in Figure 2, which caused the water to freeze with some regular shapes that may result, such as feather or blade-like structures. After the end of shaking and the beginning of freezing, the turbulent flow of water still existed, which caused the ice crystals to have different hexagonal structures, such as thin hexagonal plates or tall hexagonal columns. Under the influence of turbulent flow, these ice crystals may grow in different directions in single planes, producing the very thin ice sheets seen in some attempts. As shown in Figure 3, the red arrows point out these different growth planes. If the turbulence in the water is small, the ice crystals may grow uniformly in all directions rather than in a single plane, and then the entire bottle of water is frozen uniformly from top to bottom, as shown in Figure 4.

When ice crystals formed, due to changes in density and structure, light is refracted as it passes through the ice structure, which is why water changes from transparent to conspicuously white as it freezes. This is the flow visualization due to the phase change of water without the additional colorant, which is very interesting.

III. Visualization Technique

Figure 5. Cleaned bottles and adhesive remover

Since the fluid visualization in this assignment actually relies on the phase change and refraction of the water itself, ensuring the transparency of the container and the setup of the external environment is particularly important. Large amounts of distilled water in bottles were used for this mission. To minimize interference, the manufacturer's labels factory labels have been removed by a specialized adhesive remover as shown in Figure 5. In addition, some detergents were uniformly rubbed on bottles prior to recording, which prevented liquefied water vapor from clinging to the surface of the bottles due to the low temperatures of the bottles.

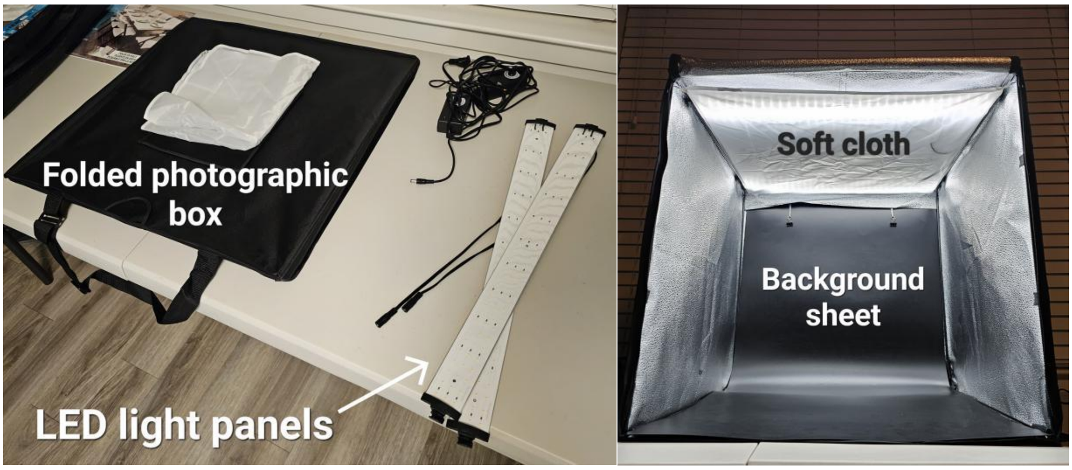

Figure 6. Photographic box

Like the previous assignments, the video was filmed in a standard photographic box as shown in Figure 6. Two long light panels full of LED beads at the top of the box. These provide lights in all directions that were uniform, bright, and their color temperatures close to sunlight. A soft cloth hanging below the light panels provided further light uniformity and prevented the various transparent or glossy objects placed at the bottom of the photographic box from clearly reflecting the annoying lamp beads. In addition, the camera box was equipped with a black background sheet to maximize the visual contrast with transparent water or white ice structures. The characteristics of the photographic box make it possible to observe the process of water freezing more clearly.

IV. Photographic Technique

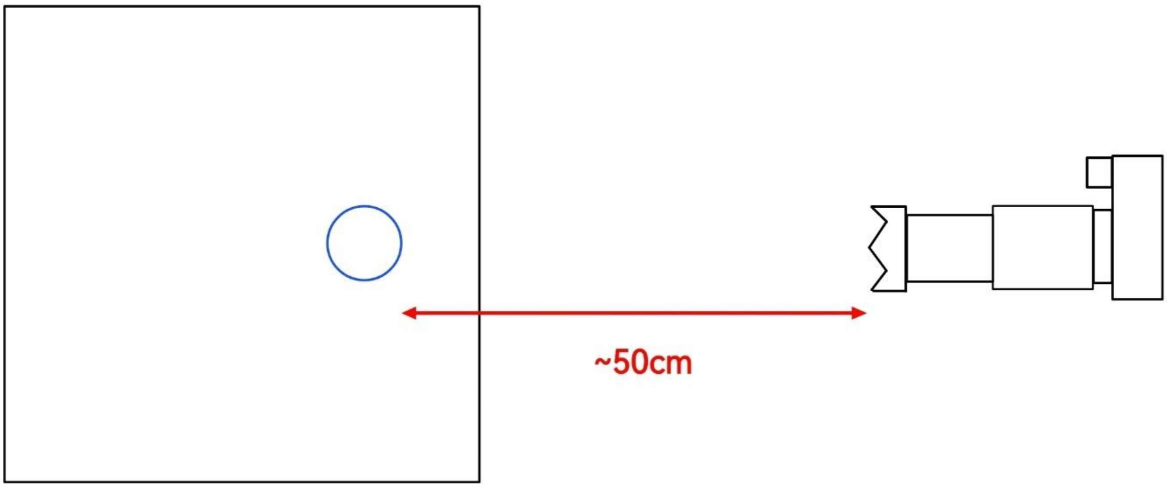

Figure 7. Recording Distance

The width of the edges of the photographic box and the backdrop is 60 cm. Therefore, it was necessary to limit the size of the field of view during recording, otherwise the walls on both sides of the camera box were captured. In addition, the smaller field of view also facilitates focusing on the freezing process of distilled water and reduces environmental disturbs. To limit the size of the field of view, a longer focal length is necessary. The lens of choice was the Tamron 18-300mm F/3.5-6.3 lens, an all-in-one lens that covers a wide range of focal lengths and field of view from wide-angle to ultra-telephoto. The camera used was Sony's ZVE-10 mirrorless digital camera with 4K 30FPS video recording capability, which is 3840 by 2160 pixels.

The camera was shot at approximately 50 cm from the bottle. The lens was set to a focal length of 200 mm, and due to the smaller APS-C size of the camera's sensor, it had a 35 mm equivalent focal length of 350 mm. The width of the field of view at this point is about 8 cm, which is close to the width of the bottle. It makes the water freezing process take up most of the video space, which allows for easy observation and greatly reduces the post-production work of the video. Since the bottle was placed vertically and water froze in a obvious top-down direction, the camera was placed vertically and the video itself was vertically too.

The water inside the bottle has a range of depths, which means that the ice inside the bottle is not at the same distance from the lens. Therefore, a relatively small aperture, f/10, was set to avoid unnecessary blur and bokeh and to make all the details inside the bottle as clear as possible. A mark also made at the bottom surface of the photographic box to memorize the position of the bottle. The focus and position of the camera were adjusted according to the position of the bottle. Due to the water freezes quickly, the camera starts recording before the bottle was shaken to capture all details and whole process of freezing. The mark on the bottom of the box makes it easy to quickly restore the position of the bottle thus avoiding the adjustment of focus and camera position during the recording process. The shutter speed was set to 1/125 second, and the ISO was set between 400 and 800, finding a reasonable balance between a large light gain and less motion blur. To ensure video quality, 4K 30FPS and a bit rate of 100MB/s were used, and the video was edited without any cropping. All the frame resizing was done directly through the zoom of the lens and controlling the place of the bottles. Finally, the works have a great sharpness and nicely display the details of the process of freezing the water.

V. Result

In this assignment, several clips of water freezing were recorded, and there were also some close-up photographs depicting the shape of the ice structure. Freezing behavior is difficult to predict and control, and it's clear to see that the water exhibited different shapes of freezing, some like snowflakes, some like feathers, and some completely freezing from top to bottom. These works provide a clear display of the physical phenomenon of snap-freezing and recorded the beauty of the shapes of these ice structures. That's what's so endearing about them.

The observability of the phenomenon was still the priority of this assignment, so photos and videos were taken vertically to observe as more of the icing process as possible. This decision has caused entanglements before, as a vertically displayed video might look strange on online media. However, audiences at the presentation did not consider this as a compelling issue, and they had indeed focused on enjoying the fascinating process of water freezing. Additionally, some pointed out that today's mobile media is growing rapidly, and vertical video just happens to be conducive to playback on cell phones.

In the future, I will probably try to make different super-cooled fluids and consider other factors that potentially affect the freezing of fluids, such as atmospheric pressure, mixing of solutions, volume of containers, and so on. I believe that these more in-depth experiments have helped me understand more about the science behind this physical phenomenon.

References

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[1] Heymsfield, Andrew J. “Ice Nuclei.” *Ice Nuclei - an Overview | ScienceDirect Topics*, www.sciencedirect.com/topics/physics-and-astronomy/ice-nuclei.

[2] Çengel, Yunus A., et al. *Fundamentals of Thermal-Fluid Sciences*. McGraw-Hill Education, 2017.

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[4] “Ice Crystal.” *Ice Crystal - Glossary of Meteorology*, glossary.ametsoc.org/wiki/Ice_crystal.

The background music for the video is *Pastorale* by Joel Cummins. The music was published by the author on YouTube Audio Library. YouTube Audio Library is a free music library that specializes in providing creators with royalty-free music. Therefore, my using this music for the video does not create a risk of copyright violations.