MCEN 5151: Flow Visualization

The Rope Coiling Instability in Water

Second Team Assignment

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For the fourth assignment in MCEN 5151: Flow Visualization, students were expected to again work in groups of 4 to produce the second team image. The idea again is to utilize the larger manpower provided by the groupsto generate more complicated and/or original experiments than would be possible with a single person. My group, consisting of Philip Latiff, Michael McCormack, Adam Sokol and myself, originally planned on capturing the rope coiling instability, which occurs when a viscous fluid is dropped from a significant enough height. When this is done right, the fluid will coil like a rope. We succeeded in achieving the instability, but the scale of the resulting "rope coil" was too small and we were not equipped with the proper lenses to capture the phenomenon. Because of this, we decided to continue with the rope coiling instability, but rather than drop the fluid onto a solid surface, we dropped it into water and observed the rope instability as the fluid fell into the water. Regular Elmer's glue was utilized as the viscous fluid to create this effect.

To capture this phenomenon, glue was dropped into a 15 gallon aquarium that was filled ¾ of the way with cold water. The tank was sitting on a 3ft high countertop. Black fabric was draped on the back and on the right side of the aquarium, and a light diffused with a white piece of paper was placed on the left side at a distance of roughly 2ft from the aquarium. Two cameras were used to photograph the effect. One of the cameras was placed horizontally about 2ft from the aquarium and filmed parallel to the water surface, whereas the other was placed at a lower height and angled 45^{O} above horizontal to photograph the surface of the water. The direct distance from the water tank to the second camera was about 1.5ft. Elmer's glue was dropped from a height of 3in to 1ft above the water surface and photographs were taken as the glue contacted and penetrated the water. **Figure 1** depicts the experimental setup, excluding the black fabric on the left side of the tank, because including it in the diagram would cover up the inside of the aquarium.

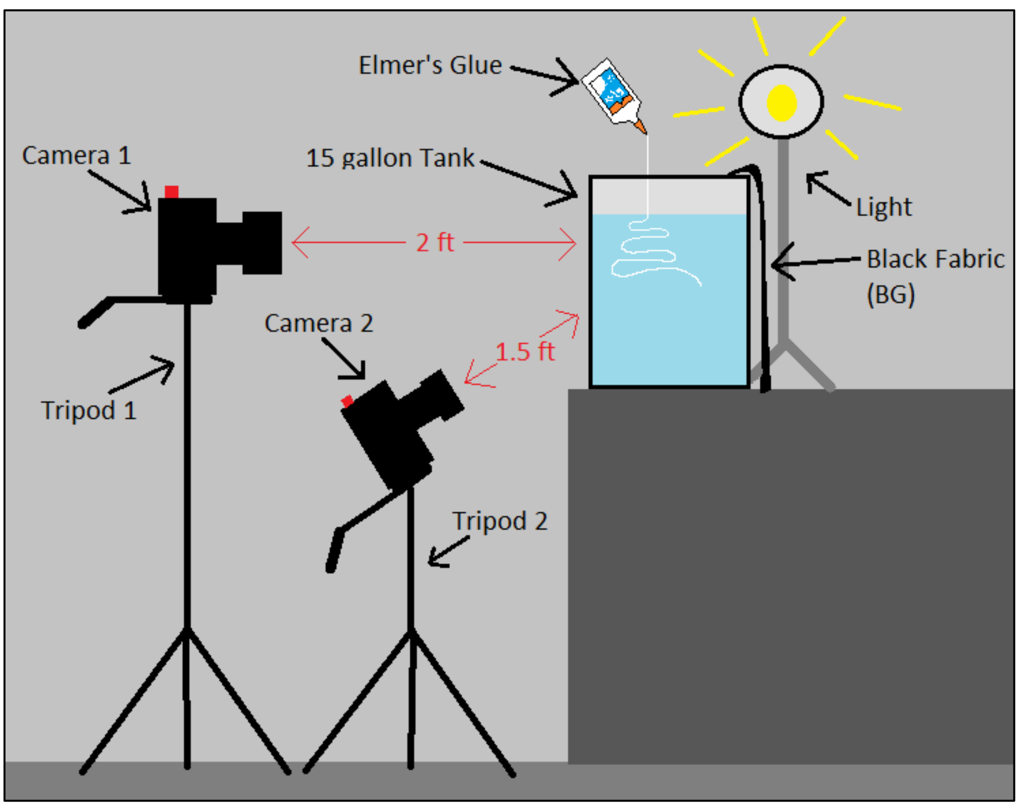

Figure 1: Experimental setup for rope coil instability experiment

Due to the relatively high viscosity of glue when compared to water, a phenomena known as the liquid rope coiling effect was observed when the glue was dropped into the water. Traditionally, the effect is conducted by dropping a viscous fluid onto a rigid surface from a sufficient height, which generates a thin liquid 'rope' coil (**Figure 2**).[4] This instability was recognized as a buckling instability by Taylor in 1968, and it is analogous to beam or column buckling under an applied load.[3] The coiling is caused by a balance between the rotational inertia and the viscous forces on the fluid as it falls, which causes the fluid to continuously wrap around on itself and build a coil tower.[3] The height of the fluid is a key factor, and there is a critical fall height associated with the onset of coiling, which varies depending on the fluid being used. Varying the fall height above the critical fall height will cause the frequency of the coils to change. The ability of a fluid to coil depends on a few parameters, which include the fluid viscosity and density, the fall height and the flow rate of the fluid.[1] Depending on what these parameters are, different regimes of liquid coiling can be observed. In total, there are three regimes of coiling: viscous, gravitational and inertial.[3]

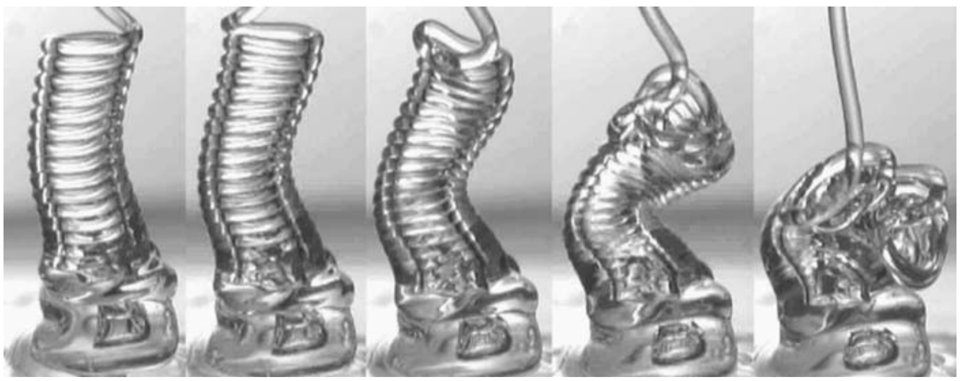

Figure 2: Depiction of liquid rope coil followed by buckling[1]

In our experiment, we did not observe viscous coiling on rigid surfaces, but instead looked at the rope coiling effect in water. This is because the rope coils achieved, like the ones seen in **Figure 2**, were only a few millimeters in diameter and less than a centimeter tall. When a viscous fluid is dropped from a critical height above water, we can look at a different case of this effect where the viscous forces and inertial forces become unbalanced immediately upon impact at the water surface, causing the fluid to whip around in the water chaotically. During experimentation, we were still able to see the rotational inertia causing the glue to swirl in the water, but because there was no rigid surface it did not build up a large coil and just danced wildly in the water. It was discovered during experimentation that the fall height is still very critical when conducting the experiment in water. If the height was not sufficient, the glue would not have enough inertia as it hit the water, and the effect will not be observed. In the case of this experiment on a rigid surface, if the height is insufficient, the fluid just collapses and creates a puddle. Because glue is about the same density as water, a "puddle" was created on the water surface when insufficient height was used. This puddle slowly diffused into the water, which clouded the tank and obscured images, and so to limit it we used cold water. Cold molecules moves slower and have less energy than fast water molecules, and so diffusion in cold fluids occurs slower than in warm fluids.[2] The photograph seen on the title page is actually an image of the aftermath of this experiment and shows a cloud of glue diffusing rather than the instability as the glue contacts the water surface.

An important question one might ask is whether or not the flow is laminar or turbulent as the stream of glue enters the surface of the water. In order to determine this, we need to find the Reynolds

Number, Re. Before we can find Re, a few parameters need to be determined and/or estimated. These include the viscosity, density, length scale and velocity. The viscosity of Elmer's glue is 10 Pa*s (kg/(m*s)), which is 4 orders of magnitude larger than water. The viscosity of the glue is about the same as water at 1.07 g/cm^3. Next, we have to estimate the length scale and velocity of the stream of glue. For the length scale, we need to determine the diameter of the stream, which I estimate to be about 1 to 2mm. Next, the velocity of the stream is desired. The glue made the 1ft high fall in about half of a second, which puts the velocity at 2ft/s. Converting to metric, we get a velocity of 0.6m/s. Now that we have all of the parameters, we can determine Re.

$$Re = \frac{\rho v L}{\mu} = \frac{\left(1070\,\frac{kg}{m^3}\right)\left(0.6\,\frac{m}{s}\right)(0.002m)}{\left(10\,\frac{kg}{m \cdot s}\right)} = 0.13$$

The transition from laminar to turbulent flow occurs at a Reynolds number of 5E5, which is much larger than the number found here. Because of this, we know that our flow is well within the laminar regime. Once the fluid enters the water, it appears to become chaotic, but this is not the same as turbulence. It is caused by the viscosity of the water, which is much greater than air, and it is the reason that the coils cannot form in water as they do in air.

This video is spatially resolved, with a shutter speed high enough to capture the fluid without motion blur. Once the fluid contacted the water, it slowed down drastically, making it easier to capture. It was still moving at a decent speed though, and so a shutter speed of 1/100 was chosen. A relatively high ISO was chosen due to the low light within the aquarium, but not so high that noise became a problem. The aperture was also chosen to increase the amount of light in the photo. An aperture of 5.6 provided a 12.5mm pupil diameter, which provided ample light to photograph the phenomena. The pixel dimensions are 4145x2663, which is 3 decades of resolution, and the field of view for the image is about 6 inches tall and 9 inches wide.

Table 1: Camera settings

Camera Body	Canon EOS Rebel T2i
Camera Lens	Canon EF 28-135mm IS USM standard zoom
Shutter Speed	1/100
ISO	800
Aperture (f-stop)	5.6
Focal Length	70mm
Pupil Diameter	12.5mm
Pixel Dimensions	4145x2663

Post processing was done using Adobe Lightroom and Adobe Photoshop. In Lightroom, the brightness, exposure and contrast were all increased significantly (10 to 20%) so that the cloud of glue became clearly visible. The image was also rotationally cropped to eliminate glare on the glass as well is a paper towel on the left side of the image (see **Figure 3**). The tint of the image was also changed to purple to add another level of beauty to the photograph. The addition of this color tint gives the photo a space-like feel, and I really liked that. To further enhance the color, the image was brought into Photoshop where the saturation, brightness and exposure were all again increased a few points. The contrast was also increased again slightly to make every detail in the glue cloud visible. A very soft vignette was also added to cause the viewer's eye to be drawn to the center of the image where all the detail lies. The final product can be seen on the title page, and the unedited photo can be seen below in **Figure 3**.

Figure 3: Unedited photo

I feel that the experiment was successful in generating a beautiful image, even though the original intent was not achieved. It also is a great illustration of the artistic and beautiful nature of fluid flow, because it is a photo of the aftermath of an experiment. In other words, the photo was essentially accidental, and it shows that even when one is not deliberately trying to make a flow beautiful, it will still occur. The post processing done on the image reveals a lot more detail than can be seen in the original image, and I think the addition of the purple tones make it much more interesting to the viewer. If I were to conduct this experiment again, I would definitely use a better lighting setup. I would also like to follow through with the original experiment and capture the rope coiling on a rigid surface rather than in water. Other than that, I am proud of the image and I do not think the image could have turned out any better.

References

[1] Habibi, Mehdi, Maniya Maleki, Ramin Golestanian, Neil Ribe, and Daniel Bonn. "Dynamics of liquid rope coiling." *Physical Review E* 74.6 (2006): Print.

[2] Iacopini, S., R. Rusconi, and R. Piazza. "The “macromolecular Tourist": Universal Temperature Dependence Of Thermal Diffusion In Aqueous Colloidal Suspensions." *THE EUROPEAN PHYSICAL JOURNAL E* 19.1 (2006): 59-67. Print.

[3] Ribe, N. M., H. E. Huppert, M. A. Hallworth, M. Habibi, and Daniel Bonn. "Multiple coexisting states of liquid rope coiling." *Journal of Fluid Mechanics* 555 (2006): 275. Print.

[4] Ribe, N. M., M. Habibi, and Daniel Bonn. "Stability of liquid rope coiling." *Physics of Fluids* 18.8 (2006): 084102. Print.