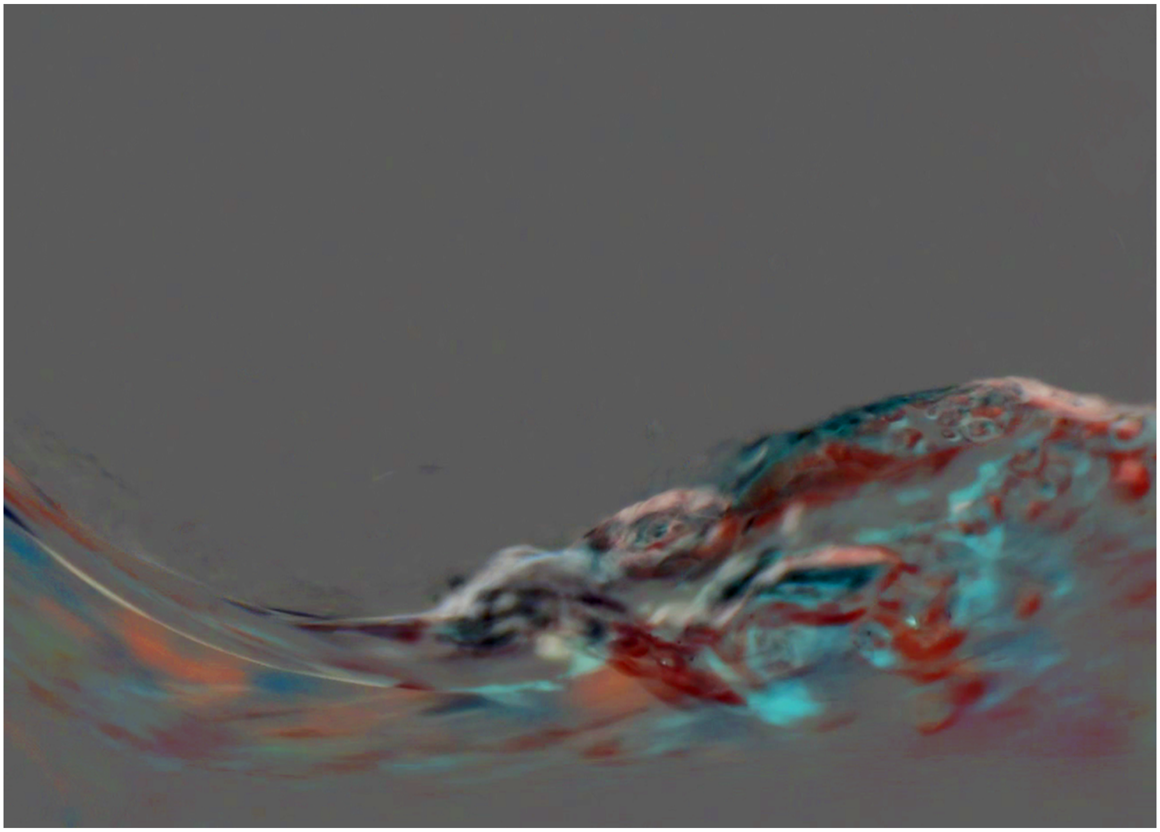

Hydraulic Jump

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Team Third Assignment
MCEN 5151: Flow Visualization
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1 Introduction

While experimenting with a variety of obstacles and flow phenomena using the flume at the university's Integrated Teaching and Learning Laboratory, my team was able to simulate a hydraulic jump. This fluid phenomenon is analogous to a shock wave in gas dynamics, where the properties of the fluid change rapidly over a very short distance. This phenomenon is also related to an adverse pressure gradient in the fluid flow, or a field in which there is a lower pressure upstream of the direction of flow. This visualization completes the requirements of the Team Third assignment for MCEN 5151: Flow Visualization. This setup was assisted by Rohan Malhotra, who started the flume and injected dye as I filmed the imagery. To enhance the artistic value of the imagery, the video was processed to show motion extraction of the turbulence. The goal of this video is to demonstrate a unique flow phenomenon in an artistically engaging format.

2 Flow Phenomena

The flow in this video demonstrates water experiencing a hydraulic jump in a canal. The flow is moving through a flume, or canal that closely simulates 2D flow. The flow hits a sinusoidal obstruction, which affects the pressure and velocity of the flow. At the end of the obstacle, the fluid is less deep and much faster than before. Further downstream, the water experiences a rapid change in pressure and velocity called a hydraulic jump. This is similar to the concept of a shock wave in gas dynamics, where the properties of fluids change over an instant in two dimensional flow. This hydraulic jump is initially far downstream in the flume, although it is pulled upstream over time until it reaches the lowest point of pressure. This is due to an adverse pressure gradient, where the direction of the pressure gradient opposes the direction of the flow. An adverse pressure gradient is a primary cause of turbulence in the study of fluid dynamics.

We may first examine the importance of the Froude number as it relates to a hydraulic jump. The Froude number relates inertia to external force, and is described as:

$$Fr = \frac{V}{\sqrt{g\,d}}$$

Through examining the individual frames of the clip, the velocity immediately after the obsticle is approximately 0.76 m/s and the depth is 0.025 m. Using these values, the initial Froude number is:

$$Fr = \frac{0.76}{\sqrt{9.81\,0.025}} = 1.54$$

We can relate the Froude numbers before and after the jump using continuity and momentum principals, as follows (Chanson, 2009):

$$\frac{d_2}{d_1} = \frac{1}{2}\left(\sqrt{1 + 8\,Fr_1^2} - 1\right)$$

$$\frac{Fr_2}{Fr_1} = \frac{2^{3/2}}{\left(\sqrt{1 + 8\,Fr_1^2} - 1\right)^{3/2}}$$

Using the first equation, we calculate the depth of the fluid after the jump as 0.044 m. This result is validated using the footage taken from the experiment, with minor discrepancies likely due to friction and air pockets affecting the depth.

To fully understand this visualization, it is important to examine the occurrence of an adverse pressure gradient. Since the flow is much faster immediately after the obstacle than it is downstream, we can use Bernoulli's principle to determine that the pressure is lower at the end of the obstacle than it is further downstream. This means that the pressure increases in the direction of flow, leading to a flow that is pulled upstream to the lower pressure. The velocity near the wall slows down because of the opposing pressure forces, while the momentum of the fluid continues to push forward. This leads to a turbulent boundary layer, where many boundary layer models break down. Although the fluid is unpredictable, it is not random as it still follows the conservation laws. Although there is chaos in this turbulent flow, Samuel and Joubert (1974) found that the flow near the wall still closely obeys this logarithmic model:

$$\frac{u}{u_\tau} = \frac{1}{\kappa}\ln(y^+) + B$$

The inner layer physics of this turbulent flow remain partially predictable throughout chaos. Although many other models break down in this turbulent flow, this may be an appropriate approximation for inner flow.

Although the turbulence in this video after the hydraulic jump is very unpredictable behavior, the general model of the hydraulic jump using Froude's number proves to be mostly accurate.

3 Visualization Technique

This visualization captures the motion extraction of turbulent flow after an obsticle in the flume. The flume setup is provided by the ITLL at the University; water is pumped from a tank, through the flume, and drained into the same tank. There is a place in the flume to hook an obstacle, where we placed a sinusoidal wave obstacle. The hydraulic jump occurs immediately after the sinusoidal wave obstacle. Additionally, we injected the flow a gel food dye to water dilution of approximately 1:50. The flow was injected using a syringe upstream, with a dilution of 20 ml per injection.

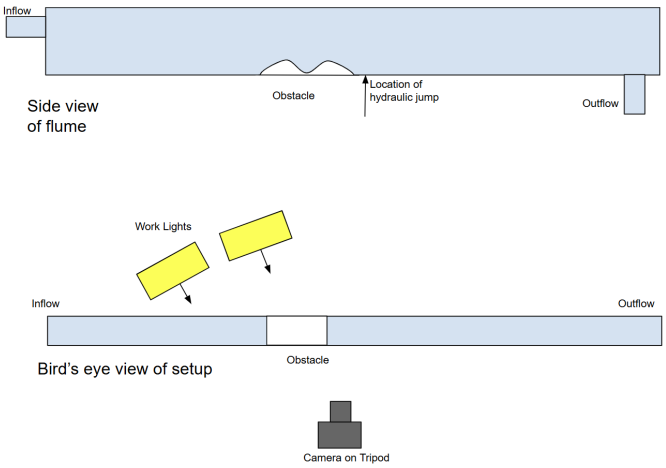

Figure 1: Diagram of flume setup.

Along with the overhead lights provided by the ITLL, this setup included two 500 Watt incandescent work lights placed behind the flume. These lights faced the camera directly, with a sheet of white copy paper taped to the backside of the flume to evenly diffuse it.

4 Photographic Technique

Captured using a Nikon D810 paired with a vintage Nikon film lens and macro attachment, this video provides close-up, high definition details of the flow. The Nikon D810 is a full frame sensor

DSLR, producing an image size of 7380 x 4928 pixels. The video is taken at a frame rate of 60 fps, although the final edited video only provides 30 fps. The lens used was a Nikon Lens Series E with a fixed focal length of 50mm and maximum aperture of f/1.8. Additionally, the Sakar Ultra Wide Macro Lens (SER VII) was attached to this lens, with a fixed focal length of 52mm. Shout out to my dad for having cool lenses from the 80s. The exposure was set as follows: ISO-320, F-stop f/Δ1, and shutter speed 1/125 sec. The aperture and ISO are relatively standard for these indoor lighting conditions, and the shutter speed was based on doubling the frame rate. I feel that the shutter speed was not fast enough, and resulted in imagery that is not time resolved. When looking at individual frames of the video, there is notable motion blur. When taking stills of the setup later in the experiment, I found that the camera needed a shutter speed of at least 1/8000 sec to isolate the turbulent motion. The field of view in the original image is roughly seven inches by five inches, and the camera was about six inches away from the subject. When looking at the image, the smallest visible bubble is 6 pixels by 8 pixels, or approximately 0.14 mm by 0.21 mm. This spatial resolution could be better for turbulent flow, although it is difficult to achieve any better without professional equipment. Manual focus was fixed on the middle of the canal using a ruler. The final video was developed using Photoshop, with a final size of 2100 x 1500 pixels. The contrast curve was adjusted to brighten the highlights and dim the shadows. To achieve the motion blur affect, the video was duplicated and edited. The top video was offset by one frame, and inverted with opacity set to fifty percent. This highlights any differences in the flow between frames. These edits add aesthetic appeal and beauty to the original, plain image, which is shown below.

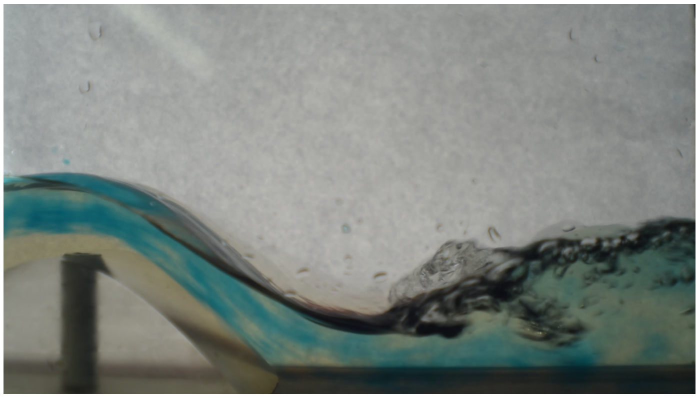

Figure 2: Unedited, original photograph

5 Artists Statement

The video discussed in this report is my favorite visualization so far. I am most proud of the controlled setup, as well as the post-processing enhancements. I think this is my most interesting work, both scientifically and artistically. Although I am very proud of this visual, the artist is never done critiquing herself. I would like to redo this experiment with a much higher shutterspeed to capture clear images of the turbulent flow. Additionally, I would like to re edit the video to contain a slow motion clip of the dye injection. Slow motion would enhance the visual understanding of the turbulence after the jump. Overall, I feel that this is a fantastic visual, and it is my greatest artistic work.

6 Citations

Chanson, H. (2009). Current knowledge in hydraulic jumps and related phenomena: A survey of experimental results. *European Journal of Mechanics B/Fluids, 28*(2), 191–210. `https://doi.org/10.1016/j.euromechflu.2008.06.004`

Samuel, A. E., & Joubert, P. N. (1974). A boundary layer developing in an increasingly adverse pressure gradient. *Journal of Fluid Mechanics, 66*(3), 481–505. `https://doi.org/10.1017/S0022112074000322`