A Trip Down the Flume

Image: Lana Pivarnik

Collaborators: Cole Smith, Kendall Shepard, Robbie Coop

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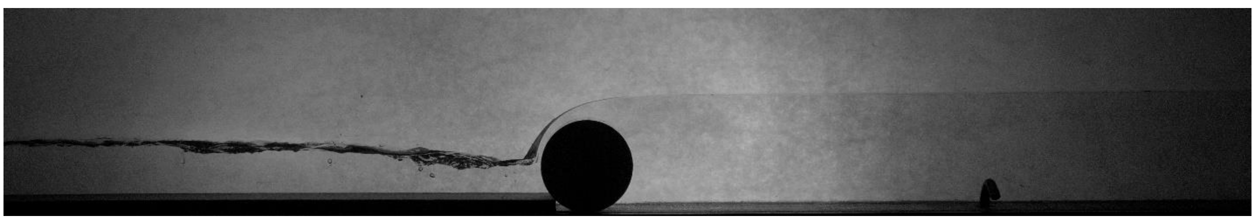


I. INTRODUCTION

For our next image/video, my team wanted to create an image with a wide aspect ratio. We wanted to capture a long flow. Initially, we were interested in how water flows through gravel underground, but when we remembered that CU's ITLL has a fluid flume, we immediately changed our focus. To use the flume, we needed some instructions from one of the engineers: after scheduling a meeting, we learned how to turn the pump on and off, how to add more water, and what could safely go into the flume. We gathered some metal and wood stock from the manufacturing center and placed them into the flume at various flow rates. I discovered that the flume is difficult to operate alone but fun with a group. Flumes are excellent tools to create measurable and controllable open-channel flows.

II. PHENOMENON

a. Setup

i. Flume

To prepare the flume, I turned the pump on and opened the valve up so that 4" of water flowed through the rectangular cross-section (3" x 16") of the flume. I let the water run for a little while to ensure the pump was working. Additionally, I tested different dye injection techniques so that about 50 drops of green food coloring was in the water. The flume operates in a closed loop, so anything that goes into the water supply stays in the water supply until it is drained and refilled. Hence, the water was a very lightly opaque green. From here, I put a 3" x 11" x 0.3" of wood into the flume so it lay flat on the bottom. It was held down with a large steel tube. Then, my teammate Cole put the 3" diameter x 3" tall cylinder into the flume on its side and it rested against the wood piece, so it was held in place. It blocked the entire flume. This created a visually appealing hydraulic jump.

ii. Lighting

Lighting in any basement is typically ugly. To help ameliorate the problem, we backlit the flume. First, I collected a roll of white butcher paper from the ITLL and lined the back side of the flume. Unfortunately, the paper was not very consistent and had a fair amount of differences with the amount of light it let through. Next, I gathered a few work lights from the ITLL and placed two of them behind the paper. The lights produced a cold white light which showed through the white paper and lit up the flume.

b. Flow

The image shows water flowing over a rapid formed by a cylinder followed by a hydraulic jump. Water flows from right to left in the image. The height of the water behind the cylinder (Location 1) is 5" and the height of the water immediately after the cylinder (Location 2) is 1.5". About 5" after the cylinder (Location 3), the water returned to a steady-state height of 3" and was less turbulent than the preceding 5". The section where the water rises from 1.5" to 3" is the hydraulic jump. To calculate the Reynolds numbers, I first use

$$Q = V * A$$

Where Q is the volumetric flow rate -- which is 10L/16s or .000625 m^3/s – and A is the cross-sectional area of the water – which varies between locations.

Table 1: Varying velocities for the different locations in the flume based on the changes in cross-sectional area.

Location	R_h	Area	Velocity
Location 1	5"	5" x 3" = 15 in^2 = .0097 m^2	.064 m/s
Location 2	1.5"	1.5" x 3" = 4.5 in^2 = .0029 m^2	.22 m/s
Location 3	3"	3" x 3" = 9 in^2 = .0058 m^2	.11 m/s

The Reynolds number is a measure of the turbulence where

$$Re = \frac{\rho V R_h}{\mu}$$

Where ρ is the density of the water (1000kg/m^3), V is the velocity (see Table 1), R_h is the hydraulic radius of the fluid in the channel, which can be approximated as the depth of the fluid (see Table 1), and μ is the dynamic viscosity of water at 20 C (0.25mPa-s). Using this, I can calculate the Reynolds numbers at each of the 3 locations listed above.

Table 2: Reynolds number is a function of the velocity and radial height of the fluid. This is shown at different locations in the flume.

Location	R_h	Velocity	Re
Location 1	5” = 0.127 m	.064 m/s	32.5
Location 2	1.5” = 0.038 m	.22 m/s	33.44
Location 3	3” = 0.076 m	.11 m/s	33.44

According to the Fundamentals of Fluid Mechanics, open-channel flows are laminar if they have a Reynolds number of less than 500. This is true in all cases in the flume, but visually this is not true in my image where Location 2 shows tendencies of turbulence.

i. **Rapid**

An energy transfer occurs over the rapid, where a change of height and velocity occurs. The location above the rapid has more potential energy because it has a higher water height and the location below the rapid has more kinetic energy because it is moving faster. This observation of the energy aligns with the differences in velocity seen in Table 2.

ii. **Hydraulic Jump**

A hydraulic jump is when water rises from a low height to a taller height, and can only occur when the flow is supercritical. The hydraulic jump occurs in a section of rapidly varied flow, where the flow becomes discontinuous. Energy is lost during a hydraulic jump, which is helpful in cases of dams where pre-energy loss values of the velocity could be damaging. Froude numbers are helpful in calculating the type of jump occurring, and a ratio of the height before and after describes this, as seen in Figure 1. Using the R_h values from Table 2, $\frac{y_3}{y_2} = \frac{3}{1.5}$, which equates to a Froude number of 1.7 and a wave type of undulant jump or weak jump.

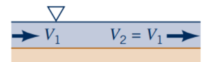
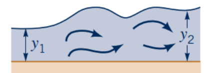
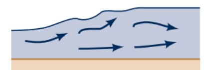
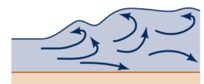
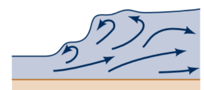
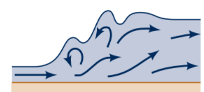
Fr_1	y_2/y_1	Classification	Sketch
<1	1	Jump impossible	
1 to 1.7	1 to 2.0	Standing wave or undulant jump	
1.7 to 2.5	2.0 to 3.1	Weak jump	
2.5 to 4.5	3.1 to 5.9	Oscillating jump	
4.5 to 9.0	5.9 to 12	Stable, well-balanced steady jump; insensitive to downstream conditions	
>9.0	>12	Rough, somewhat intermittent strong jump	

Figure 1. Classification of hydraulic jumps from their Froude numbers from Fundamentals of Fluid Mechanics (Munson).

The weak jumps and undulant jumps do not have as many vortices or as much turbulence as jumps with higher Froude numbers, which is also shown with the very similar Reynolds numbers from Table 1.

III. VISUALIZATION TECHNIQUES

Initially, we wanted to visualize dye going around an object, so we injected approximately 10 mL of green dye into the flume while preparing to take the image. This made the water slightly more opaque than water typically is, which is highlighted well in my photo. Since the photo is back lit, less light comes through the dyed water than through just the paper and glass. A distinct line occurs at the boundary between the air and the water, and this is what is visible upstream of the rapid. Two work lights were attached to a chair behind the flume so that the bright white light came through at the correct level. Ideally, more lights would illuminate the entire flume and not just the section being readily photographed.

IV. PHOTOGRAPHIC TECHNIQUE

This image was shot on a Canon EOS M50 digital camera with a Canon EF-M 15-45 f/3.5-6.3 IS STM lens. The aperture was f/4.5, the exposure was 1/4000, the focal length was 22mm and the focus distance was 1.08m. The field of view of the original image was 4' x 2.5' and the cropped image is smaller at 3' x 1.5'. I cropped the image to an aspect ratio of 1:6. The original image has a size of 4000 x 6000 px and the cropped image has a size of 3954 x 659 px. While cropping my image, I wanted it in black and white because I didn't particularly like the green color of the water, and I also wanted to brighten the overall image. The before image is supplied in Figure 2.

Figure 2. A before image showing the green water against the lit-up background of the photo

V. IMAGE

I find the image very appealing. I like how the steady state of the water is seen before and after the cylinder. I also think this image conveys some incredible fluid physics. The flow undergoes a rapid and a hydraulic jump. The physics is hard to fully grasp but can be calculated by any student who has taken a fluids class. I think that this is why this image would be incredible for the window wall for the MCEN department.

VI. APPENDIX

a. Bibliography

Munson, Bruce Roy, 1940-. Fundamentals of Fluid Mechanics. Hoboken, NJ :John Wiley & Sons, Inc., 2013.