Flow Around A Hot Wheels Car

MCEN 4151-001 Flow Visualization

Team Second Report

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Background & Introduction

Within the last 3 years I have become a big fan of Formula 1 racing. An important part of the Formula 1 race cars is how air flows and breaks around the car as it travels at speeds upwards of 330 kph. Understanding the airflow around the car is pivotal to extracting every ounce of downforce from the aero surfaces and features on the car. Being able to do this allows for an increased performance envelope and sequentially improves the pace of the car relative to the other 9 teams on the grid.

For my Team Second assignment I attempted to explore the relative fluid dynamics around a car using the flume channel provided by the ITLL. For our small scale experiment we used a Hot Wheels car to visualize the flow. This assignment was completed with the help of AJ Corne, AJ Terio, and Shane Maurry.

While our team was brainstorming ideas for the assignment we decided it would be a novel idea to inject dye into the system so we could see the streamlines of the water as it flows around the car. In practice, we were unable to do this because the water in the flume table is a closed system; meaning if we added dye, it would become enclosed and stuck within the system, unless we cleared and drained the system. For safe use of the flume channel, we completed general training with the Idea Forge staff.

The artistic and physical intent of my image, as depicted in Figure 1 below, was to capture the water breaking over the top of the blue Hot Wheels car, similar to that of a swimmer breaking from the water while swimming.

Figure 1: Water breaking over a blue Hot Wheels car as it travels down a water flume.

Methods

To help visualize the flow around a car, our team used the C4 Tilting Flume Channel in the basement of the ITLL. The flume channel is an enclosed space with a width of 3 inches, a length of approximately 38 inches, and a relative depth of roughly 8 inches. To constrict the flow within the system we use a "broad crested weir." Weirs are structures employed in the world of civil engineering whose purpose is for depth control and flow measurement of hydraulic structures like dams, reservoirs, or levies. For our experiment, our broad crested weir was a wooden block with a curved leading edge with a characteristic length of 13.5 inches. The weir was locked in place in the center of the flume channel using a metal rod on the underside of the weir. Refer to figure 2 below for a rough setup schematic of the system.

To secure the Hot Wheels car to the broad crested weir, our team decided to use small double sided adhesive sticky pads purchased from Target. I decided to use 8 of these sticky pads arranged in a grid pattern on the bottom of the car to prevent it from moving once the flume channel was turned on.

Once the physical set up was complete we turned on the flume machine and dialed in the volume of water we desired and let it run for several minutes to ensure steady state was reached.

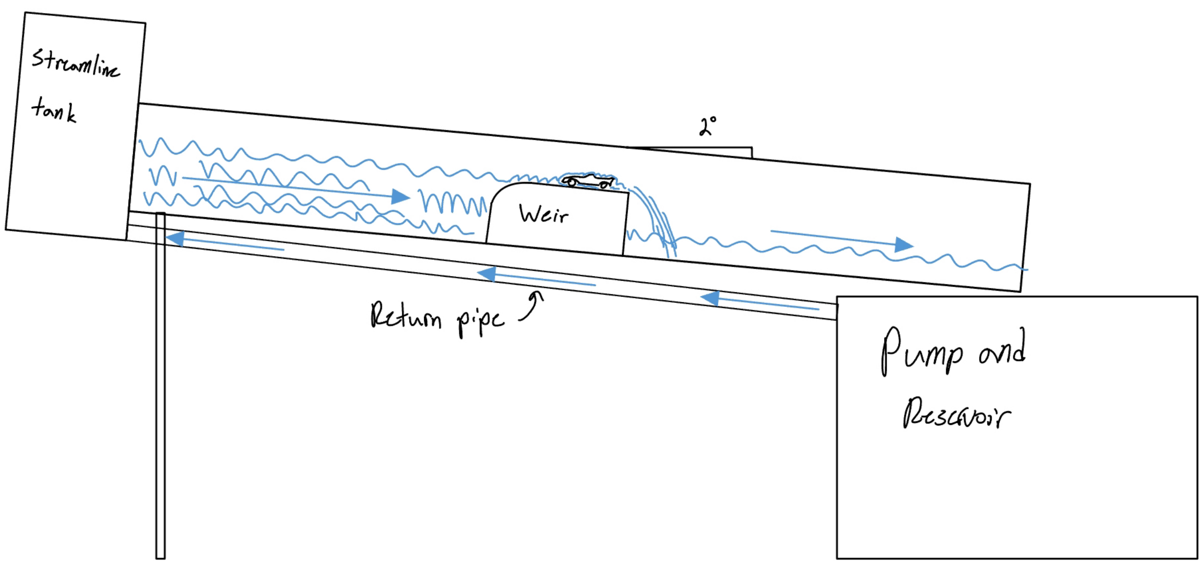


Figure 2: rough schematic of my setup

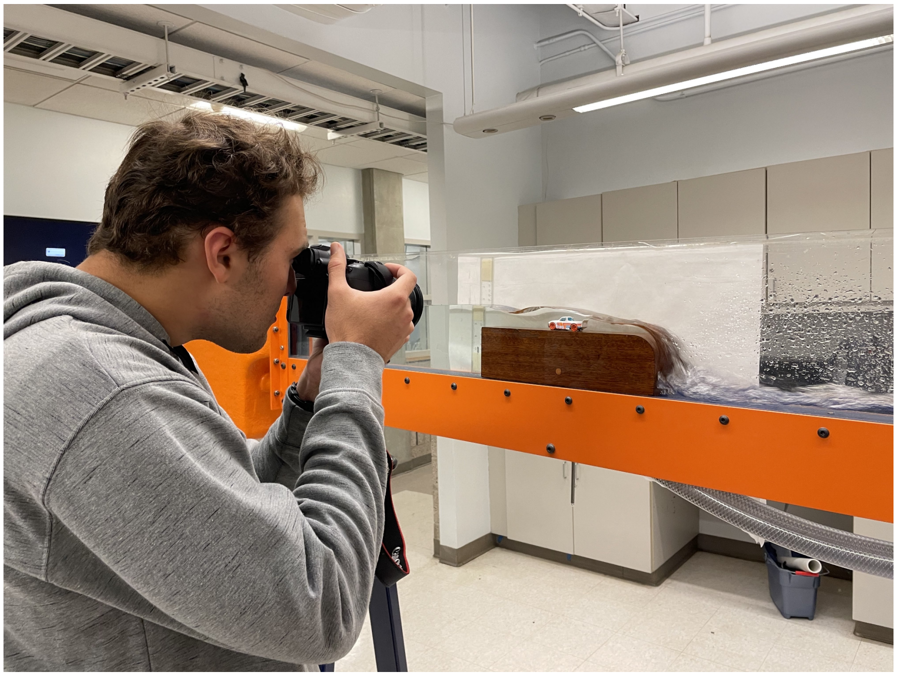


Figure 3: Image of Shane Maurry taking his photographs for his project.

Physics & Cloud Identification

The main fluid phenomenon on display is that of ‘open channel flows’. In hydraulics, the term open channel flow refers to the movement of a fluid in a conduit with a free surface open to the atmosphere. The driving force in open channel flows is gravity. This is the opposite to pipe flow in which the fluid is fully enclosed by the carrying conduit and the driving forces at play are pressure differentials. Real life examples are numerous and encompass both natural and engineered fluid conduits. Rivers, streams, culverts, and in our case, a flume channel are to name a few.

In 1890 Robert Manning, an Irish engineer, developed an empirical formula, as described in equation (1) to estimate the average velocity of a fluid flowing in an open channel.

$$Q = \frac{AR^{2/3}S_0^{\ 1/2}}{n} \qquad (1)$$

Where Q is the volumetric flow rate (m^3/s), A is the cross sectional area (m^2), R is the hydraulic radius (m), S_0 is the slope of the channel, and n is Manning’s friction coefficient for the surface of the open channel flow.

For my experiment, I calculated a water depth at the leading edge of the Hot Wheels to be ~0.5 inches, or 1.27 cm. Using the compass app on my phone, I found the slope of the channel to be 2° decline. This results in a 3.5% grade along the length of the flume. I determined Manning’s friction coefficient to be n = 0.009 for polycarbonate clear plastic [1]. The first row of Table 1 on the following page was used to determine the hydraulic radius of the system [2].

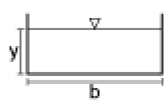
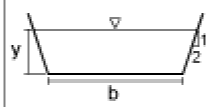
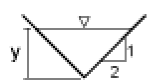
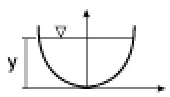
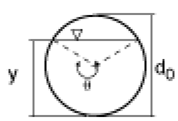
Channel type	Area A	Wetted permiter P	Hydraulic radius R	Top width T	Hydraulic depth D
	by	$\frac{by}{b+2y}$	$\frac{by}{b+2y}$	b	y
	b+2y	$b+2y\sqrt{1+z^2}$	$\frac{(b+zy)y}{b+2y\sqrt{1+z^2}}$	b+2zy	$\frac{(b+zy)y}{b+2zy}$
	zy^2	$2y\sqrt{1+z^2}$	$\frac{zy}{2\sqrt{1+z^2}}$	2zy	$\frac{1}{2}y$
	$\frac{2}{3}Ty$	$T+\frac{8}{3}\frac{y^2}{T}$	$\frac{2T^2y}{3T^2+8y^2}$	$\frac{3}{2}\frac{A}{y}$	$\frac{2}{3}y$
	$\frac{1}{8}(\theta - \sin\theta)$	$\frac{1}{2}\theta d_0$	$\frac{1}{4}\left[1-\frac{\sin\theta}{\theta}\right]d_0$	$2\sqrt{y(d_0-y)}$	$\frac{1}{8}\left(\frac{\theta - \sin\theta}{\sin\frac{\theta}{2}}\right)d_0$

Table 1: Characteristics of typical channel cross sections

Using equation (1), I determined the volumetric flow rate of the system to be 0.2233 m^3/s with a flow velocity of approximately 2.3077 m/s.

Photographic & Visualization Technique

This image was shot on a Canon EOS R6 Mark II mirrorless camera with a kit 24-105mm zoom lens positioned at a focal length of 54mm. The field of view of the image is 6 inches in width. This system uses no discrete additives like charcoal powder or food dye as a visualization technique and purely uses the water in the flume to help visualize the flow around the Hot Wheels car.

To freeze the relative motion in the flow, I decided to take short exposure shots. The exposure of an image is primarily tied to the shutter speed. In a sense, the longer the shutter remains open on the camera body, the longer light has to hit the sensor. To capture instant movement and in a sense 'freeze' the target in frame, shorter shutter speed speeds are often used. Examples of fast shutter speed action shots include photographing a Formula 1 race car flying around a race circuit, or the motion of a bird soaring through the air. These can often be shot at shutter speeds ranging from 1/125 to 1/500 of a second. Longer exposure shots, sometimes 20 to 30 seconds, are often used to take night shots of the moon or stars. I decided to use a fast shutter speed of 1/400 of a second. Choosing such a fast shutter speed allowed me to freeze the movement of the flow and use the burst mode on the camera to capture multiple images in quick succession.

Since this image was shot at such a fast shutter speed, no tripod was used to keep the camera steady. Because I decided to use a fast shutter speed of 1/400 of a second, I decided to use a medium aperture stop at f/7.1 to not blow out the image with too much light. This medium sized aperture stop constricted the amount of light able to enter the camera by closing the iris diaphragm. See figure 2 below for a pictorial representation of different aperture settings [3].

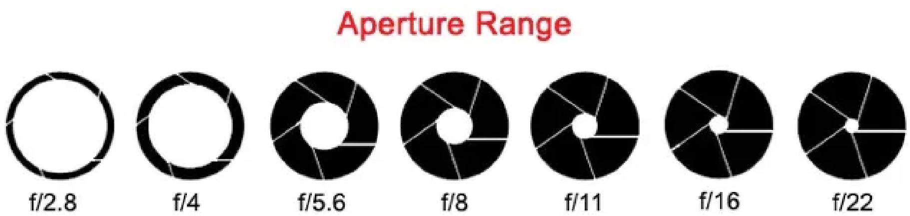


Figure 2: Pictorial representation of different aperture settings

The last setting that affects the amount of light the sensor can pick up is the ISO setting. This setting is directly tied to the camera sensor's sensitivity to light. Low ISO numbers means the camera is at its least sensitive setting. While high ISO settings can allow the camera to pick up more light by being more sensitive, it can often lead to image graining where the resulting image looks fuzzy. Sometimes this can be an artistic preference. For this project I decided to set the ISO at a relatively high value of 10,000.

The resulting image I decided to use for my project was shot at a focal length of 54mm at a focus distance of approximately 8 inches. This image was shot in the Canon native RAW format that is 6000 pixels wide by 4000 pixels tall.

I actually performed no post processing modifications to this image. The image fits the artistic intent I was aiming for and meets the course requirements for quality, focus, and pixel count. I believe there are little to no distracting elements in this image and as such no post processing was necessary. If I were to perform this experiment again I would take images at a lower ISO so there would be less graining in the image. To compensate I would add more light to the system.

The main source of light in this image was from overhead ITLL basement lights directly over the shooting scene. I also held my phone flashlight directly adjacent to my lens to increase the light on the viewed side surface of the hotwheels car. Since this image was shot during normal working hours, advanced lighting equipment could not be set up since other students and tour groups were in the ITLL at the time.

I determined that, using the following calculations, there was some motion blur in the image and that the image was nearly appropriately time resolved.

$$\frac{6000\,px\ wide}{0.1524\,meters} = 39370\frac{pixels}{meter} \tag{2}$$

$$39370\frac{pixels}{meter} \cdot \frac{2.3077\ meters}{second} \cdot \frac{1\ second}{400} \approx 227\ pixels. \tag{3}$$

Equation (2) calculates how many pixels in the image the flow moved during the exposure time. Using a field of view of 6 inches = 0.1524 meters, I calculated that the flow moving at 2.3077 m/s moved approximately 227 pixels during the exposure time. This value is approximately 3.8% of the total image pixel width. I would say that this is a considerable value and there is some motion blur in my image. To negate this, a faster shutter speed or larger field of view would be beneficial. I would say this image is spatially resolved given his fine resolution.

Conclusion & Future Notes

I believe the image and resulting revealed physics represents the principles of fluid mechanics and flow visualization I aimed to capture. Moving forward I would like to venture further into proper image lighting and composition. While I believe the image I settled on is able to convey the intended fluid mechanics I attempted to achieve, I also believe that there is plenty of room to improve. I would like to experiment with injecting dyes into the system to better visualize the streamlines as well as increase the overall lighting in the setup. Since this image was shot during normal working hours, advanced lighting equipment could not be set up since other students and tour groups were in the ITLL at the time. Overall I am pleased with this image and glad I got to use the flume machine to visualize my Formula 1 interest. I am eager to continue this new hobby of mine and I hope to get out there soon and capture my next flow!

References

[1] The Engineering ToolBox (2004). Manning's Roughness Coefficients. [online] Available at: https://www.engineeringtoolbox.com/mannings-roughness-d_799.html [Accessed 10 November 2023].

[2] "Fluid Mechanics Overview" *Stage-Discharge Relationships, a hydrologic science instructional module for NWS hydrologists*, NYS, https://kacv.net/brad/nws/lesson2.html

[3] Werner, Danielle. "Seeing in Depth of Field: A Simple Understanding of Aperture." *Digital Photography School*, Digital Photography School, 2015, digital-photography-school.com/seeing-in-depth-of-field-a-simple-understanding-of-aperture/.