Hydraulic Jump

Scott Schollenberger

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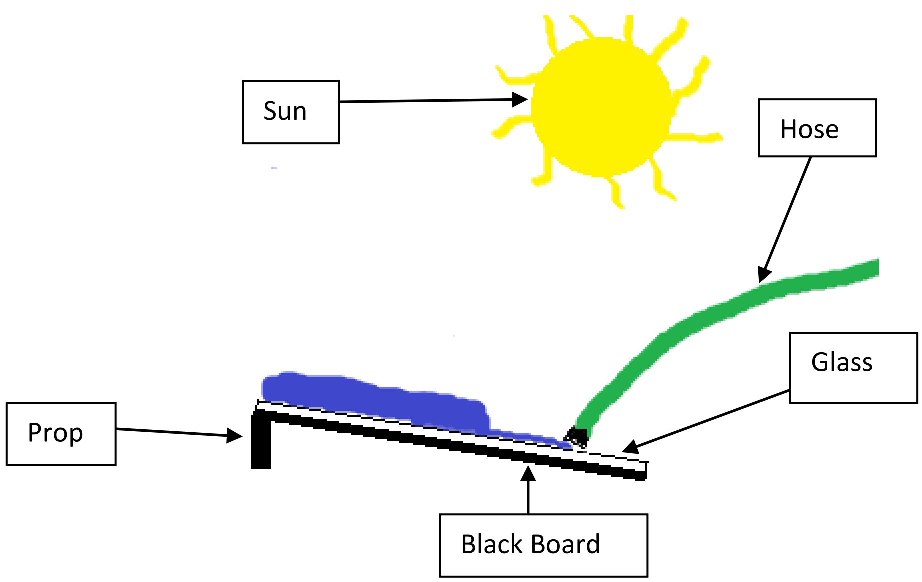
Introduction

The Hydraulic Jump image shown above was taken for the “Get Wet” project for flow visualization course. Hydraulic jumps are a common phenomenon that occurs when a relatively shallow fast moving flow enters a region in which the fluids high velocity can no longer be sustained. Hydraulic jumps are often seen in dams, spillways and even you’re kitchen sink. Because the velocity and energy of a flow decreases during a hydraulic jump they can be a useful engineered feature when building dams in order to decrease erosion or damage caused by the rapid flow.

The image for this project was achieved by flowing water from a garden hose onto an inclined sheet of glass. The image of the hydraulic jump was taken close up in order to illustrate the large difference in velocity of the flow prior to and after the jump. The objective of the work was to photograph and explain a common aspect of fluid dynamics that may often go overlooked and misunderstood.

Experimental Setup

The setup for this experiment was fairly simple. A sheet of glass approximately two feet long by three feet wide was propped up on one end by a rock to create approximately a 20 degree angle with the ground. Under the glass a black board was placed for color effects. The outlet to a running hose was the positioned near the surface of the glass. By positioning the outlet close to the glass the water exiting the hose was forced to form a high velocity thin flow. However, because the water was flowing up a slope, the fast moving flow was unsustainable and a hydraulic jump occurred. The experiment was performed outside during a sunny day for lighting purposes which allowed a fast shutter speed which minimized motion blur. The diagram below illustrates the experimental setup.



By varying the height of the prop and the distance of the hose from the surface of the glass, the point at which the hydraulic flux occurs could be varied. The camera angle used was about 20 degrees above the surface of the glass and of the same perspective shown above.

Visualization Techniques

The experiment was conducted outdoors during a sunny day. The sun was approximately 45 degrees above the horizon and the camera was positioned so that the sun was in front of the lens. The high light levels from the sun achieved two purposes. First it allowed for a low exposure. That being a fast shutter speed, low ISO and a large f-stop. A fast shutter was chosen to help reduce motion blur in the fast moving fluid before the jump. A low ISO was also desired for to decrease noise in the image and boost overall image quality. Finally a large f-stop was chosen to gain better depth of field. Even with the large f-stop the depth of field is still not large enough to capture the entire image in focus. This is due to the fact that the shot was taken close up and at a low angle so that even a relatively large depth of field is still insufficient to capture the entire image in focus. Listed below are the camera specs used.

F-stop = f/16

Shutter Speed = 1/250 seconds

ISO = 80

Focal length = 12mm

The sun also assisted in adding small amounts of glare to the ripples which helped define the texture water surface.

Fluid Dynamics

The formation of a hydraulic jump is governed by the transition between the states of a flow, and the state of the flow is determined by the Froude Number (Fr) shown in the below equation [2].

$$Fr = \frac{V}{(y*g)^{.5}}$$

Where:

V = flow velocity

y = flow depth

g = gravity

Initially the flow must be in a supercritical state, Fr greater than 1. This type of flow is generally very shallow and fast and will naturally occur on relatively steep slopes. If the conditions are such that the supercritical flow is unsustainable and the Froude number drops below one the flow will transition via a hydraulic jump into a subcritical state. Because the Froude Number depends on velocity a simple way to create a change in states is to slow down the flow making the supercritical flow unsustainable. This can be done by simply decreasing the slope surface that the water is flowing over. In the case of this experiment the water was flowing uphill and therefore losing energy and decreasing in speed. The initial speed of the flow can be estimated by the hose flow rate along with the thickness and area of the flow. Near the exit of the hose the flow is spreading out in the shape of a semi circle with a diameter of .457 meters and the following parameters [2].

Depth (y_1) = .01 m

Length of semi circle (L_c)= .0798 m

Flow rate = .000315 m^3

From this the velocity, V_1, near the outlet of the hose can be calculated.

$$V = \frac{flow\ rate}{area} = \frac{flow\ rate}{y * L_c} = 4 \quad \text{m/s}$$

However the depth and velocity above are the flow values near the hose outlet and are not the same as the flow where the jump occurs. To calculate the velocity, V_2, and the depth, y_2, of the flow right before the jump, the conservation of mass and momentum equations, shown below, are used [3]. The width of the flow for the area calculation is .35 meters, l_{c2}, which is the width of the glass used for the experiment. To simplify the equations linear one dimensional flow is assumed.

Conservation of mass:

$$V_1 * A_1 = V_2 * A_2$$

Conservation of momentum:

$$A_1 * V_1^2 = A_2 * V_2^2$$

The depth of the water, y_3, just before the jump is .00228 meters and the velocity remains at 4 meters per second. The Froude number is now calculated using the flow velocity and depth directly before the jump

$$Fr = \frac{V}{(y * g)^{.5}} = 27$$

The jump occurred because as the flow traveled up the glass slope it slows down according to the conservation of energy. The flow is also spreading out and becoming thinner which increases the Froude number. Because of this the supercritical flow leaving the hose is unsustainable and a transition from the supercritical to subcritical state occurred. Given a jump height, y_3, of .019 (.75 inches), measured during the experiment, and a flow width of approximately .35 meters, L_{c2}, a post jump velocity is determined, using the conservation of mass, to be .48 meters per second.

A Froude number greater than 9 indicates that a large jump will occur along with a significant energy or head loss. These losses are attributed primarily towards the creation of turbulence in the flow. This is opposed to momentum and mass being conserved in the jump. The equation for head loss is shown below [3].

$$Head\ Loss = \frac{(y_3 - y_2)^3}{4 * y_3 * 2}$$

Applying this depth along with the depth of the water after the jump to the head loss equation above yields a loss of .027 meters. An efficiency, η, can also be calculated [1]:

$$\eta = \frac{\left(1 + 8 * Fr^2\right)^{1.5} - 4 * Fr + 1}{8 * Fr^2 * (2 + Fr^2)}$$

Solving the above equation yields an efficiency of 10%. This shows how drastic of an energy loss a hydraulic flow can impose on a flow. Because of this a hydraulic jump is a useful feature when designing spillways and dams. In these structures the flow is usually very fast and therefore can be very erosive. To reduce the amount of erosion that the flow can cause to a given stream bed, dam or spillway the energy of the flow should be reduced. To do this the flow bed is engineered in such a way to impose a hydraulic jump on the flow. This can be done be simply decreasing the slope flow surface.

Conclusion

The photo taken for this experiment was a successful first try and was a good depiction of a hydraulic jump. If the experiment were to be conducted again more attention would have been paid to controlling the flow rate along with taking more careful measurements of flow depth. This would have assisted in being able to perform better calculations on the flow. Better background lighting would also be used as well as possible colored lighting to give better contrast to the flow.

References

[1]Bhutto, H, 1987, “Hydraulic Jump Control and Energy Dissipation”, Mehran University of Engineering and Technology, Chap. 2, PhD Thesis, http://prr.hec.gov.pk/Thesis/74.pdf

[2]Bengtson,H, 2010, “Open Channel Flow Basics – Hydraulic Jump Calculations”, Bright Hub, http://www.brighthub.com/engineering/civil/articles/55054.aspx

[3]Kundu, P., Cohen, I., 2000, “Fluid Mechanics,” Burlington, MA: Elsevier, 2008.