Flow Visualization
MCEN 5228

Assignment: Team Project 3
Presented To: Dr. Jean Hertzberg
Participants: Ben Bishop
4/29/09

The Flow Visualization course taught by Dr. Jean Hertzberg at the University of Colorado in Boulder integrates the physics of fluids with fine art in hopes of capturing flow phenomena through photography. “Team Project 3” was the sixth assignment of the course. For the project, students worked together (or individually if desired – as chosen in this case) to artistically visualize a flow of their choice. I worked individually to capture a natural flow phenomena I have always been captivated by: open channel flow. Open channel flow describe many flow fields in which the fluid is openly exposed to the atmosphere on one side and is channeled to a desired location; the most commonly recognized type being rivers. In taking this photo, I wanted to show the physics I was interested in through the abstract-shaped splashes the river creates as it weaves its way over falls and rough terrain. The photo, then, is the resultant water spray as it slips over the falls and collides with the moving water below; taken from the perspective of the river.

The photo was taken at Boulder Falls on April 25, 2009; a cold, drizzly day. From the city of Boulder, one can reach Boulder Falls by driving Westbound on Canyon Blvd. The falls can be seen on the left side of the road just on the far end of the tunnel. To capture the angle I wanted, I needed to be in the river. I was standing about four feet offshore, three feet from the base of the rightmost fall (looking at the falls) that creeps between two boulders. The camera was held seven inches above the water’s surface, angled upwards at a pitch of fifteen degrees to capture both the top of the fall and the roaring splash at its base. The splash ended up being approximately one and a half feet from the lens of the camera, while the apex of the waterfall was five feet away. Though it was getting dark as sunset approached, no light sources were needed besides the sun and the flash on the camera to achieve the full range of contrast. Figure 1 shows a schematic of the photographic set-up.

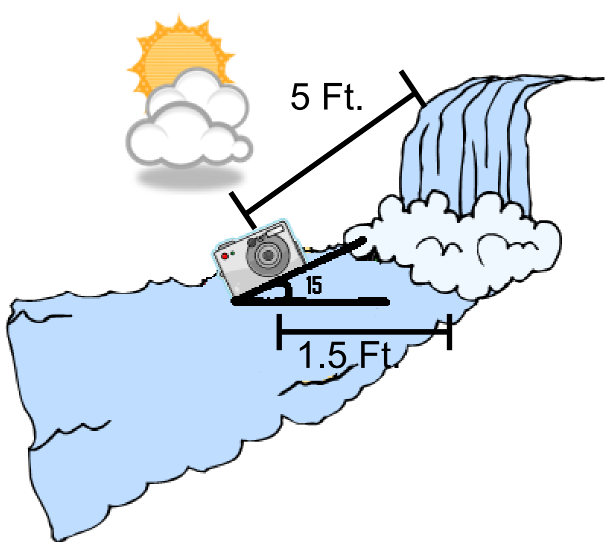

Figure 1: Schematic of Photo Setup and Dimensions

The difference between open flow and flow within pipes is that the former is under atmospheric pressure conditions. Its general characteristics are defined by the continuity equation: the change in storage of a system is defined by input-output. The flow rate, then, can be defined by $Q = AV$, where A is the cross-sectional area of the river and V is the velocity of the fluid at that point. Figure 2 shows a schematic of the velocity distribution of a channel, where the highest velocities are towards the center and the lower velocities are near the edges where friction is higher.

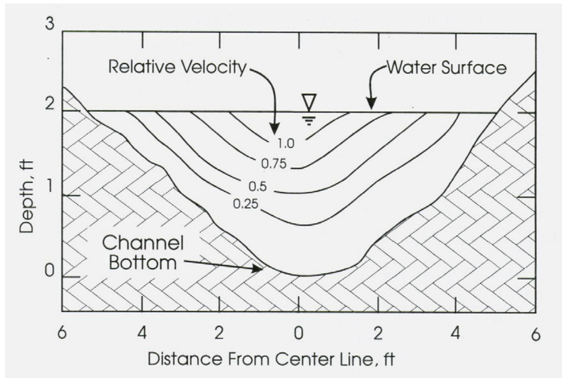

Figure 2: Velocity Schematic for Open-Channel Flow (Ward, 2008)

The velocity at any point in the river can be calculated using Manning's Equation:

$$v = \frac{1.49}{n} R^{2/3} S^{1/2}$$

found by Robert Manning, an Irish engineer, in 1889 (Ward, 2008). In the equation, v is velocity, n is the Manning's coefficient describing the roughness of the channel perimeter, R is the hydraulic radius equivalent to the cross-sectional area divided by the wetted perimeter, and S is the channel bed slope. By measuring channel widths and depths at various points along its length, one could determine the characteristics of the channel, finding the velocity, and therefore Reynolds and Froude numbers, at any given point along the length measured.

Manning's coefficient is approximated through experimental values, ranging from 0.01 to 0.9 depending upon the roughness of the channel bed. The following calculations were completed in order to find the coefficient for Boulder Falls so the flow characteristics could fully be described. At Boulder Falls, the approximated depth at its base was three feet, with an overall width of twenty feet at the surface and 16 feet along the bed. Approximating the area as a trapezoid, the cross-sectional area of that part of Boulder Creek would be <u>54 ft^2</u>.

The wetted perimeter is the length of the open channel fluid that is in contact with the channel; not the surface. Since the base of each segment is angled, it can be modeled as a hypotenuse to a triangle. Therefore the wetted perimeter is

$$P = \sqrt{w^2 + (d_2 - d_1)^2}$$

where w is the width of the segment and d represents the given depths on either side. P for Boulder falls is about <u>28.65 ft</u>.

The hydraulic radius, needed to calculate to Manning coefficient, is the cross-sectional flow area divided by the wetted perimeter calculated above.

$$R_h = \frac{A}{P}.$$

The hydraulic radius for this section is then 54 ft^2/28.65 ft = 1.88 ft. This shows how efficient the channel flow is. The greater the value, the higher the efficiency of the fluid flow. In real world situations, this equates to how well the channel moves and how likely it is to flood, with larger values decreasing the flooding likelihood. The low value of 1.88 seen for Boulder Falls shows that it has a high chance of flooding if a high volume of rain or runoff were to occur.

The flow rate, Q, can be approximated by estimating the average velocity of the river and multiplying it by the cross-sectional area. Estimating the flow velocity to be around two and a half feet per second through visual account, Q = 135 ft^3/s.

Estimating the slope of the river channel bed (the change in depth over the change in length) to be 0.002 as seen in other parts of Boulder Creek (Bishop, 2008), Manning's coefficient can be calculated from

$$n = \frac{C_o}{Q} R_h^{2/3} S_f^{1/2} A$$

where C_o is the constant seen in Manning's Equation equal to 1.49 for English units. For the area right below Boulder Falls:

$$n = \frac{1.49}{135 ft^3/s} * (1.88 ft)^{2/3} * 0.002^{1/2} * 54 ft^2 = 0.04 .$$

The Fundamentals of Hydraulic Engineering Systems textbook gives "natural channels with stones and weeds" n-values of 0.04-0.06 (Hwang, 1996). Its description matches that seen in Boulder Creek since it is a natural channel that is now in poor condition due to all of the excess rocks and sediment placed in it to create artificial habitats for fish. Also, the large boulders, themselves, create the falls. Therefore, an average flow rate of 135 ft^3/s is a reasonable guess for this section of river, and its value, along with the average velocity of 2.5 ft/sec, can be used to find the Reynolds and Froude numbers to describe the river flow.

The Reynolds number is the ration of inertial forces to viscous forces, given by

$$N_R = \frac{VR_h}{\nu},$$

where ν is the kinematic viscosity assuming standard conditions.

$N_R = \dfrac{2.5 ft/s * 1.88 ft}{1.69 * 10^{-5} ft^2/s}$ = 278,106 for the falls. This would be classified as turbulent flow since N>2000; expected due to the high turbulence and mixing seen within the water. The Froude number,

$$N_F = \frac{V}{\sqrt{gD}},$$

where V is the average velocity and D is the hydraulic depth, is used to determine whether the flow is subcritical or supercritical, with values greater than one symbolizing supercritical. Supercritical flow occurs when the flow velocity is greater than the wave velocity, creating the liquid equivalent to supersonic gas flow. For Boulder Falls, the Froude number = $\dfrac{2.5}{\sqrt{32.2 * 2.7}} = 0.27$. This flow is very subcritical, which is expected due to the collision of the falling fluids from the falls with the partially stationary fluid at its base with greater depth, slowing the overall flow rates. It is here, then, that the river has a higher specific energy than at critical depth (Bishop, 2008). These methods can be applied to any section of open channel flow to determine the roughness of the channel bed and the average velocities throughout its length. Breaking the cross-sectional area into smaller widths for calculations will result in minimized error.

For the photograph, no special visualization technique was used; the fluid was shot in its natural state in nominal conditions. The Sony digital camera used comes equipped with a flash range of (0.2-7) m wide x (0.9 to 5.6) m tall and a Carl Zeiss Vairo-Tessar 10x zoom lens. A digital Sony DSC-H10 was used to photograph the river at an approximate distance of 1.5 feet from the base of the falls. This distance created a field of view of two feet. The corresponding focal length for the image was 6.3 mm. These settings coupled with and aperture value of f/3.5, a shutter speed of 1/13 s, an f-stop value of f/9, and an ISO speed rating of 125 created the original image brightly lit by both the flash of the camera and the sun. With this shutter speed and a velocity of 2.5 ft/sec, the water could have moved 0.19 feet within the time it took to fully expose the shot. This gave the falls in the background a blurred image, very artistic in appearance. The original image began with pixel dimensions of 3264 wide x 2448 high. It was later cropped in Adobe Photoshop to overall dimensions of 2262 pixels wide x 2274 pixels high. The image was converted to black and white to remove the yellow-brown color of the water and to heighten the contrast and dramatic occurrences happening between the splashes and the falls in the background. Photoshop's curves function was used to gain a full range of contrast within the photo. The water edges were brightened and the surrounding area darkened with the same function, allowing the abstract shaped of the splashes to pop from the image. Glare occurring from the flash and the sun on the water's surface was later removed with the clone stamp function.

Overall, this photo is much better than what I set out to achieve and I was very pleased with it. Originally I had wanted to capture open channel flow through a simple black and white image of the river from a distance, much like river photos seen in museums and other public displays. When playing with the image in Photoshop, however, I found the splashes to be much more fascinating and reveal more physics than the river as a whole did from afar. This image is a unique twist to open channel flow in that is focuses on a small aspect of the big picture and effectively displays the abstractness and sheer power in an artistic manner. Changing the time of day to somewhere around high noon would have heightened the brightness of the splashes, hopefully allowing them to contrast better against the shadows of the waterfall; the one thing I would like to see improved.

References

1. Bishop, Benjamin T. “Boulder Creek Lab.” University of Colorado at Boulder – CVEN 3323. Pages 2-7. Boulder, Colorado. 2008

2. Hwang, Ned H. C. et al. Fundamentals of Hydraulic Engineering Systems – Third Edition. “Rainfall-Runoff Relationships – the Rational Method.” Pages 350-354. Prentice-Hall, Inc. Upper Saddle River, NJ. 1996

3. Ward, Andy. “Uniform Open Channel Flow.” The Ohio State University. www.streams.osu.edu/book/PowerPoints/chapter7.ppt. 2008