Flow Visualization

Get Wet Report

Written By:

John Goblirsch

Instructor:

Jean Hertzberg

2-7-2011

Introduction

Flow visualization is the capture of various elements of fluid mechanics through either still-image or video photography. This course, MCEN 5151, is designed to combine the artistic beauty of dynamic fluids with the quantitative physics that drive the fluid flow. Students are supposed to gain a greater appreciation of engineering through analyzing photographic works of art (or vice-versa, depending on the student's background). The "Get Wet" assignment is intended to get students started thinking about various fluid visualization techniques, different camera settings, and photograph set-up strategies. The restrictions on the assignment were very minimal, and each student could essentially choose any flow visualization image they liked. I decided to capture a ping-pong ball being shot from an angle into a glass of *Guinness Draught.* I wanted to capture the transition of kinetic energy from the moving ball to the still foam in the glass via the splash the ball creates upon impact. I chose *Guinness Draught* because of its notoriously light foam which gives it such a magnificent head, which turned out to produce a lovely creamy texture in the captured splash. The bubbles that form the head on a *Guinness Draught* beer are unique in their small size and nitrogen content, and have been examined by a previous student in this class (Duggan, 2009). The inspiration for the angled shot as opposed to a drop directly above came from the popular college game "beirut," where players take turns shooting ping bong balls into cups of beer (obviously!). I wanted to have some fun with this first assignment; trying to break the dichotomy between school work and college party games in a photograph that blended the two beautifully.

Image Set-up

This image was taken on a large wooden table with a plastic sheet lain on top for protection from the liquid. The backdrop used was a large white poster board for maximum contrast with the *Guinness Draught.* The lighting was created using two compact fluorescent light bulbs; one 13 Watt cfl on the ceiling directly above (approximately 4 feet from the glass), and one 65 Watt cf flood light with a dish towel filter cover placed directly to the right of the glass. The flood light was very mobile, and we tried moving it to various other locations and using various kinds of filters to get the best possible lighting for this image. In the end I decided that placing it to the right was the best location; however, the glass is highly reflective, which accounts for the small amount of visible glare seen in the image.

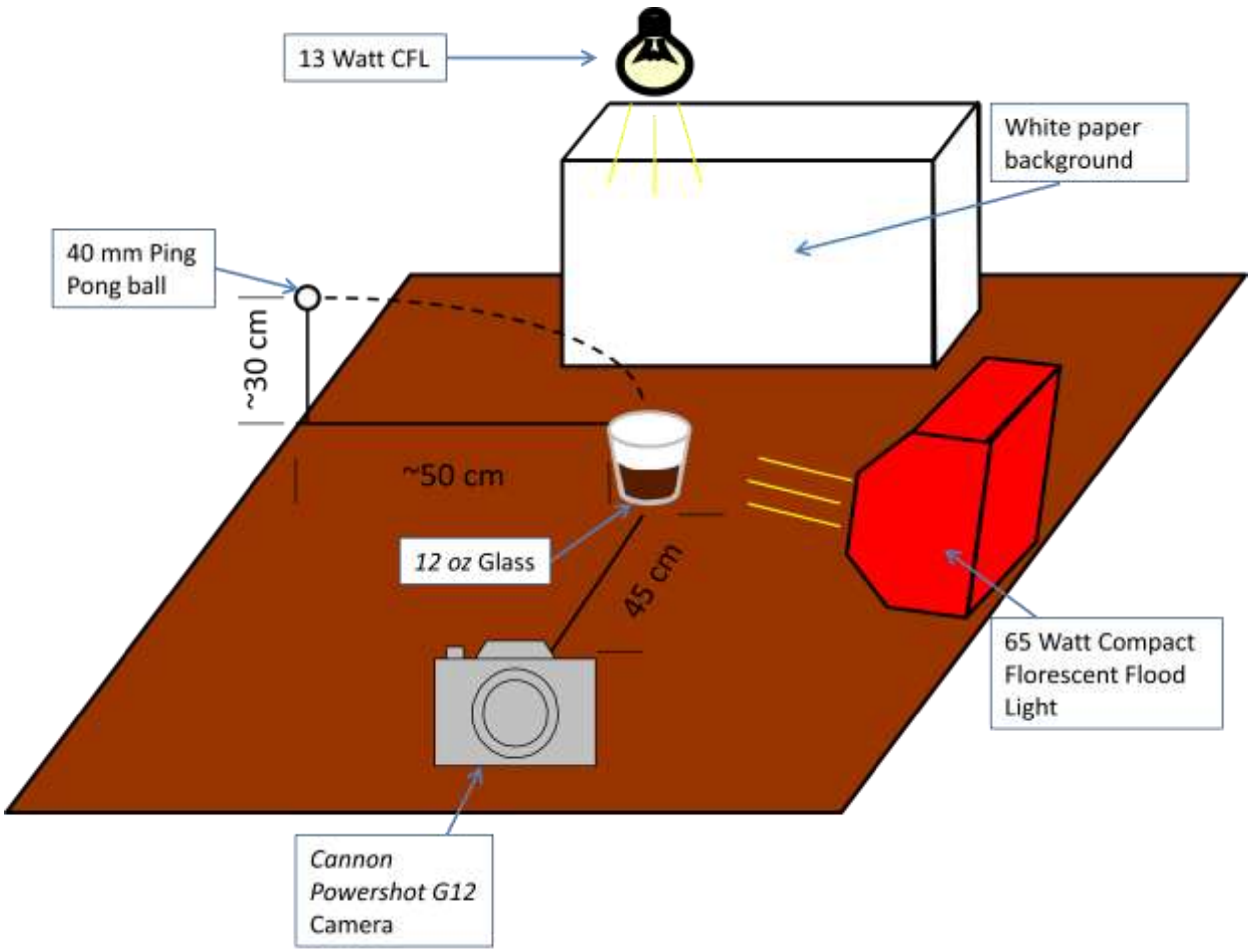

Figure 1: Photograph Set-up Schematic

The camera was approximately 45 cm (18 inches) from the glass when the image was taken (Figure 1). The glass used was a "short" 12 fluid ounce cup; approximately 10.5 cm tall and 8 cm in diameter at the top. This was chosen over the taller glass because of the larger exposed surface area for the foam; making it easier for the ball shooter to hit the cup while providing more room for the physics of the ball splash to be examined. This image was taken with the assistance of a good friend of mine, who provided the excellent ball projection while I attempted to capture the splash with perfect timing. The ball was launched approximately 50 cm from the glass to the left, 30 cm above the top of the rim. Consistency was attempted to be maintained for analysis purposes, but it was very difficult to obtain accurate measurements of ball release location and velocity in an experiment like this, so it must be noted that these values are approximated.

The camera used to capture this image was a *Cannon Powershot G12*; a high-end digital point-and-shoot camera which allows for manual adjustment in all significant photographic variables (focus, shutter speed, aperture, etc.). The biggest trick was finding an appropriate shutter speed to capture the moment of impact without motion blur but with enough light exposure to illuminate the image properly. The manual focus was also difficult in an action shot like this because it is difficult to adjust to a still focal point when the image changes completely as the ball splashes. The data for the finalized image is as follows:

Shutter Speed	1/250 sec
F-Stop	f/4.5
Max Aperture Value	f/4.5
ISO Speed Ratings	1600
Focal Length	30.5 mm
Pixel Resolution (Pre-crop)	2736 x 3648
Pixel Resolution (Post-crop)	2028 x 2984

Figure 2: Camera Data

Physical Analysis

There are several interesting physical phenomena which can be observed in this image. The first is the mutated image of the ping-pong ball seen underneath the beer head caused by different refractive indices between the air, glass, and Guinness. Although I wouldn't argue that this is the main focus of the image from a fluid dynamic perspective, it is one of my favorite components of this image and is a big reason I selected this particular image. Index of refraction is a measure of the speed of light through a substance, and is defined by **μ = c/v**; where c = the velocity of light through a vacuum and v = the velocity of light in a medium. μ in a vacuum is equal to 1.00 by definition, and will be greater than one in every other medium. Different indices of refraction for different substances results in angular shifts of light waves passing through the medium (Figure 3), which can be described for linear refraction by Snell's Law [1]:

$$n_1 * \sin\theta_1 = n_2 * \sin\theta_2$$

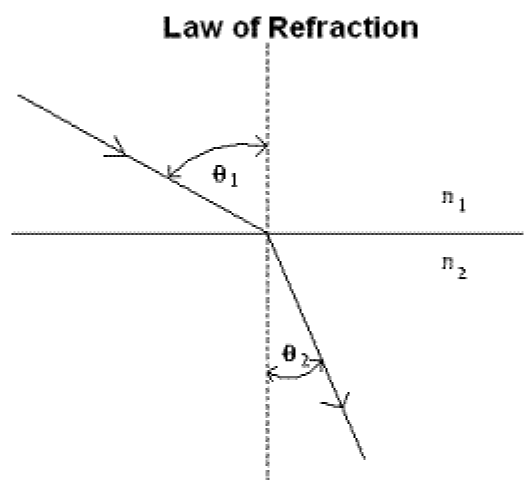

Figure 3: Snell's Law of Refraction [1]

This phenomenon can be commonly seen in looking through a glass of water with a straw in it. For this scenario, we look at the IOF for three different mediums: air = 1.00029, Pyrex glass = 1.470, and beer = 1.345 (may vary slightly with the higher density of *Guinness Draught*)[2]. It should be noted that these values are determined at STP, and the image was taken at an unrecorded pressure of less than 101.325 kPa, which would change the above values slightly. The effect of the light refraction through the glass and the beer can clearly be seen in this image, as the ball clearly looks lower and further to the right than it should be.

The image distortion through the glass is a nice aspect of this image, but the major focus in the picture has to be the transfer of kinetic energy from the ball to the beer foam, causing the smooth, circular ridge formed behind the ball and the more intense splash stream to the right of the glass. The kinetic energy of the ball as it enters the head can be determined from the equation [3]:

$$T = \frac{1}{2} * m * v^2$$

where the ball is analyzed as a single particle and m = mass of ball and v = velocity of the ball upon impact. To determine the velocity of the ball, I will use simple rectilinear motion equations to obtain a reasonable value, since ball release velocity is not a measured quantity. Assuming all the throwing velocity is in the horizontal direction, we can determine that the ball fell 30 cm in approximately .25 seconds with a velocity of approximately 2.45 m/s in the downward vertical direction. The horizontal velocity of release can be determined, neglecting air resistance from the simple equation:

$$v = \frac{\Delta s}{\Delta t}$$

Which, given Δs = 54 cm and Δt = .25s, gives a horizontal velocity of approximately 2.16 m/s. Taking the impact velocity as the square root of the horizontal and vertical components squared, we get the final impact to be about 3.27 m/s, at an angle of about 41^{o} relative to the surface of the foam. With a ping-pong ball mass of 2.6 grams, this gives a kinetic energy value of approximately .014 N*m for the ball entering the cup. Assuming that the ball stays entirely in the glass, this means that all the kinetic energy will disperse through the foam, surprisingly in a radially symmetric pattern.

A very interesting fluid mechanic phenomenon which I like to call the "impact crater phenomenon" is the symmetric splash pattern that can be seen when a rounded object impacts a flat liquid surface. This would seem obvious from a directly downward drop, but it holds true for all but very low impact angles, where the splash can become elliptical. This can easily be observed by looking at impact craters on the moon, which are all nearly perfectly circularly symmetric unless the impact angle is $<5^{o}$. This is analogous to our situation because the extremely high velocities of the meteors cause the hard ground to act as a liquid upon impact. You can also notice it the circular ripples that form when you throw a rock into still water at an angle. There has been research done regarding the science behind this effect, especially for impact craters (Poelchau [4], Kuboto [5]), but the results are often questioned by the general scientific community (Hertzberg). One idea is that the "energy density" in the liquid, which is the amount of kinetic energy being translated to the liquid from the ball, translates directly into the amount of outward force of the splash [5]. Areas with more energy density push outwards more than areas with less density until there is a symmetric balance, i.e. a circular splash. The figure below shows an image which captures this phenomenon better than the published image.

Figure 4: Circular Splash

In this image, the splash is almost perfectly circular everywhere except for in the direction in which the ball is traveling. This is also seen with a pronounced splash to the right in the original image. I believe this is caused from a more rapid dispersion of energy in the direction the ball is traveling than the other regions of the splash, combined with the presence of the far-side glass "pushing" the foam upward as there is no more horizontal room for the flow to spread. This is clearly evident in the main photograph, where the ball is nearly on the side of the glass and there is a simple lack of area for the foam to be contained.

Conclusion

The "Get Wet" project turned out to be both challenging and entertaining. The photographic component was a blast; I had a lot of fun adjusting my camera settings to get a decent image, while trying to take a high-speed action shot at the same time. The final image provided a very interesting high-velocity splash pattern which had both a smooth, circular component and a turbulent stream pushing upward from the far right end of the glass. There also was an interesting image distortion of the ball submersed in the beer; showing the varying refraction indices of the air, glass, and *Guinness.* If I were to make an adjustment I would try to provide more lighting from the left side to provide a more even light distribution and allow myself to use a faster shutter speed with lower ISO to create a sharper image.

References:

1. Deng S, Eldert G, "Index of Refraction of Glyceral," *The Physics Factbook,* 2005. http://hypertextbook.com/facts/2005/ShirleyDeng.shtml

2. "Index of Refraction Values," *3D Millenium*, http://www.m3corp.com/a/tutorials/refraction.htm

3. Hibbeler R.C., *Engineering Mechanics Dynamics*, 11th edition, Pearson Prentice Hall, 2007

4. Poelchau M. H, Kenkmann T, "Asymmetric signatures in simple craters as an indicator for an oblique impact direction," *Meteoritics & Planetary Science*, ed. *43,* 2008.

5. Kubota Y, Mochizuki O. "Influence of head shape of solid body plunging into formation," *Journal of Visualization*, 2011