# Hydropump: Plunging Water Jets

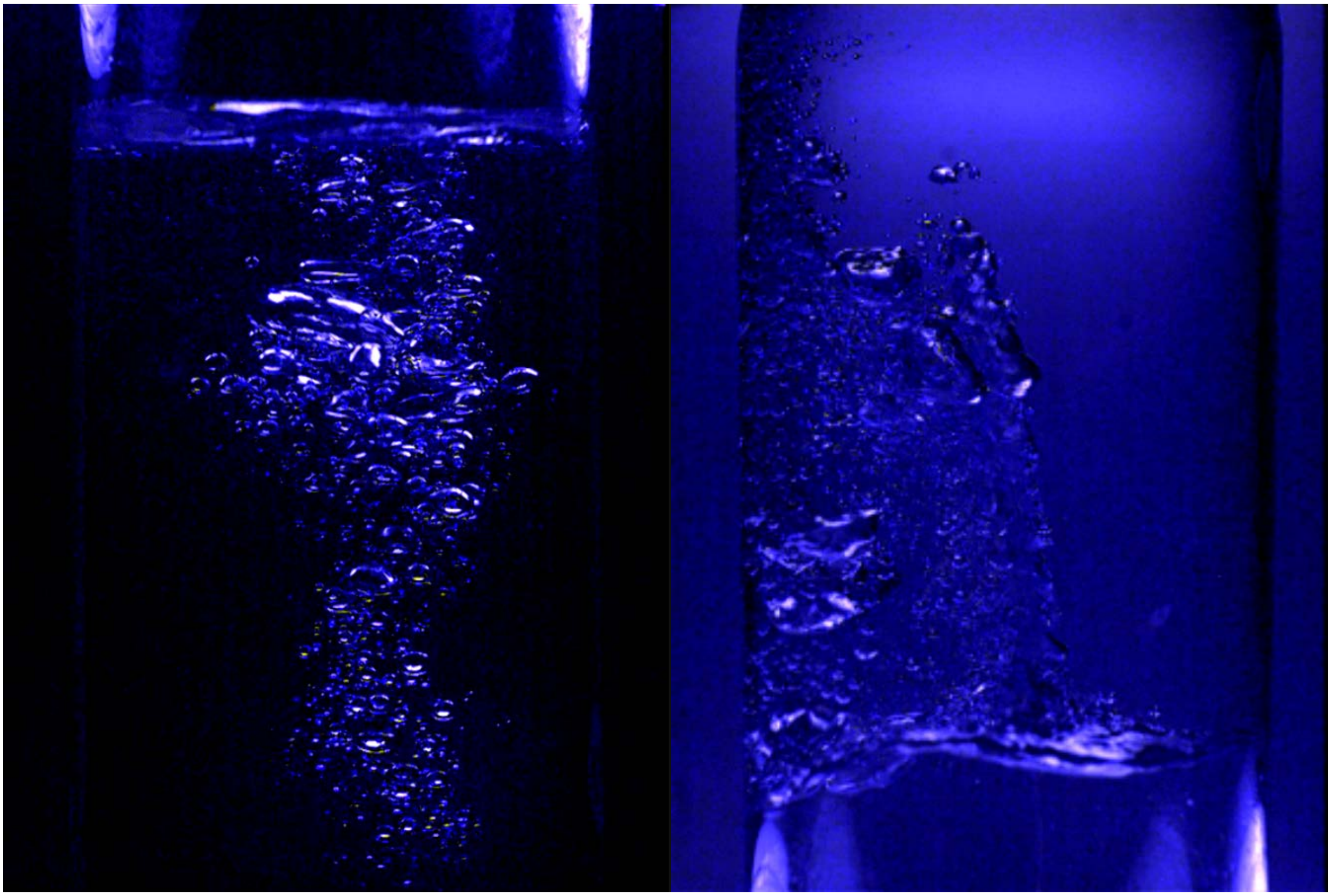

*Figure 1: Still frames from final video*

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**Team Third Report**
**MCEN 4151: Flow Visualization**
**Prof. Hertzberg**
**20 December 2015**

## Introduction

This image was produced for the Team Third assignment for the Fall 2015 Flow Visualization course offered by Professor Jean Hertzberg at the University of Colorado School of Engineering. The objective of the assignment was to produce an aesthetically appealing image that captures a unique physical phenomenon that can later be analyzed. The intent of the experiment behind this image was to examine the dynamics of a plunging water jet and its effect on the entrainment of air within the fluid. In other words, what happens when you use a squirt bottle to shoot a glass of water and film it with a high-speed camera?

Figure 1 on the cover page shows a pair of still frames, taken from the final, edited video which can be found at the following address: https://vimeo.com/147670053. The original footage was taken in the evening of October 18th in cooperation with Yasmin Mazloom and Janelle Montoya, to whom I owe a special thanks for their cooperation and persistence.

## Experimental Methodology and Observations

The setup for this experiment was relatively straightforward. A glass of water was placed level with an Olympus I-Speed camera, as shown to the right, in Figure 2. The fluorescent lights were placed in such a way as to avoid visible reflections in the video footage. It turned out that they all happened to be at an angle of about 120 degrees from the axis of the camera, in one plane or another. A squirt bottle was used to shoot a jet of tap water into the glass from a height slightly above the top of the bulbs. A simplified, dimensioned diagram can be seen to the left, in Figure 3. The dynamics of the water and air were filmed at 1000 frames per second, for a short burst of just 1.5 seconds. Both black and white backgrounds were used during filming.

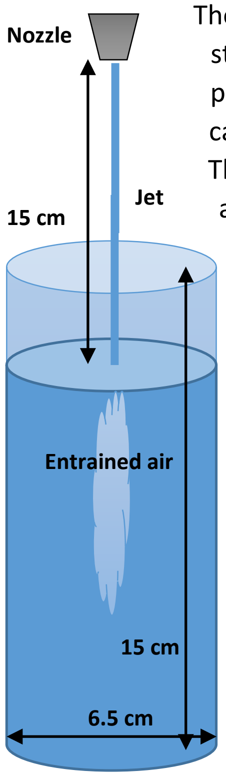

*Figure 2: Diagram of experimental procedure (not to scale)*

*Figure 3: Image of experimental setup with camera, glass, and lighting*

The primary phenomenon being observed here is part of a family of dynamic interactions that results from the mechanical penetration of one phase into another through an interface; this is frequently encountered in practice, especially instances of aeration of a fluid. The specific phenomenon in this case is gas entrainment by a plunging liquid jet of water through the free surface of the water. There is a significant amount of research on this topic and a number of its aspects have been investigated, including mechanisms, conditions for the onset of entrainment, amount of entrained gas, characteristics of bubble dispersion, and mass transfer.[1] This brief inspection will take a look at the mechanism of entrainment, properties of this system, and characteristics of bubbles.

The main characteristics of the jets that play a role in gas entrainment include its velocity and the viscosity of the liquid. Water has a dynamic viscosity of 0.89 mPa-s. With respect to the research conducted, water is thus considered a low viscosity fluid.[1] In the case of low viscosity jets, the entrainment mechanism is governed by the interactions of disturbances on the jet surface and the surface of the receiving pool. Entrainment begins with a small depression, called a dynamic inverted meniscus; when jet surface disturbances hit the depression, the surface deformation, transverse bulk liquid movement, and resulting formation/closure lead to gas entrainment at the plunging point.[1] The indentation of the pool surface that is observed immediately upon the penetration of the jet is referred to as an induction trumpet. In the first video clip, this feature is clearly visible as it entrains a large quantity of air in its initial formation. Interestingly, once the trumpet reaches its maximum depth, its tail closes up near the plunging point at about the same time; any air entrained past this development produces significantly smaller bubbles due to the new disruptions at the surface interface between the liquids. Ultimately, the quantitative prediction of the performance of the plunging jet is complicated by the effects of primary variables, including jet diameter/velocity/length and fluid properties, as well as secondary factors including nozzle design and jet inclination.

Now knowing a little bit more about the development of these jets, an inspection of the properties of this particular system might help provide some insight into its behavior. To start, the velocity of the jet can be determined by examining the original footage. By looking at the video frame-by-frame, it can be seen that the first jet in the film takes eight frames to travel from top of screen to the time it impacts the surface of the pool. Based upon the diameter of the glass being 6.5 cm, this distance is 2 cm. Thus, the jet is travelling at a velocity of 2.5 m/s before it impacts the water. It is also known that, at room temperature, the density of water is roughly 1000 kg/m$^3$, its surface tension is 73 mN/m, and its kinematic viscosity is 0.95e-6 m$^2$/s.[2,3] Judging from the size of the nozzle, a characteristic length for the jet is then assumed to be 1 mm at the point of impact. These property values allow for the calculation of the following nondimensional numbers:

$$We = \frac{\rho {V_o}^2 D}{\sigma} = \frac{1000\frac{kg}{m^3} * \left(2.5\frac{m}{s}\right)^2 * 0.001m}{0.073\frac{kg}{s^2}} \approx 86 \qquad Re = \frac{V_o D}{\nu} = \frac{2.5\frac{m}{s} * 0.001m}{.00000095\frac{m^2}{s}} \approx 2600$$

The Weber Number is used to analyze the interface between two fluids and can help characterize droplet/bubble formation. It is considered to be a useful statistic when it lies within the range of 10-300.[4] A value of 86 suggests that the inertial effects of the jet do not significantly overpower the surface tension effects of the water, meaning that the jet does not experience an extremely rapid breakup upon entering the pool. As shown by the video footage, this breakup is more gradual and the jet reaches a depth of at least half that of the pool. Additionally, with a value of about 2600 the Reynolds Number, which is used to characterize flow patterns, suggests that the flow is in a transitional phase, though more closely approximating the features of laminar flow. The transition is noticeable especially in eddies which capture the smaller bubbles that are entrained along the length of induction trumpet. The use of a high speed camera aided greatly to the inspection of these fluid properties and is certainly beneficial to further scientific inquiry.

Bubble formation and behavior, on the other hand, is its own realm of inquiry. Two main features of bubbles are expressed in this project: coalescence and shape.[5] The tap water used in this experiment corresponds to the second of two classes of liquids, with respect to bubble formation. In tap water, bubbles have the tendency to combine, i.e. coalesce. This is exemplified in the video, and in Figure 4 below, as smaller bubbles combine to form larger ones as the water jet passes across the screen. The same phenomenon is seen at the top of the pool where bubbles combine at the surface to form even larger structures that grow before eventually popping. The second characteristic is shape which generally splits into three distinct varieties, all of which are exemplified in the figure above. The smallest bubbles, with a radius of < 0.1 mm, are solid spheres. These are most prevalent at the lower parts of the glass, where they have entrained even deeper than the jet itself. The next group is between 0.1 and 1 mm in radius. These are slightly larger and are more significantly affected by drag forces as they rise, causing them to deviate from a purely spherical form. The final group is composed of bubbles larger than 1 mm in radius. These bubbles experience a strong amount of drag force that forces them into ellipsoidal forms. This is especially apparent in the flattening of the larger bubbles as they rise to the top.

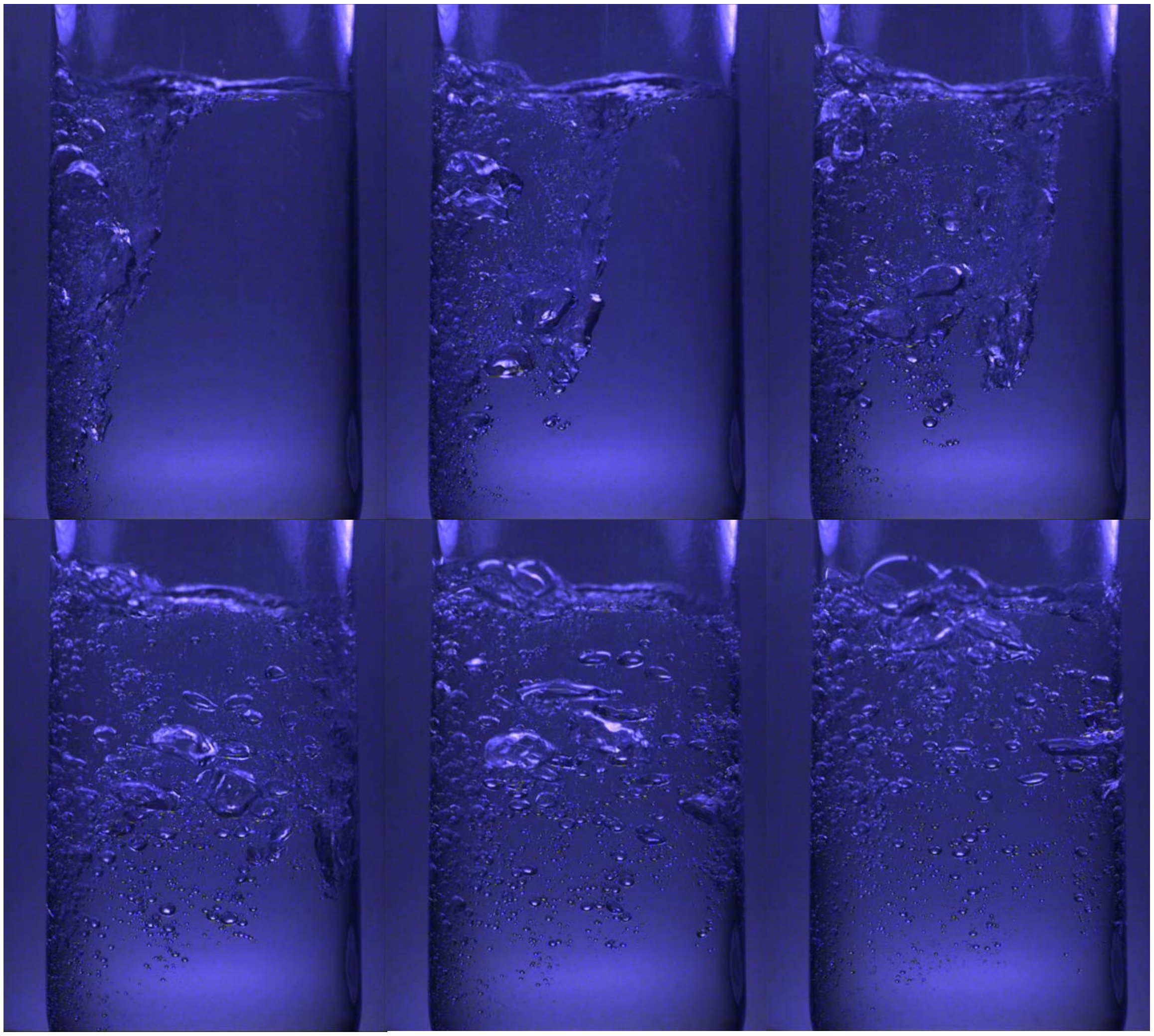

*Figure 4: Series of frames taken from original footage, showing progression of plunging jet and entrainment/rising of air bubbles*

## Visualization Technique

A regular drinking glass was used for this experiment. It was filled with tap water, as was a spray bottle normally used for cleaning purposes. The spray bottle was set to the jet/stream setting and then held approximately six inches above the surface of the water. A variety of trigger pulls were used, from long and gentle to quick and aggressive, in order to achieve different effects.

## Photographic Technique

The field of view was intended to capture the majority of the glass, with emphasis on including the surface of the water and the full range of bubble penetration. The raw video footage was captured using an Olympus I-Speed, high-speed camera, at a frame rate of 1000 fps. The lens used was approximately 15mm in diameter and was set to an aperture of f/3. The original image size was 800 x 600 pixels. At a distance of approximately one foot from the setup, the field of view is roughly 3” wide by 4” high. Lighting was one of the trickiest aspects to this experiment. Available resources allowed for three fluorescent bulbs to be used for the lighting, each producing 2600 lumens at a color temperature of 5000K, a much cooler temperature, helping to provide the blue in the image. These lights were barely bright enough to allow for filming at 1000 fps and the unusually large aperture was necessary to ensure proper contrast. A sample frame from the original footage is shown in Figure 5 below (left).

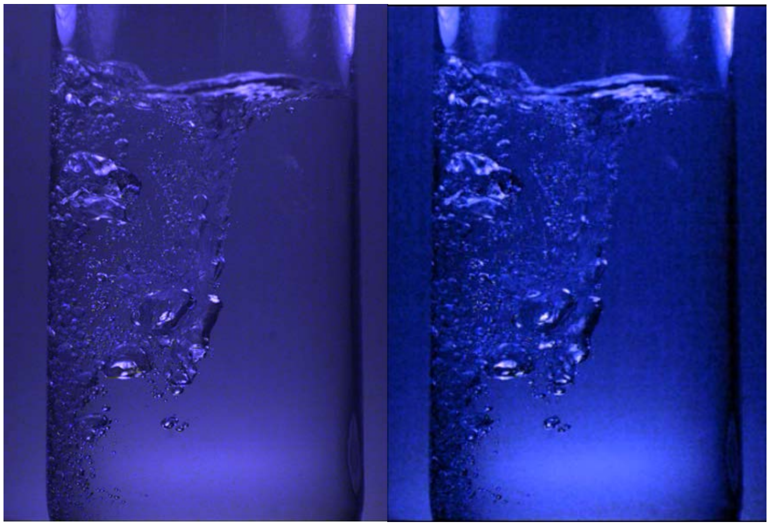

*Figure 5: Comparison of footage, before (left) and after (right) editing*

Figure 5 also shows the same frame from the final video (right), after processing. The movie was produced in Windows Movie Maker 6, a relatively basic, albeit capable, software package. A few edits were made to improve the aesthetics of the footage and the ability to visualize the flow. Increased contrast and brightness were applied in an attempt to improve the visualization of the flow. Additionally, clips from the original footage were partitioned and sped up with the software. The slowest portions of the film are providing playback of the 1000 fps footage at 30 fps, about 33 times slower than real life. Other sections were sped up from this point by 2x, 4x, or 8x speed. To simplify the math, that gives roughly 1/32 speed, 1/16 speed, 1/8 speed, and 1/4 speed for playback.

## Critique

Ultimately, this piece effectively captures a number of interesting flow characteristics and provides a pleasing aesthetic experience. The only unfortunate fact is that the software used to produce the final film was unable to save the file without an excessive amount of compression; this significantly reduced the production value of the final version. Nevertheless, the final product still allowed for a substantial inspection of the fluid dynamics of a plunging jet.

# Bibliography

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