Two Impinging Laminar Jets

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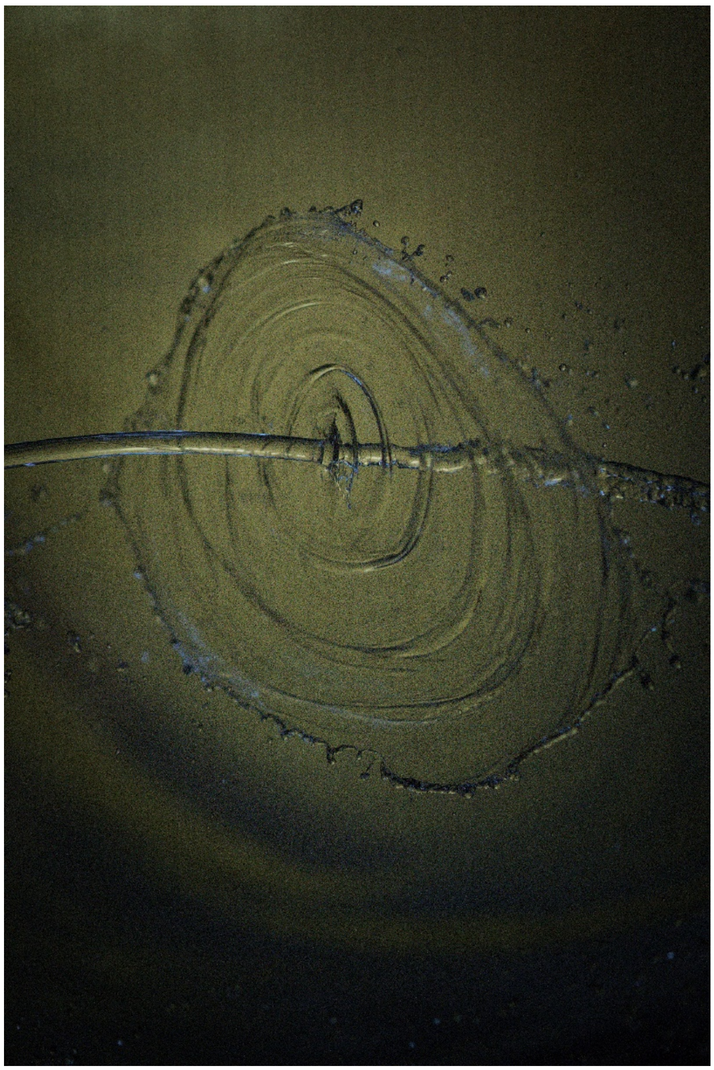

Introduction

The objective of the Image 2 project was to capture the moment when laminar jets of water impinge on each other. This idea came to me after watching people create a single laminar flow jet nozzle on youtube.com and I thought what would happen if you pointed two of them at each other. I expected to see a perfectly flat disc of water, but the image obtained tells a different story. There are more actions at play than meets the eye.

Experiment Setup

For this setup two laminar flow nozzles were created, and water flowed through them to create laminar jets of water. A diagram of the laminar flow nozzle can be seen below in Figure 1.

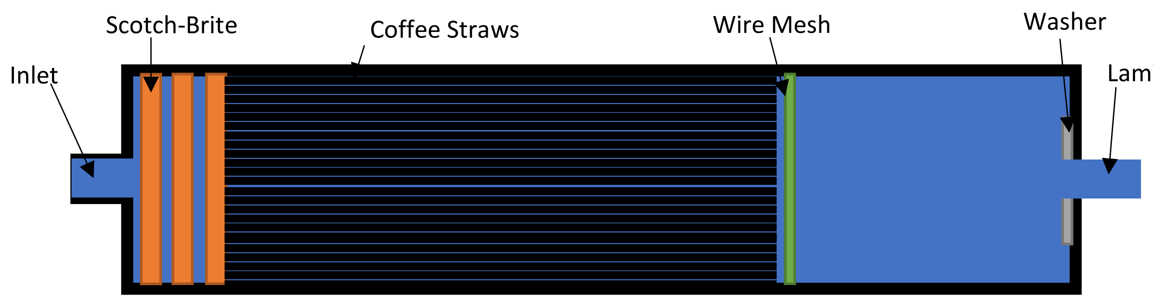

Figure 1:Laminar Flow Nozzle Diagram

Laminar flow is defined as a flow with a low Reynolds number where the “entire flow is dominated by viscosity” and the flow can be observed as having a “well defined straight path” (Kundu & Cohen, 2008). This is classically demonstrated by inserting dye into the stream field and observing if the dye mixes (an indication of turbulent flow) or if it simply follows the flows path in a straight line (an indication of laminar flow). Reynolds found that flows transition from laminar to turbulent around a relatively fixed value (Kundu & Cohen, 2008). This value is approximately between 2000 and 3000. So, for this experiment I wanted to have flows with a Reynolds number lower than 2000. Because I was not measuring the velocity of the water as it entered or exited the nozzle, I do not have exact Reynolds numbers. To achieve a lower Reynolds number, I knew I needed to slow the water down and that is what the nozzle does. Reynolds number can be calculated by Equation 1.

$$Re = (V * d)/v$$

Equation 1

Where V is the velocity of the fluid, d is the diameter of the pipe and, v is the kinematic viscosity. The laminar flow nozzles I made were created out of two-inch diameter PVC pipe and attached to a garden hose. The water entered from the garden hose and hits 3 scotch-brite pads and goes from a hose diameter of ¾ inch to a tube diameter of 2 inches. This aids in slowing the water down. Next it flows through small coffee straws that fill the diameter of the interior of the PVC pipe. The straws organize the water into flowing all in the same direction. Finally, the water is forced into a zone where it is all flowing the same direction and then forced out the outlet. This outlet was a washer that I sanded down to be very smooth to attempt to achieve a perfect tube of laminar water. Now that I had two working laminar jets, I could set them up to impinge on each other. The diagram in Figure 2 is of the experiment set up used to capture the image.

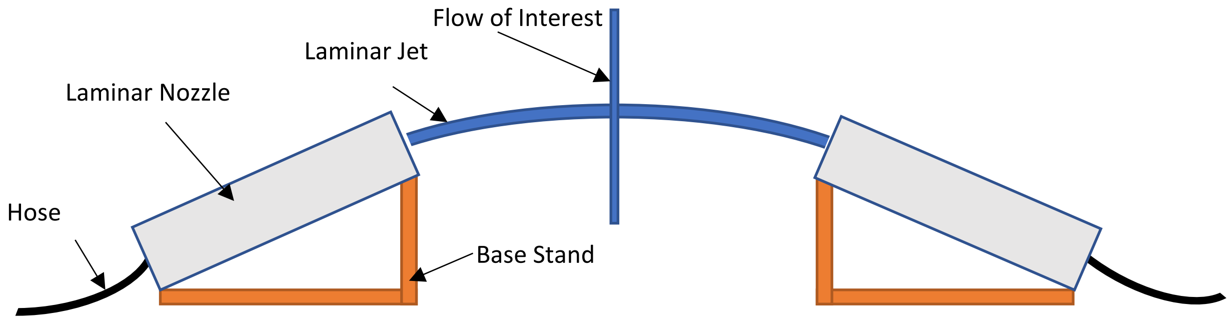

Figure 2: Experiment Setup

The laminar flow nozzles were set up on stands and positioned so the apex of the laminar jet arc was centered, and the two flows impinged on each other as evenly as possible to generate a flat disc of water that could be photographed.

Explanation of Forces

When setting up this experiment I hypothesized that the flow that would be produce would be a flat sheet of water, like if you placed a flat plate in front of a laminar water jet. Only in place of the flat plate the opposing force would be another laminar jet. Therefore, I expected a flat sheet of water. The results however were far more impressive and wildly fun to look at. There were ripples in the sheet of water as opposed to a flat sheet. This begged the question what was generating the waves seen in the image. In researching this I stumbled upon a paper from the 1960's where they study this exact phenomenon. The objective of the study was to understand the impingement of two laminar jets. The experiments were carried out by N. Dombrowski and P.C. Hooper. In their study they found that the reason the sheet of water breaks down as seen in my image is due two forces. The first was due to "the super position of aerodynamic waves" (Dombrowski & Hooper, 1963) and the second was from "hydrodynamic (or 'impact') waves" (Dombrowski & Hooper, 1963). Dombrowski and Hooper were able to determine a critical value when hydrodynamic waves dominate the disintegration of the flow. The value that matters when determining if hydrodynamic waves will cause the flow to break apart as seen is the Weber Number which can be evaluated by Equation 2

$$\mathrm{We} = \rho_l \, \mathrm{D} \, \mathrm{V}^2 \sin^2(\theta)/\gamma$$

Equation 2

Weber number is dependent on the density of the liquid, D the diameter of the tube, V the mean jet velocity, the half angle of impingement and the surface tension. Dombrowski and Hooper found that between Weber numbers of 66 and 165 impact waves are produced and cause the disintegration of the water to occur the way shown in my image. They also determined that the primary factors of the disintegration of the flat disc are the "angle of impingement and the jets velocity" (Dombrowski & Hooper, 1963). Their experiment set up was much nicer than what I have created, and they had a lot more control over the environment in which they were experimenting, even going as far as putting their setup into a vacuum chamber to really prove the hydrodynamic forces were the only explanation for the waves seen in the impingement disc.

Visualization Method

To capture the image, the nozzles were placed in front of a sheet and the camera was placed a safe distance from the action so it would not get wet. A picture of the first set up can be seen in Figure 3. During this attempt to capture the image the sunlight was quickly disappearing and many of the images that I captured were simply too dark. I also really wanted to back light the shot to accentuate the water droplets. I do not have a photo of the setup ultimately used to capture the final image, but I will do my best to describe it and show it in Figure 4. A white sheet was placed behind the laminar flow jets and a bright LED flashlight was shined behind it pointed slightly upwards. There was a reflective panel held above the flow as well to help direct light back at the flow. After some experiments with the camera settings, I settled on using an ISO 25600, 1/3200 sec exposure, f1.8 aperture, manual focus, a 55mm lens on a Sony A7iii Mirrorless Camera body. The photo was taken on 9/25/2021 at 5:26pm. See Figure 3 for an example of how the experiment was setup and Figure 4 for a diagram of the lighting setup actually used.

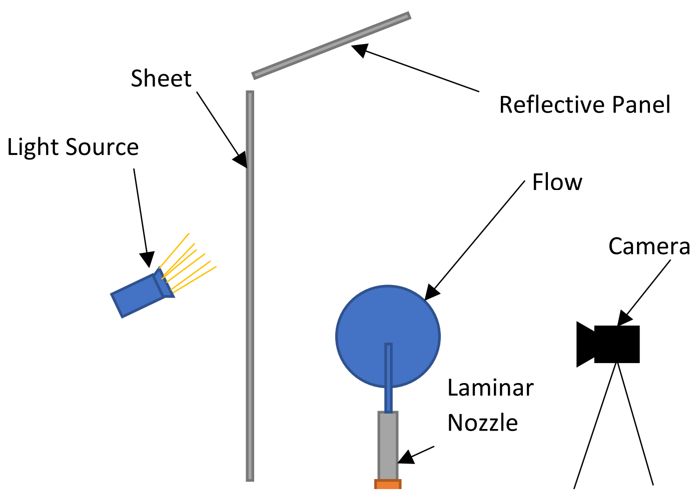

Figure 4: Lighting Diagram

Image Processing

I did some slight post processing to reduce saturation to give the image a black and white feel while really focusing on the highlights and subject of the photo. I did not like the yellowness of the sheet so that is another reason I reduced the saturation and tried to remove some of that color. I think if I was able to take this image again, I would use some remote flashes to back light the flow instead of a constant light source. I cropped the image slightly to remove the portion of the image that has the stand in it on the right-hand side and to remove the erroneous splash on the left-hand side that I think detracts from the final image. The original and edited versions are shown below.

Figure 5:Original

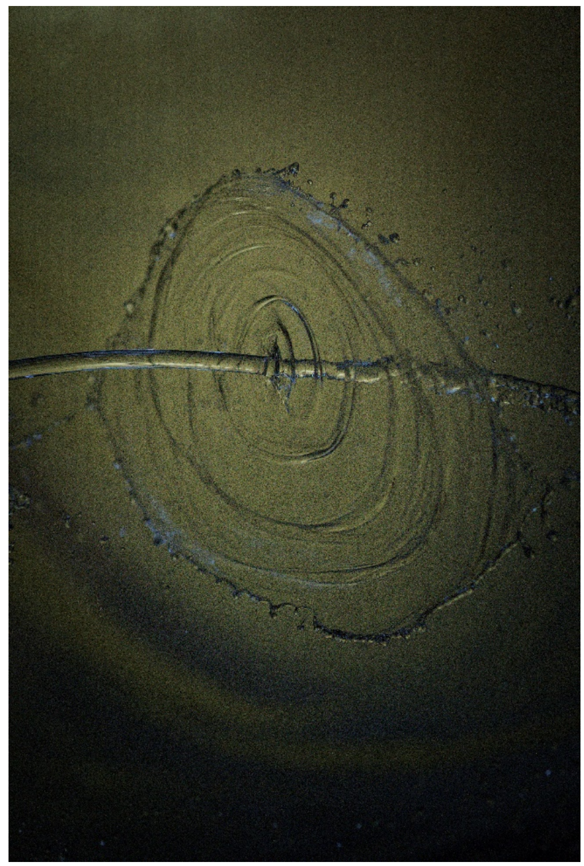

Figure 6:Edited

Final Thoughts

I think I did a great job of capturing the impingement of laminar jets. There are a few things I would do differently now that I have set up the experiment once. The first is to do it in a place where there is lots of light. This phenomenon is happening very rapidly and needs a lot of light to be able to capture the flow in a freeze frame manner. I was only able to take my images in the evenings and when the sun was setting and there simply wasn't enough light to capture the image using more optimal camera settings. The second thing I would do differently is to use a remote flash to back light the image. I think a remotely triggered flash behind the water would create a very accentuated contrast between the white sheet and the droplets formed at the outer edge of the flow where it is disintegrating. Overall, this was an incredibly fun set up to play with and there were some beautiful images captured from it. I look forward to trying to improve on this photo in the future.

References

Dombrowski, N., & Hooper, P. (1963). A Study of the Sprays Formed by Impinging Jets in Laminar and Turbulent Flow. *Journal of Fluid Mechanics, 18*(3).

Kundu, P. K., & Cohen, I. M. (2008). *Fluid Mechanics* (4 ed.). Academic Press.