Impinging Jets of Water

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MCEN 5151
Flow Visualization
University of Colorado Boulder
May 1, 2012

Purpose

This was the final assignment for the Flow Visualization course at the University of Colorado Boulder. It was another team assignment, but for this project our team decided to go their separate ways except for Emily and I who briefly worked on an idea. She came up with an idea of running two jets of water and intersecting them at a 45 degree angle and seeing what patterns emerge. At first I tried a bunch of concepts on my own like smoke around a spoon and fog coming out of a whiffle ball, but nothing seemed to capture what I wanted for the final image of the semester. Overall the setup and idea is very basic, but the physics behind the results is everything but simple.

Approach

The setup is fairly simple and can be seen below in figure 1. We had two 1/8" diameter tubes emitting a jet of water in front of a black cardboard backdrop onto a bucket. The camera rested on top of one of the fish tanks laying around for stabilization and for proper height.

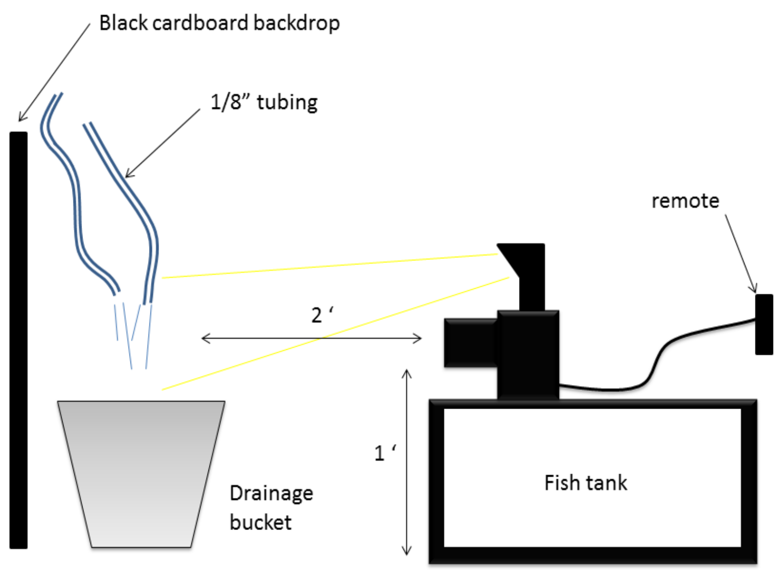

Figure 1 : Image Setup

From this setup we can calculate a series of numbers that will help us quantify and understand the flow. The first is the Reynolds Number which will give us the ratio of inertial forces to viscous forces below in equation (1).

$$Re = \frac{\rho D V}{\mu} \rightarrow \frac{\left(1000\frac{kg}{m^3}\right)(.003175m)(.5\frac{m}{s})}{(.95x10^{-3}\ Ns/m^2)} \rightarrow Re = 1671 \quad (1)$$

This shows that the water coming out of the tubes was fairly laminar giving us a nice steady jet. The surface tension of water at room temperature is roughly .0724 N/m which will help us calculate the next few values. The Bond Number shown below in equation (2) shows the effect of gravity on the impact. The Weber number in equation (3) shows the effect of the surface tension and ideally for real scenarios it should be <1.

$$Bo = \frac{D}{\sqrt{\frac{\sigma}{\rho g}}} \rightarrow \frac{(.003175\ m)}{\sqrt{\frac{.0724\ N/m}{(1000\frac{kg}{m^3})(9.81\frac{m}{s^2})}}} \rightarrow Bo \sim 1 \tag{2}$$

$$We = \frac{\rho h V^2}{2\sigma} \rightarrow \frac{\left(1000\frac{kg}{m^3}\right)(.003175m)\left(.5\frac{m}{s}\right)^2}{2\left(.0724\frac{N}{m}\right)} \rightarrow \begin{cases} Jet: We = 6 \\ Sheet: We \sim 1 \end{cases} \tag{3}$$

The Bond Number of 1 illustrates that gravity has little influence on the physical formations of the water jets collision but the Weber number shows that surface tension plays a large role in the effects seen by the sheet formation, but not the jet formation. Bernoulli shows us that the velocity from the jet stays constant when travelling to sheet [1].

$$\left(P + \frac{V^2}{2} + pgz\right)_{jet} = \left(P + \frac{V^2}{2} + pgz\right)_{sheet} \rightarrow v_{jet} = v_{sheet} \tag{4}$$

So we know that the flow coming out of the jets is laminar and traveling at high enough speeds such that gravity is negligible, meaning that the dynamics of flow is dominated by inertia and surface tension which is proven by the Weber Number [2]. Figure 2 below shows the collision zone of the two jets impacting. It points out that there is a high pressure zone at the collision site and it also depicts the collision angle as well as the radial distance r, from collision. There is also a stagnation point present in the center of the high pressure zone

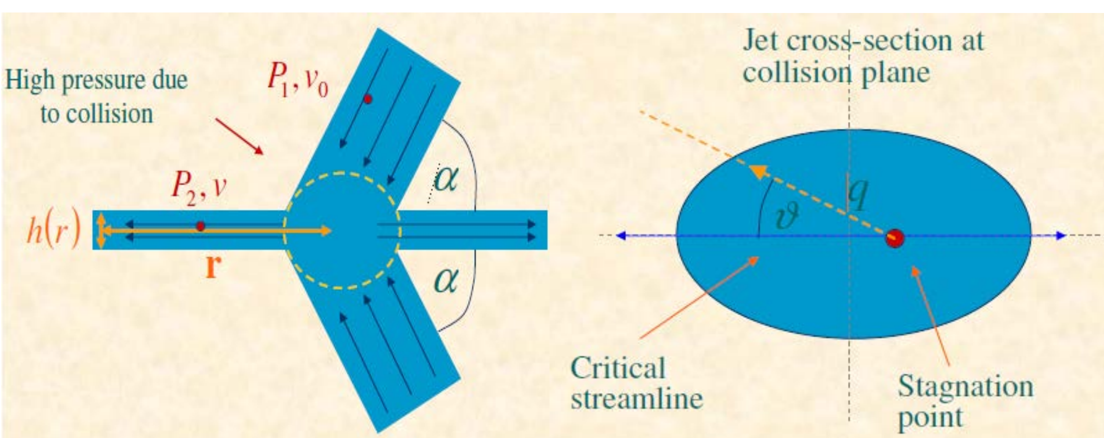

Figure 2: (Left) Collision Diagram, (Right) Cross Section of Collision [1]

Every collision is different though and there are many different formations that can result due to fluctuations in jet diameter as well as collision angle and other important variables like surface tension, density, and jet speed. The two most common flow structures are known as chains and fishbone as seen on the right. Chains are cause by an oblique collision of equal sized jets and are mutually orthogonal decreasing in size until the chain collapses into a downward stream. The sheet is formed perpendicular to the plane of incidence of the jets and the thickness of the plane thins proportional to 1/r which is the radial distance from the point of impact, until it reaches the edge of the sheet. The surface tension creates a curvature force that acts normal to the edge limiting the lateral extent giving it its unique shape. [2]

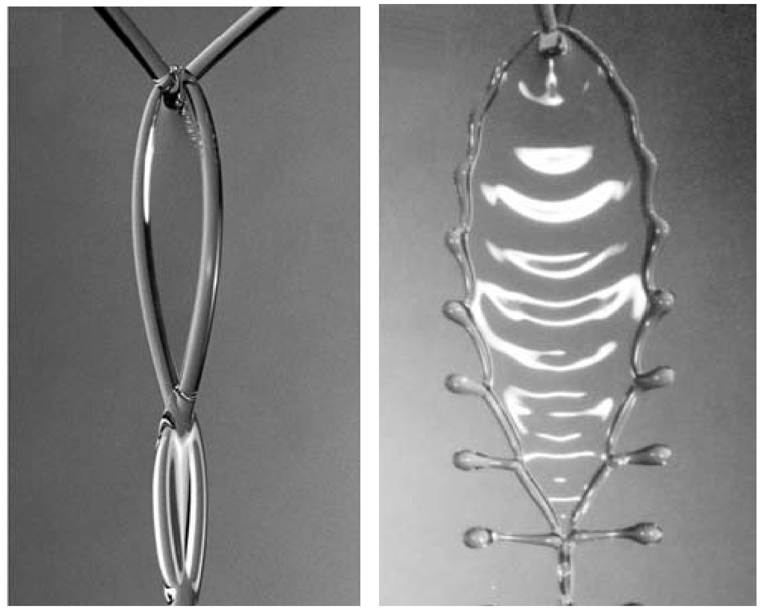

Figure 3: (Left) Chain, (Right) Fishbone

Fishbone structures are formed simply by increasing the flow rate while keeping all of the other variables constant [2]. This creates a similar sheet but instead of alternating links it forms tendrils as the excess water symmetrically jumps out from the sheet. This is clearly the structure I captured in my photo except my fishbone is slightly tilted causing a disruption in symmetry and creating more of a zigzag pattern.

There are also a few principles also related to the disintegration of the sheet. The disintegration is primarily caused by surface tension causing the sheet to form into drops as in the fishbone structure. The disintegration front comes in the form of a standing wave while the sheet boundary is a stationary wave which has the velocity found in equation (5) below.

$$c^2 = \frac{2\sigma}{\rho h} \rightarrow \sqrt{\frac{2(.0724\frac{N}{m})}{\left(1000\frac{kg}{m^3}\right)(.001m)}} \rightarrow c = .38\frac{m}{s} \tag{5}$$

It is also possible to calculate the shape of the sheet using this formula below which finds the angle from the radial line to the line of constant phase.

$$sin\psi = \frac{c}{v_0} = \frac{1}{\sqrt{We}} \rightarrow sin\psi = .76 \rightarrow \psi = 49° \tag{6}$$

From the calculation above you can see that the angle which my two jets impacted was actually 50 degrees instead of the previous 45 I estimated.

Visualization Technique

For this visualization of fluid flow we simple used water out of hose running through two parallel tubes. The tubes had approximately a 1/8" inner diameter and created a small jet. The water coming out of the tubes can be estimated at room temperature with uniform fluid properties. For the lighting we had fluorescent overhead lighting about 10 feet above as well as the direct flash from the camera used. As stated above, the setup was incredibly basic and there were no complex techniques used to visualize this phenomenon.

Photographic Technique

For this last photo I used a different camera than any of the other shots throughout the semester. I used a Canon EOS Rebel T2i 18MP that was Emily's camera since hers had better resolution capabilities and she had an flash attachment which allowed us to better freeze the water in motion. The camera was propped up about a foot off the ground and we took photos using a remote so the camera would stay very still. The image had an F-stop of 4.5, a quick shutter speed of 1/200 sec, a low ISO of 200, and a -.3 exposure bias. The subject was about 2 feet away from the camera lens and the lens had a focal length of 29mm. The camera was set to have a shutter speed priority to capture the drops perfectly without any motion blur. The field of view was approximately 2 feet wide by 1.5 feet tall. The original image can be seen below in figure 4. The dimensions of the original image were 5184 pixels wide by 3456 pixels high.

Figure 4: Original Image

The final image size is 1376 pixels wide by 2268 pixels high. For the post editing I cropped out the unnecessary background and focused on the collision of jets. I used the clone stamp to erase any water droplets on the backdrop. I used curves to adjust contrast and then I played with the brightness and contrast ratios. I also added a yellow photo filter to make the water pop out from the background.

Conclusion

Overall, I am very pleased with this image. I was very glad that Emily let me tag along on this idea and use her camera because it turned out way better than I would have imagined. The image reveals a lot of beauty as well as some very fascinating physics. I believe that I did fulfill my intent to get a very beautiful photo for my final image and I got to learn a lot about what is occurring. The only thing I would have done to develop this further would be to play around with dyed water of two different jet sizes. We didn't play with too many variables since we were happy with the results we got. I learned a lot from writing this report about the structures that can be formed by simply pointing two jets of water at each other. It really is beautiful when you can capture one of these structures because this is a beauty that is very easily overlooked since it is hard to see by with the human eye.

[1] eskola.hfd.hr/icm/download/IYPT2007/Jets.pdf

[2] Bush, John. Hasha, A. On the Collision of Laminar Jets: fluid chains and fishbone. Department of Mathematics. Massachusetts Institute of Technology. March 2004. J. Fluid Mech. Vol. 511. Pg. 285-310. < http://www-math.mit.edu/~bush/chains.pdf>