MCEN 5151: Flow Visualization

Fishbone Instability of Impinging Water Jets

Third Team Assignment

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The last assignment for MCEN 5151: Flow Visualization is the 3rd and final team image. For this assignment, like the other team assignments, students will work in larger groups to produce an image to attempt to produce an image of higher quality than would be possible with only a single person. The larger groups also allow for more complex experiments, which can in turn lead to a more interesting and higher quality image. My group, consisting of Philip Latiff, Michael McCormack, Adam Sokol and myself, decided to try and capture the so-called 'fishbone' instability of impinging water jets. This occurs when two laminar jets of water collide with one another at the correct speed and angle to produce a fishbone-like shape to the resulting combined jet. After much trial and error, we eventually succeeded in capturing the effect, which can be seen in the image on the title page.

The experimental setup for this experiment consisted on drilling holes in the caps for 2 water bottles, inserting a straw into the hole, taping it in place, and the squeezing the two bottles by hand to create the jets. Each squeeze was about 1 to 2 seconds in duration, and produced a single 'fishbone' stream of water that had to be photographed at the right time. This setup can be seen in **Figure 1**. The water bottles were filled with purple water made by combining a large amount of red and blue food dye and a bucket. The experiment was conducted over the bucket so that the water could be recycled, and no dye would be wasted. The camera was pointed towards the water bottles, and the field of view was such that the straws were not visible to the camera. The camera was tilted on its side so that the entire drop distance could be captured. The camera was on a low tripod only about 2ft off the ground, and it aimed horizontally at the experiment area, which was about 2ft away. Roughly 4ft behind where the experiment was conducted was a flat grey cement wall, which turned out to be a great background. The experiment was conducted outside, so no unnatural lighting was used. The camera was pointed away from the sun so that lens flare and glare were not issues. This did however cause shadow issues, but they were easily remedied by proper positioning.

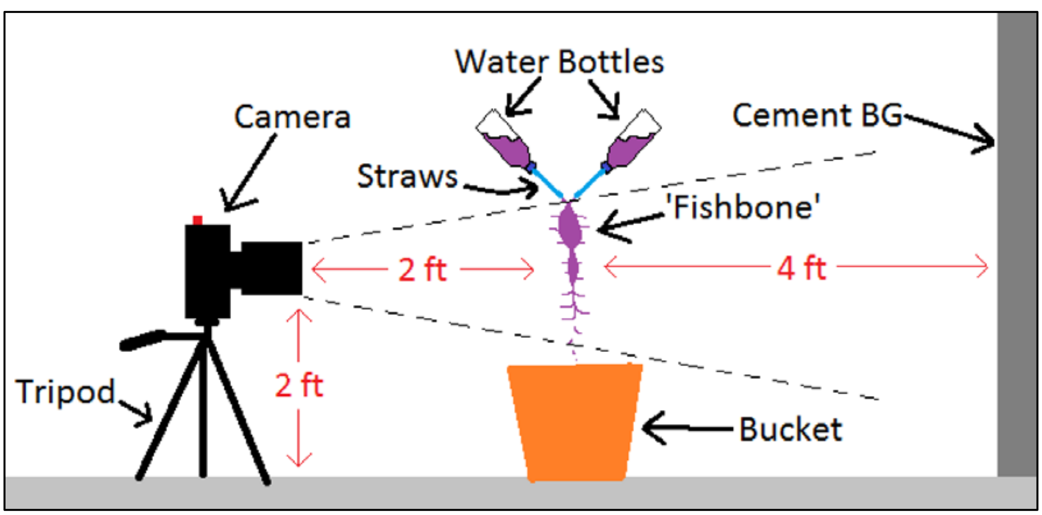

Figure 1: experimental setup for 'fishbone' instability experiment.

In order to successfully generate the 'fishbone' instability, the fluid jets need to be laminar. To determine whether or not the flow is laminar, the Reynolds Number must be calculated. To calculate this, we need the density and viscosity of water, as well as the velocity the jet was travelling and the diameter of the jet. The density and viscosity are known, but the velocity and diameter must be estimated. The calculation using estimates for these values can be seen below in **eq. (1)**.

$$\mathrm{Re} = \frac{\rho \mathrm{VD}}{\mu} = \frac{\left(1000\,\frac{\mathrm{kg}}{\mathrm{m}^3}\right)\left(1\,\frac{\mathrm{m}}{\mathrm{s}}\right)(0.005\mathrm{m})}{\left(1\cdot 10^{-3}\ \frac{\mathrm{N}\cdot\mathrm{s}}{\mathrm{m}^2}\right)} = 5000 \tag{1}$$

Knowing that the transition from laminar to turbulent flow occurs at a Reynolds Number of 5E5, we know that the flow in this experiment was in fact laminar. This Reynolds Number is on the larger end though, and so some turbulence is possible, especially when the two jets impact with one another. There are several other numbers we need to calculate to get a full understanding of this effect. The first is the Bond Number (**eq. (2)**), which gives us the ratio of gravity to curvature[2]. For this value, we need to determine the surface tension of water, which is about 7.28E-2 N/m in our case. For this instability, the Bond Number should be on the order of 1, indicating small gravitational influence. The Weber Number (**eq. (3)**) gives us the ratio of inertia to surface energy, and we expect this number to be between 1 and 100 for this instability, depending on how relevant the surface tension is to the formation of the jet or sheet. In this equation, there are no new variables.

$$\mathrm{Bo} = \frac{\mathrm{D}}{\sqrt{\frac{\sigma}{\rho \mathrm{g}}}} = \frac{0.005\ \mathrm{m}}{\sqrt{\frac{\left(7.28\cdot 10^{-2}\,\frac{\mathrm{N}}{\mathrm{m}}\right)}{\left(1000\,\frac{\mathrm{kg}}{\mathrm{m}^3}\right)\left(9.81\,\frac{\mathrm{m}}{\mathrm{s}^2}\right)}}} = 1.84 \tag{2}$$

$$\mathrm{We} = \frac{\rho \mathrm{DV}^2}{2\sigma} = \frac{\left(1000\,\frac{\mathrm{kg}}{\mathrm{m}^3}\right)(0.005\ \mathrm{m})\left(1\,\frac{\mathrm{m}}{\mathrm{s}}\right)^2}{2\left(7.28\cdot 10^{-2}\,\frac{\mathrm{N}}{\mathrm{m}}\right)} = 34.3 \tag{3}$$

Because the Bond Number is about 1, we know that there is a very low gravitational influence on the formation of this instability. A Weber Number of 34.3 is hard to interpret, but at large Weber Numbers of around 100, we know surface tension is not important for the jet, but smaller numbers of around 1 imply that it is important for a sheet[2]. Because the value is right in the middle, it seems as though surface tension may be important for both sheet and jet formation. Now that we have gone through some diagnostics to determine what influences this effect mathematically, we can look at it from a more qualitative perspective.

There are several different regimes for impinging jets. These include, in order of increasing Re, the oscillating stream regime, sheets with disintegrating rims regime, fluid chains regime, the 'fishbone' regime, spluttering chains regime, disintegrating sheets regime, and violent flapping[1]. **Figure 2** shows the chain, 'fishbone', disintegrating sheets and violent flapping regimes (from left to right). All of these regimes can be seen with a given fluid simply by increasing the diameter or velocity of the flow to increase the Reynolds Number. Changing to a less viscous fluid would also cause movement through these different regimes. Based on the comparisons of the photos, it appears as though our image is in the violent flapping regime, however in our experiment, the water jets were generated by hand and so the resulting jets were not perfect. Because of this, I believe the regime shown in the image is in fact the 'fishbone' regime, and the chaotic nature of the flow is simply due to the fact that the streams were generated in an imperfect manner. If the image on the title page is examined, the horizontal droplets, called tendrils, can be seen. These tendrils are created through the Rayleigh-Plateau mechanism, which causes individual droplets to pinch off from the bulk group[1, 3]. The Rayleigh-Taylor mechanism is responsible for the rim instability (around the edge), but it is not important to the formation of the 'fishbones'.

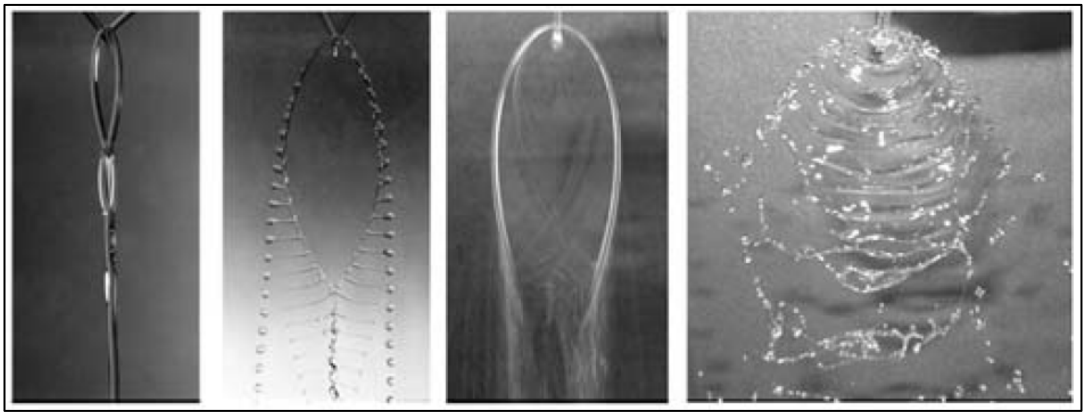

Figure 2: Regimes of impinging jets. From left to right: fluid chain, fishbone, disintegrating sheets and violent flapping[1].

In our team's experiment, the flow was visualized using red and blue food dye. A large plastic bucket was filled significantly with water. About 20 drops each of the red and the blue dyes produced the dark purple color that we desired. We wanted this darker color so that it would contrast nicely with the light grey background that was used. A fast shutter speed of 1/3200 was used to completely freeze the fluid motion, which was relatively quick moving. This high shutter speed allowed us to spatially resolve the photograph. A 1 m/s estimate for the speed of the fluid was used for the calculation, which means each particle traveled 0.3 microns during the image capture. The field of view for the photo is about 0.3m tall and 0.2m wide, meaning that a droplet traveled 1/1000 of the distance from top to bottom during each exposure. The pixel dimensions of the photo are 2868x5184, which means that each particle travelled only about 5 pixels for each exposure, which resulted in very little to no motion blur in the image. While there is little motion blur, some portions are out of focus due to the low depth of field, which is a result of the low f-stop. This was done on purpose though, because the background was a cement wall with a lot of detail. In order to eliminate the detail in the background, I wanted it to be very blurry. For this reason, I chose a low depth of field and put a significant distance between the camera focus point and the background so that it would be highly blurred. The focal length was chosen based on what would capture the most information. When too far zoomed in, only small segments of the stream were seen. By zooming out, a lot more information could be viewed. Because of the high shutter speed, the ISO had to be set relatively high at 800, even with the large pupil diameter and bright sun as the lighting.

Table 1: Camera settings

Camera Body	Canon EOS Rebel T2i
Camera Lens	Canon EF 28-135mm IS USM standard zoom
Shutter Speed	1/3200
ISO	800
Aperture (f-stop)	4.5
Focal Length	50mm
Pupil Diameter	11.11mm
Pixel Dimensions	2868x5184 pixels

Post processing for this image was done using Adobe Photoshop. The first thing that was done was cropping. In order to center the stream, the right side of the image was slightly cropped. Once this was done, the exposure was brought down a bit and the gamma correction increased slightly so that the next few adjustments could be made. First, the brightness and exposure were both increased by a small amount. The curves tool was used to increase contrast. Contrast was increased further using the contrast slider. Next, the hue and saturation were changed. The hue was adjusted to bring out the color in the stream, and the saturation was then increased to make it much brighter. The vibrance was also turned up to increase this effect. Next, the color balance was adjusted so that the background stayed a nice light brown tone while the purples in the stream were brought out more. Lastly, a slight dark vignette was placed around the edges to make the stream appear more central and really make it the focus of the image. The original image before editing can be seen in **Figure 3**.

Figure 3: Unedited photo

The feel as though the experiment was a great success. In fact, this was the first time that the experiment that our group set out to do actually worked how we wanted it to. Not only did the experiment work, but I feel as though the final image is very beautiful. It looks to me almost like a necklace or earring with jewels hanging off of it, which is very attractive. The individual droplets also have a great shine to them, which makes the image more interesting. The purple tones in the water are great, and I really like the bit of texture that the background adds. The post processing really enhanced both the background and the fluid stream, and I believe it did so for the better in both cases. While I do really like the resultant image and 'fishbone' look that I was able to achieve, it is clear from looking at **Fig. 2** that it could be a lot more apparent under the right circumstances. If I were to conduct this experiment again, I would create much better apparatus that did not depend on human interaction to run. That way, the jets could be generated perfectly at the right angle and velocity desired, and then sustained at those specifications to make the photographing easier. Aside from that, I do not think the image could have been made much better under the conditions our team had.

Works Cited

1. Bush, John W. M., and Alexander E. Hasha. "On the collision of laminar jets: fluid chains and fishbones." *Journal of Fluid Mechanics* 511 (1999): 285-310. Print.
2. *e-skola*. N.p., n.d. Web. 17 Apr. 2014. < http://eskola.hfd.hr/icm/download/IYPT2007/Jets.pdf>.
3. Strutt, John. "On the instability of jets."*Proceedings of the London Mathematical Society* 10 (1878): 4-13. Print.