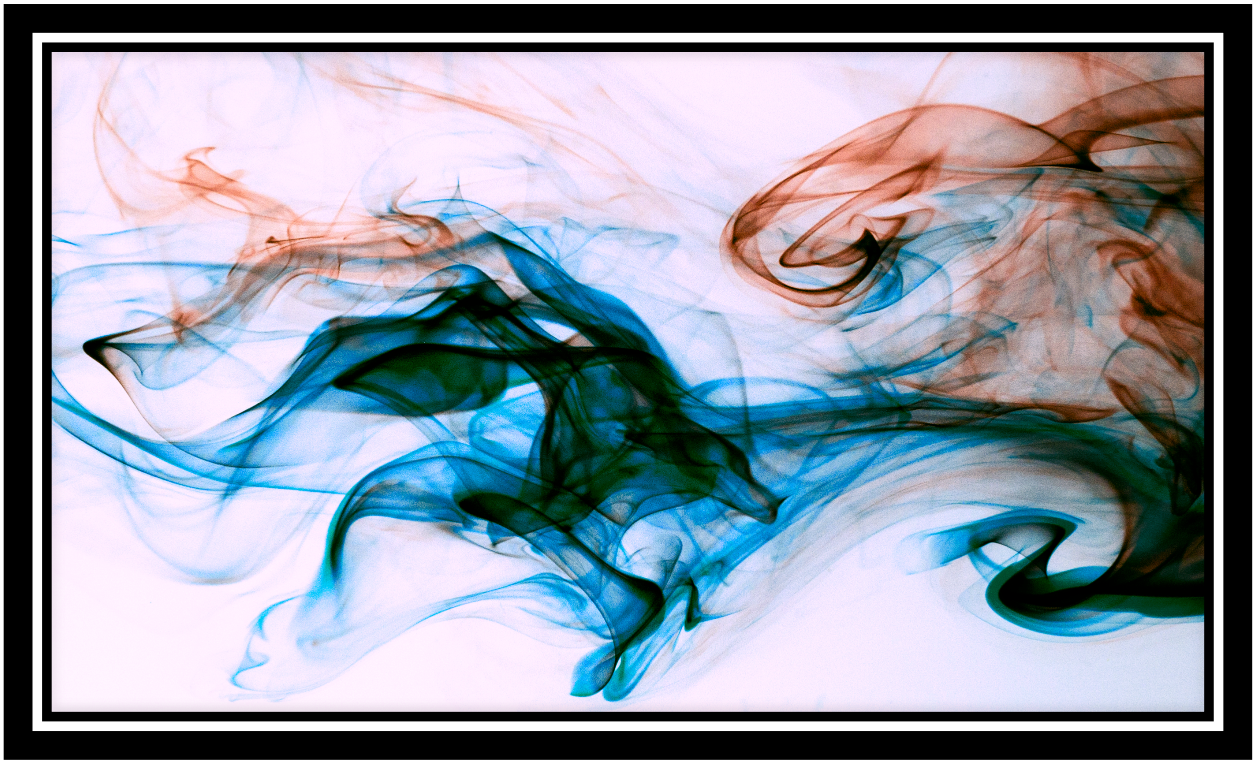
Team Project 1:
Kelvin – Helmholtz Instability

MCEN4151: Flow Visualization
March 18, 2011



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This image is the first of three that will be produced as team projects with the group consisting of Greg Kana, Andrew Scholbrock, Matthew Campbell, Kyle Manhart and myself. For the initial group assignment the team decided to pursue imaging a Karman vortex street. This is a unique flow around a cylinder in which eddies are created in the wake of the object, breaking off from the backside in an alternating fashion. This can be seen for a laminar case ($Re \approx 220$) in Figure 1. While the group experienced success in creating such a formation at more turbulent rates we were unable to capture the crisp, clean image similar to that seen in Figure 1. I felt as though such a phenomenon was better captured by video, given the scale of the flow, the turbulent nature, and the systematic movement of the eddies. Due to this I shifted the focus of my personal image to capturing the Kelvin-Helmholtz instabilities present in the same flow.

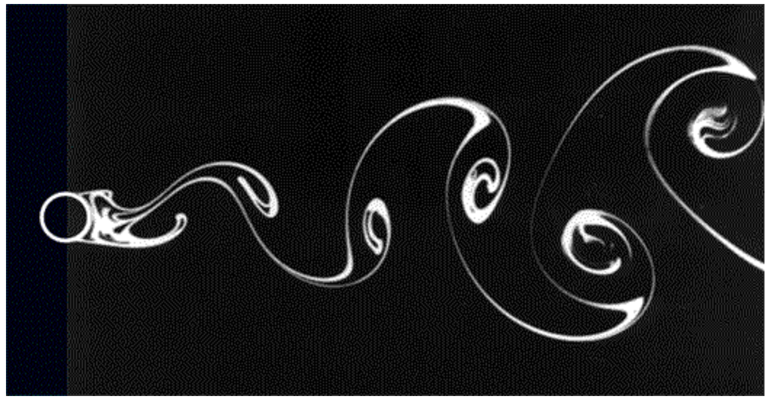

Figure 1: Laminar Von Karman Street (Van Dyke, M. An Album of Fluid Motion) [4]

This instability is similar to that of the Karman vortex street, except that the eddies do not alternate back and forth, breaking off of the backside of the cylinder. These instead formed on both the top and the bottom of the cylinder where the faster flow moving around the cylinder interacted with the slower flow behind the cylinder. This phenomenon was better captured by the still images than the Karman vortex street, as it was not as fast and turbulent. The distinct shape can be seen in Figure 2, where the shear force across the top of the cloud forms the indicative wave shape. This intent was easily realized by adjusting the speed of the flow that we were imaging to an appropriately low Reynolds number.

Figure 2: A cloudbank that shows the Kelvin-Helmholtz instability [3]

In order to control all of the parameters necessary to form the flow to an appropriate vision a fairly extensive setup was required. The main component of this setup was the flume, located in the ITLL basement. The flume is 2.5m long with a 76mm by 250mm channel [2]. The height of the water in the channel varied from one trial to the next and was adjusted by changing the volume flow rate and stacking spacers to block the flow. A 38mm diameter cylinder was cut from PVC pipe and friction fit within the flume to create the disturbance necessary to create the vortices. Dye was used to visualize the flow and was injected through a set of tubes. These tubes were attached to

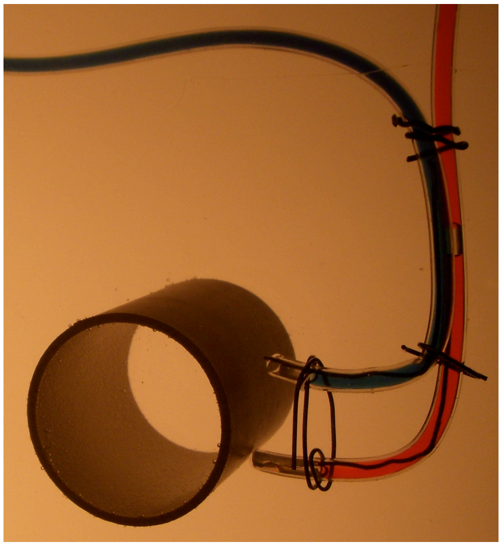

Figure 3: Dye injection setup

an injection device that allowed the user to set a volumetric flow rate for a set of syringes. Within the flume the two tubes were bent with paperclips at 90 degrees to align them with the flow and then they were attached using a small length of wiring (Figure 3). These tubes were then placed nearly incident to the cylinder so that the dye would impinge directly upon the flow along the surface of the cylinder.

In order to make the flume a more appealing image subject, the area surrounding the flume had to be prepared for shooting as well. First, the water for the flume was emptied and refilled so that there would be minimum contaminants. Next, the clear Plexiglas of was cleaned, inside and out to remove any streaks or films that would appear as distractions in a photograph. A white plastic screen was clipped to the outside of the back of the flume to provide a blank background and to contrast the dyes. The entire white background was lit with 4 halogen lamps to provide sufficient lighting and contrast. Over the course of the trials the volume flow rate, and thus the flow speed, were varied along with the injection rate of the dye, which was adjusted to match the average stream flow speed. This allowed for a range of flows to be captured, in the case of this image, a laminar flow over a cylinder. The temperature of the flow was not measured, but was at approximately room temperature (~20°C). This setup can be seen in Figure 4.

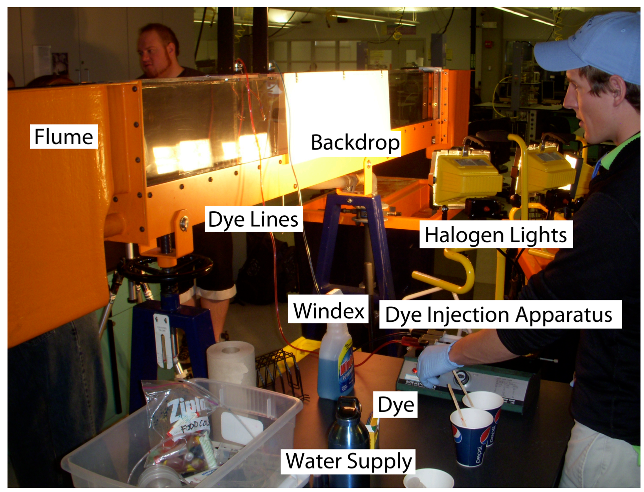

Figure 4: Setup, as viewed from behind

This setup allowed for ideal shooting of the Karman vortex street as well as the Kelvin – Helmholtz instability. The cylinder provided an appropriate disturbance to the free stream flow that created the unique instability shape. The flow directly downstream of the cylinder was slowed by the recirculation and eddying of the water flowing around the cylinder. The flow directly above and below the cylinder continues to move at the free stream value. This interaction between the faster and slower flows introduces a shear force between the two flow speeds. As the faster flow moves along the interface to the slower flow it feels the shear force from the slower flow. This results in the faster flow slowing down at the interface, which slows more and more of the free stream flow down. This interaction directs the flow towards the slower flow by turning it much the same way a river turns, with the outside of the corner moving faster than the inside. As the flow continues to progress this turning action results in a small eddy. This happens systematically along the surface of the interface of the flows, creating a row of eddies and the distinctive wave-like shape. This progression can be seen in Figure 5.

In order to have a Kelvin – Helmholtz instability the Miles-Howard condition must be satisfied [1]. This condition states that the Richardson number must be less than .25 at some point in the flow. The Richardson number is the relationship between potential and kinetic energy in the flow. The Richardson number can be calculated using the Grashof number and the Reynolds number in the following formula,

$$Ri = \frac{Gr}{Re^2}$$

where

$$Gr = \frac{g\beta(T_s - T_\infty)D^3}{\nu^2}$$

and

$$Re = \frac{VL}{\nu}$$

when g is gravitational acceleration, β is the volumetric thermal expansion coefficient, T_s and T_∞ are the surface and bulk temperatures, D is the diameter, ν is the kinematic viscosity, V is the free stream speed, and L is the length [5]. The speed of the stream was found to be V = .0129 m/s by measuring the time it took the flow to travel a set distance, as this information was available from a video taken of this specific trial. This resulted in a Reynolds number of 1.14 x 10^{-4}. In order to have a Richardson number less than .25 this means that the Grashof number has to be less than 3.27 x 10^{-9}. This may seem very small, but the Grashof number is temperature dependent, and in this situation the temperature of the surface of the cylinder was negligibly different than that of the flow, meaning that the Grashof number would be extremely small.

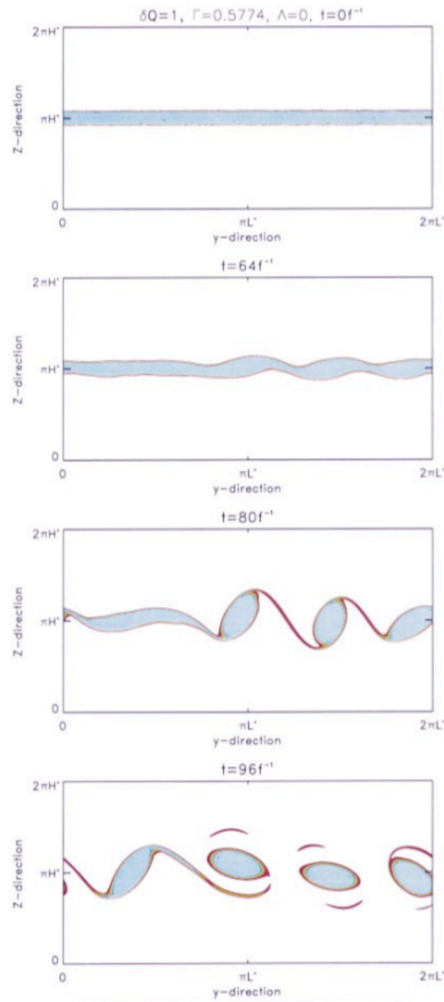

Figure 5: The development of the Kelvin - Helmholtz instability [1]

In order to fully appreciate this complex and intricate flow, dye was utilized to visualize the flow lines as they moved. The dye was injected into the stream flow immediately before the cylinder, one tube on top for one color, one tube on bottom for the other. This was done so that the dye would be at the interface of the faster stream flow and the slower flow in the eddy behind the cylinder. As to not disturb the flow the speed of the dye being injected was at or just below the speed of the rest of the stream. To achieve such strong colors 30 drops of dye were added to 120ml of water for the blue and 40 drops were added to 120ml of water for the red. To capture these dyes with the best brightness and contrast a backlit white backdrop was used. The flash on the camera was suppressed in order to avoid producing a large glare off of the Plexiglas of the flume.

To capture this image a Canon EOS 10D was utilized. This is a midrange camera between a point and shoot and a DSLR. This camera provided sufficient resolution with an appropriate lens. The specifications for this specific image can be found in Table 1. This image was shot from approximately four feet away from the face of the flume. The final shot has a field of view of 4.5 x 3 inches.

Photoshop was used extensively in order to increase the contrast and color content of the original image (Figure 6). The first adjustment made was to increase the brightness and contrast. This helped to bring the dye out from the background. Next, the curves feature was used to adjust the saturation of each color channel individually and then as an entire spectrum. In doing this it was possible to increase the color saturation in each dye as well as to make the background appear whiter. I decided that I liked the color scheme of the inverted version of the original image, but I did not want to invert the shading. To achieve the effect in the final image I created two separate layers from the original image. The top layer was inverted and then had the curves adjusted once again to bring out the colors. The bottom layer was converted to black and white and had the brightness and contrast adjusted. These two layers were then combined using color overlay, which takes the color information from the top layer and overlays it onto shading of the bottom layer.

Table 1: Camera specifications

Make	Canon
Model	EOS 10D
Date Time	3/1/2011 – 2:10 PM
Shutter Speed	1/180 sec
Exposure Program	Aperture Priority
F-Stop	f/11
Aperture Value	f/11
ISO Speed Rating	400
Focal Length	100.0 mm
Dimensions	2614 x 1496
Resolution	240 pixels/inch

Overall I would say that I am moderately happy with my final image. I was able to take advantage of an image that was not what we had originally set out to capture, as it aligned more with my personal aesthetic tastes. The physics are shown moderately well within the clear wave-like spiral, but the flow breaks down to turbulence shortly after. This did, however, result in the formation of a wolf-like shape in the center of the image. There are areas in which I would like to improve this image as well. First of all I would like to use a better camera, as the final image is slightly grainy. Also, I would like to have more clear dye trails, as they would better exemplify the flow. For future work in this area I would recommend shooting this phenomenon at a series of different Reynolds numbers.

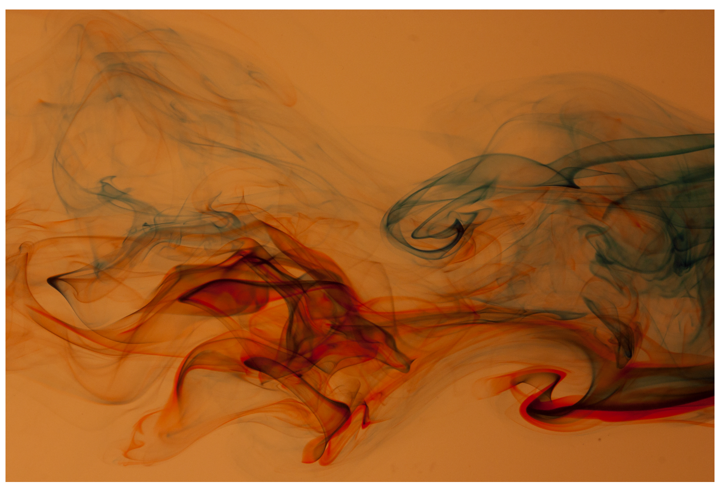

Figure 6: The original unedited image

References

[1] Esler, J. G., and L. M. Polvani. "Kelvin%u2013Helmholtz Instability of Potential Vorticity Layers: A Route to Mixing." *Journal of the Atmospheric Sciences* 61.12 (2004): 1392. Print.

[2] "Flume- Open Channel Water - ITL Program and Laboratory @ CU-Boulder." *ITLL*. Web. 15 Mar. 2011. <http://itll.colorado.edu/modular_experiments/experiment_directory/module.php?module_id=30>.

[3] Martner, Brooks. "SCATCAT 2001." *Forecast Research Branch*. Web. 15 Mar. 2011. <http://www-frd.fsl.noaa.gov/mab/scatcat/>.

[4] Van, Dyke Milton. *An Album of Fluid Motion*. Stanford, CA: Parabolic, 1982. Print.

[5] *Wikipedia*. Web. 15 Mar. 2011. <http://www.wikipedia.org/>.