Vorticity

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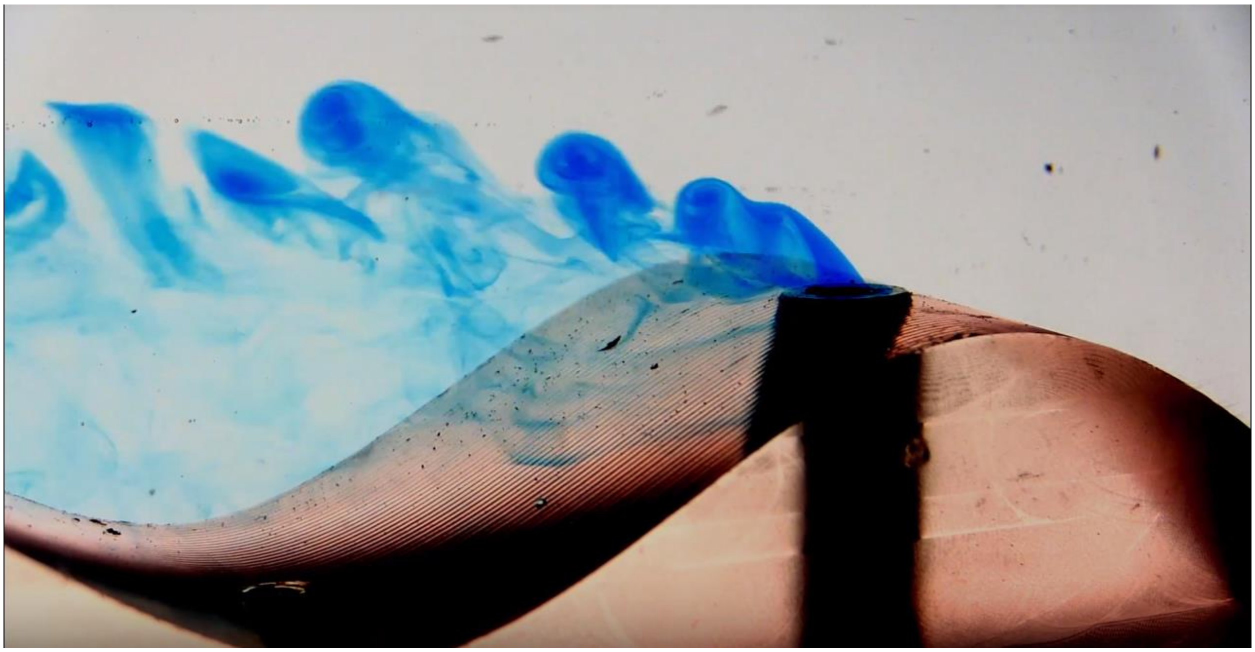

This video is titled “Vorticity” because it is intended to visualize the generation of vortices through velocity shear present in a flowing fluid. The observed phenomenon can be described by the Kelvin-Helmholtz instability. The flume located in the University of Colorado Boulder’s Integrated Teaching and Learning Laboratory (ITLL) was used to induce water flow past an obstacle, and food dye was injected through a hole in the obstacle. The injection of the dye meant that the “jet in crossflow” fluid phenomenon was also present in the video. The overall intent was to create a simple, clean series of images that clearly show the fluid flow with no distracting elements. The video format was chosen to visualize the time evolution of the fluid dynamics, showing their formation and how they travel downstream. For this visualization setup, food dye was obtained by Michael Sandoval, and both he and Cade Haley assisted with the setup and operation of the flume.

The flume consists of a narrow channel through which water flows at a constant, controllable freestream velocity. During the video, the water was flowing at approximately 1 liter per second, which is equivalent to 0.001 m^3/s. The cross-section of the water inside the flume was approximately 0.254 m by 0.127 m or 0.0323 m^2. This means that the freestream velocity of the water was (0.001)(0.0323) = 3.226×10^{-5} m/s. This gives a Reynolds number of

$Re = \frac{UD}{\nu} = \frac{(3.226\times10^{-5} m/s)(0.254\ m)}{1.004\times10^{-6}\ m^2/s} = 8.16$. This is very low and thus indicates that the flow was moving very slowly and thus was subject to strong viscous effects, namely frictional interactions with the bottom and side surfaces of the flume and the surface of the obstacle. The obstacle used was a double-humped sine wave. In the first few shots of the video, dye was injected into the flow perpendicular to the flow direction through a hole in the obstacle. This is an example of a jet in crossflow. The jet of injected dye contributes vertical momentum into the horizontal flow. As the two flows mix, the dominant horizontal flow drags the vertical flow along with it until the two flows are moving in the same direction. However, the addition of vertical momentum generates vorticity, or circular fluid motion, in the dye stream, leading to the formation of the many vortices that can be seen in the stream (Karagozian, 2014). Additional vorticity is generated in this region due to interaction with the obstacle leading to the Kelvin-Helmholtz instability, which will be discussed subsequently. Note that the red dye, which appears later in the video and was injected upstream of the obstacle and parallel to the flow, appears laminar and unperturbed by the obstacle. However, if it gets close enough, it gets caught in the recirculation zone located between the humps of the obstacle and rotational motion is induced. A recirculation zone is a stationary area of flow circulation that occurs downstream of a constriction of the flow (*Reclamation Library Glossary,* 2015). In this case, the first hump of the obstacle acts as a constriction. The water in the depression past this hump is stationary because it is not interacting with the freestream flow, but the water at the very top of the depression is dragged along with the freestream, causing a difference in horizontal velocity (velocity shear) from the bottom to the top and generating a series of large stationary vortices. The blue and red dye, as well as some of the particles suspended in the water, can be seen recirculating in the region; moving in a circular motion but not moving in the freestream direction. Another recirculation zone is generated after the second hump, as can be seen from the final shot in the video. At the interface between the freestream and the top of this region, velocity shear occurs leading to the Kelvin-Helmholtz instability. This can be most clearly seen in the video when the red dye passes across the obstacle. For simplicity it is assumed that two discrete layers of differing velocities are present, leading to a discontinuity in velocity, though this is not the case as the velocity actually varies smoothly with vertical position. At the interface between these two flows, a vertical perturbation in velocity will cause sinusoidal gravity waves, similar to ocean waves. This is because gravity and buoyancy forces attempt to restore equilibrium but often overshoot, leading to oscillation. However, due to the velocity shear at the interface, namely the fluid layer on top moving faster than the fluid below, the top of the wave is displaced further in the direction of the flow than the bottom, leading to a curling effect like ocean waves breaking near the shore (Cushman-Roisin, 2017). This produces vortices at the interface that travel with the flow as can be seen in the clips where red dye flows over the obstacle.

In order to visualize the flow characteristics of the water across the obstacle, which are normally not easily visible, a mixture containing food dye was injected through a hole in the obstacle as well as upstream of the obstacle. The dyes used were standard blue and red propylene glycol based food dyes that are easily found in most grocery stores. The dyes were mixed with isopropyl alcohol to dilute them and placed in syringes. The syringe containing the blue dye was attached to a section of plastic tubing that was connected to the hole in the obstacle, and it was injected approximately perpendicular to the freestream velocity of the water. A short length of tubing was attached to the syringe containing the red dye and this dye was injected upstream of the obstacle and approximately parallel to the freestream velocity. The lighting for the video came primarily from a 500 W twin-head halogen work light positioned approximately 6 ft behind the flume. A white translucent background was placed in front of the work light but behind the flow to provide a solid-color background and to decrease the amount of light passing into the camera. This provided diffuse backlighting, and the ceiling lights near the flume were turned off so that the dominant source of light was the backlighting, though ambient light from other areas of the lab unavoidably contributed to the lighting environment.

The video was captured using a Canon Vixia HF G20 digital camcorder, shooting a 1920 x 1080 pixel image at 24 frames per second. The camera has a fixed lens with a variable 4.25-42.5 mm focal length and a maximum aperture of f/1.8. The focal lengths used to capture the various shots in the video ranged from 20 mm to 30 mm; it is difficult to report the actual lengths because the camera does not display them. The distance between the camera lens and the front panel of the flume was maintained at approximately 1 foot (30.48 cm). The camera was kept very close to the subject to capture the small details of the flow and to ensure that no potentially distracting elements, such as the edges of the flume or the surface of the water, were captured in frame. The horizontal field of view ranged from 10 in (25.4 cm) at the largest to about 4 in (10.16 cm) at the smallest. The aperture, shutter speed, and ISO gain were f/3.7, 1/60 s, and 2 dB, respectively, though their values varied slightly between shots. These settings were chosen to take advantage of the strong backlighting of the scene because they allowed the background to appear more homogenous while allowing the flow in the foreground to be both vibrant and in focus. The video was edited and post-processed using the Hitfilm 3 Pro software. Though the exact processing differed between shots, in general the contrast of the videos was increased slightly to accentuate the richness of the dye color and make the obstacle more visible against the background. A “crush blacks and whites” effect was added to all clips of the blue dye, which allowed the dark and light pixel values of the image to be adjusted separately, effectively fine-tuning the contrast until the desired result was achieved. The color of the dyes were not shifted or changed. A royalty-free music track, “Alien Chaos,” retrieved from Pond5.com was included in the video.

Though I was initially apprehensive about how this video would turn out due to the difficult lighting conditions during the shoot, I was pleasantly surprised upon completion of the editing and consider this video to be my favorite piece of flow visualization that I have done to date. The vortices that formed in the dye are the key element and are very visible and mesmerizing. I only fully appreciated them as I was editing the video and thus decided to place the emphasis on these vortices and the physics behind them, titling the video “vorticity.” I also strove to demonstrate the difference between the flow close to the obstacle and that above it by showing the red dye flowing laminarly above and being caught in the recirculation zone between the two humps of the obstacle. I believe I was very successful in this, and I was able to create relatively clean, simple images that conveyed precisely what I wanted them to. However, I do wish there was less debris in the water, which interfered with the simple aesthetic I was going for. Furthermore, I really enjoyed the piece of music that I chose to include with this video, as it was calming but slightly strange and alien, just like the flow. I was careful to edit the video so it would match the beats and mood of the music, with the dye injection beginning as the melody begins, an ominous flow of red dye and strangely shifting lighting as it reaches its highest intensity, and cutting to black as the music ends. I was very satisfied with the way this edit turned out and I achieved exactly what I intended.

References

Alien Chaos. Pond5.com. MP3. Retrieved Nov. 16, 2015.

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