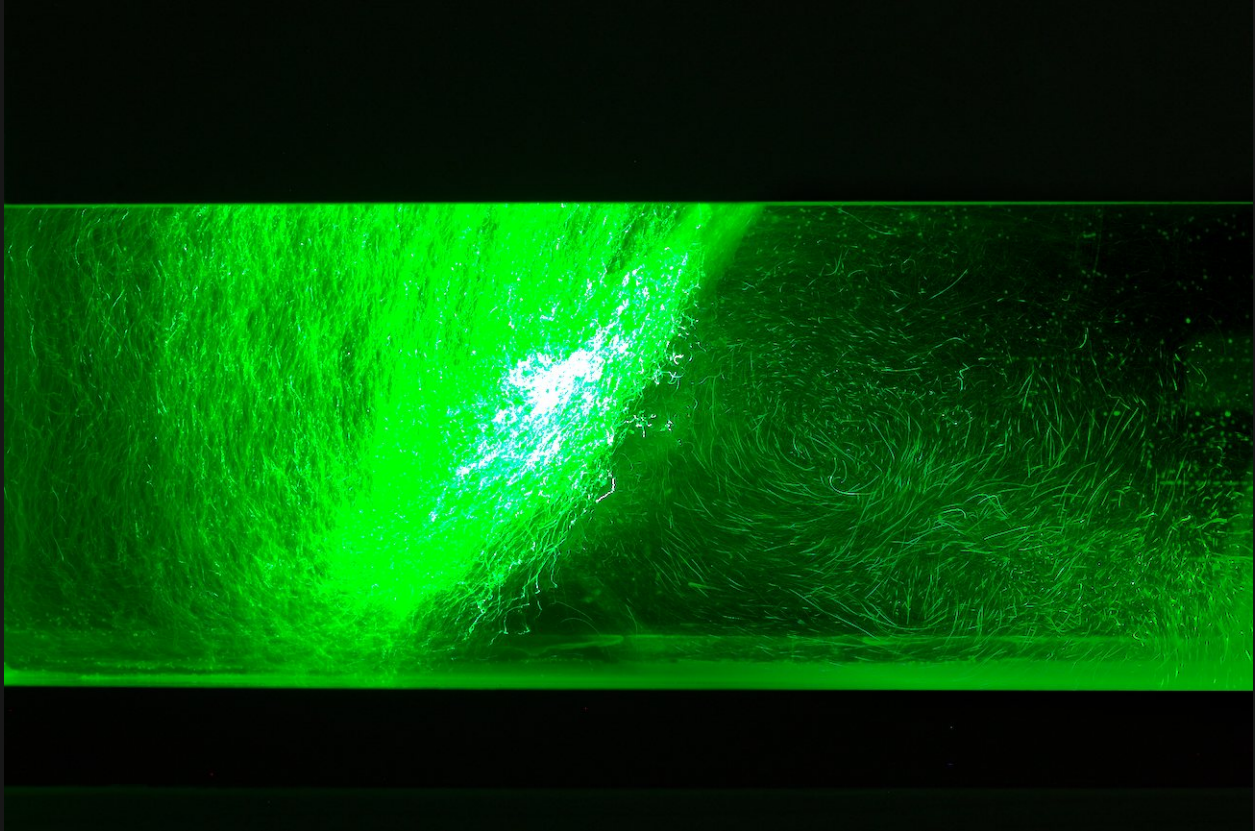


CVEN 5153 Flow Visualization Report

Team First Project

Luke Parker, 27 SEPT 2026

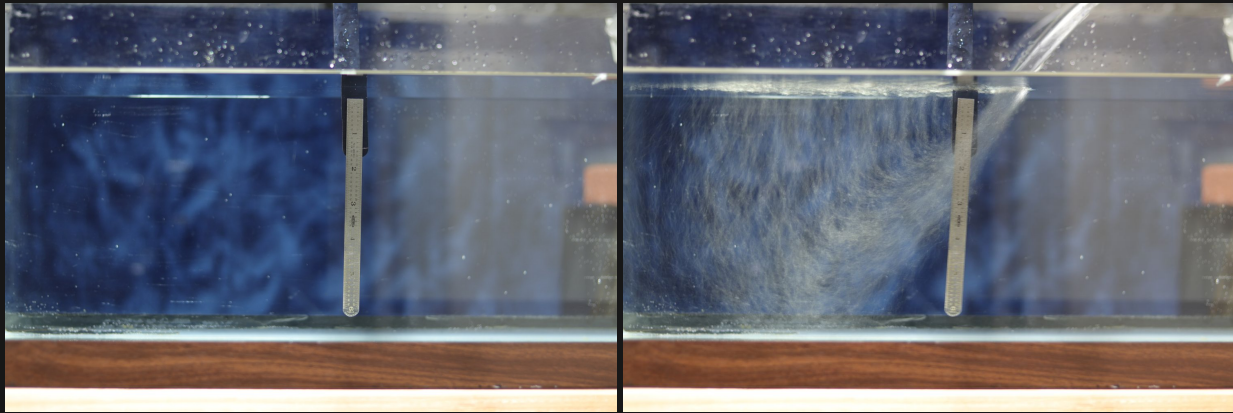
<https://www.flowvis.org/2026/09/06/luke-parker-team-first/>



Please see the post on FlowVis.org linked above for a higher-resolution version of this image, as the JPG compression algorithm is particularly insulting when processing the fine detail, high-contrast areas of this image.

This image was created for the Team First Project. The scientific intent was to capture the velocity field that is created when a stream of water moving through the air encounters a stationary body of water and mixes with it turbulently. The artistic intent was to capture this velocity field in a way that catches the eye, clearly illustrates velocity vectors across the field, and is visually appealing enough to be displayed as an art print. In order to achieve this, a fish tank was used for the stationary body of water with a bilge pump immersed within it, circulating the water up through a flexible vinyl tube to flow into the tank from a short distance above the surface of the water. (Numerical values will be provided in future paragraphs). In order to capture the velocity field, the air bubbles pulled into the tank by the stream were used as marker particles. A laser sheet was constructed under the fish tank, such that bubbles present in a vertical plane down the length of the tank refracted the laser and became visible to a camera observing the tank from the front. A dark fleece blanket was placed a few feet behind the tank to provide a uniform background, and various other measures were taken as necessary to contain the laser for safety and to prevent extraneous reflections from reaching the camera sensor. By taking a long-exposure photograph, the bubbles become short traces along the streamlines in the flow, which provides both excellent data for scientific analysis and a visually stunning artistic effect.

The following two calibration images were taken with the same field of view and focus as the final image, with a ruler for scale. The left image was taken with the pump off to allow the ruler to be stable for spatial resolution calculation, and the right image shows the flow with ambient illumination, where the discharge from the pump is visible above the water line. To reduce overexposure due to laser reflections in the final image, shutters made from scrap pieces of 1/8" medium density fiberboard were placed along the waterline at the top and the glass edge at the bottom.



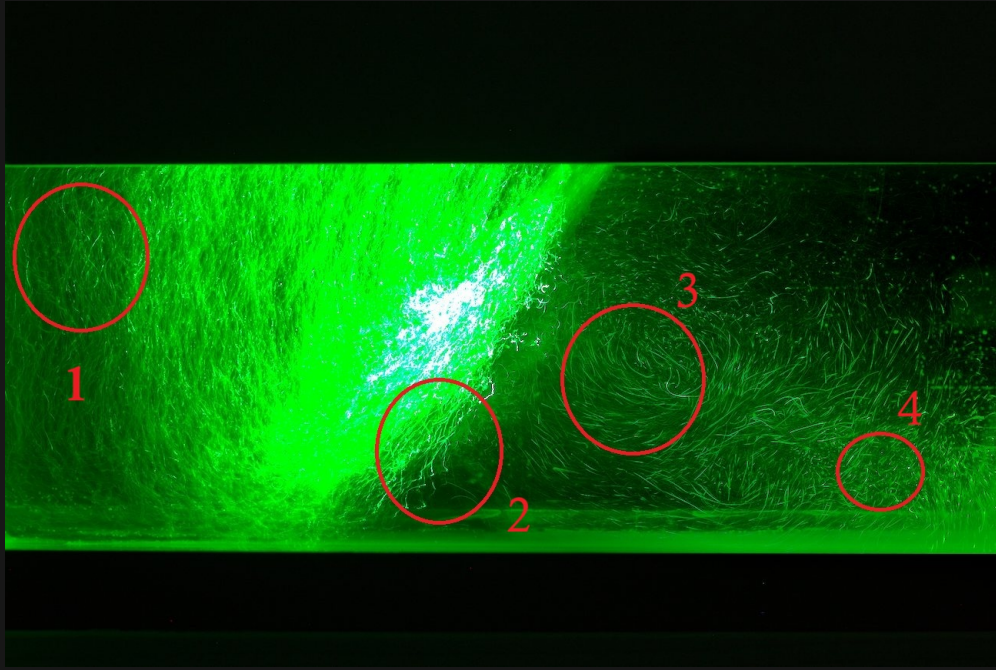
Readers should contact the author with inquiries if they desire the full resolution calibration images, which are png format and 6000x4000 pixels. The images included here are compressed jpg format and 1500x1000 to comply with flowvis.org file size requirements. For reference, the ruler is 6 inches and is fully submerged. In the full resolution images, the increments of 1/64th of an inch are clearly resolvable, and allow for the determination to be made that the spatial resolution of the final image is 344 pixels per inch, or 0.0029" [0.073mm] per pixel. The ruler was removed in the final image both to improve artistic appeal and to prevent unwanted flow disturbances from emerging due to the flow encountering a solid obstacle. From these numbers, it can be determined that the 6000x2400 pixel flow field in the final image has a size of 17.4" wide by 6.97" high.

To generate the flow, a Rule 24DA electric bilge pump rated for 6 GPM open flow and 12ft H₂O maximum head pressure at 12V was submerged in the 12"x12"x29" 18 gallon fish tank, with a 10'x5/8" ID flexible vinyl tube running from the pump outlet up out of the tank. The tube was secured to a tripod and positioned such that the last 18" of tube were horizontal and about 3" from the top of the fluid in the fish tank. Positioning the tube in this manner provided enough height that the exiting fluid mixed a significant amount of air into the tank, and enough horizontal velocity to create a scientifically and visually interesting flow.

In order to capture a vertical plane slice of the flow for the final image, a laser-sheet setup was used. This technique falls into the category of marked boundary techniques. The collimated light source used was a consumer "low-power" star-pointing green laser which claims to have an output power of <1000mW. This produced a tightly collimated beam with an estimated diameter of 0.1mm, which was refracted through a 4mm borosilicate glass stirring rod to produce a laser sheet with a thickness of about 0.5mm. The fish tank was placed on a support structure such that the bottom pane was about 22" up from the floor, and the laser sheet assembly was positioned underneath it such that the sheet ran parallel with the length of the tank, about 0.5 inches in front of the center of the flow discharge. The laser sheet was positioned in front of the discharge to allow the flow effects in the right half of the visual field to be observed, as when it was coincident with the centerline of the flow the density of air bubbles was such that the images produced were bright white overexposed blobs surrounded by pitch dark void.

One of the clearest resolvable quantities from the image is velocity. Since the shutter speed is a known 0.8 seconds, and the spatial resolution is known at 0.0029 inches per pixel, calculating velocity at various points in the flow reduces to an exercise in the estimation of the path length of particle traces, a technique known as particle-image velocimetry. For this report, the technique was completed in a very analog manner: the full resolution image was placed on a large screen and zoomed in on a particular particle trace. The trace length was then measured with calipers, the number of displayed pixels per physical screen inch at the given zoom level was recorded, and from there the number of pixels in the trace could be found. Four regions of interest were measured, as follows: The far left region (1) where the bubbles

are rising had traces of approximately 670 pixels; middle-left region (2) at the bottom of the jet had traces of 320 pixels; the middle-right region (3) where the large vortex can be seen had traces of 250 pixels; and the bottom-right region (4) where the flow is nearly stationary had traces of 113 pixels. The annotated image below indicates the regions of interest:



From the above pixel counts, the following velocities were found:

Region	1	2	3	4
Velocity (cm/s)	62	30	23	11

Using these velocity numbers, we can estimate many things. No fluid flow discussion is complete without a mention of Reynold's number, and for this flow it reveals a very interesting phenomenon. Stepping through the calculation, $Re = \frac{VL}{\nu}$, and so using the water depth of $6.97 \text{ in} = 17.704 \text{ cm}$ as our characteristic length and a water kinematic viscosity at 73°F room temperature of $9.381 \cdot 10^{-7} \frac{\text{m}^2}{\text{s}} = 9.381 \cdot 10^{-3} \frac{\text{cm}^2}{\text{s}}$ from the ever-handy Engineering Toolbox [1] we find that in the various regions of our flow, our Reynold's numbers turn out as the following:

Region	1	2	3	4
Re	19.2	12.0	7.1	3.4

The reason this result is so interesting is that even though the image appears to be quite chaotic at first, the Reynold's numbers across all parts of the flow are well under the laminar flow cutoff. What this reveals is that for a particle's local surroundings, turbulence is low and flow is quite smoothly aligned. This is mirrored visually in the smoothness of each individual particle trace over the 0.8 second exposure, as the traces are not jagged or sharp but rather follow smoothly curving paths. The swirling and eddying, therefore, are indicative of uniform bulk fluid motion, and can be concluded to be a product of the geometry of the setup. The artistic impact of the image is greatly magnified by the laminarity of the flow, since while scientifically a field of chaotic, jagged particle traces might render the same kind of data as was found here, it simply would not be as beautiful or as striking.

Another interesting observable is that in the right half of the flow field, many of the bubbles appear to be either stationary or moving horizontally. This is counter to the common intuition that bubbles always rise, and so a paper examining particle residence time in eddies [2] was consulted to potentially explain the phenomena. This paper was

mainly focused on the retention of biological particles in the eddies (they are interested in a abnormal biological hotspot), but the conclusions relevant to this report are that even low strength eddies do have significant holding power to retain particles. In order to quantify the eddy in this report, the nondimensional vorticity could be calculate for each region, however, this would be out of scope for this report. Vorticity is a measure of, for lack of a better word, spinny-ness, and is calculated as follows: $\omega = \nabla \times \vec{V}$. Nondimensionalization is a simple matter of multiplying by a characteristic length and dividing by viscosity. Having a measure of vorticity would allow quantitative discussion of the way that various regions of the flow interact with one another, however, a qualitative analysis can still provide some insight. Qualitatively, it appears that as the stream enters the tank, the angle at which it is moving pulls the surrounding flow into it from the right. This then propegates, and as the fish tank is a closed system, the flow on the far right of the tank has to flow up to compensate for the downward mass flux generated by the jet. The net result is the clear circular eddy pattern in the right half of the image.

The final phenomenon that will be discussed is the very clear correlation between bubble size and strength of refraction. The final image has been adjusted to compensate for this phenomenon in order to preserve the artistic appeal, however, the unedited image farther down in this report highlights the correlation well. Much difficulty was had attempting to capture a faithful image of the flow due to this, as an exposure value that detected the smaller bubbles in the right half of the image would result in an entirely overexposed jet. The solution to this that was achieved is discussed in a following section. The correlation between bubble size and light refraction has in fact been discussed at the IEEE Photonics Conference in 2017, where researchers concluded that larger bubbles can entirely block a communications beam, and smaller bubbles are less likely to do so [3].

The visualization technique has already been discussed in great detail, however, to collect it all in one place it will be reiterated here. No dye or solid particulate was added to the working fluid, which was Boulder Municipal tap water. Particles for the marked boundary technique were created via the natural emulsion of air into water that happens when a jet impinges on the surface of a pool, and the particles were illuminated with a 0.5mm laser sheet generated from the refraction of a 520 nm green laser around the edge of a 4mm borosilicate glass stirring rod. The geometry of this system is described in a preceding section, and the result is that the distance from the light source to the flow is effectively zero since the bubbles are essentially made to be self-luminous as they refract the laser sheet toward the camera. All other sources of environmental light were removed, as the experimental setup was constructed in an indoor environment where the lighting conditions could be tightly controlled.

The following table contains technical data on the camera system used:

Camera	Canon T7i
Lens	Canon 50mm f/1.8 EF-STM
Original image size	6000x4000px
Post-editing image size	6000x4000px
Final image size (FlowVis.org)	1300x866px
ISO	200
Aperture	f/5
Shutter speed	0.8 sec
FOV size	17.4" wide x 11.62" high
Object-lens distance	39"

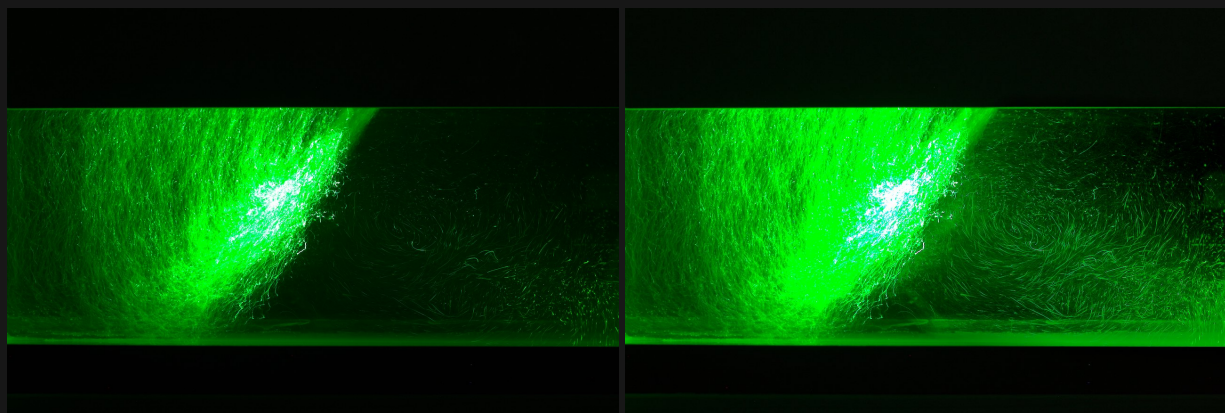
A significant amount of iteration was required to arrive at the above parameters. As discussed above, the irregularity in bubble size and density across the flow field resulted in the laser being refracted significantly more in certain areas than others, and this showed up in any image taken, regardless of shutter speed or exposure settings, as a steep gradient in brightness across the image. That in turn meant that for almost every combination of settings and lens, the following would occur: The middle portion of the image would be overexposed to the point of saturation, the left half of the image would be underexposed to the point where nearly every pixel value was (0,0,0), or both at the same time. The settings listed are one of the few effective compromises that result in a workable final image, however, the reader will still note that there is a small overexposed portion of the image directly in the center of the image corresponding to the area with the highest density of bubbles, and a small region that is almost entirely unexposed in the upper

left corner. The outstanding quality of the remainder of the image outweighed these defects since these regions are small, they do offer some small amount of insight into the flow, and they do not detract from the artistic value of the image.

Since a major goal of the class is to generate science that is also beautiful, additional post-processing was done to the image beyond that which was strictly scientifically necessary. The goal of this postprocessing was to even out the exposure across the image, and highlight the particle traces in the flow. Darktable was used as the software of choice for editing, and the edits made were as follows:

- 1) A mask was applied to the right section of the image (aligned with the diagonal of the flow)
- 2) The exposure of this region was increased by +1.353 EV. This resulted in the previously-invisible regions where any light had been captured becoming vividly apparent.
- 3) An RGB curve was applied to this region, to slightly increase the pixels between 1 and 64 brightness units. This resulted in the areas behind the bright streaks brightening, which gives some context and body to what was otherwise extremely bright streaks on a near-black background.

The author is able to provide Darktable's xmp file containing the edits made, upon request. Please see the following images for the effect of the above edits. The left image is unedited, and the right image is a smaller version of the one visible on FlowVis.org:



As discussed, the image reveals the flow patterns that occur in a stationary body of water when it is struck by a horizontally moving stream from above. The author appreciates the high contrast and clear, smooth lines of the image, and is only displeased by the limitations of optical physics that cause exposure balance issues. Further questions have begun to accumulate, such as questions about how the flow would change when encountering an obstacle, or how the flow would change in a truly semi-infinite field (such as if the same apparatus was deployed in a swimming pool). Despite these reservations and questions, the original intent was fulfilled very nicely. The next project will be used as a chance to answer some of these questions and address some of the intrinsic limitations with the setup used here, namely via the use of true self-luminous particulate rather than a laser system.

The image discussed in this report, along with supporting images, calculations, and writing, are the sole work of Luke Parker. Reid Benfield and Cutler Connaughton gave invaluable insight during the ideation phase, and no other collaborators, human or otherwise, participated in the production of any of the above work in any way whatsoever.

References

- [1] The Engineering ToolBox, "Water - Dynamic and Kinematic Viscosity at Various Temperatures and Pressures.", 2004. URL https://www.engineeringtoolbox.com/water-dynamic-kinematic-viscosity-d_596.html.
- [2] Hudson, K., Oliver, M. J., Kohut, J., Dinniman, M. S., Klinck, J. M., Moffat, C., Statscewich, H., Bernard, K. S., and Fraser, W., "A Recirculating Eddy Promotes Subsurface Particle Retention in an Antarctic Biological Hotspot," *Journal of Geophysical Research: Oceans*, Vol. 126, No. 11, 2021, p. e2021JC017304. <https://doi.org/https://doi.org/10.1029/2021JC017304>, URL <https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2021JC017304>, e2021JC017304 2021JC017304.
- [3] Oubei, H. M., ElAfandy, R. T., Park, K.-H., Ng, T. K., Alouini, M.-S., and Ooi, B. S., "Performance evaluation of underwater wireless optical communications links in the presence of different air bubble populations," *2017 IEEE Photonics Conference (IPC)*, 2017, pp. 441–448. <https://doi.org/10.1109/IPCon.2017.8116177>.