University of Colorado - Boulder

MCEN 5151
Flow Visualization

Team First Report: Turbulence in Blue

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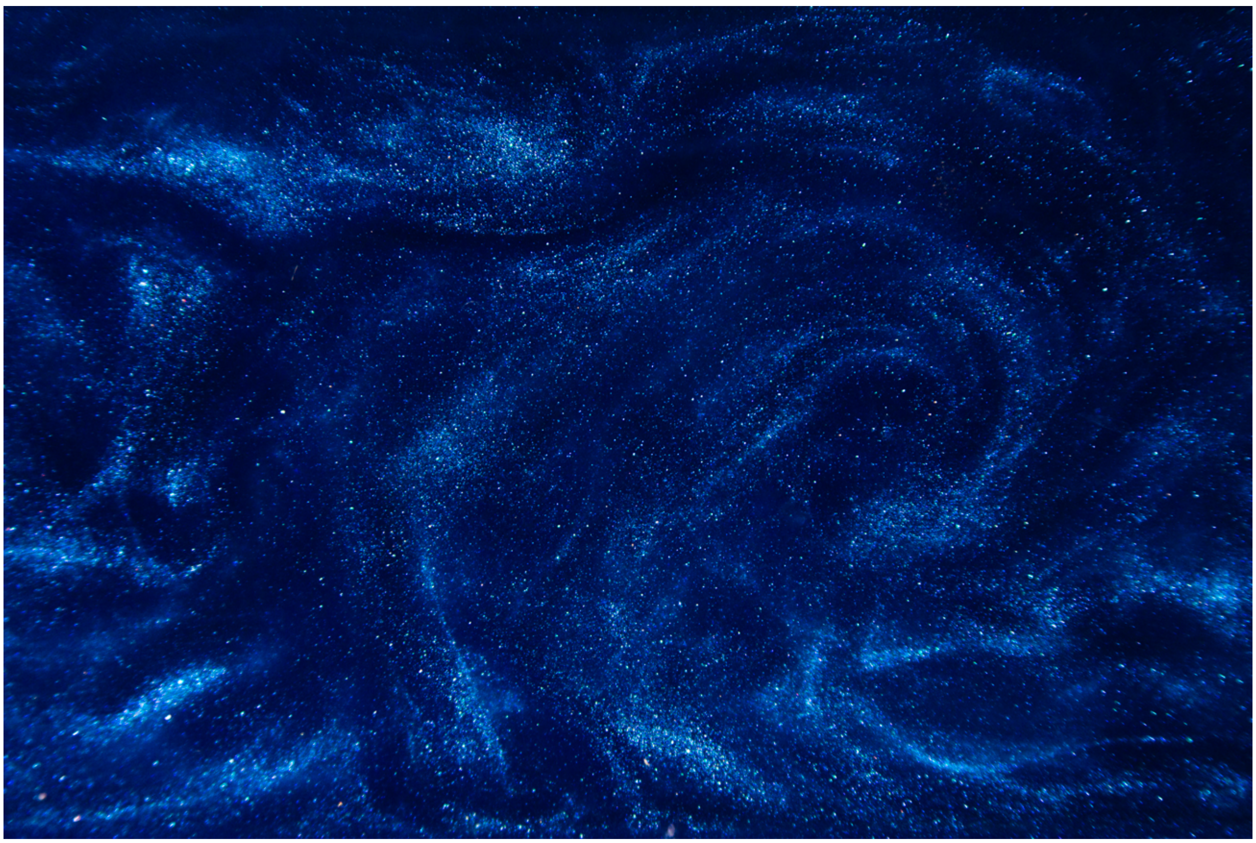

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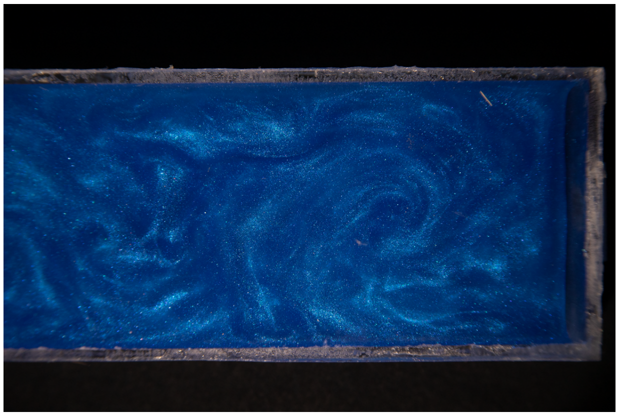


Figure 1.1.1: Original Image

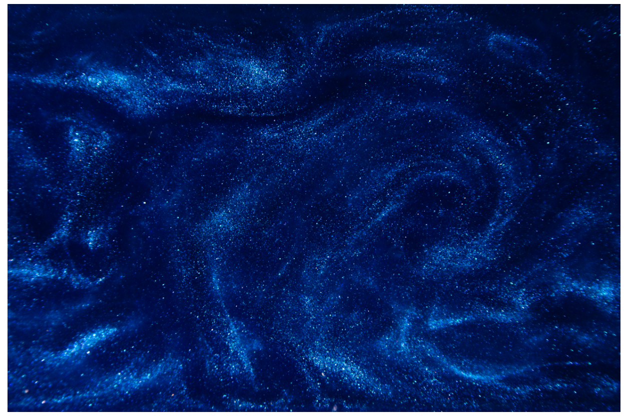


Figure 1.1.2: Edited Image

1 Introduction

1.1 Image Summary

This image represents a first-effort foray into custom-built flow-visualization tanks. Acrylic sheets [5] held together with Weld-On #4 [8] and copious amounts of silicon sealant [7] make up the tank, which holds tap water with about 1/4 teaspoon of blue mica powder [6]. The tank is fully sealed, so it can be easily tiled into any orientation. This allows for fluid mixing via several methods. Shaking the tank vigorously mixes the mica powder and water pretty well, but the report image captures a flow generated in a different way: the tank is mostly full of water, but has a small bubble of air trapped in there as well. Tilting the tank causes the bubble to move rapidly across the surface of the water, racing to stay above the more dense water. As the bubble slides across the water, it induces traveling vertices which shoot through the water volume, and which are very visible as they disturb the suspended mica powder.

For reference, original unedited image is shown in Figure 1.1.1. Both images are in a landscape orientation, but the camera was in a portrait orientation; Gravity is acting to the left in these images, in the sense that "up" is to the right, and so that's where the aforementioned bubble is visible in the unedited image. The processed image is cropped to show approximately the middle third or so of the original fluid flow; this highlights the largest vortex pattern in the flow at that point in time.

The original image was show on a Canon EOS 6D Mark II using an EF 28-135mm f/3.5-5.6 IS lens. The camera was set to a 1/250 second exposure, f/5.6 aperture at 135mm focal length, and an ISO of 1250.

The final image was cropped and transformed (so the tank walls appeared perpendicular to the image frame), a small scratch on the tank front was edited out, the lens was corrected for, the point curve was altered to increase contrast, and highlights, shadows, and saturation were turned down, all using Adobe Lightroom Classic. Before export, the final edited image was algorithmically upscaled, boosting the pixel density of the cropped image back up to avoid the loss of detail often associated with crop-zooms.

1.2 Motivation

The original concept for this image was to capture convection currents. The tank is long and thin with this in mind; heating the bottom should drive long convection currents up and down the length of the tank, clearly visualized by the mica powder. It proved difficult to heat the water sufficiently to generate currents strong enough to lift the mica powder. Future work may involve embedding heating elements into the tank it self. During testing, the bubble trapped in the tank presented an alternative method of generating cool flow patterns. It was originally not meant to be there, and was the result of a small leak in the tank. The fact that the tank cannot be statically placed in front of the camera at all times and the rapid decay of the bubble-induced flow patterns made this flow a challenge to capture as well, but the bubble vortices ended up revealing a less commonly considered set of flow physics, and hopefully produced a beautiful image.

2 Methodology

2.1 Test Setup

The test setup consists primarily of a 1" x 3" x 10" sealed acrylic tank containing approximately 1/4 tsp of navy blue mica powder suspended in approximately 450 ml of water, along with a small air bubble. The tank rests on a flat surface with guide blocks to the left and behind, such that it is physically constrained in all rigid body degrees of freedom. The surface and guide blocks are draped in a black cloth to create a consistent background. The tank is lit from the right ("down" in the report image) with by a white LED lamp of unspecified temperature and brightness. A tripod holds the imaging camera in front of the tank stand setup, keeping the end of end of the lens approximately 19" from the front surface of the tank. Interesting flow patterns can be generated in the tank by picking it up and either shaking it, for a very chaotic mixing of the mica and water, or tilting it steadily over 180 degrees one way and then 180 degrees back the other way, for a decaying-expanding vortex pattern in the mica-water mixture. The latter method is what generated the flow seen in the report image.

2.2 Visualization Technique

The imaged flow is primarily visible because of the suspended mica particles; the powder is what gives the fluid its blue color, making it a little opaque by catching the light. The mica powder is more dense than water, and does tend to settle to the bottom of the tank over a few minutes time. It is not dissolved, merely suspended in the flowing water, and so it tends to vary in bulk density across the flow field. This means that, depending on the relative speeds of moving water, the mica powder either bunches up or spreads out into areas of higher and lower mica density. This is what makes the flow visible in a static image: different amounts of mica in various areas of the flow reflect the light more or less, creating areas of more or less intense blue. In areas of particularly high mica concentration, the flow appears more shiny as well as more blue.

Figure 3.0.1: $t = 6 : 07\ s$

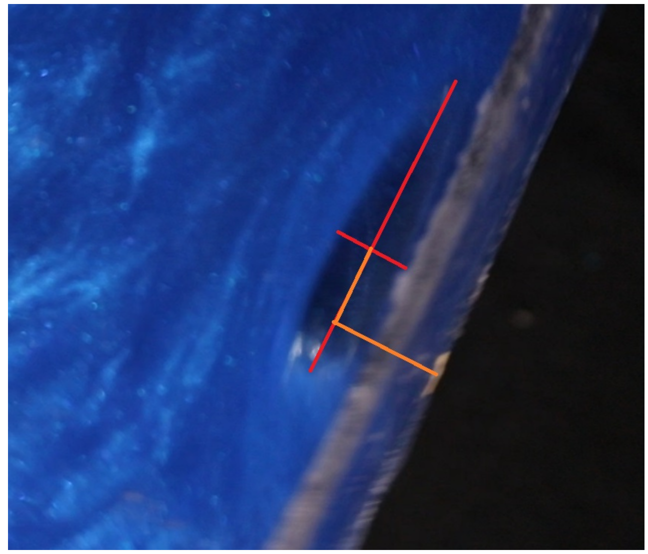


Figure 3.0.2: $t = 6 : 08$

2.3 Photographic Technique

The image was captured using a fairly inexpensive, unstable tripod. The camera is fairly heavy, and so the setup was sensitive to any external forces; pressing the shutter button moved the camera enough to un-focus and blur the flow. Additionally, it can be cumbersome to pickup, shake, and set down the water tank and then operate the camera in time to capture the most interesting flow, which dissipates away quite quickly. A remote trigger, which would solve the stability problem, would not necessarily solve the timing problem. Thus, the camera was set to capture a stream of images at 2 hertz for 20 seconds. Triggering the capture stream, mixing the fluid, and setting down the tank, and then gently adjusting its position on the table (for focus and centering) led to between 5 and 10 ”good” images per 20 second imaging pass. After about that much time, the flow slows down a lot and becomes less visually interesting.

3 Flow Discussion

The flow image primarily captures a moment in the life of a quickly decaying vortex field. The field started out life as a mostly still volume of water with mica powder distributed evenly throughout, contained within a long, thin tank. Quickly turning the tank on its head changes everything; the tank is flipped fast enough that the air bubble nominally at the top of the tank is now at the bottom. Buoyant forces quickly dominate, and the bubble rushes up the side of the tank (or, along the top from left to right, as the image is oriented). Water is about 1,000 times more dense than air, so naturally the bubble floats up quite quickly. Its passage through the water induces a large number of small vortices as well as a large bulk fluid flow in the direction the bubble traveled. The small vortices quickly decay into larger ones, and the flow becomes dominated by a large vortex taking up most of the tank's width. This is the vortex presented in this report.

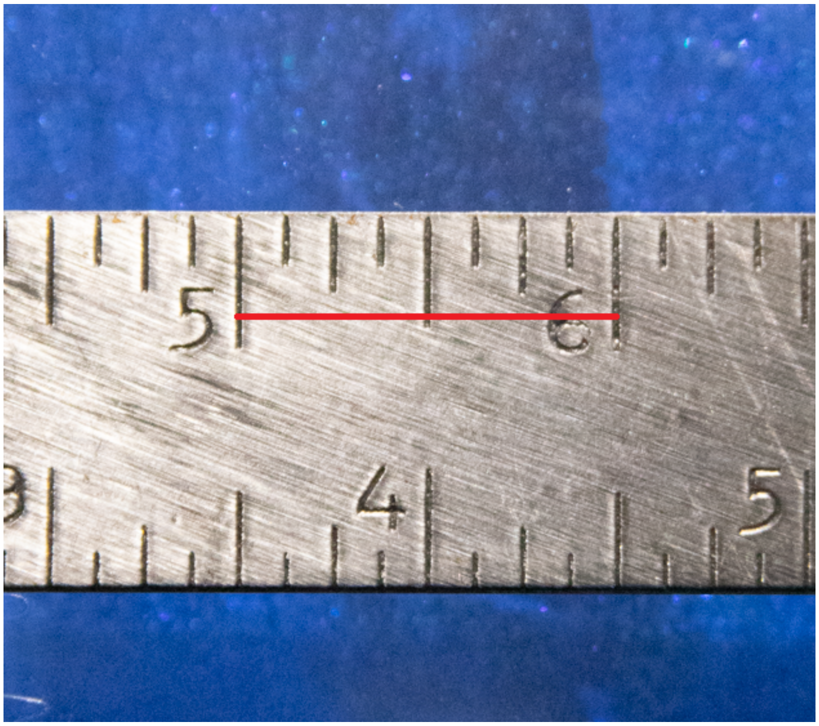
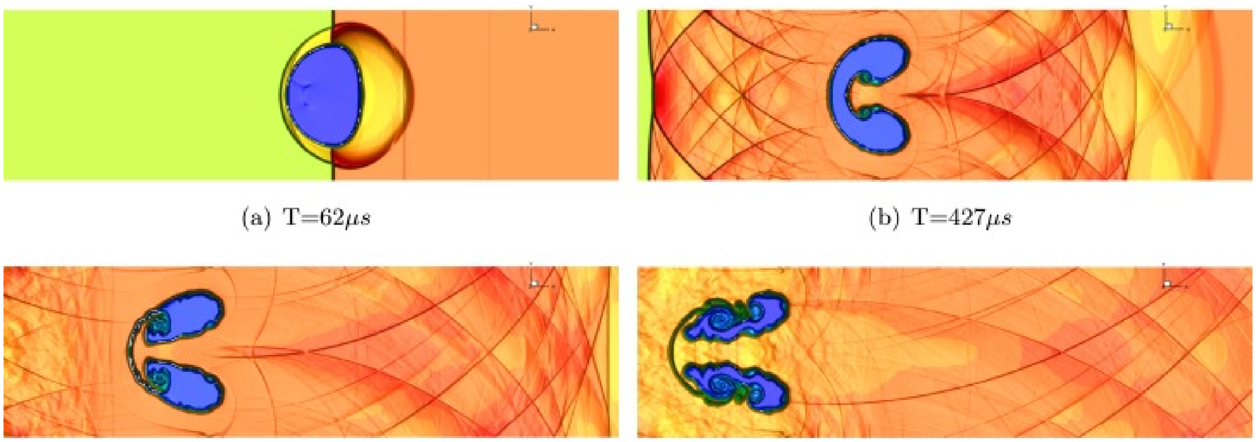


Figure 3.0.3: These images have a spatial resolution of about 294 px/in

It is tempting to say that the flow is turbulent (as the title of this report does, actually); often the phrase is brought to mind when a flow has lots of vortices moving independently from the bulk fluid motion. In this case, it is a wholly incorrect description. A fluid is considered "turbulent" if its flow has a Reynolds number above some critical value; in the case of water $Re_{crit} \approx 3500$. Neglecting the effects of the mica and assuming a density of $\rho = 1000 \ \frac{kg}{m^3}$, a dynamic viscosity of $\mu = 0.001002 \ \frac{kg}{ms}$ and a characteristic length of $L = 0.05 \ m$ (about two inches), the water in the tank needs to be moving at roughly $0.07 \ \frac{m}{s}$ to be considered turbulent. At the point in time captured by the image, this is definitely not the case (the flow is almost stopped by this point).

The flow may have been turbulent to begin with, however. Figures 3.0.1 and 3.0.2 show the bubble as it is moving up the tank approximately 1/60th of a second apart. The speed of the bubble along the surface of the water is estimated using a mark on the tank as a reference point and the image shown in Figure 3.0.3. These images all have a spatial resolution of approximately 294 pixels per inch. The approximate center of the bubble moves roughly 111 pixels (0.38 inches or 9.65 millimeters) in the 1/60'th of a second interval. Neglecting the change in size of the bubble, and taking the bubble as a fixed reference point, then the relative speed of the surface of the water at the water-bubble interface is approximately $0.579 \ \frac{m}{s}$, which exceeds the approximate turbulent transition speeds calculated previously. Thus, with back-of-the-envelope certainty, it is plausible that the flow is turbulent near the bubble as it moves across the surface of the water. This may indicate that the vortices are shed into the bulk of the fluid from a turbulent layer at the water-bubble interface.

There are lots of concepts which could explain the vortices. Kelvin-Helmholtz instability comes to mind, but the difference in density between air and water means that generally,



(a) T=62μs (b) T=427μs

(c) T=674μs (d) T=983μs

Figure 3.0.4: "Plot of 3D density solution profile for the shock-bubble interaction problem: DG(P2)-BPPP-WENO." Zhang & Cheng, 2023

air-water interfaces are not dominated by Kelvin-Helmholtz instability [2]. Wind generated waves in the ocean are a result of shearing, and they build up slowly over time; likely something else is happening here. The flow captured here may be analogous to that of fluid sloshing in an un-baffled tank. Sloshing, where two fluids in a tank move past each other impulsively, is often characterized as a two-fluid system, and numerically modeled using equations which describe each fluid flow separately as well as their interactions with each other. The most common of these, Kapila's five-equation model, was developed in 2001 by A. K. Kapila in a paper modeling detonations [1]. Since then the model has been used in ever more sophisticated numerical simulations of two-fluid systems, some of which model bubbles really well; Figure 3.0.4 is from a 2023 paper in the Journal of Computational Physics showing off the density solution of a helium bubble impacting a normal shock wave in air [4].

A bubble in a water tank is a much simpler problem, and future work could investigate computational simulations more thoroughly. A much simpler model, presented at the 2010 annual meeting of the Japan Society of Mechanical Engineers, predicts results similar to what is shown in the report image. It models bubbles rising through a fluid due to the buoyant force, and predicts speeds similar to the above estimates for bubbles of similar sizes, and does conclude that the bubbles moving through the fluid will generate vortices [3].

4 Conclusion: Revelations

The bubble's presence in the tank is something of a happy accident; getting the tank to seal properly was a much larger hurdle than it should have been. The main practical lessons learned from this project pertain to the creation of acrylic flow visualization tanks. The flow that led up to the image reveals the huge and complicated realm of two-fluid flows, and the various interplays between fluids which determine how they move together. The image itself displays just the tail end of a much more violent flow field, once it's coalesced into just a handful of large vortices. Artistically the image captures what a patch of space might look like, long after the particles shot out by the big bang have coalesced into galaxies and nebulae; hopefully it conveys a sense of wonder on both a small and large scale.

There is a non-trivial amount of blurring or distortion around the edges of the cropped region; this persists in the rest of the original image, and does not have an obvious source. Applying lens corrections does not affect it, and it probably isn't from the flat acrylic tank wall. Most likely, only the center of the frame is really in focus. The lens aperture was wide open for this shot, and the camera was as close to the tank as it could be. In the future, moving the camera further away, using a different aperture setting, or using an entirely different lens may yield an image with less distortion.

5 Acknowledgements

References

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