University of Colorado - Boulder

MCEN 5151
Flow Visualization

Team Second Report

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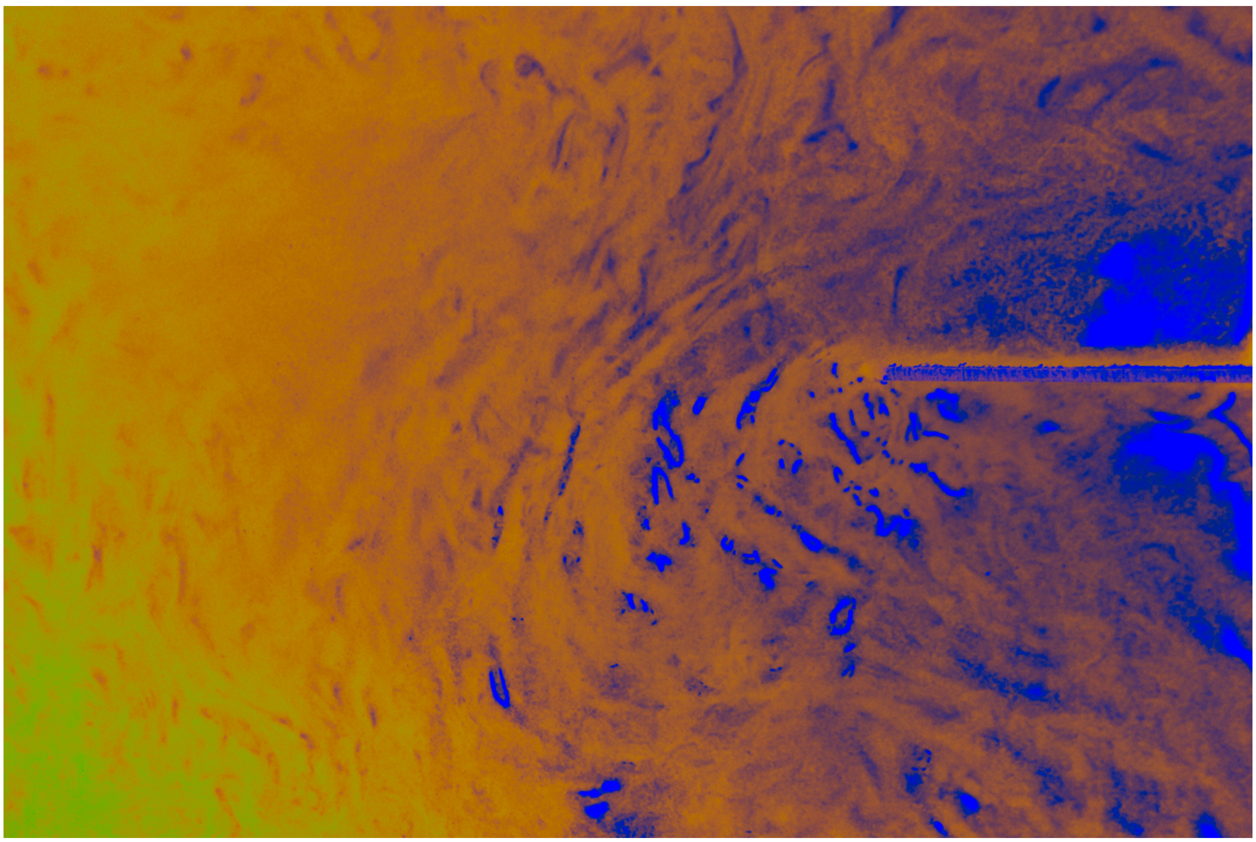

College of Engineering & Applied Science
UNIVERSITY OF COLORADO BOULDER

1 Introduction

1.1 Image Summary

This is an artistically edited photo of continuous circulating flow in a finite volume open-top tank, imaged from above. The fluid is a water and orange mica flake mixture, and is being pumped in and out of the tank at a flow rate of about 4 liters per minute. The flow is moving generally from right to left; the inlet is placed just below the wall in the middle right of the image, and the outlet is positioned on the top left just out of frame.

1.2 Motivation

The flow visualization intent with this photo shoot was to capture the shearing interaction of two layers of fluid moving at different speeds: The flow inlet is placed below a wall in the hopes that the flow above the wall would have little to no velocity, and so there would be some visible interactions at the end of the wall. The particulars of the tank setup ended up to not be conducive to isolating this interaction. The artistic intent of the image was to create something striking, with clear contrast between flows, motion perfectly frozen. This intent was poorly realized by the raw image, which was poorly lit, and by the flow itself, which was too uniform. The artistic intent led to the color editing in the final image; by subverting expectations of what a flow looks like, it leads to a more artistically interesting photo.

2 Methodology

2.1 Test Setup

The tank is 11" $\times$ 22" $\times$ 1" in size, constructed of 5 acrylic sheets making up the tank's floor and walls. The top of the tank is open to the air, in part to allow for the insertion of various items into the tank, and in part to avoid scratches, glare, and distortions that might be cause by an acrylic sheet between the flow and the camera. The tank has an approximate volume of 242 in^3 or 3.96×10^-3 m^3, and was approximately half full, containing just under 2 liters of water. The water contained approximately 6 grams of bright orange mica powder. Figure 2.1.1 shows where the water inlet and outlet are; the water is being continuously cycled from one side of the tank to the other via an electric pump and 8 mm diameter hose, which sucks water up from the upper left of the tank, creating a low pressure zone, and shoots out water from the middle right of the tank, creating a high pressure zone. The pump moves liquid at approximately 4 liters per minute.

There is a wall inserted into the flow field, to which the inlet hose is clamped, as shown in Figure 2.1.2. The inserted wall is butted up against the exterior wall of the tank with the intent of creating a stagnant area of water above the wall, opposite the side with the flow inlet. The tank was imaged from above, with white LED lights held at various locations above and outside the tank.

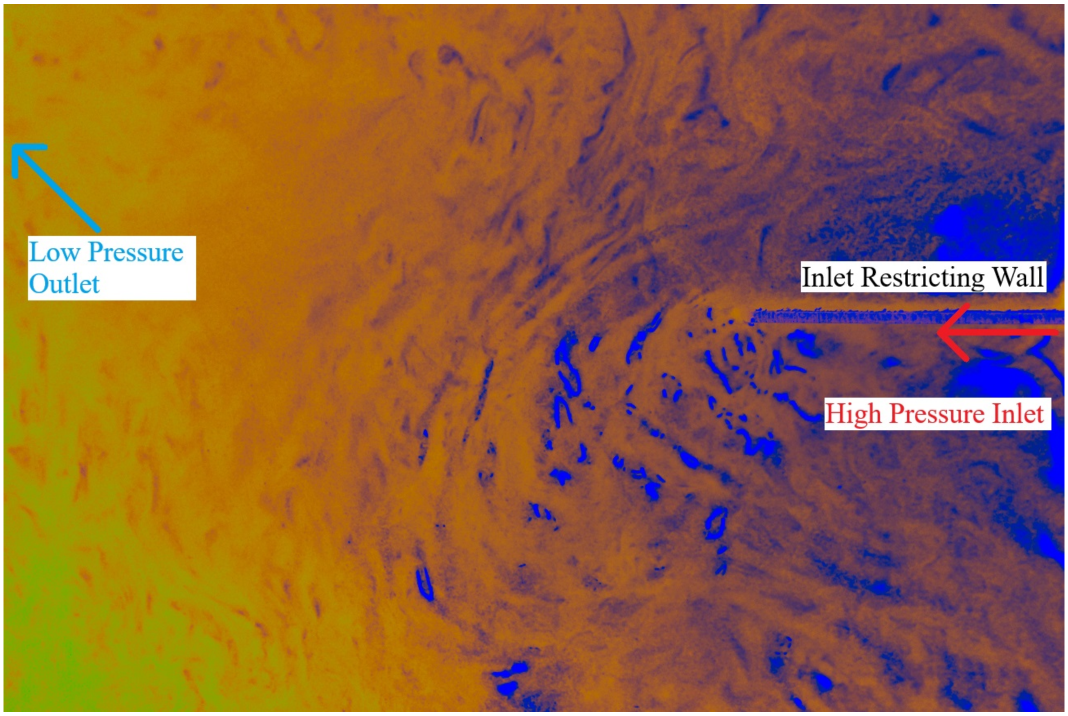

Figure 2.1.1: Flow inlet and outlet pattern.

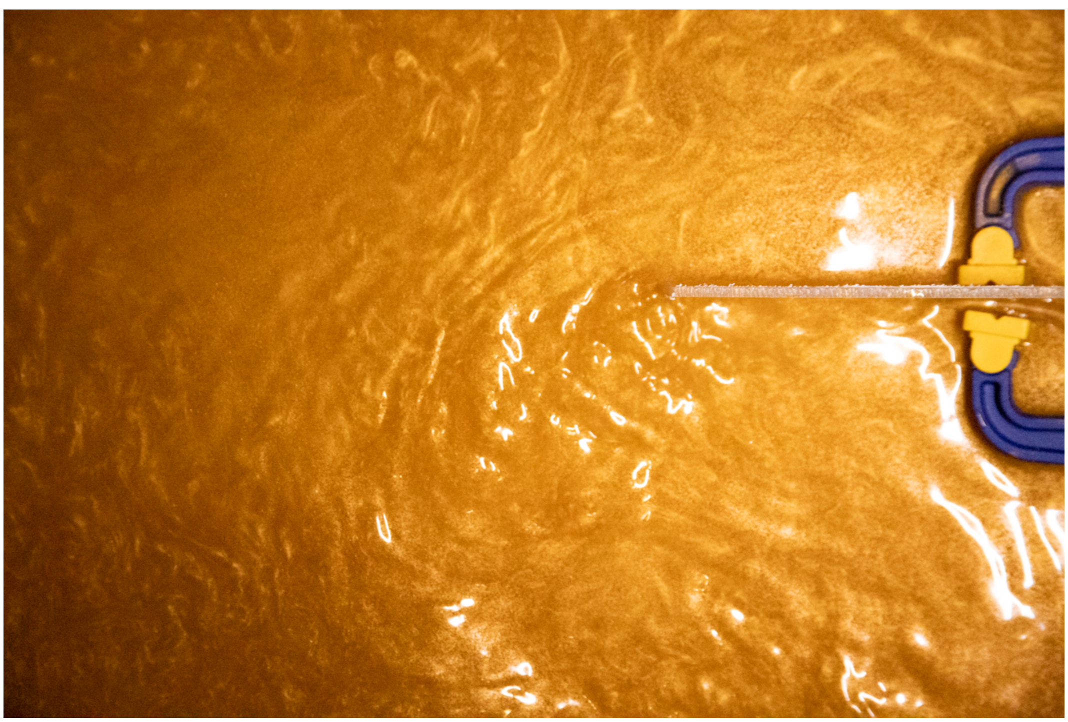

Figure 2.1.2: The unedited image, with the inlet hose visible on the right.

2.2 Visualization Technique

The flow in the water is visualized by mixing in bright orange reflective mica powder, creating a rheoscopic fluid. The mica particles are anisotropic, and so align themselves somewhat with the fluid flow they are suspended in; the varying orientations of the particles within the fluid lead to varied lighting conditions, making qualitatively different flow regions appear differently when imaged. This is useful for determining structures in the flow, but how the particles line themselves up is fairly complicated, and so it can be hard to determine what it is causing the particle alignments [1]. In the case of this image, lots of what is visible is waves on the free surface of the flowing fluid, as it is not constrained by a wall (ceiling) and so is free to push up into the open air. Because of this, much of what is visible in the flow is likely a combination of fluid vorticity and mixing effects along with gravity effects and water-air interaction effects at the free surface of the flow.

2.3 Photographic Technique

The photo was shot on a Canon EOS 6D Mark II DSLR with an EF 28-135mm f/3.5-5.6 IS USM lens, at 1/4000 sec, f/5.6, 135mm, and ISO 25600. The RAW resolution is 6240×4160, and the cropped resolution is 5600×3734. The flow was lit by several white LED lamps spread around the tank, and by a powerful white LED flashlight held above and off the the right of the tank; this is the main contributor to the glare on the water surface, which shows up in the edited image as a bright blue color.

The image was edited in Adobe Lightroom Classic, though relatively little was actually changed. Some manual denoising was applied in the form of NR luminance; all other editing was done with the color point curves: The green curve was linearly inverted and slightly attenuated at the low end, and the red curve was attenuated at both the low and high ends, leading to something like a negative parabola shape. Figures 2.3.1 and 2.3.2 show screenshots of the final curves for easy reference.

3 Flow Discussion

The flow is a fairly complicated one, made hard to decipher by the somewhat grainy quality (from the high ISO) and the relatively poor focus (the water's surface is not all in focus). Additionally, a lot of the patterns showing up in the mica are waves on the free surface of the fluid, and so are not necessarily representative of the bulk flow dynamics of the water in the tank. There are nevertheless some interesting things to explore.

Qualitatively, there are about 4 distinct regions in the flow, shown in Figure 3.0.1. The pressure in the flow is at its peak right at the inlet on the right side of the image, where it is being forced out of the pipe by the pump. The flow then interacts with the wall, causing a spreading motion downwards and to the left. This expanding flow is made visible by the waves running perpendicular to the flow direction. Below region 1 is somewhat stagnant water, some of which is induced into motion by the flow exiting the inlet nozzle. As the flow moves outwards from region 1, some of it begins to stagnate in region 3, the bulk of it curves upwards to region 4 (where the outlet is) and some of it is swept up into region 2. Flow is

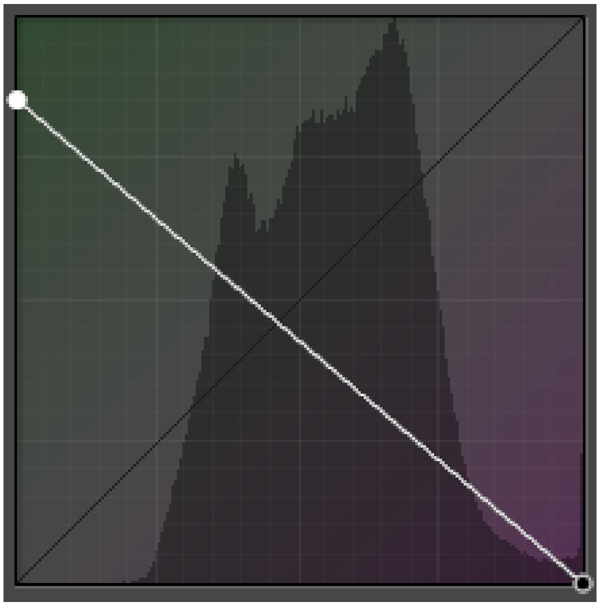

Figure 2.3.1: The green tone point curve.

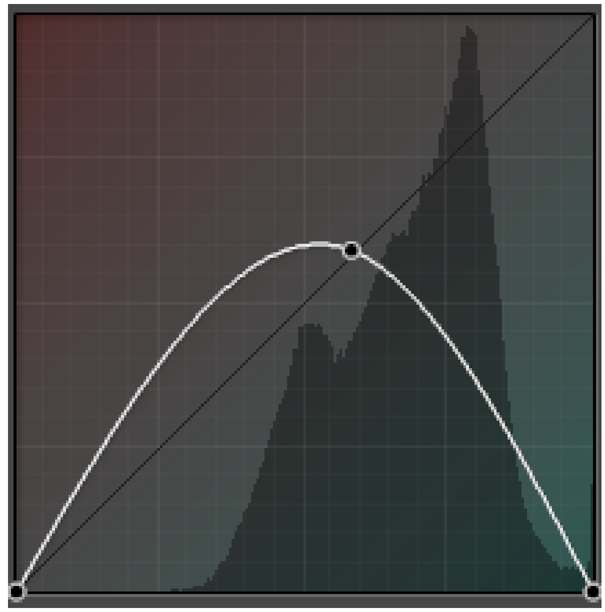

Figure 2.3.2: The red tone point curve.

primarily driven by pressure gradients; the inlet is effectively a low pressure zone, so that is where most of the flow ends up. Regions 2 and 3, however, are lower pressure than the inlet. This explains why some flow does travel in that direction. Other contributing factors include shear between regions of water moving at different speeds. This happens most obviously just the left of the end of the wall, where the fast moving flow shears against the slower fluid above, creating a clockwise rotation in the fluid as some of the flow is induced upwards into the lower pressure region 2.

Somewhat more quantitatively, analysis can be done using pipe flow theory to estimate some basic flow properties of the fluid system, at least withing the pipe and at the entrance and exit points to the pipe-pump portion of the system. Pumps create fluid motion in a variety of ways, but at its base, fluid flow through pipes is driven by pressure gradients; pumps can be modeled as compressors, creating a pressure gradient which then drives flow through the pipe. The following analysis is based largely on understanding shakily drawn from Donald C. Rennels' 2nd edition of *Pipe Flow: A Practical and Comprehensive Guide*, published in 2022 [2].

We can begin by estimating the mass flow rate of the system, assuming the pump is operating at the manufacturer-quoted rate of 240 liters per hour, or about 4 liters per minute. Assuming the fluid has the density of water, $4/;l/min$ works out to be a mass flow rate $\dot{m}$ of approximately 0.067 kg/s. The assumption that the fluid can be treated as water is maybe surprising because of how much mica is mixed in to the water, however, the mica makes up only 1% of the fluid by volume, and has approximately $1/4^{th}$ the density of water. For simplicity's sake, it is neglected. The velocity of the water through the pipe can be calculated directly from the mass flow rate using Equation 3.1, where u is velocity, ρ is density, and $A = \pi R^2$ is the cross sectional area of the pipe:

$$u = \frac{\dot{m}}{\rho A} \tag{3.1}$$

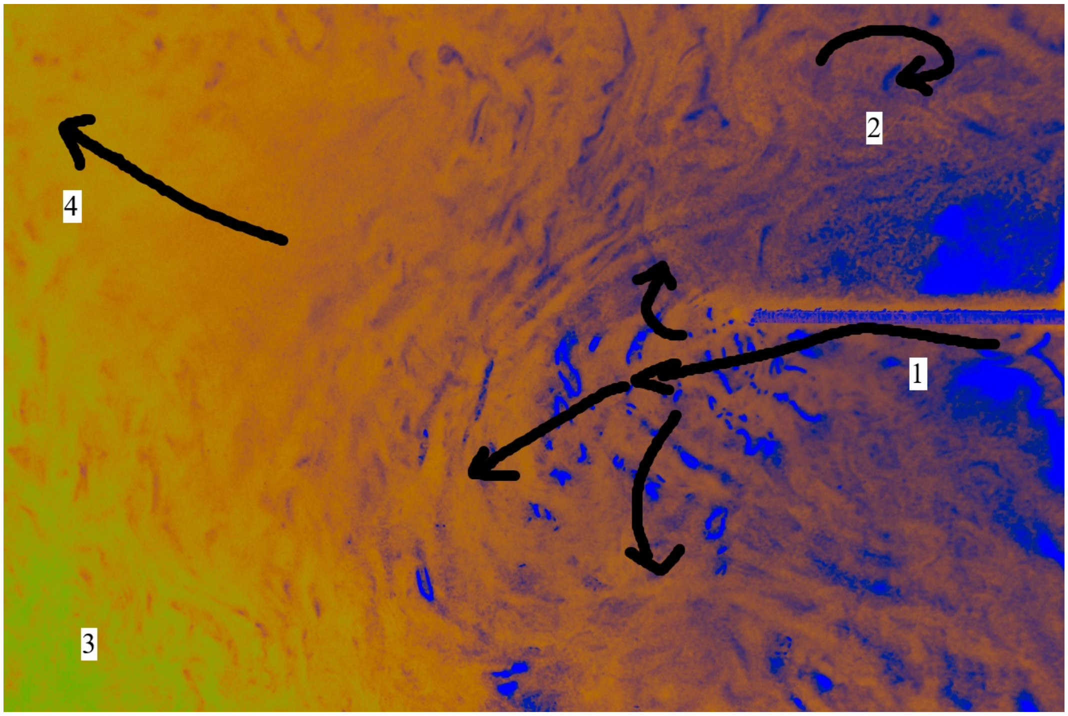

Figure 3.0.1: The bulk flow moves water from inlet to outlet.

The pipe has a diameter of 8 mm, so Eq. 3.1 gives $u_{pipe} \approx 1.33/; m/s$. The viscosity of the fluid can be calculated using Sutherland's Formula (Equation 3.2) [3], again neglecting the mica powder and assuming a fluid temperature of $72°F = 295\ K$:

$$\mu = (1.458 \times 10^{-6})\frac{T^{1.5}}{T + 110.4} = 1.822 \times 10^{-5}\ \left[\frac{kg}{ms}\right] \tag{3.2}$$

Using the diameter of the pipe as the length scale, the Reynolds number for the pipe flow is as follows:

$$Re = \frac{\rho u L}{\mu} = 583,973.7 \tag{3.3}$$

This is much larger than the critical Reynolds number ($Re_{crit} \approx 4000$), so the flow in the pipe is completely turbulent.

The pressure at the inlet and outlet can also be estimated. The speed of sound in water is about 1500 m/s. Compressible effects start being relevant at around Mach = 0.4; 40% of the speed of sound in water is about 600 m/s, and so the pipe flow is not anywhere close to the compressible flow regime. Thus, the density of the fluid safely assumed to be equal throughout the flow system. Neglecting wall friction and assuming for a moment that the points at the center of the outlet (Point 1) and inlet (Point 2) lie on a stream line, Bernoulli's equation can be applied [4]. Assuming that the pressure at some point in the open tank, P_∞, is approximately equal to the average atmospheric pressure in Boulder, CO of 88.9 kPa, that the inlet pressure $P_1 = P_\infty$, and that the inlet flow velocity $u_2 = u = 1.33\ m/s$, Equation 3.4 gives the pressure at the inlet using Bernoulli's Equation:

$$P_2 = P_\infty - \frac{1}{2}\rho u_2^2 = 88.016\ kPa \tag{3.4}$$

This gives us a pressure gradient across the pump of approximately $\Delta P = 884\ Pa$. This is the pressure gradient driving the fluid motion shown in the report image. Forces in pipes are a bit weird, but the acceleration of fluid through a pipe can be analyzed using conservation of momentum, which describes how forces cause changes in momentum. The "force" on the fluid caused by the pump, then, can be approximated using Equation 3.5:

$$F = P_1 A_1 - P_2 A_2 + \dot{m}(u_1 - u_2) \tag{3.5}$$

Assuming $A_1 = A_2$ and $u_1 = u_2$, then the force of the pump is simply $F = \Delta P A = (884)(0.0002) = 0.178\ N$; not a lot of force!

4 Conclusion: Revelations

The biggest thing I learned from this project is that getting very specific flow patterns to show up is harder than I expected. Much more time would need to be spent in order to get a cleanly isolated shear boundary interaction caught on camera. Additionally, pipe flow is fascinating, and the question of how best to understand pipes (Do the impart flow, or pressure?) is a great thing to think about. It was also lots of fun to create an artistically strange looking flow just by playing with the intensities of the color channels; it is fascinating what the human brain recognizes as a flow and what it rejects outright, simply because it is a different color pallette.

References

[1] Daniel Borrero-Echeverry, Christopher J. Crowley, and Tyler P. Riddick. "Rheoscopic Fluids in a Post-Kalliroscope World". In: *Physics of Fluids* (2018).

[2] Donald C. Rennels. *Pipe Flow: A Practical and Comprehensive Guide*. John Wiley Sons, Inc., 2022.

[3] NASA. *Air Viscosity: Sutherland's Formula*. https://www.grc.nasa.gov/www/BGH/viscosity.html.

[4] Princeton. *Bernoulli's Equation*. https://www.princeton.edu/~asmits/Bicycle_web/Bernoulli.html.