Gravity Current Traveling Down a Slope

MCEN 5151 Flow Visualization - Get Wet Report

Luke Freyhof

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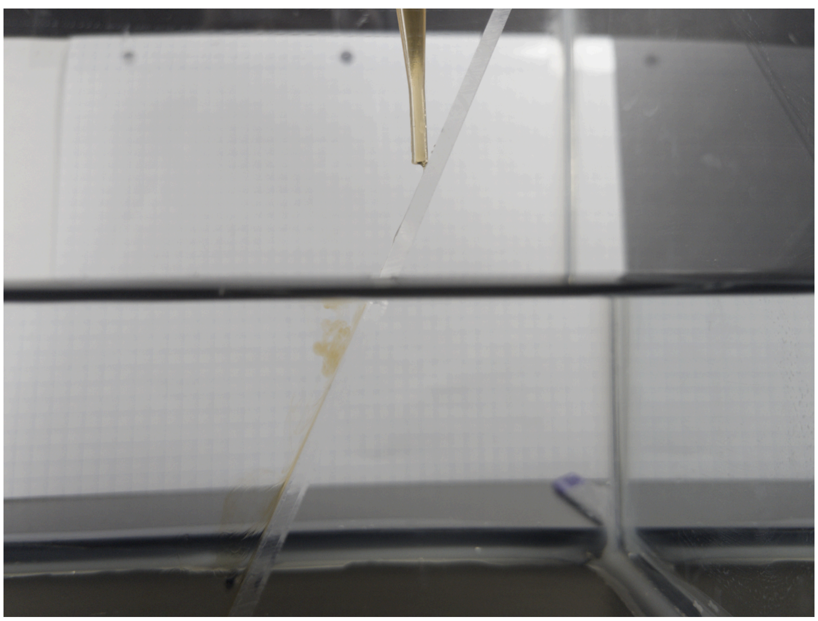
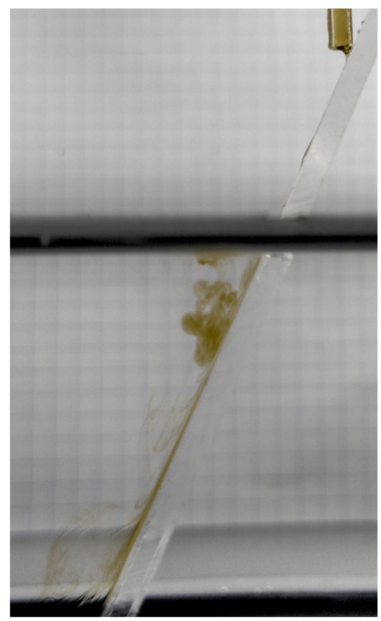
Statement of Meaning Figure 1 was created for the first flow visualization assignment and shows a droplet flowing down a slope and entering a larger body of fluid. This setup illustrates a gravity driven flow, particularly the time immediately following the collision of the droplet with the boundary in a *pycnocline* — an area in a fluid where the density changes rapidly as a function of depth. The image in Figure 1A was taken after the second (of two) droplets of saltwater had collided with the pycnocline boundary, with the goal of capturing the behavior of a gravity flow colliding with a pycnocline boundary.



(A) Compressed Unedited Photo



(B) Edited Photo

Figure 1: Gravity flow down a sloped piece of acrylic into a tank of deionized (DI) water. The orange liquid is dyed saltwater.

Setup and Flow Description To create this flow, a sheet of clear acrylic was placed at approximately 66° inside a tank partially filled with deionized water. A black mark was added to the acrylic to mark the location where the droplet was to be released, and keep the location consistent. Graph paper was taped onto the black foamboard placed behind the tank, for an attempted "background-oriented schlieren" setup. Two 10 W, 4500 K color temperature LED panel lamps were

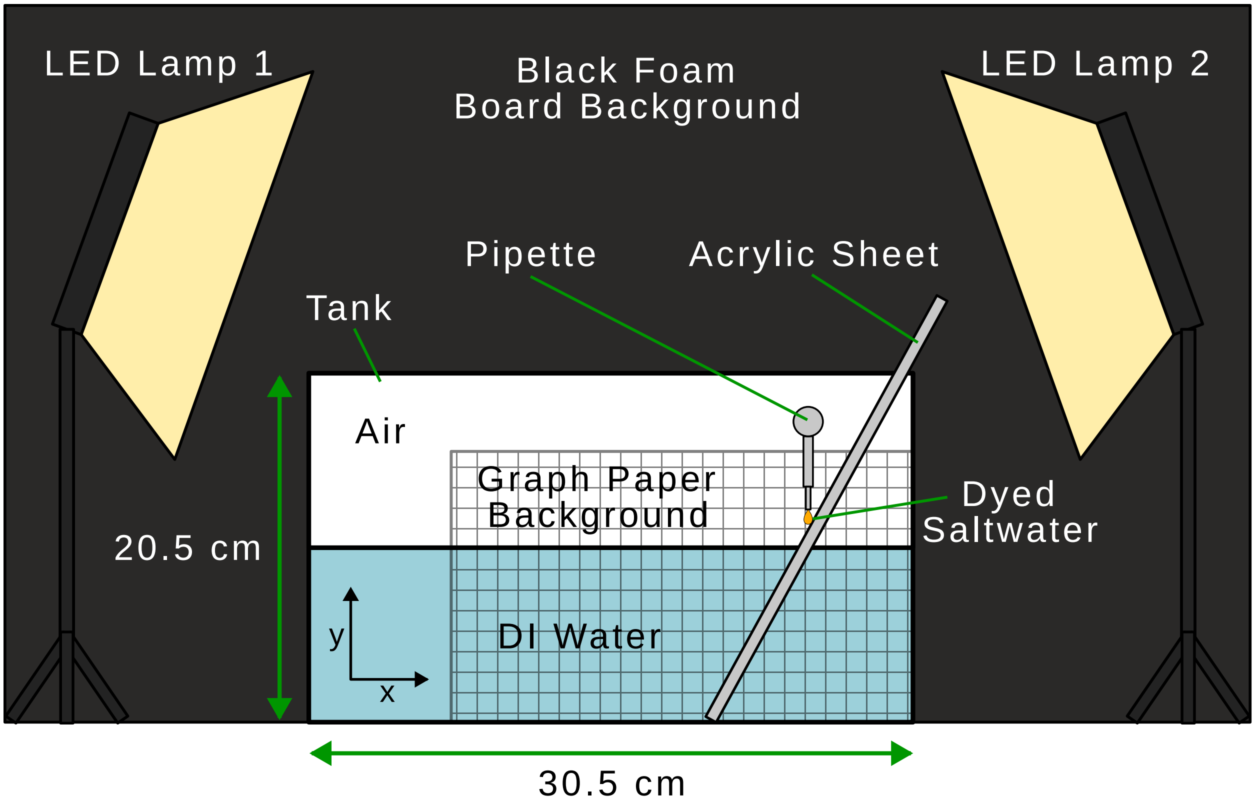


Figure 2: Visualization Setup

placed on the sides of the tank for illumination. A Google Pixel 6A (phone) camera was placed on a tripod and used to capture the images using the OpenCamera app.[1] The camera was situated 0.4 m away from the droplet (in the positive Z coordinate direction) and angled parallel to the front wall of the tank. A 0.01 s shutter speed, f/1.7 aperture, and 57 ISO were used for the image exposure.

After the drop was applied to the acrylic by the pipette, it rolled down the acrylic toward the surface of the DI water. The drop might not have reached its maximum possible speed due to the short distance between where the drop was applied and the surface of the water. When the drop met the surface of the water, it slowed down momentarily before breaking the surface tension of the DI water, after which it accelerated below the surface. Some of the drop was left near the surface of the DI water as shown in Figure 1B, though most of it moved below the surface and remained near the acrylic. When the drop moved below the surface of the DI water, it initially retained the shape it had above the water line, though quickly deformed as the salt water and DI water mixed.

Nondimensional numbers were estimated for the flow of the drop through the DI water. The Richardson number (see Equation 1) describes the relation between the buoyancy and shear forces, while the Reynolds number (see Equation 2) describes the relation between the viscous and inertial forces. The Grashof number (see Equation 3) describes the relation between the buoyant and viscous forces. These dimensionless numbers can help describe, and even predict the behavior of a gravity current. Quantities used to calculate the dimensionless numbers are listed in Table 1.

$$\mathrm{Ri} = \frac{\frac{g(\rho-\rho_1)}{\rho_1} h \cos\theta}{U^2} = \frac{\frac{(9.81)(1.028-1)}{1} 3.0^{-3} (\cos 66)}{(6.5^{-2})^2} = 0.08 \tag{1}$$

Constant	Description	Value
h	thickness of plume	3.0×10^{-3} m
U	mean velocity	6.5×10^{-2} m s^{-1}
θ	angle of slope	66°
ρ	density of salt water	1.028 kg/m^3
ρ_1	density of DI water	1.0 kg/m^3
g	gravitational acceleration	9.81 m/s^2
ν	kinematic viscosity of water	1.0023×10^{-6} m^2/s

Table 1: Constants and Measurements. Some measurements (heights and velocities) were measured using Fiji.[2]

$$\text{Re} = \frac{hU}{\nu} = \frac{(3.0^{-3})6.5^{-2}}{1.0023^{-6}} = 190 \tag{2}$$

$$\text{Gr} = \frac{h\sqrt{h\frac{g(\rho-\rho_1)}{\rho_1}}}{\nu} = \frac{(3.0^{-3})\sqrt{(3.0^{-3})\frac{9.81(1.028-1)}{1}}}{1.0023^{-6}} = 86 \tag{3}$$

Studies analyzing the behavior of gravity flows down an incline in homogeneous[3] and pycnoclines[4] have been conducted. As the gravity current descends along the pycnocline, mixing occurs between the gravity flow and the ambient fluid.[4] In my setup, mixing only occured within the lower level, because DI water and salt water mix more readily than air and salt water. The mixing caused the "head" of the gravity flow to expand and slow down. This mixing effect increases as a function of slope angle.[3]

Gravity flows in pycnoclines split into an interflow and an underflow, though the allotment in this split is dependent on the Richardson number. At smaller Richardson numbers, underflow is more prevalent than interflow while at larger Richardson numbers, the converse is true.[4] My flow had a small Richardson number (see Equation 1)— lower than any tested in the Tanimoto *et al.* — and experienced significant underflow, thus corroborating previous findings..[4] However, my image still shows a non-negligible interflow, possibly due to interaction of the salt water drop with surface tension or capillary effects at the air-water interface. My calculated Reynolds and Grashof numbers (see Equation 2 and Equation 3) were also lower than those seen in Tanimoto *et al.*, indicating that my flow had larger viscous effects relative to inertial and buoyant effects. These numbers and conclusions could align with the capillary and surface tension effects I mentioned previously, or they could indicate poor measurements on my part.

Visualization Technique Five drops of orange-yellow food dye (ArtNet) were mixed with 50 mL of DI water and 2 g of salt to create the dyed salt water mixture. The piece of acrylic was angled at 66° from the horizontal DI water surface. Drops of the salt water mixture were applied to the acrylic 2 cm above the water's surface and recorded as they slid down the acrylic slope. A piece of graph paper was taped to a black foam board which was placed behind the tank. The graph paper background was intended to create a background-oriented schlieren visualization. Two 10 W, 8 inch LED panels (Ubeesize brand) were angled down toward the tank as shown in Figure 2. Overhead lights in the room were turned off.

Photographic Technique The image was taken with the smallest field of view I could set without using digital zooming features on my phone, which left my phone approximately 0.4 m away from the drop of salt water. A ruler was placed in the tank and the phone was manually focused on the lettering on the ruler to ensure proper focusing on the falling droplets. The lens in the Pixel 6A phone has a fixed aperture of f/1.7, a focal length of 27.9 mm (35 mm equivalent), a minimum focus distance of 0.1 m, and a view angle of $65.6 \times 51.6°$. The 12.1 megapixel digital image sensor has an area of 23.9 mm and produces images at sizes up to 4032×3024 pixels, which was the size of the original image. After cropping and editing, the final image was 1222×2023 pixels. Exposure was set with an ISO of 57 and a shutter speed of 0.01 s when taking the photo shown in Figure 1. Post processing of the photo increased the contrast in the image and highlighted the orange color of the salt water using the RGB curves tool in darktable.

Analysis and Reflection As mentioned previously, the image shows a droplet driven by gravity through a pycnocline interface. I like the small area toward the bottom of the image that shows the density differences (background-oriented schlieren), but think the image could be improved in many ways. The fluid physics could have been better shown with a closer and darker background pattern as well as lighting from the back of the tank (behind the graph paper). A darker food dye color could have also been used to increase contrast, especially in areas toward the bottom of the image where the dye spread out. Attempting the experiment without dye could have improved the visibility of the density gradients visualized using schlieren techniques.

$$\frac{14{,}803\,\text{pixels}}{\text{m}} \times \frac{0.065\,\text{m}}{\text{s}} \times \frac{1\,\text{s}}{100\,\text{frames}} = 9.2\,\text{pixels/frame} \tag{4}$$

Regarding camera settings, the phone could have been moved closer to the tank, as it is technically able to focus at distances of 0.1 m. Repeating the experiment with a mirrorless or DSLR camera with interchangeable lenses could also improve the outcome, as a zoom or macro lens would enable a closer view of the flow without sacrificing resolution and leading to a blurry/grainy look. Using a mirrorless or DSLR with a larger sensor would also enable proper exposure while decreasing the necessary shutter speed and maintaining a low ISO value. Shortening the shutter speed is important, as Equation 4 shows that the object moved 9.2 pixels/frame in my image, leading to motion blur. Interchangeable lenses would allow for aperture changes, which could improve the depth of field in this image and improve the clarity of the schlieren background. Implementing these changes would help me better achieve my intent of imaging a pycnocline.

Future tests could incorporate the suggestions above but also explore gravity flows with immiscible liquids (water flowing into oil for example). A more homogeneous pycnocline could also be used with fluids of the same phase (liquid-liquid) rather than the two different phases I used (liquid-gas).

References

[1] "Open Camera," SourceForge. (Aug. 27, 2025), [Online]. Available: https://sourceforge.net/projects/opencamera/ (visited on 09/24/2025).

[2] J. Schindelin, I. Arganda-Carreras, E. Frise, *et al.*, "Fiji: An open-source platform for biological-image analysis," *Nature Methods*, vol. 9, no. 7, pp. 676–682, Jul. 2012, ISSN: 1548-7105. DOI: 10.1038/nmeth.2019. [Online]. Available: https://www.nature.com/articles/nmeth.2019 (visited on 09/24/2025).

[3] R. E. Britter and P. F. Linden, "The motion of the front of a gravity current travelling down an incline," *Journal of Fluid Mechanics*, vol. 99, no. 3, pp. 531–543, Aug. 1980, ISSN: 1469-7645, 0022-1120. DOI: 10.1017/S0022112080000754. [Online]. Available: https://www.cambridge.org/core/journals/journal-of-fluid-mechanics/article/motion-of-the-front-of-a-gravity-current-travelling-down-an-incline/0F2028458C9C6E9C5BCC8A7D19176130 (visited on 09/23/2025).

[4] Y. Tanimoto, N. T. Ouellette, and J. R. Koseff, "Interaction between an inclined gravity current and a pycnocline in a two-layer stratification," *Journal of Fluid Mechanics*, vol. 887, A8, Mar. 2020, ISSN: 0022-1120, 1469-7645. DOI: 10.1017/jfm.2020.9. [Online]. Available: https://www.cambridge.org/core/journals/journal-of-fluid-mechanics/article/interaction-between-an-inclined-gravity-current-and-a-pycnocline-in-a-twolayer-stratification/59C1B9ACCC208C63BF8BBBB593432441 (visited on 09/22/2025).