Team Third Report

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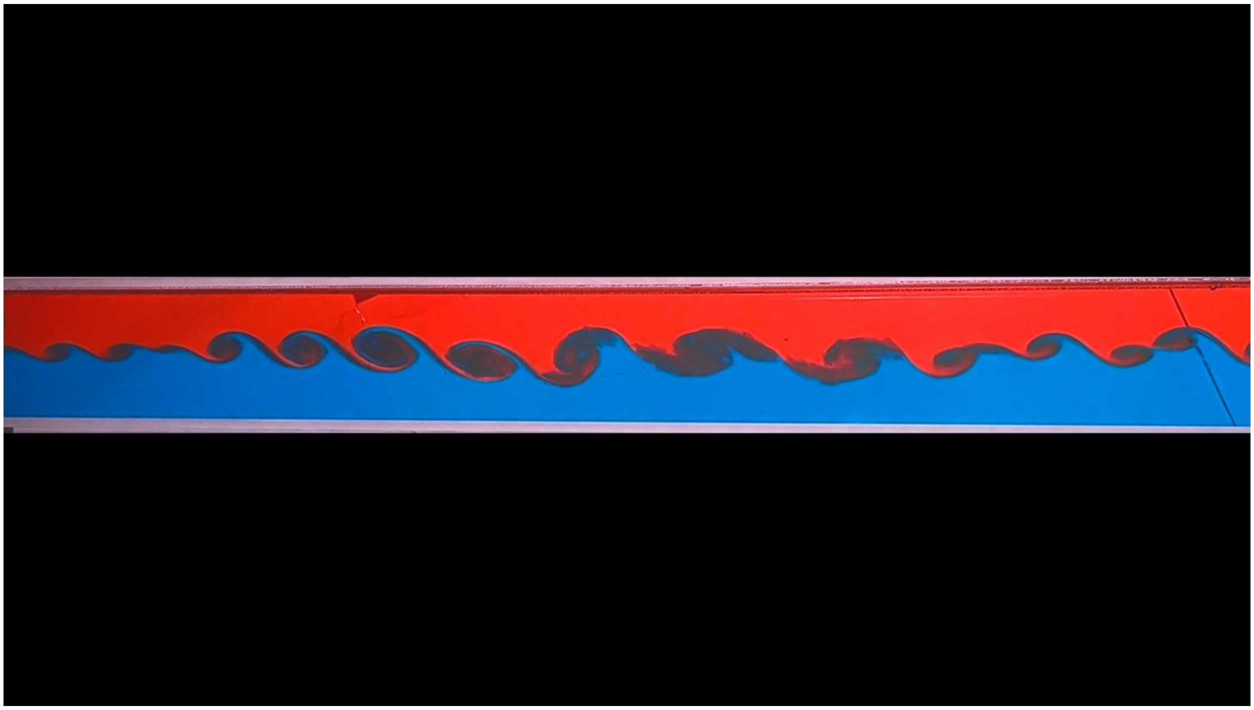


1. Introduction

The objective of this experiment is to visualize the Kelvin–Helmholtz instability, which forms characteristic rolling billows when two fluid layers experience strong velocity shear. The phenomenon is visually striking: once the shear is established, waves along the interface grow almost simultaneously, creating a repeating pattern of overturning crests. It is equally remarkable how sharply defined the interface remains as these waves develop, allowing the structure of the instability to be seen with exceptional clarity.

2. Experiment

This experiment was performed in a long, rectangular acrylic tank that was approximately 8ft long, 4.5 in tall, and 1.5 in wide. The tank includes an air vent on one end and a fill valve on the other, with the inlet located at the bottom. First the tank is filled with 4L (about half the tank's volume) of fresh water which has been dyed red. Next, a solution of 9% salt by weight was mixed and dyed blue. This denser salt water was carefully injected beneath the fresh water at a very slow rate to preserve a sharp, stratified interface. The tank was filled completely, allowing a small amount of fresh water to spill out to ensure that no air pockets remained. After the system was allowed to settle, one end of the tank was elevated onto a table, tilting the entire apparatus to an angle of approximately 26°. The salt concentration and tilt angle were selected based on values reported in [1], but the procedure was adapted for this experiment.

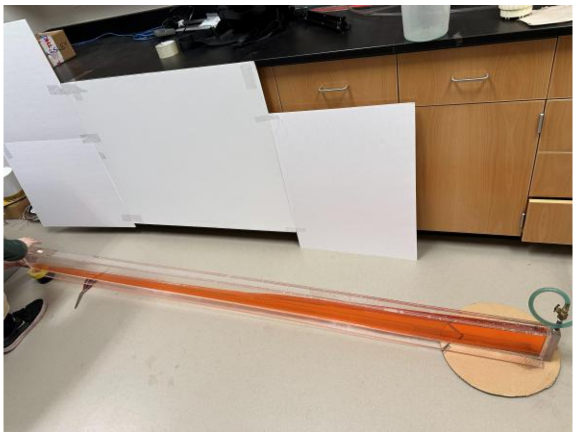
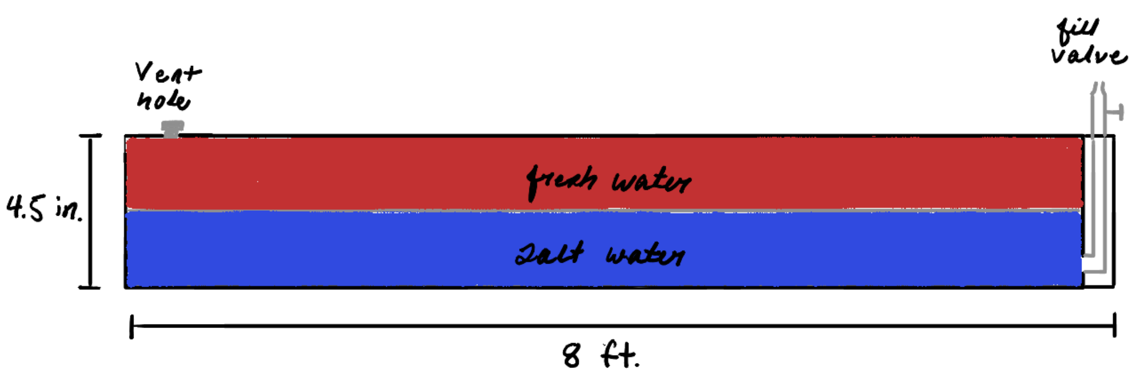
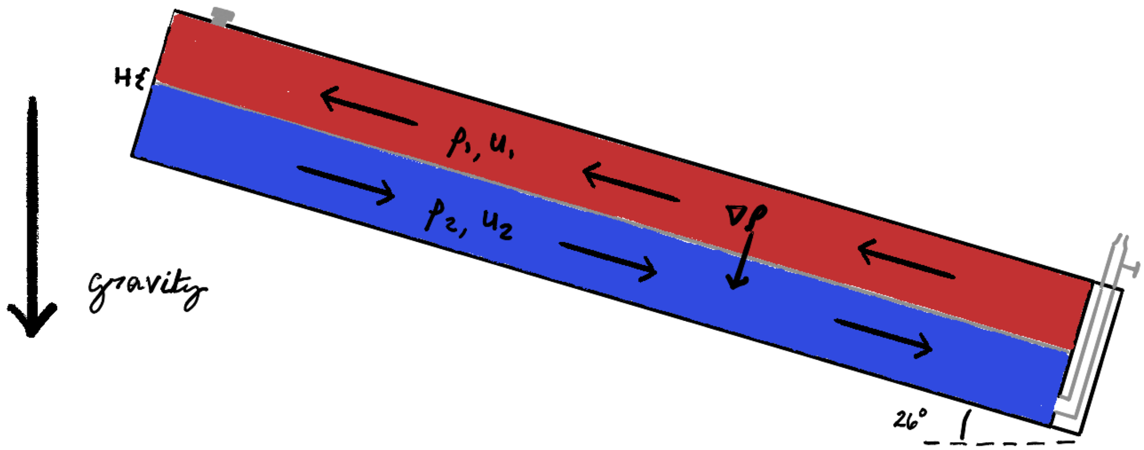


Figure 1: Freshwater has been added

Figure 2: Saltwater nearly done filling

Quickly after the tank has been tilted, the denser salt water begins to slide beneath the lighter fresh water, causing the lower layer to accelerate to the right while the upper layer moves to the left. This creates a strong shear at the interface. Small disturbances along the boundary are amplified by this velocity difference, forming periodic waves characteristic of the onset of Kelvin–Helmholtz instability. As these waves grow, the shear forces them to overturn, lifting dense fluid upward and pushing light fluid downward. In this process, kinetic energy from the shear flow is converted into gravitational potential energy, enabling the billows to roll up and eventually break down into mixing.





This experiment is a great demonstration of a baroclinic flow, in which the surfaces of constant density and constant pressure are not parallel. Hydrostatic pressure acts downward, while the tilted tank has a diagonal density gradient. Because the net pressure force does not pass through the center of mass, a torque is imparted to the flow, resulting in fluid rotation and vortex generation [2].

The fluid velocity, estimated from the video, was found to be ~30 in/s. With this information we may then calculate the Richardson number, which represents the ratio of buoyancy to shear forces.

$$Ri = \frac{buoyancy}{shear} = \frac{g(\frac{\partial\rho}{\partial z})}{\rho_0\left(\frac{\partial U}{\partial z}\right)^2} = \frac{g(\rho_2 - \rho_1)H}{\rho_0(U_2 - U_1)^2}$$

Where g is the gravitational acceleration, H is the interface layer thickness, ρ_0 is a reference density (average in this case), and ρ_2, U_2, ρ_1, U_1 are the densities and velocities of the lower and upper layers respectively.

$$Ri = \frac{(9.81\frac{m^2}{s})(1090\frac{kg}{m^3} - 1000\frac{kg}{m^2})(0.005m)}{\left(\frac{1090\frac{kg}{m^3} + 1000\frac{kg}{m^3}}{2}\right)\left(0.762\frac{m}{s} + 0.762\frac{m}{s}\right)^2} = \mathbf{1.82 * 10^{-3}}$$

This result satisfies the criteria $Ri < \frac{1}{4}$, which is the condition for Kelvin Helmholtz instability to occur [2].

3. Photographic Technique

Photographic Technique White foam boards were fixed behind the tank to provide a clean background for the shoot. Multiple cameras were placed about 2ft from the tank, facing head on to capture a nearly 2D profile. The entire experiment was lit by a strong standing work light (halogen), which was placed behind the camera, angled downwards. This provided good bounce lighting from the white background, while avoiding glare on the tank.

Camera	iPhone 13 Pro
Focal Length	26 mm
Aperture	f1.5
Framerate	120 / 240 fps
ISO	Unknown
Field of View	6.5 x 4.3 ft
Camera-Subject Distance	3 ft
Image size	1920x1280
Spatial Resolution	~ 24.6 pixels per inch
Temporal Resolution	0.25 in per frame

The video was processed in DaVinci Resolve. Pitch and yaw adjustments were applied to correct the perspective, the background was cropped out, and the footage was rotated to level the tank horizontally. To restore the red dye, the washed-out orange tones were shifted toward red using the Hue vs. Hue curve, followed by additional refinement in the Color Warper to pull values away from orange, green, and gray. The overall saturation was then increased to 1.2. These edits were applied to two clips, one recorded at 120 fps and the other at 240 fps, with both played back at 24 fps to produce effective slowdowns of 0.2x and 0.1x respectively.

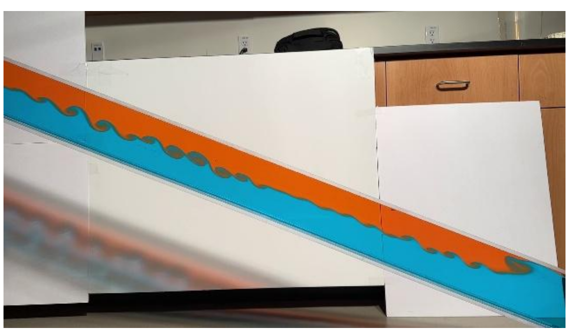


Figure 3: Original frame

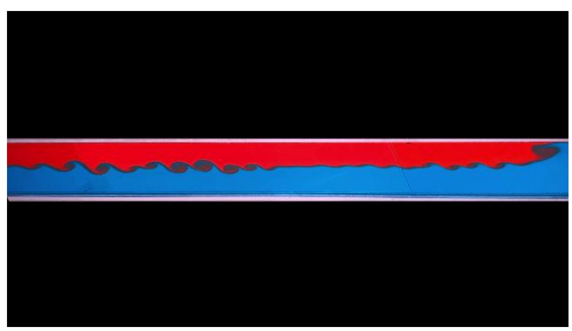


Figure 4: Edited frame

4. Reflection

This experiment performed exceptionally well overall; the only drawback is that the billows did not form in perfect synchrony, likely because we had to lift and slide the tank onto the table, introducing slight disturbances before the shear fully developed. In future iterations, experimenting with different combinations of salinity and tilt angle could help refine the result. The most visually striking Kelvin–Helmholtz billows occur when the two layers have nearly matching densities, but this also makes the interface more prone to mixing. Reducing the salinity contrast would also require a smaller tilt angle to generate the necessary velocity difference, potentially producing a slower, longer-lived instability. Both salinity and tilt angle strongly influence the size and character of the billows [1], so varying these parameters could produce a clearer or more dramatic visualization. Finally, using a more saturated dye, such as leak-detection tablets instead of food coloring, could create sharper and more vibrant images.

5. Acknowledgement

I would like to extend my thanks to Prof. Scott Kittelman for allowing us to use his lab space, equipment, and for assisting us during setup. I would also like to thank my groupmates Will Ball and Nick Rhodes for providing extra cameras and lights to make this phenomenal visual.

6. References

[1] Gibbons, M. M., Muldoon, D., and Khalil, I., “Demonstrating the Kelvin–Helmholtz Instability Using a Low-Cost Experimental Apparatus and Computational Fluid Dynamics Simulations,” Fluids, Vol. 8, No. 12, 2023, p. 318. doi:10.3390/fluids8120318.

[2] Kundu, P. K., Cohen, I. M., and Dowling, D. R., Fluid Mechanics, 6th ed., Academic Press, Cambridge, MA, 2016.