Kelvin-Helmholtz Waves

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MCEN 5151: Flow Visualization – Get Wet

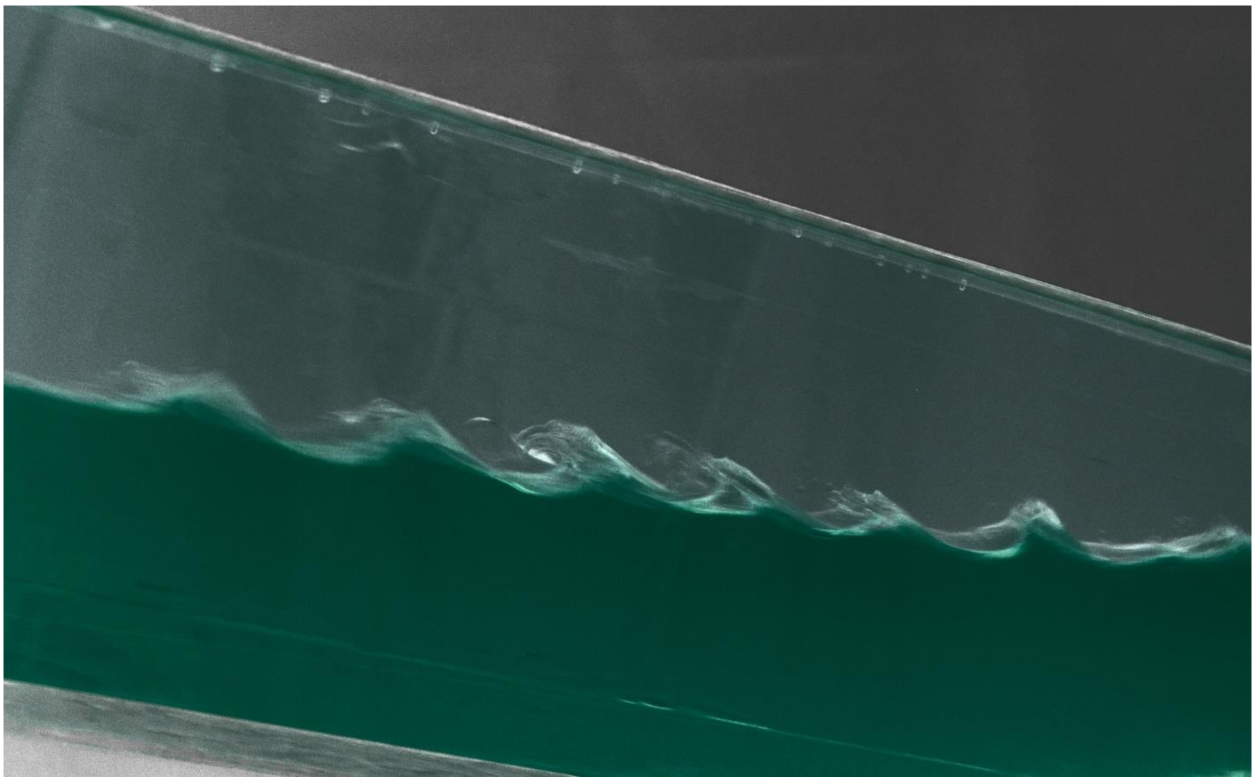

Figure 1: Kelvin Helmholtz waves

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Introduction

Figure 1 shows Kelvin-Helmholtz waves: an instability that occurs when adjacent fluids move at different velocities. These waves were generated by placing two immiscible fluids in a long acrylic tank, then tilting the tank so that the heavier fluid slid toward one side and the lighter fluid toward the other. The fluids moving in opposite directions induce vorticity at the fluid interface, which at some point becomes unstable, causing the interface to suddenly erupt into waves. Figure 1 shows these waves shortly after they appeared.

Using a tilted tank to show the Kelvin-Helmholtz instability is a decades-old practice, used even by Osbourne Reyolds in the 1880s, who conducted similar experiments using a glass tube. These experiments were more rigorously expanded on in the 1960s by S.A. Thorpe, who examined the effect in three dimensions, both with miscible and immiscible liquids (Thorpe, 1968). Thorpe noted that miscible fluids created the well-known Kelvin-Helmholtz spiral patterns, but immiscible fluids are less likely to create the same patterns, stopped by the fluids' immiscibility. Thorpe explains that while both create waves; to create waves in a tilting tank, the tank must be tilted steeper for immiscible fluids than for miscible ones. Additionally, the immiscible fluids create more irregular waves.

In nature, the Kelvin-Helmholtz instability is a mechanism to create mixing between layers, notably in mixing between ocean layers (Smyth & Moum, 2012), and in the atmosphere (Scinocca, 1995). In the atmosphere, the instability is known to display these waves in clouds. Pilots recognize these clouds as indicators of high turbulence in the region.

Experiment Overview

Figure 2 shows the tank used to the experiment, which is a 32" long, 4.5" tall, 1.5" wide acrylic tank. The denser fluid in Figure 1 is canola oil, and the other fluid is 90% isopropyl alcohol. These two fluids were chosen because they are immiscible (allowing the experiment to be repeated easily) and because when mixed with food coloring, they hold different colors.

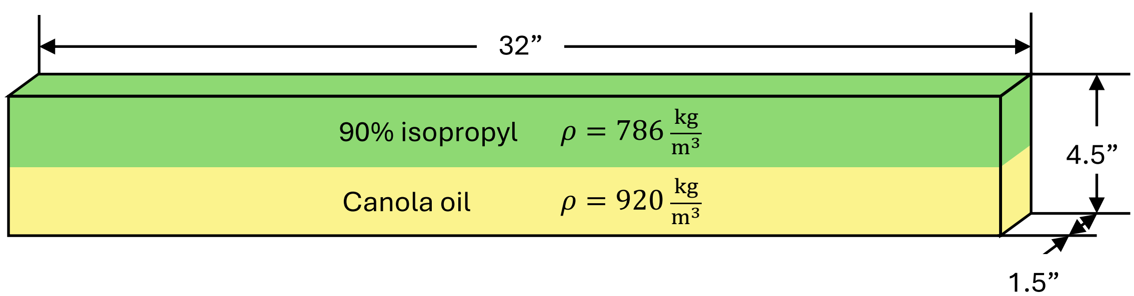
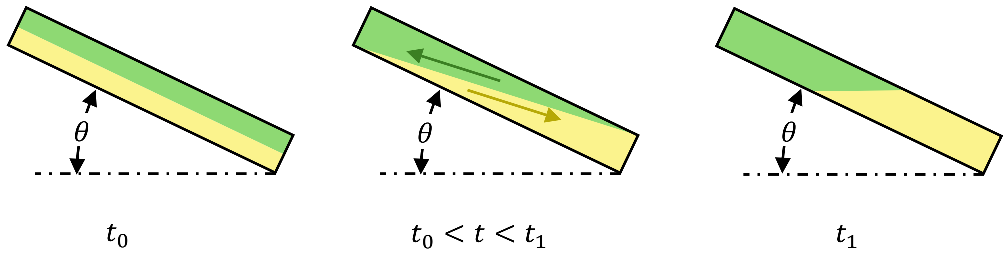


Figure 2: Schematic of tank and fluids

Figure 3 shows the procedure taken to generate the waves. Before the experiment, the tank was set horizontally and the fluids were allowed to come to rest, and any bubbles that had formed at the interface were allowed to dissipate. Then the tank was tilted to some angle θ (approximately 20°), causing the fluids to move in opposite directions. As the fluids moved, Kelvin-Helmholtz waves could be observed. Another set of Kelvin-Helmholtz waves were produced when the tank was returned to the horizontal, but those were not photographed since the first set of waves created bubbles at the fluid interface, making the second set less clear.



Tank is initially tipped to some angle θ

Fluids rush to opposite ends of the tank. Kelvin-Helmholtz waves appear.

Fluids reach new positions and grow still

Figure 3: Experiment procedure

To capture Kelvin-Helmholtz waves, it is necessary that the fluids flow stably, without initial mixing (not turbulent). No visual indicators of turbulence were observed prior to wave generation in the tank, and this can be verified with an estimate of the Reynolds number. The exact velocities of the fluids are unknown, but an upper bound can be placed on their values. The velocity of a fluid free-falling from height h is:

$$u_{\text{max}} = \sqrt{2gh} \tag{1}$$

The farthest vertical distance any of the oil can move is $h = \frac{1}{2} L \sin\theta$, where L is the length of the tank.

Applying Equation 1 to the oil, we obtain:

$$u_{\text{max}} = \sqrt{\left(9.80665\ \frac{\text{m}}{\text{s}^2}\right)\left(32\ \text{in} \times \frac{2.54\ \text{cm}}{1\ \text{in}} \times \frac{1\ \text{in}}{100\ \text{cm}}\right)\sin(20°)} \approx 1.651\ \frac{\text{m}}{\text{s}} \tag{2}$$

The Reynolds number based on hydraulic diameter for a rectangular channel is given in Equation 3:

$$\text{Re} = \frac{4HDu\rho}{(2H + 2D)\mu} \tag{3}$$

Where H and D are the height and depth of the tank, respectively. The fluid properties of the oil and alcohol are listed in Table 1.

Table 1: Fluid properties

	Density ρ	Viscosity μ	Kinematic viscosity ν
Canola oil	$920\ \frac{\text{kg}}{\text{m}^3}$	$0.0462\ \text{Pa}\cdot\text{s}$	$5.021 \times 10^{-5}\ \frac{\text{m}^2}{\text{s}}$

90% isopropyl alcohol	$786\ \frac{\text{kg}}{\text{m}^3}$	$0.00226\ \text{Pa}\cdot\text{s}$	$2.875\times10^{-6}\ \frac{\text{m}^2}{\text{s}}$

Then the maximum Reynolds number in the tank is:

$$\text{Re}_{\text{max}} = \frac{4(4.5\ \text{in})(1.5\ \text{in})\left(\frac{2.54\ \text{cm}}{1\ \text{in}}\times\frac{1\ \text{in}}{100\ \text{cm}}\right)^2\left(1.651\ \frac{\text{m}}{\text{s}}\right)\left(920\ \frac{\text{kg}}{\text{m}^3}\right)}{\left(2(4.5\ \text{in})+2(1.5\ \text{in})\right)\left(\frac{2.54\ \text{cm}}{1\ \text{in}}\times\frac{1\ \text{in}}{100\ \text{cm}}\right)(0.0462\ \text{Pa}\cdot\text{s})}\approx 1880 \tag{4}$$

This is below the typical pipe flow transition Reynolds number of 2000, even for the uppermost bound, indicating that the fluid flow is laminar before the instability occurs, as intended. If the Reynolds number was truly 1880, we would expect some signs of transition, however the assumption that the velocity in the tank is equivalent to the velocity of the fluid in free-fall is a significant overestimate. Equation 4 simply provides an upper bound on the Reynolds number.

Visualization Technique

The Kelvin-Helmholtz waves were visualized by dying one of the fluids a contrasting color. The isopropyl alcohol was dyed with green food coloring to stand out against the light-yellow oil. The tank was set up in front of a white backdrop to more clearly show the transparent fluids inside. The lighting in that room was a single fluorescent bulb.

Photographic Technique

The camera information and settings are listed in Table 2.

Table 2: Camera information/settings

Camera model	Canon EOS REBEL T3i
Lens	EF-S18-135mm f/3.5-5.6 IS USM
Focal length	24.0 mm
Aperture	5.0
Exposure	1/25
ISO	1600
Image size	5184 x 3456

The image in Figure 1 has been recolored and cropped. The original is shown in Figure 4, which is what the information in Table 2 applies to. The distance from the tank to the camera lens was approximately 24”. The field of view was approximately 1.86’ x1.24’.

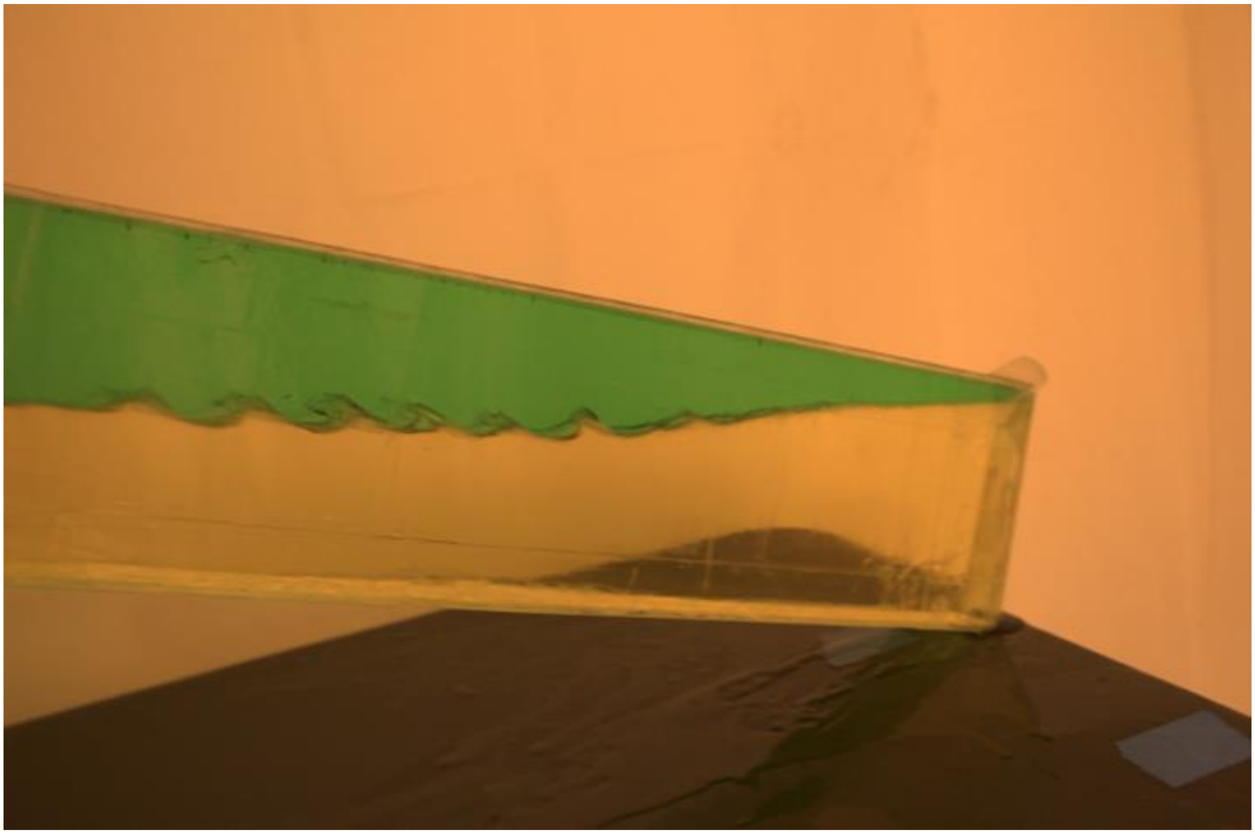


Figure 4: Original image

The camera settings were chosen primarily in an attempt to get the clearest, brightest photo possible with the poor lighting in the room. And ISO setting higher than 1600 was found to be too grainy, so that was chosen as the ISO speed, and the shutter speed was the fastest the camera could go and still capture a reasonably bright photo.

Figure 4 was edited to create the final image. The following changes were made:

1. Cropping to remove the oily table in the background.
2. Slight denoising to remove some of the ISO 1600 graininess.
3. Contrast increased via editing tone curve.
4. Significant recoloring to create more natural looking fluid colors. Oil was recolored to a dark blue-green, and alcohol to a much grayer version of that. Additionally, the backdrop, which was originally indistinguishable from the oil, was recolored to a darker gray to show more clearly that this was a tank.

Conclusion/Recommendations

The image in Figure 1 clearly shows Kelvin-Helmholtz waves between immiscible fluids, but there are things that could be improved about both the experiment and the photography setup:

1. Experiment

  a. A longer tank would increase the region free from end-effects in the tank where Kelvin-Helmholtz waves would appear. Additionally, it would allow for a shallower, more controlled tilt angle to allow the fluids to build up speed. This should create more uniform waves.
  b. Different fluids or tank construction should be used if this experiment is repeated. Isopropyl alcohol degrades acrylic. This was known beforehand, but it was not known how aggressive this could be, especially with the higher concentrations. The acrylic weld between panels degraded the fastest, causing the tank to leak severely, requiring taping on the edges. This reduced the region of the tank that could be photographed, and even then, some tape is visible in the final image. Additionally, the isopropyl cracked the acrylic within an hour, again limiting the areas that could be photographed.
  c. An adjustable hinge to tilt the tank would help with repeatability, (as opposed to manually lifting the tank). Another benefit to this is that if it is combined with a longer tank, the steady velocity in the tank is much easier to approximate, since stacked, steadily flowing fluids have a known velocity profile, and end effects become less important.
2. Photography
  a. Better lighting would improve the range of possible shutter speeds. 1/25 captures the phenomenon, but motion blur is still visible.
  b. A backdrop color that differed more from the oil would improve the contrast in the original image.