Team Third

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Group 7

MCEN 5121: Flow Visualization

Fall 2015

December 16, 2015

Purpose

The purpose behind this experiment was to capture the development of a Kelvin-Helmholtz instability that retained its scientific meaning but was also artful. This was done for the third team project for the Flow Visualization class taught by Professor Jean Hertzberg at the University of Colorado in the Fall of 2015. Personally, I'm intrigued by the development of Kelvin-Helmholtz instabilities and their occurrences throughout nature. Because of this, I was greatly interested in working with Scott Kittelman from the Department of Atmospheric and Oceanic Sciences to use his equipment in generating these specific fluid flows.

Experimental Setup

From the outside, the setup for this experiment seems relatively simple. On the most basic level, the setup requires a container to be filled with two separate fluids of varying density with the heavier one on the bottom. After filling this container, one side of it is then lifted and the way the fluids moves develops a shear at the interface. At this point in time, the Kelvin-Helmholtz instability is generated and the video can be captured. In all actuality, the setup is probably the most difficult part of this experiment to achieve for it is quite time consuming and unforgiving of mistakes.

All of the equipment and setup was made possible by my team, Group 7, which was comprised of Kelsea Anderson, Sam Ballard, Haleigh Cook, and myself, and also by Scott Kittelman of the ATOC department at the University of Colorado at Boulder. To actually setup the experiment, the first step was really just cleaning. To truly see all the small scale structures, the container used had to be polished to make the plastic as clear as possible. In addition to this, the setup had to take place in Scott Kittelman's lab, and therefore we had to open up a large enough area for the apparatus to be setup. The container used was approximately 2 meters in length, 18 centimeters tall, and 2 centimeters wide. On one side of the container, there was an inlet valve that ran to the bottom of the tank to allow the tank to be filled from the bottom up. On the other side, there was a threaded hole to allow easy plugging with a plastic bolt, but more importantly, to allow air to escape as the tank was filled. To allow ample space for the tank to be tilted on, it was set on top of two pieces of 4x4 wood so that it could stand above the table.

Next, the two fluids needed to be prepared so the tank could be filled. In total the tank holds approximately 7.8 liters of fluid, and so 3.9 liters of each fluid must be made. In actuality, this requires 5 liters of each fluid to be prepared so that there is excess. The first fluid to enter the tank is the lighter of the fluids, which in this case was water from the tap with red food coloring added. 5 liters of the water was collected and then allowed to sit for approximately an hour to allow any air to escape and the temperature to even out with the room. During this hour, approximately 20 drops of Kroger brand red food coloring was added to the water. This was then allowed to fill the main container by being gravity fed into the intel. As soon as the halfway point on the tank was reached (about 9 cm), this feed was shut off. For the second fluid, a similar process had to followed but with a few additional steps. The second fluid needs to have a higher density than that of water, so salt was added to the solution. In this case, it was determined from previous trials that an increase in density of approximately 2% would yield the best results. To accomplish this, 20 grams of sodium chloride was added per liter of water, totaling 100 grams for the entirety of the fluid. Similarly to the first fluid, this was then allowed to sit to deaerate and thermally equilibrate while approximately 15 drops of Kroger brand blue food coloring was added to the solution. After sitting for long enough and container being partially filled, the second fluid could be added. For the second fluid, the inlet flow rate was lowered to the absolute minimum to ensure that no mixing occurred as the container was filled.

To completely fill the container, the second fluid had to flow into the tank for approximately 2 hours. Upon completion, the final task for filling the tank was to remove as many air bubbles as possible. To accomplish this the container had to be gently tilted using laboratory jacks so that the entire tank was inclined a few degrees. Because of air being so much lighter than the liquid, buoyancy slowly carried all the bubbles to the open hole at the opposite side of the inlet to escape, allowing more of the salt water solution to be added. Finally, to allow complete quiescence and thermal equilibrium, the system was left to sit over night. In the morning, the procedure was much simpler. First lighting had to be added by suspending two 200 watt light fixtures and putting a white backdrop behind the tank. To avoid any glare on the tank, the lights were directed at the backdrop itself, and not at the actual tank. Next, cameras were either put on tripods to record, or their respective owners held them about 3-4 meters away from the container. Finally, a stand 43 centimeters in height was placed next to the container. Once everyone was in position, Sam lifted the tank while Scott Kittelman placed the stand underneath of it, and I operated as a brace on the other end to ensure there was no slippage of the tank. The flow was then allowed to proceed and the images and videos were captured. The setup can be seen below in Figure 1.

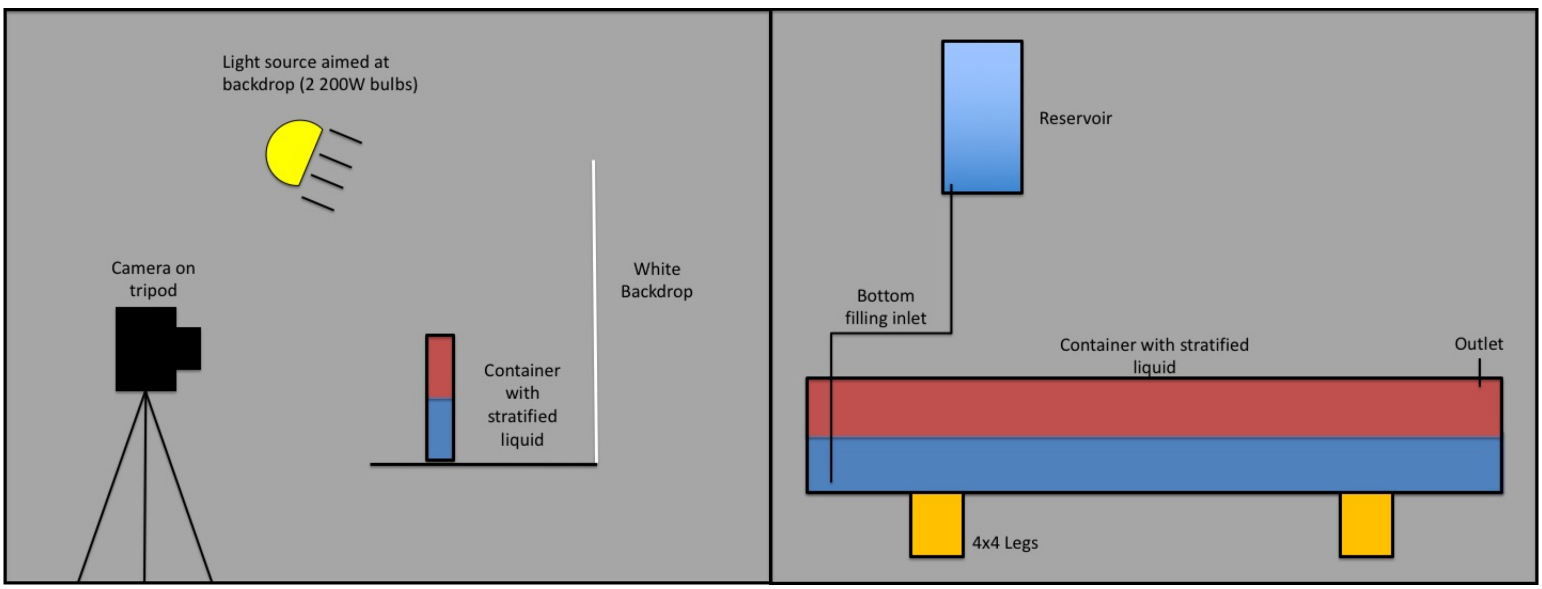

Figure 1: The experimental setup from both the side view during photographing (left) and frontal view during filling (right)

Fluid Physics

Throughout various journals and other sources of literature, there is a plethora of knowledge and insight into different forms of the Kelvin-Helmholtz instability because it does occur in a great deal of situations from ocean flows to atmospheric conditions. Unfortunately, not all of these can be explored due to the scope of this report, but the important points will be touched. The basic idea behind the development of a Kelvin-Helmholtz instability (KH) is that an interface exists over which density and velocity are not constant. In addition to this, there is also some perturbation to this interface. As time continues, surface tension, shear, and buoyant effects cause this perturbation to grow nonlinearly and manifest itself in the form of a KH [1–4].

The keys to generating a proper KH lie in multiple factors. The first of which is a sharp density difference. This density difference can be categorized by the Atwood number (the difference of the densities divided by the sum), which in our case is approximately .01. Given the methodology used in our approach, it is impossible to tell the exact gradient, but according to our results and the literature, it was sharp enough. Secondly, the initial Richardson number, a measure of the difference between the stabilizing force of buoyancy and the destabilizing effects of the shear layer, must start off at a value lower than .25 to ensure that the flow will develop into a KH. There are multiple forms of the Richardson number, but all of them involve the velocity gradient. By allowing our system to rest overnight, the velocities should be close to zero, meaning that our Richardson number was also approaching zero. Finally, some sort of perturbation and velocity must be applied. Both of these were obtained by our method of raising one end of the container. By causing an abrupt movement, some sort of perturbation must be applied to the interface, and the change in the alignment of the gravitational field causes the two fluids to move. According to the laws of conservation of momentum, because their densities are different, their velocities must also be different, and so we end up with a shear layer [1,3,4].

To characterize this flow, the Reynolds number is the most insightful measurement available to use to make. According to Thorpe's work using a very similar stratified tank setup, the Reynold's number can be defined as follows.

$$Re = 0.28\left(\frac{\rho_1 - \rho_2}{\rho_1 + \rho_2}\right)\sin(\alpha)\left(\frac{g^2 t^3}{\nu}\right)^{\frac{1}{2}}$$

In the above equation, the density relationship is just our Atwood number, α is the angle of our tank (12.4 degrees), g is the acceleration due to gravity (9.8 m/s^2), t is the time from raising the tank until the first perturbation is visible (10 s), and ν is the viscosity of water ($1.004*10^{-6}$ m^2/s). By plugging in the numbers, we get the result that the Reynolds number is approximately 200. This indicated to us that our flow is not in the turbulent regime, and therefore we should be resolving the scales perfectly fine [1].

Also, based on the knowledge of this flow that we have, we are able to make some predictions as to the shapes it should make. From the flow being viscous, we know we should develop a vortex sheet, but that the vortical structures should center around a stable, unmoving spiral point, which is exactly a phenomenon that we see. We also know that because of the low Reynolds number, we should expect there to be a significant source of viscous diffusion that causes the instability remain at large scales. We can see this in the sense that there are some small structures but they all appear blurry. This is not a result of focus, but rather mostly an effect due to viscous diffusion causing mixing and dissipation. Further investigations of this flow, either more experiments need to be done, varying such parameters like the Atwood number, the heights of the individual fluids, and the degree of the incline, or a more robust measurement technique needs to be used such as PIV to get a velocity field [2,3].

Photographic Technique

The camera used to film the flow was a Nikon D3300 with a Nikkor 18-55mm lens and was filmed in 1920x1080 pixels at 60 frames per second. As mentioned in the setup, the camera was approximately 3-4 meters from the flow, and everything was light with two 200-watt light fixtures. To edit the movie, Apple's iMovie program was utilized and there were a few key things modified. First of all, the film was trimmed and cropped to capture just the 45 seconds of actual flow and to remove unwanted background items. The final video only has about ½ of the domain of the original video because all of the edges beyond the white backdrop were removed. In order to get a good contrast, the color profiles had to be changed. First, the white balance needed to be readjusted, then the contrast was boosted, and the saturation increased. The end results of these adjustments can be seen in Figure 2. Finally, the last adjustments made were to add in titles, credits, and music to supply the audience with what they are watching and to create the intended mood.

Figure 2: The original coloring of the video (left) and the edited version (right)

Conclusion

Overall, this project was a huge success, and I greatly enjoyed working on it. It did require a significant amount of time to setup, but the end result was completely worth the work. If I were to repeat this project, though, there are a few things I would improve upon. First of all, we had another light source that contained a 750-watt and 250-watt bulb that would have greatly improved our lighting. Unfortunately, the bulbs burned out, and the ITLL did not have replacements for them. Secondly, I would find a bigger white backdrop. The one used was large enough to suit our purposes, but having a larger version would allow us to light the entire flow better, and give us more options for getting it perfectly in frame. Finally, I believed that iMovie was able to rotate videos, which is true, but only in 90 degree increments, so I would like to film the flow at the angle that the container ends up at.

Bibliography

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