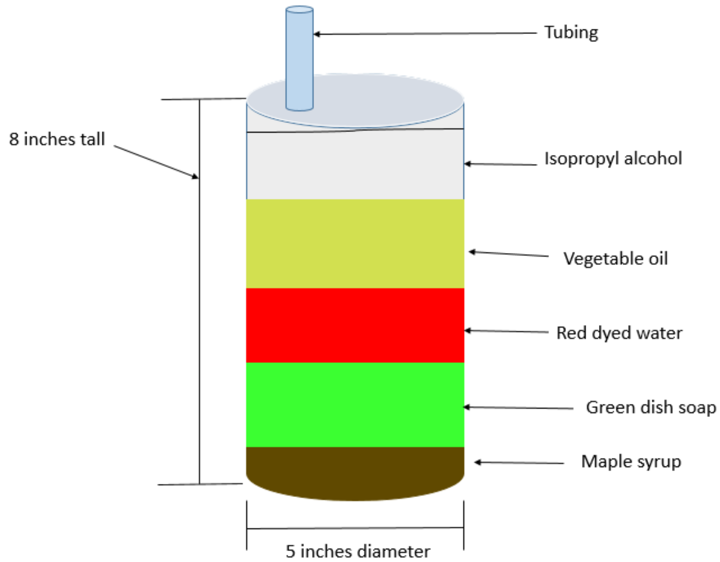
Boundary Layer

By: Sam Brown

For this experiment our team (Audrey Viland, Dawood Ahmad, Faisal Alismail, Meg Ivy, and I) wanted to capture interesting fluid phenomena that occurs when you have multiple fluids in a container, five plus, that are separated in layers that get disturbed. I was very intrigued by this idea because I was unsure what would happen. I thought that when the fluid layers were disturbed, that because of their varying densities, they would naturally return back to their respective layers. I also saw the opportunity to capture multi fluid level boundary layers. By this I wanted to see the fluid, after being disturbed, show a clear multi fluid level profile showing the shear forces at work.

In order to accomplish our goal, we needed to carefully place fluid layers one on top of another. To do this we stacked these layers in order of density at room temperature. The first layer placed in the vase consisted of maple syrup which has a density of $1.37\,\frac{g}{cm^2}$. The second layer placed carefully on top of the syrup was dish soap with a density of $1.06\,\frac{g}{cm^2}$. The third layer placed on top of the dish soap was red dyed water with a density of $1.0\,\frac{g}{cm^2}$. The fourth layer on top of the water was vegetable oil which has a density of $0.93\,\frac{g}{cm^2}$. Finally the last layer placed on top of the oil was a layer of isopropyl alcohol with a density of $0.786\,\frac{g}{cm^2}$. Placing these fluid levels proved more difficult than we had originally imagined. To make sure that we didn't destroy the layers by the act of pouring another on top, we made use of a tube to slowly and gently place the fluids on top of each other. By using this tube we were able to control the speed which we placed the fluid as well as the location. This gave us very fine control over the fluids used in this set up. In **Figure (1)** we can see what the final set up looked like once all the fluid layers were placed.

Figure 1: Fluid Layer experimental set up



Once the experiment was set up as depicted in **figure (1)** we were able to begin manipulating the fluid layers. I took advantage of the tubing and the shear forces it was applying on the fluids. I did this by simply pulling the tube very slowly upwards. Roughly 2 cm/sec. We quickly found out that the fluid layers behaved in a very beautiful and text book way. This act of pulling the tube upwards was creating very clear boundary layers. To better understand why we are seeing such a well-defined boundary layer, The Reynolds number can be defined as follows.

Reynolds Number: $$Re = \frac{Ul}{v}$$ [1]

Kinematic Viscosity: $$v = \frac{\mu}{\rho}$$ [1]

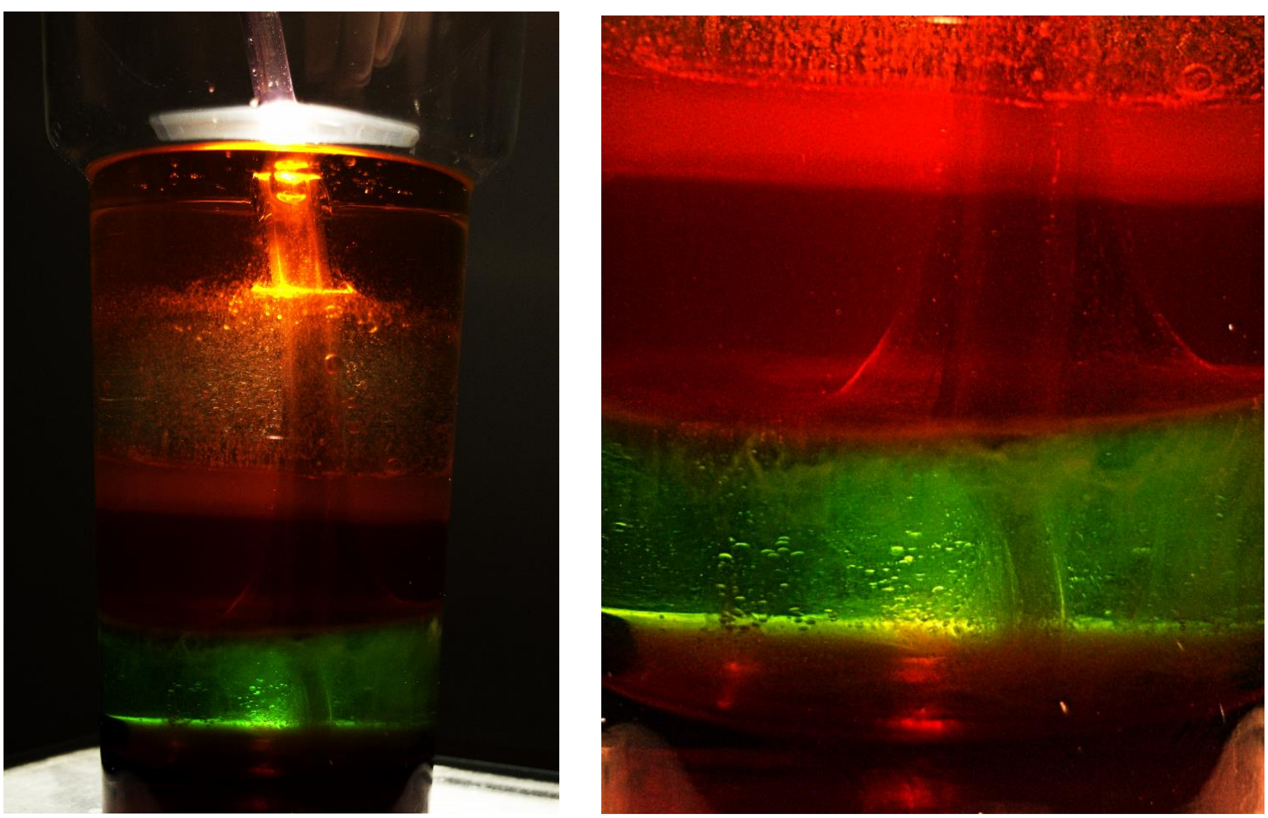
Where U = Velocity of the tube (2 cm per second), l = length of tube in contact with the dish soap (4 cm), μ = absolute viscosity (3,500 centipoise), and ρ = density of the dish soap ($1060\frac{kg}{m^3}$). It is important to note that we are interested in only the dish soap because the boundary layer that the image depicts is the dish soap being dragged into the red water layer as shown in **figure (2)**. Meaning that the boundary layer that was captured was that of the soap and not because of contact with the water as it might see. Because the dish soap is being dragged upward, we want to quantify the Reynolds number to better understand why this layer is so well defined. Below are some simple calculations to define the Reynolds number.

$$v = \frac{3{,}500*10^{-3}\frac{kg}{ms}}{1060\frac{kg}{m^3}} = 0.0033\,\frac{m^2}{s}, \quad Re = \frac{0.02\,\frac{m}{s}*0.04\,m}{0.0033\frac{m^2}{s}} = 0.24$$

To create a well-defined boundary layer the Reynolds number need to be relatively small Re < 5 [1] . In this specific case we see a Reynolds number of 0.24 which is reasonable considering how slowly the tube was being moved and how viscous the dish soap was. In this experiment if we were to have moved the tube faster we would see very different effects on the boundary layer. Because of this I believe the speed chosen for this experiment was extremely effective and allowed us to capture a beautiful boundary layer profile.

To achieve this image we used a projector to provide a lot of light in order to illuminate the fluid layers effectively from the bottom. As mentioned before we made use of dyed water and other naturally colored fluids to create an interesting image. Once we had lighting set up we then tried to create a non-distracting background. To achieve this we used a white projector screen. Using all of the described methods we were able to create many effective images of the fluid phenomena. The image set up needed to be heavily edited in order to create a non-distracting image.

Figure 2: Depicted below are the unedited image and the edited image.



It is easy to see that it is difficult to properly illuminate the fluid layers effectively. The original image in **figure (2)** shows how dark the fluid layers were before processing. The equipment used for this experiment was a Nikon 3300. The ISO was set to 898, with an F-Stop of f/4.2, and an exposure of 1/500 seconds. This high shutter speed is what contributes to the darkness of the image, however it is fully necessary to capture the dynamics in the image for a crystal clear image. The photo was taken about 9 inches from the fluid container. The focal length used here is 20mm. In post processing I edited quite a few features. I first cropped it to better frame the fluid phenomena that I cared about, in this case the boundary layer that formed in-between the dish soap and the water layer. I then played with the colors of the image. My goal here was to make the green really glow to achieve good contrast with the water layers. I also brightened the image to compensate for the darkness of the original image. I also played around with the sharpen tool in darktable. This allowed me to make the profile of the boundary layer really crisp. The most difficult part of editing this image was not crossing the line of too much grain. I was fighting grain throughout this process and did not want to create a final grainy image.

In summary I think this image shows the dynamics involved when you layer fluids of varying densities and manipulate them using shear forces. Because of this I believe this image is very effective. The boundary layer came out much clearer than I had originally anticipated. If I were to create the image again I would set up a better situation that provided more light. I would also adjust my focus to really be centered on the boundary layer instead of the entire fluid container. To further develop this idea I would be interested to see how to best show this boundary layer profile, beyond just a zoomed in image.

[1] Munson, B., Okiishi, T., Huebsch, W. and Rothmayer, A. (n.d.). *Fundamentals of fluid mechanics*. 7th ed.