GET WET

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Introduction

The image shown was created for MCEN 5151-Flow Visualization as the first experimental assignment of the course. The intent of the assignment was to help students “get their feet wet” in regards to combining fluid physics and photography to create unique images that capture the aesthetic of certain fluid phenomena and clearly illustrate the mechanics driving the effect. Accordingly, there were no strict guidelines dictating what and how to capture the flow, only that the image conveys the flow clearly. The intent of the image is to illustrate the beauty in a fluid flow that viewers are likely already familiar with. The diffusion of food dye through cold water creates the umbrella-shaped flows known as the Rayleigh-Taylor instability. This fluid effect was investigated because it offers a very calm, aesthetic appeal but also conveys some interesting fluid mechanics. The following report will detail the experimental setup and photographic techniques used to capture the flow as well as the fluid mechanics driving the effect illustrated in the image.

Fluid Physics

The image illustrates a clear example of a fluid dynamics phenomena called the Rayleigh-Taylor instability that results in the umbrella-shaped plumes that form as the food coloring diffuses into the water. The diffusion is driven by the differences in density between the water and the food dye. The dye was added to the surface of the water and diffused downward due to gravitational acceleration. This is because the dye is denser than the water and this difference in density causes the dye to displace the water below it and lower the potential energy of the system (Drazin). The potential energy is initially translated into kinetic energy, as the fluids are in motion, and eventually dissipate largely into heat via turbulence in between the two fluids.

The Rayleigh-Taylor instability is a fluid effect that is primary dictated by two, dimensionless parameters: Reynold’s number and Atwood number. A fluid’s Reynold’s number is the ratio of inertial forces to viscous forces, and describes how “smooth” a fluid’s flow is (Cabot and Cook). A higher Reynold’s number (>10,000) indicates a more turbulent flow while a lower Reynold’s number (<2300) indicates a laminar flow. The Reynolds number for the diffusion of the dye can be calculated by making a few assumptions: V=0.05 m/s (it took about 2 seconds for the initial linear diffusion to travel about 10cm), R= 1cm (determined by the width of the linear diffusion and the scale of the image), and a viscosity of ν= 4.5E-7 m^2/s.

$$Re_D = \frac{V_D * r}{\nu} = \frac{\left(\frac{0.05m}{s}\right) * (0.01m)}{(4.5\text{E} - 7\frac{m^2}{s})} = 1{,}111$$

Since the Reynold’s number is <2300, the initial diffusion of the dye through the water can be categorized as laminar, inviscid flow. This type of laminar flow is ideal for creating the slow diffusions and increase the amount of “plumage” in the Rayleigh-Taylor instability within a finite volume. This was necessary to create the transition from the linear flow into the broad instability pattern captured in the image.

The Atwood number describes the density ratio between two fluids (Davies Wyke and Dalziel). The penetration depth of each instability is directly influenced by the Atwood number, as the "heavier" fluid (ρ_H) permeates the "lighter" fluid (ρ_L). The dye is assumed to have a density of 1030 kg/m^3 while water has a density of 1000 kg/m^3.

$$A = \frac{\rho_H - \rho_L}{\rho_H + \rho_L} = \frac{(1030\frac{\text{kg}}{m^3} - 1000\frac{\text{kg}}{m^3})}{(1030\frac{\text{kg}}{m^3} + 1000\frac{\text{kg}}{m^3})} = 0.0148$$

Since the Atwood number is <<1 the flow is ideal for the formation of Rayleigh-Taylor instabilities in a small-volume experimental setup.

Experimental Setup

To create the image shown, a relatively simple setup was utilized, consisting of common items and a little trial and error to create the correct lighting and fluid conditions. The lighting was creating using a lamp with five bulbs that could be independently oriented. The experiment was staged in a corner with textured, white paint and the lamp was positioned nearby. After turning on all five bulbs, the lamps were oriented in different directions, facing the wall. By using the light reflected off the white walls, the flow was easily illuminated and reduced any glare spots on the wine glass that would occur from direct exposure to the bulbs. The camera was placed upon a thick book to offer increased stability and position the lens normal to the flow.

The wine glass was filled with cold water from the tap and then stirred to remove lingering bubbles suspended in the water and the attached to the walls of the wine glass. Initially, the food dye was added directly to the surface of the water from varying heights and producing Rayleigh-Taylor instability patterns, but not the types of large diffusion patterns being targeted. The challenge was that the dye diffused into the water too quickly and resulted in small, singular instabilities. While these were appealing and interesting, it was not the desired outcome. In order to facilitate a larger diffusion, a small volume of vegetable oil was added to the surface of the water to prevent the dye from diffusing prematurely into the water. The amount of dye that could be suspended in the meniscus of the oil was dependent upon the amount of oil added and thus the thickness of the oil layer. The oil layer also allowed for better prediction of the flow pattern because it allowed for precise control of where the oil was going to contact the water.

Figure 1: Experimental Setup

Photographic Technique

The image was shot on September 11th, 2016 in the living room of a typical apartment, using a Canon Rebel XTI digital DSLR camera. The following equipment and parameters were used to capture the image:

- Lens: 18-55mm Macroscopic Lens
- Shutter Speed: 1/100 Second
- Exposure Settings: ISO 400, F/2.2
- Image Resolution: Original- 4032 × 3024 pixels, Edited- 2636 × 2825 pixels
- Editing: Photoshop CS6 was utilized to crop the image and adjust the color balance

A fast shutter speed was utilized to freeze the flow as the dye diffused into the water, minimizing the presence of any motion blur. An ISO of 400 was selected since there was ample lighting conditions. A large aperture of f/2.2 was selected in order to allow lots of light into the camera from such a close up perspective and a very fast shutter speed. The goal was to try and pull more light through the periphery of the diffusion, to highlight the differences in folds and ripples on the edges of the plume. The field of view is approximately 4in x 5in in the original image. While the image turned out very well, the focus is not completely crisp throughout the entire image. This was a challenging because the diffusion was a 3-dimensional shape that often deviated in and out of the focal plane.

Photoshop CS6 was used to post process the image. The resolution of the initial image was 4032 × 3024 pixels and was cropped down to 2636 × 2825 pixels to remove any distracting elements from the photo and focus on the flow being illustrated. The color balance was adjusted the bring out the folds in the flow of the Rayleigh-Taylor instability. Consequently, this also brought out the appealing color gradient in the back, caused by the refraction of light in the curvature of the wine glass. The clone stamp tool was used to remove a few glares from the surface of the glass. Lastly the image was rotate 180 degrees to make the “tree” visual.

Original Image

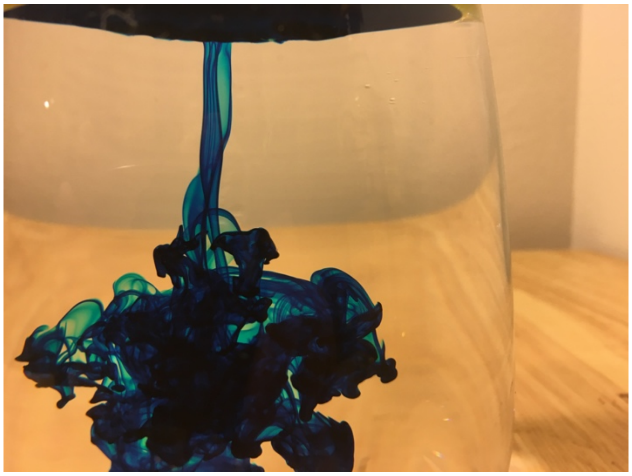

Figure 3: Original Image, Unedited

Edited Image

Figure 2: Final Image, After Post Processing

Commentary

Overall I am very pleased with how this image turned out, there is little I would change if I were to retry this experiment. I have always been fascinated by the aesthetics of the Rayleigh-Taylor instability, it has a natural, calming visual appeal. The warm, pink color gradient in background is reminiscent of a summer sunset and the cool, deeper blue tones of the flow offer a very appealing contrast in the image. This effect also helps to draw the viewer's eyes toward boundary at the periphery of the flow, which was the initial goal of the experiment.

Citations

1. Drazin, P. G. (2002). Introduction to Hydrodynamic Stability. Cambridge, UK: Cambridge University Press
2. Cabot, W. H., and A. W. Cook. "Reynolds Number Effects on Rayleigh-Taylor Instability with Implications for Type Ia Supernovae." *Lawrence Livermore Nation Labratory* (2006): n.pag. Web. 26 Sept. 2016.
3. Davies Wyke, Megan, and Stuart Dalziel. *Rayleigh-Taylor Instability Between Two Stable Stratifications*. N.p.: University of Cambridge, 09 Oct. 2012. Web. 26 Sept. 2016.