THE UNIVERSITY OF COLORADO

Get Wet Image Report

Marangoni Flows Over Settled Oobleck

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Flow Visualization

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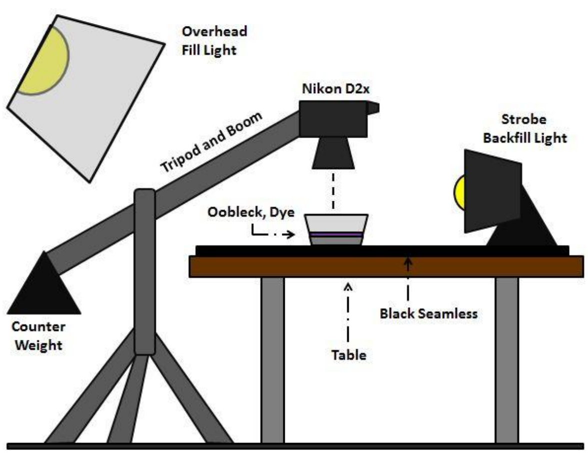
1. Purpose of Image

The image for this report was captured for the initial 'Get Wet' assignment for The University of Colorado, Boulder's MCEN 4151: Flow Visualization course. The class is designed to encompass multiple disciplines ranging from engineers to visual arts students. For the 'Get Wet' assignment, students were asked to observe a fluid phenomenon of interest and document it through whatever visual medium he or she thought best represented the fluid flow. For the image taken, the fluid flow in question pertained to Marangoni flows – in this case the dispersion of soap and dye over a settled Oobleck base. The image was intended to capture the dispersion of dye over a surface immediately after it was added to a steady state soap surface. In this image, flow vortices were also unintentionally generated due to the presence of a soap bubble near the location where dye was added. The resulting image dramatically shows the effects of a Marangoni fluid flow.

2. Image Set Up and Approach

In order to obtain the image, several steps had to be carried out. The first step was to properly place and mount the camera. The camera was position directly above the focal plane, looking down the Z-Axis. The lens was fixed approximately It was mounted to a three legged tripod with an adjustable boom fixed with counter weights. This fixture ensured that the camera had a stable platform from which to shoot. The cup used to contain the Oobleck, soap, and dye was placed atop a black seamless covered table. Two strobes were used to illuminate the image. A direct, uncovered strobe bulb was placed on the positive Y-Axis side of the image, and another was suspended at an angle above the table. This strobe was covered with a fill umbrella approximately 3x3 ft in size to disperse the light over the entire area when activated. Each strobe light was connected via wireless to a module attached to the top of the camera.

Figure 1: Schematic of 'Get Wet' set up



A remote was connected to camera, and had a wire which extended to an image capture button. When the button was depressed, the camera simultaneously flashed the strobe lights, and captured the digital image. Using a remote eliminated any possible motion blur that could have been an artifact of depressing the image capture button. This set up was aided and facilitated with the studio and equipment of Reg Francklyn Photography.

3. The Physics behind the Flow

For this image, the desired flow effects were visualized using regular food coloring dye and dish washing soap. Initially, the flow effect to be captured surrounded the use of Oobleck, a common do-it-yourself, non-Newtonian fluid. A non-Newtonian fluid exhibits a changed viscosity or given flow behavior with the sudden onset of an applied force or stress [1]. This is a result of the material composition of these fluids. In most non-Newtonian fluids (and in the case of Oobleck), long polymer chains (cornstarch) are suspended within a fluid matrix (in this case water). When a force is suddenly applied to the substance, the long polymer changes do not have time to rearrange to allow the smooth transmission of the force, but rather act as a tightly woven net which 'catches' the force and disperses it over a greater surface area. When this happens, the liquid behaves in a more solid manner. However, when a force or stress is gradually applied, the polymer substrate has time to shift and reorient so that the force is readily transmitted, thereby behaving as a liquid.

For this experiment, the Oobleck was used to form a base layer for the application of dye. Initially, purple dye was added to the surface of the Oobleck. Common dish soap was then added to the middle of the dye drop. The resulting flow pattern is described as a Marangoni flow. Dish soap – composed of molecular sized surfactants – interacts with the fat content of the Oobleck and forms a soap film. This soap film is stabilized by the surfactants, and results in a lower average surface tension where the soap exists [3]. A surface tension gradient emerges as the soap films stabilize, and the nearby fluid flows from the area of low surface tension towards any one with greater surface tension [2]. This phenomenon is described by a dimensionless quantity known as the Marangoni Number, which is defined as:

$$Ma = \frac{(\gamma_i - \gamma_b)H_l}{\mu D} \qquad [8]$$

Where the above variables are defined as:

$\gamma_i = Surface\ Tension\ at\ Interface = 0.064\ N/m\ (Assumed\ to\ be\ Glycerol\ [9])$

$\gamma_b = Surface\ Tension\ in\ the\ Bulk = 0.0728\ N/m\ \ (Assumed\ to\ be\ Water\ [9])$

$H_l = Film\ Thickness = 0.001\ m\ (Assumed)$

$\mu = Dynamic\ Viscosity = 1.002E - 3\ N * s/m^2\ (Water\ [5])$

$D = Diffusivity = 0.146E - 6\ m^2/s\ (\ Water\ [6])$

The Marangoni Number is then calculated to be:

$$Ma = -\frac{(\gamma_i - \gamma_b)H_l}{\mu D} = \frac{\left(0.064\frac{N}{m} - \frac{0.0728N}{m}\right)(0.001\ m)}{\left(1.002E - 3\ N * \frac{s}{m^2}\right)\left(0.146E - 6\frac{m^2}{s}\right)} = \mathbf{61415.63}$$

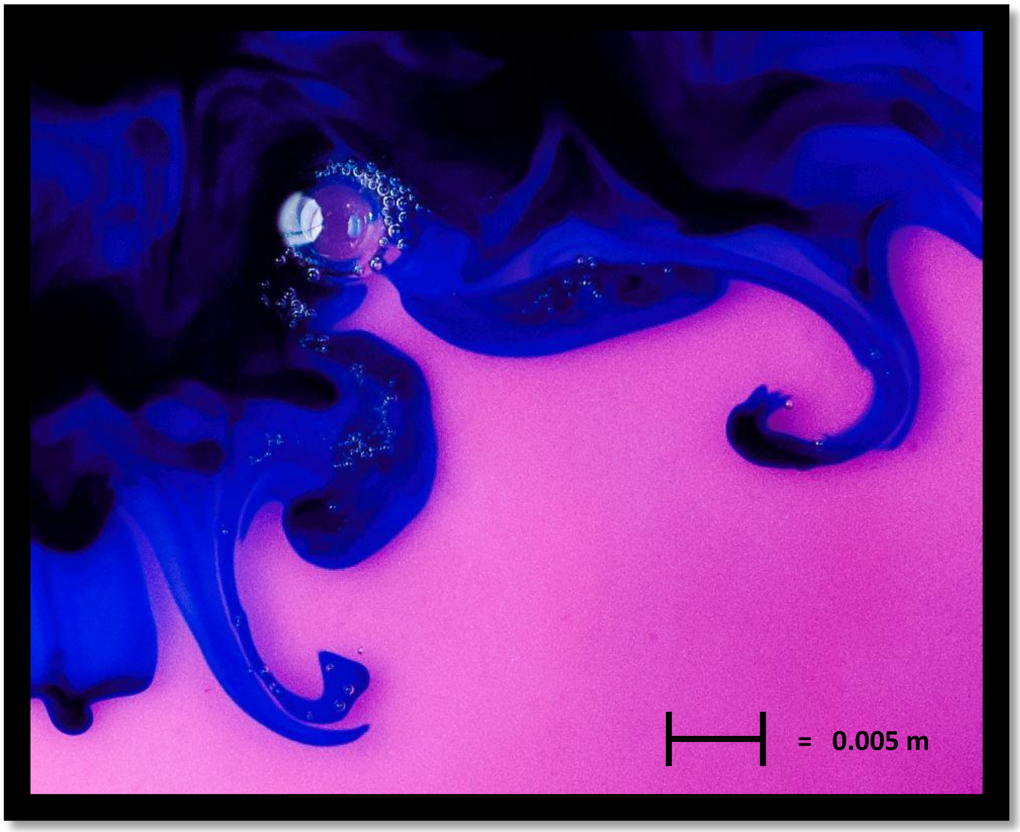


Figure 2: Close Up View of Soap Bubble and Resulting Turbulent Flow

An additional unintended flow effect in the image is the presence of turbulent flow around a large soap bubble. The turbulent flow is in the direction of fluid flow as dictated by the Marangoni number. The bubble can be assumed to have the same effect on the flow as a vertical cylinder protruding through the fluid would. At the surface of this cylinder, a no slip condition exists. With a high enough Reynolds number (a dimensionless ratio of the fluid inertial forces to the fluid viscous forces), the flow after the cylinder will become turbulent. This critical Reynolds number is 2300 [10].

$$Re = \frac{UL_c}{\nu}$$

Where the above variables are defined as:

$U = Average\ Velocity = 0.05\ m/s (Empirically\ Assumed)$

$L_c = Characteristic\ Length\ of\ Flow = 0.05\ m\ (Distance\ of\ Flow\ around\ Soap\ Bubble)$

$\nu = Kinematic\ Viscosity = 1.004E-6\ m^2/s\ (Water, At\ Room\ Temperature\ 20°C, [9])$

Reynolds number is then calculated to be:

$$Re = \frac{UL_c}{\nu} = \frac{(0.05\frac{m}{s})(0.05\ m)}{(1.004E-6\frac{m^2}{s})} \approx \mathbf{2490}$$

Since the Reynolds number is just barely larger than the critical number required for turbulence, the flow distal to the soap bubble is just beginning to exhibit turbulent characteristics. Both of the shed vortices mirror each other almost perfectly, and point to the underlying fluid flow around the soap bubble as it is driven by the previously described Marangoni effects caused by the addition of soap.

4. Visualization Technique

The required elements to visualize this specific fluid phenomena were Oobleck, food coloring dye, and dish soap. While the non-Newtonian nature of the Oobleck proved to be a non-essential aspect of the experiment, the fat content within its constituents (the cornstarch) were vital to obtaining the Marangoni, surface tension driven flow. Typically, these flows are visualized using milk, dye, and soap. The fat molecules within the Oobleck serve to generate the surface tension gradient in the exact same way that the milk typically does. To some extent, the Oobleck may also have contributed to the graceful three dimensional nature of the dye flow. Since the original Oobleck, soap, and purple dye had been allowed to reach a steady state point, a thin layer of water (squeezed from the slowly settling Oobleck) and soap resided over the denser layer of purple dye, which had settled to rest on top of the Oobleck. This purple dye had been disperse by itself via a Marangoni flow, and had thus produced a very pleasing gradient backdrop for the image.

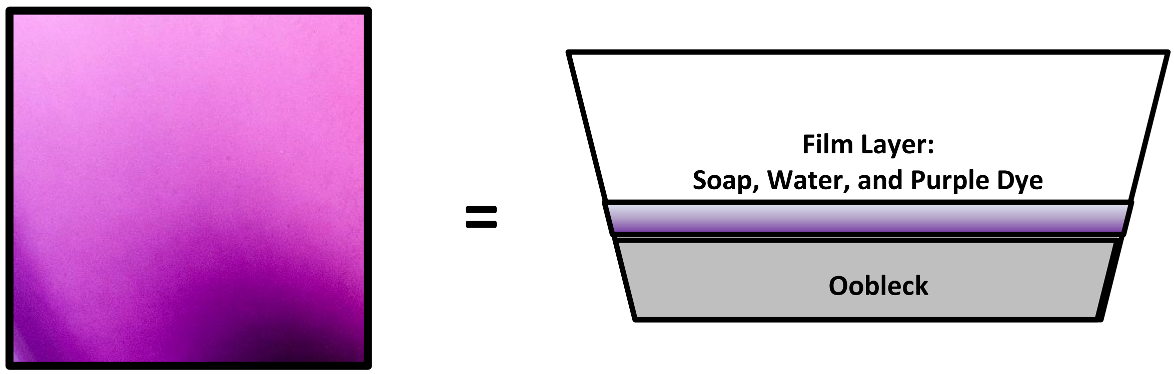


Figure 3: Actual Background Color Gradient and Schematic

When the blue dye was dropped into this surface mixture, it was (for the most part) vertically constrained by the thick layer of Oobleck in the bottom of the glass. However, due to the thin nature of the film layer on top, the three dimensional flow patterns of the blue dye were readily able to be captured by the cameras sensor. The resulting is the wispy, lacy nature to some of the fringes of the blue dye pattern.

5. Photographic Technique

The camera used to capture this image was a Nikon D2x. The camera lens was a 60mm Macro-Nikkor F28 lens. The camera itself was fixed to the extended boom of a three-leg tripod. It was oriented to look down at the surface of the fluid, and was leveled in both the x and y directions to ensure that no image distortion occurred. A remote cord was attached to the camera so that no artificial noise would be induced during the actual image capture. Alien B studio strobes were used for both the backlight and fill light, and were wirelessly connected to the camera. The overhead fill light was roughly 3 feet from the table surface, while the backlight was approximately 1 foot behind and to the right of the image, pointing right to left. The image was captured as a RAW file and was post processed as a JPEG-Fine. The camera settings were an ISO 160, a focal length of 60 mm, an aperture size of f/5.6, and a shutter speed of 1/125sec. The field of view is approximately four square inches. Post processing was done in Adobe Lightroom, and was comprised of a slight modification to contrast (less than one full stop) and hue (slightly enhanced the blue and magenta levels), and an image crop to remove unwanted container edges. The original image (Approximately 3000 x 4000 pixels) is shown below.

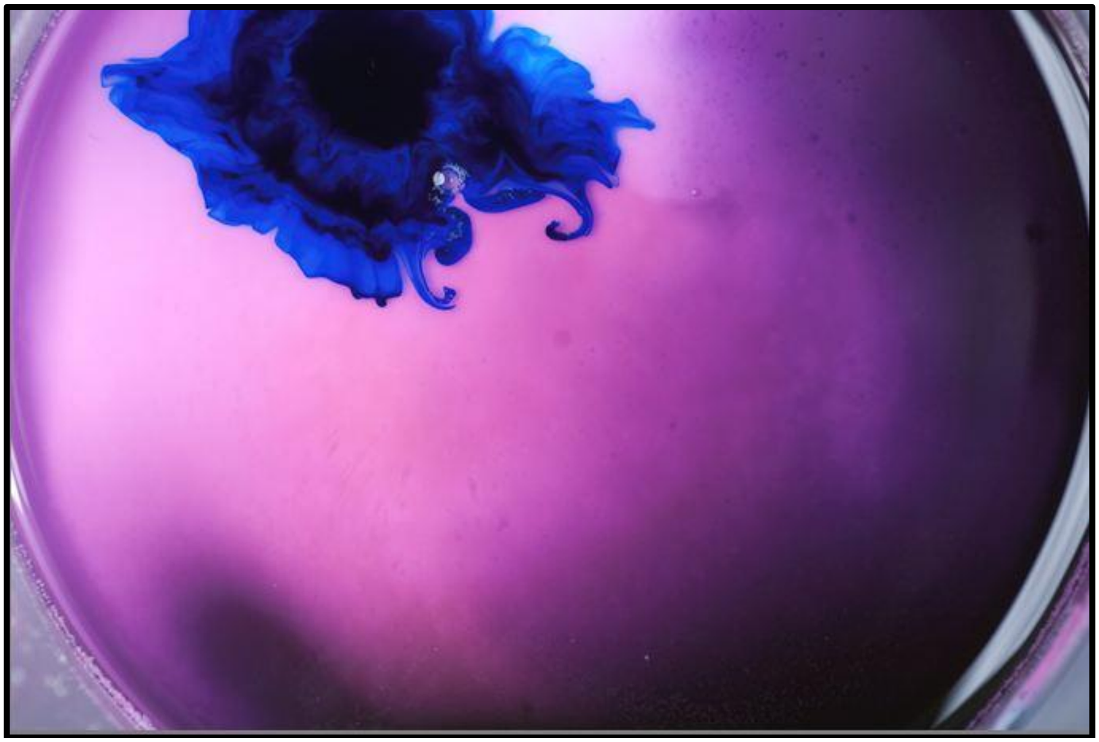


Figure 4: Original, Unedited Image

6. Conclusion

This image beautifully captured the effects of not only a Marangoni surface tension driven flow, but also turbulent flow around a stationary object. The color depth was very vivid, thanks in part to the purple gradient background, and the sharpness and clarity of the blue dye. The focal point was perfectly centered onto the surface of the flow. Also, while unintended, the addition of the lone soap bubble provides a good sense of contrast and physical grounding to the image, and helps provide a sense of depth. The only correction to the image would be to attempt to center the blue dye pattern within the field of view. While the rule of thirds worked to enhance the beauty, more opportunities could potentially have been pursued had a complete dye pattern been captured. Overall, this image turned out perfectly and well described multiple fluid flow ideas.

Works Cited

[1] http://www.sciencelearn.org.nz/Science-Stories/Strange-Liquids/Non-Newtonian-fluids

[2] http://web.mit.edu/1.63/www/Lec-notes/Surfacetension/Lecture4.pdf

[3] http://en.wikipedia.org/wiki/Soap_film

[4] http://en.wikipedia.org/wiki/Marangoni_number

[5] Young. , Munson, , Okiishi, , & Huebsch, (2007). *A brief introduction to fluid mechanics*. (4th ed.). Hoboken, NJ: Wiley.

[6] http://en.wikipedia.org/wiki/Thermal_diffusivity

[7] http://www.ann.jussieu.fr/~frey/papers/coalescence/Mao%20Z.S.,%20Numerical%20simulation%20of%20the%20Marangoni%20effect%20on%20mass%20transfer%20to%20single%20slowly%20moving%20drops%20in%20the%20liquid%E2%80%93liquid%20system.pdf

[8] http://www.descsite.nl/Publications/Thesis/Molenkamp/molenkamp_c4.pdf

[9] http://www.engineeringtoolbox.com/surface-tension-d_962.html

[10] http://labman.phys.utk.edu/phys221/modules/m9/turbulence.htm