MCEN 4151 | Flow Visualization | Team First

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Introduction

The purpose of the Team First assignment is to further explore different fluid phenomena in a group setting. For the image captured in this report, thin film interference is the phenomenon being observed where a thin soap film serves as the medium. A cup is dipped into a soapy solution to create a thin film, and the interference patterns are photographed. The idea for the setup was created alongside Fiona Wohlfarth and Alisen Bol.

Apparatus Setup

As shown in Figure 1 below, the setup requires a light source with a white cover that can diffuse the light, a bowl containing the soap solution, and an opaque cup. A white piece of paper can be substituted if the light source does not have its own cover. The light source is placed as close as possible to the cup to ensure that the thin soap film is capturing the reflection of the white cover as much as possible. In doing so, the thin soap film is more visible, and distracting reflections are also eliminated. For this particular setup, the light source is 1 inch away from the thin soap film surface. The camera is positioned approximately 24 inches away and 30˚ above the horizontal. Also, the diameter of the cup is 3.25 inches. The height of the cup is not an important variable for the photography of thin film interference.

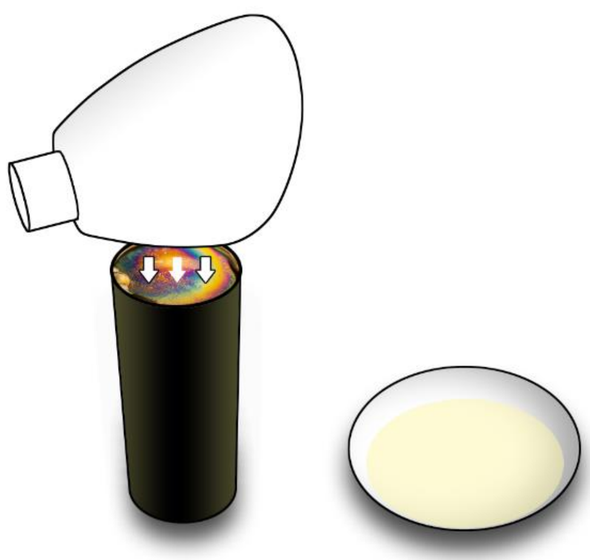

Figure 1: Apparatus setup showing the cup, bowl containing solution, and the lighting source.

Fluid Dynamics

Soap

The properties of soap allows for the thin film interference phenomenon to be observed. A soap molecule contains a hydrophilic end (attracted to water) and a hydrophobic end (repels water). The hydrophobic end of the soap molecule forces its way out of the water and causes separation between neighboring water molecules [1]. By increasing the distance between the water molecules, the surface tension of the water decreases and a thin layer of water can be sustained without collapsing under its own surface tension. In Figure 2 below, a soap bubble forms by orienting the soap bubbles in such a way where the hydrophobic ends are pointing away from the water and the hydrophilic ends are pointed inwards, trapping a thin layer of water.

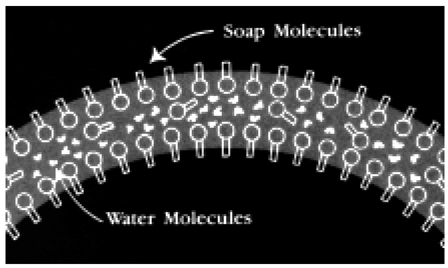

Figure 2: Soap molecules trapping a thin layer of water [1].

Thin Film Interference

The color bands observed in thin film interference is due to the varying thicknesses of the soap film and changes of index of refraction as the light ray passes through the soap film. To better understand, Figure 3 displays the effect of index of refraction. The index of refraction (IOR) is the ratio of the speed of light in vacuum to the speed of light in the medium. The IOR of air is 1.0003, which means air doesn't do much to slow down the speed of light. However, in a mixture of soap and water, the IOR is approximately 1.32 which means light travels 75.75% the speed of light in vacuum. The consequence of this higher IOR is that the light ray will bend when entering the soap film.

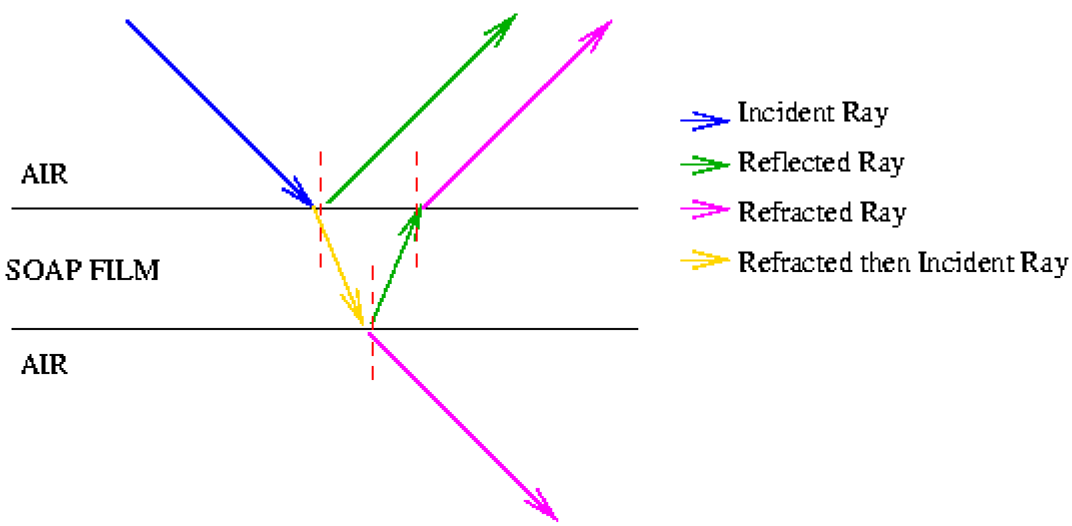

Figure 3: Pathway of incident ray in a soap film [2].

Snell's Law predicts the angle at which the light ray will exit, designated by θ_2 in the equation below where n_1 is the IOR of air, n_2 is the IOR of the soap film, and θ_1 is the angle of the incoming light ray.

$$\frac{n_1}{n_2} = \frac{\sin(\theta_2)}{\sin(\theta_1)}$$

If a light ray in air enters a soap film medium at an angle of 45˚ from the normal line of the surface, then:

$$\frac{1.0003}{1.32} = \frac{\sin(\theta_2)}{\sin(45^\circ)}$$

$$\theta_2 = \sin^{-1}\left(\frac{1.0003\sin(45^\circ)}{1.32}\right) = 32.40^\circ\ from\ the\ normal\ line\ of\ the\ surface$$

Referring to Figure 3 again, the yellow line designates the 32.40˚ line called the refracted incident ray. Notice that the blue incident ray has also partially reflected off the top of the soap film surface at 45˚. Similarly, the refracted incident ray will also reflect off the bottom surface of the soap film before entering in air below. Because there was a change in IOR, the two reflected rays above the surface of the soap film are out of phase. In other words, the reflected ray in magenta appears at a later time because it had to travel through the soap film first and then reflect back into air. This phase difference creates an interference pattern between the two reflected waves and forms a new wave with its own wavelength.

By changing the thickness of the soap bubble, it is possible to form different wavelengths because the phase of the reflected waves are changing. The wavelength inside the soap film can be determined by [3]:

$$\lambda_n = \frac{\lambda}{n}$$

Where λ is the incoming wavelength, and n is the IOR of the soap film. For an incoming wavelength of 500 nm, then:

$$\lambda_{1.32} = \frac{500\ nm}{1.32} = 379\ nm$$

The wavelength inside the soap film is important in determining the thickness of the soap film. Therefore, the thickness of the soap film can be determined based on the color seen. This relationship is determined by the equations

$$d = \frac{1}{2}m\lambda_{1.32} \qquad \text{(Max Intensity)}$$

$$d = \frac{1}{2}\left(m + \frac{1}{2}\right)\lambda_{1.32} \qquad \text{(Min Intensity)}$$

where d is the distance the wavelength travels through the soap film, m is an integer value, and $\lambda_{1.32}$ is the wavelength inside the soap film for an incoming ray of 500 nm as derived earlier. Since d is the distance the wavelength travels through the wave, the actual thickness of the film is dependent on the angle of the incoming light ray and the resulting angle due to refraction. The modified distance equation to give thickness is:

$$d = \frac{1}{4} m\lambda_{1.32}\cos(\theta) \qquad \text{(Max Intensity)}$$

$$d = \frac{1}{4}\left(m + \frac{1}{2}\right)\lambda_{1.32}\cos(\theta) \qquad \text{(Min Intensity)}$$

where $\cos(\theta)/2$ is multiplied to find the vertical component between the top and bottom of the soap film and also to account for the reflected wave that travels through the film twice. The maximum intensity equations says that for an incoming ray of 500 nm that is normal to the surface of the soap film, cyan should show up best in areas where the soap film thickness is 95 nm, 190 nm, 284 nm, and so on. Conversely, the minimum intensity equations says that cyan is least expected to show up where the soap film thickness is 142 nm, 237 nm, 332 nm, and so on.

Flow Patterns

The forces acting on the fluid are gravity, and surface tension. Convection also influences the flow of the fluid by evaporation, where the heat from the lamp accelerates the evaporation and causes concentration gradients. Gravity acts uniformly across the soap film, and circular rings can be seen. On the outer edges of the soap film, the color is red which has a wavelength of about 700 nm. Using the above equations and assuming m = 1, the thickness at the outer edges is 132 nm. For higher wavelengths, it is expected that the thickness is largest. This makes physical sense because gravity will want to pull down on the liquid, and the heaviest region would be expected to be at the bottom. Interestingly, the top portion of the soap film is also red which suggests a thicker layer. One theory is that the top red layer is in the process of evaporating. As the top layer evaporates, the surrounding soap film moves inwards to fill the void. The mushroom like plumes indicate that the direction of the flow is also towards the center. These mushroom plumes could be a result of the Taylor-Saffman instability or viscous fingering where an interface between two fluids of different densities form. Since the mixture contains some undissolved sugar, the likely hood of the fluid having two different densities is probable, increasing the driving force for Taylor-Saffman instability.

Visualization Technique

The visualization of the thin soap film requires an opaque cup, a bowl containing the soap solution, and a light source with a white diffuser. The soap solution uses one quarter cup of water, 2 tablespoons of dishwasher soap, and 5 tablespoons of sugar. Soap, when mixed with water, makes it possible for bubbles or thin surfaces to form around a loop. The sugar is added to increase the overall longevity of the thin film by increasing the viscosity, which decreases the rate of water evaporation. This soap solution will provide a life-time of 1-2 minutes before popping compared to 10 seconds in the solution without sugar. To create the thin soap film, submerge the entire lip of the cup fully into the bowl of soap solution. Carefully remove the cup from the bowl of soap solution so that the thin film does not pop. It is helpful to wet the cup first with water so that the soap can adhere better to the surface of the cup.

The lighting of the scene is minimal and requires a single source with a white material that can diffuse the light. Harsh lighting will cause large white spots to appear on the reflection of the soap film. The diffuser removes the harsh spot and spreads it across the reflection of the soap film. The overall light intensity also decreases, and as a result, the colors become more visible.

Photographic Technique

The specifications for the photograph are shown below in Table 1. A low ISO of 100 was chosen to minimize noise within the image. Furthermore, there was sufficient lighting, which did not require any more sensitivity from the camera sensor. The shutter speed was experimented with, and 1/250 s was chosen as it provided enough light and time resolution where motion blur was not photographed. The aperture is set to f/4, which allowed enough light to enter the camera, but not too much where fluid features became overexposed.

Table 1: Image Specifications

Camera	Canon EOS Rebel XS
Lens	Helios 44-2 58/2
Aperture	f/4
Shutter Speed (s)	1/250
ISO	100
Focal Length	58 mm
RAW Image Dimension	3888x2592
Final Image Dimension	1421x763

Field of View and Distance from Object to Lens

The horizontal dimension is 1.95 inches, which is approximately 60% the diameter of the cup (3.25 inches), and the vertical dimension is 1.05 inches. The distance from the thin soap film and camera lens was approximately 24 inches.

Post-Processing

As shown in the figure below, the left figure is the original image, and the right figure is the final image. The original image was cropped to remove distracting features such as the cup and the light source. Minor clone stamping in Photoshop was performed in the top left corner to fill in the void that was previously in the original image. No further image processing was performed.

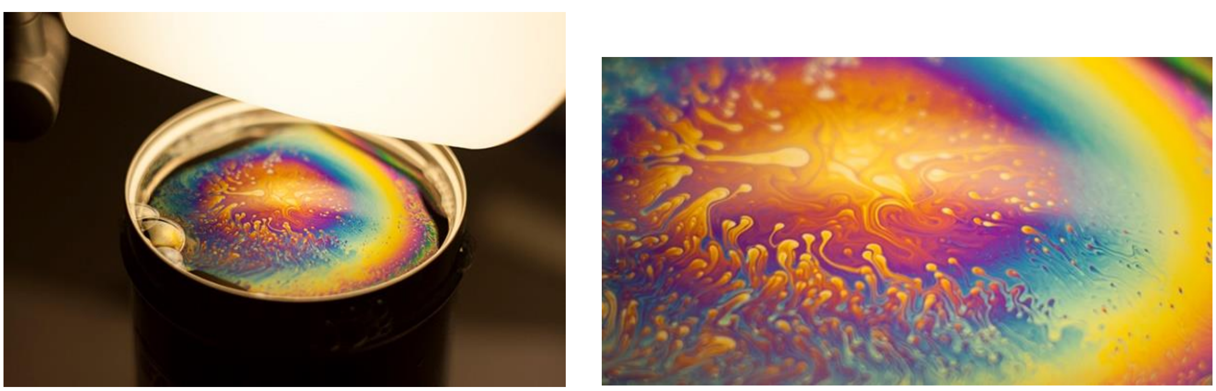

Figure 4: Original image on the left and the post-processed image on the right.

Conclusion

The image reveals many things about the physics of soap bubbles and interference patterns. Where the wavelength is higher, the expected thickness of the soap film is highest compared to its neighbors. Red layers are thicker and violet layers are thinnest. The outer edges are red, which indicates that the thickness is due to gravity pulling the liquid down and settling on the rim of the cup. For this image, I should've used an opaque cup that didn't have a reflective surface inside. An edge inside the cup can be seen through the soap film, which is distracting. I also wished I had a camera with a larger pixel density or a camera lens that would allow me to get closer while staying in focus. I had to stand 24 inches away to get the soap film in focus, and I end up capturing a lot of the background as seen in the original image. Overall, I am happy with how the image came out because of the brilliant colors and clarity.

References

[1] "Soap," [Online]. Available: http://www.exploratorium.edu/ronh/bubbles/soap.html. [Accessed 4 November 2015].

[2] "Soap Films," [Online]. Available: http://laser.physics.sunysb.edu/~hilary/presentations/pres2.html. [Accessed 4 November 2015].

[3] "Reflection and Interference From Thin FIlms," [Online]. Available: http://www.phys.ufl.edu/courses/phy2049/f08/lectures/lecture_wave_interference_2B.pdf. [Accessed 4 November 2015].