Studying The Optics of Soap Films

Final Project - Physics Lab 3 (PHY-2020-1)

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Experiments performed from March 2023 to May 2023

Submission Date: May 05, 2023

Objectives

The study of thin films and their optical properties has a long and fascinating history. From the iridescent colors of soap bubbles to the anti-reflective coatings on camera lenses, thin films play a critical role in our everyday lives and offer a rich playground for exploring the fundamental physics of light. In this project, I investigate the optics of soap films, which are formed by dipping a string loop into a soap solution and pulling it out, creating a thin film of soap that spans the loop. Soap films provide a simple and inexpensive model system for studying the interference of light waves and the effects of film thickness. By observing interference patterns, we can gain insight into the underlying physical principles of thin-film interference.

In this experiment, we have the following objectives:

1. **Horizontal Soap Film**: To use a sodium vapor lamp and a mercury vapor lamp to observe interference patterns on a horizontal soap film and verify that it displays thin film interference.
2. **Vertical Soap Film**: To use a sodium vapor lamp and a mercury vapor lamp to observe interference patterns on a vertical soap film, and to measure these patterns using image analysis to obtain a thickness profile of the film.

Introduction and Theoretical Background

Interference of Light

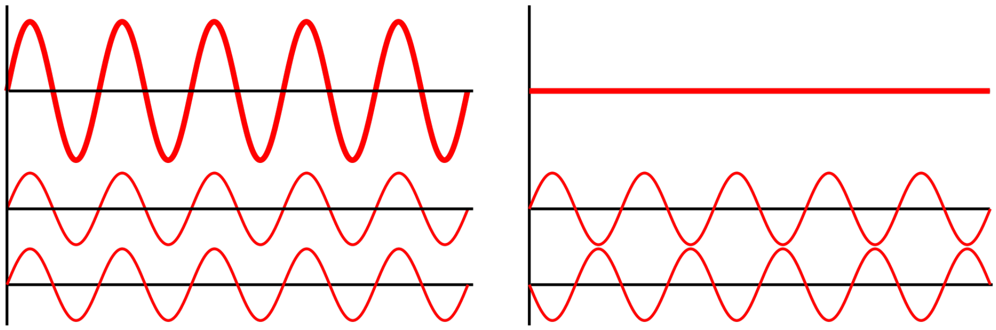


Figure 1: The interference of two waves. When in phase, the two lower waves create constructive interference (left), resulting in a wave of added amplitude. When 180° out of phase, they create destructive interference (right), resulting in a wave of zero amplitude. [1]

Interference is a fundamental phenomenon in physics that occurs when two coherent waves combine by adding their intensities or displacements with due consideration for their phase difference. The result of this combination may be a wave with greater intensity (constructive interference) or a wave with lower amplitude (destructive interference) depending on whether the two waves are in phase or out of phase, respectively. This phenomenon can be observed in all types of waves, including light, radio, acoustic, surface water waves, gravity waves, and matter waves, as well as in loudspeakers as electrical waves. The principle of superposition of waves states that when two or more propagating waves of the same type are incident on the same point, the resultant amplitude at that point is equal to the vector sum of the amplitudes of the individual waves.

If a crest of a wave meets a crest of another wave of the same frequency at the same point, then the amplitude is the sum of the individual amplitudes, resulting in constructive interference. On the other hand, if a crest of one wave meets a trough of another wave, then the amplitude is equal to the difference in the individual amplitudes, resulting in destructive interference. In ideal mediums, such as water and air, energy is always conserved. At points of destructive interference, energy is stored in the elasticity of the medium. For instance, when we drop two pebbles into a pond, we can observe a pattern, but eventually, waves continue, and only when they reach the shore is energy absorbed away from the medium.

In the case of light interference, we can never observe superposition of the electromagnetic field directly as we can in water. However, superposition in the EM field is an assumed and necessary requirement, fundamentally, where two light beams pass through each other and continue on their respective paths. Light can be explained classically by the superposition of waves, but a deeper understanding of light interference requires knowledge of wave-particle duality of light, which is due to quantum mechanics. Examples of light interference include the famous double-slit experiment, laser speckle, anti-reflective coatings, and interferometers.

The phase difference between two waves is an essential factor in determining whether the interference will be constructive or destructive. Constructive interference occurs when the phase difference between the waves is an even multiple of π, whereas destructive interference occurs when the difference is an odd multiple of π. If the difference between the phases is intermediate between these two extremes, then the magnitude of the displacement of the summed waves lies between the minimum and maximum values.

Thin Film Interference

Thin-film interference is a natural occurrence where light waves reflected by the top and bottom surfaces of a thin film interact with each other, causing either an increase or decrease in the reflected light. When the thickness of the film is an odd multiple of one quarter-wavelength of the light on it, the reflected waves from both surfaces interfere to cancel each other out, resulting in complete transmission. Conversely, when the thickness is a multiple of a half-wavelength of the light, the two reflected waves reinforce each other, leading to increased reflection and decreased transmission. As a result, when white light is incident on the film, some colors are amplified while others are weakened, resulting in the various hues observed in light reflected from soap bubbles and oil films on water. This phenomenon is also the basis for antireflection coatings used on glasses and camera lenses.

The true thickness of the film depends on both its refractive index and the angle of incidence of the light. The speed of light is slower in a medium with a higher refractive index, so the film's thickness is proportional to the wavelength of the light passing through it. When the light is incident at an oblique angle, the thickness is equivalent to the cosine of the angle at the quarter or half-wavelength positions, resulting in changing colors as the viewing angle changes. This constructive/destructive interference produces narrow reflection/transmission bandwidths, resulting in a mix of various wavelengths, rather than distinct colors of the rainbow. Thus, the colors observed are often brown, gold, turquoise, teal, bright blue, purple, and magenta.

Studying the light reflected or transmitted by a thin film can provide valuable information about the film's thickness or the effective refractive index of the film medium. Thin films have numerous commercial applications, including anti-reflection coatings, mirrors, and optical filters.

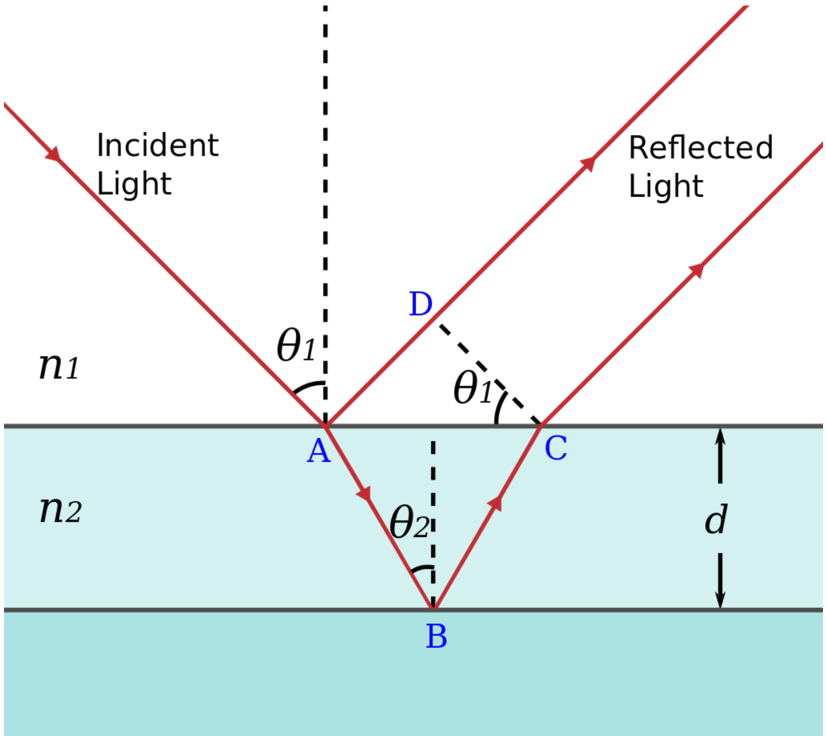


Figure 2: Demonstration of the optical path length difference for light reflected from the upper and lower boundaries of a thin film. [2]

In the field of optics, a thin film is a layer of material that has a thickness within the range of sub-nanometers to microns. When light interacts with the surface of a thin film, it can either be transmitted or reflected at the upper surface. Light that is transmitted can then be reflected or transmitted again at the bottom surface. The Fresnel equations provide a way to quantify the amount of light that will be reflected or transmitted at an interface. The reflected light from both surfaces of the film will interfere with each other, and the level of constructive or destructive interference between the two waves is determined by the difference in their phase. This phase difference is dependent on the thickness of the film layer, the refractive index of the film, and the angle of incidence of the incident wave on the film. Furthermore, a phase shift of π radians can occur upon reflection at an interface, depending on the refractive indices of the materials on either side of the boundary. This phase shift happens if the refractive index of the medium that the light is passing through is less than that of the material it is striking. If $n_1 < n_2$

and the light is moving from material 1 to material 2, then a phase shift occurs upon reflection. The interference pattern produced by this interaction can manifest as either light and dark bands or colorful bands, depending on the source of the incident light. To determine the interference condition, the optical path difference (OPD) between the reflected waves from the upper and lower boundaries must be calculated. Referring to the diagram provided, the OPD between the two waves is as follows:

$$OPD = n_2(AB + BC) - n_1(AD) \tag{1}$$

where

$$AB = BC = \frac{d}{\cos\theta_2} \tag{2}$$

$$AD = 2d\tan\theta_2 \sin\theta_1 \tag{3}$$

From Snell's law, we have $n_1 \sin\theta_1 = n_2 \sin\theta_2$. This gives us

$$\begin{aligned} OPD &= n_2\left(\frac{d}{\cos\theta_2}\right) - 2d\tan\theta_2 n_2 \sin\theta_2 && (4)\\ &= 2n_2 d\left(\frac{1-\sin^2\theta_2}{\cos\theta_2}\right) && (5)\\ &= 2n_2 d\cos\theta_2 && (6)\end{aligned}$$

Let the film be a denser medium than the surrounding medium, The reflection that occurs at the upper boundary of the film will introduce a π phase shift in the reflected wave because $n_2 > n_1$. This will add $\lambda/2$ to the optical path difference. Light that is transmitted at the upper interface will continue to the lower interface where it can be reflected or transmitted. The reflection that occurs at this boundary will not change the phase of the reflected wave because $n_1 < n_2$.

Interference will be constructive if the optical path difference is equal to an integer multiple of the wavelength of light, λ. Therefore, including the phase shift term, we get the following condition for constructive interference:

$$2n_2 d\cos\theta_2 + \frac{\lambda}{2} = m\lambda \tag{7}$$

$$\implies 2n_2 d\cos\theta_2 = \left(m - \frac{1}{2}\right)\lambda \tag{8}$$

Interference will be destructive if the optical path difference is equal to an odd integer multiple of $\lambda/2$. Therefore, including the phase shift term, we get the following condition for destructive interference:

$$2n_2 d\cos\theta_2 + \frac{\lambda}{2} = \left(m + \frac{1}{2}\right)\lambda \tag{9}$$

$$\implies 2n_2 d\cos\theta_2 = m\lambda \tag{10}$$

Wedge-Shaped Film

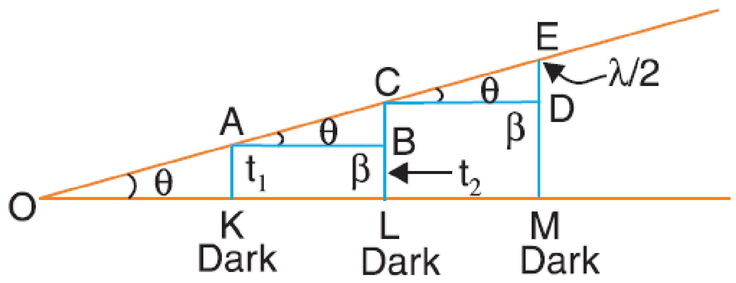


Figure 3: Diagram of interference due to wedge-shaped film. [3]

A thin film having zero thickness at one end and progressively increasing to a particular thickness at the other end is called a wedge. The wedge angle is usually very small and of the order of a fraction of a degree. When a parallel beam of monochromatic light illuminates the wedge from above, the rays reflected from its two bounding surfaces will not be parallel. They appear to diverge from a point near the film. The path difference between the rays reflected from the upper and lower surfaces of the air film varies along its length due to variation in film thickness. Therefore, alternate bright and dark fringes are observed on its top surface. The fringes are localized at the top surface of the film.

The light incident on the wedge from above is partially reflected from the top surface of the film and partially transmitted through the film, and is then partially reflected at the lower boundary of the film. The two rays BC and DE are coherent as they are derived from the same ray AB through division of amplitude.

The optical path difference between the two rays BC and DE is given by

$$\Delta = 2nt\cos r - \frac{\lambda}{2} \tag{11}$$

where the $\lambda/2$ term accounts for the phase change of the reflected ray at the top surface of the film when the film has higher refractive index than the surrounding medium, and at the bottom surface when the film has lower refractive index than the surrounding medium.

Maxima occur when the optical path difference $\Delta = m\lambda$. If the difference in the optical path between the two rays is equal to an integral number of full waves, then the rays meet each other in phase. The crests of one wave falls on the crests of the others and the waves interfere constructively. This requires that

$$2nt\cos r - \frac{\lambda}{2} = m\lambda \tag{12}$$

$$\implies 2nt\cos r = \left(m + \frac{1}{2}\right)\lambda \tag{13}$$

Minima occur when the optical path difference is $\Delta = (2m+1)\lambda/2$. If the difference in the optical path between the two rays is equal to an odd integral number of half-waves, then the rays meet each other in opposite phase. The crests of one wave falls on the troughs of the others and the waves interfere destructively. This requires that

$$2nt\cos r - \frac{\lambda}{2} = (2m+1)\frac{\lambda}{2} \tag{14}$$

$$\implies 2nt\cos r = m\lambda \tag{15}$$

Let us say that a dark fringe occurs at A. Then, if the thickness of the film at A is t_1, and if normal incidence is assumed, then at A, we have

$$2nt_1 = m\lambda \tag{16}$$

Let us say that the next dark fringe will occur at C where the thickness CL=t_2. Then, at C, we have

$$2nt_2 = (m+1)\lambda \tag{17}$$

Subtracting eq(16) from eq(17), we get

$$2n(t_2 - t_1) = \lambda \tag{18}$$

From the figure, we can see that $t_2 - t_1 = \text{BC} = \text{AB}\tan\theta$. AB is the distance between successive dark fringes and it also equals the separation of the successive bright fringes. It is, therefore, called the fringe width β. Hence, we have AB $= \beta$. Putting this into eq(18), we get the following expression for the fringe width:

$$\beta = \frac{\lambda}{2n\tan\theta} \tag{19}$$

Thus, if we know the fringe width, we can use this expression to calculate the wedge angle $\tan\theta$. The thickness t at any point is then simply $l\tan\theta$, if l is the distance on the lower boundary corresponding to this point. Therefore, the thickness is given by

$$t = \frac{\lambda l}{2n\beta} \tag{20}$$

Generalisation to Non-Uniform Variation in Thickness

Now, we shall generalise the analysis developed in the previous section to a film with a curved edge. If this curvature is small, we can approximate such a film at each point as a wedge-shaped film, with the angle changing depending upon the distance from the point of zero thickness. This variable thickness results in varying fringe widths. Since the film still closely resembles a wedge, we can approximate the thickness at each point using eq(20).

Sodium Vapor Lamp

A sodium-vapor lamp is a gas-discharge lamp that uses sodium in an excited state to produce light at a characteristic wavelength near 589 nm.

Two varieties of such lamps exist: low pressure and high pressure. Low-pressure sodium lamps are highly efficient electrical light sources, but their yellow light restricts applications to outdoor lighting, such as street lamps, where they are widely used. High-pressure sodium lamps emit a broader spectrum of light than the low-pressure lamps, but they still have poorer color rendering than other types of lamps. Low-pressure sodium lamps only give monochromatic yellow light and so inhibit color vision at night.

Single ended self-starting lamps are insulated with a mica disc and contained in a borosilicate glass gas discharge tube (arc tube) and a metal cap. They include the sodium-vapor lamp that is the gas-discharge lamp in street lighting.

Low-pressure sodium (LPS) lamps have a borosilicate glass gas discharge tube (arc tube) containing solid sodium and a small amount of neon and argon gas in a Penning mixture to start the gas discharge. The discharge tube may be linear (SLI lamp) or U-shaped. When the lamp is first started, it emits a dim red/pink light to warm the sodium metal; within a few minutes as the sodium metal vaporizes, the emission becomes the common bright yellow. These lamps produce a virtually monochromatic light averaging a 589.3 nm wavelength (actually two dominant spectral lines very close together at 589.0 and 589.6 nm). The colors of objects illuminated by only this narrow bandwidth are difficult to distinguish.

Mercury Vapor Lamp

A mercury-vapor lamp is a gas-discharge lamp that uses an electric arc through vaporized mercury to produce light. The arc discharge is generally confined to a small fused quartz arc tube mounted within a larger soda lime or borosilicate glass bulb. The outer bulb may be clear or coated with a phosphor; in either case, the outer bulb provides thermal insulation, protection from the ultraviolet radiation the light produces, and a convenient mounting for the fused quartz arc tube.

Mercury vapor lamps are more energy efficient than incandescent lamps with luminous efficacies of 35 to 55 lumens/watt. Their other advantages are a long bulb lifetime in the range of 24,000 hours and a high intensity, clear white light output. For these reasons, they are used for large area overhead lighting, such as in factories, warehouses, and sports arenas as well as for streetlights. Clear mercury lamps produce a greenish light due to mercury's combination of spectral lines. This is not flattering to human skin color, so such lamps are typically not used in retail stores. "Color corrected" mercury bulbs overcome this problem with a phosphor on the inside of the outer bulb that emits at the red wavelengths, offering whiter light and better color rendition.

Mercury vapor lights operate at an internal pressure of around one atmosphere and require special fixtures, as well as an electrical ballast. They also require a warm-up period of four to seven minutes to reach full light output. Mercury vapor lamps are becoming obsolete due to the higher efficiency and better color balance of metal halide lamps.

The peaks of the emission line spectrum in the visible region are:

1. 404.7 nm (Violet)
2. 435.8 nm (Blue)
3. 546.1 nm (Green)
4. 578.2 nm (Yellow-orange)

Soap Film

Soap films are thin layers of liquid (usually water-based) surrounded by air. For example, if two soap bubbles come into contact, they merge and a thin film is created in between. Soap films can be used as model systems for displaying thin film interference, which causes iridescent colors to be seen in soap films.

Variation in Thickness of Vertical Soap FIlm

When a soap film is kept horizontal, its thickness is largely uniform. However, when it is kept vertical, the lower parts of the film are thicker than the upper parts due to the effect of gravity, forming a film whose thickness can be estimated by using the formula obtained for a wedge-shaped film.

In Frederik Brasz's model of the dynamics of a soap film, the thickness profile of a vertical soap film is given by

$$\hat{H}(\hat{z}) = \frac{1}{2}e^{-\hat{z}} \tag{21}$$

where $\hat{H} = H/\bar{H}$, $\hat{z} = z/L$ and $L = \frac{2(\gamma_0 - \bar{\gamma})}{\rho g H}$. Here, H is the thickness of a film of surface tension γ_0 at height z, and $\bar{H}$ is the thickness of a film of surface tension $ga\bar{m}ma$ at a reference height $z = 0$.

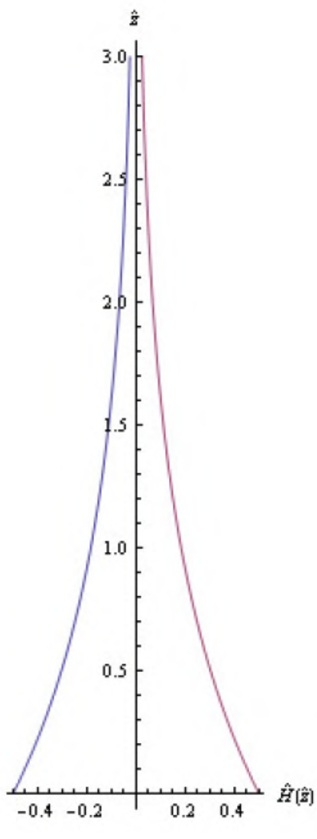


Figure 4: The thickness profile of a vertical soap film with insoluble soap, in dimensionless form. [4]

Experimental Setup

Apparatus

1. Detergent
2. Tap water
3. 400 ml beaker
4. Stirrer
5. Nylon string
6. Sodium vapor lamp
7. Mercury vapor lamp
8. Retort stand
9. Clamps
10. White thermocol
11. DSLR camera
12. Tripod stand
13. Scissors
14. Ruler
15. ImageJ software

Making the Circular Frame for the Film

1. A nylon string is taken and cut using scissors.
2. A loop is made out of a portion of the cut string by tying a knot, and the remainder of the string is used as a handle.
3. It is ensured that the length of the handle is appropriate. It should be cut appropriately if it is too long.

4. It should be ensured that the loop forms a closed shape. It is not necessary for the loop to be perfectly circular. It can take any shape as long as it is closed.

5. It should be ensured that the loop is contained in a single plane. Otherwise, when it is dipped in soap solution, the film formed may break.

Making the Soap Solution

1. A 400 ml beaker is taken and filled with water.

2. 4 ml of detergent is measured by pouring it into a measuring cylinder.

3. The detergent is transferred from the measuring cylinder to the 400 ml beaker.

4. The contents of the beaker are stirred using a stirrer.

5. The circular frame is now dipped into the solution contained in the beaker to test if a soap film is formed. If we observe the formation of a soap film, the soap solution is now ready to be used.

Procedure

Horizontal Soap Film

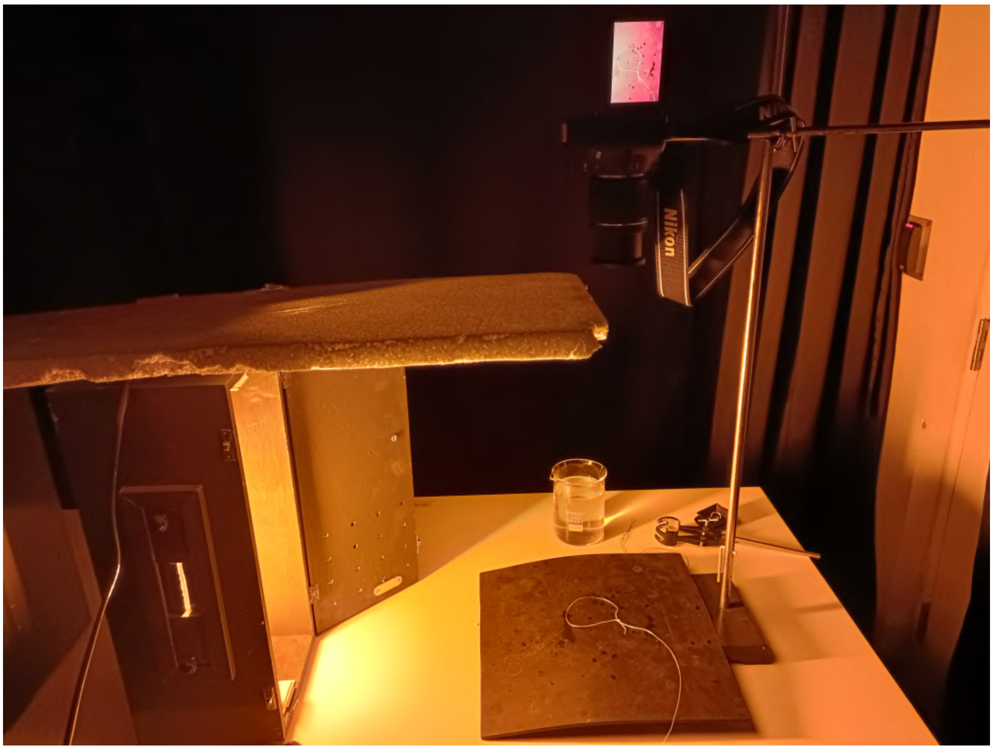


Figure 5: Experimental setup to observe interference for horizontal soap film.

1. The apparatus is set up inside a dark room as shown in Figure 5. It should be ensured that the light is perfectly or approximately normally incident on the the film. It should also be ensured that the camera is placed directly over the circular frame.

2. The soap film is created by dipping the frame into the soap solution and then carefully laying it horizontally in front of the camera

3. The film is photographed using the DSLR camera. Appropriate changes should be made to the set up or camera settings if the interference fringes are not seen in the photograph. Multiple photographs are taken.

4. The sodium vapor lamp is replaced with a mercury vapor lamp, and the same steps are repeated.

Vertical Soap Film

Figure 6: Experimental setup to observe interference for vertical soap film.

1. The apparatus is set up inside a dark room as shown in Figure 6. It should be ensured that the light is perfectly or approximately normally incident on the the film. It should also be ensured that the camera is placed at the same level as the circular frame.

2. The soap film is created by raising the beaker up to the frame so that the frame is contained completely within the solution, and then lowering it (or equivalently, the frame can be lowered and then raised, but this is more difficult to do while trying to keep the frame stable).

3. The film is photographed using the DSLR camera. Appropriate changes should be made to the set up or camera settings if the interference fringes are not seen in the photograph.

4. The sodium vapor lamp is replaced with a mercury vapor lamp, and the same steps are repeated.

ImageJ Analysis

1. The image to be analyzed is imported into *ImageJ* as an 8-bit image.
2. The contrast of the image is enhanced until most of the fringes are clearly seen.
3. The vertical diameter of the string loop is set as the calibration length.
4. Points are marked using the "Multi-point" tool, and their positions are measured by using the "Measure" function. The measurements are recorded in the "Results" window, which can then be saved into an excel workbook.
5. Lengths are measured by drawing a line using the "Straight line" tool, and measuring the lengths of these lines using the "Measure" function. The measurements are recorded in the "Results" window, which can then be saved into an excel workbook.

Precautions

1. While observing the horizontal soap film, the camera should be kept directly over the frame.
2. While observing the vertical soap film, the camera should be kept at the same horizontal level as the frame. However, it need not necessarily be directly in front of the soap film. This is because vertical distances will remain unaffected if the the film does not face the camera, provided the camera and the film are at the same horizontal level.
3. It should be ensured that the light from the sodium or mercury vapor lamp reflected by the white thermocol is (at least approximately) normally incident on the film.
4. If the photograph of the soap film is taken too soon, it may not have time to enter a steady state, whereas if we wait too long to take the photograph, it may burst before the photograph is taken.

Observations and Analysis

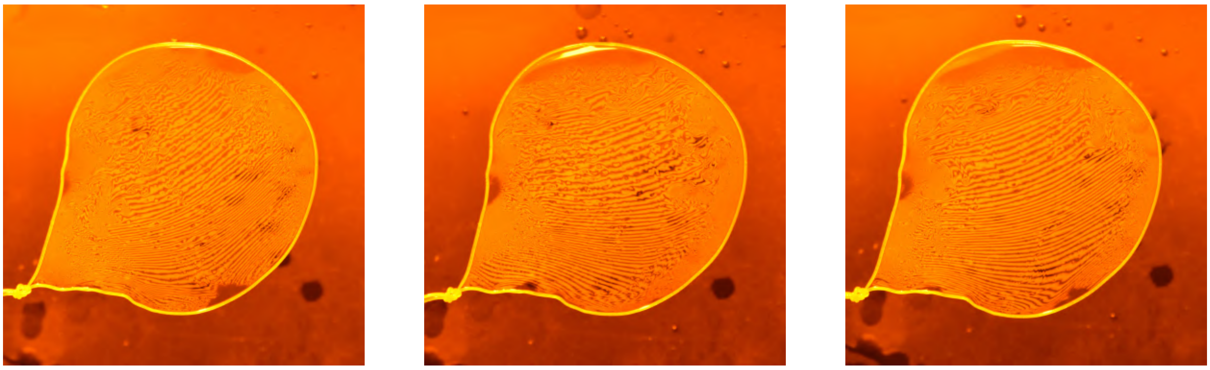
Least count of ruler: 1 mm

Diameter of frame (calibration length): 79 mm

Volume of Solution Used: 400 ml

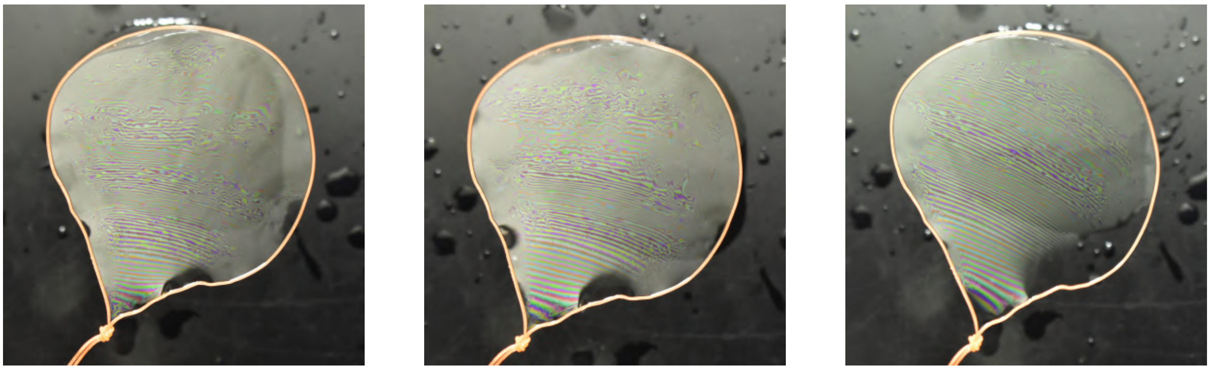
Horizontal Soap Film

On following the procedure written, we obtain the following images:



(a) Image 1 (b) Image 2 (c) Image 3

Figure 7: Fringes observed on horizontal soap film with sodium lamp.



(a) Image 1 (b) Image 2 (c) Image 3

Figure 8: Fringes observed on horizontal soap film with mercury lamp.

In the images for the sodium lamp, we can clearly see the formation of fringes. This tells us that light rays are interfering constructively and destructively at various points, and so the soap film seems to be acting like a thin film. In the images for the mercury lamp, we can clearly see fringes of the four colours that are emitted by mercury, which shows that the conditions for constructive and destructive interference are satisfied at different points for different wavelengths. Therefore, this shows that soap film acts like a thin film and gives rise to thin film interference.

Vertical Soap Film

On following the procedure written, we obtain the following images:

(a) Image 1 (b) Image 2 (c) Image 3

Figure 9: Fringes observed on vertical soap film with sodium lamp.

(a) Image 1 (b) Image 2 (c) Image 3

Figure 10: Fringes observed on vertical soap film with mercury lamp.

In the images for the mercury lamp, we can see that we obtain interference patterns for the four wavelengths of light corresponding to the lines of emission of mercury in the visible region of the electromagnetic spectrum.

On analysing the images for the sodium lamp using ImageJ, we get the positions of the dark fringes. From this, we get the distance from the top to each dark fringe, as well as the fringe width for each dark fringe. Using eq(20), we can calculate the thickness corresponding to each fringe. On plotting the thickness of the film at a particular point against the vertical distance of this point from the top of the frame for all three images, we get

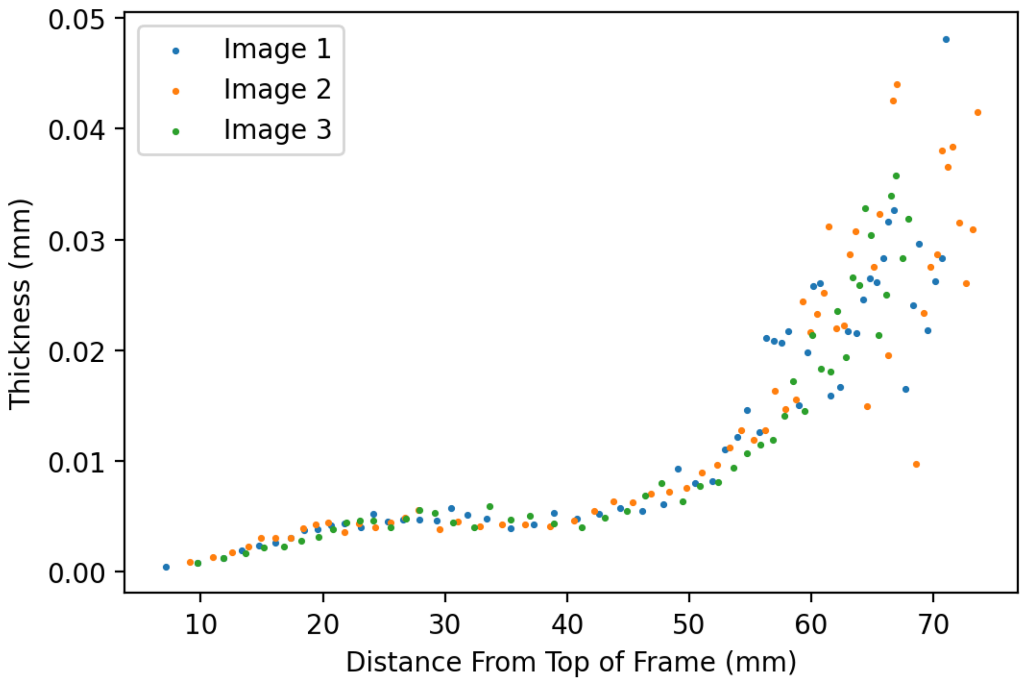


Figure 11: Thickness profile of the film obtained using three different images of three films.

We can clearly see that the data for the three images match, and so there is a specific curve followed, rather than random ones. This looks different than the exponential curve predicted by eq(21). The reasons for this are explored further in the discussion section.

From this analysis, we find the following minimum thickness, maximum thickness and mean thickness corresponding to each image:

	Image 1	Image 2	Image 3
Minimum Thickness (μm)	0.465	0.468	0.423
Maximum Thickness (μm)	48.1	41.5	31.9
Mean Thickness (μm)	13.3	15.3	12.0

Table 1: Minimum, maximum and mean thickness of soap film corresponding to each image analysed.

Taking the average values, we find that the minimum thickness (at the top of the film) is $\mathbf{0.452\,\mu m}$, the maximum thickness (at the bottom of the film) is $\mathbf{40.5\,\mu m}$, and the average thickness is $\mathbf{13.6\,\mu m}$.

Error Analysis

While analysing the images in ImageJ, it became clear that the error in marking points and lengths was around 0.01 mm. Therefore, we have $\delta l = \delta\beta = 0.01\,\text{mm}$. We know that the thickness is given by

$$t = \frac{\lambda l}{2n\beta} \tag{22}$$

Thus, the error in thickness δt is given by

$$\delta t = t\sqrt{\left(\frac{\delta l}{l}\right)^2 + \left(\frac{\delta\beta}{\beta}\right)^2} \tag{23}$$

This gives us the following values of absolute and relative error:

	Thickness (μm)	**Absolute Error (μm)**	**% Error**
Minimum Thickness	0.452	0.002	0.33%
Maximum Thickness	40.5	1	3.06%
Mean Thickness	13.6	0.004	0.03%

Table 2: Absolute and percentage errors for minimum, maximum and mean thicknesses.

Conclusions

On shining light from a sodium vapor lamp on a horizontal soap film, we obtained interference patterns, with light and dark fringes. On then shining light from a mercury vapor lamp on the horizontal soap film, we obtained the formation of fringes of the various colours of light in the emission spectra of mercury. Therefore, we verified that the soap film is a thin film and undergoes thin film interference.

On shining light from a mercury vapor lamp on the vertical soap film, we obtained the formation of fringes of the various colours of light in the emission spectra of mercury, demonstrating thin film interference for a wedge-shaped film. On then shining light from a sodium vapor lamp on the vertical soap film, we observed the interference patterns formed on the film to obtain a thickness profile of the film. The minimum thickness is estimated to be $\mathbf{0.452 \pm 2\,\mu m}$, the maximum thickness is estimated to be $\mathbf{40.5 \pm 1\,\mu m}$, and the mean thickness is estimated to be $\mathbf{13.6 \pm 0.004\,\mu m}$.

Discussion

1. A possible direction to obtain more data is to analyse the images for the horizontal soap film and use that to calculate the thickness of the film at various points. This was attempted in this project. However, in this case, analysing these images proved to be greatly challenging due to the non-uniformity of the fringes and the excessive number of vortices formed. Further, the images for both the horizontal as well as vertical soap films corresponding to the mercury lamp could have been used for analysis, with each colour being analysed separately to give multiple values for the thickness of the film. However, this was again challenging, as the it was not very easy to separate the colours from each other.

2. The soap solution was made using detergent so that a lesser quantity of soap was needed. First, *Vim* dishwashing soap was used, but for the film to be stable and for interference patterns to be clearly visible, a concentration of about 1 in 10 was required, whereas for detergent, a concentration of about 1 in 100 was required, and the fringes formed were also clearer.

3. The thickness profile found experimentally does not seem to match the exponential curve expected. This may be due to the fact that several ideal conditions were assumed to derive the exponential trend, which may not have held in practice. For instance, the frame was made of nylon string, so it was not possible for it to be a closed shape, which led to various boundary conditions that were not included in the original model. Further, turbulence and non-uniformity in the soap solution may have caused the experimentally estimated data to deviate further from an exponential graph. Another possibility is that once the film reaches a steady state, the thickness profile follows an exponential curve, and before that, it may not necessarily be an exponential. In fact, from the graph (Figure 11), it seems that the curve is built out of two exponential functions with different constants: one for roughly the upper half of the film, and another for roughly the lower half of the film.

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