

# Lab Journal

PH2233 - Physics Lab II

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## LEE'S METHOD

**Date of Experiment:** 11 January 2025

### Introduction

In this experiment, we are trying to find the the thermal conductivity of the material. We will place a brass disc with different materials and we will try to find the thermal conductivity of the given material placed in contact with brass disc and let it cool. We will try to do it different materials and will compare their thermal conductivity.

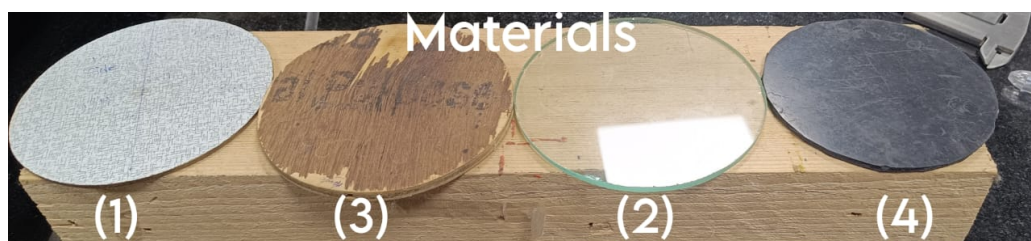
### Theory

In the first part of the experiment, we will heat the the brass disc by placing the material disc between the bottom brass disc and the upper disc connected to steam. Steam will cross through the upper disc hence heating it, thereon heating the bottom disc by conducting through the material in between. We will wait for the point where the temperature for the upper disc and lower disc reach to a steady state(constant for at least 10 minutes). Then we will heat the lower disc directly without placing the material disc in between. We will raise the lower disc temperature by  $7^{\circ}$  celsius. After which we will again put back the material on it but without having steam connected upper disc. Hence it will cool down, and by analyzing the cooling pattern we will determine the instantaneous rate of cooling.

Thermal Conductivity: Watt per unit Kelvin

So, it is the heat per unit time per unit length for per unit temperature difference.

So, we will see the thermal conductivity at its peak while cooling from its highest attainable temperature (steady state) with particular material in between the heating disc and bottom disc.



**Figure 1.1:** Image of different materials



## Observations

Here is presented the table for diameter and thickness readings:

Material	Main Scale	Vernier Scale	Reading	Mean D	Area ( $\times 10^{-3} m^2$ )
Material 1	11.1	9	11.19	11.03	9.555
	11	0	11.00		
	10.9	7	10.97		
	10.9	5	10.95		
Material 2	11.1	0	11.10	11.09	9.664
	11.1	3	11.13		
	11	8	11.08		
	11	6	11.06		
Material 3	11	8	11.08	11.07	9.620
	11	9	11.09		
	11	3	11.03		
	11	7	11.07		
Material 4	10	0	10.00	9.97	7.803
	10	0	10.00		
	9.9	0	9.90		
	9.9	7	9.97		

**Table 1.1:** Diameter of Materials: Mean Values (in cm) and least count of Vernier Scale is 0.01 mm with no error.

Material	Main Scale	Circular Scale	Reading + 0.10	Mean Thickness (mm)
Material 1	2	25	2.25+0.10	2.4167
	2	33	2.33+0.10	
	2	41	2.41+0.10	
	2	24	2.24+0.10	
	2	41	2.41+0.10	
	2	26	2.26+0.10	
Material 2	4	19	4.19+0.10	4.286
	4	23	4.23+0.10	
	4	18	4.18+0.10	
	4	16	4.16+0.10	
	4	17	4.17+0.10	
Material 3	4	54	4.54+0.10	4.528
	4	09	4.09+0.10	
	4	49	4.49+0.10	
	4	36	4.36+0.10	
	4	33	4.33+0.10	
	4	76	4.76+0.10	
Material 4	3	47	3.47+0.10	3.612
	3	40	3.40+0.10	
	3	54	3.54+0.10	
	3	59	3.59+0.10	
	3	56	3.56+0.10	

**Table 1.2:** Thickness of Materials (in mm). Least count of the screw gauge is 0.01 mm with 10 circular scale divisions of negative error.

Time(Seconds)	Material 1	Material 2	Material 3	Material 4
30	83.0	91.0	74.5	86.0
60	81.5	90.0	72.5	83.5
80	79.5	89.0	71.0	81.5
120	78.5	87.5	70.0	79.5
150	77.0	86.5	69.0	78.5
180	76.0	85.0	68.0	77.5
210	75.0	84.0	67.0	76.0
240	74.0	83.0	66.5	75.0
270	73.0	82.0	65.5	74.0
300	72.0	81.0	64.5	73.5

**Table 1.3:** Cooling Pattern of different material and temperature is in degree celsius

## Analysis

We are going to use some relations:

1) Fourier's Law of Heat Conductance: Rate at which transfer of heat between two objects at temperatures  $T_2$  and  $T_1$  connected by a conductor with conductivity  $k$  and cross-sectional area  $A$  (assumed uniform) and length  $l$ .

$$\frac{\Delta Q}{\Delta t} = k \frac{A}{l} (T_2 - T_1) \quad (1.1)$$

2) The rate at which heat is lost by the disc, if  $m$  is the mass of the disc and  $s$  is the specific heat of the material:

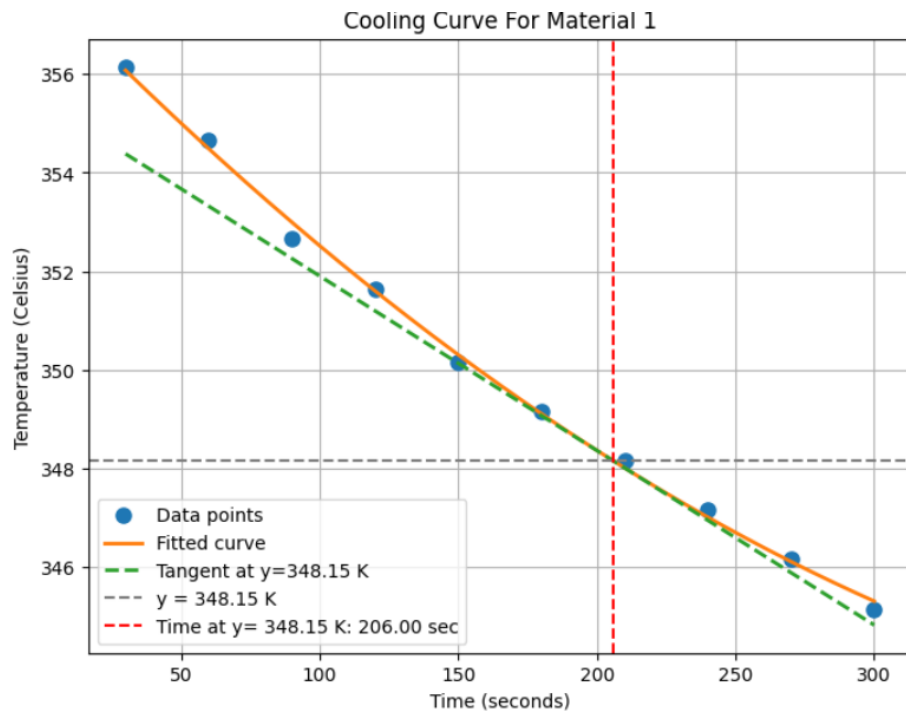
$$\frac{\Delta Q}{\Delta t} = ms \left( \frac{dT_1}{dt} \right) \quad (1.2)$$

3) Heat Balance in the experiment is given by combining (1.1) and (1.2):

$$k = ms \frac{(dT/dt)l}{A(T_2 - T_1)} \quad (1.3)$$

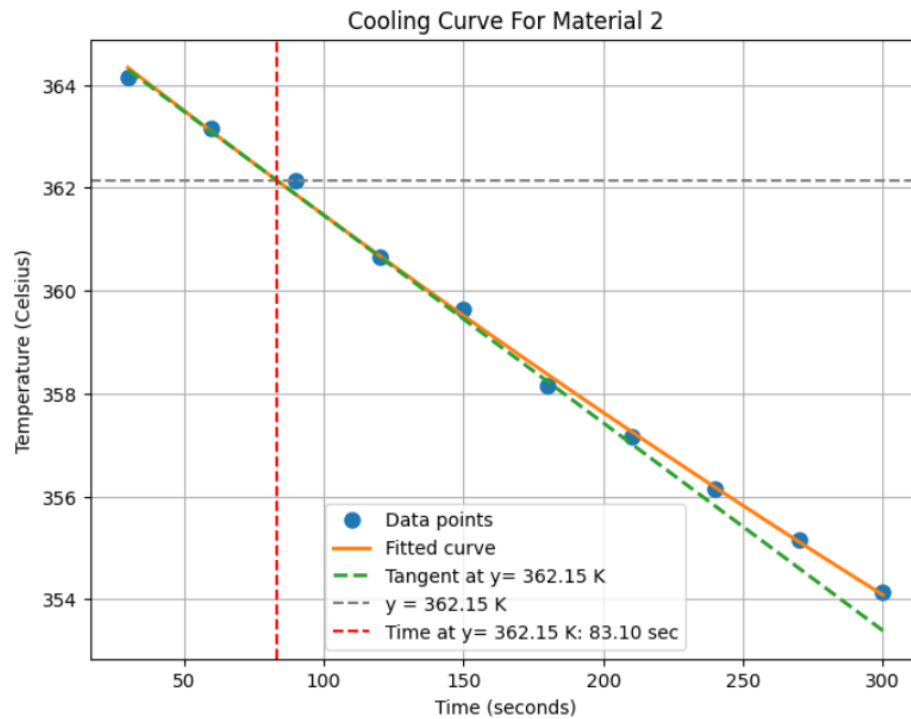
Material	$dT/dt$	$T_2 - T_1$	Area ( $\times 10^{-3} m^2$ )	Thickness (mm)	Thermal Conductivity ( $W/(m \cdot K)$ )
1	-0.03541	22.0	9.555	2.4167	0.14014
2	-0.04039	7.0	9.664	4.286	0.88092
3	-0.02384	31	9.620	4.528	0.12461
4	-0.06836	14	7.803	3.612	0.77808

**Table 1.4:** Value of Thermal Conductivity, Mass of disc = 0.9059 kg,  $s = 380 J/kg K$



The fitted polynomial equation is:  $0.0001x^2 + -0.0580x + 357.7667$   
 Slope:  $-0.03541287526950219$ , Intercept:  $355.4449175323403$   
 Fitted parameters:  $[5.47138025e-05 -5.79545455e-02 3.57766667e+02]$   
 Slope at time 206.00 sec:  $-0.0354 \pm 0.0048$

Figure 1.2: Material 1



The fitted polynomial equation is:  $0.0000147306x^2 + -0.0428x + 365.6083$   
 Slope:  $-0.04039269330509305$ , Intercept:  $365.50661064009745$   
 Fitted parameters:  $[1.47306375e-05 -4.28409091e-02 3.65608333e+02]$   
 Slope at time 206.00 sec:  $-0.0368 \pm 0.0044$

Figure 1.3: Material 2

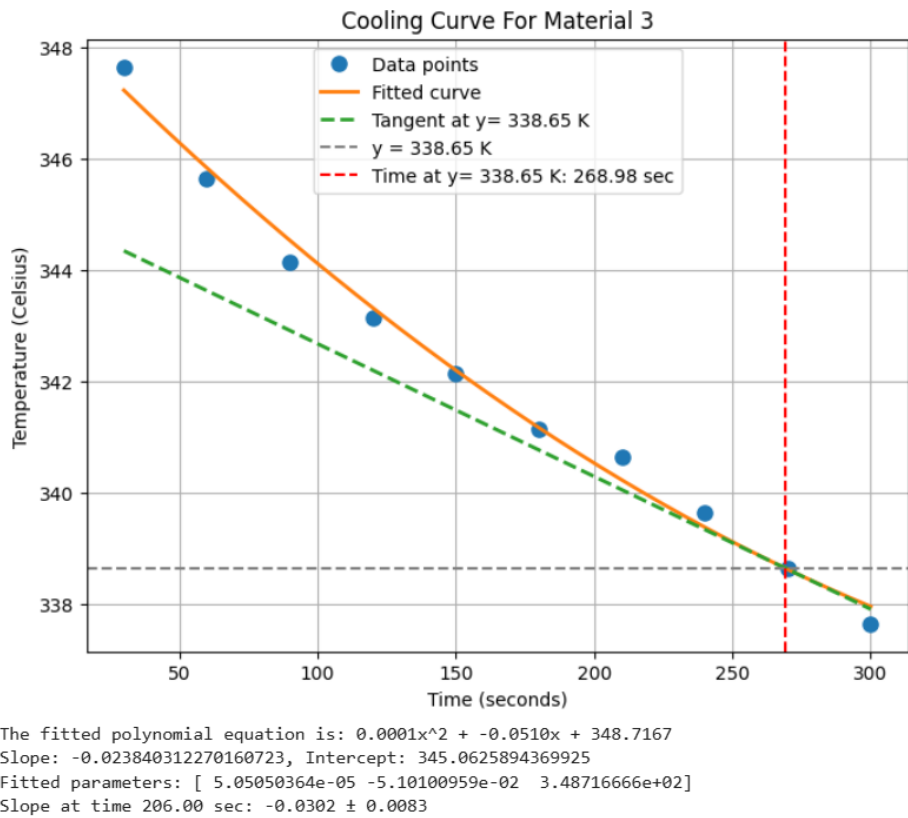


Figure 1.4: Material 3

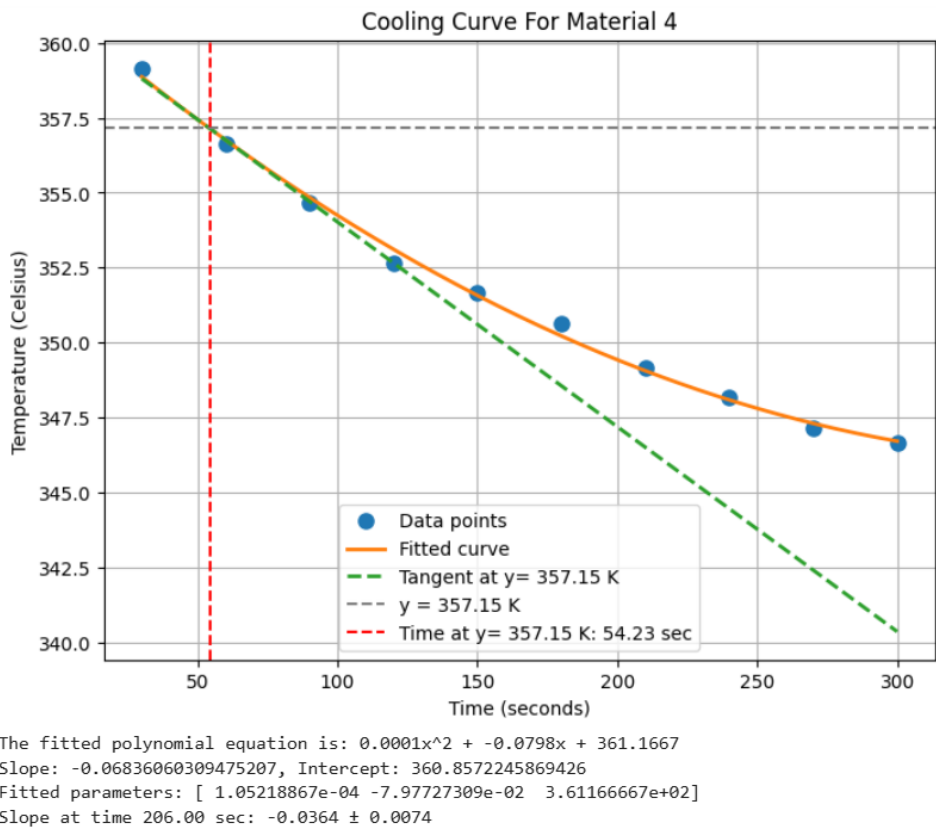


Figure 1.5: Material 4

## Error Analysis

For finding the uncertainty in  $k$ , we will use the below given expression:

$$\frac{\Delta k}{k} = \sqrt{\left(\frac{\Delta\left(\frac{dT}{dt}\right)}{\frac{dT}{dt}}\right)^2 + \left(2 \cdot \frac{\Delta d}{d}\right)^2 + \left(\frac{\Delta x}{x}\right)^2 + \left(\frac{\Delta T_2 + \Delta T_1}{T_2 - T_1}\right)^2} \quad (1.4)$$

For one material, if we try to do it multiple times for multiple values for  $T_2$  and  $T_1$ , but it is time consuming. So, we take  $\Delta T_2$  and  $\Delta T_1$  as 0.5 because it is least count in the digital thermometer. And for  $\Delta\left(\frac{dT}{dt}\right)$ , we could have done the heating and cooling multiple times, then plotting multiple cooling plot and then finding  $\Delta\left(\frac{dT}{dt}\right)$  from multiple values of  $\frac{dT}{dt}$ . But again, it is time consuming. So for  $\Delta\left(\frac{dT}{dt}\right)$ , I am using *curvefit* from *scipy.optimize*. And used *param errors* for finding the uncertainty in the slope.

Material	$\Delta d$	$\Delta x$	$\Delta\left(\frac{dT}{dt}\right)$	$\Delta k/k$	$\Delta k$
1	0.11	0.0789	0.0048	0.148	0.02074
2	0.02986	0.027	0.0044	0.17986	0.1584
3	0.0263	0.2259	0.0083	0.3532	0.04401
4	0.0472	0.0766	0.0074	0.1318	0.1025

**Table 1.5:**  $\Delta k / k$  values for different materials.

### Probable errors and precautions:

- There are some big gaps in  $T_1$  and  $T_2$  and I also checked the data of other trials (by different students), may be I assumed steady state before the actual one. That's why I got value less than actual maximum thermal conductivity (as available on the internet).
- There are some losses from the edges. Therefore, the thickness should be sufficiently less than its diameter as it won't contribute more.

## Results

Thermal Conductivity of the materials:

$$2 > 4 > 1 > 3$$

As I have used curve fit function from *scipy.optimize*, also used *param errors* for finding error in

Material	$k(W/(m \cdot K))$	% error
1	$0.14014 \pm 0.02074$	14.8
2	$0.88092 \pm 0.1584$	17.986
3	$0.12461 \pm 0.04401$	35.32
4	$0.77808 \pm 0.1025$	13.18

**Table 1.6:**  $k$  values for different materials.

slope. So Errors obtained in  $k$  is mostly because of uncertainty in slope.

## Points to Ponder

**1. Why is it necessary to have a thin disk in the experiment?**

Because we are trying to find thermal conductivity of bad conductors so we have to take thin disk otherwise (the difference of  $T_2$  and  $T_1$  will be higher) the heating and cooling time will be more. But it will also increase the circular area of the edge due to thickness and then it will cause the heat loss to the ambient environment and as the area other than contact increase, the heat loss will play significant role and hence will result into wrong thermal conductivity value because significant value of heat is lost through other than the material's contact for which we are trying to find the value of  $k$ .

**2. Would this method work for measuring the conductivity of a good conductor?** Obviously it will work but as the conductivity is very high due to which the difference of  $T_2$  and  $T_1$  will be lower so we need instruments with precision and least count and less errors. And also it will also radiate heat to ambient temperature so we need to have good controls on instruments.

**3. In the cooling part of the experiment, why is the brass disc D1 covered by the glass disc? Is it crucial to do so?** While heating with the glass disc, we reached to a steady state and then for cooling we used same glass disc to see the cooling by the thermal conductivity through the same material. In the heating part, we figured out the steady state where the heating by the material's conductivity and heat radiated is same. And while cooling at the same steady state temperature, we observed the heat loss that will be only through the glass disc. If we will not put the glass disc then the  $dT/dt$  at the steady state, will not be because of the glass disc, so we can't use it in (1.2).

**4. Why do we take the cooling data asymmetrically around  $T_1$  in the second half of the experiment?** Because we have interest in finding thermal conductivity of the disc placed in between and we have to make the heat flow from the lower brass disc to the material at the steady state temperature.

# MICHELSON'S INTERFEROMETER

**Date of Experiment:** 18 January 2025

## Introduction

In this experiment, we are taking a coherent light source, and because of same phase, we pass it to a beam splitter and then using two mirror to have the focus the laser on single point on the screen. Then using divergence lens in front of lens. Now because of the light interfering at the screen will behave at it is coming from two sources having little difference between their distance, causing the interference of light from coherent source.

## Theory

Here, we will see the constructive and destructive interference of lights coming from Mirror 1 and 2. We are placing the Mirror 1 and 2 as the distance traveled from laser to mirror then from mirror to screen are equal for both beams interfering at the screen. Otherwise their amplitude will differ and won't give perfect constructive (bright fringes) or destructive (dark fringes) interference.

In the first part we are shifting the mirror 2 position and it is kind of same effect as in the double slit experiment, as by moving the micrometer, we are changing the distance between the slits (analogy). By doing it with green laser, we figured the value of Calibration constant. So in second part we did it with red laser and used the calibration constant obtained from the first part to calculate the wavelength for red laser.

In the third part, by placing the glass slide before the screen we are making the light to pass through the glass. But for calculating the refractive index of the glass, we will calculate the fringes moved by moving the slide by some angle. Actually by moving the slide by some angle, the incident angle is decreasing (or, increasing) lead to shift of bright and dark fringes.

In the fourth part, we are passing the light through air with different pressures, and due to changing the pressure waves shift and due to which the fringes will shift.



Figure 2.1: Fringes observed by us

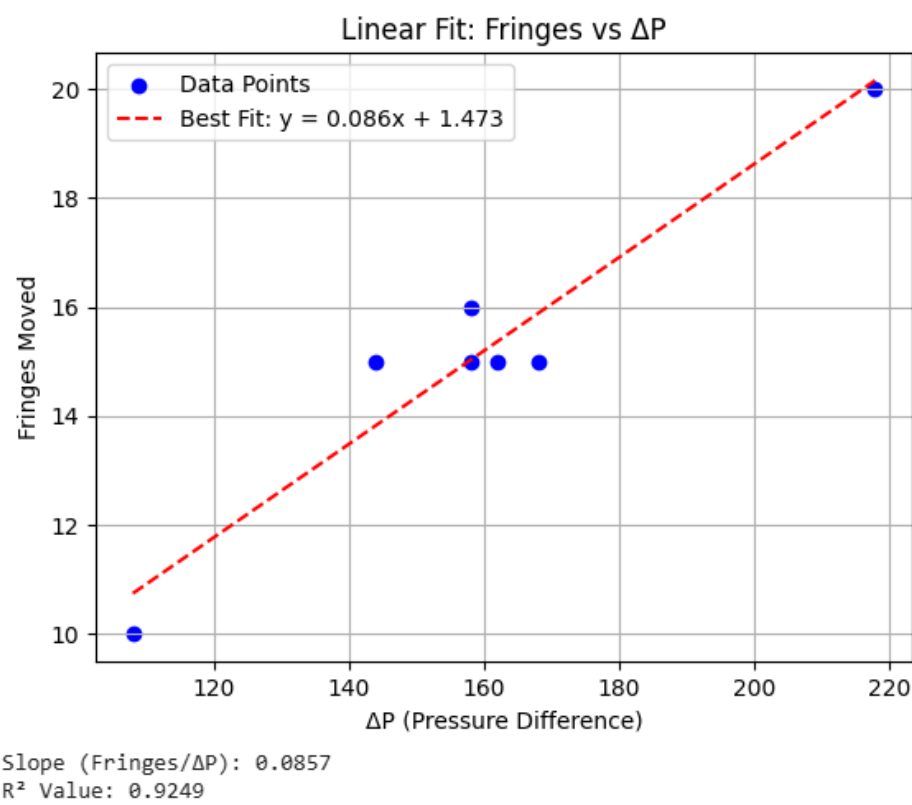


Figure 2.2: Slope of graph ( $m_{\Delta P}/\Delta P$ )

Observations

Here is presented the table for readings and evaluated calibration constant:



S. No.	No. of Fringes	Difference (in mm)	Calibration Constant ( $\Delta$ )
1	18	0.23	0.0208
2	20	0.24	0.022167
3	20	0.21	0.02533
4	20	0.23	0.02313
5	20	0.20	0.0266
6	20	0.21	0.02533
7	20	0.22	0.02418
8	20	0.21	0.02533

**Table 2.1:** Using Green laser (532nm) to find the calibration constant

S. No.	No. of Fringes	Difference (in mm)	Wavelength ( $\lambda$ in nm)
1	20	0.25	602.709
2	20	0.24	578.601
3	20	0.24	578.601
4	20	0.25	602.709
5	25	0.32	617.174
6	25	0.33	636.461
7	25	0.33	636.461
8	25	0.32	617.174

**Table 2.2:** Calculating wavelength of red laser using the calibration constant obtained by using the green laser (532nm)

S. No.	Fringes Moved	Angles Moved	Refractive Index
1	20	11	1.36
2	20	10	1.47
3	20	11	1.36
4	20	10	1.47
5	25	14	1.25
6	25	15	1.21
7	30	16	1.23
8	30	13	1.39

**Table 2.3:** Finding refractive index from the third part

S. No.	Fringes Moved	$P_1$	$P_2$	$\Delta P$
1	10	200	92	108
2	15	220	62	158
3	20	258	40	218
4	15	256	112	144
5	15	252	84	168
6	15	252	90	162
7	16	238	80	158

**Table 2.4:** Finding refractive index for air, pressure is in mm Hg, Refractive index obtained by this data is 1.002165

## Analysis

1) The wavelength of laser is calculated by:

$$\lambda = \frac{2d}{N} \cdot \Delta \quad (2.1)$$

We used the  $\Delta$  (Calibration Constant) obtained by the green laser for finding  $\lambda$  for red laser.

**2) For the refractive index of glass slide:**

$$n = \frac{(2t - N\lambda)(1 - \cos\theta)}{2t(1 - \cos\theta) - N\lambda} \quad (2.2)$$

$t$  = thickness of the glass slide

$N$  = the number of fringes counted

$\lambda$  = the wavelength of light used

$\theta$  = the angle turned for  $N$  fringes

**3) Refractive Index of air**

$$m_{\Delta P} = \frac{2d(n-1)}{\lambda} \cdot \frac{\Delta P}{P_{atm}}$$

$$n - 1 = \frac{m_{\Delta P}}{\Delta P} \cdot \frac{\lambda}{2d} \quad (2.3)$$

$d$  = length of the pressure cell

$\frac{m_{\Delta P}}{\Delta P}$  = slope obtained by graph

**Results****1) Calibration Constant:**

$$\Delta = 0.02411 \pm 0.001941$$

There is 8% error in wavelength because of  $\sigma$  of calibration constant.

Wavelength calculated with our data is  $608.736 \pm (3.71 + 8) \% \text{ nm}$ .

$$\lambda = 608.736 \pm 71.283 \text{ nm}$$

**2) Refractive of glass obtained**

$$n = 1.3425 \pm 0.1029(\sigma)$$

**3) Slope( $m_{\Delta P}/\Delta P$ ) = 0.0857**

$$n = 1 + 0.002165 = 1.002165$$

**Error Analysis**

1. While calculating the angle moved, it was hard to accurately measure the angle. We can have better way to move and measure the angle.
2. While moving micrometer, even little disturbance causes flickering. When we started moving the micrometer, initially the 2-3 fringes moved inward and then suddenly started moving outward for rest pf micrometer movement.
3. While stopping the micrometer and placing your hand off from it, 2-3 fringes will move inward. Again we have to take care while having any movement on apparatus.
4. Human error is very obvious here, it is more better if we can film the micrometer movement and the number of fringes moved and then analyzing it for avoiding human error.

5. We counted for only 10-30 fringes and some small micrometer distance. So, we can't get near to correct value, if we are not considering high number of fringes. It is almost like applying Central Limit Theorem. We are doing it multiple but each time the sample space should be enough big, then we can only get more correct values. But it needs more time for it.

## Points to Ponder

1. What do you understand by interference of light?

When two light waves come and overlap, combine to produce a resultant wave of greater, lower, or the same amplitude. This occurs due to the superposition principle. Even two waves of same amplitude are in opposite phase, and then it will cancel out each other will give dark fringes because of destructive interference. While superposition in same phase will give constructive interference, makes bright fringes.

2. What is a coherent light source?

A coherent light source emits light waves of constant phase difference (over time), and it emits light of a single or narrow range of wavelength.

3. What is the role of coherence of the light source in the Michelson interferometer?

For clear interference patterns, we need to have light waves with constant phase, while incoherent light sources produce blurred fringes. The path difference is also fixed because of the coherent length of the light source. That's why we are getting flickering waves.

## BREWSTER'S ANGLE

**Date of Experiment:** 25 January 2025

### Introduction

We are going to find the Brewster's angle and the refractive index of the material used to measure the Brewster's angle.

The Fresnel equation\*s (or Fresnel coefficients) describe the reflection and transmission of light (or electromagnetic radiation in general) when incident on an interface between different optical media. They were deduced by French engineer and physicist Fresnel who was the first to understand that light is a transverse wave, when no one realized that the waves were electric and magnetic fields. For the first time, polarization could be understood quantitatively, as Fresnel's equation\*s correctly predicted the differing behaviour of waves of the s and p polarizations incident upon a material interface.

### Theory

**Fresnel's equation\*s for Reflection and Transmission:**

**For s-polarized light (Electric field perpendicular to the plane of incidence):**

$$\frac{E_R}{E_I} = \frac{\cos \theta_I - \mu \cos \theta_T}{\cos \theta_I + \mu \cos \theta_T} \qquad \frac{E_T}{E_I} = \frac{2 \cos \theta_I}{\cos \theta_I + \mu \cos \theta_T}$$

**For p-polarized light (Electric field parallel to the plane of incidence):**

$$\frac{E_R}{E_I} = \frac{\cos \theta_T - \mu \cos \theta_I}{\cos \theta_T + \mu \cos \theta_I} \qquad \frac{E_T}{E_I} = \frac{2 \cos \theta_I}{\cos \theta_T + \mu \cos \theta_I}$$

**Snell's Law:**

$$\sin \theta_I = \mu \sin \theta_T$$

where  $\theta_I$  is the angle of incidence and  $\theta_T$  is the angle of transmission, both measured with respect to the surface normal.

**Fresnel's Sine and Tangent Laws:**

$$r_s = -\frac{\sin(\theta_i - \theta_t)}{\sin(\theta_i + \theta_T)} \quad (\text{Fresnel's sine law})$$

$$r_p = \frac{\tan(\theta_i - \theta_t)}{\tan(\theta_i + \theta_T)} \quad (\text{Fresnel's tangent law})$$

**Electric Field Strength and Intensity:** The electric field strengths ( $E_x$ ) are related to intensity using:

$$I = \frac{1}{2} \epsilon_0 |E|^2 c$$

where  $\epsilon_0$  is the permittivity of free space and  $c$  is the speed of light.

**Brewster's Law:** For p-polarized light, the intensity of the reflected ray becomes zero when:

$$\cos \theta_T = \mu \cos \theta_I$$

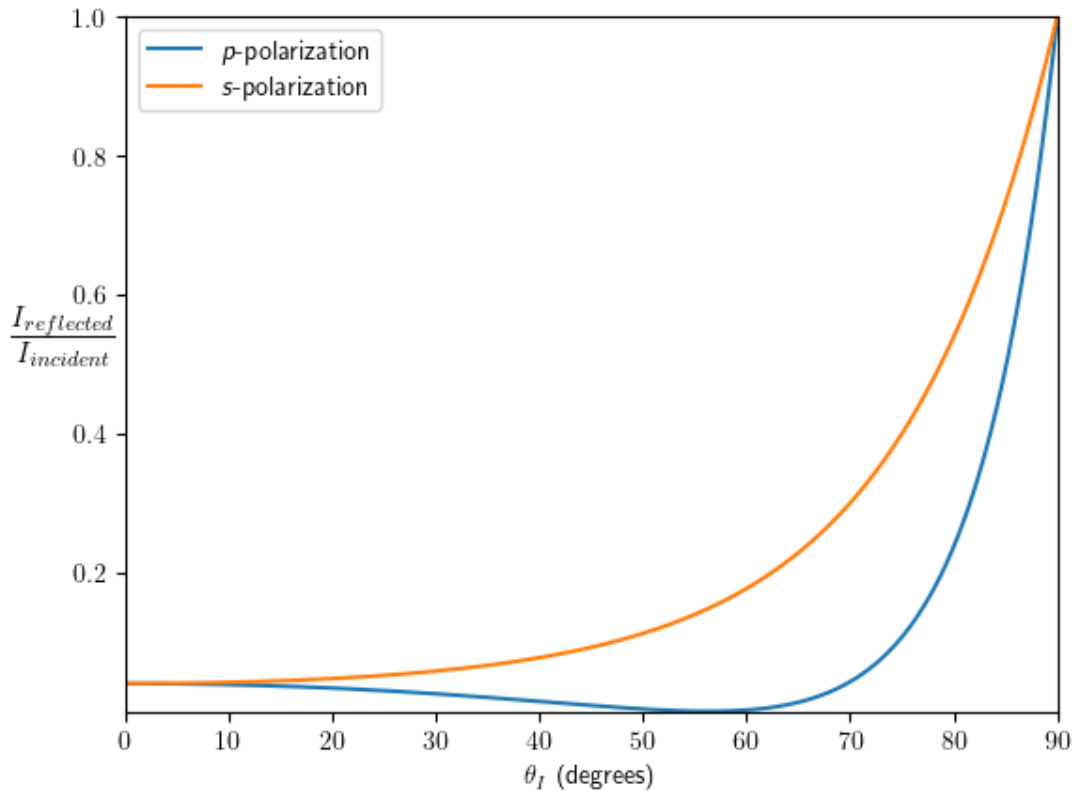
Using Snell's law ( $\sin \theta_I = \mu \sin \theta_T$ ), these two conditions are simultaneously satisfied only when:

$$\theta_I + \theta_T = \frac{\pi}{2}$$

which implies:

$$\tan \theta_I = \mu$$

This is known as **Brewster's Law**. It states that when light is incident at an angle equal to  $\tan^{-1} \mu$ , the intensity of the p-polarized reflected light becomes zero. This property is useful for determining the refractive index of a material by measuring the angle at which no p-polarized light is reflected.



## Observations

**Table 3.1:** Reflected intensity measurements for different angles of incidence. The uncertainty in intensity measurements for all datasets is  $\pm 0.005$ . All values are in mA.

Set 1		Set 2		Set 3	
$\theta^\circ$	Value (mA)	$\theta^\circ$	Value (mA)	$\theta^\circ$	Value (mA)
-	-	10	1.3	-	-
-	-	15	1.2	15	0.5
20	1.1	20	1.2	20	0.9
25	1.0	25	1.0	25	0.8
30	1.1	30	0.8	30	0.6
35	0.8	35	0.7	35	0.5
40	0.6	40	0.7	40	0.6
45	0.2	45	0.6	45	0.4
50	0.097	50	0.6	50	0.3
55	0.053	54	0.6	51	0.2
60	0.2	55	0.4	52	0.1
65	0.5	56	0.6	53	0.4
70	1.0	57	0.5	54	0.4
75	5.5	58	0.8	55	0.6
-	-	59	0.8	60	0.7
-	-	60	0.9	65	1.6
-	-	65	1.3	70	2.6
-	-	70	2.4	75	4.9
-	-	75	5.7	-	-

## Analysis

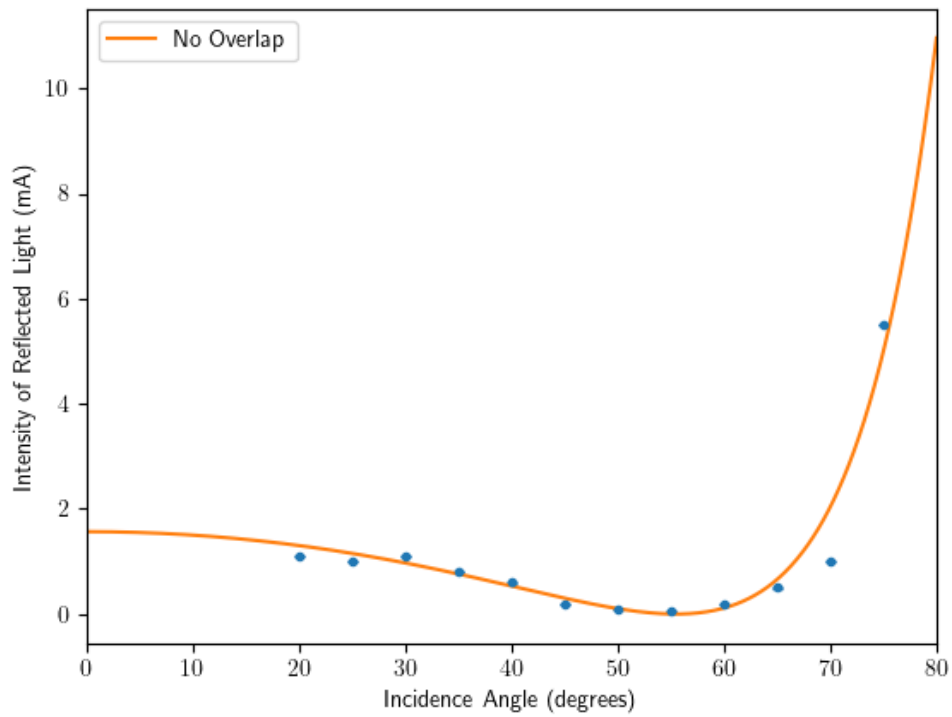
We can see that we haven't observed zero anywhere, it may be because of instrument error or imperfect polarisation. As instrument was showing zero without any intensity, then probably some s polarised component was also there that's why the even at the brewster's angle we haven't observed 0 current(intensity). So, we will try to fit the curve by removing the s component from that.

### S and P polarisation

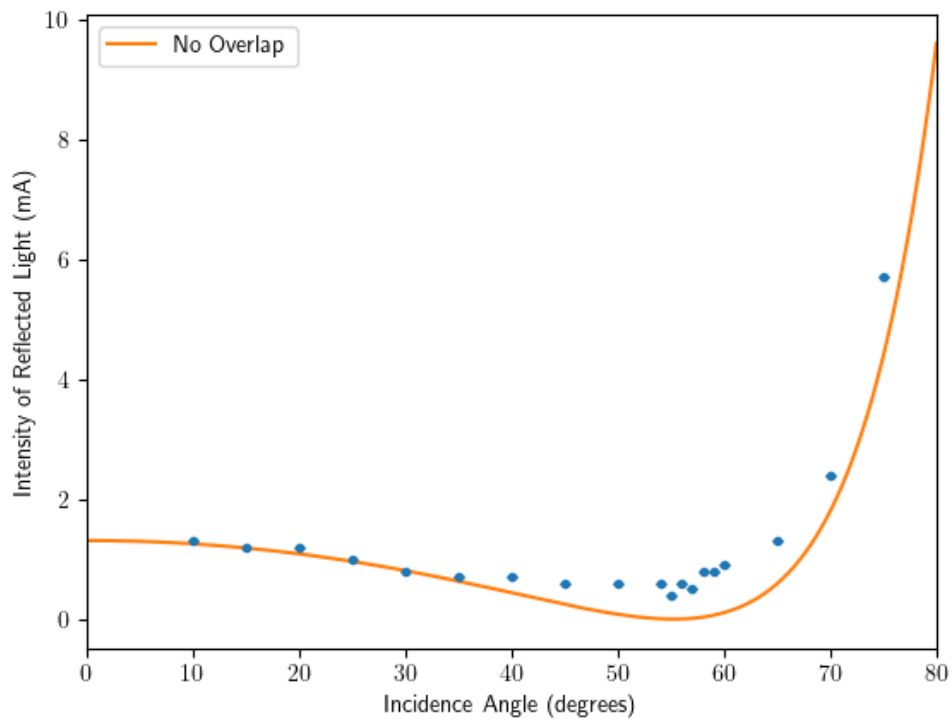
We can detect the transmittance and reflectivity of the laser simultaneously then we can able to detect the problem with polariser and can fit with the transmittance and reflectivity with fresnel equation, can verify it more explicitly.

### Brewster's Angle and Fitting Issues

Our theoretical fit did not align with the experimental data, primarily because the reflected intensity at Brewster's angle should ideally drop to zero but did not in our measurements. I am considering s component and removing from it then trying to fit it.



**Figure 3.1:** (Set 1) Without considering *s*-polarised mixing



**Figure 3.2:** (Set 2) Without considering *s*-polarised mixing

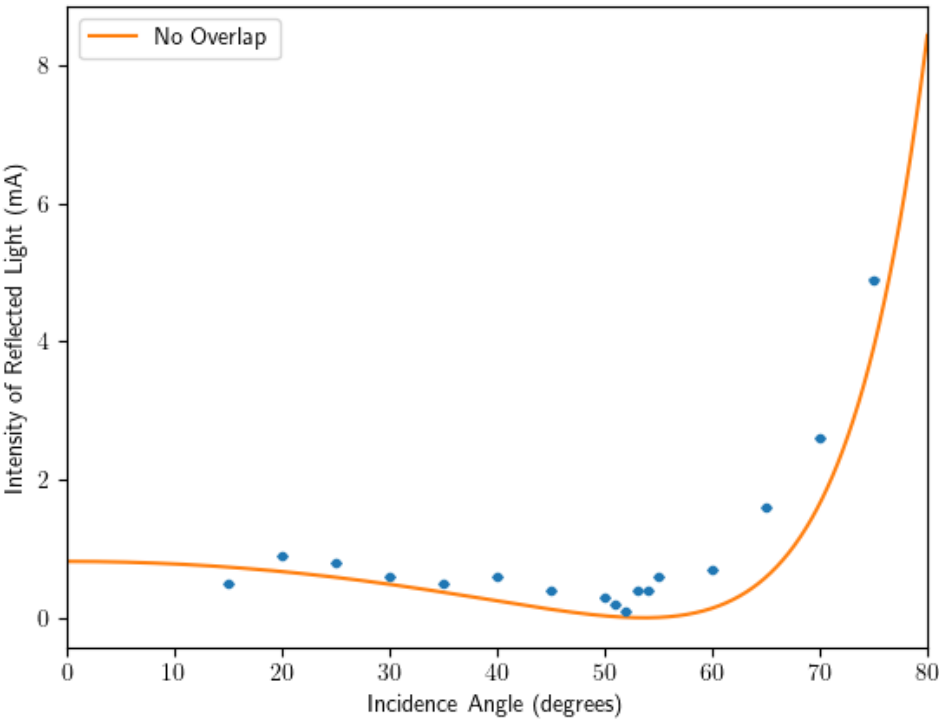


Figure 3.3: (Set 3) Without considering s- polarised mixing

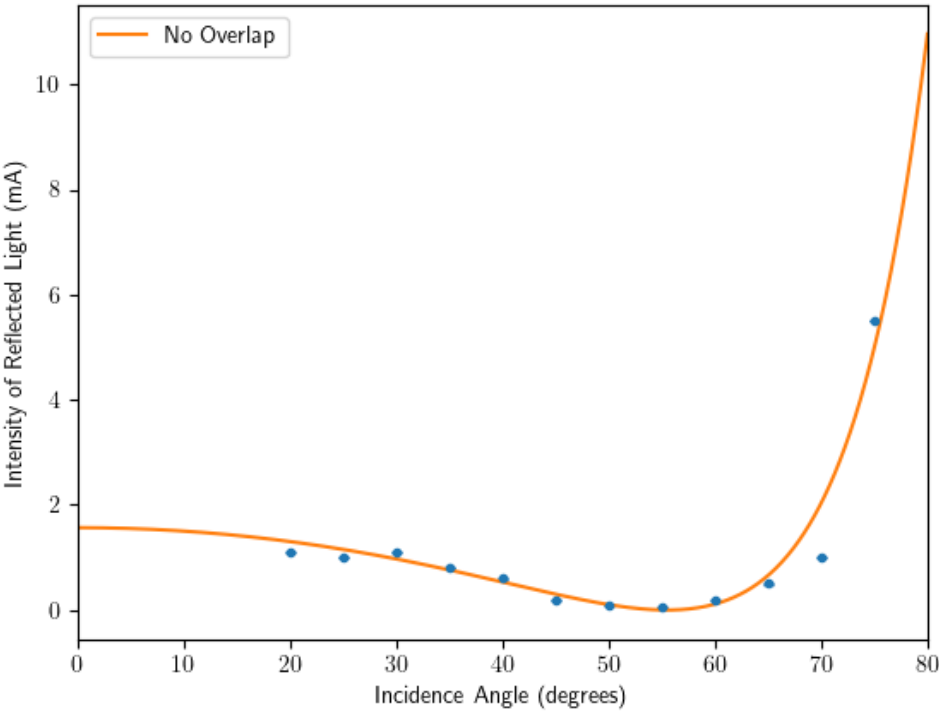
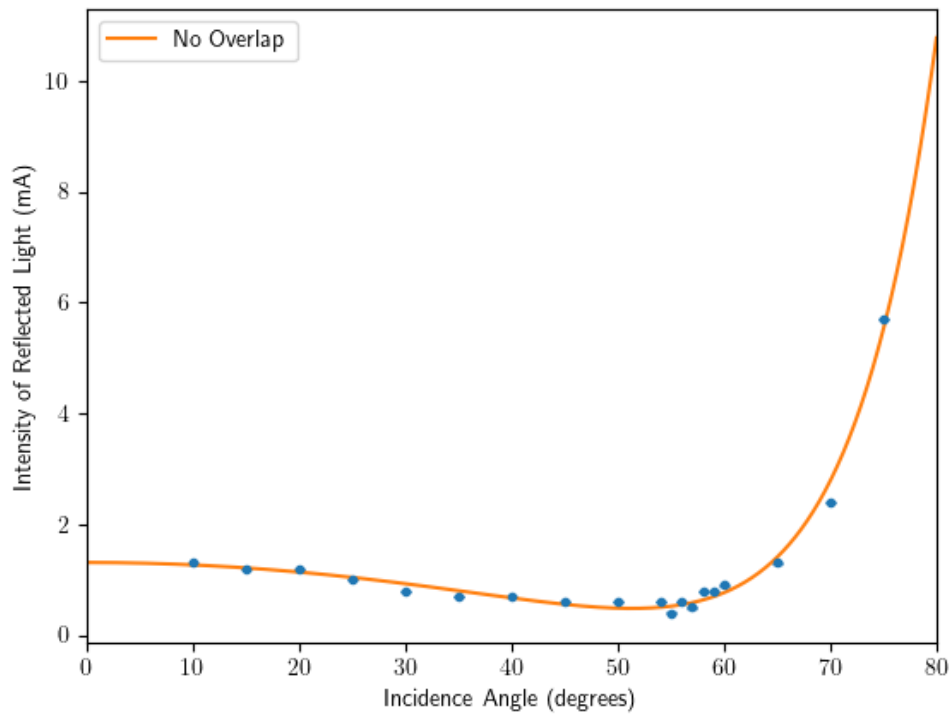
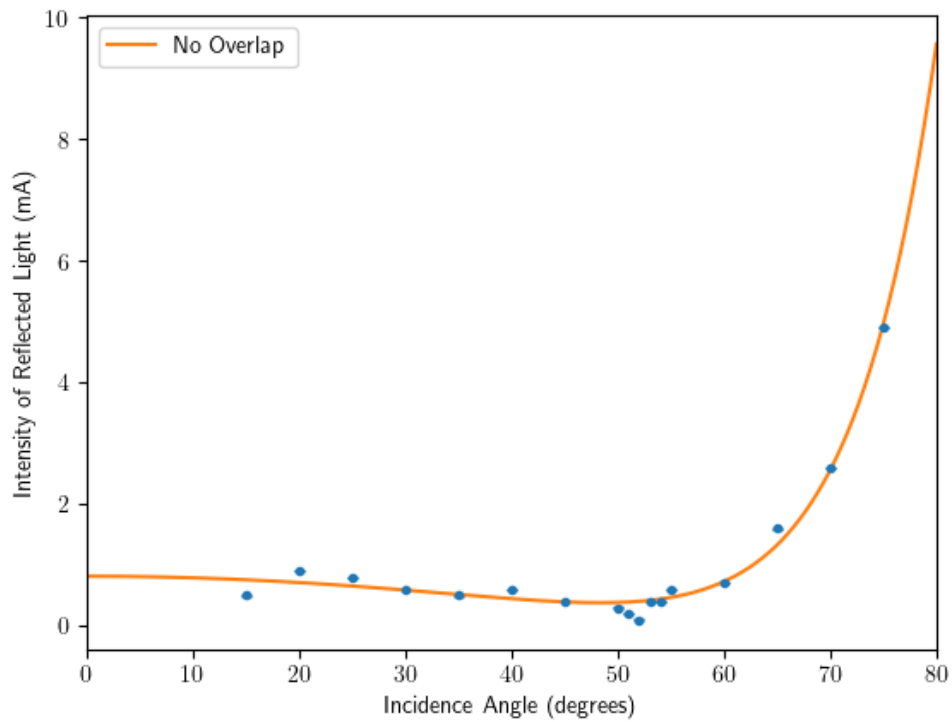


Figure 3.4: (Set 1) With considering s- polarised mixing and fitting





**Figure 3.5:** (Set 2) With considering s- polarised mixing and fitting



**Figure 3.6:** (Set 3) With considering s- polarised mixing and fitting

## Results

This refractive index and polarisation angle is obtained by curve fit of `scipy.optimize`.

Set	Refractive Index	Polarization Angle (°)	Intensity (mA)
1	$1.45 \pm 0.00$	0.00	$45.84 \pm 0.04$
2	$1.44 \pm 0.00$	$19.12 \pm 0.04$	$40.04 \pm 0.05$
3	$1.36 \pm 0.00$	$21.85 \pm 0.06$	$35.14 \pm 0.06$

**Table 3.2**

## Error

One of the primary sources of uncertainty in our experiment arises from the fact that the laser beams are not idealized point sources. Due to their finite spread, we had to manually scan the illuminated area on the detector apparatus to locate the highest intensity, introducing potential manual errors. Additionally, the detector apparatus itself may have inherent measurement errors, though these appear to be minimal in our case.

## Results and Conclusion

We have a lot of discrepancies in our data and we also tried to take it into account. As we tried to remove s component from the reflected part and tried to remove it also. Ultimately, we determined the refractive index of glass to be:

$$\mu = 1.44 \pm 0.01$$

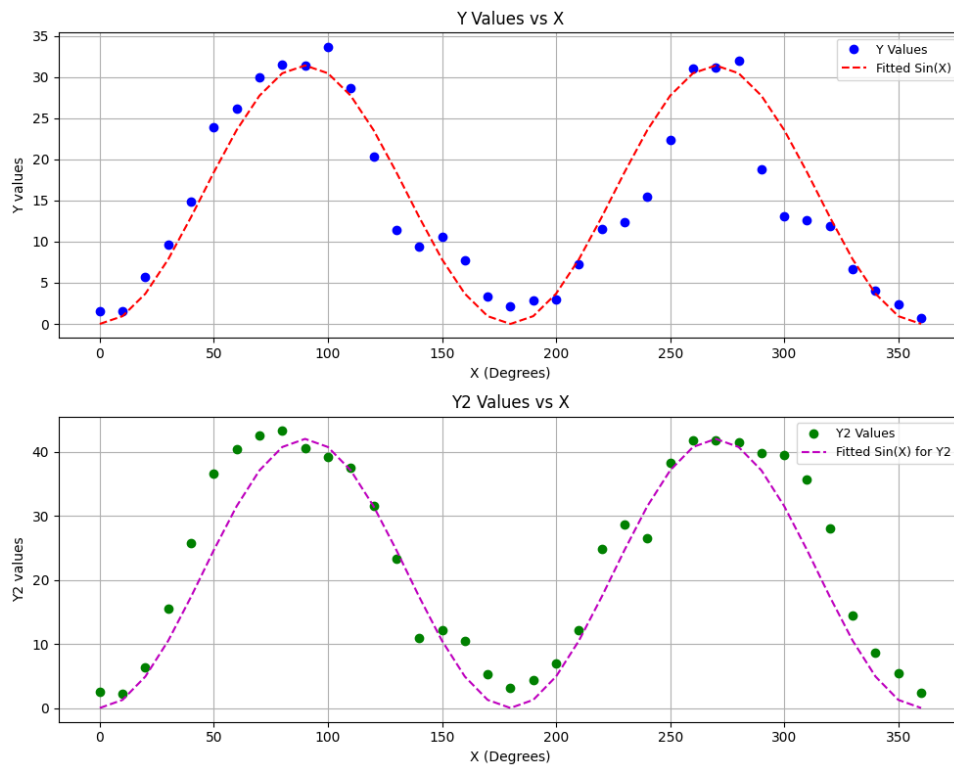
which is quite close to the accepted value of 1.5.

I am not considering the third set not for now, as it was off the value and kind of accepting that it was wrong with the apparatus and I did it with red beam for red beam and it was showing beam splitting due to which minimum values were not acceptable at 52-53 degrees. Beam splitting happens because of the double reflection phenomenon. Our analysis suggests that the failure of a naive fit can be attributed to two key factors:

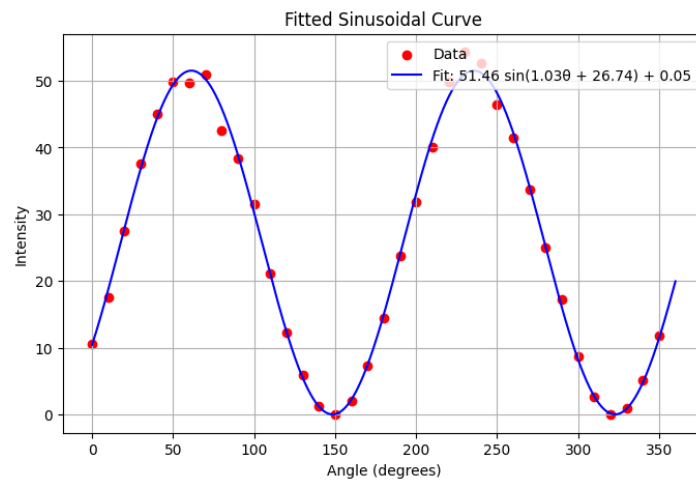
- (i) Imperfect polarization of the incident beam, and
- (ii) The double reflection phenomenon, which significantly impacts measurements at both low and high incidence angles.

Achieving a completely polarized incident beam may not be feasible. However, the issue of double reflection can be mitigated by employing a thicker glass slab. A thicker slab ensures that the beam splitting remains sufficiently large, preventing the overlap of the two reflected rays on the detector. Furthermore, it would absorb much of the transmitted beam, thereby reducing the intensity of the secondary reflected ray, leading to more accurate measurements.

## Verification of Malus's Law



**Figure 3.7:** Verification of Malus Law



**Figure 3.8:** Data: From Sankar, Verification of Malus Law

## BALMER SERIES AND RYDBERG CONSTANT

Date of Experiment: 01 February 2025

### Introduction

In a discharge lamp, hydrogen atoms emit a series of lines in the visible part of the spectrum. Balmer found this series, by trial and error, a formula. The formula is given by

$$\frac{1}{\lambda} = R \left[ \frac{1}{2^2} - \frac{1}{n^2} \right]$$

Rydberg found several series of spectra that would fit a more general relationship, similar to Balmer's empirical formula. This general relationship is known as the Rydberg formula and is given by

$$\frac{1}{\lambda} = R \left[ \frac{1}{n_f^2} - \frac{1}{n_i^2} \right]$$

where  $n_i$  and  $n_f$  are integers 1, 2, 3, 4, 5... up to infinity, with  $n_i > n_f$ . For the H atoms,  $n_i = 2$  corresponds to the Balmer series.

### Theory

Energy of photon = -[Energy of final state - Energy of initial state]

$$\Delta E = E_i - E_f = h\nu = h \frac{c}{\lambda}$$

Bohr further postulated that the magnitude of the orbiting electron's angular momentum would be quantized and that must be an integral multiple of the quantity  $h/2\pi$ .

$$L = m_e v_n r_n = \frac{nh}{2\pi}$$

and  $n = 1, 2, 3, \dots$

The electron in a hydrogen atom orbits the proton under the influence of the Coulomb force, which provides the centripetal force. The forces are balanced as:

$$\frac{e^2}{4\pi\epsilon_0 r_n^2} = \frac{m_e v_n^2}{r_n}$$

The angular momentum is quantized:

$$m_e v_n r_n = n \hbar$$

Solving these equations simultaneously gives the radius and speed of the electron:

$$r_n = \frac{4\pi\epsilon_0 \hbar^2 n^2}{m_e e^2}, \quad v_n = \frac{e^2}{4\pi\epsilon_0 \hbar n}$$

The total energy of the electron is the sum of its kinetic and potential energy:

$$E_n = \frac{1}{2} m_e v_n^2 - \frac{e^2}{4\pi\epsilon_0 r_n}$$

Substituting  $r_n$  and  $v_n$  gives:

$$E_n = -\frac{m_e e^4}{8\epsilon_0^2 \hbar^2 n^2}$$

For a transition from  $n_i$  to  $n_f$ , the energy change is:

$$\Delta E = E_f - E_i = \frac{m_e e^4}{8\epsilon_0^2 \hbar^2} \left( \frac{1}{n_f^2} - \frac{1}{n_i^2} \right)$$

The wavelength of the emitted photon is:

$$\frac{1}{\lambda} = \frac{\Delta E}{hc} = R \left( \frac{1}{n_f^2} - \frac{1}{n_i^2} \right)$$

where the Rydberg constant  $R$  is:

$$R = \frac{m_e e^4}{8\epsilon_0^2 \hbar^3 c}$$

## Observations

We did the experiment with Hydrogen and Mercury Discharge tube. We have to calibrate it first. We have 15000 lines per inch as grating value, and wavelength values observed are not calibrated with the actual values, i will calibrate it and will use the calibration constant to correct the wavelength. In the below table, *Values* are taken from Internet from National Institute of Standards and Technology ( NIST ). <https://www.physics.nist.gov/PhysRefData/Handbook/Tables/mercurytable2.htm>

Now we will use it to find out actual wavelength values for the hydrogen spectral lines.

## Analysis

**Table 4.1: Mercury Lamp Spectral Data**

Colour	$\theta_R$	$\theta_L$	$Cor\theta_R$	$\theta_R$ (rad)	$\theta_L$ (rad)	$\lambda_R$ (nm)	$\lambda_L$ (nm)	Values	Calibration
Violet	192.4	12.350	12.400	0.216	0.216	363.612	362.160	435.833	1.197
Light green	194.0	13.983	14.000	0.244	0.244	409.648	409.160	Ignored	
Green	195.65	15.500	15.650	0.273	0.271	456.786	452.516	546.074	1.195
Yellow 1	196.47	16.446	16.465	0.287	0.287	479.961	479.961	576.960	1.202
Yellow 2	196.58	16.483	16.583	0.289	0.288	482.276	480.443	570.066	1.193
Faded orange 1	197.05	16.783	17.050	0.298	0.293	496.488	488.938	587.128	1.183
Faded orange 2	197.47	17.250	17.466	0.305	0.301	508.228	502.135	Ignored	
Faded orange 3	197.65	17.400	17.650	0.300	0.304	513.413	506.367	614.644	1.197
Red 1	197.75	17.583	17.750	0.310	0.309	516.223	511.526	614.948	1.191
Violet(m=2)	205.2	25.000	25.200	0.440	0.436	360.487	357.811	435.833	1.209
Green(m=2)	211.98	31.900	31.983	0.558	0.557	448.445	447.404	546.074	1.218
Yellow 1(m=2)	213.97	33.750	33.967	0.593	0.589	473.078	470.376	576.960	1.220
Yellow 2(m=2)	214.0	34.000	34.000	0.593	0.593	473.443	473.443	570.066	1.223

**Table 4.2: Calibration Constants**

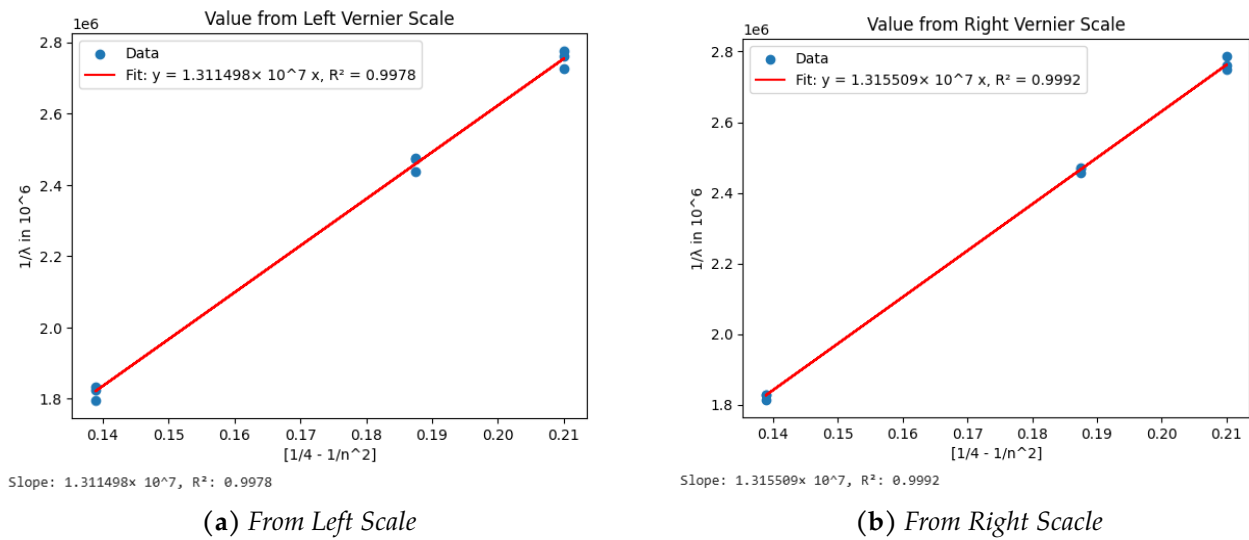
Calibration Constant Mean	Standard Deviation	Standard Deviation (%)
1.203	0.017	1.056

**Table 4.3: Hydrogen Lamp Spectral Data**

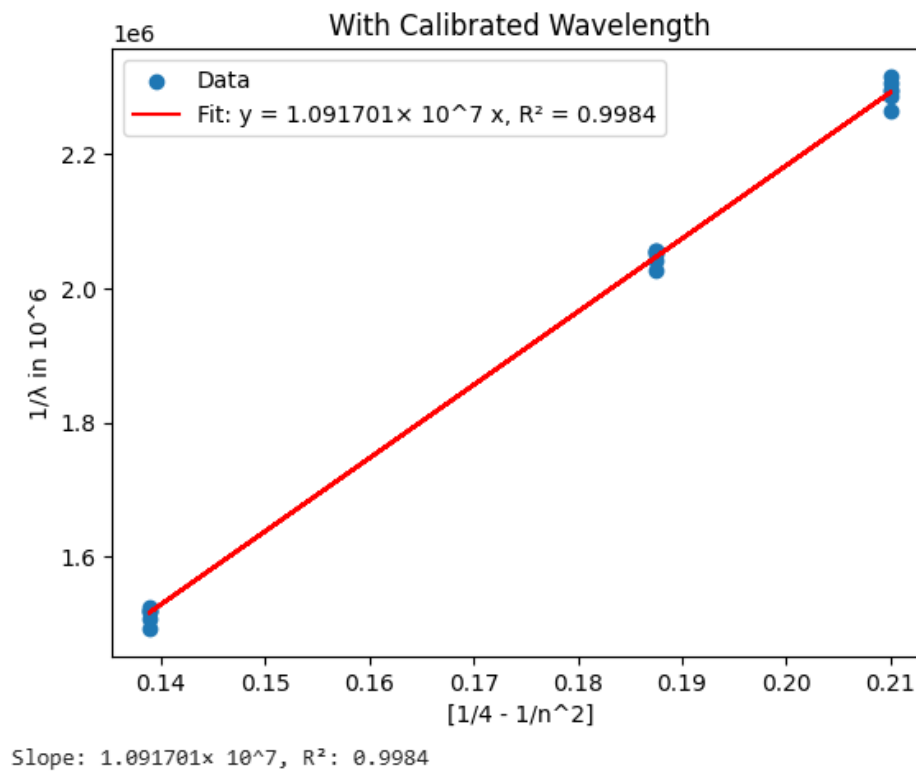
Colour	$n$	$m$	$\theta_R$	$\theta_L$	$Cor\theta_R$	$\theta_R$ (rad)	$\theta_L$ (rad)	$\lambda_R$ (nm)	$\lambda_L$ (nm)
Violet	5	1	192.233	12.283	12.233	0.214	0.214	358.791	300.235
Turquoise	4	1	193.833	13.816	13.833	0.241	0.241	404.857	404.369
Red	3	1	198.850	18.800	18.850	0.329	0.328	547.093	545.694
Violet	5	2	205.316	25.330	25.316	0.442	0.442	362.038	362.225
Turquoise	4	2	208.583	28.500	28.583	0.499	0.497	405.066	403.988
Red	3	2	220.216	40.330	40.216	0.702	0.704	546.660	547.946
Violet	5	1	167.600	12.517	12.400	0.216	0.218	363.612	366.989
Turquoise	4	1	166.083	14.017	13.917	0.248	0.245	407.267	410.135
Red	3	1	161.000	19.200	19.000	0.332	0.334	551.286	556.872

**Table 4.4: Calibrated Spectral Data**

Colour	$n$	$m$	$\lambda_R$ (nm)	$\lambda_L$ (nm)	$\frac{1}{4} - \frac{1}{n^2}$	$\frac{1}{\lambda_R(nm)}$	$\frac{1}{\lambda_L(nm)}$
Violet	5	1	431.687	433.424	0.210	0.002316	0.002307
Turquoise	4	1	487.113	486.526	0.188	0.002053	0.002055
Red	3	1	658.247	656.564	0.139	0.001519	0.001523
Violet	5	2	435.594	435.819	0.210	0.002296	0.002295
Turquoise	4	2	487.364	486.067	0.188	0.002052	0.002057
Red	3	2	657.726	659.273	0.139	0.001520	0.001517
Violet	5	1	437.488	441.551	0.210	0.002286	0.002265
Turquoise	4	1	490.012	493.463	0.188	0.002041	0.002026
Red	3	1	663.292	670.012	0.139	0.001508	0.001493



**Figure 4.1:**  $R$  calculated by without calibrated wavelength



**Figure 4.2:**  $R$  calculated by with calibrated wavelength

## Error Analysis

- Labeling of Spectrometer table and slit should be adjusted.
- Changes in temperature cause expansion/contraction of the diffraction grating, slightly altering spacing.
- Incorrect calibration of the spectrometer or diffraction grating leads to systematic shifts in wavelength measurements.

## Results

**Table 4.5:** *Hydrogen Emission Lines: Calculated vs Actual Wavelengths*

Colour	$n$	$\lambda_{\text{Uncal}}$ (nm)	$\lambda_{\text{Cal}}$ (nm)	$\lambda_{\text{Actual}}$ (nm)	% Diff (Uncal)	% Diff (Cal)
Violet	5	362.56	436.19	434.00	16.47	0.50
Turquoise	4	406.04	488.41	486.10	16.47	0.48
Red	3	548.41	659.44	656.30	16.47	0.48

## Percent Difference Calculation

The percent difference is calculated using the formula:

$$\% \text{Difference} = \frac{|\text{Accepted Value} - \text{Measured Value}|}{\text{Accepted Value}} \times 100\%$$

## Rydberg Constant Comparison

- Uncalibrated Rydberg Constant:  $R_{\text{Uncal}} = 1.3135035 \times 10^7 \text{ m}^{-1}$
- Calibrated Rydberg Constant:  $R_{\text{Cal}} = 1.091701 \times 10^7 \text{ m}^{-1}$
- Accepted Rydberg Constant:  $R_{\text{Accepted}} = 1.097373 \times 10^7 \text{ m}^{-1}$

The percent differences for the Rydberg constants are:

$$\% \text{Difference (Uncal)} = \frac{|1.097373 \times 10^7 - 1.3135035 \times 10^7|}{1.097373 \times 10^7} \times 100\% = 19.69\%$$

$$\% \text{Difference (Cal)} = \frac{|1.097373 \times 10^7 - 1.091701 \times 10^7|}{1.097373 \times 10^7} \times 100\% = 0.52\%$$



# THERMISTOR

**Date of Experiment:** 08 February 2025

## Introduction

In this experiment, basically we are trying to find out change in the resistance of the thermistor with change in the temperature. For certain semiconductors, the change in resistivity with temperature can be very rapid. Such materials can be used to make resistors with high temperature sensitivity, and are called thermistors. They can be used as temperature sensors.

## Theory

The change in resistivity of a thermistor due to temperature variations is primarily due to the underlying physics of charge carriers in semiconductors. Basically thermistor behavior depends on the material either it is a Negative Temperature Coefficient or Positive Temperature Coefficient type. In case of NTC Thermistors, the resistivity decreases as temperature increases. This is because of excitation of electrons from valence band to conduction band. While in PTC Thermistors, resistivity increases with temperature due to lattice vibration (phonon scattering) or phase transitions in some case.

## Observation

While doing the experiment, the way at which the temperature is changing also decides the change in resistivity. I will show the part where I tried rapid cooling (forced by adding ice or directly taking out of the medium to normal room temperature). Sudden change causes different effects in resistance so, it affects the way we are cooling or heating it.

## Analysis

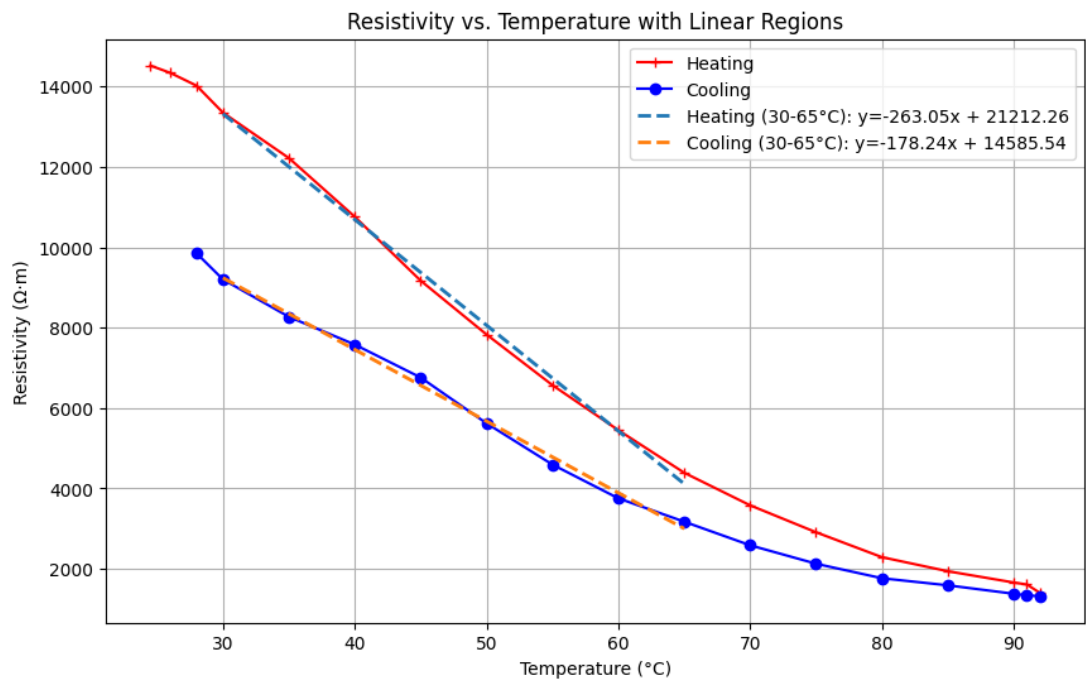


Figure 5.1: Heating and Cooling without forcing it to accelerate

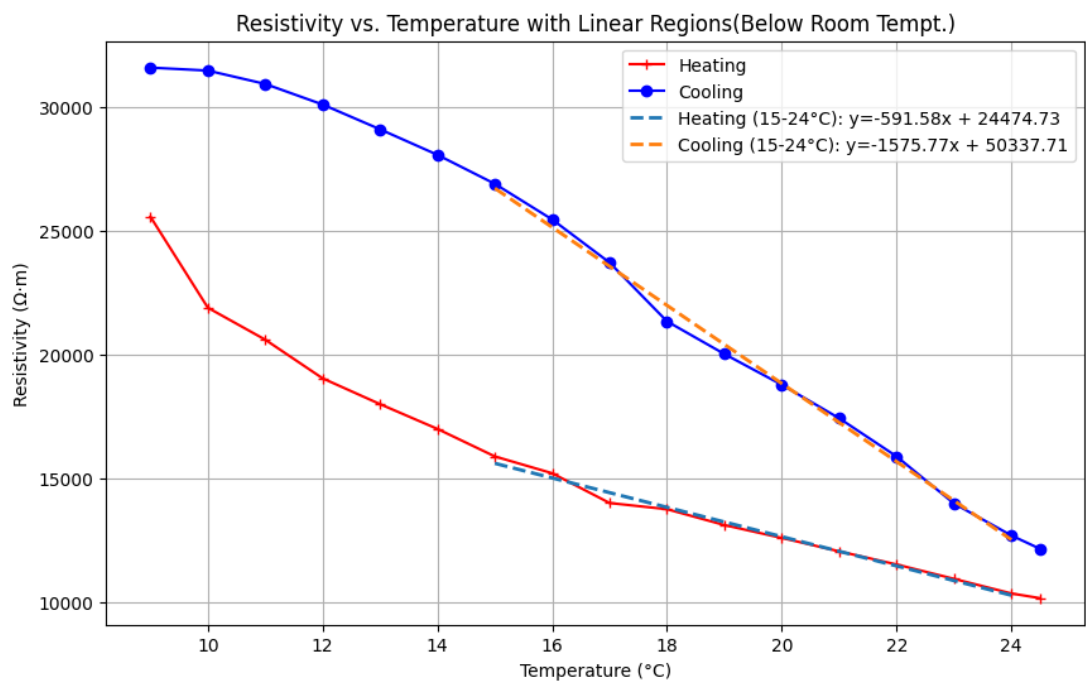
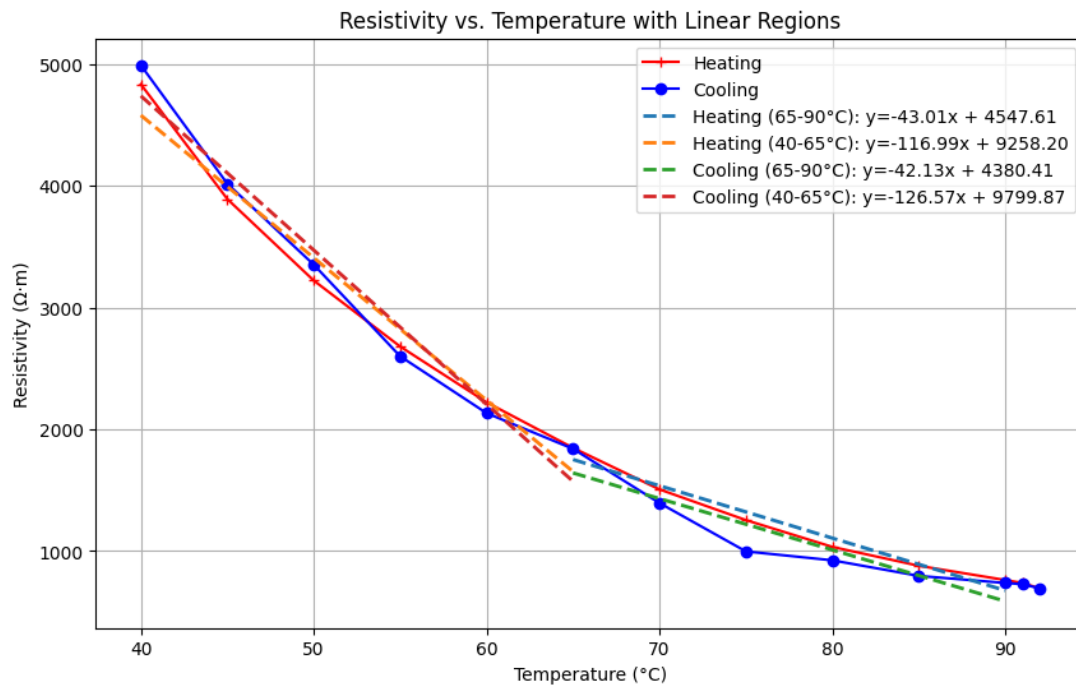
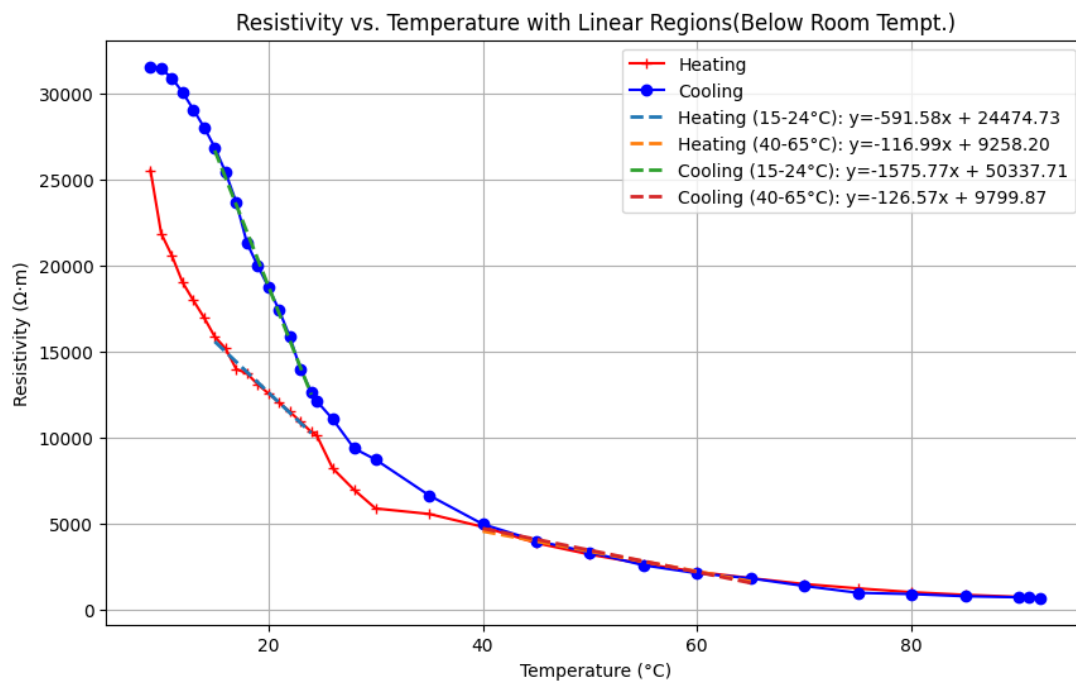


Figure 5.2: Cooling and heating below room temperature without sudden forcing



**Figure 5.3:** Heating and Cooling without forcing it to accelerate (*Apparatus 2*)

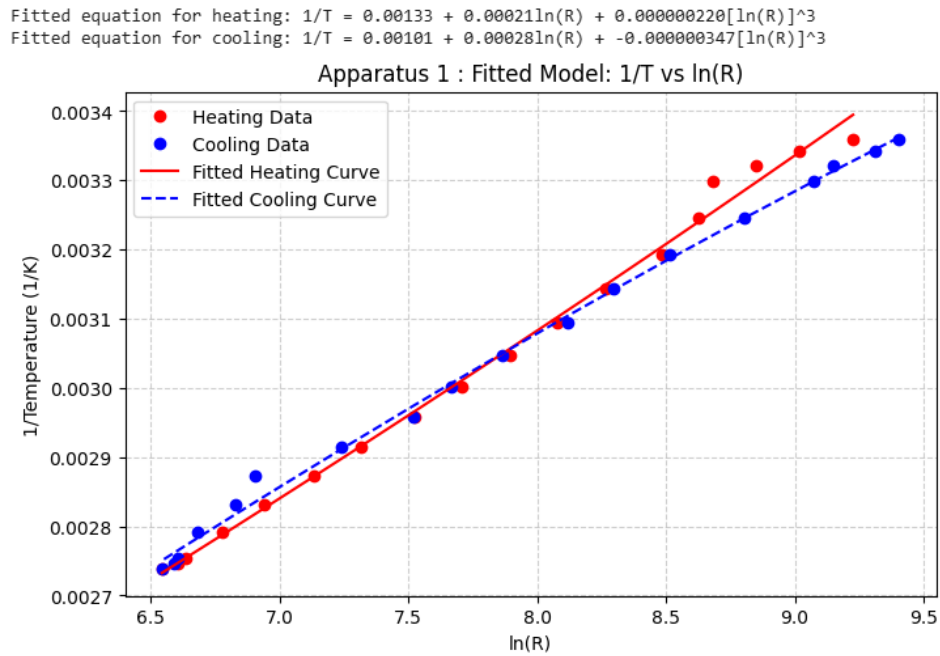


**Figure 5.4:** Cooling and heating below and above room temperature and perturbation at the room temperature because changing water to ice suddenly lifted resistance change

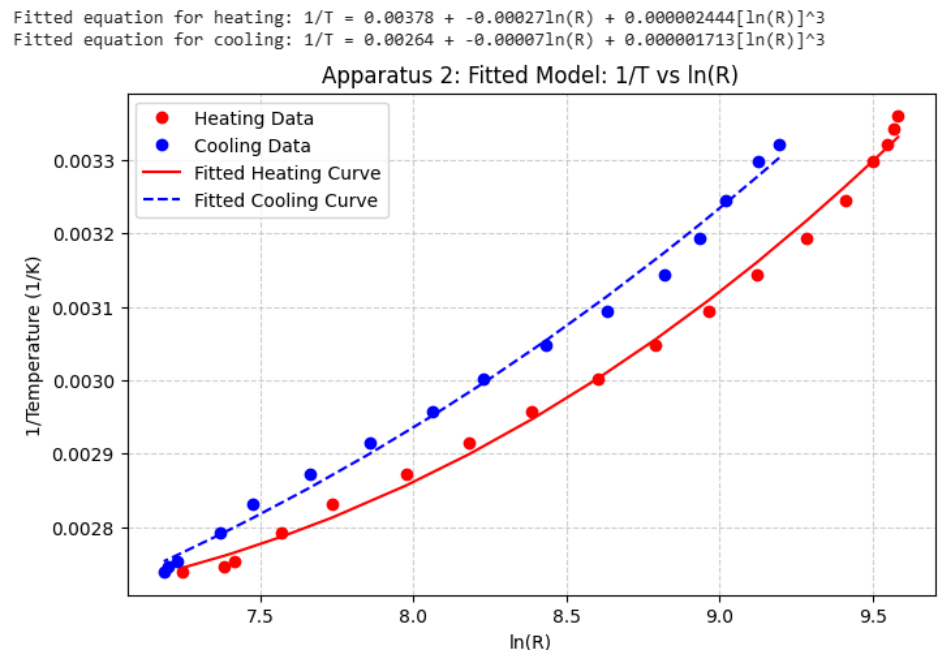
Using the Analysis based on the temperature dependence of the resistance of a semiconductor can be modeled as

$$\frac{1}{T} = A + B[\ln R] + C[\ln R]^3$$

By plotting a graph of  $1/T$  vs  $\ln(R)$ , the coefficients can be determined by a cubic fit to the data.



**Figure 5.5:** Cooling and heating below and above room temperature and perturbation at the room temperature because changing water to ice suddenly lifted resistance change



**Figure 5.6:** Heating and Cooling without forcing it to accelerate (Apparatus 2)

Even we tried to plot it using Power Law Fit:

$$R(T) = aT^b$$

$$\ln R = \ln a + b \ln T$$

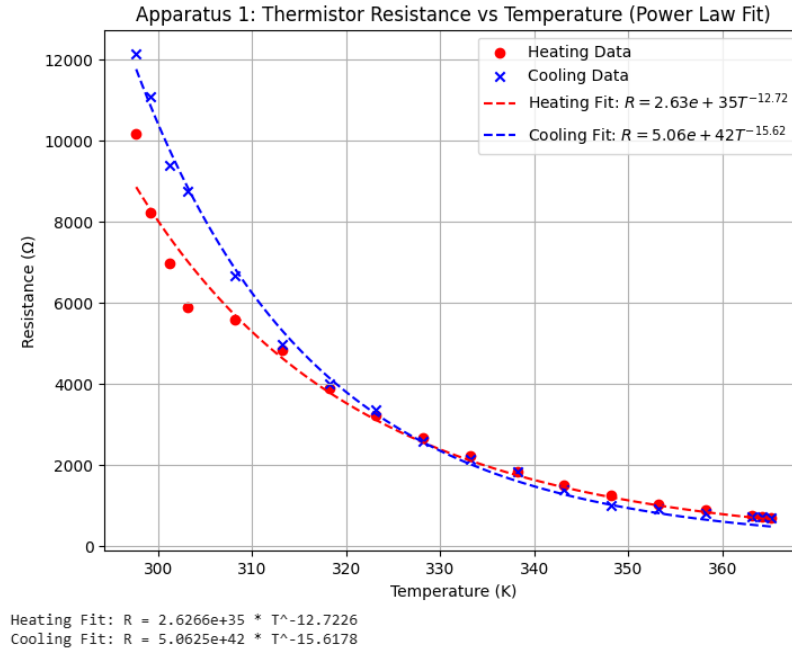


Figure 5.7: Apparatus 1 : Power Law Fit

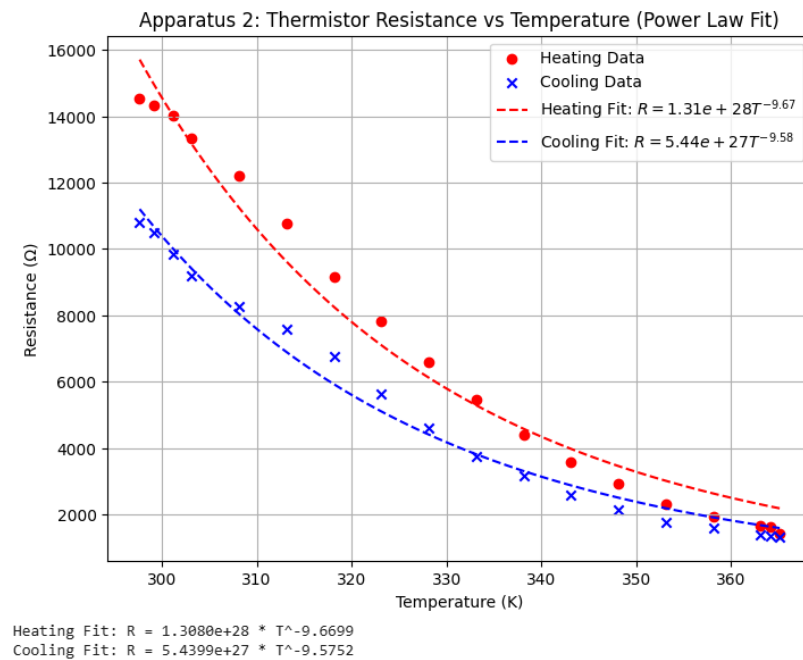


Figure 5.8: Apparatus 2 : Power Law Fit

## Results

Using Steinhart-Hart Equation, we plotted and figured out the coefficient of those:

- For Apparatus 1:  
-Heating ( $R^2 = 0.99487$ )

$$\frac{1}{T} = 0.00133 + 0.00021[\ln R] + 0.000000220[\ln R]^3$$

- Cooling ( $R^2 = 0.99678$ )

$$\frac{1}{T} = 0.00101 + 0.00028[\ln R] + 0.000000347[\ln R]^3$$

- For Apparatus 2:  
-Heating ( $R^2 = 0.99528$ )

$$\frac{1}{T} = 0.00378 + 0.00027[\ln R] + 0.000002444[\ln R]^3$$

- Cooling ( $R^2 = 0.99379$ )

$$\frac{1}{T} = 0.00264 + 0.00007[\ln R] + 0.000001713[\ln R]^3$$

Resistance is highly sensitive to temperature in case of thermistor, and even increase linearly in some temperature range.

#### **-Hysteresis (Heating vs Cooling Behavior)**

Cooling and heating curves differ, and hysteresis exists. This means the resistance at a given temperature depends on whether the thermistor was heated or cooled. There can be different reasons for this like internal heating effects, material response lag and slow thermal equilibration.

**-Cooling curve is under the heating curve if heating first while the heating curve is under the cooling curve if cooling is done first.**

### **Points to Ponder**

#### **1. On the basis of observations, can you find a range in which a thermistor behaves linearly?**

- Yes, under slow changes in temperature, the thermistor appears to behave approximately linear in the range of 30–65°C. The exact range may vary slightly depending on the thermistor type, but within this interval, the relationship between resistance and temperature follows a nearly straight-line trend.

#### **2. Is a thermistor more useful for measuring small or large temperature changes accurately?**

- A thermistor is more useful for detecting small temperature changes because its resistance varies rapidly with temperature, allowing for high sensitivity. For large temperature changes, its response becomes nonlinear, making accurate measurements more challenging. Therefore, thermistors are ideal for applications where precise detection of minor fluctuations is needed.

## THERMAL EXPANSION

### Aim

All materials expand when heated and contract when cooled. Heating changes the length, area, and volume of the substance. The change rate of a substance's length with temperature is called the coefficient of thermal expansion  $\alpha$  of that material. In this experiment, ( $\alpha$ ) is measured for four metals.

### Theory

In a thermal expansion experiment involving a rod with a temperature gradient, the standard approach for calculating the coefficient of linear expansion ( $\alpha$ ) must be adapted to account for non-uniform heating. Below is the theoretical framework for determining  $\alpha$  under these conditions.

#### Temperature Distribution

Assume the rod has a linear temperature gradient along its length  $L_0$ , with temperatures  $T_{\text{hot}}$  at the heated end ( $x = 0$ ) and  $T_{\text{cold}}$  at the opposite end ( $x = L_0$ ). The temperature  $T(x)$  at position  $x$  is:

$$T(x) = T_{\text{hot}} - \left( \frac{T_{\text{hot}} - T_{\text{cold}}}{L_0} \right) x.$$

#### Local Expansion

The differential expansion  $dL$  of an infinitesimal segment  $dx$  at position  $x$  is given by:

$$dL = \alpha [T(x) - T_0] dx,$$

where  $T_0$  is the initial (room) temperature.

#### Total Expansion

To find the total elongation  $\Delta L$ , integrate over the entire length of the rod:

$$\Delta L = \alpha \int_0^{L_0} \left( T_{\text{hot}} - T_0 - \frac{T_{\text{hot}} - T_{\text{cold}}}{L_0} x \right) dx.$$

Solving the integral yields:

$$\Delta L = \alpha L_0 \left( \frac{T_{\text{hot}} + T_{\text{cold}}}{2} - T_0 \right).$$

## Coefficient of Linear Expansion

Rearranging the expression to solve for  $\alpha$ , we get:

$$\alpha = \frac{\Delta L}{L_0 \left( \frac{T_{\text{hot}} + T_{\text{cold}}}{2} - T_0 \right)}.$$

## Key Simplification

This result reduces to the standard formula  $\Delta L = \alpha L_0 \Delta T$  when  $T_{\text{hot}} = T_{\text{cold}}$ , with  $\Delta T$  being the uniform temperature change.

## Uncertainties

Using standard rules for uncertainty propagation in a product/division:

$$\left( \frac{\delta \alpha}{\alpha} \right)^2 = \left( \frac{\delta(\Delta L)}{\Delta L} \right)^2 + \left( \frac{\delta L_0}{L_0} \right)^2 + \left( \frac{\delta(\Delta T_{\text{avg}})}{\Delta T_{\text{avg}}} \right)^2$$

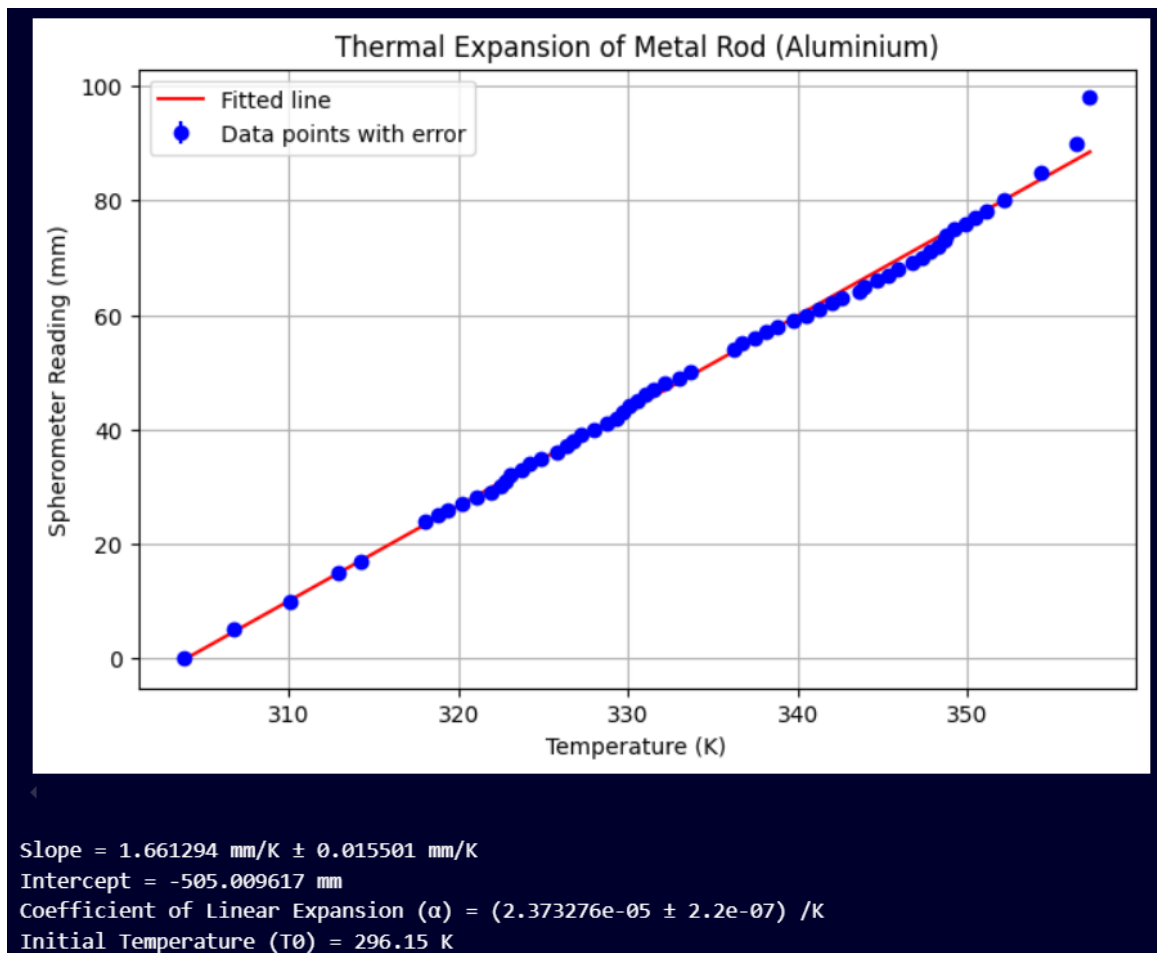
The uncertainty in the average temperature difference is given by:

$$\delta(\Delta T_{\text{avg}})^2 = \left( \frac{1}{2} \delta T_{\text{hot}} \right)^2 + \left( \frac{1}{2} \delta T_{\text{cold}} \right)^2 + (\delta T_0)^2$$

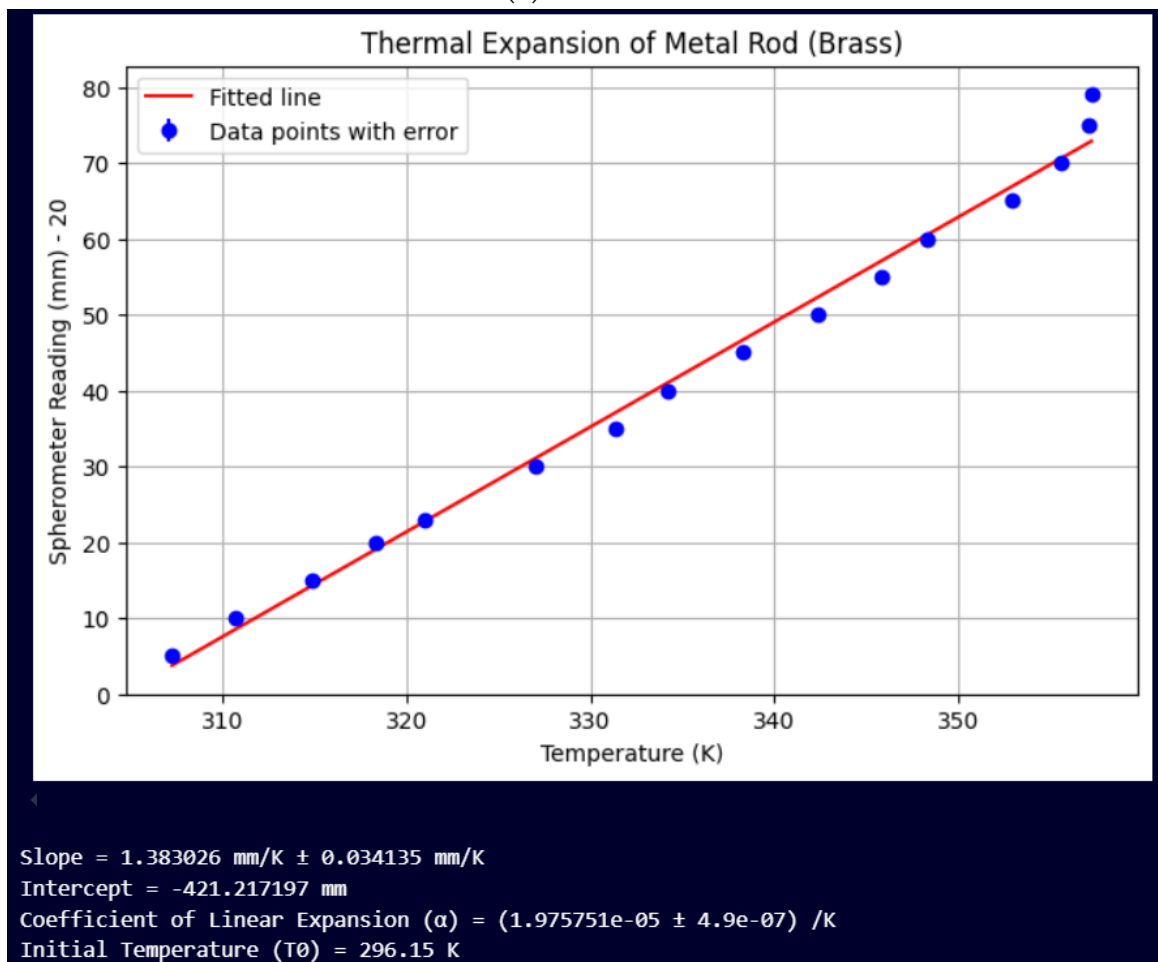
Thus, the final propagated uncertainty in  $\alpha$  is:

$$\delta \alpha = \alpha \cdot \sqrt{\left( \frac{\delta(\Delta L)}{\Delta L} \right)^2 + \left( \frac{\delta L_0}{L_0} \right)^2 + \left( \frac{\sqrt{\left( \frac{\delta T_{\text{hot}}}{2} \right)^2 + \left( \frac{\delta T_{\text{cold}}}{2} \right)^2 + \delta T_0^2}}{\Delta T_{\text{avg}}} \right)^2}$$

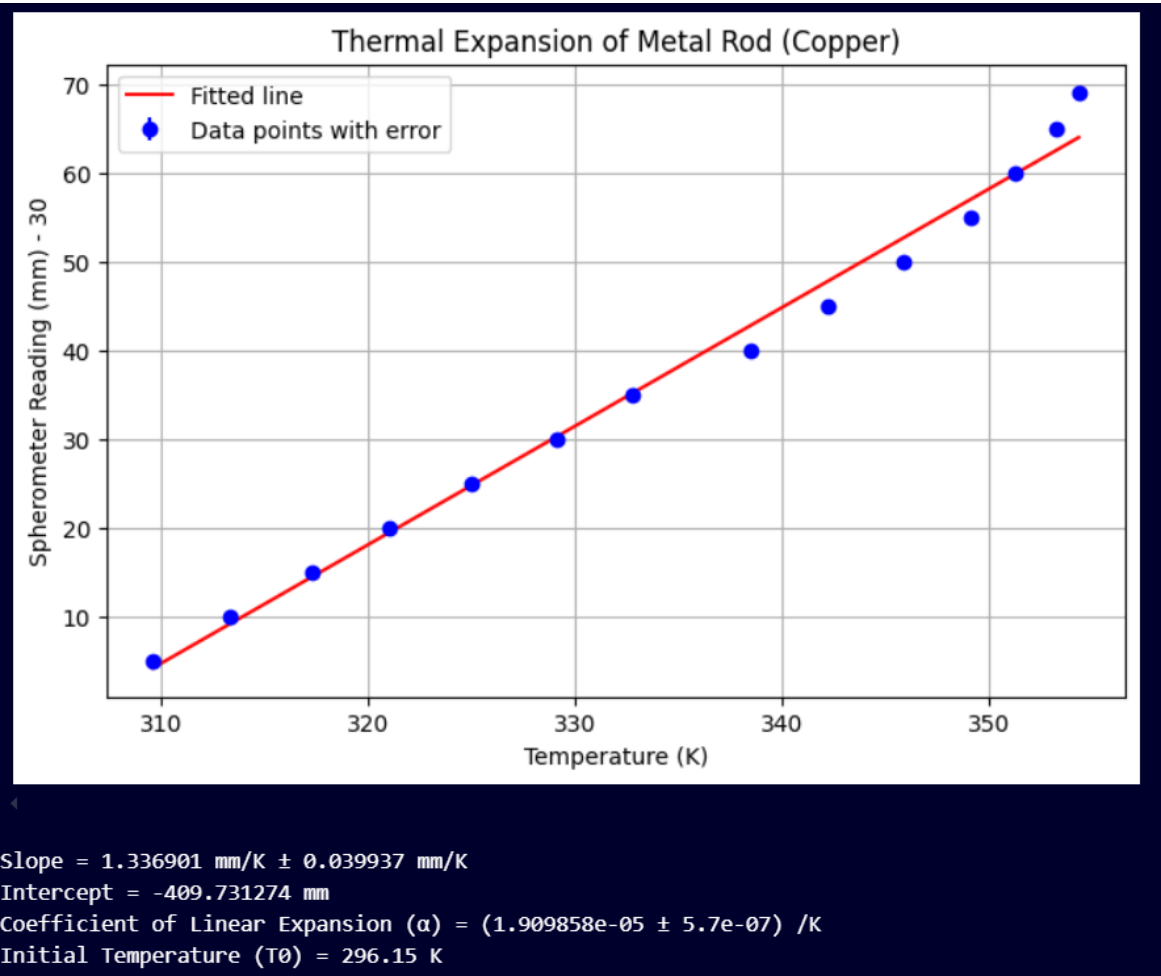




(a) Aluminium



(b) Brass



(a) Final reading

Figure 6.2: Copper

Analysis

The values are calculated from the individual data point and averaged over the whole data set. While the values obtained from curve fitting is given in the graphs itself.

Table 6.1: Thermal Expansion Coefficients of Materials (in $\mu\epsilon/^{\circ}\text{C}$ )			
Material	Measured Coefficient ( $\mu\epsilon/^{\circ}\text{C}$ )	Std. Dev. ( $\mu\epsilon/^{\circ}\text{C}$ )	Accepted Value ( $\mu\epsilon/^{\circ}\text{C}$ )
Aluminum	23.58	0.52	23.1
Brass	19.34	0.89	19.0
Copper	18.67	0.75	16.5-18.7
Steel	18.03	1.28	11.0

## Error Analysis

$$\begin{aligned}\text{Aluminum: } & \frac{|23.58 - 23.1|}{23.1} \times 100 = 2.08\% \\ \text{Brass: } & \frac{|19.34 - 19.0|}{19.0} \times 100 = 1.79\% \\ \text{Copper: } & \frac{|18.67 - 17.6|}{17.6} \times 100 = 6.08\% \quad (\text{using midpoint of } 16.5\text{--}18.7) \\ \text{Steel: } & \frac{|18.03 - 11.0|}{11.0} \times 100 = 63.00\%\end{aligned}$$

## Result

We used a different approach for finding the coefficient of thermal expansion for copper, brass, and aluminum. In the experiment, we aimed to determine the temperature using a thermocouple placed at one point; however, this gives a localized temperature reading. To improve accuracy, I placed two thermocouples at both ends of the rod and took the average temperature. This method is also derived and explained in the manual. As a result, we observed coefficient values that closely match the accepted values for these materials.

However, for steel, the experiment was conducted using only one thermocouple. Consequently, the measured coefficient differed significantly from the accepted value.

## Precautions

- Handle the apparatus carefully, as it is heated to around 100 °C.
- Ensure the spherometer is properly aligned to avoid incorrect readings.
- Using two thermocouples and applying a gradient-based approach provides more accurate temperature measurements.

## STEFAN'S LAW

### Aim

To verify the Stefan-Boltzmann law by determining the relation between the power radiated by a heated filament and its temperature, and to calculate the effective surface area of the filament.

The Stefan-Boltzmann law describes the power radiated from a black body in terms of its temperature. This law is fundamental to thermal radiation and provides an essential relation for understanding energy transfer by radiation.

### Theory

According to the Stefan-Boltzmann law, the power  $P$  radiated by a black body is proportional to the fourth power of its absolute temperature  $T$ :

$$P = \sigma A(T^4 - T_a^4) \quad (7.1)$$

where:

- $P$  is the power radiated (W)
- $\sigma$  is the Stefan-Boltzmann constant ( $5.67 \times 10^{-8} \text{W m}^{-2} \text{K}^{-4}$ )
- $A$  is the surface area of the radiating body ( $\text{m}^2$ )
- $T$  is the temperature of the body (K)
- $T_a$  is the ambient temperature (K)

Since the temperature of the filament is significantly higher than the ambient temperature, the contribution of  $T_a$  is often neglected for simplicity.

Additionally, the resistance  $R$  of the filament changes with temperature according to the relation:

$$R(T) = R_0(1 + aT + bT^2) \quad (7.2)$$

where  $R_0$  is the resistance at a reference temperature, and  $a$  and  $b$  are material constants.

### Proportionality of Power with $T^4$

The Stefan-Boltzmann law suggests that the radiative power of a black body increases as the fourth power of its temperature. By plotting  $\log(P)$  versus  $\log(T)$ , the slope of the resulting line should ideally be close to 4, which provides experimental verification of the law. In our analysis, this relationship is used to validate the theoretical prediction.

## Observations

The measured voltages, currents, and ambient temperatures are given below:

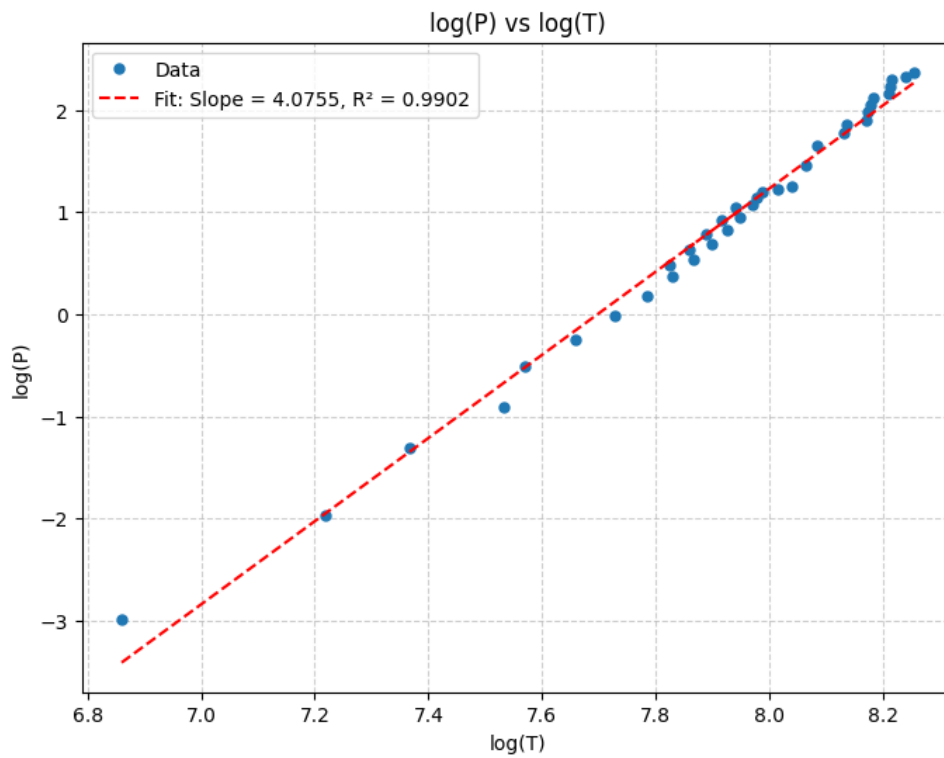


Figure 7.1: Fourth-Power Verification

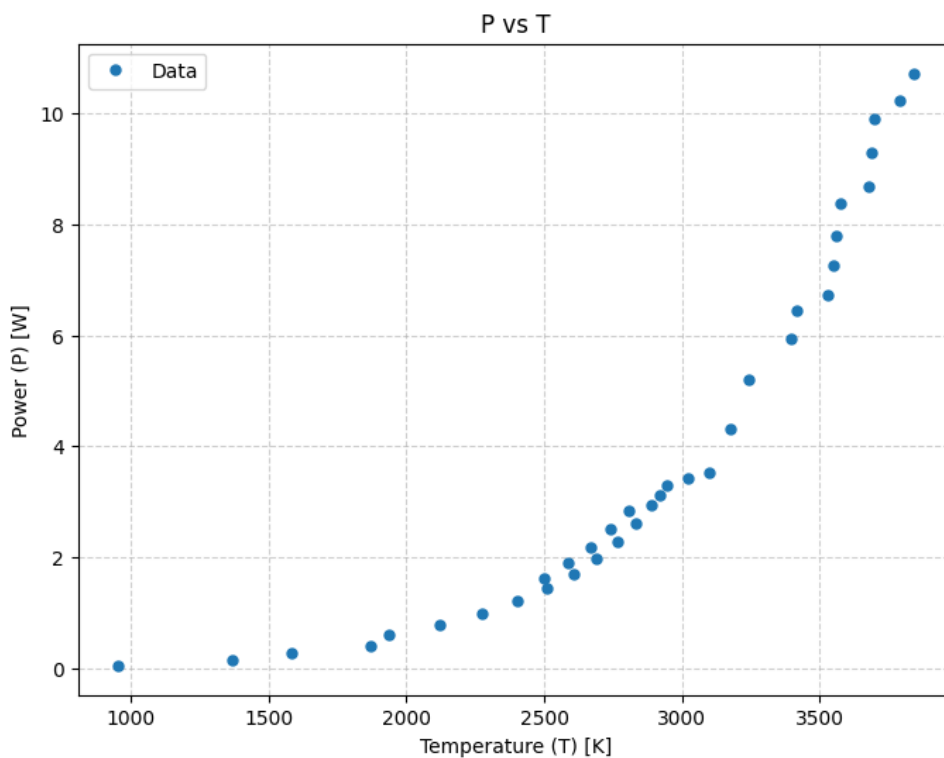


Figure 7.2:  $P$  vs  $T$

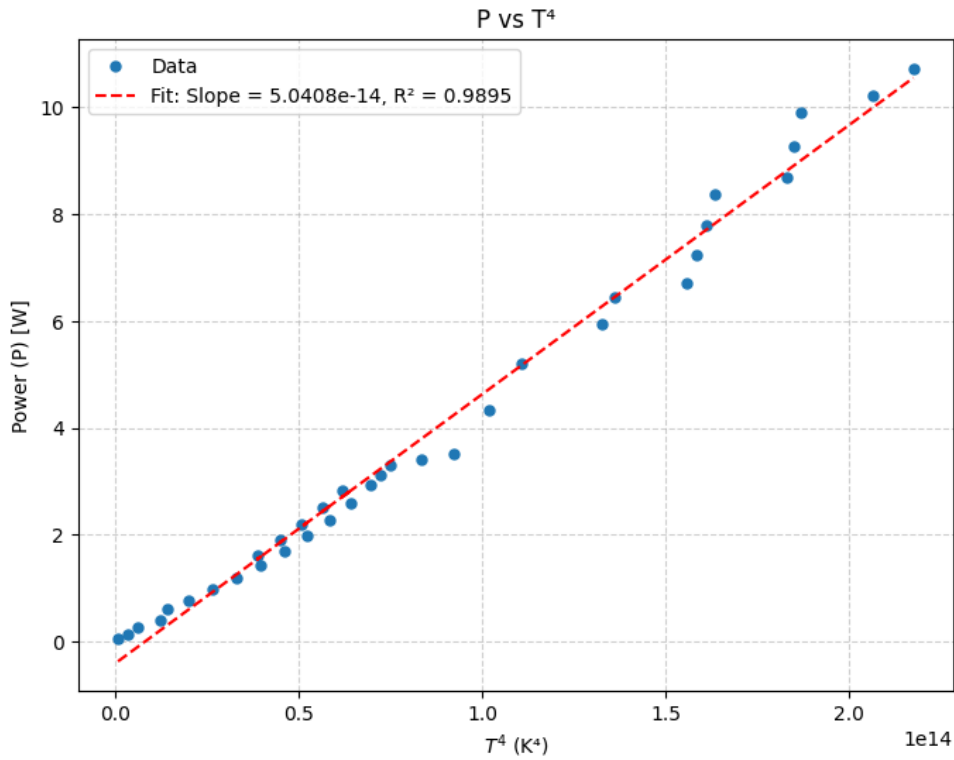


Figure 7.3: Proportionality Constant

## Uncertainties

### 1. Instrumental Uncertainties

The least count in the apparatus was 0.01 Amp for current and 0.1 Volt for Voltage, and current values remained the same for some small 1-2 Volt changes, and it will cause wrong values as we are not able to detect small changes in the current with that apparatus.

### 2. Environmental Uncertainties

Fluctuations in ambient temperature will cause errors while calculating the area of the filament, and there are losses by convection and conduction also.

### 3. Theoretical and Experimental Assumptions

We are assuming it as an ideal blackbody, but obviously there is nothing like an ideal blackbody. So, the filament's emissivity is obviously less than 1 as well, and not all electrical power converts into radiation.

## Analysis

Using the measured values, we computed the filament temperature, power, and effective surface area using the following relation:

$$A = \frac{P}{0.35 \times \sigma \times (T^4 - T_a^4)} \quad (7.3)$$

The calculated Surface area values are:

- Mean of area:  $1.5341 \times 10^{-6} \text{m}^2$
- Standard Deviation of area:  $2.0107 \times 10^{-7} \text{m}^2$

For ambient temperature, we waited for the temperature of ambient temperature to stabilize. The constant of proportionality is  $5.04 \times 10^{-14}$  for the Stefan-Boltzmann law.

## Result

By plotting, we have recovered a slope of 4.0755, which is very near to 4. Hence, it verifies the Stefan-Boltzmann law.

The mean surface area of the filament was found to be approximately  $1.5341 \times 10^{-6} \text{ m}^2$ .

## Precautions

1. Ensure accurate measurement of voltage and current using calibrated instruments.
2. Avoid touching the heated bulb otherwise, it will cause a burn.
3. Minimize heat losses and external disturbances.

## Points to Ponder

### 1. How would you reduce the error in determining when the filament just starts glowing?

**Solution:** The error in determining the exact moment when the filament starts glowing can be reduced by:

- Observing the filament in a darkened environment to enhance visibility.
- Using a photodetector or light sensor to detect the first emission of visible light.
- Increasing the current in very small increments to pinpoint the exact threshold.
- Using a high-resolution camera to record and analyze the onset of glow.

### 2. How much is the error in neglecting the $T_a$ term in the heat exchange expression?

**Solution:** The error due to neglecting the ambient temperature ( $T_a$ ) in the heat exchange expression depends on the difference between the ambient temperature and the system's temperature. If  $T_a$  is significantly different from the surroundings, the error can be considerable.

## SPECIFIC HEAT OF SOLIDS

### Aim

The temperature change ( $\Delta T$ ) of a material when a fixed amount of heat energy ( $\Delta Q$ ) is supplied depends on both the intrinsic properties of the material and its mass ( $m$ ). This relationship is governed by the specific heat capacity ( $c$ ) of the substance, which quantifies the heat required to raise the temperature of a unit mass of the material by one degree. Mathematically, this relationship is expressed as:

$$\Delta Q = cm\Delta T \quad (8.1)$$

To determine the specific heat capacity of a given substance, we introduce a known quantity of heat energy and measure the corresponding temperature rise, allowing for an experimental evaluation of  $c$ . This measurement provides insight into the material's thermal properties, which is essential for applications in thermodynamics and material science.

### Theory

The specific heat capacity of a substance is defined as the amount of heat energy required to raise the temperature of a unit mass of the material by one Kelvin. The SI unit for specific heat is joules per kilogram per kelvin ( $\text{J/kg/K}$ ). Different materials exhibit varying specific heat capacities due to differences in their atomic structure and bonding. For instance, water has one of the highest specific heat capacities among common substances, with a value of  $4184 \text{ J/kg/K}$ , which historically was set to  $1 \text{ cal/g/}^\circ\text{C}$  in the cgs system.

Another important thermal property is the molar specific heat, which refers to the heat required to raise the temperature of one mole of a substance by one degree. In crystalline solids, the molar heat capacity at room temperature tends to be nearly constant due to uniform vibrational energy distributions among atoms. However, certain materials, such as diamonds, deviate significantly from this trend due to their strong atomic bonds and rigid lattice structures, resulting in lower specific heat values.

Experimentally, the specific heat capacity of a substance can be determined by calorimetry. When a heated sample (such as metal shots) is introduced into a known mass of water, thermal equilibrium is reached, and heat transfer occurs between the sample and the water. The heat lost by the sample ( $\Delta Q_s$ ) is given by:



$$\Delta Q_s = c_s m_s (\theta_s - \theta_m) \quad (8.2)$$

where  $\theta_s$  is the initial temperature of the sample, and  $\theta_m$  is the final equilibrium temperature of the mixture.

Similarly, the heat gained by the water ( $\Delta Q_w$ ) is expressed as:

$$\Delta Q_w = c_w m_w (\theta_m - \theta_w) \quad (8.3)$$

$\theta_w$  is the initial temperature of the water. Ideally, assuming no heat loss to the surroundings, the heat lost by the sample equals the heat gained by the water. However, in reality, heat is also absorbed by the calorimeter flask. To correct for this, we introduce an effective water mass  $m_f$  that accounts for the heat absorbed by the flask. The corrected equation for determining the specific heat capacity of the sample is:

$$c_s = \frac{(m_w + m_f)(\theta_m - \theta_w)}{m_s(\theta_s - \theta_m)} \quad (8.4)$$

By applying this equation, we can accurately measure the specific heat capacity of a given material while accounting for thermal losses in the experimental setup.

## Observations

**Table 8.1:** Observation Table for Specific Heat Measurement

Material	Mass (g)	Temperature of Shots (°C)	Water Temperature Change (°C)
Ceramic Bead	19.3	96.4	21.8 → 23.2
Iron Bead	50.0	94.6	23.6 → 25.3
Copper Bead	25.0	94.9	23.9 → 24.7
Acrylic Bead	25.0	96.1	23.6 → 25.4

**Table 8.2:** Calculated Specific Heat Capacities

Material	$m_s$ (g)	$\theta_s$ (°C)	$\theta_w$ (°C)	$\theta_m$ (°C)	$c_s$ (J/g/K)
Ceramic Bead	19.3	96.4	21.8	23.2	0.7948
Iron Bead	50	94.6	23.6	25.3	0.3934
Copper Bead	25	94.9	23.9	24.7	0.3655
Acrylic Bead	25	96.1	23.6	25.4	0.8167

**Table 8.3:** Data from Rajat: Thermal Conductivity and Specific Heat Capacities of Materials

Material	$m_s$ (g)	$\theta_s$ (°C)	$\theta_w$ (°C)	$\theta_m$ (°C)	$c_s$ (J/g/K)	Thermal Conductivity (W/m·K)
Ceramic Bead	34.3	94.9	23.6	26.1	0.8494	1 to 30
Iron Bead	190.2	94.2	23.4	30.2	0.4479	80
Copper Bead	197.5	97.1	24.5	30.8	0.3858	385
Acrylic Bead	65.7	95.8	24.8	29.5	0.8651	0.2

## Uncertainties

- While heating the beads, we are heating the balls for enough time, but as the steam is not passing uniformly, we haven't checked, but there are good chances that the specific heat will

be under estimated because we are not sure that core of the beads are also heated to the same temperature of the surface of the beads.

- We should have a larger surface area to volume ratio for proper heating, and it will help to reduce the uncertainty.
- We need to wait while heating and cooling because it will help to evaluate accurate values for specific heat.

## Analysis

For my part, the specific heat values do not match the accepted values. In the case of all materials, values are underestimated because of improper prolonged heating, which is why the temperature that we took is of the surface. The temperature of the core and surface of the beads are not the same. The calculation of the calorimeter is shown in the last section, named Points to Ponder.

## Error Analysis

**Table 8.4:** Comparison of Accepted and Observed Specific Heat Capacities

Material	Accepted $c_s$ (J/g/K)	Mine $c_s$ (J/g/K)	% Error (Mine)	Rajat $c_s$ (J/g/K)	% Error(Rajat)
Ceramic Bead	0.84	0.7948	5.37%	0.8494	1.12%
Iron Bead	0.45	0.3934	12.58%	0.4479	0.47%
Copper Bead	0.385	0.3655	5.06%	0.3858	0.21%
Acrylic Bead	1.47	0.8167	44.44%	0.8651	41.14%

## Result

When I experimented, I used fewer beads and it may have lost some heat, hence affecting values by so much. While Rajat's values are accurate as he used 8-9 times the weight of beads that I used. So my values are little more off, while the values taken from Rajat are close to accepted values.

But if you compare the values of acrylic, you can see a significant error of around 40 percent. The reason for this is the very low thermal conductivity of acrylic, and it is briefly written in uncertainties part (1).

If we want to get correct values, then while heating and as well as while cooling, we need to wait long to uniformly heat and cool acrylic heat from inside to outside properly.

The water equivalent of Dewar used for the calculation is **11.63 g**.

## Precautions

1. While heating the beads to around 100 degrees celsius, we need to handle them very carefully.
2. While operating the heating process, we have to operate on lower power and need to check any clogs in the pipe as well the steam output otherwise, pressurized water vapour will come out forcefully. The forceful expulsion of steam and hot water is dangerous for people sitting just next to the apparatus, so taking precautions is important.
3. Properly cover hand with thermally insulated gloves for lifting or transferring heated beads.

## Points to Ponder

### 1. How would you determine the water equivalent of the Dewar if it were not given to you?

**Solution:** The water equivalent ( $W$ ) of a calorimeter is the mass of water that would absorb the same amount of heat as the calorimeter itself. It is determined using the principle of heat exchange, assuming no heat loss to the surroundings.

### Given Data

- Mass of water in calorimeter,  $m_w = 203.6 \text{ g}$
- Initial temperature of calorimeter,  $\theta_c = 22^\circ\text{C}$
- Initial temperature of water,  $\theta_w = 59^\circ\text{C}$
- Final equilibrium temperature,  $\theta_m = 57^\circ\text{C}$
- Specific heat capacity of water,  $c_w = 4.184 \text{ J/g/K}$

### Heat Lost by Water

The heat lost by the water when it cools from  $\theta_w$  to  $\theta_m$  is:

$$Q_w = m_w c_w (\theta_w - \theta_m) \quad (8.5)$$

$$Q_w = 1703.7 \text{ J} \quad (8.6)$$

### Heat Gained by the Calorimeter

The heat gained by the calorimeter is given by:

$$Q_c = W c_w (\theta_m - \theta_c) \quad (8.7)$$

Since the heat lost by water is equal to the heat gained by the calorimeter:

$$Q_w = Q_c \quad (8.8)$$

$$1703.7 = W \times 4.184 \times (57 - 22) \quad (8.9)$$

$$W \approx 11.63 \text{ g} \quad (8.10)$$

The water equivalent of the calorimeter is found to be approximately **11.63 g**. This means that the calorimeter absorbs heat equivalent to 11.63 g of water during the process.

## PHOTOELECTRIC EFFECT

### Aim

The photoelectric effect experiment aims to investigate the emission of electrons from a metal surface when exposed to electromagnetic radiation, thereby demonstrating the particle nature of light. The experiment aims to show that the emission of electrons depends on the **frequency** of the incident light rather than its intensity. There is a threshold frequency below which no electrons are emitted, regardless of the light intensity. Furthermore, it seeks to establish the linear relationship between the maximum kinetic energy of the emitted electrons and the frequency of the incident light, as described by Einstein's photoelectric equation:

$$K_{\max} = hf - \phi$$

where  $K_{\max}$  is the maximum kinetic energy of the emitted electrons,  $h$  is Planck's constant,  $f$  is the frequency of the incident light, and  $\phi$  is the work function of the metal. This experiment provides fundamental evidence for the quantum nature of light and supports the concept that light consists of discrete energy packets called photons.

### Theory

The photoelectric effect occurs when light strikes a material and causes electrons to be ejected. This seemingly simple phenomenon led to groundbreaking discoveries in physics. It provided key evidence for the quantum nature of light, challenging the classical wave theory of light.

Classical physics predicted that increasing the intensity of light would always eject electrons, regardless of its frequency. However, experiments showed that no electrons are emitted if the light frequency is below a certain threshold, no matter how intense the light is. Albert Einstein resolved this by proposing that light is made of discrete energy packets called *photons*. This idea laid the foundation for quantum mechanics.

### Photon Energy

Einstein proposed that each photon carries an energy proportional to its frequency:

$$E = hf, \tag{9.1}$$

where:

- $h$  is Planck's constant ( $6.626 \times 10^{-34} \text{ J} \cdot \text{s}$ ),
- $f$  is the frequency of the light.

The higher the frequency of the light, the more energy each photon carries.

### How the Photoelectric Effect Works

When a photon strikes the surface of a material, its energy is transferred to an electron. This energy is used in two ways:

1. A portion of the energy, equal to the *work function*  $\phi$ , is used to free the electron from the material. The work function is the minimum energy required to remove an electron from the material.
2. Any leftover energy becomes the kinetic energy  $K_{\text{max}}$  of the emitted electron.

This energy balance can be written as:

$$hf = \phi + K_{\text{max}}, \quad (9.2)$$

where:

- $hf$  is the energy of the photon,
- $\phi$  is the work function of the material,
- $K_{\text{max}}$  is the maximum kinetic energy of the emitted electron.

### Threshold Frequency

For electrons to be emitted, the photon energy  $hf$  must be greater than or equal to the work function  $\phi$ . This means the light must have a minimum frequency, called the *threshold frequency*  $f_0$ , given by:

$$f_0 = \frac{\phi}{h}. \quad (9.3)$$

If the frequency of the light  $f$  is below  $f_0$ , no electrons are emitted, regardless of the light's intensity. This behavior could not be explained by classical wave theory.

### Kinetic Energy of Electrons

When the frequency of the light  $f$  exceeds the threshold frequency  $f_0$ , the kinetic energy of the emitted electrons is:

$$K_{\text{max}} = h(f - f_0). \quad (9.4)$$

This equation shows that the kinetic energy of the electrons depends linearly on the frequency of the light.

### Stopping Potential

In experiments, emitted electrons can be stopped by applying a retarding potential  $V_s$ . The stopping potential is related to the maximum kinetic energy of the electrons by:

$$K_{\text{max}} = eV_s, \quad (9.5)$$

where  $e$  is the elementary charge ( $1.602 \times 10^{-19}$  C). Substituting for  $K_{\max}$ , we get:

$$eV_s = hf - \phi, \quad (9.6)$$

or equivalently:

$$V_s = \frac{hf - \phi}{e}. \quad (9.7)$$

The stopping potential varies linearly with the frequency of the light, confirming Einstein's equation.

## Intensity and Current

The intensity of light determines the number of photons incident on the material per second. Since each photon can eject at most one electron, the photoelectric current is proportional to the light intensity, provided the frequency of the light is above the threshold frequency  $f_0$ . However, the energy of the emitted electrons depends only on the frequency of the light, not its intensity.

## Experimental Evidence

Einstein's theory of the photoelectric effect has been validated by key experimental observations:

- The kinetic energy of emitted electrons depends on the frequency of the light, not its intensity.
- There is a well-defined threshold frequency below which no electrons are emitted.
- The stopping potential varies linearly with the frequency of the light.

The photoelectric effect was pivotal in establishing the quantum theory of light. Einstein's equation:

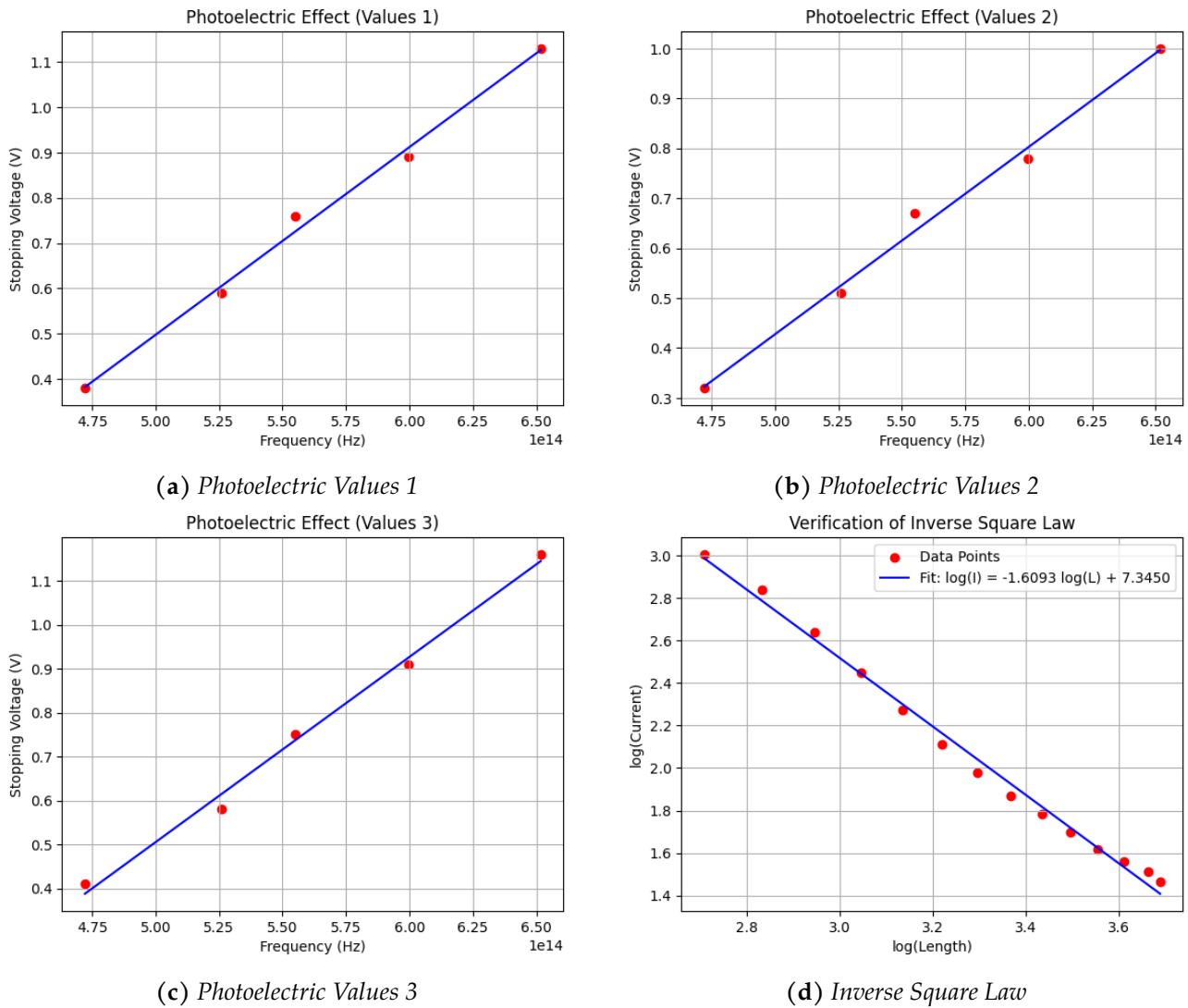
$$K_{\max} = hf - \phi, \quad (9.8)$$

showed that light behaves as particles (photons) in certain situations. This explanation resolved experimental puzzles and earned Einstein the Nobel Prize in Physics in 1921. The photoelectric effect remains a cornerstone of quantum mechanics, influencing modern technology like solar cells and photodetectors.

## Observations

**Table 9.1:** Wavelengths and Stopping potential Values

Wavelength (nm)	Value 1	Value 2	Value 3
460	1.13	1.00	1.16
500	0.89	0.78	0.91
540	0.76	0.67	0.75
570	0.59	0.51	0.58
635	0.38	0.32	0.41



**Figure 9.1:** Comparison of Photoelectric Values and Verification of the Inverse Square Law

## Uncertainties

There are multiple uncertainties in this experiment:

- We are not sure that the filter bandwidth given was correct or not, and there were some mixing of different wavelength of light.
- Although intensity does not affect the energy of individual photoelectrons, fluctuations can impact the number of electrons emitted, thereby affecting current detection and threshold measurements. There are also possibility of misalignment between the light source and the metal surface leading to reduce the effective illumination.
- The work function may vary due to oxidation, contamination, or surface roughness(uneven surface) of the photoemissive material, leading to systematic errors. With changing temperature , there can be some chnage in the work function.

## Analysis

**Table 9.2:** Results of Photoelectric Effect Measurements

Set	Planck's Constant (Js)	Work Function (eV)	$R^2$ Value
Values One	$6.6449 \times 10^{-34}$	1.5763	0.9945
Values Two	$6.0154 \times 10^{-34}$	1.4499	0.9927
Values Three	$6.7502 \times 10^{-34}$	1.6012	0.9932

## Error Analysis

In the photoelectric effect experiment, the key relation used is:

$$eV_s = hf - \phi$$

### 1. Uncertainty in Planck's Constant ( $h$ )

From the linear relation  $V_s = \frac{h}{e}f - \frac{\phi}{e}$ , we obtain  $h$  from the slope of a  $V_s$  vs.  $f$  graph:

$$h = e \cdot \text{slope}$$

Thus, the uncertainty in  $h$  is given by:

$$\Delta h = e \cdot \Delta(\text{slope})$$

### 2. Uncertainty in Work Function ( $\phi$ )

The uncertainty in  $\phi$  is:

$$\Delta\phi = e \cdot \Delta(\text{intercept})$$

### 3. Propagation of Uncertainty in Stopping Potential (Due to problem in apparatus readings account for this part)

If the stopping potential  $V_s$  is measured with an uncertainty  $\Delta V_s$ , it directly affects the calculated kinetic energy:

$$\Delta(KE) = e \cdot \Delta V_s$$

### 4. Propagation of Uncertainty in Frequency

This affects the energy of incident photons:

$$\Delta E = h \cdot \Delta f$$



## 5. Least Squares Regression Errors

When fitting a line to  $V_s$  vs.  $f$  data, uncertainties arise in slope ( $m$ ) and intercept ( $c$ ). These are calculated from standard formulas:

$$\Delta m = \sqrt{\frac{1}{n-2} \cdot \frac{\sum (y_i - mx_i - c)^2}{\sum (x_i - \bar{x})^2}}, \quad \Delta c = \Delta m \cdot \sqrt{\frac{\sum x_i^2}{n}}$$

## 6. Total Uncertainty in $h$

Combining statistical and instrumental errors, the total uncertainty in  $h$  can be written as:

$$\Delta h_{\text{total}} = \sqrt{(\Delta h_{\text{fit}})^2 + (\Delta h_{\text{instr}})^2}$$

## Result

By this experiment, we have figured out the values of Planck's constant as given in the analysis table. It is quite near to acceptable values. For the inverse square law, we got a slope of -1.6093, but it should be -2 (log current vs. log distance). This could be because of the non-point size of the light source and possible problems in the apparatus and color filter, as we have observed the visibility of other colors from the filter. Additionally, we are getting different stopping potentials when changing the distance, which shouldn't happen.

## Precautions

S.No	Precaution
1	This instrument should be operated in a dry, cool indoor space.
2	The instrument should be kept in a dust-proof and moisture-proof environment. If there is dust on the phototube, color filter, lens, etc., clean it using absorbent cotton with a few drops of alcohol.
3	The color filter should be stored in a dry and dust-proof environment.
4	After finishing the experiment, remember to switch off power and cover the drawtube with the lens cover provided. The phototube is a light-sensitive device, and its sensitivity decreases with exposure to light due to aging.

**Table 9.3:** Precautions for the Experiment

## MILLIKAN'S OIL DROP

### Aim

Millikan's oil drop experiment aims to determine the elementary electric charge ( $e$ ) by measuring the charge on tiny oil droplets suspended in an electric field. This experiment provides direct evidence for the quantization of electric charge and enables the calculation of the fundamental charge of an electron. By analyzing the motion of charged oil droplets under the influence of gravity and an electric field, the experiment allows for the precise determination of the charge carried by each droplet, ultimately confirming that charge exists in discrete packets of a fundamental unit.

### Theory

Consider a spherical oil droplet of radius  $r$  and density  $\rho$  falling under the gravitational force. This droplet in air is acted upon by a constant force and soon reaches a terminal velocity given by Stokes' law,  $F_D = 6\pi\eta r v_f$ , where  $\eta$  is the coefficient of viscosity of air and  $v_f$  is the terminal velocity during the fall. The gravitational and buoyancy forces acting on the droplet are balanced by  $F_D$ :

$$\frac{4}{3}\pi r^3 \rho g - \frac{4}{3}\pi r^3 \rho_a g = 6\pi\eta r v_f \quad (10.1)$$

Here,  $\rho_a$  is the density of air. Solving for the falling velocity  $v_f$ :

$$v_f = \frac{2}{9} \cdot \frac{r^2 g (\rho - \rho_a)}{\eta} \quad (10.2)$$

If the droplet carries a charge  $ne$  and is moving upward with terminal velocity  $v_r$ , under the influence of an electric field  $E = V/d$  between the parallel plates, the force balance becomes:

$$\frac{4}{3}\pi r^3 (\rho - \rho_a) g + 6\pi\eta r v_r = \frac{Vne}{d} \quad (10.3)$$

Solving for  $ne$ :

$$ne = \frac{6\pi\eta r d}{V} (v_r + v_f) \quad (10.4)$$

Dividing Eq. (4) by Eq. (2):

$$ne = \frac{4\pi}{3} \cdot \frac{gd}{V} (\rho - \rho_a) r^3 \left( 1 + \frac{v_r}{v_f} \right) \quad (10.5)$$

This derivation assumes that:

- The droplets move slowly (so Stokes' law applies),
- There is no slippage at the surface,
- The medium is continuous and uniform.

Since droplet radii are very small (on the order of 1 micron), these assumptions begin to break down. To correct for the effect of air molecule free path (non-continuum effects), the terminal velocity is corrected as:

$$v_f = \frac{2gr^2}{9\eta}(\rho - \rho_a) \left(1 + \frac{c}{Pr}\right) \quad (10.6)$$

where  $c = 6.17 \times 10^{-8}$  m of Hg · m and  $P$  is atmospheric pressure (in mm Hg).

We define two new variables:

$$\xi = \frac{9\eta}{2g} \cdot \frac{v_f}{(\rho - \rho_a)} \quad (10.7)$$

$$\zeta = \frac{c}{2P} \quad (10.8)$$

Using Eqs. (7) and (8), Eq. (6) becomes a quadratic in  $r$ :

$$r^2 + 2\zeta r - \xi = 0 \quad (10.9)$$

Solving the quadratic gives:

$$r = -\zeta + \sqrt{\zeta^2 + \xi} \quad (10.10)$$

Once  $r$  is calculated, charge  $ne$  is obtained by substituting into Eq. (5).

## Balancing Method

In the balancing method, the droplet is stationary ( $v_r = 0$ ), and the upward electric force balances gravity:

$$ne = \frac{4\pi}{3} \cdot \frac{gd}{V_b}(\rho - \rho_a)r^3 \quad (10.11)$$

Where  $V_b$  is the balancing voltage.

## Observations

The raw data were collected using the dynamic method (measuring falling and rising times under various voltages) and the balancing method (measuring falling times and balancing Voltages). We need to calibrate the length between the lines on the panel with the actual length inside the oil container. We are also using magnification, so we need to take care of the relation as well.

## Analysis

### Dynamic Method

S.No.	F.Fall Time	Rise Time	L (m)	Length (m)	Voltage (V)	$V_f$ (m/s)	$\xi$ ( $\times 10^{-13}$ )	$r$ (m)	$r^3$ (m <sup>3</sup> )
1	29.47	16.815	2	3.14E-03	352	1.07E-04	9.75	9.45E-07	8.44E-19
2	18.8025	5.6775	1	1.57E-03	121	8.35E-05	7.64	8.32E-07	5.76E-19
3	12.734	3.286	2	3.14E-03	133	2.47E-04	22.6	1.46E-06	3.11E-18
4	18.356	7.422	2	3.14E-03	133	1.71E-04	15.7	1.21E-06	1.76E-18
5	14.15	4.963	2	3.14E-03	120	2.22E-04	20.3	1.38E-06	2.64E-18
6	33.42	8.0475	2	3.14E-03	120	9.40E-05	8.60	8.85E-07	6.93E-19
7	22.64	5.742	2	3.14E-03	120	1.39E-04	12.7	1.08E-06	1.27E-18

**Table 10.1:** Free fall, rise time, voltage, and derived radii for droplets using the dynamic method.

Droplet No.	$T$	Charge $q$ (C)	$ne$	$ne/n_{ef}$	Nearest Integer
1	2.75	1.25E-18	7.83	1.00	1
2	4.31	3.90E-18	24.34	3.11	3
3	4.88	2.17E-17	135.22	17.27	17
4	3.47	8.76E-18	54.70	6.98	8
5	3.85	1.61E-17	100.59	12.84	15
6	5.15	5.66E-18	35.31	4.51	Ignored
7	4.94	9.98E-18	62.27	7.95	8

**Table 10.2:** Computed Charge

### Balancing Method Data

Droplet No.	Free Fall Time	L (m)	Length (m)	$V_b$ (V)	$V_f$ (m/s)	$\xi$ ( $\times 10^{-12}$ )	$r$ (m)	$r^3$ (m <sup>3</sup> )	$T$
1	4.2	2	3.14E-03	132.33	7.48E-04	6.70	2.55E-06	1.65E-17	1.00
2	10.1	2	3.14E-03	192	3.11E-04	2.79	1.63E-06	4.30E-18	1.00
3	21.616	2	3.14E-03	120	1.45E-04	1.30	1.10E-06	1.33E-18	1.00
4	22.0075	2	3.14E-03	124	1.43E-04	1.28	1.09E-06	1.29E-18	1.00
5	10.642	2	3.14E-03	147	2.95E-04	2.65	1.58E-06	3.97E-18	1.00

**Table 10.3:** Free fall time, voltage, and derived radii for droplets using the balancing method.

Droplet No.	Charge $q$ (C)	$ne$	$ne/n_{ef}$	Nearest Integer	$ne/n_{ef}$ Value
1	2.37E-17	148.02	11.99	12.5	Ignored
2	4.26E-18	26.61	2.16	2	13.31
3	2.10E-18	13.12	1.06	1	13.12
4	1.98E-18	12.34	1.00	1	12.34
5	5.14E-18	32.07	2.60	2.5	Ignored

**Table 10.4:** Computed charge and quantization for droplets using the balancing method.

## Uncertainties

The most obvious issue with this apparatus is that we don't know whether the camera is calibrated to the parallel plates.

In the manual, it is written that the distance between the parallel plates is 5mm and the distance between the two lines is 1mm, but as far as our analysis goes, it is not possible.

The size of 1 droplet is roughly  $10^{-6}m$  and dividing the distance between two lines (1mm) by the diameter of the droplet, that is roughly  $10^{-6}m$ . It gives the value of 1000 drops.

So, between two lines, ideally 1000 drops should fit if stacked one over another. That is impossible with Zoom; that's why the distance given in the manual is wrong.

So, for this, we have to calibrate the screen with the upper and lower plate and need to define ratios. Then we need to divide the distance by the zoom (like 30x in this case).

## Result

From the analysis, we were getting comparatively larger drops, due to which we couldn't get the charge of a single electron; for this, we need to derive things back from the theoretical model. Then we need to verify the existence of such drops and their free fall, rise time, with their respective voltage. Because we have seen the calibration, we don't know whether the distance is correct or not. We need to calibrate everything and check its validity.

To get fewer charges, we need to see drops at low voltages, slow-moving droplets (upwards) at lower voltages are better for analysis.

## Precautions

1. Use oil spray sparingly to avoid clogging and crowding the view with too many droplets.
2. Do not lose sight of the droplet during measurements; focus and practice help.
3. Choose droplets with small charge ( $1e-3e$ ) for easier analysis and clearer results.
4. Apply voltage slowly to avoid sudden jumps or loss of the droplet.
5. Wait for the droplet to reach terminal velocity before timing.
6. Keep the chamber temperature stable to avoid changes in air viscosity.
7. Calibrate the measurement scale carefully before taking data.



