Thermal Radiation

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This experiment was performed in collaboration with *Danielle Hodgkinson*.

Abstract

The Stefan-Boltzmann law was verified at both low temperatures ($25℃ - 130℃$) and high temperatures (1000℃-2500℃).
The inverse-square law of intensity was investigated using a filament bulb and varying the position of the thermopile relative to the bulb over the range of distances 47-837mm.
The exponential behaviour of absorption of radiation was investigated keeping a thermopile a fixed distance from a filament bulb and successively adding up to 12 layers of PTFE tape.

1. Introduction

Radiative heat transfer plays a crucial role in medical physics. For example it has applications in designing more accurate thermometers such as the temporal artery thermometer [1]. These kinds of thermometer rely on the infrared radiation measured from the skin. An understanding of thermal radiation is not only important in measuring temperatures but regulating them as well. For example a premature baby can experience dangerous levels of cooling if the temperature of the incubator walls are not properly regulated [2]. Thorough control of heat transfer also plays a part in quantum computers where some systems have typical operating temperatures of 20millikelvin [3]

2. Theory

2.1 Inverse square law

In the inverse square law experiment we investigate how the intensity changes with respect to the separation from the source. As the radiation travels from source to detector the radiation propagates radially outwards forming the surface area of a sphere. Thus the intensity measured at a distance r away from the source is proportional to the inverse of the surface area of a sphere with radius r.

$$I \propto r^{-2}$$

2.2 Stefan-Boltzmann law

The following is based upon University Physics [4]

The rate of energy radiated from a surface is given by the following equation:

$$H = Ae\sigma T^4$$

Where H is the radiated power, A is the surface area, σ is Stefan's constant and T is the absolute temperature of the surface. The quantity e is the emissivity of the surface and can only take a value between 0 and 1. A radiator with e equal to 1 is known as a blackbody.

As a body is radiating at a temperature T, the surroundings also radiate and the body absorbs some of this radiation. If the body is in thermal equilibrium with its surroundings, $T = T_s$, the rates of radiation and absorption must be equal.

In order for this to hold, the rate of absorption must be given by $H = Ae\sigma T_s^4$

Therefore the net radiation from the body is given by the following equation.

$$H_{net} = Ae\sigma(T^4 - T_s^4)$$

2.3 Wien's law

The spectrum of thermal radiation is given by the Planck radiation law and has a peak wavelength, λ_m, whose value depends on the temperature according to Wien's displacement law $\lambda_m T = k$.

Where $k = 2.90\times10^{-3}$mK.

2.4 Absorption of radiation

Attenuation of radiation generally involves absorption and scattering. For a monochromatic source of intensity I_0, the intensity I transmitted by a thickness d of material can be written as $I = I_0 e^{\alpha d}$ where α is the absorption coefficient which generally has a part due to absorption and a part due to scattering.

From a white light source like a filament bulb a range of wavelengths is emitted, however we can treat the source as though it emits a single wavelength, the peak wavelength, given by Wien's law.

3. Experimental method

3.1 Stefan-Boltzmann at low temperatures

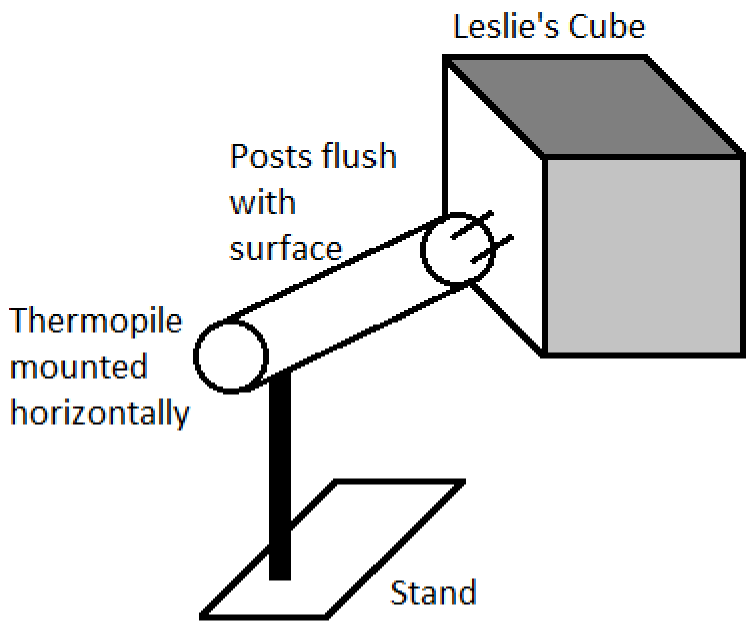

Figure 1: Low temperature set up

Figure 1 shows the experimental set up for the low temperature experiment.

The Leslie cube is heated using an internal filament light bulb. Each surface of the Leslie's cube has a thermistor imbedded. We were unable to directly measure the temperature of the surfaces therefore we instead measured the resistance using a digital meter. These readings were compared against the calibration values of resistance against temperature given. To ensure all measurements were taken as consistently as possible, for every measurement we made sure the two posts on the thermopile were flush against the surface of the Leslie's cube perpendicular to the surface. This ensured that all measurements were taken at the same angle at a fixed distance. We also took care to make sure measurements were taken at the centre of the face. This is because the cube was not well sealed at the edges and the radiation received was therefore stronger in those areas. We heated the Leslie's cube to near its maximum temperature and took our measurements as the cube cooled.

We produced a calibration graph from the calibration table of results shown in Figure 2 below.

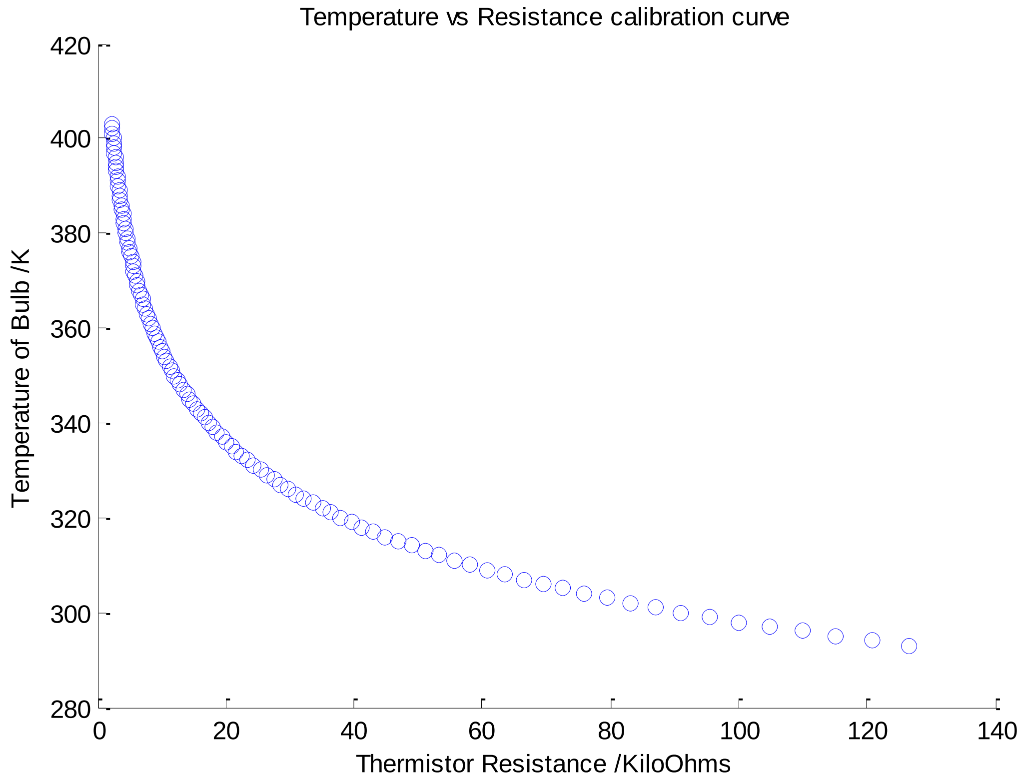

Figure 2: Leslie's cube calibration graph

We decided to linearise the calibration curve as seen in Figure 3. This was because we felt that fitting a best fit curve and reading our values against it would introduce additional errors. Linearising the graph allowed us to obtain a relationship between the temperature and resistance and thus calculate values of temperature from the resistance.

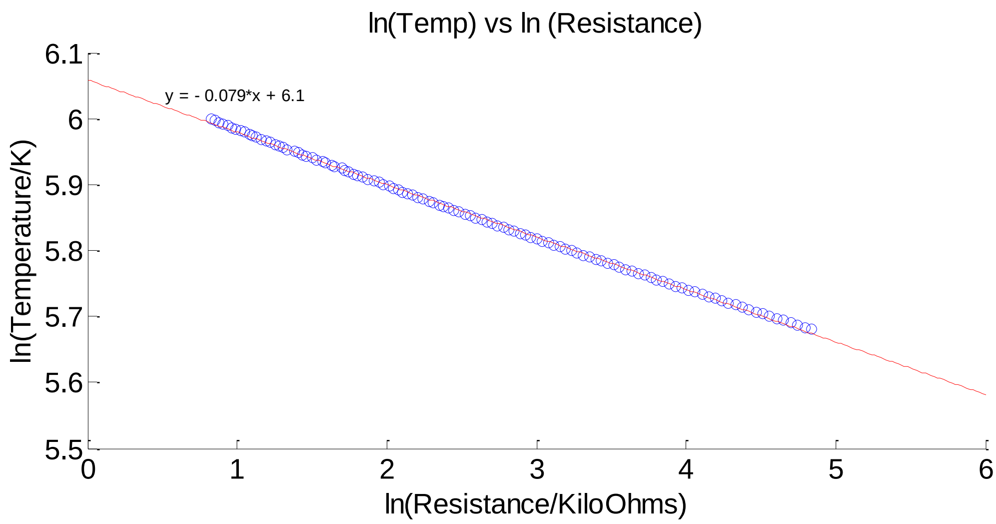

Figure 3: Linearised Leslie's cube calibration graph

We recorded the resistance and received power at given time intervals over the range 25℃ – 130℃. Due to the experiment being carried out at such a low temperature; we could not ignore the temperature of the surroundings. The temperature of the room was therefore recorded as 25℃.

3.2 Stefan-Boltzmann at high temperatures

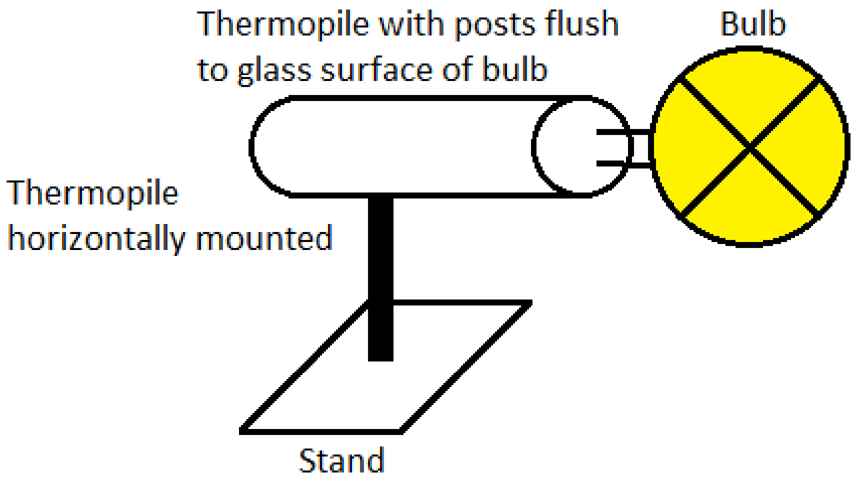

Figure 4: High temperature set up

Figure 4 shows the high temperature experimental set up. For the high temperature experiment we used a tungsten-filament bulb. At these high temperatures we could ignore the temperature of the surroundings as they would have a negligible effect on the power output. The resistance of the bulb was calculated by taking measurements of the current and potential difference across the bulb. We could then use resistivity versus temperature values to work out the temperature of the bulb.

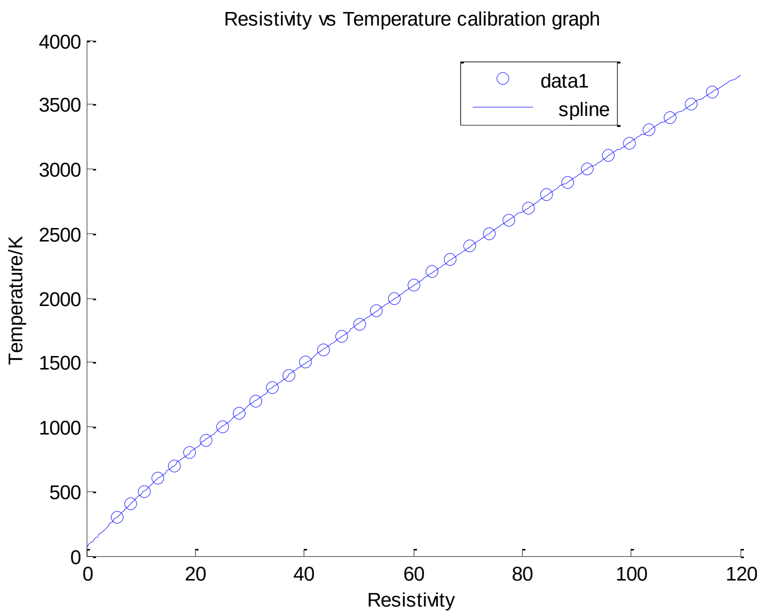

Figure 5: High temperature calibration graph

Figure 5 above shows the calibration graph produced from the resistivity and temperature tables given. This graph was then linearised as in Figure 6 below to allow us to calculate the temperature of the filament bulb given the resistance.

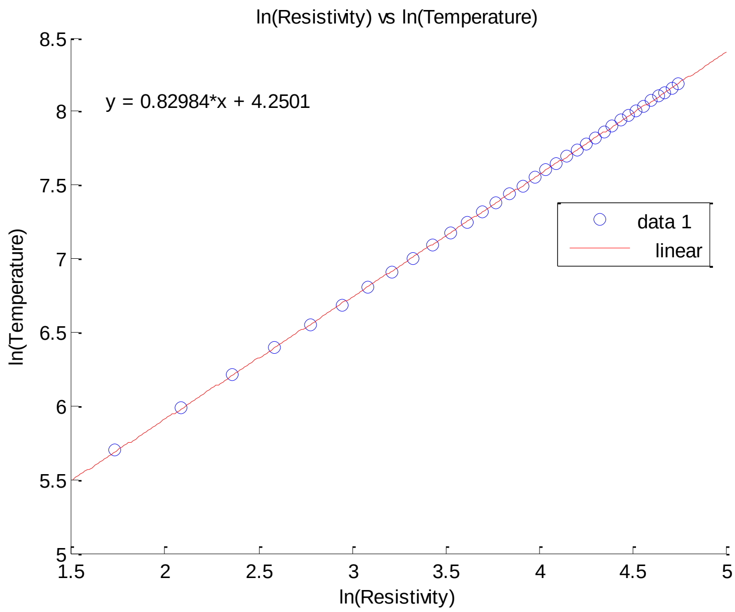

Figure 6: Linearised high temperature calibration graph

3.3 Inverse Square Law

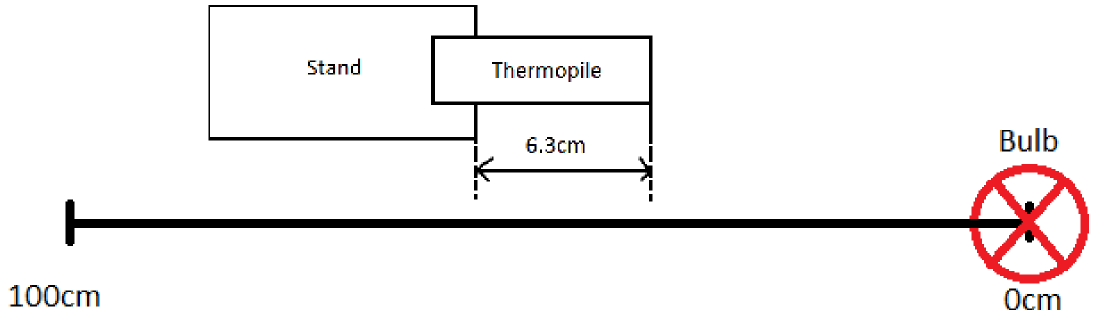

Figure 7: Inverse square law set up

Figure 7 shows the setup for the inverse square law experiment.

The room was dimmed as much as possible as an attempt to reduce interference with the experiment. We fixed a 100cm ruler with 1mm divisions with the zero-point of the ruler fixed against the centre of the bulb.

We mounted the thermopile horizontally, level with the centre of the bulb.

Measurements were taken over the range 37-837mm.

3.4 Absorption of Radiation

For this experiment, the setup was identical to figure 4, however this time the power of the bulb was kept constant and layers of PTFE tape were applied over the sensor of the thermopile as shown in Figure 8. The drop in the voltage of the thermopile was recorded as the thickness of PTFE tape increased.

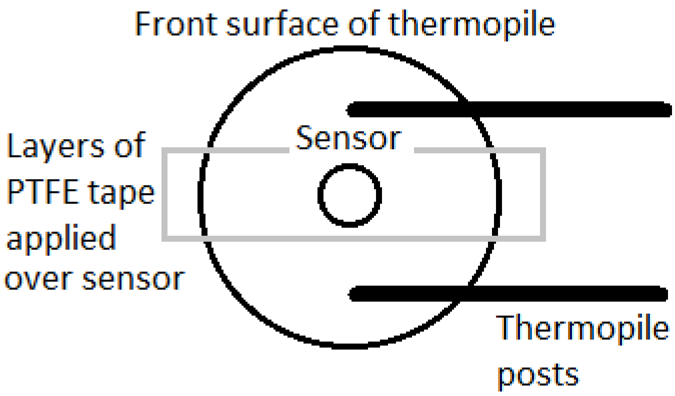

Figure 8: Application of PTFE tape

4. Results

4.1 Low Temperature

Error propagation: For the low temperature experiment we measured the potential difference across the thermopile and the resistance on the bulb of the Leslie's cube. This means error could be introduced through the calibration curve and the reading of the thermopile output. We assumed no error in the calibration curve, so our only uncertainty was in the measurement of the potential difference across the thermopile. No repeat measurements were taken for this experiment due to time constraints therefore the uncertainty in the measured potential difference was simply half the smallest division ±0.05mV. Figure 9 below shows the results for the low temperature white surface.

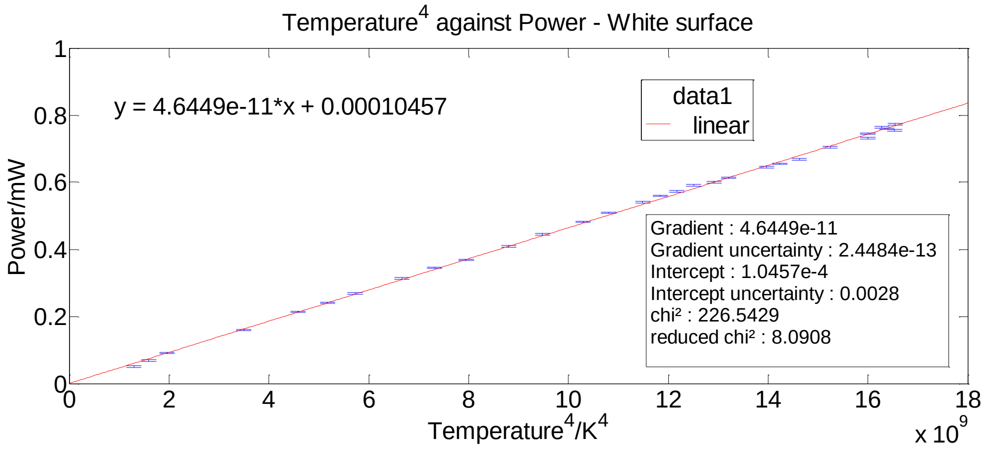

Figure 9: Low temperature white surface

4.2 High Temperature

As in the low temperature experiment the uncertainty in the potential difference across the thermopile was given by half the smallest division ±0.05mV.

For this experiment the relationship $H \propto T^n$ was assumed, therefore a log-log plot of temperature against voltage (which is proportional to power) was appropriate as seen in Figure 10 below.

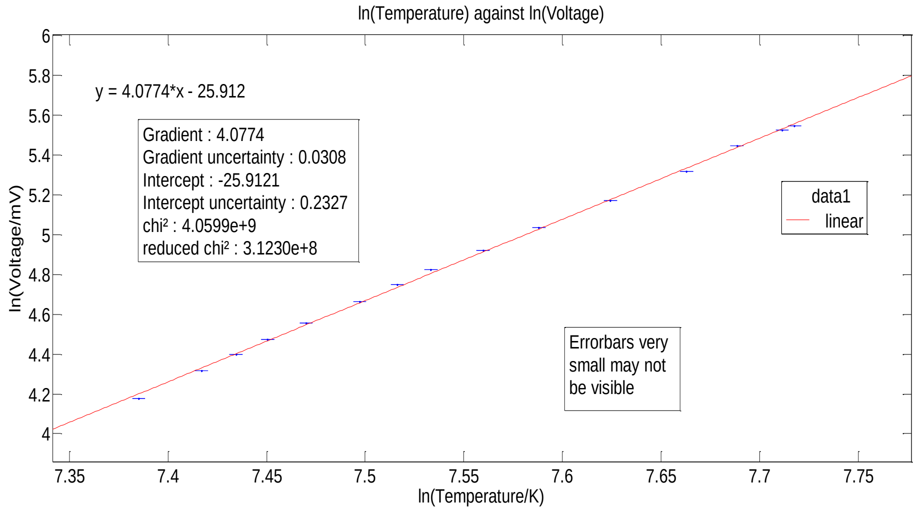

Figure 10: High temperature results

4.3 Inverse square law

For this experiment we had insufficient time to take repeat measurements for each distance. Therefore the uncertainty in the measured potential difference across the thermopile, σ_V, was simply half of the smallest division : ±0.05 mV.

Due to error propagation, the uncertainty in $\ln V$ is given by $\frac{\sigma_V}{V}$ which is what was used for the error bars seen in Figure 11 and Figure 12 below.

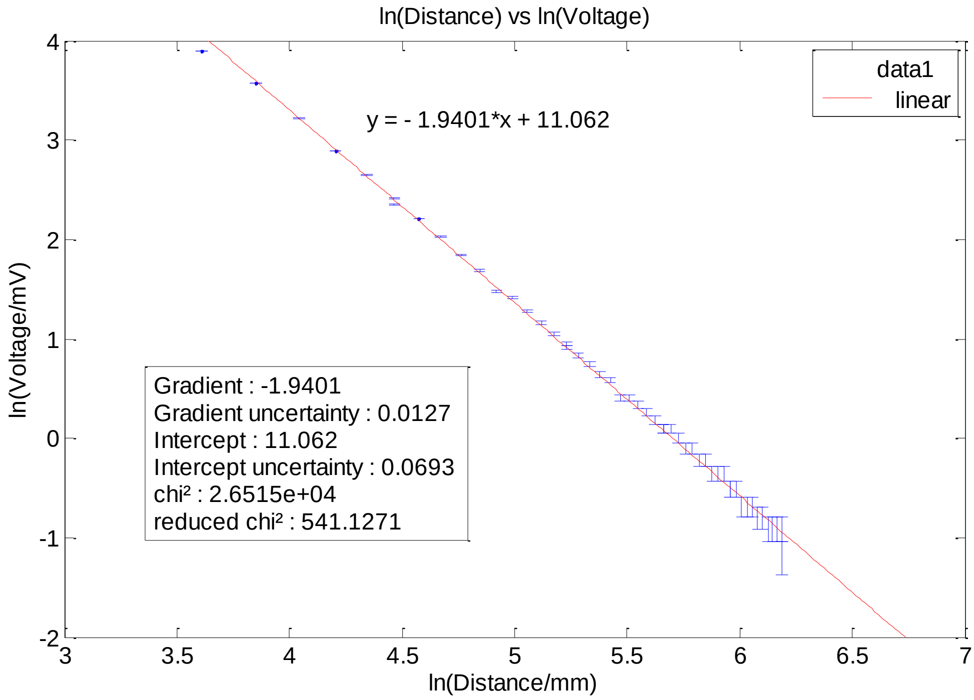

Figure 11: Before removal of data

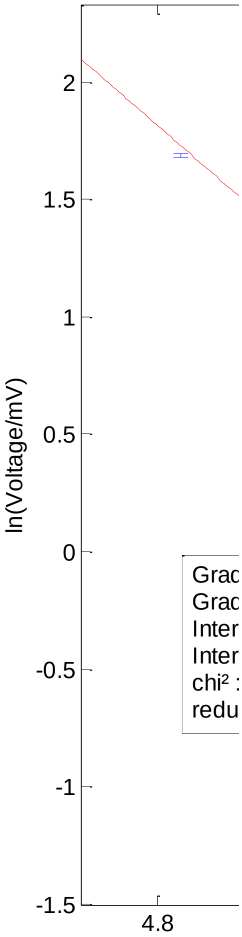

Figure 12: After removal of anomalies

4.4 Absorption of radiation

For the absorption of radiation we want to find out if the intensity decays exponentially with thickness of PTFE tape. If we assume the intensity I follows the relationship

I= $I_0 e^{-\alpha d}$ where $I \propto V$, then it follows that $V = V_0 e^{-\alpha d}$. Therefore taking logs of both sides we obtain $\ln V = \ln(V_0 e^{-\alpha d})$ which reduces to $\ln V = -\alpha d + \ln V_0$.

Therefore plotting Thickness against ln (Intensity/mV) will give us a straight line if the intensity does decay exponentially.

Figure 13 below shows the straight line obtained, and the absorption coefficient α is obtained as the negative of the gradient of the line.

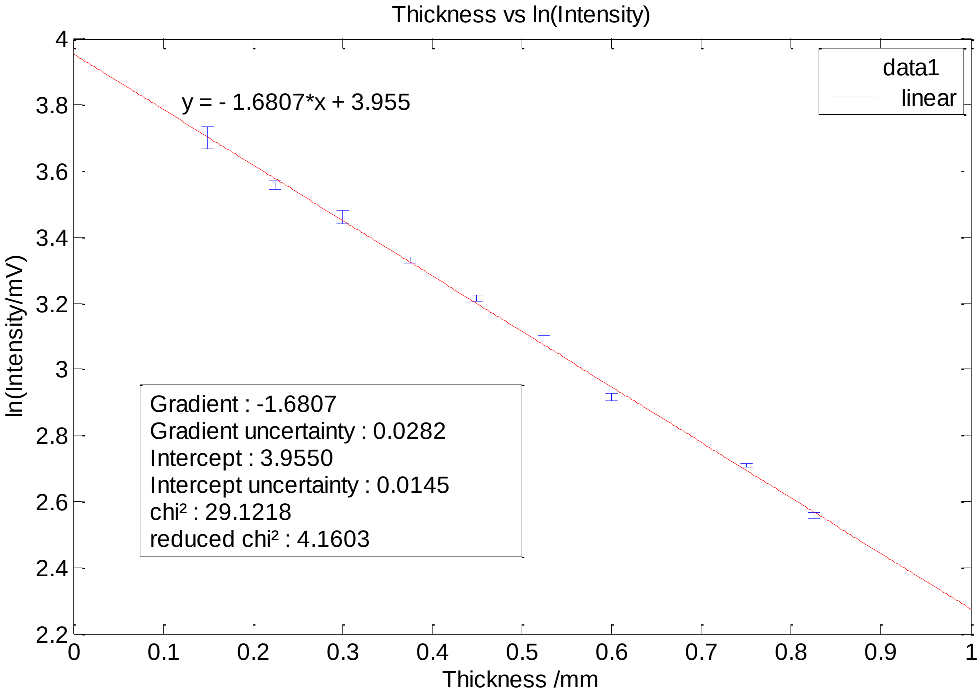

Figure 13: Absorption of radiation results

5. Discussion and Conclusion

5.1 Low temperature

For the low temperature results, we were able to show that the power increases linearly with temperature to the fourth power which can be seen from Figure 9. The reduced χ^2 value of around 8 shows that the best-fit line is a reasonably good fit for 30 data points, so we can be reasonably confident that we have verified the Stefan-Boltzmann law.

5.2 High temperature

By eye, the graph obtained shown in Figure 10 appears to be a good fit. However since the errors in $\ln V$ is equal to $\frac{\sigma_v}{V}$ the errors get smaller as V gets larger. This led to uncertainties that were far too small. So although our result of n=4.0774 is within three standard deviations of the accurate result, the χ^2 value is far too large to justify a good fit to the data.

5.3 Inverse Square Law

The value of n we obtained was accurate to the true value of -2 to within one standard deviation. This combined with the χ^2 value of 1.27 suggests that this experiment was a success. The line of best fit was a good fit to the data points and the uncertainty in our distance measurements seemed reasonable. Most of the data points that we removed were either close to the source or far away from the source. Our data points that were close to the source were probably inaccurate because at short distances from the source the bulb cannot be seen as a point source anymore. At points far away from the bulb, the received intensity was lower and as a result background disturbances will have a much larger effect on the results. For example although the room was dimmed other students were carrying out the experiment at the same time and their bulbs may have interfered with our own on these scales.

5.4 Absorption of Radiation

I think our data shows good evidence of exponential behaviour as we obtained a straight line with a reduced χ^2 value of 4.16 with 9 data points. This suggests that the line is a reasonable fit to the data and hence the intensity decays exponentially. One thing of note is that to obtain the results as in Figure 13, data points of lower thicknesses had to be removed. This suggests that at small thicknesses of PTFE tape the intensity decays according to some other relationship, perhaps linear. This might be due to the lightbulb emitting over a range of wavelengths as opposed to the ideal monochromatic wavelength assumed.

6. References

[1] Page 614 Young Freedman, University Physics, Pearson Education Limited Thirteenth Edition

[2] Page 636 Young Freedman, University Physics, Pearson Education Limited Thirteenth Edition

[3] http://www.dwavesys.com/tutorials/background-reading-series/introduction-d-wave-quantum-hardware accessed 05/02/15

[4] Page 635 Young Freedman, University Physics, Pearson Education Limited Thirteenth Edition

7. Length and Date

The length of this document is 1,922 words excluding captions.

The date of submission is 05/02/2015.