International Baccalaureate

PHYSICS

Extended Essay

The Relationship Between Temperature and Visible Thermal Radiation of an Incandescent Tungsten

Word count: 3966

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1. INTRODUCTION

1.1 Rationale

I have always been interested in how everyday objects like incandescent light bulbs can demonstrate key physics principles such as thermal radiation and electromagnetic waves. As a child, I was curious about the warm glow of light bulbs and how such a small object could produce both heat and light. Learning that this glow was the result of heating a tungsten filament sparked my desire to understand the process further. The conversion of electrical energy into both light and heat provides a simple yet powerful example of energy transformation.

What makes this topic interesting is how thermal radiation and electromagnetic waves are closely connected. As the filament heats up, the emitted radiation transitions from invisible infrared to visible light all depending on temperature. By manipulating something as straightforward as electrical power, we can observe this shift and better understand the physics behind it. This experiment allows me to explore concepts that have been part of my surroundings in a more scientific and structured way and illustrates how everyday observations are connected to broader scientific ideas.

1.2 Overview

In this experiment, I will explore the principles of thermal radiation by investigating the relationship between temperature and the visible radiation emitted by a heated object. I will collect experimental data on the current, resistance, and temperature of the filament as the voltage changes. Afterwards, I will compare the temperature values with secondary data and find the error in my calculations. Then, I will calculate the thermal radiation emitted by applying Stefan-Boltzmann's Law to analyze the results.

1.3 Theoretical Background Information

1.3.1 Thermal Radiation

Thermal energy is the collective motion of molecules within a system, representing the total kinetic energy of its particles.[1] Heat, on the other hand, transfers this thermal energy between systems due to temperature differences. The flow of heat always moves from regions of higher temperature to lower temperature and transfers energy through collisions of vibrating atoms until thermal equilibrium is achieved.[2] Heat transfer occurs via three main mechanisms: conduction, convection, and radiation.[3] In this study, visible thermal radiation will be investigated.

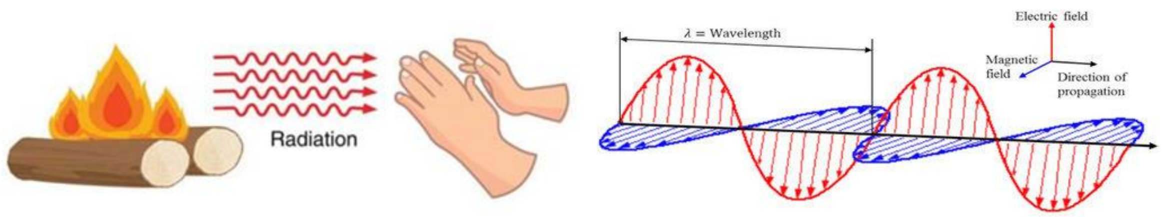

Figure 1. Heat transfer by radiation[4] through electromagnetic waves[5].

Radiation is the emission or transmission of energy through electromagnetic waves, which can propagate without needing a medium. Thermal radiation refers to the transfer of heat via these waves, emitted by particles of matter at the speed of light.[6] All matter with a temperature above absolute zero ($0K$ or -$273.15°C$) emits thermal radiation.[7]

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[1] Encyclopædia Britannica, (2024, December 16). *Thermal energy*, https://www.britannica.com/science/thermal-energy

[2] Beretta, Gian Paolo & Gyftopoulos, Elias, (2015), Journal of Energy Resources Technology. 137. 021004. 10.1115/1.4026382.

[3] E.A. Kay, (2007, September 2), 5.3.3 Heat transfer and heat loss, Advanced Concrete Technology https://www.sciencedirect.com/science/article/abs/pii/B9780750656863502524

[4] Khayal, O. M. E. S. (n.d.), https://www.researchgate.net/figure/The-method-of-heat-transfer-by-radiation-Figure-4-below-shows-the-methods-of-heat_fig1_381424586

[5] Electromagnetic Waves. (n.d.). *Electromagnetic Wave and Its Main Features Diagram*. https://www.researchgate.net/figure/Electromagnetic-wave-and-its-main-features NOAA_fig20_303377557/actions#reference

[6] Miller, G. E. (2012, July 27). *14.3.5 Thermal Radiation*. Introduction to Biomedical Engineering (Third Edition). https://www.sciencedirect.com/science/article/abs/pii/B9780123749796000149

[7] Sokolova, I. (2008, August 6). *Radiation*. Encyclopedia of Ecology. https://www.sciencedirect.com/science/article/abs/pii/B9780080454054005528

The higher the temperature of an object, the greater the intensity of the radiation and the shorter the wavelength of the emitted wave. As an electrical current is applied to the filament, it heats up, and the energy is radiated away in the infrared and visible light range.

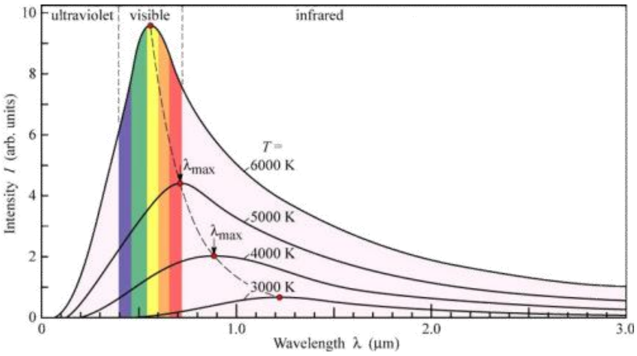

Figure 2. The relationship between temperature (K), wavelength (λ), and intensity (W/m^2) of thermal radiation at different spectrums.[8]

1.3.2 Incandescent Light Bulb and Tungsten Filament

An incandescent light bulb contains a tungsten filament, a wire that heats up when a voltage is applied. When a current passes through the filament, it heats up due to resistance reaching temperatures quite high for the filament such that it can emit light according to Joule heating. This light is a form of thermal radiation, as the intense heat excites the atoms within the tungsten and causes them to release energy as visible light.[9]

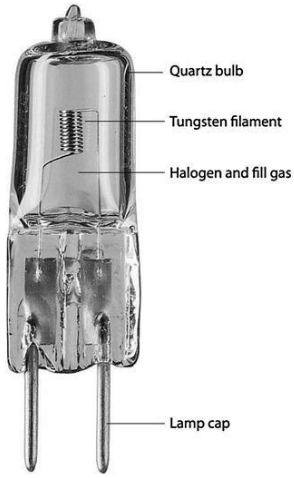

Figure 3. Light bulb with tungsten filament[10]

[8] Aprilia, Riana & Alifaturrohmah, Marisa & Purnama, Gilang & Wahyuni, Siti. (2022). The Examination of the Wien's Displacement Constant with Simulation and Simple Numerical Approaches. Physics Communication. 6. 71-78. 10.15294/physcomm.v6i2.39821.

[9] Jouhara, H. (2021, January 7). *2.4 Joule heating*. International Journal of Thermofluids. https://www.sciencedirect.com/science/article/pii/S266620272100001X

[10] Bommel, W. van. (1970, January 1). Halogen lamp. SpringerLink. https://link.springer.com/referenceworkentry/10.1007/978-3-642-27851-8_126-8

1.3.3 Emissivity, Black and Grey Body

Emissivity (ε) quantifies how effectively a material radiates thermal energy compared to an ideal black body. It is defined as the ratio of thermal radiation emitted by the material to the thermal radiation emitted by a perfect black body at the same temperature.[11] Emissivity values can vary between 0 and 1:

- A value of 1 signifies a perfect black body, which radiates the maximum amount of thermal energy possible at a given temperature.
- Conversely, a value of 0 represents an ideal reflector that does not emit any thermal radiation.

Real objects, including the tungsten filament are not perfect black bodies. Instead, they are considered grey bodies which emit less radiation than a black body at the same temperature. Grey bodies have emissivity values less than 1 but greater than 0, depending on the material properties.[12]

For tungsten, the emissivity changes as temperature increases. Since the temperature values in this experiment range between $300K$ and $400K$, and the "***emissivity of tungsten at 300 K is approximately 0.03***"[13], any emissivity variations within this limited range are minimal. Furthermore, finding precise emissivity values for such specific temperatures is difficult. Therefore, 0.03 will be accepted for the emissivity of tungsten in calculations within this temperature range and its limitation will be discussed in evaluation.

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[11] NPL Website. (n.d.). What *is emissivity and why is it important?* https://www.npl.co.uk/resources/q-a/why-is-emissivity-important

[12] Zwinkels, J. C. (2015). Blackbody and blackbody radiation. Encyclopedia of Color Science and Technology, 1–5. https://doi.org/10.1007/978-3-642-27851-8_370-1

[13] Seos Project Website (n.d) 2. Thermal radiation Grey and colored emitters/ Incandescent lamps. https://seos-project.eu/earthspectra/earthspectra-c02-p11.html#:~:text=The%20emissivity%20of%20tungsten%20depends,C%20(or%202500%20K).

1.3.4 Stefan-Boltzmann Law

The Stefan-Boltzmann Law states that the total amount of energy emitted by a perfect black body per unit area is proportional to the fourth power of its absolute temperature.[14] In simpler terms, as the temperature of an object increases, it radiates more energy. Moreover, this increase in energy output grows significantly with even small temperature increases.

$$\boldsymbol{P = \sigma \varepsilon A T^4} \qquad [\mathbf{14}]$$

Where:

$\boldsymbol{P}$: Total radiant power emitted by the body (W)

$\boldsymbol{\sigma}$: Stefan-Boltzmann constant ($5.67 \times 10^{-8} W/m^2 \times K^4$)

$\boldsymbol{\varepsilon}$: The emissivity of the material

$\boldsymbol{A}$: Surface area of the light bulb (m^2)

$\boldsymbol{T}$: Absolute temperature (K)

1.4 Research Question

To what extent does altering the voltage ($1V$ increments between $1V$-$11V$) applied to an incandescent light bulb with a tungsten filament in a circuit impacts the relationship between temperature (K) and total visible emitted radiant power (W), according to Stefan-Boltzmann's Law?

[14] Tsokos, K. A. (2023). *Physics for the IB diploma. Coursebook*. Cambridge University Press.

1.5 Hypothesis

As the applied voltage increases, the electrical power supplied to the tungsten filament also increases, leading to a rise in the filament's temperature due to higher energy dissipation as heat. According to Stefan-Boltzmann's Law, the total radiant power emitted is directly proportional to the fourth power of the absolute temperature. This means even a small increase in temperature will result in a significant rise in the emitted radiant power. Since the filament emits more visible light as it gets hotter, the experiment is expected to show a steep increase in visible radiant power with increasing voltage.

2. METHODOLOGY

2.1 Key Variables

Experimental Variables	Name of the Variable	Method of Measurement
Independent Variable	The voltage applied to the incandescent tungsten	Voltage is adjusted between $1V$ to $11V$ by incrementing $1V$ on the DC power supply.
Dependent Variable	The temperature of the incandescent tungsten	The thermometer section of the multimeter.
	The total emitted visible radiant power of tungsten	Calculated by applying Stephan-Boltzmann Law.

Table 1. Independent and Dependent Variable/Measurement Methods.

Experimental Variables	Name of the Variable	Reason
Controlled Variables	Voltage Application Rate	The voltage increment is $1V$ at each step for accurate comparisons.
	Filament Material and Dimensions of the Tungsten	The same tungsten filament with consistent physical properties is used throughout the experiment to avoid variations in resistance and emissivity.
	Measurement Time	Every temperature is measured after a time limit of 1 minute after power is supplied.
	Power Supply (DC)	The power supply is stable and capable of delivering consistent and accurate voltage without fluctuations.
	Measurement Tools	The same apparatus is used for the entire experiment to ensure consistency in data collection.
	Circuit Configuration	The circuit configuration is kept constant to ensure consistent electrical parameters except for the manipulated voltage.
Uncontrolled Variables	Cooling Time	As the voltage increases, the temperature rises accordingly. Consequently, the time required for the system to reach thermal equilibrium also increases due to the additional heat that needs to be dissipated. Therefore, the cooling time for each voltage is not a fixed value. It increases as the voltage rises.
	Measurement Uncertainty	Variations in the precision and accuracy of measurement tools could lead to small errors in recorded data.
	Ambient Temperature	Small variations in the surrounding environment could influence the filament’s ability to dissipate heat, impacting the temperature and thus the radiant power.
	Filament Geometry and Surface Condition	Small inconsistencies in the filament’s surface area or shape could cause slight variations in the emitted power.

Table 2. Controlled and Uncontrolled Variables and Reasons.

2.2 Apparatus

Material	Purpose	Size	Unit
Incandescent tungsten filament bulb (DC)	Emits visible radiant power when heated by the flow of electricity. It is used to represent a blackbody.	35W, GY6, 12V	-
DC Power supply	Supplies electrical energy (1V-11V) to the tungsten filament, allowing control over the voltage applied.	1	Volt (V)
Rheostat	Adjusts the resistance in an electric circuit. By changing the resistance, it regulates the voltage and current in the circuit	1 (20Ω, 5A)	Ohm (Ω)
Multimeter	One multimeter is employed to measure the resistance of the tungsten filament, ensuring that its resistance remains relatively stable throughout the experiment.	1 (±0.001)	Ohm (Ω)
	The other multimeter features a thermometer function and is used with thermocouples to measure the temperature of the tungsten filament.	1 (±0.1)	Celsius Degrees (°C)
Voltmeter	Measures the voltage across the incandescent tungsten filament.	1 (±0.001)	Volt (V)
Ammeter	Measures the electric current flowing through the incandescent tungsten filament	1 (±0.001)	Current (A)
Black Cardboard	Inside of the foam box is covered with black cardboard. Since the black colour does not reflect light, it minimizes reflections to simulate an ideal blackbody environment.	2(32cm×11cm) 2(12 cm×11cm) 1(32cm×12cm) Rectangles	-
White Foam Box	The foam box represents the medium in which the light emitted from a blackbody travels. Since the white colour reflects the light, it reduces interference from outside sources.	Height:32cm Depth:11cm Width:12cm	-
Crocodile Cables	Used for making temporary electrical connections between the filament, power supply, and measurement devices. They provide a convenient way to connect and disconnect components quickly.	8	-
Non-Transparent Tape	Used to secure and position the tungsten into the foam box.	1	-
Scissors	For cutting pieces of black cardboard.	1	-
Glue	To stick the black cardboard pieces onto the inside surface of the foam box.	1	-

Table 3. The function, size, and unit of the apparatus.

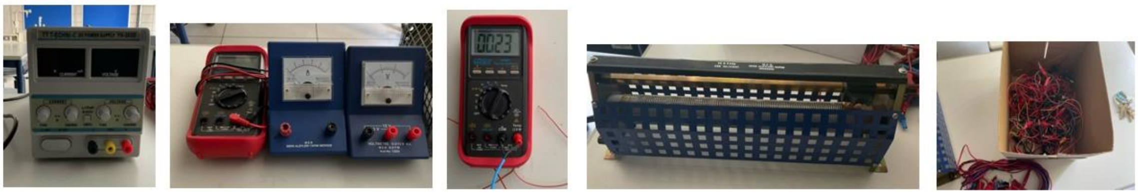


Figure 4. Apparatus for circuit connection (DC power supply, multimeter, ammeter, voltmeter, multimeter with thermocouples, rheostat, and crocodile cables respectively.)

2.3 Procedure

2.3.1 Setup of the Foam Box and Incandescent Light Bulb

- Cut two 32cm×11cm, two 12cm×11cm, and one 32cm×12cm rectangle from the black cardboard using scissors.
- Attach the cardboard rectangles to the inner surfaces of the foam box, ensuring full coverage.
- Obtain an incandescent light bulb with a tungsten filament.
- Wrap two cables, one white and one orange, around the opposite ends of the light bulb (one cable for the negative terminal and the other for the positive terminal).
- Securely twist the wires together.
- Make two holes (diameter of 0.25) in one of the 12cm×11cm surfaces of the foam box.
- Insert the ends of the wires through the holes, each wire through a different hole and tape it onto the hole.
- Place the foam box on a table, with the light bulb oriented downwards and perpendicular to the surface.

Figure 5. Foam Box with the light bulb.

2.3.2 Circuit Connection

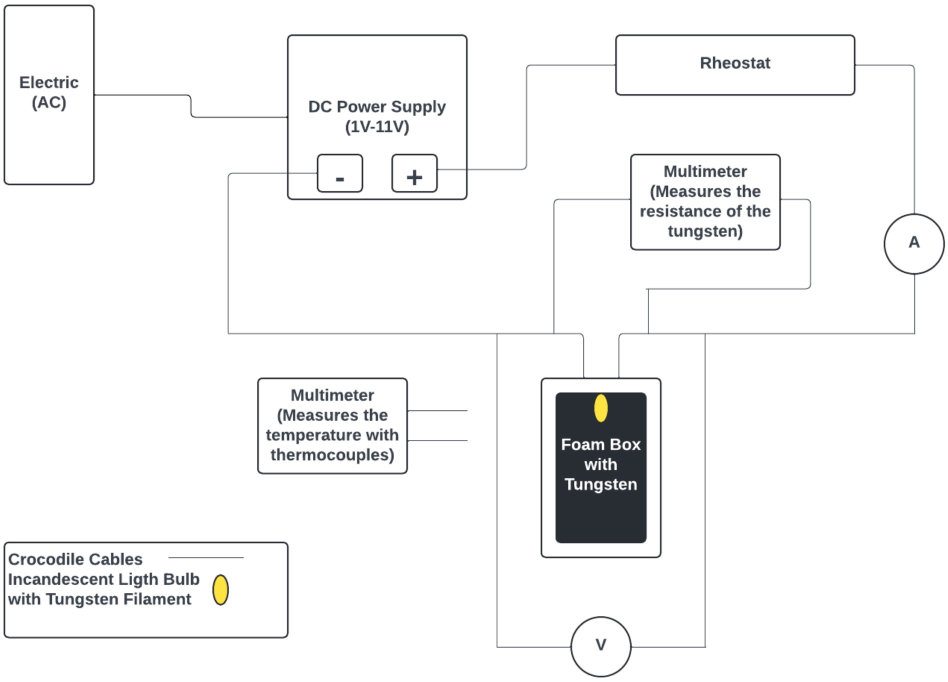


Figure 6. The diagram of the experimental setup

- Connect the positive side of the DC power supply to the rheostat and ammeter in series to the positive side of the wire of the light bulb with crocodile cables.
- Connect the negative side of the DC power supply to the negative side of the wire of the light bulb.
- Connect the voltmeter in parallel to the light bulb.
- Connect the multimeter that measures the resistance of the filament parallel to the light bulb.
- Ensure all connections are secure before powering up the circuit and be cautious of high temperatures and electrical safety throughout the experiment.

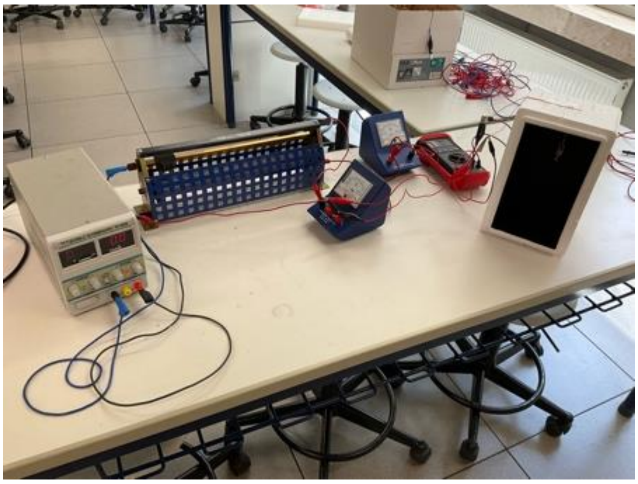


Figure 7. Circuit Connection

2.3.3 Raw Data Collection

- Before powering the circuit, record the initial resistance of the light bulb at room temperature with the resistance side of the multimeter.
- Record the ambient temperature of the room, with the thermometer section of the second multimeter.
- Plug the DC power supply into the socket and power the circuit.
- Adjust the voltage from the DC power supply from $1V$ to $11V$ by incrementing by $1V$.
- After each increment, wait for 1 minute to record the data.
- For each voltage, record the voltage across the light bulb using the voltmeter.
- Record the current flowing through the light bulb using the ammeter.
- Use the thermocouples of the multimeter to measure the temperature ($°C$) of the light bulb. Ensure the thermocouples are in direct contact with the light bulb.
- Record the resistance of the filament using the multimeter set to the resistance measurement function.
- After recording all the data for 1 increment wait for the tungsten to reach thermal equilibrium before moving on to the next.
- Repeat the experiment 5 times to ensure the reliability and consistency of the results.

2.4 Justification

The method used in this experiment ensures that data collection is precise and accurate. First, covering the foam box with black cardboard helps reduce the reflection of light and heat within the box, making sure that heat absorption is maximized and systematic errors related to reflection are minimized. Black materials absorb all wavelengths of light, which allows for a more controlled environment where the emitted radiant power from the light bulb can be measured without interference. The use of a foam box provides insulation, ensuring that heat generated from the light bulb does not easily escape, stabilizing the temperature, and allowing for accurate thermocouple readings.

The step-by-step increase of voltage from $1V$ to $11V$ and waiting for thermal equilibrium before moving to the next, helps in obtaining a good comparison for each voltage level. This incremental adjustment prevents rapid heating, which might distort the readings by causing the thermocouples or multimeter to lag sudden temperature changes. Moreover, using thermocouples in direct contact with the bulb allows for precise temperature measurements.

2.5 Risk Assessment and Ethical Considerations

The main risks involve high temperatures and electrical hazards. The incandescent light bulb can become extremely hot, posing a burn risk. To mitigate this, the experiment includes waiting for the bulb to cool before handling, and thermocouples are used to measure temperature without direct contact. Electrical risks include potential short circuits or shocks from loose connections. Ensuring secure connections with crocodile clips and managing the power supply with dry hands minimizes these risks and ensures safe operation throughout the experiment. To reduce environmental impact, ethical considerations include ensuring proper disposal of the foam box and cardboard by recycling. Other materials continue to be used.

3. DATA and ANALYSIS

3.1 Raw Data

3.1.2 Qualitative Data

- As the voltage increases, the light bulb emits brighter light, and the filament's glow becomes more intense shifting from a reddish color to a bright white.
- As the voltage increases, the tungsten filament generates more heat raising the temperature of the light bulb.

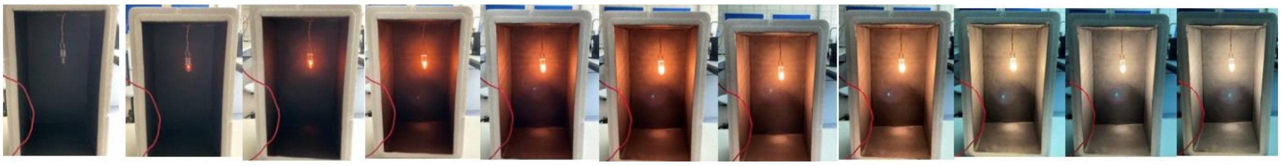


Figure 8. These pictures are taken at each voltage increment from $1V$ to $11V$, capturing the changes in the filament's glow and brightness.

3.1.3 Quantitative Data

The data was collected from five trials, and each measurement's average was written in Table 4 The following formula is used to determine the average of the measurements collected from all five experiments.

$$\frac{\boldsymbol{R_1} + \boldsymbol{R_2} + \boldsymbol{R_3} + \boldsymbol{R_4} + \boldsymbol{R_5}}{\mathbf{5}} = \boldsymbol{R_{Avarage}}$$

Where R is the result obtained from the experiment and the numbers indicate which trial the data is from.

Potential Difference (V) (±0.001)	Electric Current (A) (±0.001)	Temperature of the Tungsten ($°C$) (±0.1)	Resistance in temperature of the medium (Ω) (±0.001)
1.000	0.083	28.2	12.600
2.000	0.147	30.5	12.600
3.000	0.196	33.4	12.600
4.000	0.268	38.7	12.600
5.000	0.283	46.1	12.600
6.000	0.295	57.3	12.600
7.000	0.333	69.4	12.600
8.000	0.367	84.5	12.600
9.000	0.397	101.8	12.600
10.000	0.411	121.5	12.600
11.000	0.435	143.8	12.600

Table 4. Indicates the average of raw data collected via the instruments. It shows how the values of electric current, temperature output of the multimeter, and resistance of the medium change with respect to the potential difference applied to the light bulb.

Voltage is essential for moving electrons, as their movement requires work to be done. When moving through a metal, electrons suffer collisions with the atoms of the metal. The collisions are inelastic which means the electrons lose energy which the atoms in the wire gain.[15] Hence, the atoms of the wire start to vibrate with increased kinetic energy. As temperature is the measure of the kinetic energy of molecules, it increases as well. This explains the increase in temperature in Table 4 and the heating effect observed in the qualitative data. Furthermore, the resistance of the resistor is constant because there is no change in the temperature of the room.

[15] Nave, R. (n.d.). *Resistance: Temperature coefficient*. Temperature Coefficient of Resistance. http://hyperphysics.phy-astr.gsu.edu/hbase/electric/restmp.html

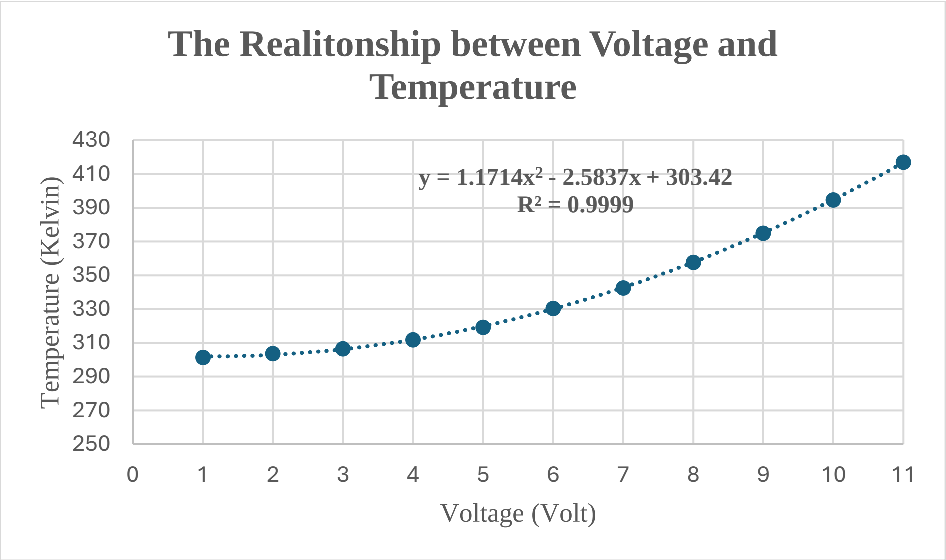
3.2 Processed Data

3.2.1 Relationship between Temperature and Voltage

To convert the temperature of the tungsten to Kelvin 273.15°C is added.

Potential Difference (V) (±0.001)	Temperature of the Tungsten (°C) (±0.1)	Temperature of the Tungsten (K) (±0.1)
1.000	28.2	301.35
2.000	30.5	303.65
3.000	33.4	306.55
4.000	38.7	311.85
5.000	46.1	319.25
6.000	57.3	330.45
7.000	69.4	342.55
8.000	84.5	357.65
9.000	101.8	374.95
10.000	121.5	394.65
11.000	143.8	416.95

Table 5. The temperature of the tungsten in Kelvins for each voltage.



Graph 1. The data points of temperature (K) and voltage (V) according to Table 5. The horizontal error bar is (± 0.001) and the vertical error bar is (± 0.1). However, due to being a small number they do not show on the graph.

A polynomial trendline is drawn to show that the data points are not increasing linearly. This indicates that as the voltage increases, the temperature rises more steeply. This nonlinear relationship is due to the property of the tungsten, the material used for the filament. Tungsten has a temperature-dependent resistivity, meaning its resistance increases as its temperature rises. Initially, as voltage increases, the current causes the filament to heat up, increasing its temperature. However, as the temperature rises, tungsten's resistance also increases, which reduces the current flow for the same applied voltage. This, in turn, slows the rate of temperature increase, as the electrical power converted into heat becomes less efficient at higher temperatures and creates a polynomial relationship between them. The R^2 value is 0.9999 which is extremely close to 1 indicating that the quadratic model accurately represents the data and illustrates a high correlation between temperature and voltage.

3.2.2 Secondary Calculation for Temperature

I determined the temperatures corresponding to each voltage increment from $1V$ to $11V$ through experimental measurements. However, to ensure the accuracy of my results and identify any potential errors in my experimental values, I will perform a secondary calculation through resistance with 4 steps. This calculation will serve as a control to verify the consistency and reliability of the temperatures I obtained experimentally.

3.2.2.1 Resistance of the Filament (R_T)

In the experiment, the voltage and current values are recorded. Therefore, the resistance of the filament can be calculated using Ohm's Law, which states that the voltage across a circuit is directly proportional to the current flowing through it and the total resistance in the circuit.

$$\boldsymbol{V = I \times R \Rightarrow R_T = \frac{V}{I}} \qquad [\mathbf{14}]$$

Where:

$\boldsymbol{V}$: Voltage (V)

$\boldsymbol{I}$: Current (A)

$\boldsymbol{R_T}$: Resistance of the filament (Ω)

Uncertainty Calculation for Division[16]

$$\frac{\Delta z}{z} = \sqrt{\left(\frac{\Delta x}{x}\right)^2 + \left(\frac{\Delta y}{y}\right)^2}$$

$$\Delta z = z \times \sqrt{\left(\frac{\Delta x}{x}\right)^2 + \left(\frac{\Delta y}{y}\right)^2}$$

Sample Calculation for (1.000 ± 000.1) Volts and (0.083 ± 0.001) Amperes:

$V = 1.000\ V$

$I = 0.083\ A$

$R_T = \frac{1.000}{0.083} = 12.04819277 \approx 12.048$

$\Delta R = 12.048 \times \sqrt{\left(\frac{0.001}{1.000}\right)^2 + \left(\frac{0.001}{0.083}\right)^2} \approx 12.048 \times 0.0121 \approx 0.146\ \Omega$

$R_T = 12.048 \pm 0.146\ \Omega$

[16] Lindberg, V. (2000, July 1), Uncertainties and Error Propagation. http://www.geol.lsu.edu/jlorenzo/geophysics/uncertainties/Uncertaintiespart2.html

Potential Difference (V) (±0.001)	Electric Current (A) (±0.001)	Resistance of the Filament (R_T) (Ω)
1.000	0.083	12.048 ± 0.146
2.000	0.147	13.605 ± 0.093
3.000	0.196	15.306 ± 0.078
4.000	0.268	14.925 ± 0.056
5.000	0.283	17.668 ± 0.063
6.000	0.295	20.339 ± 0.069
7.000	0.333	21.021 ± 0.063
8.000	0.367	21.798 ± 0.059
9.000	0.397	22.670 ± 0.057
10.000	0.411	24.331 ± 0.059
11.000	0.435	25.287 ± 0.058

Table 6. The resistance of the filament for each voltage.

3.2.2.2 Relative Resistance

Since incandescent bulbs operate at much higher temperatures than room temperature, the relative change in resistance is calculated by finding the ratio:

$$\boldsymbol{Relative\ Resistivity = \frac{R_T}{R_{room}}}$$ [17]

Where:

$\boldsymbol{R_T}$**:** Resistance of the filament after the adjusted voltages.

$\boldsymbol{R_{room}}$**:** Resistance of the filament at room temperature.

The uncertainty is calculated using the uncertainty for division formula given before.

[17] *Resistance: Temperature coefficient*. Temperature Coefficient of Resistance. (n.d.). http://hyperphysics.phy-astr.gsu.edu/hbase/electric/restmp.html

Resistance of the Filament (R_T) (Ω)	Resistance in Temperature of the Medium (R_{room}) (Ω) (±0.001)	Relative Resistance of the Filament $\left(\frac{R_T}{R_{room}}\right)$
12.048 ± 0.146	12.600	0.956 ± 0.012
13.605 ± 0.093	12.600	1.080 ± 0.007
15.306 ± 0.078	12.600	1.215 ± 0.006
14.925 ± 0.056	12.600	1.185 ± 0.004
17.668 ± 0.063	12.600	1.402 ± 0.005
20.339 ± 0.069	12.600	1.614 ± 0.005
21.021 ± 0.063	12.600	1.668 ± 0.005
21.798 ± 0.059	12.600	1.730 ± 0.005
22.670 ± 0.057	12.600	1.800 ± 0.005
24.331 ± 0.059	12.600	1.931 ± 0.005
25.287 ± 0.058	12.600	2.007 ± 0.005

Table 7. The relative resistance of the filament for each voltage.

The relative resistance is found to understand how the resistance of the tungsten filament changes with temperature. By, comparing the filament's resistance to its room temperature resistance, the effects of temperature on the tungsten's behavior are isolated. This approach is taken due to the temperature-dependent nature of resistance in tungsten as explained in Graph 1. Furthermore, Table.7 proves that as voltage increases the relative resistance of the tungsten increases.

3.2.2.3 Temperature of the filament

The equation below describes how the resistance depends on temperature and allows us to derive the temperature from the relative resistance.

$$\frac{R_T}{R_{room}} = [\,1 + \alpha\,(T - T_{room})] \qquad [17]$$

Where R_T is the resistance at temperature $T(°C)$ and R_{room} is the resistance at room temperature $T_{room}\,(°C)$. α which depends on the material is the percentage change in resistivity per unit time and for tungsten it is ($\approx 0.0045°C^{-1}$).

However, the equation above does not explain the relation between temperature and resistance as it is valid only for small temperature changes. This is because it assumes a linear relationship between resistance and temperature, which is an approximation that holds true only over a limited temperature range. Due to the property tungsten exhibits resistance and temperature becomes nonlinear for larger temperatures.

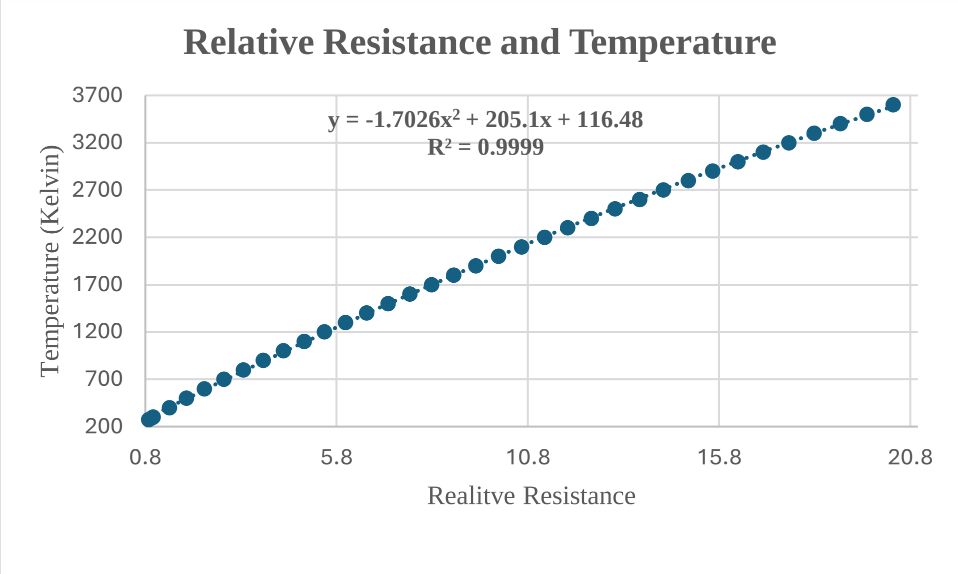
In this experiment, the temperature changes are large which is why I will not be using this equation to calculate temperature. Instead, I will use secondary data[18] on the relative resistance and temperature relationship and graph it. Then, I will find the equation of the trendline. After that, I will find the new temperature data by putting my relative resistance data into the equation.

$\left(\frac{R_T}{R_{room}}\right)$	**Temperature (K)**
0.885	273
0.972	293
1	300
1.43	400
1.87	500
2.34	600
2.85	700
3.36	800
3.88	900
4.41	1000
4.95	1100
5.48	1200
6.03	1300
6.58	1400
7.14	1500
7.71	1600
8.28	1700
8.86	1800

$\left(\frac{R_T}{R_{room}}\right)$	**Temperature (K)**
9.44	1900
10.03	2000
10.63	2100
11.24	2200
11.84	2300
12.46	2400
13.08	2500
13.72	2600
14.34	2700
14.99	2800
15.63	2900
16.29	3000
16.95	3100
17.62	3200
18.28	3300
18.97	3400
19.66	3500
20.35	3600

Table 8. Secondary data on resistivity and temperature of the tungsten.[18]

[18] H. A. Jones, (July 1926) A Temperature Scale for Tungsten, Phys. Rev. 28, p.202-207



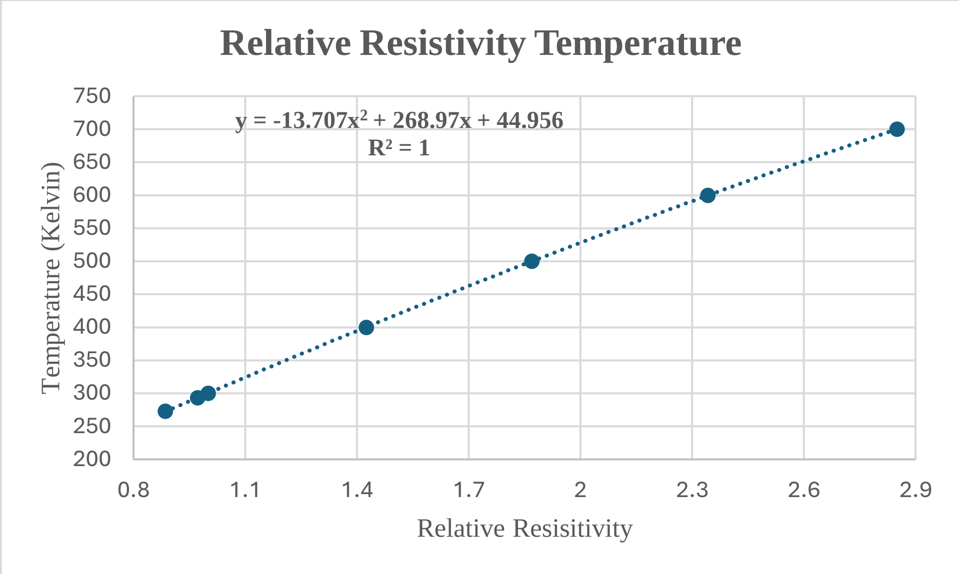
Graph 2. The relative resistance and temperature graph according to Table 8.

The quadratic trendline illustrates that temperature and relative resistance have a nonlinear relationship.

$\left(\frac{R_T}{R_{room}}\right)$	**Temperature (K)**
0.885	273
0.972	293
1.000	300
1.425	400
1.869	500
2.342	600
2.850	700

Table 9. The data I found for relative resistance is between the ranges 0.956 ± 0.012 and 2.007 ± 0.005. The table shows the secondary data on the relative resistance and temperature of the tungsten between the ranges I found.

To improve accuracy, the data points on Graph 2 are reduced within the range of the relative resistance values measured in my calculations. This ensures that the model closely represents the behaviour of tungsten's resistivity across the observed conditions.



Graph 3. The secondary data on temperature and relative resistance between the ranges of the relative resistance from my calculations.

Estimate the temperature by using the trendline equation:

$$\boldsymbol{y = -13.707x^2 + 268.97x + 44.956}$$

x is the relative resistance of the filament that I found by experiment in Table.7

y gives the temperature of the filament.

<u>Uncertainty Calculation for Quadratic Equation by Error Propagation</u>[17]

The uncertainty in y, can be approximated as

$$\boldsymbol{\Delta y = \sqrt{\left(\Delta x \frac{\partial y}{\partial x}\right)^2}}$$

Where:

$\frac{\partial y}{\partial x}$: The derivative of y with respect to x

Δx: The uncertainty in x

<u>Sample Calculation for (1.000 ± 000.1) Volt:</u>

$T = -13.707\left(\frac{R_T}{R_{room}}\right)^2 + 268.97\left(\frac{R_T}{R_{room}}\right) + 44.956$

$\left(\frac{R_T}{R_{room}}\right) = 0.956 \pm 0.012 \Rightarrow T = -13.707 \times (0.956)^2 + 268.97 \times (0.956) + 44.956 = 289.56$

$\frac{\partial y}{\partial x} = -27.414x + 268.97 = 242.762$

$\Delta y = \sqrt{(0.012 \times 243.762)^2}$

$T = 289.56 \pm 2.91\ K$

$$\boldsymbol{Percentage\ Error} = \frac{|T_{Secondary} - T_{Experiment}|}{T_{Secondary}} \times \mathbf{100} \quad [19]$$

Relative Resistance of the Filament $\left(\frac{R_T}{R_{roo}}\right)$	Temperature (K) of the Tungsten (By Equation)	The temperature (K) of the Tungsten (± 0.1) (By experiment)	Percentage Error (%)
0.956 ± 0.012	289.56 ± 2.91	301.35	3.91
1.080 ± 0.007	319.46 ± 1.68	303.65	5.21
1.215 ± 0.006	351.52 ± 1.41	306.55	14.67
1.185 ± 0.004	344.44 ± 0.95	311.85	10.45
1.402 ± 0.005	395.11 ± 1.15	319.25	23.77
1.614 ± 0.005	443.37 ± 1.12	330.45	34.17
1.668 ± 0.005	455.46 ± 1.12	342.55	32.96
1.730 ± 0.005	469.25 ± 1.11	357.65	31.24
1.800 ± 0.005	484.69 ± 1.10	374.95	29.30
1.931 ± 0.005	513.23 ± 1.08	394.65	30.40
2.007 ± 0.005	529.57 ± 1.07	416.95	27.04

Table 10. Comparison of Temperature (K) of the Tungsten calculated by equation and measured by experiment.

The reason the temperature data in the secondary source is significantly higher than my measurements is that I measured each temperature per volt for one minute to ensure accurate

[19] BYJU'S. (2020, September 16). *Percent error formula - how to calculate percent error using solved examples*. BYJUS. https://byjus.com/percent-error-formula/

comparisons. However, tungsten's high thermal inertia may prevent it from reaching a truly stable temperature within this time and potentially introduce inconsistencies in the data. Additionally, the secondary data reflects a different time range (longer than my calculations) for each measurement. Further limitations will be discussed in the evaluation.

3.2.3 Calculation of Total Radiant Power

3.2.3.1 The Surface Area of the Tungsten

I compared the shape of the tungsten light bulb to a cylinder as this approximation would simplify my calculations. To find the surface area of the tungsten filament, I used the formula for the surface area of a cylinder, given by $\boldsymbol{2\pi r^2} + (\boldsymbol{2\pi r} \times \boldsymbol{h})$ where r is the radius and h is the height. The scale of the image did not shift from the real-life size.

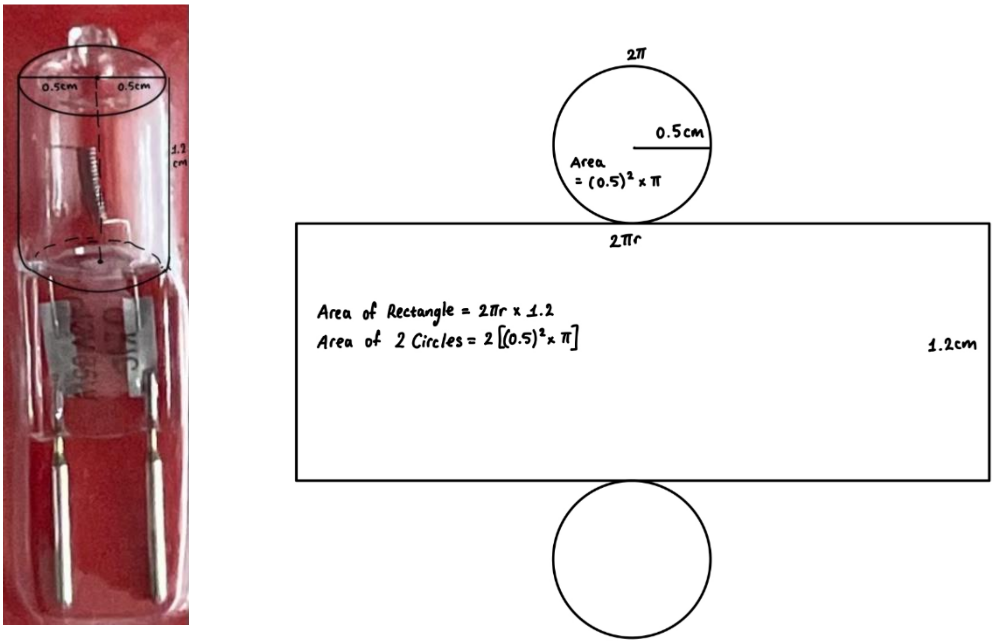


Figure 9. Image of the light bulb and its cylinder expansion.

The surface area of a cylinder = $\boldsymbol{2\pi r^2} + (\boldsymbol{2\pi r} \times \boldsymbol{h})$

$$2\pi(0.5)2 \;+\; 1.2[2\pi \times (0.5)] \;=\; 5.340707511 \;\approx\; 5.34\;cm^2$$

$$5.34\;cm^2 \;=\; 0.000534\;m^2$$

3.2.3.2 Stefan-Boltzmann Calculation

$$\boldsymbol{P = \sigma \varepsilon A T^4} \qquad [\mathbf{14}]$$

Where:

$\boldsymbol{P}$: Total radiant power emitted by the body (W)

$\boldsymbol{\sigma}$: 5.67×10^{-8} $W/m^2 \times K^4$

$\boldsymbol{\varepsilon}$: 0.03

$\boldsymbol{A}$: $0.000534\ m^2$

$\boldsymbol{T}$: Absolute temperature (K).

Sample Calculation for (1.000 ± 000.1) Volt and (301.35 ± 0.1) located in Table 5:

$\boldsymbol{T}$: 301.35 K

$P = 5.67 \times 10^{-8} \times 0.03 \times 0.000534 \times (301.35)^4 = 0.0074908371 \approx 0.00749$W

Sample Calculation for Uncertainty by Error Propagation:[18]

To calculate the uncertainty, the derivative of power with respect to temperature is used.Then, multiplied with ΔT.

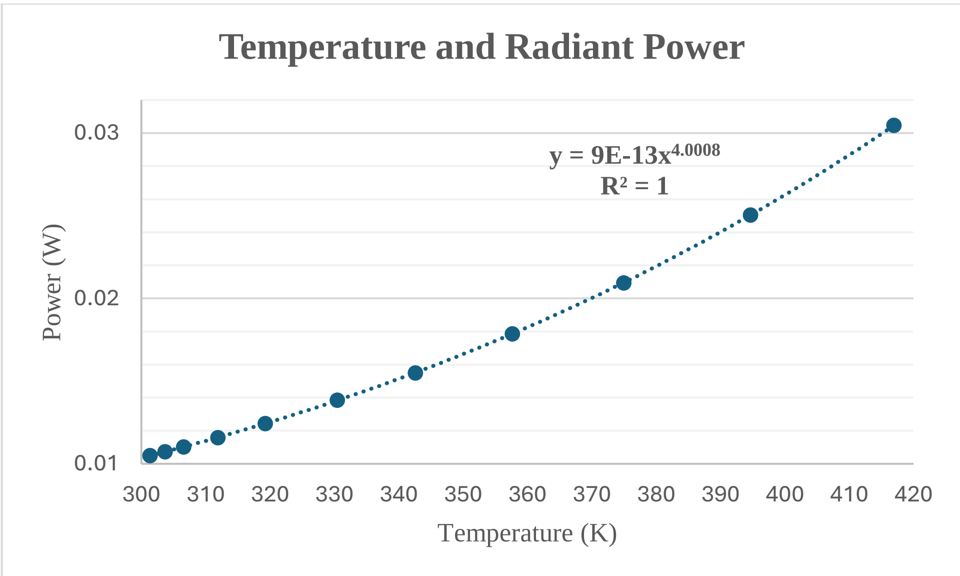
$\frac{dP}{dT} = \boldsymbol{4\sigma\varepsilon A T^3} \Rightarrow \frac{dP}{dT} = 4 \times 5.67 \times 10^{-8} \times 0.03 \times 0.0000534 \times (301.35)^3 \approx 0.00010$

ΔT: Uncertainty of the temperature (0.1℃).

$$\Delta \boldsymbol{P} = \left|\frac{\boldsymbol{dP}}{\boldsymbol{dT}}\right| \times \Delta \boldsymbol{T} \Rightarrow 0.0010 \times 0.1 = 0.00010\ W$$

Potential Difference (V) (± 0.001)	**Temperature (K) of the Tungsten (By experiment) (± 0.10)**	**Radiant Power (W)**
1.000	301.35	0.00749 ± 0.00010
2.000	303.65	0.00772 ± 0.00010
3.000	306.55	0.00802 ± 0.00010
4.000	311.85	0.00859 ± 0.00011
5.000	319.25	0.00944 ± 0.00012
6.000	330.45	0.01084 ± 0.00013
7.000	342.55	0.01250 ± 0.00015
8.000	357.65	0.01486 ± 0.00016
9.000	374.95	0.01794 ± 0.00019
10.000	394.65	0.02205 ± 0.00022
11.000	416.95	0.02746 ± 0.00027

Table 11. The emitted radiant power (W) for each voltage increment.



Graph 4. The relationship between temperature and radiant power, according to Table 11. As the uncertainties are so small, the graph does not show error bars.

The exponential nature of the relationship suggests that as temperature increases, the emitted radiant power grows at an accelerating rate. This aligns with the Stefan-Boltzmann law, which states that radiated power is proportional to T^4. The high R^2 value of 1 indicates a strong correlation, meaning the model effectively describes the data trend.

Hence, this experiment shows that as the voltage increases both the temperature and the resistivity of the tungsten filament increase. This rise in temperature also leads to an increase in the emitted visible thermal radiation since higher temperatures cause the filament to emit more radiant power.

4. CONCLUSION

The results of this experiment demonstrate a strong relationship between voltage, temperature, resistivity, and emitted visible radiant power in an incandescent tungsten filament. It was observed that as the voltage increased, the filament's temperature rose significantly, which led to an exponential increase in the total emitted visible radiant power according to Stephan-Boltzmann Law. This behavior aligns with the hypothesis. Also, I noticed that the light bulb became brighter as the voltage increased. Furthermore, I observed that the resistance of tungsten metal behaves differently than that of other metals. As the voltage increased, the filament's resistance also increased and affected the temperature in a non-linear manner. This discovery highlights the unique properties of tungsten and emphasizes the importance of material choice in experiments involving electrical resistance and heat generation. Additionally, I gained insights into the fundamental role that temperature plays in thermodynamics, affecting everything from resistance in materials to the intensity of radiant power emitted by a heated object.

4.1 Evaluation

4.1.1 Strengths

- The experimental setup was designed precisely, ensuring consistent conditions for accurate data collection.
- Fixed measurements such as the constant surface area of the tungsten filament and controlled voltage increments and minimized variability.
- Performing five trials for each data point improved reliability by reducing random errors through averaging.
- The use of error propagation and uncertainty calculations further strengthened the experiment by being aware of potential measurement errors.

4.1.2 Limitations

- One significant limitation of the experiment is the temperature measurement process. The temperatures were recorded exactly one minute after applying the voltage. However, this time frame might not have been sufficient for the tungsten filament to reach thermal equilibrium leading to inaccurate temperature readings. Additionally, the limited temperature range measured may not fully capture tungsten's behavior across a broader spectrum.
- The assumption of constant emissivity (0.03) for tungsten introduced potential inaccuracies, as emissivity varies with temperature.
- Estimating the filament’s surface area also added some errors in power calculations.
- Even though measuring instruments were used precisely, slight calibration errors could contribute to measurement inaccuracies such as in 3V and 4V measurements. The resistivity decreases when it should increase.

- When comparing experimental data to secondary data, a noticeable difference in temperature values was observed. This difference is likely due to variations in the time range used for temperature measurements. In secondary data, temperatures may have been measured after a longer period, allowing more time for the system to reach thermal equilibrium. This does not imply that the calculations in this experiment are incorrect, as the observed relationship (increased voltage leads to higher temperature and resistivity) remains valid. The difference is solely due to the differing time frames for temperature measurements which affects the comparison but not the accuracy of the experimental trend.

4.1.3 Improvements

- Allowing more time for the filament to reach thermal equilibrium can ensure more accurate temperature readings.
- Expanding the range of temperatures measured can better capture the full behaviour of tungsten under different thermal conditions.
- Standardizing the time frame for both experimental and secondary data temperature measurements can improve the accuracy of data comparisons.

4.2 Further Investigation

In order to investigate the impact of voltage on the temperature of the filament and corresponding radiant power, a large-scale experiment would be conducted comparing the characteristics of various materials (not only tungsten) at the same voltage range. This would enable comparison of how various metals with various resistances impact temperature and radiant power when subjected to the same conditions. Additionally, the change in filament geometry (such as length and cross-sectional area) can be explored to see its impact on temperature and resistance. Furthermore, plotting the spectrum of the light at varying voltages and comparing it with the temperature variations could be investigated. This could possibly indicate how the distribution of wavelength shifts with the rising temperature of the filament.

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6. APPENDIX

Experiment 1

Potential Difference (V) (± 0.001)	Electric Current (A) (± 0.001)	Temperature of the Tungsten ($°C$) (± 0.1)	Resistance in temperature of the medium (Ω) (± 0.001)
1.000	0.079	27.9	12.600
2.000	0.143	30.3	12.600
3.000	0.184	33.1	12.600
4.000	0.268	38.2	12.600
5.000	0.278	45.6	12.600
6.000	0.292	56.8	12.600
7.000	0.327	68.7	12.600
8.000	0.362	84.0	12.600
9.000	0.396	101.5	12.600
10.000	0.407	121.7	12.600
11.000	0.434	144.1	12.600

Experiment 2

Potential Difference (V) (± 0.001)	Electric Current (A) (± 0.001)	Temperature of the Tungsten ($°C$) (± 0.1)	Resistance in temperature of the medium (Ω) (± 0.001)
1.000	0.082	28.5	12.600
2.000	0.153	30.9	12.600
3.000	0.198	32.8	12.600
4.000	0.262	39.0	12.600
5.000	0.276	46.3	12.600
6.000	0.287	57.7	12.600
7.000	0.335	69.5	12.600
8.000	0.368	85.1	12.600
9.000	0.402	102.4	12.600
10.000	0.415	121.1	12.600
11.000	0.429	143.0	12.600

Experiment 3

Potential Difference (V) (± 0.001)	Electric Current (A) (± 0.001)	Temperature of the Tungsten (°C) (± 0.1)	Resistance in temperature of the medium (Ω) (± 0.001)
1.000	0.085	28.2	12.600
2.000	0.144	29.8	12.600
3.000	0.189	33.5	12.600
4.000	0.274	38.8	12.600
5.000	0.289	46.0	12.600
6.000	0.295	57.9	12.600
7.000	0.339	69.3	12.600
8.000	0.373	83.9	12.600
9.000	0.394	101.2	12.600
10.000	0.403	120.5	12.600
11.000	0.430	144.3	12.600

Experiment 4

Potential Difference (V) (± 0.001)	Electric Current (A) (± 0.001)	Temperature of the Tungsten (°C) (± 0.1)	Resistance in temperature of the medium (Ω) (± 0.001)
1.000	0.093	27.8	12.600
2.000	0.151	31.0	12.600
3.000	0.195	33.9	12.600
4.000	0.271	38.4	12.600
5.000	0.287	45.9	12.600
6.000	0.304	57.1	12.600
7.000	0.343	69.9	12.600
8.000	0.360	84.3	12.600
9.000	0.408	102.0	12.600
10.000	0.411	121.9	12.600
11.000	0.439	143.7	12.600

Experiment 5

Potential Difference (V) (± 0.001)	Electric Current (A) (± 0.001)	Temperature of the Tungsten (°C) (± 0.1)	Resistance in temperature of the medium (Ω) (± 0.001)
1.000	0.076	28.6	12.600
2.000	0.146	30.5	12.600
3.000	0.213	33.7	12.600
4.000	0.266	39.1	12.600
5.000	0.286	46.7	12.600
6.000	0.301	57.0	12.600
7.000	0.322	69.6	12.600
8.000	0.371	85.2	12.600
9.000	0.386	101.9	12.600
10.000	0.418	122.3	12.600
11.000	0.442	143.9	12.600