

Relationship between Temperature & Resistance of a metallic wire

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1. Research Design

1.1 Introduction

The effect of temperature change on the resistance of a metallic wire is an important concept in electrical systems, with applications in many industries like telecommunications and automobile where conductive materials are key to driving performance. This study aims at assessing the effect of temperature on resistance of metallic wires by combining theoretical concepts with practical experimentations.

The idea arose from a personal experience while I was charging my phone. I observed that a heated phone takes longer to charge than the phone which is not heated up. This raised my curiosity and made me understand the temperature-resistance relationship of metal conductors.

Theoretically, the resistance of a metal conductor increases with temperature. As rising temperatures cause more vibrations of metal ions, it leads to more frequent collisions with free electrons and increased resistance. This is expressed mathematically as:

$$\rho_2 = \rho_1[1 + \alpha(T_2 - T_1)]$$

Equation1: Resistance relationship with Temperature

where ρ_2 is the electrical resistivity at temperature T_2 , ρ_1 electrical resistivity at a reference temperature T_1 , and α is the temperature coefficient of resistivity.

This experimental study tries to combine theoretical concepts with empirical data to model the effect of temperature on resistance. The observations from this study can help better understand the relationship of temperature and resistance and has practical applications in real-life situations.

1.2 Research Question

What is the effect of temperature on the resistance of a metallic wire, and how can this relationship be experimentally determined?

1.3 Theoretical Background

The electrical resistance of a metallic wire depends on temperature, a crucial factor in designing electronic components and sensors. Resistance (R) is related to resistivity (ρ), length (l), and cross-sectional area (A) by

$$R = \frac{\rho L}{A}$$

Equation2: Resistance relationship with Length & Area

Here, (ρ) is given by equation1 above. Although related, (R) and (ρ) are distinct concepts:

- (R) is defined by the object's dimensions and the resistivity of the material that it is made of. It is specific to the given object.

- (ρ) is the intrinsic property of the material in terms of how it opposes the flow of current. It is not dependent on shape and size.

α is the temperature coefficient of resistivity and it gives the change in resistivity (ρ) of a material with changes in temperature. Metals like copper and aluminum have positive α , meaning their resistivity increases with temperature, while alloys like nichrome, with higher resistivity and lower α , are less temperature-sensitive.

At low temperatures, resistivity deviates from linear behavior, as per Matthiessen's Rule – (which states that the total resistivity of a metal is the sum of the resistivity due to phonon scattering – electrons colliding with lattice vibrations - which is temperature dependent and the resistivity due to the presence of impurities which is temperature independent¹).

$$\rho(T) = \rho_{\text{defect}} + \rho_{\text{thermal}}$$

Equation3: Matthiessen's Rule

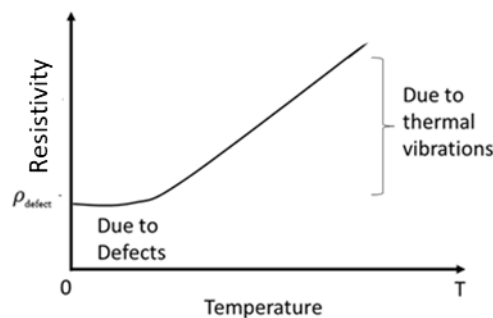


Figure1: Matthiessen's Rule2

Current is produced when free electrons in metals travel in the direction of an electric field. Electrons collide with lattice ions which reduce drift velocity. These collisions are increased at high temperatures thus increasing resistance.

By using Ohm's Law ($V=IR$) and plotting resistance against temperature, the temperature coefficient of resistivity (α) can be determined.

¹Gopalan Colleges of Engineering and Management. (n.d.). *Electrical properties of materials & applications*. Retrieved from <https://www.gopalancolleges.com/gcem/pdf/syllabus/physics/cse/module-4-electrical-properties-of-materials-applications-02.pdf>. (Accessed Jan 2025)

²DoITPoMS. (n.d.). *Thermal and electrical properties of materials: Composition effects*. Department of Materials Science and Metallurgy, University of Cambridge. Retrieved from https://www.doitpoms.ac.uk/tlplib/thermal_electrical/composition.php. (Accessed Jan 2025)

1.4 Hypothesis

The hypothesis for this experiment is: with an increase in temperature of a metal wire, its resistance increases linearly with a constant temperature coefficient of resistance (α).

The null hypothesis (H_0) is that resistance and temperature have no relation and that observed changes are due to random variations or errors.

The alternate hypothesis (H_1) supports a linear relationship.

The experiment will measure resistance at varying temperatures to calculate α and test the linear relationship using the equations

$$\rho_2 = \rho_1[1 + \alpha(T_2 - T_1)] \text{ and } R = \frac{\rho L}{A}$$

1.5 Variables:

Control Variable	Why it is Controlled?	Method of Controlling
Wire	Different materials can have different resistance	Wire was used from same bundle thus reducing the impact.
Length of Wire	Resistance is directly proportional to the length of the wire	Same wire was used in the entire experiment
Cross-sectional area of the wire	Resistance is inversely proportional to the cross-sectional area	Same wire was used in the entire experiment
Environmental conditions	External factors like temperature, humidity	Experiment conducted in the same room for the entire experiment
Measuring equipment	Different equipment may have different accuracy and thus can lead to varying results	Same instruments were leveraged during experiments

Table 1: Control variables in the experiment

1.6 Materials Required for the Experiment

Material	Description	Purpose
Metallic Wire	I used an aluminum wire of length 2 meter and a very small cross-sectional area	Study the effect of temperature on resistance.
Digital Thermometer/Thermocouple LC: 0.1 °C Uncertainty in Measurement: 0.05 °C	Accurate digital thermometer or thermocouple with a wide temperature range (e.g., -50°C to 150°C).	To measure the temperature of the metallic wire accurately.
Digital Multimeter LC: 0.1 Ω Uncertainty in Measurement: 0.05 Ω	High-precision digital multimeter with low-resistance measurement capability.	To measure the electrical resistance of the metallic wire.
Heat Source	Controlled heat source such as a hot water bath.	To vary the temperature of the metallic wire systematically.
Ice Bath	Container with ice and water mixture.	To cool the wire and measure resistance at low temperatures.
Insulating Gloves	Heat-resistant gloves.	To handle the wire safely when it is hot.
Ruler or Measuring Tape LC: 1 mm Uncertainty in Measurement: 0.05 mm	Accurate ruler or measuring tape.	To measure and ensure the length of the wire remains constant.
Connecting Wires and Alligator Clips	Insulated connecting wires with alligator clips.	To connect the wire to the multimeter for resistance measurement.
Safety Goggles	Standard laboratory safety goggles.	To protect eyes during the experiment.

Table 2: Materials in the experiment

1.7 Procedure

Gather Materials: Collect all required materials from the experiment plan.

Setup:

- Prepare and secure a straight metallic wire (2 meters) using clamps. One meter ruler was taken and one end of wire was put at one end and clamped. Wire was measured and reversed to get full 2-meter wire.
- Connect the ends of wire to a multimeter. Wire was peeled off the insulation and rolled over the end of the multimeter and clamps were put.
- Set up a controllable heat source (water boiler).

Calibration:

- Measure and record the wire's length and initial resistance at room temperature.

Experiment:

- **Temperature control:** Gradually heat the wire, taking resistance measurements at regular temperature.

Data Collection:

- Record temperature-resistance readings.
- Determine the temperature coefficient (α)
- Calculate calculated resistance

Cleanup:

- Disconnect instruments, dispose hot water carefully and clean the workspace



Thermocouple



Digital Thermometer



Wire wrapped on
Test tube



Copper Wire

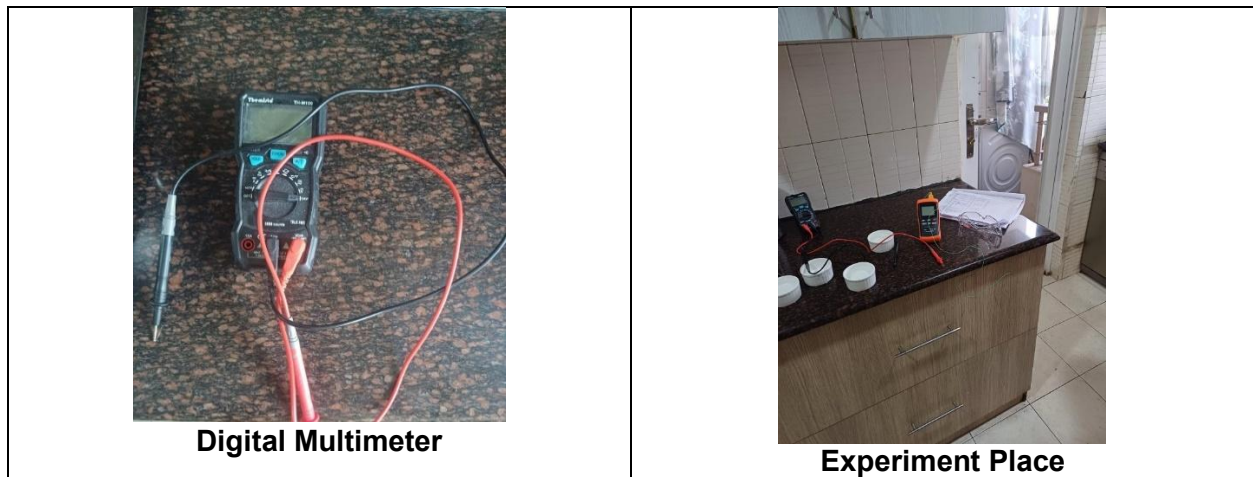


Figure2: Equipment Photos

The above pictures provide the details of the experiment setup.

1.8 Risk Assessment

Key risks in the experiment include:

1. Thermal Hazards: Skin burns from heated wires or water baths.
Mitigation: Use heat-resistant gloves and allow cooling before handling.
2. Electrical Hazards: Shocks caused by improper connections of wire.
Mitigation: Insulate property and avoid contact with live circuits.
3. Glassware Breakage: Cuts or spills from broken glass containers.
Mitigation: Handle with care.
4. Measurement Errors: Incorrect measurements due to calibration errors.
Mitigation: Calibrate equipment and ensure uniform environmental conditions.
5. Spills: Spilling of water results in slips.
Mitigation: Immediately clean up the spills and maintain the surface dry.

These measures ensure a safe and experimental process.

1.9 Preliminary trials

Preliminary trials helped to refine the process by testing the setup, identifying issues (e.g., unstable temperatures), and refining measurement techniques. They also improved safety and data quality by refining temperature and resistance measurement methods.

1.9.1 Preliminary Test Observations

Conducted various trials to get the results:

Trial 1:

In the first trial, copper wire was heated, and resistance was measured at varying temperatures using bowls of water at different temperatures: 10°C, room temperature (~25°C), 60°C, and 90°C. Throughout the test, control variables, such as the length of the wire and room temperature were kept constant.

Results:

Temperature vs. Resistance: As the temperature of the water increased, the resistance of the wire also increased. However, the accurate measurement of resistance was an issue due to below factors.

Key Challenges:

1. Low Resistance Values:

The multimeter was not able to take precise readings since copper's resistance is negligible and very sensitive to slight changes.

2. Temperature Instability:

The wire cooled rapidly once removed from the water bath, leading to inconsistent temperature readings. Additionally, the water itself lost heat quickly to the surroundings, affecting the accuracy of temperature measurements.

Trial 2:

In second trial, resistor was used along with wire to note the impact of temperature. Expectation was that once copper wire is heated, resistance will change, given it is connected with a second resistor in series. Using voltage drop and measuring the current, copper resistance can be calculated.

Results:

The correct determination of resistance could not be obtained due to a number of factors.

Key Challenges:

1. Simultaneous Measurements:

Difficulty was measuring voltage and current at same time, which is necessary for accurate calculation of resistance using Ohm's law.

2. Battery Concerns:

The extremely low resistance made the battery to overload the setup and cause harm to the setup.

1.9.2 Key Changes for Main Experiment:

Use Insulation: Used insulation material to reduce cooling rate of both the wire and the water in order to achieve more consistent readings.

Dual Multimeters: Used two multimeters to measure voltage and current at the same time for more accurate measurement of resistance.

Sequential Measurements: Use measuring cups in sequence to maintain temperature stability across trials.

Simultaneous Measurements: Temperature and resistance were measured simultaneously, thus reducing the impact of temperature change and resistance measurement.

1.9.3 Secondary Test Observations

Another trial was conducted with insulated copper wire, it also failed to yield consistent results since copper is very conductive. In response, the next trial was designed using aluminum wire. Aluminum, being less conductive than copper, it provided better measurable resistance values. This test also involved a thinner, longer wire with insulation to further enhance the accuracy of the resistance measurements and temperature control.

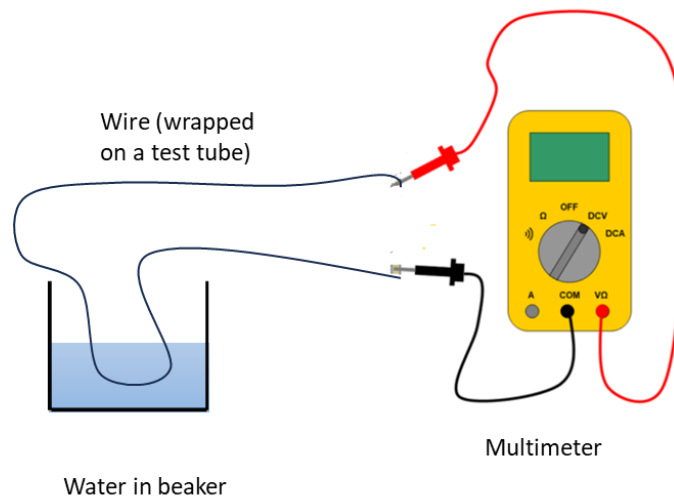
1.10 Final Trials (A set of 3 trials)

In the 1st of the final set of trials, a 2-meter length of thin aluminum wire was used for the experiment. The wire was carefully wrapped around a test tube for faster heat transfer. One end of the wire was peeled off for a longer length to facilitate easy attachment to the measuring equipment. Both peeled ends of the wire were connected securely to alligator clips, which were then attached to a digital multimeter to measure resistance.

1.10.1 Initial Setup:

Wire Preparation: The aluminum wire was wrapped around the test tube, with the ends peeled and connected to the digital multimeter.

Initial Measurement: The initial resistance of the wire was recorded at room temperature to establish a baseline reading.



Multimeter photo source - <https://www.sciencebuddies.org/science-fair-projects/references/how-to-use-a-multimeter>

Figure3: Initial trial set-up

1.10.2 Temperature Variation:

To study the effect of temperature on the resistance of the wire, separate beakers of water at different temperatures were prepared. The wire was sequentially dipped into the water at each temperature to measure changes in resistance. The temperatures were monitored using both a digital thermometer and a thermocouple for accuracy.

The temperatures and corresponding resistances were recorded.

2.Data Collected

The following table shows the recorded temperatures and corresponding resistance values:

Temperature Range ° C	Trials	Length (m)	Resistance (Ω)
5 - 15	1	2.0	1.2
5 - 15	2	1.7	0.7
5 - 15	3	3.9	1.4
25-30	1	2.0	1.7
45-55	1	2.0	2.2
45-55	2	1.7	1.1
45-55	3	3.9	1.8
75-90	1	2.0	2.9
75-90	2	1.7	1.6
75-90	3	3.9	2.1

Table3: Temperature vs Resistance (Trial 1)

Trial 1 – 27.8 ° C in range 25-30 is used room temperature reference

2.1 Calculations

2.1.1 Temperature Coefficient of Resistance (α)

The temperature coefficient of resistance, α , can be calculated using the formula:

$$\alpha = \frac{R - R_0}{R_0(T - T_0)}$$

Equation4: Temperature coefficient of resistance

Where:

- R is the resistance at a given temperature T.
- R_0 (1.7 Ω) is the initial resistance at reference temperature T_0 (room temperature, 27.8°C in this case).

Using the values in the data table for Trial 1

1. For T=14.67 °C, R=1.2 Ω:

$$\alpha = \frac{1.2 - 1.7}{1.7 \times (14.67 - 27.8)} = 0.0224 \text{ } ^\circ\text{C}^{-1}$$

2. For T=55.9 °C, R=2.2 Ω:

$$\alpha = \frac{2.2 - 1.7}{1.7 \times (55.9 - 27.8)} = 0.010467 \text{ } ^\circ\text{C}^{-1}$$

3. For $T=84.2\text{ }^{\circ}\text{C}$, $R=2.9\text{ }\Omega$:

$$\alpha = \frac{2.9 - 1.7}{1.7 \times (84.2 - 27.8)} = 0.012516\text{ }^{\circ}\text{C}^{-1}$$

The average α value across these points is approximately:

$$\alpha_{\text{avg}}=0.015128\text{ }^{\circ}\text{C}^{-1}$$

2.1.2 Cross-Sectional Area Calculation

Given the diameter of the wire is 0.695 mm (measured by screw gauge), the cross-sectional area A can be calculated as:

1. Convert diameter from mm to meters:

$$0.695\text{ mm}=0.000695\text{ m}$$

2. Calculate the area:

$$A = \pi \left(\frac{d}{2} \right)^2$$

$$A = \pi \left(\frac{0.000695}{2} \right)^2 = 3.8 \times 10^{-7} \text{ m}^2$$

2.1.3 Verification of Resistance Using Resistivity Formula

Calculating the (ρ), which is the resistivity of aluminum, that we calculate at room temperature using R_0 as:

$$\rho = \frac{R_0 \cdot A}{l}$$

$$\rho = \frac{1.7 \times 3.8 \times 10^{-7}}{2} = 3.23 \times 10^{-7} \Omega \cdot \text{m}$$

2.1.4 Calculating Expected Resistance Values at Each Temperature

$$R = \frac{\rho \cdot l}{A} \times (1 + \alpha \cdot (T - T_0))$$

where $\alpha_{\text{avg}}=0.015128$

Using the known resistivity of aluminum ρ , we can calculate the resistance at each temperature with the formula provided above. We substitute $\alpha_{\text{avg}}=0.015128$, $T_0 = 27.8^{\circ}\text{C}$, and the specific temperatures to obtain:

- For ($T = 14.67^{\circ}\text{C}$): $[R = \frac{3.23 \times 10^{-7} \times 2}{3.8 \times 10^{-7}} \times (1 + 0.015128 \cdot (14.67 - 27.8)) = 1.36 \Omega]$

- For ($T = 55.9^{\circ}\text{C}$): $[R = \frac{3.23 \times 10^{-7} \times 2}{3.8 \times 10^{-7}} \times (1 + 0.015128 \cdot (55.9 - 27.8)) = 2.42 \Omega]$

- For ($T = 84.2^{\circ}\text{C}$): $[R = \frac{3.23 \times 10^{-7} \times 2}{3.8 \times 10^{-7}} \times (1 + 0.015128 \cdot (84.2 - 27.8)) = 3.15 \Omega]$

Using this resistivity, the expected resistance at each temperature is calculated. Similarly for trial 2 & 3 resistivity was calculated. The table below, shows the observed resistance and calculated resistance values. Room temperature resistance is assumed proportional to trial1.

Trials	Temperature (°C)	Observed Resistance (Ω)	Calculated Resistance (Ω)
1	14.67	1.2	1.36
1	27.80	1.7	1.70
1	55.90	2.2	2.42
1	84.20	2.9	3.15
2	9.80	0.7	1.27
2	49.20	1.1	1.65
2	77.50	1.6	1.92
3	11.00	1.4	3.11
3	54.20	1.8	3.64
3	88.30	2.1	4.05

Table4: Observed vs Calculated Resistance

The calculated values also increase with temperature validating the theoretical model.

2.2 Graph and Analysis

The graph below illustrates the observed and calculated resistance values as well as the linear relationship between temperature and resistance, supporting the hypothesis.

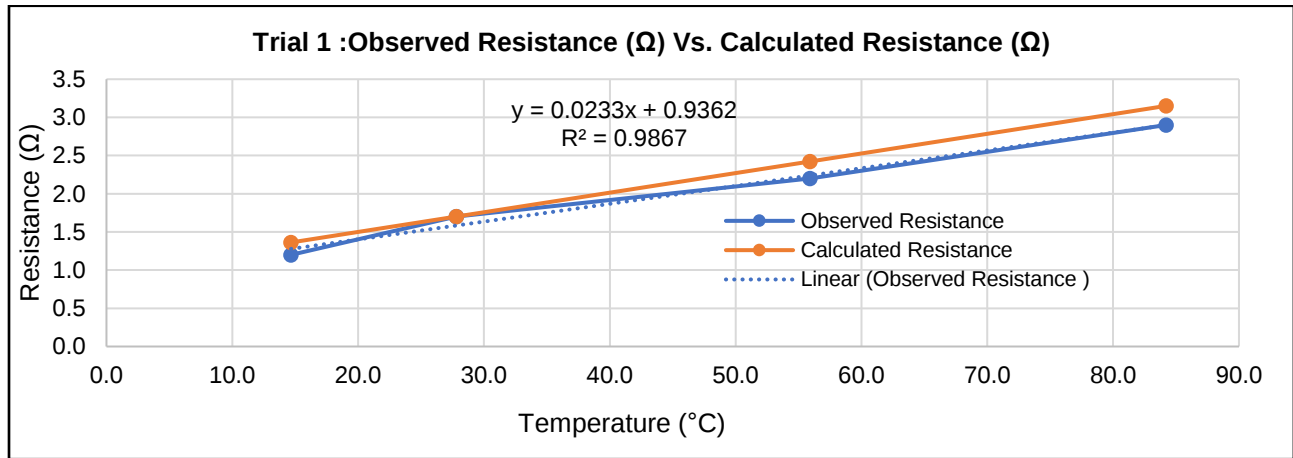


Figure4: Graph Observed vs Calculated Resistance Trial 1

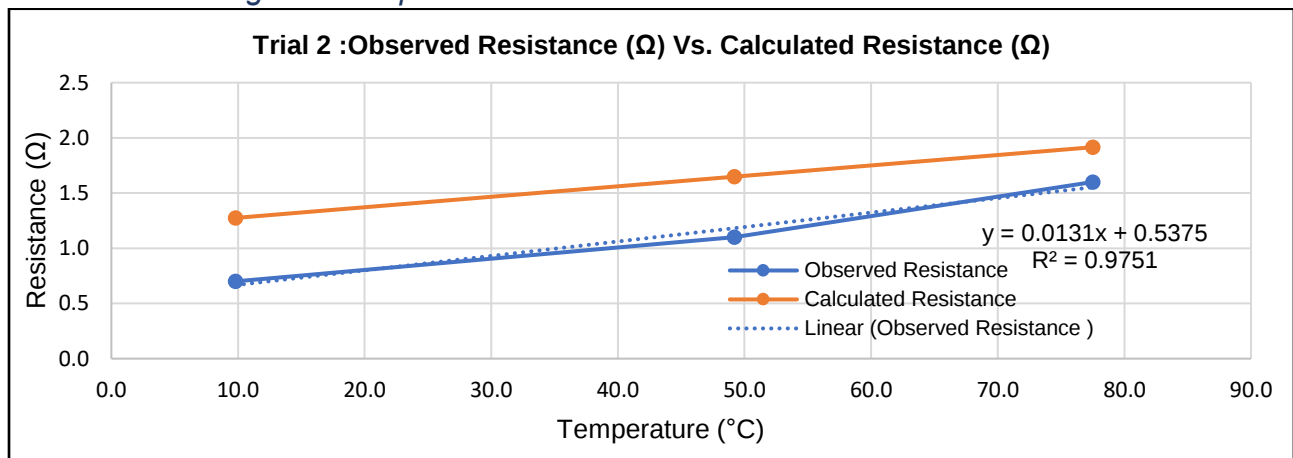


Figure5: Graph Observed vs Calculated Resistance Trial 2

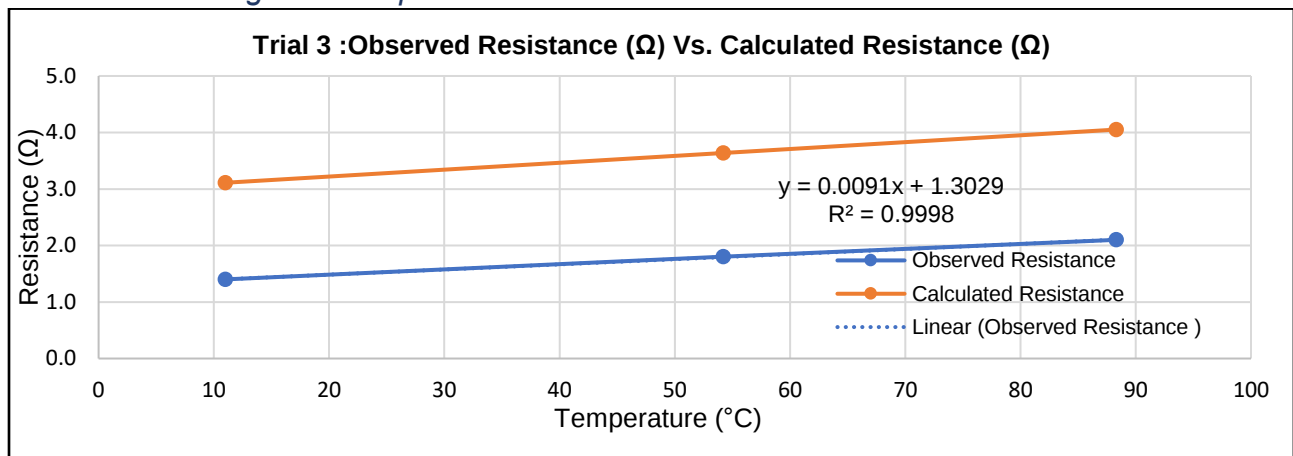


Figure6: Graph Observed vs Calculated Resistance Trial 3

The high R^2 (98+%) across three trials indicates that 98% of the variation in observed resistance is explained by the temperature of the metallic wire.

The Correlation Coefficient (Trial1) is: $r = \sqrt{R^2} \approx \sqrt{0.9867} \approx 0.993$.

The high positive r-value indicates an extremely strong positive correlation between temperature (x) and resistance (y). Same trend is for all trials.

The experiment confirms a linear increase in resistance with temperature, supporting the alternate hypothesis (H_1). The null hypothesis (H_0) is rejected, validating the predictable behavior of metals.

3. Conclusion

The aim of this experiment conducted was to investigate this relationship by measuring the resistance of a metallic wire at varying temperatures across trials. Results from experiments with three trials 1, 2, and 3 supports that as the temperature of a metallic wire increases, its electrical resistance increases linearly. Below is the summarized table across temperature ranges-

Temperature Range	Avg Observed Resistance (Ω)	Avg Calculated Resistance (Ω)
5 - 15	1.1	1.91
45-55	1.7	2.56
75-90	2.2	3.03

Table5: Final results of the trials

This observation is in line with theoretical hypothesis that in metallic conductors, increased thermal agitation of atoms impedes the flow of free electrons, thus increasing resistance. In some measurements, minor deviations were observed and can be attributed to the limitations of the setup of the experiment, including the lack of standard research instruments.

The observed and calculated resistances showed a high degree of correlation - resistance increases as temperature increases. This indicates a statistically significant and systematic relationship between temperature and resistance in metallic wires, affirming the linear dependency predicted by the theoretical framework as given in various literatures. For example - Sir William Siemens³ in 1871 first described that resistance increased with increased temperature. Similarly, in 1971, Eriksson, Keuther, and Glatzel⁴ identified six noble metal alloys with approximately linear resistance temperature characteristics.

³Wikipedia. (n.d.). *Resistance thermometer: History*. Retrieved from https://en.wikipedia.org/wiki/Resistance_thermometer#History. (Accessed Jan 2025).

⁴Eriksson, L. J., Keuther, F. W., & Glatzel, J. J. (1971). *A linear resistance thermometer*. Proceedings of the Fifth Temperature Symposium, Washington, DC, pp. 989–995

In conclusion, the experiment successfully tested the theory on the relationship of resistance in metallic wires with temperature. Future studies using more precise instruments and a more controlled environment could provide us with more accurate results, that can further improve our understanding of this relationship. It may also help us understand nonlinear patterns, especially at extreme temperatures.

4.Evaluation

4.1 Strength of Experiment

Accuracy of any experiment is driven by number of trials conducted and relationship between actual and predicted values. In this experiment, we have done three trials which allowed accurate measurement of all necessary results and also minimized random error.

Another strength of this experiment was use of same material across all the trials including very sensitive instruments including digital multimeter and digital thermometer. Also, same protocol was leveraged across all three trials. Preliminary trials conducted also helped to refine the setup. The experimental results aligned with scientific studies published over the years.

4.2 Sources of Error

Type of Error	Source	Impact	Mitigation
Random Errors - Unpredictable variations that affect the precision of measurements. These errors arise from inherent fluctuations in experimental conditions and instrumentation, making it difficult to obtain perfectly consistent results	Temperature fluctuations, multimeter noise, timing delays	Minor resistance deviations, especially at high temperatures	Improved insulation, repeated measurements and more insulated environment for temperature measurement
Systematic Errors- Introduce consistent biases in measurements, leading to shifts in calculated values. These errors affect accuracy and can result in overestimation or underestimation of key parameters	Calibration errors, wire non-uniformity, contact resistance	Over/underestimation of α (coefficients of resistance)	Calibrate instruments, use quality connectors, measure wire dimensions thoroughly.

Table6: Sources of Error

4.3. Quantifying Uncertainty

To estimate the errors, we consider the percentage uncertainty in resistance (R) and temperature (T) measurements.

Given

$$R = \frac{\rho L}{A}$$

$$\frac{\Delta R}{R} = \sqrt{(\alpha \Delta T)^2 + \left(\frac{\Delta L}{L}\right)^2 + \left(\frac{\Delta A}{A}\right)^2}$$

And given

$$\frac{\Delta \rho}{\rho} = \alpha \Delta T$$

Thus

$$\frac{\Delta R}{R} = \sqrt{(\alpha \Delta T)^2 + \left(\frac{\Delta L}{L}\right)^2 + \left(\frac{\Delta A}{A}\right)^2}$$

1. Temperature Uncertainty:

If the thermometer has an uncertainty of $\pm 0.05^\circ\text{C}$ and a measured temperature of $T = 55.9^\circ\text{C}$:

$$\text{Percentage Uncertainty in } T = \frac{0.05}{55.9} \times 100 = 0.089\%$$

2. Length Uncertainty: For a 2 m, uncertainty in length measurement is 0.05 mm

$$\frac{\Delta L}{L} = 0.0025\%$$

3. Area Uncertainty: Given the diameter is 0.695 mm and LC of screw gauge is 0.01 mm

$$\frac{\Delta A}{A} = 2 \times \frac{\Delta r}{r}$$

$$\frac{\Delta A}{A} = 1.44\%$$

4. Total Uncertainty: Using α for aluminum for each trial, following is the uncertainty. Values are very same as it is driven by area calculation

Trials	Temperature (°C)	Observed Resistance (Ω)	Uncertainty
1	14.67	1.2	1.4408%
1	27.80	1.7	1.4408%
1	55.90	2.2	1.4408%
1	84.20	2.9	1.4408%
2	9.80	0.7	1.4392%
2	49.20	1.1	1.4392%
2	77.50	1.6	1.4392%
3	11.00	1.4	1.4390%
3	54.20	1.8	1.4390%
3	88.30	2.1	1.4390%

Table7: Uncertainty Across Experiments

4.4 Conclusion on Errors and Results

Uncertainty of approx. 1.5% is low and can be improved with better setup. Also experiment confirmed a strong linear relationship between temperature and resistance, with consistent observed vs predicted, aligning with theoretical predictions. By further mitigating random and systematic errors with future refinements, the experimental results can be improved for more precision and accuracy.

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