Determining Thermal Conductivity of Aluminium, Copper, and Steel using Heating Sensors with and without Insulation

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April 8, 2025

Abstract

We investigate the thermal conductivity of aluminium, copper, and steel by measuring steady-state temperature gradients along each metal rod. An Arduino-based data acquisition system with multiple thermocouples records the temperature at various points while one end of the rod is heated. Fourier's law is then used to convert these temperature differences into estimates of thermal conductivity. Experiments conducted without insulation highlight significant radial heat losses, resulting in artificially low thermal conductivity values. By contrast, enclosing the rods in fibrous insulation better directs heat flow along their length, improving agreement with reference data.

Contents

1 Introduction

Heat can be transferred through conduction, convection, and radiation. In this project, we focused on thermal conduction as governed by Fourier's Law:

$$\vec{q} = -k\nabla T, \tag{1}$$

where q is the heat flow rate per unit area, or heat flux, k is the thermal conductivity of the material, and ∇T represents the temperature gradient. Since the heat flux is a vector quantity, there is a negative sign in the front and it indicates that if T decreases, for example, with position, q will be positive and vice versa. Therefore, the larger the k value is, the better to conduct heat. Our experiment takes into account only the x-direction of the heat flow, and the length of the rod is sufficiently larger than its height and width, so we neglected the y and z-directions. Accordingly, the above equation can be simplified to one dimensional form:

$$q = -k\frac{dT}{dx}. \tag{2}$$

To calculate the value of k, we need another expression of q:

$$q = \frac{Q}{t} \cdot \frac{1}{A} = \frac{P_{applied}}{A} = \frac{V^2}{R} \cdot \frac{n}{62499} \cdot \frac{1}{A}, \tag{3}$$

where Q is heat energy, t is unit time, $P_{applied}$ is an applied power, V is a voltage through the heater, R is the resistance of the heater, n is an applied PWM value, and A is the cross-sectional area of the metal rod. We multiplied $n/62499$ because we applied only a fraction of the max PWM size which is 62499. Eventually, we can determine the thermal conductivity k by equating Eq.(2) and Eq.(3):

$$k = -\frac{\Delta x}{\Delta T} \cdot \frac{V^2}{R} \cdot \frac{n}{62499} \cdot \frac{1}{A}, \tag{4}$$

where Δx and ΔT are the differences between the final and initial position and temperature for different sensors, respectively.

2 Materials and Methods

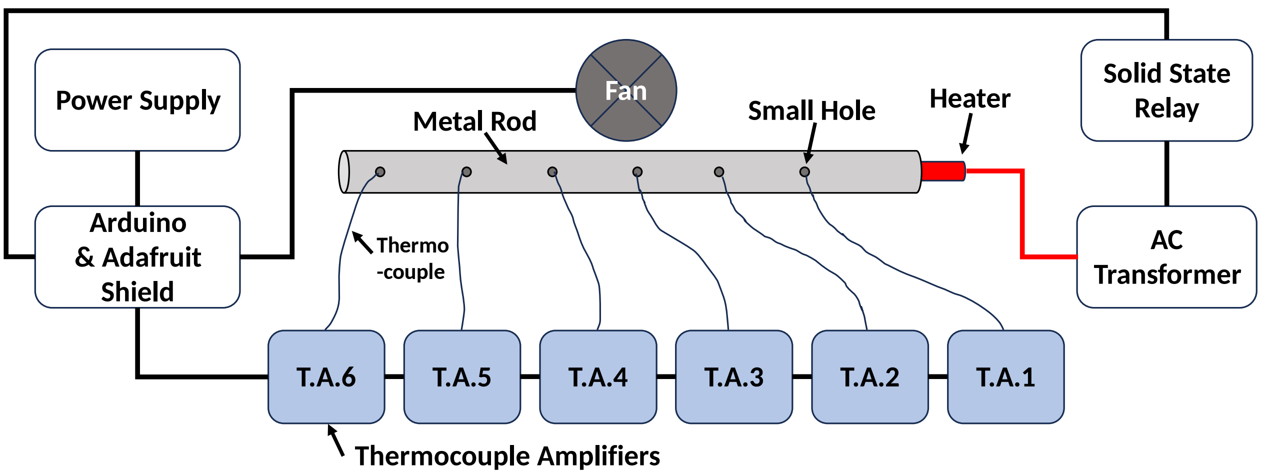


Figure 1: Experimental configuration. Real image of this setup is attached in Appendix (6).

We measured the thermal conductivity k of metal rods by monitoring temperature distributions using an Arduino-based data acquisition system. The rods (aluminium, copper, and steel) have uniform cross-sections and lengths of 15cm. Six thermocouple amplifiers (T.A.) are placed inside the holes along each rod at 2cm intervals. The rod is mounted horizontally, and a heater cartridge is placed at one end to supply heat.

During each trial, the rod is initially at a uniform temperature. Once the heater is switched on, the Arduino continuously reads temperatures from all sensors at fixed time intervals, sending data to a computer for logging. This continues until the rod approaches its steady-state temperature, where the amount of heat gained is exactly equal to the amount of heat lost. In this state, although heat may still be flowing through the system, there is no net accumulation of heat at any point. We repeated this procedure for rods of different materials under identical conditions.

3 Part 1: Thermal Conductivity without Insulator

Parameter	Value
Distance between T.A.s	20.0 ± 0.5mm
Applied voltage	4.922 ± 0.001 V
Resistance of heater cartridge	$14.3 \pm 0.1\ \Omega$
Radius of metal rod	9.5 ± 0.1 mm
PWM value (without insulator)	23000/62499
PWM value (with insulator)	7000/62499

Table 1: Experimental parameters with their uncertainties.

3.1 Results

Thermal Cond. k (W/mK)	Copper	Aluminium	Steel
Interval 1	56 ± 3	21 ± 1	11.7 ± 0.6
Interval 2	64 ± 3	28 ± 1	14.3 ± 0.7
Interval 3	78 ± 4	117 ± 6	17.0 ± 0.8
Interval 4	83 ± 4	105 ± 5	30 ± 2
Interval 5	260 ± 10	187 ± 9	73 ± 4
Reference value at 100°C	398 ± 4	235 ± 5	50 ± 3

Table 2: Measured thermal conductivities of each metal without an insulator, with corresponding uncertainties. Interval i represents the geometric interval between the i^{th} and $i+1^{th}$ thermocouple (i.e., Interval 1 represents the region between T.A.1 and T.A.2 in Fig. (1)). The standard values are cited from [1].

In the first attempt, no insulator was placed around the metal rod, and the resulting conductivity values shown in Table (2) generally deviate strongly from the reference value. For copper and aluminium, all intervals fall below the reference value of 398 ± 4 W/mK. Steel, by contrast, starts out with much lower-than-expected values in the first few intervals but then exceeds the reference in the final interval.

For each rod, the measured k in every interval remains below the published reference value (except for steel in Interval 5), with the lowest conductivities observed near the heater and higher ones further along the rod. Among all intervals, the best measured conductivities for copper, aluminium, and steel are approximately 260 W/mK, 187 W/mK, and 30 W/mK, corresponding to about 65%, 79%, and 60% of their respective reference values.

3.2 Discussion

A key pattern in the uninsulated measurements is that the calculated conductivity values tend to increase with distance from the heater for all three metals. Near the heater, there is greater radial heat loss to the surroundings because the temperature is much higher there, which in turn produces a larger temperature gradient and thus smaller calculated conductivities as ΔT is in the denominator according to Eq. (4). By contrast, intervals farther away from the heater experience less heat loss and a steadier temperature, causing the smaller ΔT to yield a higher computed k. Consequently, these uninsulated measurements—particularly near the heat source—underestimate the true thermal conductivity and are unreliable for comparison to reference data. They illustrate the importance of minimizing radial heat loss to approximate the ideal scenario that Fourier's law assumes. In practice, this is done by insulating the rod, thereby forcing more of the heat to flow along its length rather than out into the environment, which was done in the next section.

Despite these discrepancies, the fact that copper achieves the largest k of all three metals, while steel exhibits the smallest, aligns with the well-known ranking of metal conductivities. With improved insulation around the rod and more careful control of boundary conditions—such as sealing the rod or reducing convective air currents—it would be possible to minimize heat losses, thereby bringing the measured conductivities closer to idealized standards.

4 Part 2: Thermal Conductivity with Insulator

4.1 Results

Thermal Cond. k (W/mK)	**Copper**	**Aluminium**	**Steel**
Interval 1	43 ± 2	29 ± 1	11.3 ± 0.6
Interval 2	71 ± 4	30 ± 1	10.9 ± 0.5
Interval 3	95 ± 5	49 ± 2	12.8 ± 0.5
Interval 4	200 ± 10	154 ± 8	11.6 ± 0.6
Interval 5	310 ± 20	213 ± 9	12.0 ± 0.6
Reference value at 100°C	398 ± 4	235 ± 5	50 ± 3

Table 3: Measured thermal conductivities of each metal with an insulator(fiberglass), with corresponding uncertainties. Although k depends on temperature in reality, due to its sensitivity and the relatively small changes within our temperature range, we have chosen to use each metal's reference k value at 100°C only for comparison.

To reduce radial and convective heat losses, we enclosed each metal rod in fiberglass insulation. We also decreased the heater power from PWM23000 to PWM7000, ensuring the rod did not overheat, but this does not matter because although the resulting steady-state temperatures were somewhat lower overall, the key quantity for calculating thermal conductivity is the temperature difference between sensors rather than the absolute temperature. Under these conditions, copper and aluminium showed higher conductivity values than in the uninsulated trials, approaching the reference values across most intervals. The best measured conductivities were 310 W/mK for copper and 213 W/mK for aluminium, corresponding to around 78% and 91% of their respective references. By contrast, steel persisted in the range of 11–13 W/mK, with a maximum of 12.8 W/mK, which is about 26% of its benchmark. We obtained uniform thermal conductivities for steel, since its temperature difference between intervals does not vary significantly, as displayed in Fig. (2).

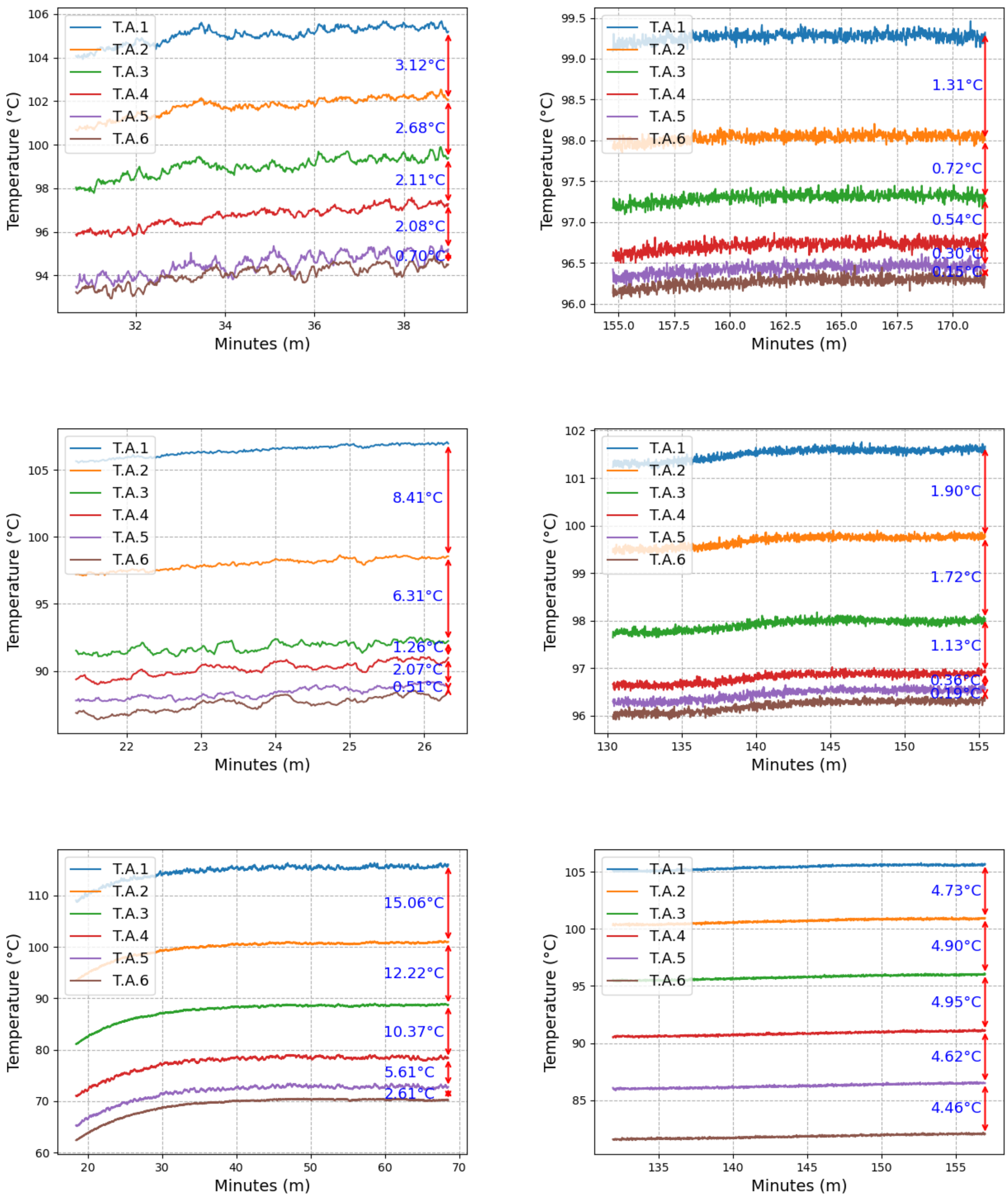
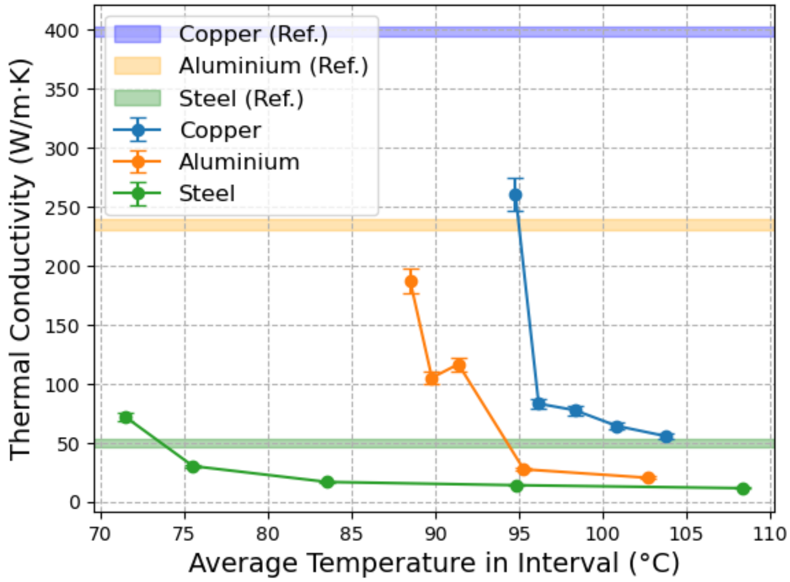
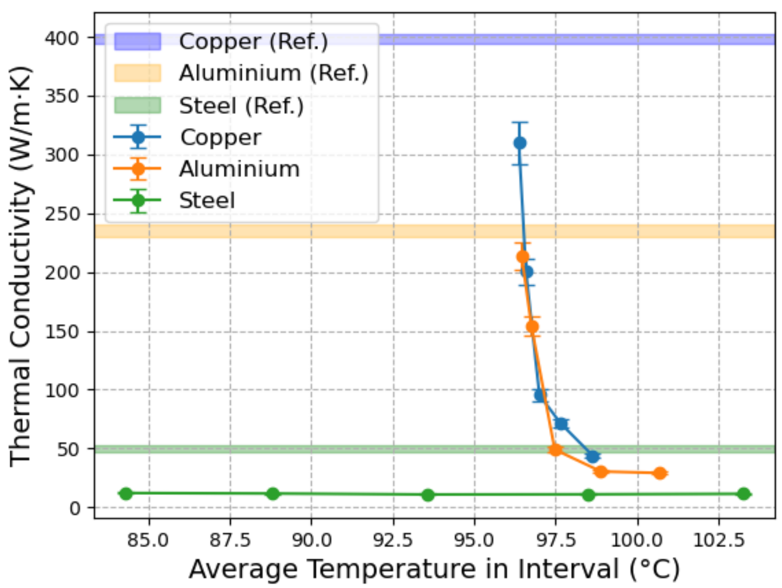


Figure 2: The first column represents the setup without insulation, while the second column shows the setup with insulation. Each row corresponds to copper, aluminum, and steel, respectively. We cropped the graphs to display only the final portion where steady-state temperature is achieved. On the right end of each graph, we marked the temperature difference relative to the previous thermocouple amplifiers(T.A.). These differences are smaller in the second column, reflecting the thermal insulation's effectiveness in reducing heat loss.



(a)



(b)

Figure 3: Scattered thermal conductivity values as a function of temperature for each metal, using the calculated k values from Tables (2) and (3). The colored boxes indicate the reference(Ref.) k value for each metal, with the box thickness representing the uncertainty. (a) Uninsulated case, and (b) Insulated case.

Additional analysis was conducted by plotting conductivity versus temperature for both insulated and uninsulated rods, shown in Fig. (3). For copper and aluminium, the plots showed a general decrease in k at higher temperatures. However, for steel, the uninsulated conductivity continuously decreased with temperature, while the insulated conductivity maintained a relatively uniform conductivity.

4.2 Discussion

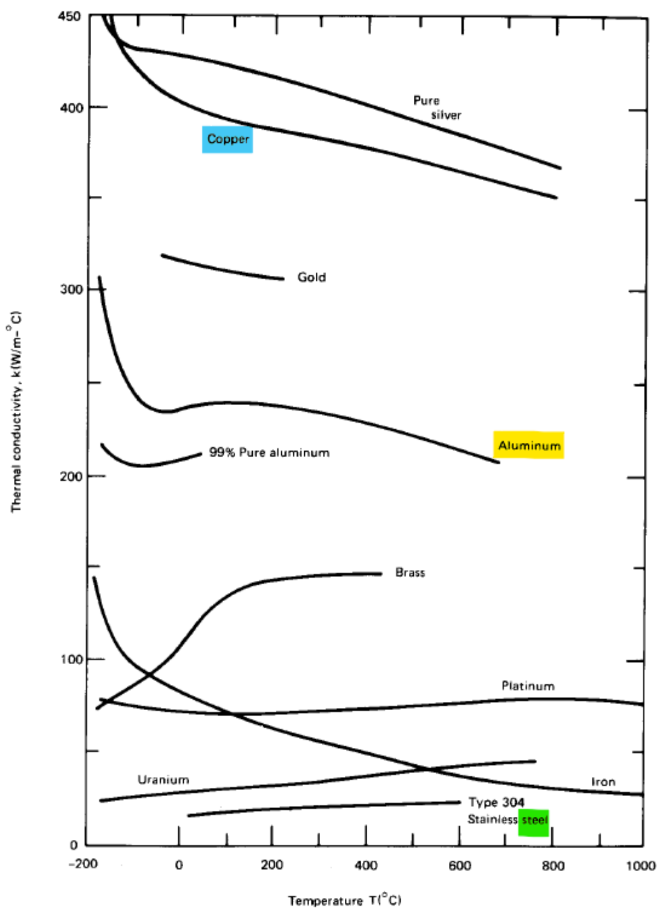


Figure 4: Reference thermal conductivity for various metals. Copper is marked with blue, aluminium with yellow, and steel with green. Adapted from [2].

The improved conductivity values for copper and aluminium upon adding insulation underscore the principal benefit of limiting radiative and convective heat losses along the rod. In essence, fiberglass wrap reduces the heat transfer pathways to the environment, forcing more of the heater's energy to propagate axially along the rod. This narrowed conduction channel raises the measured thermal conductivity closer to its ideal reference value.

In Fig. (3), an apparent trend is observed: thermal conductivity k decreases exponentially with increasing temperature. While this general correlation of decreasing behaviour holds true for many metals (except for steel, as it behaves reversely) [2], our experimental results do not support this behavior convincingly. In particular, the measured k values for copper and aluminium exhibit a sharp decline over a narrow temperature range, which contradicts the mild decrease over a large temperature range in the reference data. This discrepancy suggests additional losses of heat or measurement uncertainties still amplify the undesirable effect. For instance, as shown in Fig. (4), copper's k decreases by less than 10 W/mK with increasing temperature around 100°C. In conclusion, although our experiment correctly identifies the relative thermal conductivities of different metals and captures the overall decreasing trend, it falls short of producing accurate, quantitative values for k. Hence, better insulation or more uniform heating would likely narrow the gap between the mild real-world trend and our more drastic observed drop.

Unlike copper and aluminium, steel is expected to show a mild increase in conductivity with temperature, or at least remain nearly flat within the range of 95–105°C. Our uninsulated data instead show a distinct decrease, indicating that heat losses in the unwrapped steel rod dominate the conduction pathway. Once insulated, however, steel's conductivity remains consistently at around 11–13 W/mK, regardless of local temperatures, implying the insulation effectively stabilized the rod's thermal environment. Although these steel values still fall well short of the reference standard at 100 °C, the uniformity of the measurement points to diminished heat leakage. Overall, the big difference between uninsulated and insulated results for steel reaffirms that robust insulation helps preserve a more accurate and stable conduction profile, even if the absolute conductivities remain below literature benchmarks.

5 Conclusions

In this study, we measured and compared the thermal conductivities of aluminium, copper, and steel rods by tracking the temperature distribution along each sample with thermocouples and an Arduino-based data acquisition system. By applying Fourier's law to temperature gradients, we were able to estimate each metal's ability to transfer heat under both uninsulated and insulated conditions.

In the uninsulated trials, radial heat losses near the heater yielded severely low conductivity values at the hotter intervals compared to the reference values. Further from the heater, the reduced losses raised the measured conductivities, though most still remained below published references. Once we added insulation, copper and aluminium displayed higher, more consistent conductivities, approaching $78 - 91\%$ of their literature benchmarks.

For steel, the uninsulated rod showed a continuous drop in conductivity with increasing temperature, which does not agree with the mild increase that references predict. However, once insulated, steel's conductivity remained fairly uniform ($11 - 13$ W/mK) across the tested temperature range, suggesting that insulation mitigated radial losses and thus brought the measurement closer to the theoretical flat (or gently rising) trend.

Overall, these results confirm that controlling heat losses is crucial to improving the accuracy of thermal conductivity measurements. While some discrepancies persist—likely from sensor placement, residual end losses, and temperature-dependent inhomogeneities—the relative conductivity rankings among the three metals remain consistent with known behavior: copper, aluminum, and steel in the decreasing order. Employing an even more robust insulation could further minimize radial and convective losses, potentially narrowing the gap between measured and reference values.

References

[1] Engineering Page, "Thermal conductivity of metals," 2024, accessed: 2025-04-06. [Online]. Available: https://www.engineeringpage.com/technology/properties/metal_conductivity.html 3

[2] J. H. L. IV and J. H. L. V, *A Heat Transfer Textbook*, 5th ed. PHLOGISTON PRESS, 2020, ch. 1.3, 2.1. 8, 9

6 Appendix

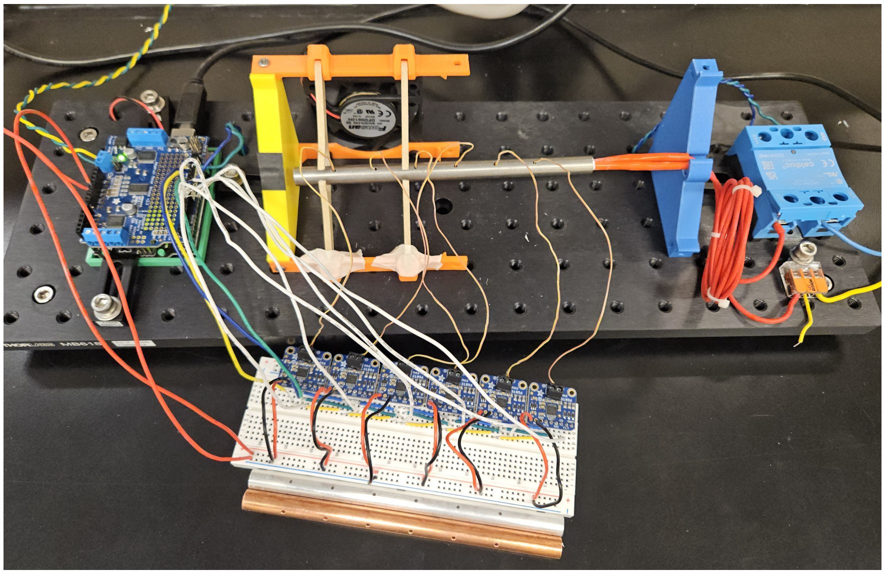


Figure 5: Real image of the setup without insulator.

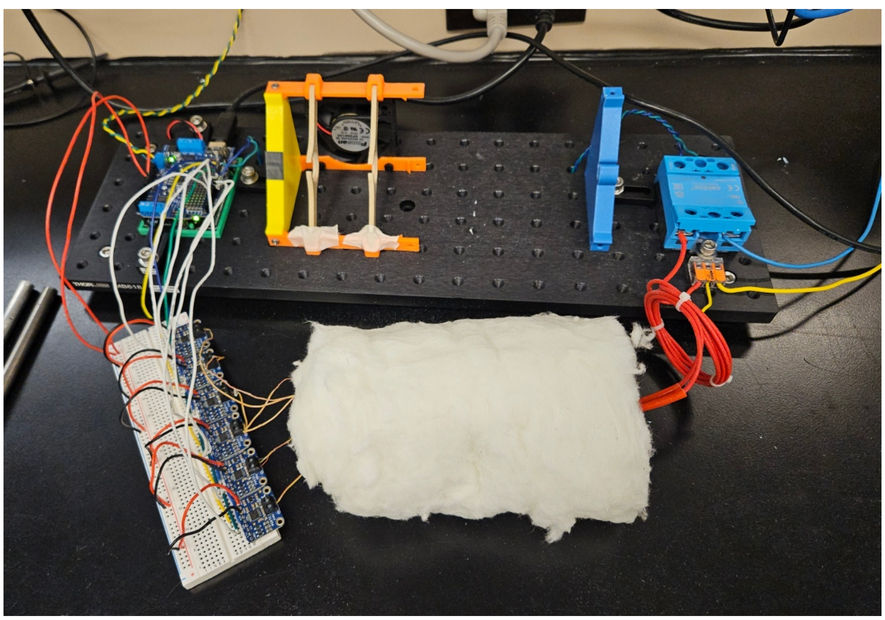


Figure 6: Real image of the setup with insulator (fiberglass).