Measurement of Copper's Seebeck coefficient

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(Dated: February 15, 2025)

This study presents the development and implementation of an experimental setup to measure the Seebeck coefficient of copper wire using a four-probe method. The experiment utilizes a peltier cell to generate a temperature gradient across the sample, with temperature and voltage data collected during both heating and cooling phases. A linear regression analysis was employed to calculate the Seebeck coefficient. The results showed a strong linear relationship during heating, with slight deviations observed during cooling due to transient thermal effects, however, the results aligns reasonably well with known literature values, considering the temperature limitations of the experimental setup. This work contributes to a better understanding of the thermoelectric properties of metallic conductors and offers insights into improving measurement techniques for Seebeck coefficient determination.

Keywords: Seebeck coefficient, thermoelectric effect, copper, four-probe method, linear regression, temperature gradient.

I. INTRODUCTION

The thermoelectric effect involves the direct transformation of heat into electrical energy, making it a promising technology for recovering waste heat. Thermoelectric energy conversion offers several benefits, such as high reliability, long operational lifespan, and scalability. However, its broader adoption has been limited due to low efficiency. The performance of thermoelectric materials is assessed using a dimensionless figure of merit, $ZT = \frac{S^2 T}{\rho\kappa}$, where S represents the Seebeck coefficient, ρ is the electrical resistivity, κ denotes the thermal conductivity, and T is the absolute temperature.

Recent research has focused on improving thermoelectric materials by maximizing their ZT values, with accurate Seebeck coefficient measurement being essential for evaluating performance. Measurement techniques are mainly divided into two-probe and four-probe methods. The two-probe method, simpler and suitable for bulk samples, measures temperature across metal contacts but overlooks contact thermal resistance. In contrast, the four-probe method measures temperature directly on the sample and is better for thin or small samples where contact resistance is significant.

In this study, we developed an apparatus for measuring the Seebeck coefficient of a 5 cm copper wire within a temperature difference range of 5 to 35 K. The sample is a cylindrical copper wire with a length of 5 cm and a diameter of 3 mm. Due to the nature of the sample, we implemented the four-probe measurement scheme to ensure accuracy. To improve measurement efficiency, a quasi-steady-state differential method was employed, allowing for reduced measurement time. To enhance thermal contact between the sample and the thermocouples, we used Kapton tape at the contact points.

The sample holder consists of two wooden blocks, each with a square base of approximately 25 cm^2 and a height of 4 cm. These blocks serve as support structures for the thermocouple contact points and the copper wire ends. Although the setup is not highly compact, the use of wood ensures minimal thermal conductivity, preventing unwanted heat dissipation and maintaining a stable temperature gradient along the sample.

Our goal is to develop a reliable and accessible method for characterizing the Seebeck coefficient of metallic conductors, contributing to a better understanding of their thermoelectric properties.

II. EXPERIMENTAL DETAILS

A. Design of Experimental Holder

Figure 1 shows a photograph of the sample holder used for Seebeck coefficient measurements. The holder consists of two symmetrical parts, each made of a wooden base and an alumina holder secured with two screws. An additional hole in the alumina holder is used to attach the thermocouple wire, while a layer of Bakelite insulates the thermocouple from the alumina. During measurements, a thin, bar-shaped copper wire sample is suspended between the two wooden bases, which are separated by approximately 2.5 cm. Two Peltier plates apply a temperature gradient along the axial direction of the sample in a reversible manner. Temperature readings are taken at two adequately separated points on the sample using two type K thermocouples equipped with MAX6675 amplifiers.

The thermocouple heads are pressed against the wire ends at the peltier cells using the alumina holder. To ensure electrical insulation between the two thermocouples, a small sample of Kapton is placed between the thermocouple heads and the copper wire. In this configuration, the Kapton is the only material in direct contact with the thermocouple heads. In addition to providing electrical insulation, the Kapton also enhances thermal conductivity.

The alumina holder can be adjusted with screws to

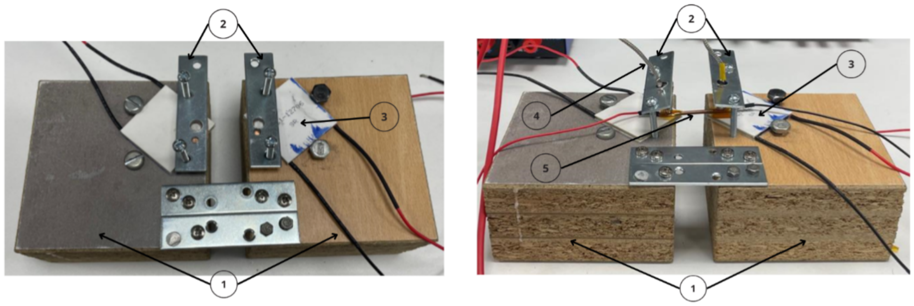

FIG. 1. [(a) and (b)] The photograph of the sample holder for the Seebeck coefficient measurement. ① Wood bases; ② alumina holder; ③ Peltier plate; ④ thermocouple; and ⑤ copper wire.

apply pressure between the thermocouple heads and the wire. This method not only simplifies the sample mounting process but also prevents the deterioration of thermal contact due to mismatched thermal expansion coefficients between the sample and other components.

B. Experimental Procedure

To determine the Seebeck coefficient, it was assumed that the heating process of the copper rod was slow enough to allow voltage and temperature measurements to correspond to a quasi-static state.

The measurement of the Seebeck coefficient of Copper, targeting temperature differences from 5 K to 35 K, was conducted in two phases: heating and cooling. Right after the Peltier plates were activated to generate the temperature gradient, thermocouples and voltmeter recorded data every 500 μS, using an Arduino program. This recorded the increasing temperature gradient and corresponding voltage growth. Once the temperature differences reached 35 K, the Peltier plates were deactivated, and the system was left to cool while measurements continued to collect an additional dataset.

C. Mathemathical Model

For calculating the Seebeck coefficient of a copper rod, the experiment was based on a model that describes the thermoelectric behavior of a material through the following relation between current density, electromotive field, and temperature gradient [1].

$$\boldsymbol{J} = \sigma \boldsymbol{\mathcal{E}} - \sigma S \nabla T \tag{1}$$

where $\boldsymbol{J}$ is the current density, $\boldsymbol{\mathcal{E}}$ the electromotive field, σ the electrical conductivity of the material, ∇T the temperature gradient and S the Seebeck Coefficient at a given point in the circuit. By considering the steady state-case condition ($\boldsymbol{J} = 0$), and by rewriting $\boldsymbol{\mathcal{E}} = -\nabla V$, eq. 1 simplifies to:

$$\nabla V = -S \nabla T \tag{2}$$

For the system described in Fig.1, integration of eq. 2 leads to a voltage between points A-B [1] given by

$$\Delta V_{AB} = -\int_{T_b}^{T_a} (S_{Cu} - S_{wire})\, dT$$

Following this work's prediction that in the temperature range 25° C to 85° C the Seebeck coefficient of copper can be approximated as a constant and neglecting the thermoelectric effect of the wire, i.e. $S_{wire} \approx 0$, the equation takes the form

$$\Delta V_{AB} = -S_{Cu} \Delta T_{AB} \tag{3}$$

This is the mathematical model used to determine an approximation of the copper Seebeck coefficient. Thus, the experimental data were fitted using linear regression to obtain a numerical approximation of S_{Cu}.

III. RESULTS AND DISCUSSION

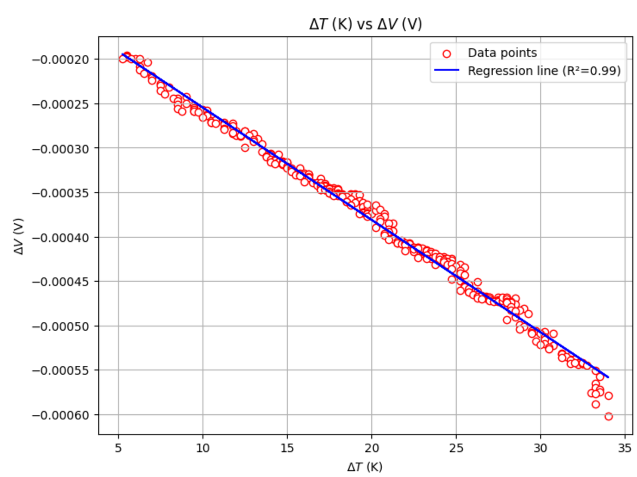

FIG. 2. ΔT vs ΔV for extracting the Seebeck coefficient of Copper in a heating stage, the solid line is a linear fitting of experimental data.

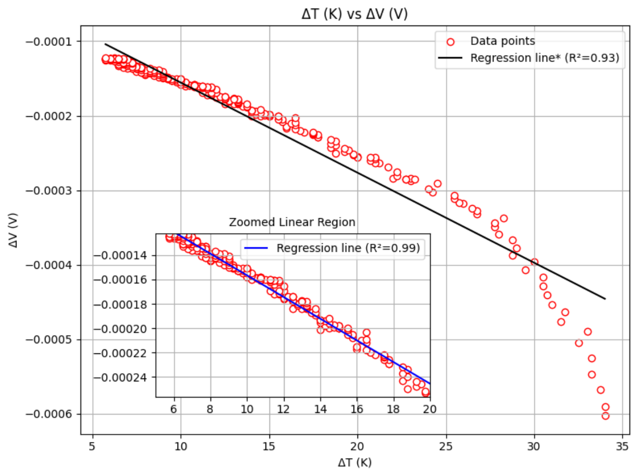

FIG. 3. ΔT vs ΔV plot used to extract the Seebeck coefficient of copper during a cooling stage. The solid lines represent linear fits applied to distinct regimes within the same experimental dataset.

As mentioned in section II B, measurements were taken in two phases. During the heating stage, the collected data led to the result shown in Fig.2. The linear behavior predicted in eq. 3 is strongly supported by the computed value of $R^2 = 0.99$ for the linear regression. The fitting parameters yield an experimental coefficient of:

$$S_{Cu} = (12.66 \pm 0.40)\ \ \mu V/K$$

Comparing this to the literature value $S_{Cu} = 6.5\ \ \mu V/K$ for Cu at 0 K [2], the result appears reasonable, given that the cold point of the copper rod was always at a temperature above 25°C.

For the cooling stage, the result is shown in Fig. 3. A clear non-linear tendency emerges as the temperature gradient increases, reflected in an $R^2 = 0.93$. For this data points the linear fitting leads to a coefficient of

$$S_{Cu} = (12.09 \pm 0.79)\ \ \mu V/K$$

which is relatively close to the value obtained in the heating stage. However, this behavior is primarily due to a higher density of data points at smaller temperature differences.

These results must be interpreted under the assumptions stated in Sections II C and II B. The assumptions that the thermoelectric contribution of the wire is negligible and the procedure operates in a quasi-static regime introduce potential sources of systematic error.

To improve the precision of the linear fit, the same data set for the cooling phase was analyzed but restricted to temperature differences between 5° C and 20° C, where the cooling process is slow and leads to a region that seems to be more linear. These results correspond to the zoomed inset Fig.3. And define a coefficient

$$S_{Cu} = (8.896 \pm 0.63)\ \ \mu V/K$$

that is much closer to the one taken from the literature.

Finally, it is important to highlight that the uncertainty intervals were determined by combining the standard error of the slope from the linear fitting and the propagation of uncertainties from the instrumentation.

IV. CONCLUSION

The experimental results confirm that the Seebeck coefficient of copper can be estimated through linear regression of voltage vs. temperature difference. The data obtained from the heating phase exhibit a strong linear correlation ($R^2 = 0.99$), supporting the theoretical model. However, during the cooling phase, some deviations from linearity were observed ($R^2 = 0.93$), particularly at larger temperature differences, likely due to transient thermal effects.

To improve the accuracy of the Seebeck coefficient estimation, the cooling data were restricted to a smaller temperature range ($5°C \leq \Delta T \leq 20°C$), where the system remained closer to thermal equilibrium. This refined dataset resulted in a coefficient

$$S_{Cu} = (8.896 \pm 0.63)\ \ \mu V/K,$$

which is much closer to literature values.

The uncertainties in this study were carefully evaluated by incorporating both statistical regression errors and instrumental uncertainties. While the experimental values are reasonably close to reference values, potential systematic errors—such as the assumption of a quasi-static regime and the neglection of wire thermoelectric effects—may influence the results. Future work could explore improved insulation techniques and more precise temperature control to refine the accuracy of the measurements.

[1] S. J. Blundell and K. M. Blundell, *Concepts in Thermal Physics*, 2nd ed. (Oxford University Press, 2009).
[2] M. Li, S. Xu, Q. Chen, and L.-R. Zheng, Thermoelectric-generator-based dc–dc conversion networks for automotive applications, Journal of Electronic Materials **40**, 1276 (2011).