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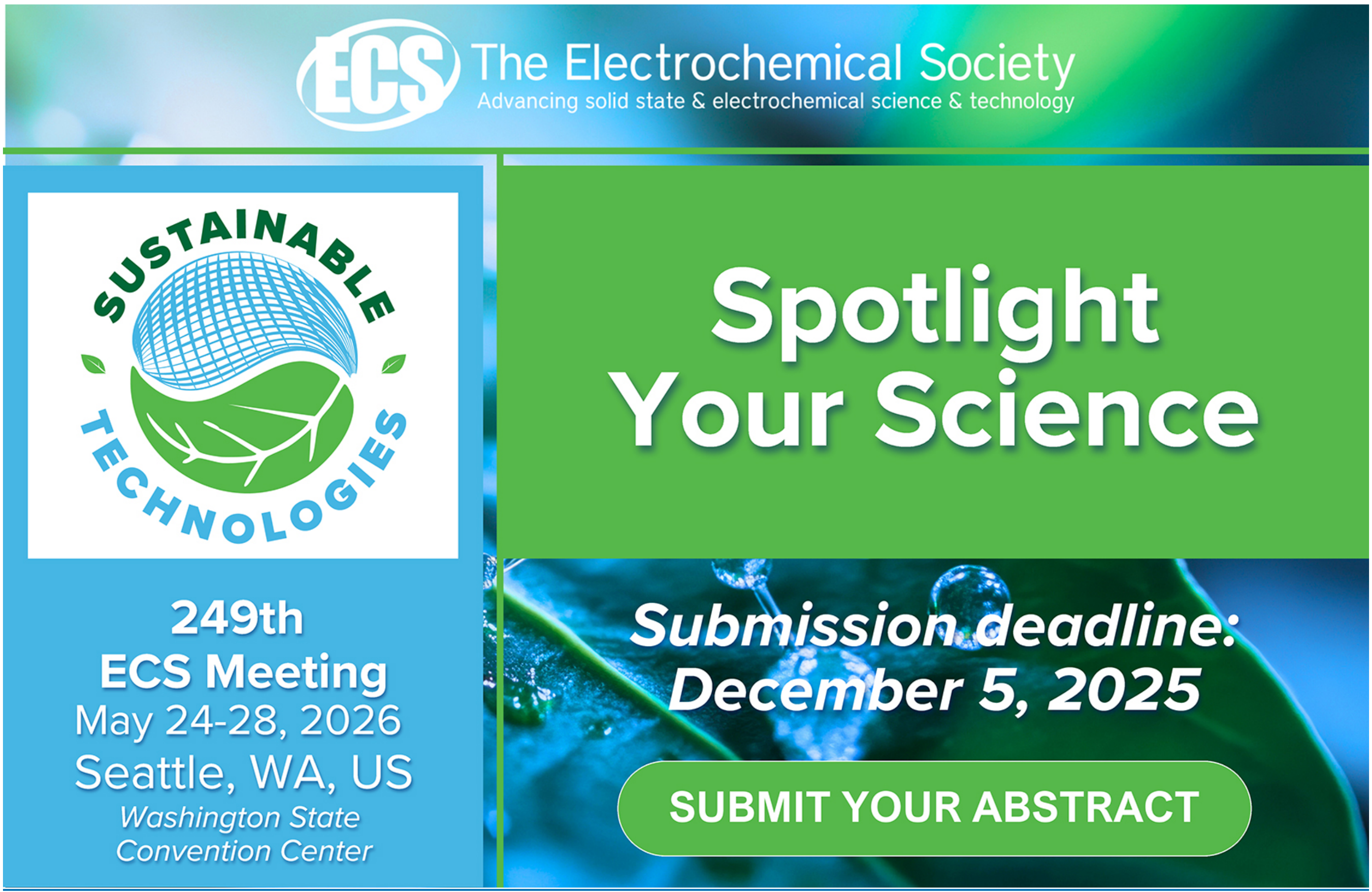

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Development and Validation of Thermocouple for Thermodynamics Experiment

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Abstract. Undergraduate students often struggle with Thermodynamics due to a lack of hands-on experience with the devices and sensors discussed in coursework. Traditional experimental setups—such as engine test benches and HVAC systems—are prohibitively expensive and maintenance-intensive, limiting student access and requiring large group work that can reduce individual engagement. To address this issue, we developed and implemented a cost-effective thermocouple calibration apparatus for use in undergraduate Thermodynamics laboratories. The equipment utilizes affordable, readily available components, enabling the creation of multiple identical setups within a constrained budget. This allows students to work in smaller groups, increasing interaction and individual learning opportunities. The apparatus supports instruction in key Thermodynamics concepts, including temperature measurement, sensible and latent heat, and the Seebeck effect. Results from implementation show improved student comprehension and engagement. This approach offers a scalable, practical solution for enhancing Thermodynamics education, with potential applications across engineering curricula seeking to improve experiential learning within limited resources.

Keywords: Thermocouple, Thermodynamics, Calibration, Experiments

1. Introduction

Thermodynamics is widely recognized as a challenging subject for undergraduate students, particularly due to its abstract concepts and the mathematical rigor involved [1]–[3]. One contributing factor is the limited hands-on experience students have with the types of devices and sensors discussed in lectures. This disconnect can hinder conceptual understanding and student engagement. Research has shown that introducing experimental activities early in the curriculum can significantly enhance comprehension and motivation [4], especially when students can directly observe thermal phenomena and measurement processes.

In many engineering programs, thermodynamics experiments involve large and complex equipment such as gas turbines [5], gasoline engines, refrigerators, and even power plant systems [6], [7]. While these setups provide realistic and advanced learning experiences, their high cost, maintenance demands, and space requirements often restrict access. Consequently, students typically engage with these systems in large groups, limiting individual interaction and learning.

To address this gap in accessible and affordable laboratory equipment, we developed a simple, low-cost thermocouple calibration experiment tailored for undergraduate instruction. At the Department of Mechanical Engineering, President University, this experiment has been integrated into the curriculum to help students:

1. Understand the fundamentals of temperature measurement,
2. Learn the working principles of thermocouples based on the Seebeck effect [8],
3. Apply thermodynamic concepts such as sensible and latent heat,
4. Practice data analysis using the least squares method.

The experimental setup involves small, handmade electric furnaces used to heat metals with known melting points, allowing students to calibrate two types of thermocouples. Despite the relatively long heating process, the experiment fits within a standard laboratory session by using multiple furnaces prepared in advance. This approach enables small-group or individual participation, enhancing engagement and learning outcomes.

Unlike many commercial setups that treat sensors as black boxes, this experiment emphasizes hands-on construction and understanding of measurement tools. Moreover, it serves a dual educational purpose: not only do students gain practical thermodynamics knowledge, but junior technical staffs also receive training in equipment construction, material sourcing, and maintenance. This contributes to departmental self-sufficiency and skill development.

This paper presents a novel scalable and replicable model for low-cost thermodynamics experiments solution that can be readily implemented in resource-constrained academic settings. Compared to previous studies that rely heavily on commercial systems or large-scale equipment [9], our approach prioritizes accessibility, interactivity, and foundational understanding—key elements in improving thermodynamics education.

2. Experiment Setups and Experiment Procedure

This experiment investigates the thermoelectric behavior of thermocouples by calibrating them using the known melting points of selected metals. The approach involves precise instrumentation setup, careful calibration procedures, and adherence to safety protocols to ensure both accuracy and student safety.

2.1 Materials and Equipment

Two dissimilar electrical conductors are joined to form thermocouples, which generate a voltage (Seebeck voltage) based on the junction temperature due to the Seebeck effect. When the relationship between junction temperature and output voltage is well-characterized, the thermocouple serves as a reliable temperature sensor [10]–[13]. The Seebeck voltage E_{AB} is related to the absolute thermoelectric powers S_A and S_B of the conductors [10], [13]. In practical applications, this voltage is approximated using a second-order polynomial, where a and b are experimentally determined constants.

$$\frac{dE_{AB}}{dT} = S_B - S_A \tag{1}$$

$$\mathrm{E_{AB}} = \int (\mathrm{S_B} - \mathrm{S_A})\vec{\nabla} \cdot \overrightarrow{\mathrm{dx}} \tag{2}$$

$$E_{AB} \approx \mathrm{aT} + \mathrm{b}T^2 \tag{3}$$

For calibration, metals with well-known and stable melting points were selected: tin, lead, and zinc. These metals exhibit minimal supercooling behavior and are thermally stable under laboratory conditions. Water's melting and boiling points were also used as calibration benchmarks are listed in Table 1. Aluminum was excluded due to its high melting point (660.3°C), which could not be reliably achieved with the experimental apparatus. Three identical electric furnaces are built for the three metal specimens. The overview of the experiment setup is shown in Fig. 1.

Table 1. Melting and Boiling Points of the Speciments

Specimen	Melting or boiling point (°C)
Ice water mixture	0
Boiling water	100.0
Tin	231.9
Lead	327.4
Zinc	419.4

2.2 Apparatus Design and Calibration Procedures

Three identical electric furnaces were custom-built for the three metallic specimens. Each furnace consisted of the following components, (1) A ceramic Tamman tube (test-tube-shaped with one closed end) that houses the metal specimen, (2) A thermocouple assembly inserted into the specimen and sheathed in a thin ceramic tube to allow replacement without contamination, (3) The ceramic tube is suspended inside the Tamman tube using a wire collar to ensure it does not touch the walls, avoiding thermal conduction errors, (4) The Tamman tube is inserted into a larger ceramic tube wrapped with a nichrome heating wire (rated ~50 W), powered by a DC source, and (5) The outer casing of the furnace is a stainless-steel lunchbox, repurposed for thermal insulation. Mineral wool is packed between the ceramic tube and the casing for effective heat retention.

All thermocouples are pre-tested and calibrated at 0°C and 100°C using an ice-water mixture and boiling water respectively. The reference junctions (formed from Iron and Constantan) are submerged in the ice-water bath and insulated using thin plastic tubes to prevent electrical interference. A high-precision voltmeter is used to record the thermoelectric voltage output. Three identical electric furnaces are built for the three metal specimens. The overview of the experiment setup is shown in Fig. 1.

2.3 Addressing Experimental Challenges

To address typical problems encountered in undergraduate thermodynamics labs, such as equipment unreliability and unclear procedures, the following steps were taken, (1) Modular thermocouple design allows for easy replacement in case of malfunction without disturbing the experiment, (2) The custom-built furnaces are low-cost and durable, made from commonly available materials, reducing equipment downtime and maintenance issues, (3) Clear assembly diagrams (Figs. 1–5) support student understanding and reduce ambiguity during setup, and (4) By dedicating one furnace per metal, group work is streamlined, allowing multiple students to work simultaneously and effectively in smaller teams.

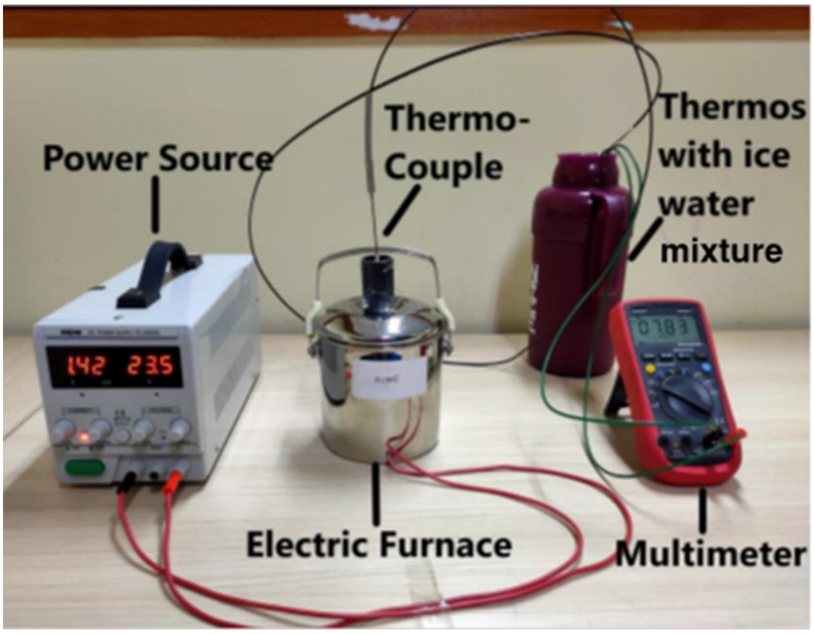

Figure 1. Thermocouple Calibration Setup

2.4 Safety Considerations

Given the use of heating elements and molten materials, stringent safety measures were implemented i.e. nichrome wires are fully insulated and enclosed to prevent accidental contact. All ceramic and metallic components are thermally stable at the operating temperatures. Heat-resistant gloves and goggles are mandatory during operation. The stainless-steel casing remains cool to the touch due to mineral wool insulation, reducing burn risks. Emergency power shutoff switches are installed on each furnace for quick disconnection in case of overheating or malfunction. Proper ventilation is ensured to mitigate exposure to metal fumes during melting, especially for lead.

The specimen is placed inside a ceramic Tamman tube, which is a test-tube shaped tube with one end closed. A thermocouple covered with a thin ceramic tube is placed inside the specimen as shown in Fig. 2. The thin ceramic tube is fixed to the collar at the top of the Tamman tube with a thin wire so that the thin ceramic tube does not touch the Tamman tube inside surface. By placing the thermocouple in the thin ceramic tube, it is possible to change the thermocouples without contaminating the specimen.

The Tamman tube is placed in another ceramic tube as shown in Fig. 3. The details of a thermocouple are shown in Fig. 4. The sensing junction of the thermocouple is electrically insulated and covered with stainless steel sheath. A nichrome wire, capacity of about 50 W, is wrapped around the outer ceramic tube. By applying electricity to the nichrome wire from a direct current power source, the specimen within the Tamman tube is heated. The outside casing of the electric furnace is a stainless-steel lunchbox purchased at a local supermarket. Mineral wool insulation is placed in the casing. As shown in Fig. 5, the reference junctions, which are the connections between metals A and B, and copper wires, are placed in ice water mixture at 0°C. The reference junctions are covered with thin plastic tubes so that they are electrically isolated from ice water mixture. The temperature of the ice water mixture is monitored using a bar thermometer. The voltage between the reference junctions is measured by a voltmeter. The reference junctions are made from Iron and constant wires.

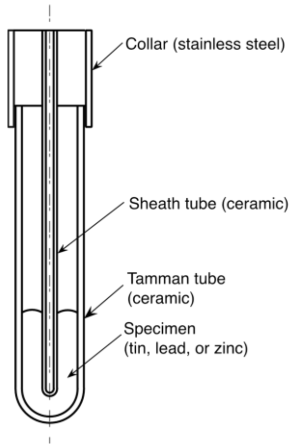

Figure 2. Tamman Tube

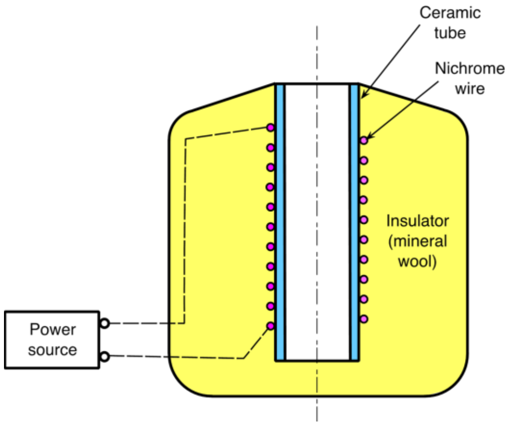

Figure 3. Electric Furnace

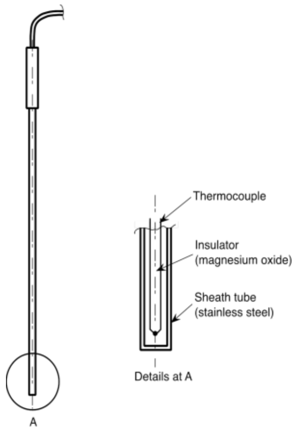

Figure 4. Thermocouple Details

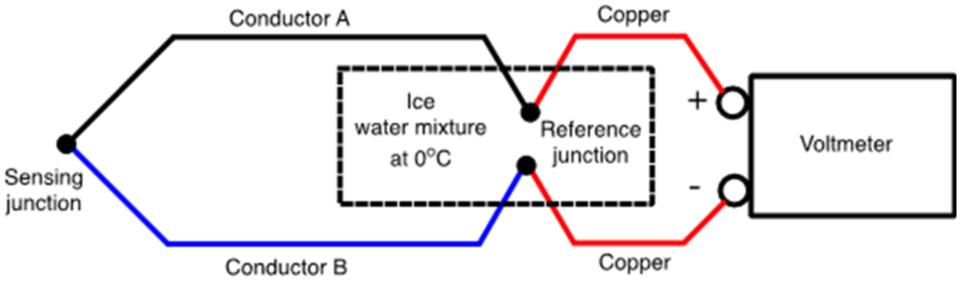

Figure 5. Thermocouple Calibration Setup Electric Connections

3. Results and Discussion

In this experiment, students calibrated thermocouples by observing the voltage output during the phase transitions of three metal specimens: lead, tin, and zinc. Heating was provided by nichrome wire elements wrapped around ceramic tubes, and voltage readings were recorded every 20 seconds using a voltmeter. As the specimen was heated and approached its melting point, the voltage increased. When melting occurred, the temperature—and thus the output voltage—stabilized temporarily, forming a plateau that was used to identify the freezing or melting point of each material. This behavior aligns with the theoretical Seebeck effect, where the thermoelectric voltage E_{AB} between two conductors is related to the temperature difference across the junctions, Eq (1). The freezing plateau, where the temperature remains constant during phase transition, corresponds to a stable Seebeck voltage, enabling accurate calibration against known melting points.

3.1 Voltage Readings at Melting Points

In the experiment, the specimen inside the Tamman tube is heated by applying direct current to the nichrome wire. Since it is practically impossible to visually check the state of the specimens, the students are informed the voltmeter reading, which is determined by the instructor in advance, to turn off the heater for each specimen. When the nichrome wire heater is turned off, the output voltage starts to reduce as the temperature of the specimen decreases by heat loss through the insulation layer. The students read and record the voltmeter reading every 20 seconds. At the melting point of the specimen, the voltage is kept a constant or close to constant value for more than 2 minutes. When all of the specimen solidifies, the voltage starts to reduce again. The measurement is finished, when the students confirm the voltage reduces for another couple of minutes. The procedure of the experiment is summarized in Fig. 6. Table 2 summarizes the steady-state voltages (plateau values) recorded during melting for each metal using both K-type and T-type thermocouples.

Table 2. Plateau values recorded during melting for each metal using both K-type and T-type thermocouples

Material	Known Melting Point (°C)	Voltage at Plateau (K-Type, mV)	Voltage at Plateau (T-Type, mV)
Lead	327.5	13.23	16.35
Tin	231.9	9.43	10.95
Zinc	419.5	17.21	—

Each of three electric furnaces has different metal specimen inside. The students are separated into two or three groups. Each group works on one of the specimens at a time. By repeating the same procedure on the three specimens, each group measures the relation between the voltage output values and the three melting points. While waiting the specimens to melt, the groups also measure the voltage reading for ice-water mixture and boiling water. In this experiment, old-fashioned measurement configuration is purposely adopted so that Seebeck effect is visible from the students. Instead of the temperature measurement function of multimeters, the output voltage from the thermocouples is read using a voltmeter.

In all cases, voltage readings remained stable for approximately 2–3 minutes during melting, confirming that thermal equilibrium was achieved and phase change occurred. The measured voltages were then compared to values calculated from the Japanese Industrial Standards (JIS) tables for Seebeck voltage versus temperature for K-type and T-type thermocouples.

3.2 Calibration Using Water

To anchor the calibration, experiments were also conducted using the freezing (0°C) and boiling (100°C) points of water. The thermocouple tips were immersed in boiling water while the reference junctions were maintained in an ice-water bath.

Table 3. Calibration anchor

Condition	Expected Voltage (mV)	Measured (K-Type)	Measured (T-Type)
0–100°C (Water)	~3.97 (K), ~4.22 (T)	3.98	4.19

These results closely matched theoretical expectations, validating the setup's basic accuracy and confirming the linearity of the Seebeck response in this temperature range.

3.3 Accuracy and Error Analysis

The measured Seebeck voltages were compared to the JIS standard values for each thermocouple type. The percent deviation from the expected values was calculated using the Eq. (4) for the lead melting point (327.5°C) with a K-type thermocouple, JIS value ≈ 13.05 mV, Measured value = 13.23 mV, Percent error ≈ 1.38%. Similar analyses showed that most deviations were within 2–3%, indicating strong alignment with theoretical predictions. Minor deviations may result from ambient thermal gradients or cooling during measurement, contact resistance or slight contamination at thermocouple junctions, inherent limitations of manual timing and analog voltmeter readings.

$$\text{Percent Error} = \frac{\text{Measured}-\text{Expected}}{\text{Expected}} \times 100\% \qquad (4)$$

3.4 Least Squares Fitting

To emphasize the nonlinearity of the Seebeck effect over the temperature range, a second-order least squares polynomial fit was applied to the experimental data. The curve fit coefficients were calculated by students and plotted in Fig. 7, demonstrating how Seebeck voltage varies with temperature in accordance with:

$$E_{AB}(T) \approx aT + bT^2 \qquad (5)$$

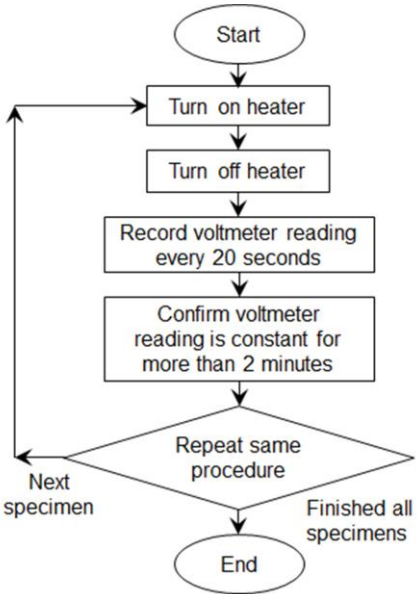

Figure 6. Experiment procedure

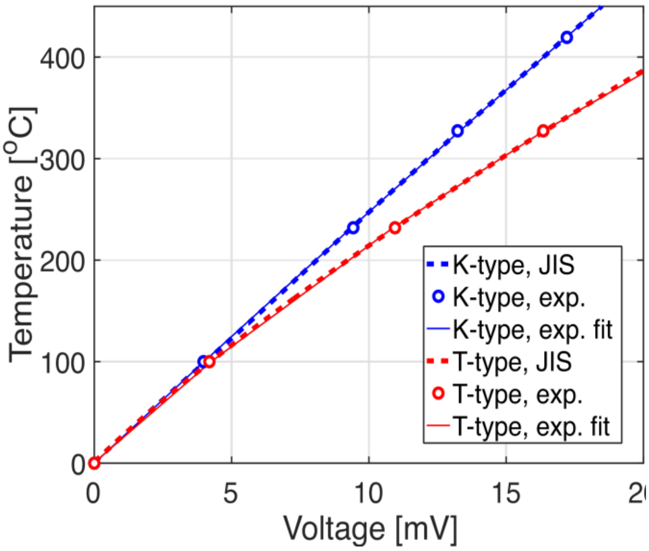

Figure 7. Thermocouple Calibration Sample Results

These fits closely traced the JIS reference curve (Fig. 7), reinforcing students' understanding of the voltage–temperature relationship in thermocouples. Three metal materials were tested, such as lead with weight of 180 grams, tin and zinc, with weight of 120 grams. By inserting each material into the tamman tube, then followed by inserting the sheath tube in each tamman tube as well. Tamman tube that has been filled with each material is inserted again into the electric furnance, one by one. In addition, the K-type thermocouple and / or T-type thermocouple is insert one end of the sheath tube and the other end is connected to the multimeter and thermos with ice water contents with a temperature of 0 °C. The current and voltage measurement results are generated from the power-supply cable connection to the nichrome wire in the electric furnance. The experiment results are carried out by power-supply setting on each material using a K-Type Thermocouple, with 1.72 mA current, 28.3 V voltage and 17.15 mV multimeter target for lead material. Furthermore, in case of the tin material, 1.02 mA current and 28.6 V voltage are setted on the power-supply, and the target on the multimeter is 13.00 mV.

Meanwhile, for the zinc material, 1.44 mA current and 23.5 V voltage are setted on the power-supply, and the target on the multimeter is 18.90 mV.

3.5 Educational and Practical Implications

By avoiding digital temperature displays and instead using direct voltage readings, students gained hands-on experience with the raw thermoelectric behavior of materials. The consistent detection of melting points and comparison to JIS tables demonstrate that even a low-cost, manually operated system can yield results with high accuracy and educational value.

The experiment results for thermocouple measurement of boling water is include in the graph as shown in Fig. 8. The comparison graph between the experiment data following the Seebeck voltage equation and the property table of the thermocouple, as shown in Fig. 9. The results in the graph are explained that the experiments using a thermocouple which were carried out above 100 °C temperature are in line with those in the property table [14].

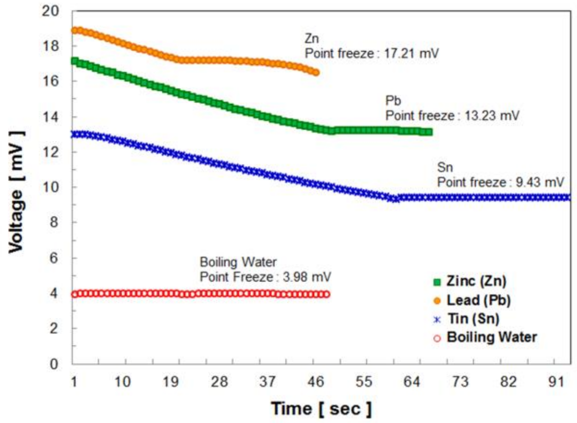

Figure 8. Graph of Thermodynamics Experiment Results with Point Freeze for Metals and Boiling Water

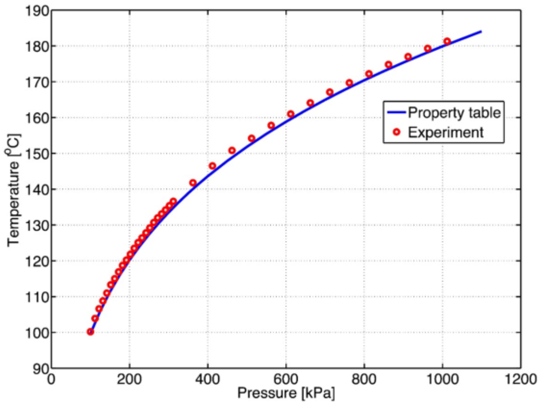

Figure 9. Heating profile of thermocouple experiment and it compared with the property table [14]

4. Concluding Remarks

This study demonstrates the successful design and implementation of a low-cost thermocouple calibration apparatus using small, handmade electric furnaces. By leveraging the known melting points of metals, students are able to calibrate thermocouples through direct comparison of measured temperatures and output voltages. The simplicity and affordability of the setup allow multiple identical stations to be prepared, enabling students to work in smaller groups and engage more actively with the experiment.

The apparatus supports the broader goal of improving thermodynamics education by offering a hands-on, accessible introduction to key concepts such as temperature measurement, the Seebeck effect, and least squares data fitting. Its practical design also reinforces fundamental skills in experimental procedures, safety, and report writing. Because the equipment is easy to operate and produces reliable results close to standard values, it serves as an effective learning tool for early-stage engineering students.

In practical terms, this setup is well-suited for institutions with limited resources, offering a scalable and replicable model for teaching core thermodynamics principles. For future development, the experiment could be enhanced by integrating digital data acquisition, enabling automated logging and analysis. Additional research could explore its impact on student learning outcomes compared to traditional or commercial systems. The approach could also be adapted to cover other fundamental measurements in thermodynamics, further expanding its educational value.

Acknowledgment

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Author Contributions

Lydia Anggraini contributed to the conceptualization of the research, literature review, and the design of the experimental setup. She also led the data analysis and manuscript preparation.
Rendi Hernawan was responsible for the development and calibration of the thermocouple system, conducted the experimental work, and contributed to data collection and result validation.

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