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Peltier Effect

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1 Phenomenological Introduction

In metals, electrical and heat conductivity are primarily due to free electrons. Non-equilibrium dynamics can hence directly convert temperature differences to electric voltage and vice versa. This gives rise to two first-order thermoelectric effects, called the Seebeck effect and Peltier effect.

The Seebeck effect discovered by Thomas Johann Seebeck in 1821, is the diffusion of charge carriers due to a temperature gradient in the material. In a simplified picture, when a region of a metal is heated, the free electrons there gain more energy and will move away towards the cooler ends of the metal (see Figure 1a). As a result, the warmer regions become more positively charged, and due to the uneven charge distribution in the metal, there is a voltage induced. The electric field per temperature gradient is a property of the material, called the Seebeck coefficient ϵ.

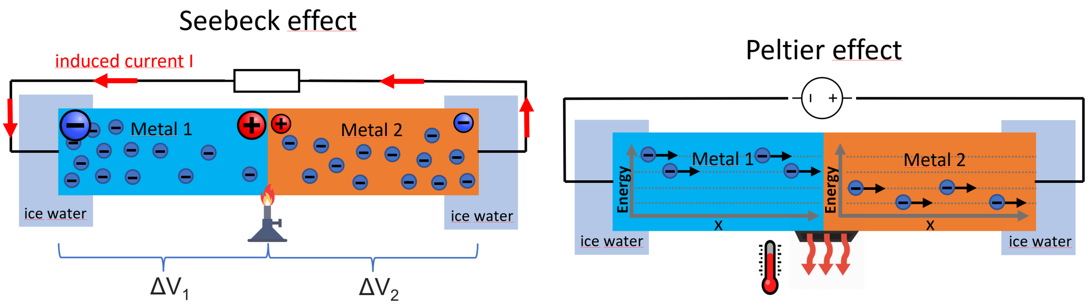
The fact that this property is material dependent can be explained by use of the "band theory of solids", which is an important concept in Solid State Physics. Since electrons are fermions, the Pauli exclusion principle demands that no more than two electrons in a quantum system occupy the same quantum state. In a single atom, this leads to the idea of electronic orbitals, where each orbital can only be occupied by a specific maximum number of electrons at a discrete energy level. However, when two atoms are placed close to each other, their orbitals overlap. Since the Pauli exclusion principle in this new quantum system still needs to hold, two overlapping orbitals now split up into two discrete molecular orbitals, each one with a slightly different energy level.

However in a solid, where the atomic density and thus the orbital overlap is very high, the energy differences between adjacent molecular orbitals become very small. The overlapping orbitals can thus be considered as a continuum, a so called energy band [1]. These energy bands have defined lower and upper energy boundaries, and are discretely distributed over the whole energy spectrum. The electronic configuration of a metal can then be described by electrons within the energy band and their degree of occupation.

On the other hand, as any physical system wants to attain a state of lowest energy, electrons will settle into the lowest possible energy states by filling the energy bands from the bottom up. This means that only the energy bands with higher energy levels, which are only partially filled or completely unoccupied, offer any degrees of freedom for the transition of electrons into adjacent energy levels. The position of the relevant bands is determined by the Fermi level of the metal. At absolute zero temperature, the electrons will occupy the lowest possible energy levels, thus forming a *Fermi sea* of electronic energy levels where the Fermi level is the surface of this sea named Fermi energy E_f, and it marks the highest energy level occupied at 0 K.

The closest energy bands below and above the Fermi level are called valence and conduction band, respectively. As the name suggests, it is the conduction band that allows for the movement of electrons along the metal, enabling current and heat flow on a macroscopic scale. Yet, only the electrons in the uppermost region of the valence band even have a chance of transitioning to the mostly unoccupied energy level in the conduction band. The energy separation between valence and conduction band, as well as the occupancy of the valence band is called energy band gap and is what distinguishes conductors, semiconductors, and insulators.

Since such properties like distribution of energy bands, Fermi level, and electron occupancy are material specific, the energy levels carried by electrons flowing in an electrical current are also material specific. This also means that heat conduction in a metal is material specific. As a result, macroscopic relationships like electric field per temperature gradient, as given by the Seebeck coefficient ϵ, are also dependent on the material itself.



(a) (b)

Figure 1: (1a) scheme of the Seebeck effect using an external source of heat depicted by the Bunsen burner and (1b) illustrates Peltier effect scheme in a thermocouple where we see the energy levels along the two dissimilar metals.

The Peltier effect, discovered by Jean Charles Athanase Peltier in 1834, is the heating or cooling at an electrified junction of two different conductors, it is actually the inverse of the Seebeck effect. With the Seebeck effect, we managed to drive a current by heating a junction of two dissimilar metals. On the other hand, the Peltier effect will allow us to heat or cool such a junction by running a current through it. To visualize this, we consider again two dissimilar conductors joined together at one end forming a junction, with the other ends connected to a voltage source. Such a setup is shown in Figure 1b. The voltage difference will cause an electric current in this given circuit.

By Kirchhoff's first law, the incoming current $\boldsymbol{I}_{in}$ at the junction and the outgoing current $\boldsymbol{I}_{out}$ must be equal. Therefore the amount of electrons entering the junction must equal the amount leaving the junction. However, as the energy levels in conduction band differ for dissimilar metals, these electrons will carry different energies. These energies are given by the Peltier coefficient Π. It states the amount of heat i.e. energy carried per unit charge, and has unit Volt. Lets consider the case where the conduction band energy in metal 1 contains higher energy levels than the conduction band in metal 2, as implied in Figure 1b. This means that an electron travelling from metal 1 to metal 2 will enter the conduction band of metal 2 with a higher energy than necessary. Hence, the electrons moves to lower energy states, releasing the spare energy at the junction in the form of heat, represented by the thermometer in Figure 1b. If the direction of current is inverted, the electrons will have to take up energy in order to move to the higher energy conduction band. This excess or deficiency energy released or gained at the junction will heat or cool the junction, respectively [2]. The energy released per unit charge at the junction is called the Peltier coefficient Π_{12} of this thermocouple, and it depends on the Peltier coefficients Π_1 and Π_2 of the materials forming the junction. This effect is called Peltier heating or Peltier cooling, respectively.

Those concepts can be explored to convert heat into an electric current. For this purpose, consider two dissimilar conductors joined together at one end forming a junction, with the other ends connected by a wire over a resistor. Such a setup is shown in Figure 1a, where metal 1 and metal 2 are dissimilar. When the junction is now externally heated (as implied by the Bunsen burner in Figure 1a), electrons will diffuse away from the junction to the cooler ends. This induces a voltage ΔV_1 and ΔV_2 in the two metals, respectively. These voltages depend on the Seebeck coefficients ϵ_1 and ϵ_2 of the metals, and will consequently be of different magnitude. As a result, there is an overall nonzero voltage $V_{tot} = |\Delta V_1 - \Delta V_2|$, which induces a current I in the closed circuit.

A similar setup can now be used to measure the temperature at the junction. To do that, the two ends of the conductors need to be held at a known constant reference temperature T_{ref}, e.g by use of an ice bath. Then, the overall voltage V_{tot} in the circuit is measured with a voltmeter. The only unknown quantity in the system is now the temperature difference $\Delta T = T_j - T_{ref}$ between the temperature at the junction T_j and the reference temperature T_{ref}. Within a small temperature range and in linear approximation, it is linked to the voltage by $V_{tot} = (\epsilon_1 - \epsilon_2)\Delta T$. Hence, if the Seebeck coefficients of the involved metals are known, T_j can be determined. Note that any additional temperature-related potential differences in the wires cancel out, since they consist of the same material and are connected to the same reference temperature T_{ref}. Such a setup as described here is referred to as a thermocouple, and it is widely used for temperature measurements, also in this experiment. In practice however, the relation between overall voltage and temperature difference is more complicated, as the Seebeck coefficients itself are temperature dependent. Precise calibration of various thermocouples is thus an extensive field of study on its own.

This experiment examines the Peltier effect by determining the Peltier coefficient of the junction of a copper rod and a constantan[1] rod. The Seebeck effect is applied to measure temperature differences using thermocouples.

2 Theoretical Background

Since their discovery, a solid theoretical framework has been developed to describe the thermoelectric effects. The so-called "Onsager relations" capture the linear response of electric current density $\boldsymbol{J}$ and heat current density $\boldsymbol{U}$ to electric field $\boldsymbol{E}$ and temperature gradient ∇T inside a conductor [?]. Slightly re-arranged for simplicity, they read

$$\boldsymbol{E} = \rho \boldsymbol{J} + \epsilon \nabla T \tag{1}$$

$$\boldsymbol{U} = \Pi \boldsymbol{J} - \kappa \nabla T, \tag{2}$$

where ρ is the electric resistivity, and κ the thermal conductivity. From Equation (1), one recovers Ohm's law for $\nabla T = 0$ and the Seebeck effect for $\boldsymbol{J} = 0$. Equation (2) describes Fourier's law for heat conduction for $\boldsymbol{J} = 0$ and the evolution of heat accompanying the flow of an electric current for $\nabla T = 0$. If the latter happens at an isothermal junction of two metals 1 and 2, , i.e when the temperature gradient ∇T is zero, the heat current density has a discontinuity,

$$\boldsymbol{U}_{12} \equiv \boldsymbol{U}_1 - \boldsymbol{U}_2 = (\Pi_1 - \Pi_2)\boldsymbol{J} \equiv \Pi_{12}\boldsymbol{J}. \tag{3}$$

The constant Π_{12} is the Peltier coefficient of the junction, and it is assumed to be positive depending on the current density $\boldsymbol{J}$. If it is positive, the excess heat will warm up the junction. When the direction of the electric current is inverted, the sign changes, and the junction will be cooled down.

It is not obvious, but based on the principle of microscopic reversibility, Onsager's theorem states that $\Pi = \epsilon T$. This shows the close link between Seebeck and Peltier effect. It also implies that the Peltier coefficient depends on the properties of the material, as well as on the temperature. It shall be noted that while the macroscopic treatment of the phenomena is sufficient here, the Seebeck coefficient can be calculated within the framework of the electron theory of metals.

Unwanted but unavoidable in this experiment is the non-negligible effect of "Joule heating," which is the local generation of heat when a current flows through a resistive material. Even though it is related, it is generally not considered a thermoelectric effect, and, in contrast to the Seebeck and Peltier effect, it is thermodynamically irreversible [?]. Joule heating depends on the resistivity of the metal, and will thus not affect dissimilar metals equally. Hence, in order to determine the Peltier coefficient of a junction of two dissimilar metals, it is necessary to account for the presence of Joule heating. In order to do that, consider the local conservation of heat,

$$\frac{\mathrm{d}u}{\mathrm{d}t} = -\nabla \cdot \boldsymbol{U} + \boldsymbol{J} \cdot \boldsymbol{E}. \tag{4}$$

[1] Constantan is a copper-nickel alloy usually consisting of 55 % copper and 45 % nickel.

where u is the local energy density, and $\boldsymbol{J} \cdot \boldsymbol{E}$ is the Joule heat generated per unit volume. By inserting Equations (1) and (2) for $\boldsymbol{E}$ and $\boldsymbol{U}$, respectively, one finds to first order (i.e assuming that ϵ and κ are temperature independent)

$$\frac{du}{dt} = -\nabla\Pi \cdot \boldsymbol{J} - \Pi\nabla \cdot \boldsymbol{J} + \kappa\nabla^2 T + \rho \boldsymbol{J}^2 + \epsilon \boldsymbol{J} \cdot \nabla T \tag{5}$$

Note that this equation is an approximation, as ϵ and κ actually are temperature dependent. However in this derivation, we assume that their temperature dependence is small, thus making the terms $\nabla\epsilon$ and $\nabla\kappa$ negligible. In the experiment, we will only be interested in the steady state of the system, i.e when $\frac{du}{dt} = 0$ and $\nabla \cdot \boldsymbol{J} = 0$. The first and last term cancel by inserting the relation $\Pi = \epsilon T$, and one is left with

$$\kappa\nabla^2 T(\boldsymbol{x}) = -\rho \boldsymbol{J}(\boldsymbol{x})^2. \tag{6}$$

This equation describes how Joule heating changes the temperature gradient in a metal with thermal conductivity κ and electrical resistivity ρ. We see that the right-hand-side of Equation (6) is always negative, meaning that Joule heating will always counteract the presence of temperature gradients in a metal. Also note that Joule heating depends on $\boldsymbol{J}^2$ and is therefore independent of the direction of the electric current.

3 Measurement Method

The Peltier coefficient of a copper-constantan Peltier element is determined as a function of temperature. It consists of a copper and a constantan rod with lengths L_1 and L_2, and cross sectional areas F_1 and F_2, respectively (top of Figure 2). Their junction is soldered and their far ends are rigidly connected to copper blocks, which are kept at a constant temperature T_b by immersion in an oil bath.

The x-axis is set alongside the two rods, with the origin $x = 0$ at the junction, and $x > 0$ within the constantan rod, as depicted at the bottom of Figure 2. Given this coordinate system, a positive current $+I$ runs from the copper rod to the constantan rod. It causes Peltier heating at the junction and Joule heating along the two rods. After some time, a steady state will be reached, where local temperatures stay constant. In particular, the junction will have constant temperature T_J^+. In the following derivation, the superscripts $^+$ or $^-$ mean that we are considering a positive current $+I$ or a negative current $-I$, respectively. Then, the temperature difference $\Delta T^+ = T_\mathrm{J}^+ - T_\mathrm{b}$ between the junction and the oil bath is measured. For the reversed current, $-I$, the junction is cooled, and, in analogy, the temperature difference ΔT^- is measured. This procedure is repeated for currents of $I = (2,\ 4,\ 8,\ 12,\ 16, 20)\,\mathrm{A}$ and oil bath temperatures of $T_\mathrm{b} = (30,\ 50,\ 70,\ 90, 110)\,°\mathrm{C}$.

The results from Section 2 are now used to derive formulas for the Peltier coefficient based on the measurements of $\Delta T^\pm$. This temperature difference is a result of both Peltier and Joule heating. However, one needs to subtract the contribution from Joule heating in order to relate the temperature difference to the Peltier coefficient Π_{12}.

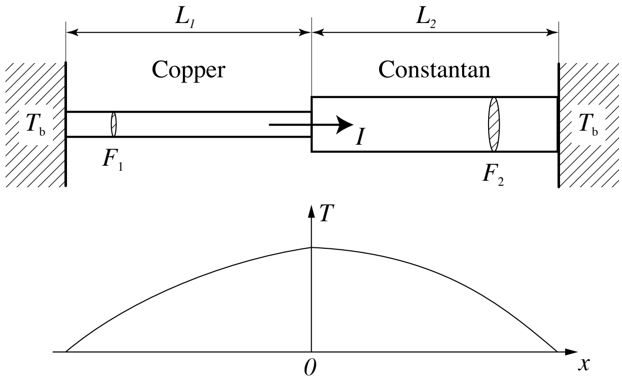


Figure 2: *Top:* Illustration of the copper-constantan Peltier element. The copper blocks at the outer ends act as heat exchangers and are kept at a fixed temperature T_b. *Bottom:* Schematic depiction of the temperature gradient along the rods, which is generated by Peltier and Joule heating for a positive input current I.

We assume that the temperature $T(\boldsymbol{x})$ in the rods depends only on the x coordinate. Thus, the temperature in a cross-section of the rods parallel to the $y-z$ plane is considered to be constant. We further assume that $\boldsymbol{J}(\boldsymbol{x}) = \boldsymbol{J}(x) = \frac{I}{F1}\hat{\mathbf{x}} = \frac{I}{F_2}\hat{\mathbf{x}}$. In that case, Equation (6) takes the form

$$\kappa \frac{\partial^2 T(x)}{\partial x^2} = -\rho \boldsymbol{J}(x)^2 \tag{7}$$

By integrating Equation (7) once with respect to x, one gets an expression for the temperature gradient $\nabla T = \frac{\partial T}{\partial x}$ as a function of position x:

$$\nabla T_1(x)^{\pm} = -\frac{\rho_1}{\kappa_1}(\frac{\pm I}{F_1})^2 x + C^{\pm} \quad \text{for } x \leq 0 \tag{8}$$

$$\nabla T_2(x)^{\pm} = -\frac{\rho_2}{\kappa_2}(\frac{\pm I}{F_2})^2 x + D^{\pm} \quad \text{for } x \geq 0 \tag{9}$$

where $C^{\pm}$ and $D^{\pm}$ are constants of integration. Integrating again from $x = -L_1$ to $x = 0$ and from $x = L_2$ to $x = 0$, one finds expressions for the temperature differences $\Delta T^{\pm}$ measured before. For the copper rod, one has

$$\Delta T_1^{\pm} = \frac{\rho_1}{2\kappa_1 F_1^2} L_1^2 I^2 + L_1 C^{\pm}, \tag{10}$$

and for the constantan rod, one finds

$$\Delta T_2^{\pm} = \frac{\rho_2}{2\kappa_2 F_2^2} L_2^2 I^2 - L_2 D^{\pm}. \tag{11}$$

When the stationary state is reached, the energy flux into and out of the junction must be equal, $F_1 U_1(0) = F_2 U_2(0)$, assuming negligible lateral heat conduction into the air. Therefore, from Equation (2) one can get

$$0 = F_1 U_1(0) - F_2 U_2(0) = \pm(\Pi_1 I - \Pi_2 I) + \kappa_2 F_2 \nabla T_1(0)^{\pm} - \kappa_1 F_1 \nabla T_2(0)^{\pm} \tag{12}$$

for positive and negative current $\pm I$. This can be rearranged to read

$$\pm\Pi_{12} I = \kappa_1 F_1 \nabla T_1(0)^{\pm} - \kappa_2 F_2 \nabla T_1(0)^{\pm}. \tag{13}$$

By inserting Equations (8) and (9) for $\nabla T_1(x)^{\pm}$ and $\nabla T_2(x)^{\pm}$ at $x = 0$, respectively, one gets

$$\pm\Pi_{12} I = \kappa_1 F_1 C^{\pm} - \kappa_2 F_2 D^{\pm} \tag{14}$$

Next, one uses Equations (10) and (11) for the unknown integration constants $C^{\pm}$ and $D^{\pm}$, respectively. One arrives at

$$\pm\Pi_{12} I = \left(\frac{\kappa_1 F_1}{L_1} + \frac{\kappa_2 F_2}{L_2}\right) \Delta T^{\pm} - \frac{R_1 + R_2}{2} I^2, \tag{15}$$

where one makes use of the fact that the temperature difference between the junction and the copper blocks $\Delta T^{\pm} = \Delta T_1^{\pm} = \Delta T_2^{\pm}$ is the same for both rods, and where $R_{1,2} = \rho_{1,2} L_{1,2}/F_{1,2}$ are the rod's resistances. In Equation (15), the last term represents the contribution from the Joule heating.

For positive and negative current polarizations, one can eliminate Joule heating by subtracting the two Equations (15) to find

$$\Pi_{12}^{(I)} = \left(\frac{\kappa_1 F_1}{L_1} + \frac{\kappa_2 F_2}{L_2}\right) \frac{\Delta T^{+} - \Delta T^{-}}{2I}. \tag{16}$$

Additionally, from adding the two equations, one gets

$$\left(\frac{\kappa_1 F_1}{L_1} + \frac{\kappa_2 F_2}{L_2}\right) \frac{\Delta T^{+} + \Delta T^{-}}{I} = (R_1 + R_2)\, I \simeq V_{\mathrm{P}}, \tag{17}$$

where V_{P} is the voltage between the two far ends of the rods, and the last equality holds when contact resistances can be neglected. Insert this into Equation (16) to obtain

$$\Pi_{12}^{(V)} = \frac{V_{\mathrm{P}}}{2} \frac{\Delta T^{+} - \Delta T^{-}}{\Delta T^{+} + \Delta T^{-}}. \tag{18}$$

The Peltier coefficient of the copper-constantan junction can therefore be computed as $\Pi_{12}^{(I)}$ and $\Pi_{12}^{(V)}$ from measurable quantities readable from Equations (16) and (18).

4 Experimental Setup

The copper-constantan Peltier element (parameters given in Table 1) is housed in a glass diving bell, which is immersed in an oil bath such that only the heat exchanging copper

Table 1: Experimental parameters. Use inter- or extrapolation when necessary.

	Copper	Constantan
Rod length (mm)	$L_1 = 50$	$L_2 = 50$
Rod diameter (mm)	2.03	7.04
rod resistance ($10^{-8}\,\Omega\,\mathrm{m}$)	$\rho_1 = 1.68..2.06$ at $(293..353)\,\mathrm{K}$	$\rho_2 = 44$
thermal conductivity ($\mathrm{W\,m^{-1}\,K^{-1}}$)	$\kappa_1 = 401..391$ at $(250..400)\,\mathrm{K}$	$\kappa_2 = 21.9..26.6$ at $(275..400)\,\mathrm{K}$

blocks at the ends get in contact with the oil. The oil bath is kept at the constant temperature T_b by a feedback-controlled heater, while a magnetic stirrer circulates the oil to reduce temperature gradients.

A power generator in series with a shunt resistor is connected in series to the heat exchangers (Figure 3) to provide the stable currents $\pm I$ through the Peltier element. By measuring the voltage V_s across the shunt and dividing it by its resistance, the input current $\pm I$ can be precisely measured and regulated. For every new current setting, the system takes about 25 minutes to thermalize. One should measure ΔT repeatedly during that time to make sure a steady state was reached.

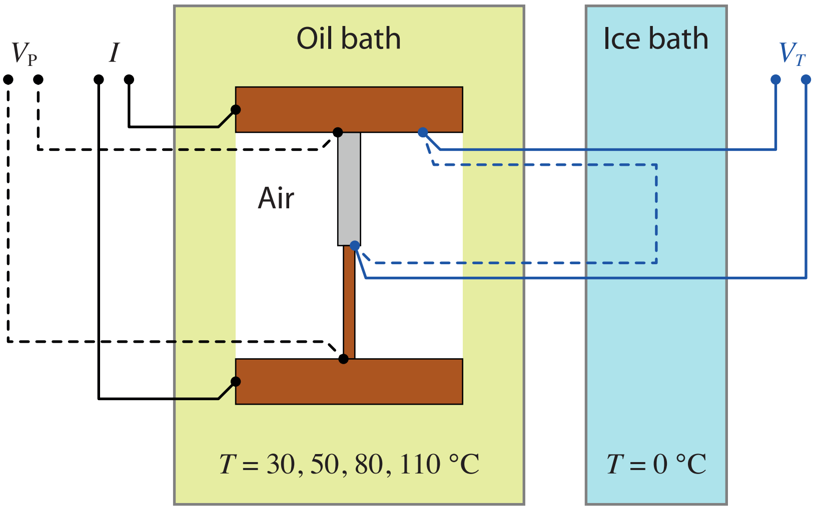


Figure 3: Schematic of the Peltier element inside the oil bath and electric connections. Current-carrying and voltage-sensing wires are separate to allow for four-terminal sensing. Two K-type thermocouples (blue) are used to measure the voltage difference between junction and far ends of the Peltier element. Reference junctions of the thermocouples are immersed in iced water. Note that in the experimental setup, the copper rod is on top and the constantan rod (gray) on the bottom.

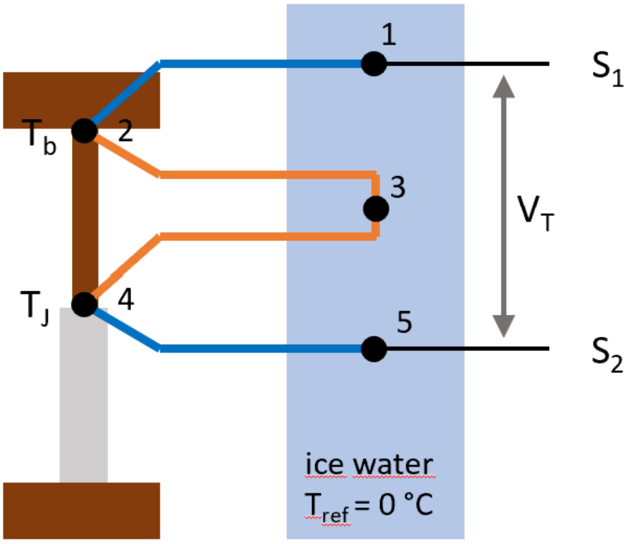


Figure 4: Schematic of the two type K thermocouples employed to determine the temperature difference $T_J - T_b$ between the junction and the oil bath.

The voltage drop across the Peltier element, V_P, can be measured on a separate pair of wires (see Figure 3) that are directly soldered to the far ends of the copper and constantan rods (four-terminal sensing).

Two type K thermocouples are used to differentially measure the temperature difference $\Delta T^{\pm}$ between the Peltier element's junction and the copper blocks (blue lines in Figure 3). A more precise schematic of the setup is shown in Figure 4. A thermocouple consists of two dissimilar metal cables A and B (blue and orange in Figure 4) connected at one end to form an electrified junction. As explained in Section 1, if the temperature at the two open ends is known, the induced voltage can be used to determine the temperature at the junction. If one wants to measure the difference between two temperatures T_b and T_J, two thermocouples of the same type need to be linked in order AB-BA, as shown in Figure 4. The total induced voltage V_T between the two open ends is connected via two copper wires (black in Figure 4). The two copper-metal-A junctions (1 and 5), as well as the B-B junction (3) are held at a constant known reference temperature. In our case, an ice-water bath provides $T_{ref} = 0°\mathrm{C}$. Note again that as long as the two terminals S_1 and S_2 of the copper wires have equal temperature, any voltage contributions in the copper wires due to a temperature gradient between the ice water and the terminals cancel out. Thus, the total voltage V_T is composed of the Seebeck voltages ($V = \epsilon \Delta T$) in the thermocouples:

$$\begin{aligned} V_T &= V_{1\leftrightarrow 2} - V_{2\leftrightarrow 3} + V_{3\leftrightarrow 4} - V_{4\leftrightarrow 5} \\ &= (\epsilon_A - \epsilon_B)(T_b - T_{ref}) + (\epsilon_B - \epsilon_A)(T_J - T_{ref}) \\ &= (\epsilon_A - \epsilon_B)(T_b - T_J) \end{aligned} \tag{19}$$

where ϵ_A and ϵ_B are the Seebeck coefficients of the respective metals. The terms with the reference temperature cancel out, and we get an expression for $\Delta T^{\pm} = T_J^{\pm} - T_b$. The respective temperature differences can then be derived from V_T using Table 2.

Table 2: Reference table for a type K thermocouple. Thermoelectric voltage V_T in mV [5]

°C	0	1	2	3	4	5	6	7	8	9	10
-10	-0.392	-0.353	-0.314	-0.275	-0.236	-0.197	-0.157	-0.118	-0.079	-0.039	0.000
0	0.000	0.039	0.079	0.119	0.158	0.198	0.238	0.277	0.317	0.357	0.397
10	0.397	0.437	0.477	0.517	0.557	0.597	0.637	0.677	0.718	0.758	0.798

The induced thermoelectric voltages V_T between terminals S_1 and S_2 are only on the mV range. It is therefore advantageous to eliminate the resistance contribution of the wiring, contact resistances and a voltmeter by measuring the small voltage in a current-free configuration using a compensation circuit (Figure 5). While not in use for a longer time, the batteries should be disconnected from the circuit to save energy.

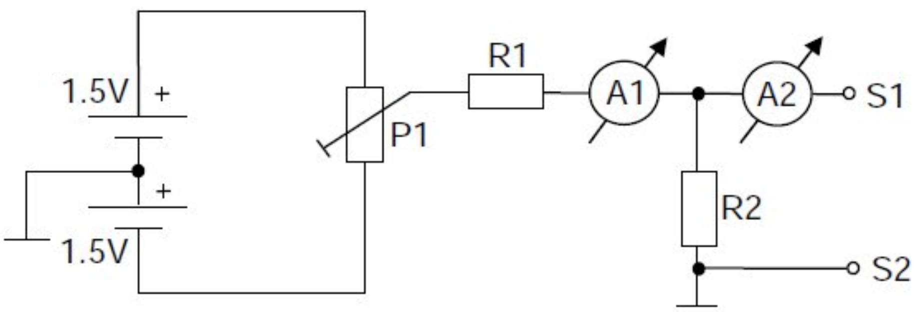


Figure 5: Compensation circuit for low-voltage measurements between terminals S_1 and S_2. The potentiometer P_1 is tuned such that the galvanometer A_2 shows zero current. The values of the resistors are $P_1 = 200\,\Omega$, $R_1 = 1200\,\Omega$ and $R_2 = 389\,\text{m}\Omega$.

The galvanometer should be zero-calibrated once before taking measurements. To do so, the knob on the left should be turned to position "1". Next, short-circuit the galvanometer by plugging the two ends of a single wire into the connector terminals. The line in the display should then move to zero position. The galvanometer is now ready to be connected to the compensation circuit as shown in Figure 5. Make sure the knob is set to "1" during the measurements. While a current I is flowing through the Peltier element and the system is moving towards thermal equilibrium, the line will deviate from zero position. Make sure to wait long enough ($\approx$ 25 minutes) until the line stops moving significantly. This means that the voltage V_T has converged to a constant value, and that the system is ready for temperature measurement. The potentiometer acts as voltage divider, thus providing a manually adjustable output voltage across R_1 and R_2 from the fixed input voltage of the two batteries. Turn the knob on the potentiometer P_1 until the line is again at zero position. This means that there is zero current through the galvanometer, and hence the voltage across R_2 equals the voltage V_T between the terminals S_1 and S_2. The thermoelectric voltage V_T can then be calculated as

$$V_T = I_T R_2 \tag{20}$$

from the compensation current I_T read from A_1. At the end of the measurements and when moving the instrument, the galvanometer must be short-circuited by turning the knob to position “shorted”.

5 Tasks

1. Understand the setup and the devices at the experiment site.
2. Complete all electric wirings and let the assistant check them.
3. A single measurement consists of measuring I_T and V_P for a given current I and oil bath temperature T_b. Make sure that the magnetic stirrer functions properly and that a steady state is reached.
4. Take measurements for currents of $I = \pm(2,\ 4,\ 8,\ 12,\ 16, 20)\,\mathrm{A}$ and oil bath temperatures of $T_\mathrm{b} = (30,\ 50,\ 70,\ 90, 110)\,°\mathrm{C}$.
5. Make three plots of $\Delta T^{\pm}$, $(\Delta T^{+} - \Delta T^{-})$ and $(\Delta T^{+} + \Delta T^{-}$ versus I in order to evaluate the quality of your measurements. Discuss their functional dependencies.
6. Use the results of the temperature measurements to calculate the Peltier coefficients for each temperature using Equations (16) and (18), and compute their error as the standard deviation of the mean. Find literature values and compare your results.
7. Plot $\Pi_{12}^{(I)}$ and $\Pi_{12}^{(V)}$ versus I and discuss the result.
8. Document your measurements and computed results concisely, for example by appending a table with columns for I, V, ΔT^{+}, ΔT^{-}, $\Pi_{12}^{(I)}$, $\Pi_{12}^{(V)}$ for every temperature.

6 Common sources of error

1. It is advisable to complete all measurement on the same day.
2. Make sure to wait long enough after changing the oil bath temperature T_b (≥ 40 minutes). The system needs to thermalize before taking any measurements.

3. Measure from largest negative to largest positive current I, or vice versa. Keep in mind that inverting the direction of the current will change whether the junction is heated or cooled.

4. Check the ice water regularly and change it when necessary.

5. Use the pump to pump out the oil leaking into the air chamber containing the Peltier element.

6. Make sure you use a frequency higher than 300 RPM for the magnetic stirrer.

7 Preliminary Questions

In order to deepen your understanding of the phenomena present in this experiment you should be ready to answer the following preparatory questions at the introductory meeting with the assistant.

1. How does one arrive at Equation (6)? What does it tell one about the temperature profile of an electrified long metal rod whose ends are kept at a constant temperature T_b?

2. Sketch a temperature profile of the thermocouple as in Figure 2 for the case of cooling at the junction.

3. Be prepared to derive Equations (10) and (15).

4. Assuming a reference value for the Peltier coefficient of about $\Pi_{12} = 12.5\,\mathrm{mV}$ at $30\,^\circ\mathrm{C}$, derive an expected value for the temperature ΔT^+ at a current of $16\,\mathrm{A}$.

5. What is the advantage of measuring V_P with a separate pair of wires instead of using the current-supplying wires?

6. Explain why two thermocouples are used as depicted in Figure 3.

7. The ammeters and voltmeters are rather old devices. Depending on the range, they have internal resistances of about $(100..1000)\,\Omega$. Discuss why this is not a problem for how they are used in this experiment.

8 Guidelines for the written report

1. For a general description on how to write a scientific report (structure, content etc.) and to check the criteria that the report has to satisfy, please refer to the documents on the VP web page.[2] You may check the “Anleitung zum Verfassen eines Praktikumsberichts” by Thomas Ihn.[3]

[2] `http://vp.phys.ethz.ch/index.php?page=doku`

[3] `http://vp.phys.ethz.ch/Dokumente/pdf/BerichteSchreiben.pdf`

2. Plagiarism: Reports with material copied from other sources and not properly cited cannot be accepted.[4,5]

3. The report should not be longer than 12 pages, including diagrams.

4. Make sure to give relevant equations.

5. A helpful introduction to error calculations is "Messungen und Messfehler" by Bernd Schönfeld.[6]

6. "Common Bugs in Writing" might help with your written English.[7]

7. Have a look at "Modern myths: shortcomings in scientific writing" by Jean-Luc Doumont.[8]

8. Useful LaTeX packages are `siunitx`, `booktabs`, `geometry`, `caption`.

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