

## Laboratory experiment

# Measurement of characteristics of a Peltier cell

## 1.1 Task

Get acquainted with the behavior of the Peltier cell as a thermoelectric generator (TEG) and a thermoelectric cooler (TEC). In the TEG mode:

- measure the temperature dependence of the thermoelectric emf and plot it in a graph,
- calculate the Seebeck coefficient from the measured data,
- calculate the efficiency rating of the Peltier cell in the TEG mode and compare the calculated value with the efficiency rating of the Carnot-cycle heat engine.

In TEC mode:

- measure the time dependence of the temperature on both sides of the Peltier cell and plot both the curves in one graph.

## 1.2 Thermoelectric effects in metals

The conduction of electric current in a metal conductor is mediated by the ordered motion of free electrons through a crystal lattice, formed by positive ions of a given metal, under the influence of an external electric field. Electrons cannot spontaneously escape the metal conductor. When they move between ions, the local electric field acts on them more or less the same way from all the directions. At the surface and just above it, however, a one-sided attractive Coulomb force arises, by which positively charged ions draw potentially escaping (negatively charged) electrons back into the crystal lattice. Thus, at the surface of the metal, the escape of electrons is prevented by a potential barrier, over which a certain energy, called the work function, is required.

If we denote the electron charge  $q_e$  and the difference of the potentials at the edges of the potential barrier  $U_v$ , the work function can be introduced as  $A = q_e U_v$ . The potential barrier height  $U_v$  is different for individual metals and it depends on their internal structure.

Similarly as in the case of gas molecules, there is a certain probability of very high velocities of electrons due to their random thermal motion. If an electron with such a high velocity (and thus kinetic energy) accidentally moved perpendicular to the metal surface, it could overcome the potential barrier and escape the metal. At room temperature, however, the electron escape from the metal to the air is practically negligible due to the high value of  $U_v$ .

A different situation will occur if two metals A and B with different values of  $U_{vA}$  and  $U_{vB}$  touch each other. The difference  $U_{vA} - U_{vB}$  can be such that, e.g., the electrons can leave the metal A more easily and enter the metal B than in the opposite direction. Thus, the metal B starts to be negatively charged compared to the metal A, thus a contact potential  $U_{AB} = U_{vA} - U_{vB}$  is established at the contact of the metals. The resulting electric field (having the direction perpendicular to the interface from metal A to metal B) begins to prevent more and more electrons from passing through the interface until dynamic equilibrium is established, when the same number of electrons pass through in both directions.

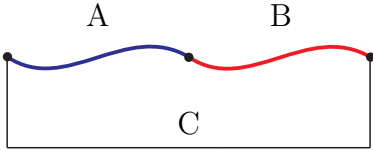


Figure 1.1: Regarding the contact potential.

The contact potential is not easy to measure because under normal conditions it cannot generate electric current in a closed circuit. Consider two conductors made of metals A and B connected by a conductor made of metal C, see Fig. 1.1. Electric current

$$I = \frac{U_{CA} + U_{AB} + U_{BC}}{R} = \frac{U_{vC} - U_{vA} + U_{vA} - U_{vB} + U_{vB} - U_{vC}}{R} = 0$$

will flow through the circuit, where  $R$  is the total resistance.

However, this result only applies if the temperature of all the contact points is the same. It is because the magnitude of the potential barrier and contact potential depends on the temperature.

Consider now, see Fig. 1.2, that the junction of the metals A and B is kept at temperature  $T_2$  and the junctions with the metal C are kept at temperature  $T_1$ . It holds for the electric current flowing through the circuit that

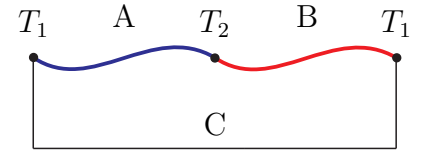


Figure 1.2: Thermocouple.

$$\begin{aligned} I &= \frac{U_{CA}(T_1) + U_{AB}(T_2) + U_{BC}(T_1)}{R} = \\ &= \frac{U_{vC}(T_1) - U_{vA}(T_1) + U_{vA}(T_2) - U_{vB}(T_2) + U_{vB}(T_1) - U_{vC}(T_1)}{R} = \frac{U_{AB}(T_2) - U_{AB}(T_1)}{R}, \end{aligned}$$

which is in this case non-zero, and it is generated by the total emf  $\mathcal{E} = U_{AB}(T_2) - U_{AB}(T_1)$ . This arrangement is called a thermocouple, and the corresponding phenomenon, according to its discoverer, is called *the Seebeck effect*. Note that the thermoelectric emf does not depend at all on the material C.

The opposite effect to the Seebeck effect is *the Peltier effect*. It consists in the fact that the junction of two different metals with the flow of an electric current either gets cold or warm, where the generated heat depends on the magnitude and orientation of the electric current.

The heat generated by this current weakens the change caused by the Seebeck effect. This means that when the current flows through the junction of two conductors in the same direction as the current generated by the Seebeck effect when this junction is heated, this junction cools down (by the Peltier effect).

The third thermoelectric effect is *the Thomson effect*. An emf is generated in a conductor with a temperature gradient due to the thermal diffusion of the electron gas. By passing an electric current along the temperature gradient, heat can be released or absorbed in the conductor.

### 1.3 Thermocouple

A thermocouple is the device most commonly used to measure temperature based on the Seebeck and Thomson effect. One (so-called comparative) junction of two welded or joined conductors made of suitably selected materials is maintained at temperature  $T_1$  (e.g., by immersing into the water-ice mixture, it would hold  $T_1 = 0^\circ\text{C}$ ), while the second (so-called measuring) junction is placed in a location of unknown temperature  $T_2$ . The generated thermoelectric emf measured with a millivoltmeter can be approximated with sufficient accuracy using the formula

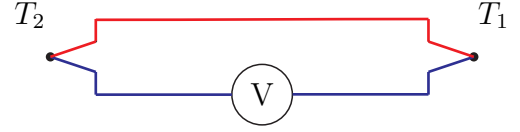


Figure 1.3: Thermocouple.

$$\mathcal{E} = \alpha(T_2 - T_1) + \beta(T_2 - T_1)^2, \quad (1.1)$$

where the so-called Seebeck coefficients  $\alpha$  and  $\beta$  depend on the thermocouple material and are determined by measurement. For example, for an iron-constantan thermocouple (alloy of 55 %Cu + 45 % Ni) it holds  $\alpha = 50\mu\text{V}/^\circ\text{C}$ ,  $\beta = 0,03\mu\text{V}/^\circ\text{C}^2$ . From this it can be seen that for small temperature differences the dependence of the emf on temperature can be considered roughly linear.

### 1.4 Peltier cell

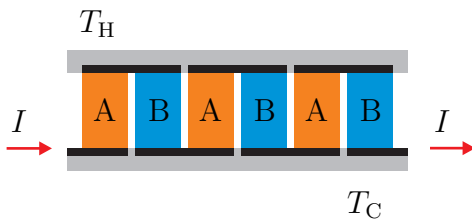


Figure 1.4: Peltier cell.

A Peltier cell is a thermoelectric device, working on the principle of the Peltier effect, which is most often used for active cooling, as it allows heat to be pumped from a cooler place to a warmer place, i.e., in the opposite direction to the natural flow of heat through the conduction. By using a Peltier cell we can cool the bodies even below the ambient (equilibrium) temperature. Peltier cells are most often constructed in such a way that a large number of elements, usually made of semiconductor materials, are connected in series in terms of electric current flow, and in parallel in terms of heat flow, see Fig. 1.4.

#### Energy balance of a Peltier cell in TEC mode

For the heat released (absorbed) per unit time by the flow of electric current  $I$  through the junction of two different conductors in a Peltier cell due to the Peltier effect it holds

$$\frac{\Delta Q_P}{\Delta t} = P_P = \alpha TI,$$

where  $\alpha$  is the Seebeck coefficient<sup>1</sup> and  $T$  is the thermodynamic temperature of the junction. The flow of electric current through the cell releases Joule heat in the electrical resistance  $R$ , for which it holds

$$\frac{\Delta Q_J}{\Delta t} = P_J = RI^2.$$

<sup>1</sup>In fact, the Seebeck coefficient  $\alpha$  is temperature-dependent. It can be shown, see [3], that if we use the value of this coefficient for the average temperature in the analysis, we do not have to consider the Thomson effect, which simplifies the analysis.

For the heat passing through the cell per unit time from the warmer side with temperature  $T_H$  to the colder side with temperature  $T_C$  we get from the Fourier law

$$\frac{\Delta Q_F}{\Delta t} = P_F = \lambda S \frac{T_H - T_C}{d} = \Lambda \Delta T,$$

where  $\Delta T = T_H - T_C$ ,  $\lambda$  is the thermal conductivity of the used material,  $S$  is the cross-section,  $d$  is the cell thickness, and  $\Lambda = \lambda S/d$ .

For the heat (cooling) capacity of the pump on the cold side (see Fig. 1.5) we get

$$P_C = \alpha I T_C - \frac{R I^2}{2} - \Lambda \Delta T, \quad (1.2)$$

while for the heat capacity of the pump on the hot side it holds

$$P_H = \alpha I T_H + \frac{R I^2}{2} - \Lambda \Delta T. \quad (1.3)$$

Once the steady state is reached, when the individual quantities no longer change with time, the law of conservation of energy must hold for the electrical power supplied to the cell

$$P_E = UI = P_H - P_C = \alpha I \Delta T + R I^2. \quad (1.4)$$

We define the cooling efficiency rating of a Peltier cell (and of a cooling device in general) as the ratio of what we want (to extract heat from the cold side) to what we pay for (electrical input), i.e.,

$$\eta_{\text{TEC}} = \frac{P_C}{P_E} = \frac{\alpha I T_C - \frac{R I^2}{2} - \Lambda \Delta T}{\alpha I \Delta T + R I^2}. \quad (1.5)$$

From the formula for efficiency rating, it can be seen that the Joule heat released in the resistance of the cell reduces its efficiency because half of it heats up the cold side of the cell. Thermal conductivity also contributes to the reduction in efficiency, as it allows some of the heat to flow in the opposite direction to that transported by the Peltier cell. If both of these negative phenomena could be eliminated<sup>2</sup> ( $R = 0, \Lambda = 0$ ), it would hold for the cooling efficiency rating

$$\eta'_{\text{TEC}} = \frac{T_C}{T_H - T_C},$$

which is the well-known relationship from thermodynamics for the efficiency rating of an ideal cooling device<sup>3</sup>.

It can be seen from Eq. (1.2) that the cooling capacity  $P_C$  of the Peltier cell, decreased by the Joule heat, is not a monotonic function of electric current  $I$ . There exists an optimal current, for which the cooling capacity is maximum:

$$\frac{dP_C}{dI} = \alpha T_C - R I \stackrel{!}{=} 0 \quad \Rightarrow \quad I_{\text{opt}} = \frac{\alpha T_C}{R}.$$

<sup>2</sup>This is unfortunately very difficult, because conductors that conduct electricity well also conduct heat well.

<sup>3</sup>The perceptive reader will have noticed that, for the efficiency rating defined in this way, the following can (and usually does) apply:  $\eta > 1$ .

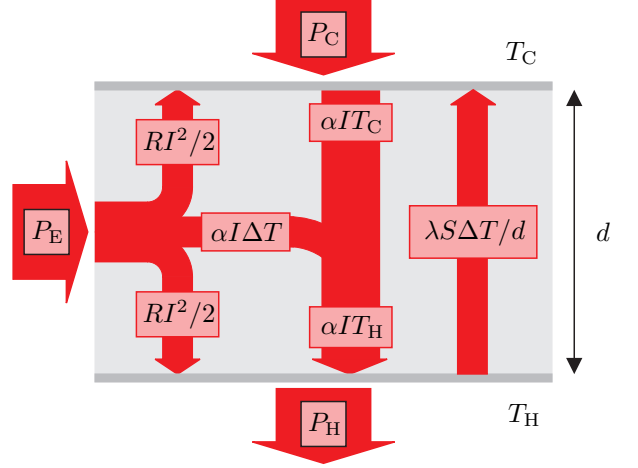


Figure 1.5: Heat flow in a Peltier cell.

The cooling capacity with this optimum current reads

$$P_{C\text{opt}} = \frac{\alpha^2 T_C^2}{2R} - \Lambda \Delta T.$$

The minimum achievable temperature on the cold side (at a given temperature  $T_H$ ) is obtained from the condition that no heat passes through the cold side of the Peltier cell, i.e., by the (positive) solution of the (quadratic) equation  $P_{C\text{opt}} = 0$  as

$$T_{C\text{min}} = \frac{\Lambda R}{\alpha^2} \left( \sqrt{1 + \frac{2\alpha^2 T_H}{\Lambda R}} - 1 \right).$$

The formula shows, among other things, that to achieve a low temperature on the cold side, the temperature on the hot side must not be too high. The heat from the hot side of the Peltier cell must therefore be efficiently taken away.

## 1.5 Procedure

**WARNING:** Do not exceed the limits of the Peltier cell. It may be destroyed, if the current passing through exceeds  $I_{\text{max}} = 4 \text{ A}$ , and/or the temperature of the hot side exceeds  $T_{H\text{max}} = 100^\circ\text{C}$ .

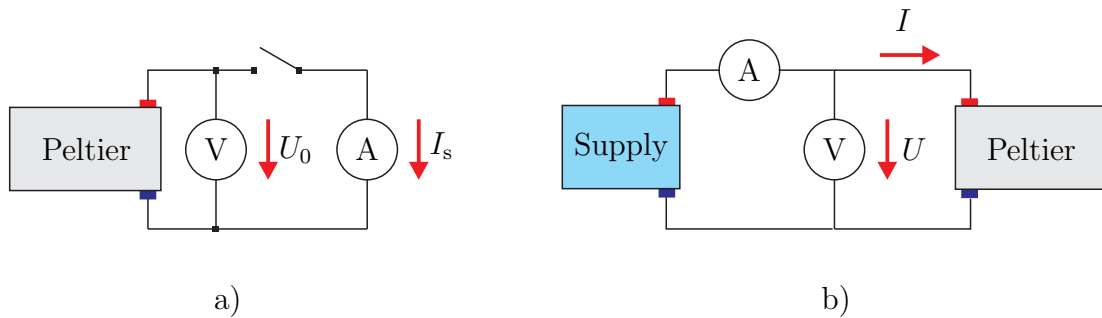


Figure 1.6: Measurement of the characteristics of a Peltier cell.

### 1.5.1 Peltier cell as a source of electricity

1. Connect the Peltier cell to a voltmeter and ammeter (on a range of 10 A or 20 A), see Fig. 1.6 a). Connect the pump that draws water from the external reservoir to the heat exchanger on one side of the Peltier cell. Pour the water boiled in the kettle into the container on the other side of the Peltier cell to a height of 1 mm below the rim of the container. If there is water in the container after the previous measurement, remove it beforehand with a syringe. Cover the container with water with a heat-insulating cap.
2. The temperatures on the sides of the Peltier cell will gradually begin to equilibrate. Wait a moment for the temperature between the hot-water container and the Peltier cell to equalize (about 30 s) – until the temperature on the hot side begins to decrease with time. Measure the dependence of the thermoelectric voltage  $U_0$  and the temperatures  $T_H$ ,  $T_C$  on time. After each thermoelectric voltage reading, short-circuit the voltmeter with an ammeter and measure the short-circuit current  $I_s$ .

- Plot the thermoelectric voltage versus temperature difference  $\Delta T$  and calculate the Seebeck coefficient  $\alpha$ . Although the temperature dependence of the thermoelectric voltage, see Eq. (1.1), is nonlinear, in a given temperature range and given the accuracy of the measurements, you can consider the dependence to be linear:  $U_0 = \alpha\Delta T$ . To calculate the coefficient  $\alpha$  (and to plot the graph), use the least squares method – an approximation by the first degree polynomial (e.g., the Universal tool for plotting graphs at <https://planck.fel.cvut.cz/praktikum/>).
- For the selected temperature, estimate the efficiency rating of the Peltier cell as a source of electricity, which is defined as

$$\eta_{\text{TEG}} = \frac{P_{\text{E}}}{P_{\text{H}}},$$

where  $P_{\text{E}}$  is an estimate of the theoretical maximum power delivered by the cell to the load, which we get as<sup>4</sup>

$$P_{\text{E}} = \frac{1}{4}U_0I_{\text{s}}$$

and  $P_{\text{H}}$  is the heat per unit time passing through the hot side to the Peltier cell. If we assume that all the heat from the (thermally insulated) hot-water container passes through the Peltier cell, we can estimate this heat as

$$P_{\text{H}} \approx \frac{\Delta Q_{\text{H}}}{\Delta t} = \frac{C_{\text{tot}}(T_{\text{H1}} - T_{\text{H2}})}{t_1 - t_2},$$

where  $C_{\text{tot}}$  is the total heat capacity of the water container on the hot side of the Peltier cell for which it applies, see Appendix,  $C_{\text{tot}} = 1121 \text{ J K}^{-1}$ , and  $T_{\text{H1}}$  and  $T_{\text{H2}}$  are the temperatures on the hot side at the times  $t_1$  and  $t_2$ . Make this estimate for the values obtained during the beginning of the measurement when the temperature difference  $\Delta T$  is large.

- Compare (in percentage terms) the estimated efficiency rating of  $\eta_{\text{TEG}}$  with the maximum possible efficiency rating of an ideal reciprocating heat engine working between given temperatures  $T_{\text{H}}$  and  $T_{\text{C}}$ , for which it applies<sup>5</sup>

$$\eta'_{\text{TEG}} = \frac{T_{\text{H}} - T_{\text{C}}}{T_{\text{H}}}.$$

## 1.5.2 Peltier cell as a cooling device

- Fill the container on the side of the Peltier cell about 1 mm below the rim with tap water at approximately room temperature. Connect the Peltier cell to a voltage source, see Fig. 1.6 b). Wait about 3 minutes for the temperatures on the sides of the Peltier cell to equilibrate. Cover the water container with thermal-insulation cap.
- Switch on the power supply, the current through the cell should not exceed  $I_{\text{max}} = 4 \text{ A}$ , the value of the current is best adjusted by the current limiter on the laboratory power supply<sup>6</sup>.

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<sup>4</sup>You can easily see that the maximum power delivered to a load with resistance  $R_1$  is supplied by a voltage source with internal resistance  $R_i$  if  $R_1 = R_i$ . Then there is a voltage  $U_0/2$  (divider) across the resistor  $R_1$  and a current  $I_{\text{s}}/2$  flows through it (compared to the circuit for measuring the short-circuit current, there is now another resistor in series with  $R_1$ ).

<sup>5</sup>Do not forget to put the temperature in kelvin in the denominator of the formula!

<sup>6</sup>Set the potentiometers regulating the voltage and current to the **minimum** value. Set the voltage regulation potentiometer to the maximum value. Use the current limiter (potentiometer) to set the desired current.

3. Measure temperatures  $T_H$  and  $T_C$  at one-minute intervals<sup>7</sup>. Check continuously that the current through the cell does not change with time.
4. Plot the graph of the time-dependence of the temperatures  $T_H$  and  $T_C$ .
5. What is the lowest temperature you have managed to obtain?

### 1.5.3 If you have left time – Peltier cell as a heater (heat pump)

1. Disconnect the Peltier cell from the power supply.
2. Fill the container on the side of the Peltier cell about 1 mm below the rim with tap water at approximately room temperature. Wait about 3 minutes for the temperatures on the sides of the Peltier cell to equilibrate. Cover the water container with thermal-insulation cap.
3. Re-polarize the output of the lab power supply so that current flows through the Peltier cell in the opposite direction – the water container will be on the hot side of the cell this time.
4. Measure temperatures  $T_H$  and  $T_C$  at one-minute intervals. Check continuously that the current through the cell does not change with time. Do not let the temperature on the hot side of the cell exceed approx. 70°C.
5. Plot the graph of the time-dependence of the temperatures  $T_H$  and  $T_C$ .
6. Would you be able to explain why you achieve a greater temperature difference faster in this mode than in the TEC mode?

## 1.6 References

1. B. Klimeš, J. Kracík, A. Ženíšek: *Základy fyziky II*, Academia, Praha, 1982.
2. B. Sedlák, I. Štoll: *Elektrina a magnetismus*, Academia, Praha, 2002.
3. A. V. Da Rosa: *Fundamentals of Renewable Energy Processes*, 2<sup>nd</sup> edition, Academic Press, 2009.

## 1.7 Appendix – Calculation of the heat capacity $C_{\text{tot}}$

When calculating the heat capacity of a body heated (cooled) by a Peltier cell, we must take into account the heat capacity of the water as well as the copper blocks on the sides of the cell and the brass water containers. It is therefore

$$C_{\text{tot}} = m_{\text{H}_2\text{O}} \cdot c_{\text{H}_2\text{O}} + m_{\text{Cu}} \cdot c_{\text{Cu}} + m_{\text{CuZn}} \cdot c_{\text{CuZn}},$$

where  $m_i$  are the masses and  $c_i$  the specific heat capacities. As it applies  $c_{\text{H}_2\text{O}} = 4182 \text{ J kg}^{-1}\text{K}^{-1}$ ,  $c_{\text{Cu}} = 383 \text{ J kg}^{-1}\text{K}^{-1}$ ,  $c_{\text{CuZn}} = 381 \text{ J kg}^{-1}\text{K}^{-1}$ , and in this specific case  $m_{\text{H}_2\text{O}} = 0.194 \text{ kg}$ ,  $m_{\text{Cu}} = 0.712 \text{ kg}$ ,  $m_{\text{CuZn}} = 0.0983 \text{ kg}$ , and thus  $C_{\text{tot}} = 1121 \text{ J K}^{-1}$ .

June 15, 2021, Milan Červenka, Ladislav Sieger, [milan.cervenka@fel.cvut.cz](mailto:milan.cervenka@fel.cvut.cz)

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<sup>7</sup>If you have connected terminals of the same color on the Peltier cell and the power supply, the cold side is where you poured the water.