IIW6

Modul Thermodynamics

Peltier heat pump

The target of this experiment is to study the thermoelectricity using a Peltier heat pump.
More specifically, we are aiming to characterise a thermogenerator: calculate its heating/cooling capacities and its efficiency via different methods and under several operating conditions.

Experiment IIW6 - Peltier heat pump

The target of this experiment is to study the thermoelectricity using a Peltier heat pump. More specifically, we are aiming to characterise a thermogenerator: calculate its heating/cooling capacities and its efficiency via different methods and under several operating conditions.

1.1 Preliminary Questions

- What is the cause of thermoelectricity?
- From what does the size of the thermal power depend on?
- How does a thermal generator function?
- What is the Seebeck effect and what does it describe?
- What is the Peltier effect and what does it describe?
- What is the Thomson effect and what does it describe?
- What is the unit of the Seebeck, Peltier, and Thomson coefficients?
- What is the difference between the performance by Thomson and Joule?

1.2 Theory

1.2.1 Thermoelectricity

If two different metals are brought into contact with each other, the temperature-dependent contact voltage is developed as a thermal diffusion of conduction electrons. A temperature difference between the two contact points generates an electrical current (SEEBECK EFFECT). Also, the flow leads to an electrical current, along the flow direction of different solders against each other metals, to the fact that the one contact, depending on the flow direction of the current, cools and the other is heated (PELTIER EFFECT). Even in a homogeneous conductor, the flow of current generates heat if the temeperature gradient of the conductor is maintained (THOMSON EFFECT). The decisive factor is that, depending on the metal, the presence of such a temperature gradient between two points or more or less can be heated, as solely by the thermal conductivity, ie without current flow.

1.2.2 Contact potential

Between the available metal electrons and positive ions are attractive forces. To solve the freely moving conduction electrons of the metal, the so-called *work function* W_a against these forces of attraction is achieved. This work function corresponds to the depth of the highest occupied electron states and therefore, is dependently different from the kind of solid and generally for the different metals. If a contact between two different metals $a1$ and $a2$ with work function W_{a1} and W_{a2} (where $|W_{a1}| < |W_{a2}|$) is produced, so the electrons from the metal $a1$ move around to the metal $a2$. The metal $a1$ is therefore positive and the metal $a2$ is negative. The resulting space-charge produces an opposing electrical field, which is directed opposite to the flow and the electron drifts back again. Once the currents are equal in both directions, the system is in equilibrium. The potential ϕ of the two metals is shifted by the space charges, so that a *contact voltage* $U = \phi_2 - \phi_1$ arises (see Figure 1.1).
This contact voltage is equal and opposite to the difference of the two Fermi levels. In this state, equilibrium occurs, and therefore, the same number of electrons diffuse from 1 to 2, such that from 2 to 1 is a result of the resulting electric field. The fact that the contact stress depends on the temperature of the contact, it may be explained, that the particle concentrations n_1 and n_2 are considered. In thermal equilibrium, their two electron gases approximately describe

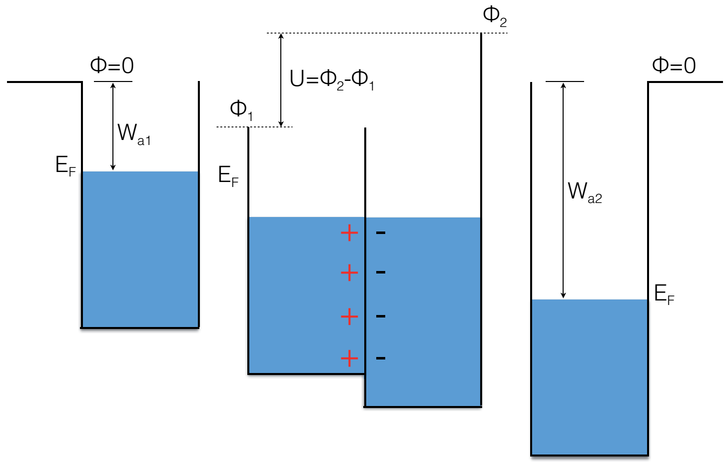

Figure 1.1: Schematic representation of the contact voltage $U = \phi_2 - \phi_1$ of two metals 1 and 2 with work functions W_{a1} and W_{a2}

.

Boltzmann statistics.[1] The contact voltage is then given by the ratio of the particle number densities:

$$\begin{aligned} \frac{n_2}{n_1} &= \exp\left(-\frac{\Delta E}{k_B T}\right) = \exp\left(-\frac{(E_2 - E_1)}{k_B T}\right) \\ &= \exp\left(-\frac{e(\phi_2 - \phi_1)}{k_B T}\right) = \exp\left(-\frac{eU}{k_B T}\right) \end{aligned} \tag{1.1}$$

and is given by:

$$U = \frac{k_B T}{e} \ln\left(\frac{n_1}{n_2}\right) \tag{1.2}$$

1.2.3 Seebeck effect

We now form both connected metals to a ring. Leave the ring open, so that it forms an electric field between the two open ends, connect the two ends, so that they are from the same contact stress. The current does not flow because the two voltages are mutually connected. First through the heating of one contact point are both contact stresses (despite an identical ratio n_2/n_1) are different so that a *thermal current* flows. The necessary energy comes from doing the Heat source.

This property is used in so-called *thermocouples*. Turn it into a closed ring made of two different metals in the metal, using a voltage measurement device, one can measure the *thermal voltage*. This depends on the previous considerations, in addition to the characteristic properties of the two metals only to the temperature from between the two contact points. Bring to a contact point on a constant temperature and allow the circuit to be a very sensitive thermometer with large heat capacity and very low inertia.

According to the previous considerations, this thermal stress can be thus calculated using the

[1] Due to the high density of the electron gas in the metal, the electrons follows a Fermi distribution. The limit $\Delta E \gg k_B T$ still applies to them, but is approximately Eq. (1.1).

formula (1.2) expressed:

$$\begin{aligned} U_{th} &= \Delta U = U_2 - U_1 \\ &= \frac{k_B}{e} \ln\left(\frac{n_1}{n_2}\right) \Delta T \end{aligned} \tag{1.3}$$

The material-dependent properties are also the so-called *Seebeck coefficients* S_A, S_B ($[S_i] = V/K$) merged according to:

$$U_{th} = (S_A - S_B)(T_1 - T_2) \tag{1.4}$$

The Seebeck coefficients are temperature dependent and strongly depend in semiconductors on the doping impurity

.

Depending on the combination of metals, Eq. (1.3) is in a small or wider range of ΔT. More generally, obtained by using the Fermi distribution, the following is also valid for higher powers of the ΔT expression:

$$U_{th} = a \cdot \Delta T + b \cdot \Delta T^2 \tag{1.5}$$

The sensitivity of such a thermocouple is expressed by the *thermal power*, which is given by the change in thermal stress with temperature:

$$F_{th} = \frac{dU_{th}}{dT} = a + 2B\Delta T \tag{1.6}$$

Under the direct conversion of heat energy into electrical energy, which offers *thermal generators* the clear advantage that with them, there is no detour going between the mechanical energy.

1.2.4 The Thermal generator

The thermal generator consists of two materials 1 and 2, the heat is throughout a large-area bridge contact on its upper side. The bottom of both materials is maintained at the same temperature T_0. Now, one may (through resistance R) be connected, and receive the electric power from the thermovoltage. Unlike other heat engines, the efficiency for thermodynamic reasons, is much smaller than $(T - T_0)/T$. The efficiencies of $p-$ and $n-$ type semiconductors are between 8 and 10%, respectively.
In the current experiment is such a thermal generator. The generator block is located between two nickel-plated copper plates of 142 semiconductor thermocouples. By means of heat transfer, 10mm thick copper plates, each with a 7mm- bore for receiving a thermometer, are provided. Electrically, the thermocouples are in series and switched to increase the output voltage.

1.2.5 Peltier effect

The so-called Peltier effect is the reverse of the generation of a thermal stream. If a contact between two materials A and B is in the order ABA and can pass a flowing stream, then the one contact point cools the other heat themselves. This temperature change would be much stronger than we achieved by *Joule heat*. Reversing the current leads as well to reversing the

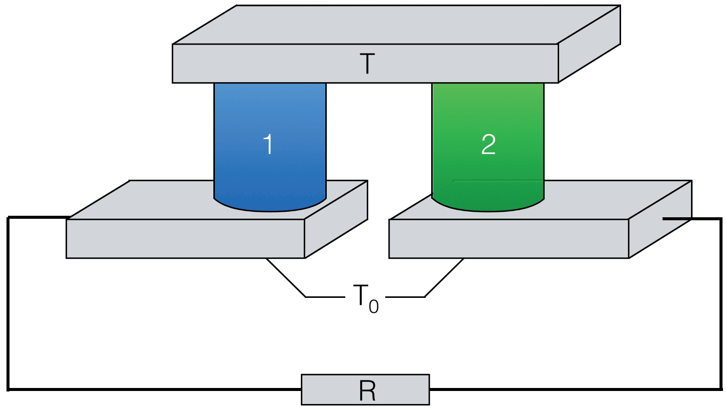

Figure 1.2: Schematic diagram of a thermal generator.

sign of the temperature $\Delta T_{1,2}$ at the two contact points. The generated heat at the contact point of the thermal input is proportional to the current I, in accordance with:

$$P = \frac{dW}{dt} = (\Pi_A - \Pi_B) \cdot I \tag{1.7}$$

where Π_A and Π_B are the Peltier coefficients of materials A and B, respectively. The sign of the thermal power P depends on the current direction. For $P > 0$, heat is generated, for $P < 0$, the contact point extracts heat, then cools. Between thermoelectric voltage U_{th} and the Peltier coefficient Π is the following relationship:

$$U_{th} = \frac{\Pi}{T} \cdot \Delta T \tag{1.8}$$

and between the thermopower F_{th} and the Peltier coefficient Π is the following relationship:

$$\Pi = F_{th} \cdot T \tag{1.9}$$

1.2.6 Thomson effect

The generation of heat when a current flows in a homogeneous conductor is also possible if a temperature gradient $\Delta T/l$ is maintained. The heat output in this case is:

$$P = -\sigma \cdot I \cdot \Delta T \tag{1.10}$$

where σ corresponds to the *Thomson coefficients*. In contrast to the thermal output according to Thomson, the *Joule power* is proportional to I^2. The Thomson coefficient is by *Thomson relations* closely related with the Peltier-coefficients, the Seeback coefficients, linked with thermopower:

$$\begin{aligned} \Pi &= S \cdot T \\ \sigma &= T \cdot \frac{dS}{dT} \end{aligned} \tag{1.11}$$

1.3 Experiment

1.3.1 Equipment

Components	Number
Thermogenerator	1
Open water tank	1
Closed water tank with 2 pipe connections	1
Variable resistor	1
Water entrance pipe	1
Water exit pipe	1
Digital multimeter	4
Hairdryer	1
Heating coil	1
Tripod adapted to the coil	1
Thermometer -10...+50 °C	2
Thermal conductive paste	1
Digital stopwatch	1
Power supply	1
Connecting line 32 A, 750 mm, blue	2
Connecting line 32 A, 750 mm, red	1
Connecting line 32 A, 500 mm, red	3
Connecting line 32 A, 500 mm, blue	2
Connecting line 32 A, 250 mm, red	3

1.3.2 Experimental setup and execution

Note: In this experiment, water and electrical devices are handled. Therefore, the next safety rules must be striclty followed:

- **Always handle water with care, i.e. don't rush to set up and perform the experiments.**
- **When you fill or empty the water containers, make sure that all electric circuits are off AND water doesn't flow into the pipes.**

Preliminary work

Start by looking attentively at both the setup and the figure 1.3 and reflect to the following questions:

- Where is the thermogenerator? Where are the sides A and B? Where can you set the voltage applied to the thermogenerator? And the current?
- Where is the coil? What's its function? How to change its applied current and voltage?
- Where is the variable resistor? How to change its resistance?
- Which are the multimeters corresponding to, respectively, I_{ther}, U_{ther}, I_{coil} and U_{coil}? Set accordingly each multimeter on its suitable operating mode.
  Tip: Check if there are operating in AC or DC.

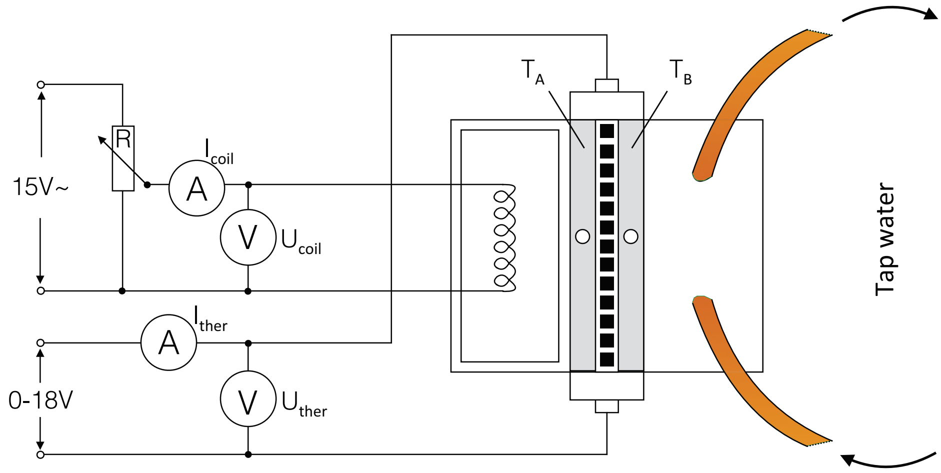

Figure 1.3: Setup for determining the cooling capacity.

Once you find out the answers, call your assistant to reply orally to these questions.
You can now perform, under the supervision of you assistant, the following tasks:

- Fill the water bath (side A) with water tap using the smallest beaker.
- Connect the wires to the thermogenerator.
- Open the tap in order to make flow water inside the pipes.
- Place the two large thermometers in the openings provided in the thermogenerator. If necessary, use some heat-conducting paste to make better contact.
- Turn on the generator (the switch is behind) and set some value (not too high) of I_{ther} and U_{ther}.
- Look at T_A: is it heating or cooling? What about T_B?
- Set the current to zero then invert the wires connected to the thermogenerator.
- Set back the current. Does T_A still show the same behaviour?
- Switch off the generator and close the water tap.

Remember well in which configuration you are cooling (or heating) a given side.

Calculation of cooling efficiency η_c and determination of the cooling power P_c function of the power applied P_{ther}

- Remove the water from the bath using the big beaker. Empty the beaker into the sink.
- Refill now the bath with $V = 350\,mL$ of fresh water.
- Connect the wires to the thermogenerator such the side A is cooled.
- Turn the water tap on.
- Check that $T_A = T_B$. If it's not the case wait until the temperature has stabilised (not more than 5-10 min) or change again the water to speed up the process.
- Carefully dip the heating coil into the water bath.
- Switch on the power supply and set an arbitrary I_{ther} and U_{ther} (don't choose too high values).
- Turn on the coil current ($P = 15$) and, using the variable resistance, adjust the heating power of the coil so that the temperature difference between the cold and the warm side be negligible again ($T_A = T_B$).
  The power of the coil should now correspond to the cooling power of the thermogenerator.
- By repeating the two last steps, measure 5 sets of the following parameters: I_{ther},U_{ther}, U_{coil}, I_{coil}, T_A and T_B.

  Note: Don't forget to note the error on these values as well!
- Switch off the generator and close the water tap.

Determination of the heating power P_h of the thermogenerator and its efficiency η_h at constant applied Power P_{ther} and constant temperature on the cooling side

- Carefully remove the heating coil.
- Remove the water from the bath using the big beaker. Empty the beaker into the sink.
- Refill now the bath with $V = 350\,mL$ of fresh water.
- Connect the wires to the thermogenerator such the side A is heated.
- Turn the water tap on.
- Check that $T_A = T_B$. If it's not the case wait until the temperature has stabilised (not more than 5-10 min) or change again the water to speed up the process.
- Switch on the power supply.
- During 15 min, measure the temperature rise of the water T_A as a function of time at constant current I_{ther} and voltage U_{ther}. Also measure T_B.
- Turn both current and voltage to zero and switch off the power supply.
- Switch off the generator and close the water tap.

Determination of P_c, η_c and P_h, η_h simultaneously from the relationship between temperature and time

- Remove the water from the bath using the big beaker. Empty the beaker into the sink.
- Refill now the bath with $V = 350\,mL$ of fresh water.
- Connect the wires to the thermogenerator (in the configuration you want).
- Check that $T_A = T_B$. If it's not the case wait until the temperature has stabilised (not more than 5-10 min). You can also change again the water or temporarily open the tap to speed up the process.
- Switch on the power supply.
- Measure both temperatures T_A and T_B as a function of time during 15 min at constant current and voltage (arbitrary chosen). Note also the values of I_{ther} and U_{ther} that you choose.
- Turn both current and voltage to zero and switch off the power supply.
- Switch off the generator and close the water tap.

Investigation of the temperature behaviour when the cooling part of the thermogenerator is heat by a hair dryer

- Remove the water from the bath using the big beaker. Empty the beaker into the sink.
- Refill now the bath with $V = 350\,mL$ of fresh water.
- Connect the wires to the thermogenerator such the side A is cooled.
- Turn the water tap on.
- Check that $T_A = T_B$. If it's not the case wait until the temperature has stabilised (not more than 5-10 min) or change again the water to speed up the process.
- Switch on the power supply.
- For a given I_{ther} and U_{ther}, measure T_A for 15 minutes as a function of time, once in usual condition (static atmospheric air) and once during which the temperature is heated by a hair dryer. Note also the values of I_{ther} and U_{ther} that you choose.
- Turn both current and voltage to zero and switch off the power supply.
- Switch off the generator and close the water tap. Unplug the wire on the thermogenerator, store adequately the thermometers.
- Remove the water from the bath using the big beaker. Empty the beaker into the sink.
- Clean your table and enjoy the rest of your afternoon!

1.3.3 Tasks for Evaluation

Calculation of cooling efficiency η_c and determination of the cooling power P_c function of the power applied P_{ther}

- When we say that a machine (anything, from a computer to a car or even, in our case, a thermogenerator) has a good efficiency, that means this machine is using well the energy that we must give to make it work.

  Actually, we don't specifically care about the absolute energy we give but we actually want to know: "if I give X amount of energy each second, how much energy each second I can use". And, by definition, the "energy each second" is the power.

  Therefore, the general definition of an efficiency η is:

  $$\eta = \frac{P_{useful}}{P_{given}}$$

  a) Define the cooling efficiency η_c of the thermogenerator.

  b) Compute the cooling efficiency η_c corresponding to the different values of P_{ther} including its errors.

- Plot the cooling power P_c (i.e. the power transmit to cool down our system) against the power applied to the thermogenerator P_{ther}. Don't forget to add the errors on both axis (calculated via propagation of uncertainty formula if necessary).

- Discuss your results. For example:

  Did you expect what you get? Why?

  Did you get efficiency higher than 1? If so, how is it possible?

  ...

Determination of the heating power P_h of the thermogenerator and its efficiency η_h at constant applied Power P_{ther} and constant temperature on the cooling side

- Given that, in our experiment, we have the following masses: $m_{Cu} = 200\,g$, $m_{Al} = 100\,g$ and $m_{H_2O} = 350\,g$; calculate the heat capacity of the copper block C_1, the metal bath C_2, the water C_3 and finally C_{tot} the total heat capacity [2].

- We want to find the heating power P_h of the thermogenerator. But, unlike the cooling power, we can't use the coil as a buffer to calculate it.
  We define: $E(t)$ the total heating energy after a time t, T_i the initial temperature of the system and $T_A(t)$ the temperature at time t.

  a) Plot the temperature T_A against time.

  b) Find a relationship between $E(t)$; C_{tot}; $T_A(t)$ and T_i.

  c) Using your plot (quest. a)), find a expression of $T_A(t)$ when $t \gg 1\,min$.

  d) Derive your formula in order to make appear P_h and do the numerical calculation to finally get the value of P_h. As usual, don't forget to calculate the error as well.

[2] The specific heat capacities of (solid) copper, (solid) aluminium and (liquid) water are, respectively: $c_{H_2O} = 4186\,J \cdot K^{-1} \cdot kg^{-1}$, $c_{Cu} = 385\,J \cdot K^{-1} \cdot kg^{-1}$ and $c_{Al} = 897\,J \cdot K^{-1} \cdot kg^{-1}$

- Calculate the heating efficiency η_h of the thermogenerator.
- Discuss your results. For example:

  Did you expect what you get? Why?

  Is the cooling efficiency independent of time? If so, why did you find an unique value?

  ...

Determination of P_c, η_c and P_h, η_h simultaneously from the relationship between temperature and time

- On a same graph, plot the temperatures T_A and T_B versus time.
- Using the same methods than previous section, calculate the heating and cooling powers P_h and P_c.
- Compute both efficiencies η_c and η_h.
- Discuss your results. For example:

  Is your graph symmetric? Why?

  Did you get the same value of η_c and η_h than what you previously found? If not, what can explain the difference?

  ...

Investigation of the temperature behaviour when the cooling part of the thermogenerator is heat by a hair dryer.

- Plot for both series of measurements the temperature T_A as a function of time.
- Calculate the cooling power P_c during the first series of measurements.
- About the second series:

  a) Is the system heated or cooled?

  b) Calculate the apparent cooling/heating power P_{app}.

  c) Taking into account the 2 previous questions, find a relationships between P_c, P_{app} and the heating power due only to the air dryer P_{air}.

  d) Compute P_{air}.
- Discuss your results. For example:

  Do you expect such order of magnitude for the value of P_{air}? Is it comparable with the power an usual air dryer consumed?

  What would be the (approximative) efficiency of such a system (heat something with air dryer only)?

  ...

1.4 Literature

- D. Meschede, "*Gerthsen Physik*", Springer Verlag, Berlin Heidelberg
- W. Demtröder, "*Experimentalphysik 2*", Springer Verlag, Berlin Heidelberg