# Semiconductor thermogenerator

LEP 4.1.07 -00

## Related topics

Seebeck effect (thermoelectric effect), thermoelectric e.m.f., efficiency, Peltier coefficient, Thomson coefficient, Seebeck coefficient, direct energy conversion, Thomson equations.

## Principle

In a semi-conductor thermogenerator, the no-load voltage and the short-circuit current are measured as a function of the temperature difference. The internal resistance, the Seebeck coefficient and the efficiency are determined.

## Equipment

| | | |
|---|---|---|
| Thermogenerator | 04366.00 | 1 |
| Flow-through heat exchanger | 04366.01 | 2 |
| Heat conductive paste, 50 g | 03747.00 | 1 |
| Connection box | 06030.23 | 1 |
| Rheostat, 33 Ohm, 3.1 A | 06112.02 | 1 |
| Voltmeter, 0.3-300 VDC, 10-300 VAC | 07035.00 | 1 |
| Ammeter 1/5 A DC | 07038.00 | 1 |
| Stopwatch, digital, 1/100 sec. | 03071.01 | 1 |
| Immersion thermostat TC10 | 08492.93 | 1 |
| Accessory set for TC10 | 08492.01 | 1 |
| Bath for thermostat, Makrolon | 08487.02 | 1 |
| Lab thermometer, -10...+100°C | 38056.00 | 1 |
| Thermometer, -10...+ 50°C | 38033.00 | 1 |
| Resistor 3.3 Ohm | 39104.25 | 1 |
| Rubber tubing, i.d. 6 mm | 39282.00 | 4 |
| Connecting cord, $l$ = 500 mm, red | 07361.01 | 3 |
| Connecting cord, $l$ = 500 mm, blue | 07361.04 | 2 |

## Tasks

1. To measure no-load voltage $U_o$ and short-circuit current $I_s$ at different temperature differences and to determine the Seebeck coefficient.
2. To measure current and voltage at a constant temperature difference but with different load resistors, and to determine the internal resistance $R_i$ from the measured values.
3. To determine the efficiency of energy conversion, from the quantity of heat consumed and the electrical energy produced per unit time.

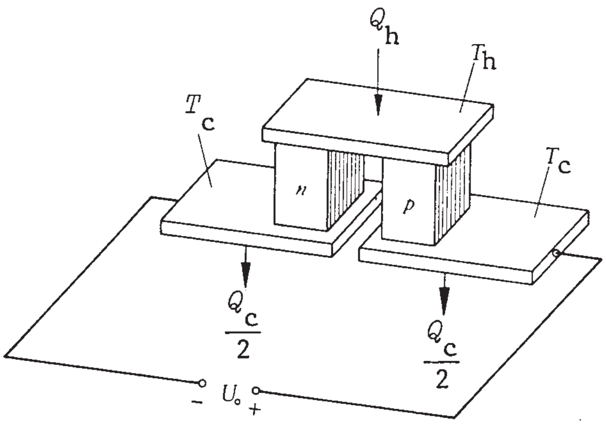
## Set-up and procedure

The experiment is set up as shown in Fig. 1.

1. Secure flow-type heat exchangers to each side of the thermogenerator. Fill the cold side with tap water and set the temperature of the hot side on the thermostat. The two temperatures are measured using the holes in the thermogenerator provided for the purpose. The short-circuit current and the no-load voltage are measured directly, the internal resistance of the measuring equipment being disregarded.

Fig. 1: Experimental set-up for measuring no-load voltage and short-circuit current as a function of temperature difference.

Fig. 2: Construction of a semiconductor Seebeck element. Several elements are generally connected electrically in series and thermally in parallel.




2. Connect rheostat $R_{ext.}$ to the thermogenerator at a constant average temperature difference. Measure the current and voltage at different settings and plot the results on a graph.

3. Remove the heat exchanger which was connected to the thermostat and put a water bath brim-full of boiling water in its place. Measure the temperature of the hot side $T_h = f(t)$ and of the cold side $T_c = f(t)$ as a function of time. Measure the current and the voltage across an external resistance of approximately the same value as the internal resistance.

**Theory and evaluation**

If a temperature drop is created along a current-free branch of a conductor made up of different materials, heat flows from the warmer region to the cooler one. The charge carriers which take part in this transfer of heat are unevenly distributed along the conductor. An internal field strength is set up, which can be shown to be the e.m.f. $U_o$ at the open ends of the conductor (Seebeck effect).

The voltage level depends on the temperature difference and on the materials used. To a first approximation, the voltage may be written:

$$U_o = \alpha_{1,2}\,(T_h - T_c) = \alpha_{1,2}\,\Delta T$$

where $\alpha_{1,2}$ is the Seebeck coefficient of the combination of materials used, $T_h$ is the temperature of the hot side and $T_c$ the temperature of the cold side.

1. Applying the regression expression

$$U_o = a + b\,\Delta T$$

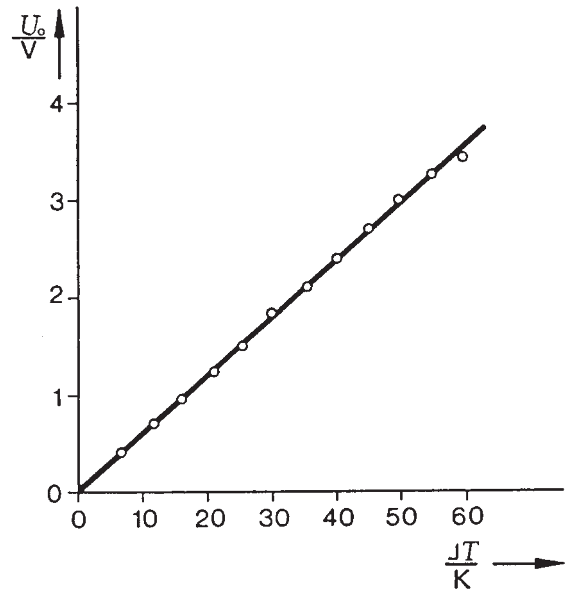
to the measured values in Fig. 3, we obtain

$$b = 0.0587\ \frac{\mathrm{V}}{\mathrm{K}}$$

with the standard error

$$s_b = 0.0006\ \frac{\mathrm{V}}{\mathrm{K}}$$

Fig. 3: No-load voltage as a function of the temperature difference.




The thermogenerator consists of 142 elements connected in series. The Seebeck coefficient of the semiconductor combination used is therefore

$$\alpha_{1,2} = 4.13 \cdot 10^{-4}\ \frac{\mathrm{V}}{\mathrm{K}}$$

with the standard error

$$s_{\alpha_{1,2}} = 4.04 \cdot 10^{-4}\ \frac{\mathrm{V}}{\mathrm{K}}$$

As the short-circuit also increases linearly with the temperature, the internal resistance of the thermogenerator is constant in the temperature range considered.

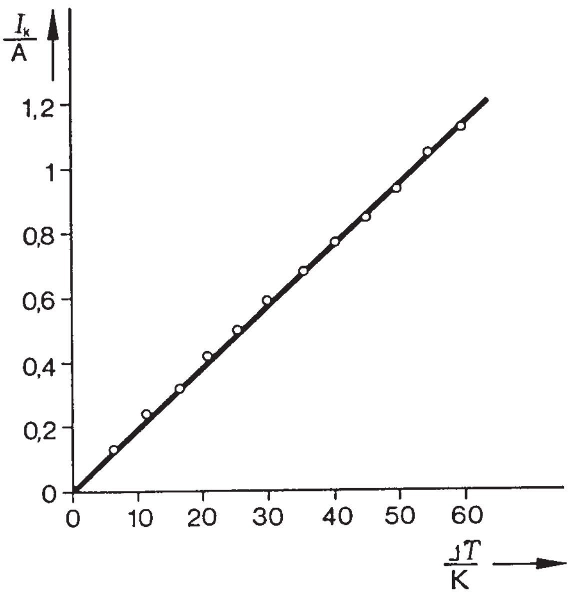
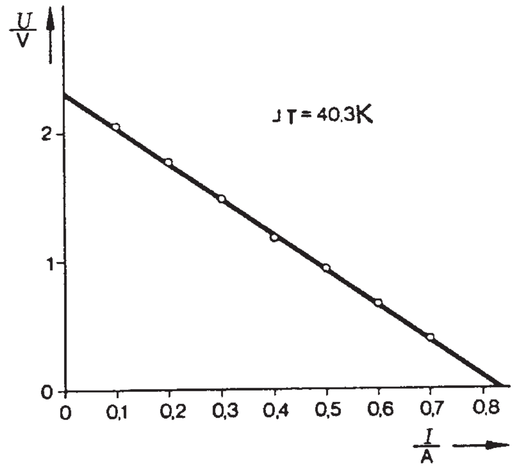



Fig. 4: Short-circuit current as a function of the temperature difference.

Fig. 5: Terminal voltage as a function of the current strength of a constant temperature difference.




2. Applying the regression expression $U = a + b\,I$ to the measured values from Fig. 5 we obtain

$$a = U_o = 2.34\text{ V}$$
$$s_a = s_{U_o} = 0.01\text{ V}$$
and
$$|b| = R_i = 2.80\ \Omega$$
$$s_b = s_{R_i} = 0.02\ \Omega.$$

and the short circuit current

$$I_s = \frac{U_o}{R_i} = 0.84\text{ A}$$

with $s_{I_s} = 0.01$ A

3. From Fig. 6 we determine the slope of the (descending) curve at one point by drawing a tangent or by linear regression.

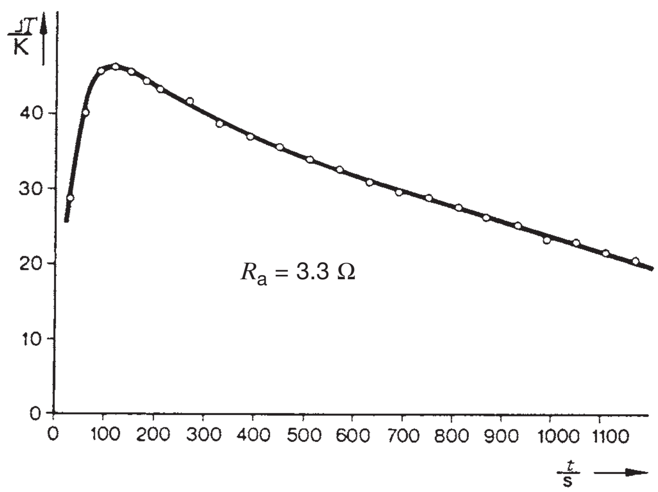
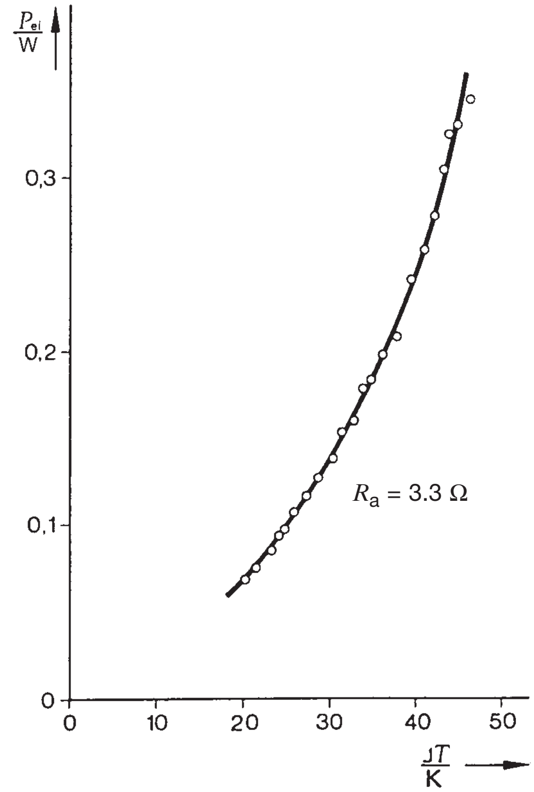



Fig. 6: Temperature difference as a function of time.

Fig. 7: Electrical power generated as a function of the temperature difference.




At a temperature difference $\Delta T$ of 40 K we obtain the following for the nearest measured values, using the regression expression $\Delta T = a + b\,t$:

$$b = \frac{\mathrm{d}\Delta T}{\mathrm{d}t} = -0.0361\ \frac{\text{K}}{\text{s}}$$

We can thus work out the quantity of heat $Q$ flowing through the generator in unit time in accordance with

$$\frac{\mathrm{d}Q}{\mathrm{d}t} = P_{th.} = C \cdot \frac{\mathrm{d}\Delta T}{\mathrm{d}t}$$

As the mass of water $m_W$ = 0.194 kg and the specific heat capacity if water

$$c_W = 4182\ \frac{\text{J}}{\text{K}}$$

we obtain

$$C = m_W \cdot c_W = 811\ \frac{\text{J}}{\text{Kg K}}$$

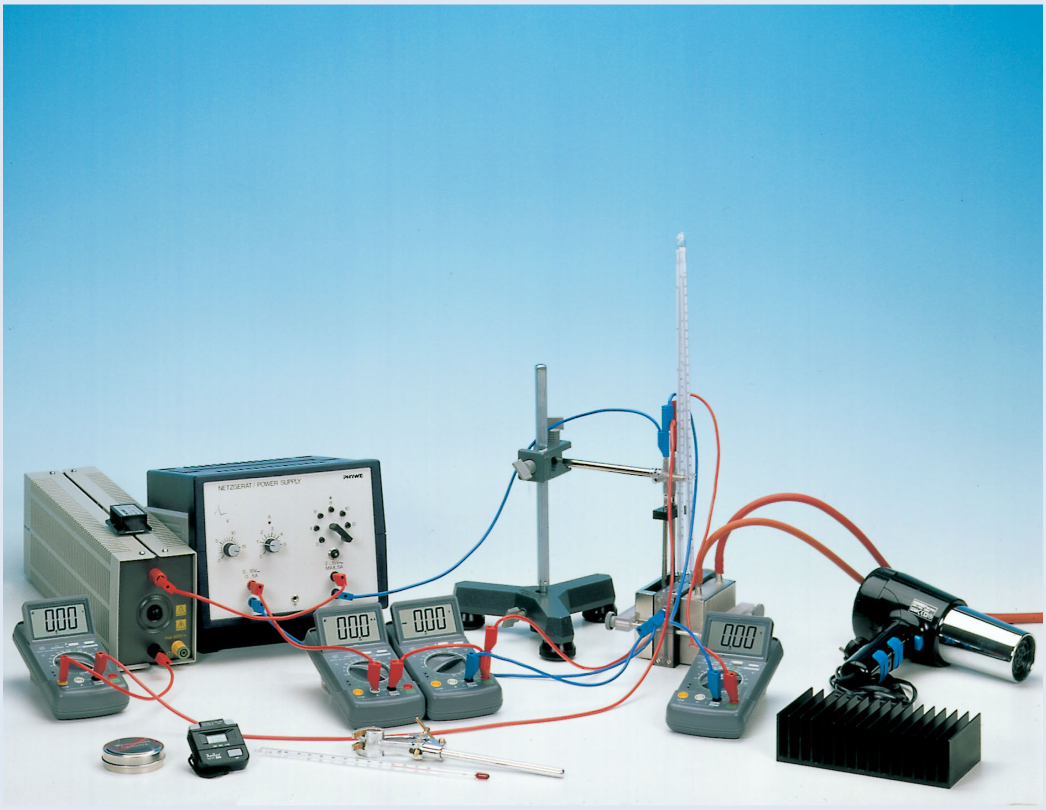
so that

$$P_{th.} = 29.3\ \frac{\text{J}}{\text{s}}$$

The electrical power, measured at constant load, $P_{el.}$, can be obtained from Fig. 7. For a temperature difference $\Delta T$ = 40 K we obtain $P_{el.}$ = 0.25 W, so that the efficiency

$$\eta = \frac{P_{el.}}{P_{th.}} = \ = 0.009 \text{ or } 0.9\%$$

# 4.1.08-00 Peltier heat pump



## What you can learn about …

- → Peltier effect
- → Heat pipe
- → Termoelectric e.m.f.
- → Peltier coefficient
- → Cooling capacity
- → Heating capacity
- → Efficiency rating
- → Thomson coefficient
- → Seebeck coefficient
- → Thomson equations
- → Heat conduction
- → Convection
- → Forced cooling
- → Joule effect

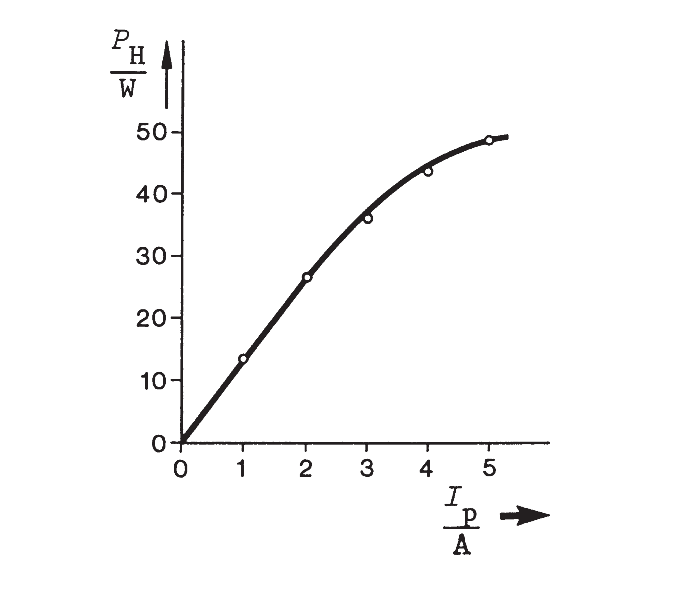
## Principle:

The cooling capacity heating capacity and efficiency rating of a Peltier heat pump are determined under different operating conditions.

## What you need:

| | | |
|---|---|---|
| Thermogenerator | 04366.00 | 1 |
| Flow-through heat exchanger | 04366.01 | 1 |
| Air cooler | 04366.02 | 1 |
| Heating coil with sockets | 04450.00 | 1 |
| Distributor | 06024.00 | 1 |
| Rheostats, 33 Ω, 3.1 A | 06112.02 | 1 |
| Connecting plug, pack of 2 | 07278.05 | 1 |
| Power supply, universal | 13500.93 | 1 |
| Digital multimeter 2010 | 07128.00 | 4 |
| Stopwatch, digital, 1/100 s | 03071.01 | 1 |
| Hot/cold air blower, 1700 W | 04030.93 | 1 |
| Laboratory thermometers, -10...+100°C | 38056.00 | 1 |
| Precision mercury thermometers, -10...+ 50°C | 38034.00 | 2 |
| Rubber tubing, $d_i$ = 6 mm, $l$ = 1 m | 39282.00 | 1 |
| Universal clamp | 37718.00 | 1 |
| Tripod base -PASS- | 02002.55 | 1 |
| Support rod -PASS-, square, $l$ = 250 mm | 02025.55 | 1 |
| Right angle clamp -PASS- | 02040.55 | 1 |
| Connecting cable, 4 mm plug, 32 A, red, $l$ = 25 cm | 07360.01 | 3 |
| Connecting cable, 4 mm plug, 32 A, red, $l$ = 50 cm | 07361.01 | 3 |
| Connecting cable, 4 mm plug, 32 A, blue, $l$ = 50 cm | 07361.04 | 2 |
| Connecting cable, 4 mm plug, 32 A, blue, $l$ = 75 cm | 07362.04 | 2 |
| Connecting cable, 4 mm plug, 32 A, red, $l$ = 75 cm | 07362.01 | 1 |
| Heat conductive paste, 50 g | 03747.00 | 1 |

**Complete Equipment Set, Manual on CD-ROM included**
**Peltier heat pump P2410800**




Pump cooling capacity as a function of the operating current.

## Tasks:

1. To determine the cooling capacity $P_c$ the pump as a function of the current and to calculate the efficiency rating hc at maximum output.
2. To determine the heating capacity $P_w$ of the pump and its efficiency rating hw at constant current and constant temperature on the cold side.
3. To determine $P_w$ , $\eta_w$ and $P_c$ , $\eta_c$ from the relation ship between temperature and time on the hot and cold sides.
4. To investigate the temperature behaviour when the pump is used for cooling, with the hot side air-cooled.

PHYWE excellence in science

# Peltier heat pump

LEP 4.1.08 -00

## Related topics

Peltier effect, heat pipe, thermoelectric e. m. f., Peltier coefficient, cooling capacity, heating capacity, efficiency rating, Thomson coefficient, Seebeck coefficient, Thomson equations, heat conduction, convection, forced cooling, Joule effect.

## Principle

The cooling capacity) heating capacity and efficiency rating of a Peltier heat pump are determined under different operating conditions.

## Equipment

| | | |
|---|---|---|
| Thermogenerator | 04366.00 | 1 |
| Flow-through heat exchanger | 04366.01 | 1 |
| Air cooler | 04366.02 | 1 |
| Heating coil with sockets | 04450.00 | 1 |
| Distributor | 06024.00 | 1 |
| Rheostat, 33 Ohm, 3.1 A | 06112.02 | 1 |
| Connecting plug, 2 pcs. | 07278.05 | 1 |
| Power supply, universal | 13500.93 | 1 |
| Digital multimeter | 07134.00 | 4 |
| Stopwatch, digital, 1/100 sec. | 03071.01 | 1 |
| Cold a. hot air blower, 1700 W | 04030.93 | 1 |
| Lab thermometer, -10…+100°C | 38056.00 | 1 |
| Thermometer, -10…+ 50°C | 38033.00 | 2 |
| Rubber tubing, i.d. 6 mm | 39282.00 | 1 |
| Universal clamp | 37715.00 | 1 |
| Tripod base -PASS- | 02002.55 | 1 |
| Support rod -PASS, $l$ = 250 mm | 02025.55 | 1 |
| Right angle clamp -PASS- | 02040.55 | 1 |
| Connecting cord, $l$ = 250 mm, red | 07360.01 | 3 |
| Connecting cord, $l$ = 500 mm, red | 07361.01 | 3 |
| Connecting cord, $l$ = 500 mm, blue | 07361.04 | 2 |
| Connecting cord, $l$ = 750 mm, blue | 07362.04 | 2 |
| Connecting cord, $l$ = 750 mm, red | 07362.01 | 1 |
| Heat conductive paste, 50 g | 03747.00 | 1 |

## Tasks

1. To determine the cooling capacity $P_c$ the pump as a function of the current and to calculate the efficiency rating $\eta_c$ at maximum output.
2. To determine the heating capacity $P_w$ of the pump and its efficiency rating $\eta_w$ at constant current and constant temperature on the cold side.
3. To determine $P_w$, $\eta_w$ and $P_c$, $\eta_c$ from the relationship between temperature and time on the hot and cold sides.
4. To investigate the temperature behaviour when the pump is used for cooling, with the hot side air-cooled.

Fig. 1: Experimental set-up for measuring cooling capacity.

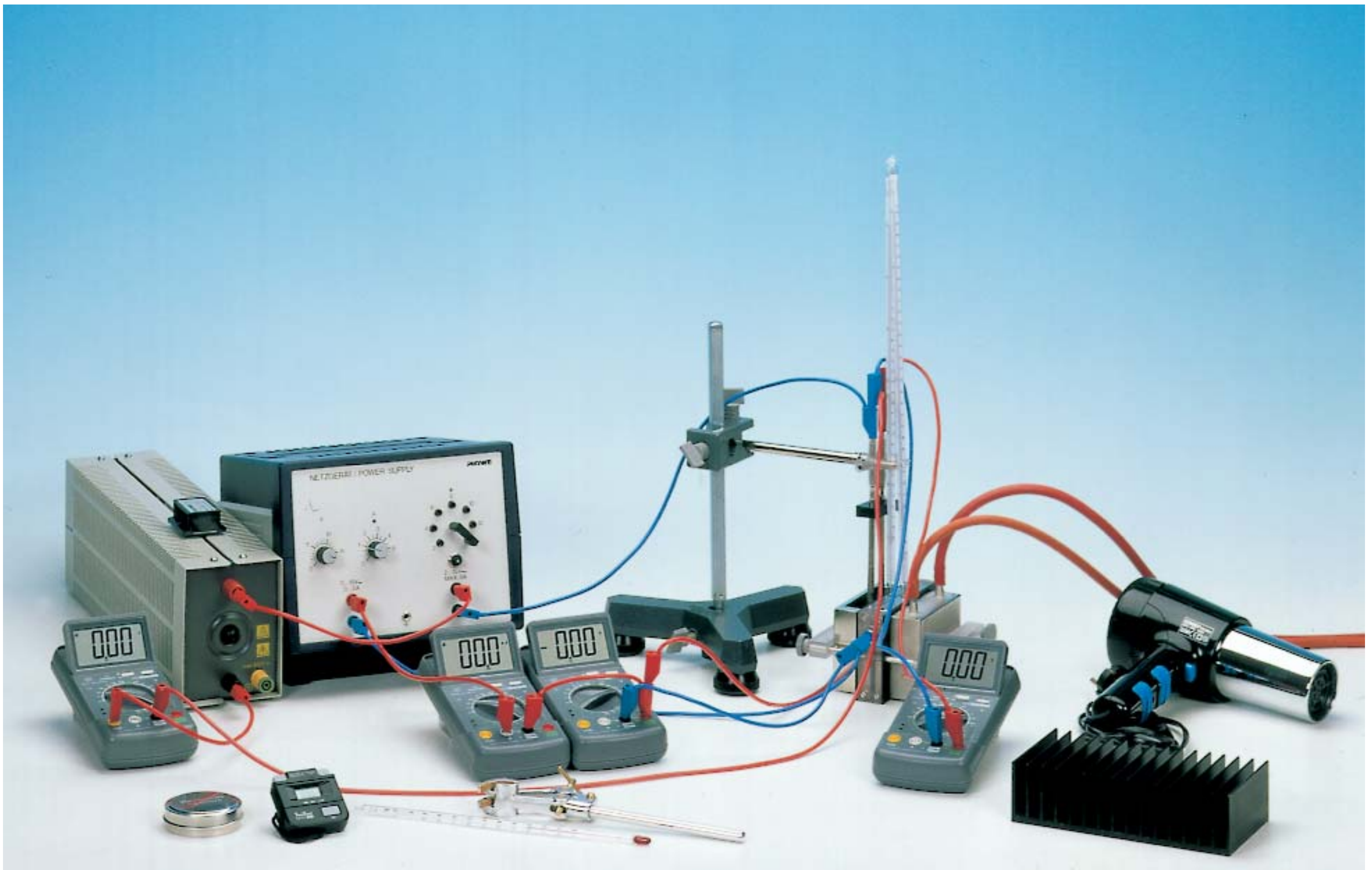
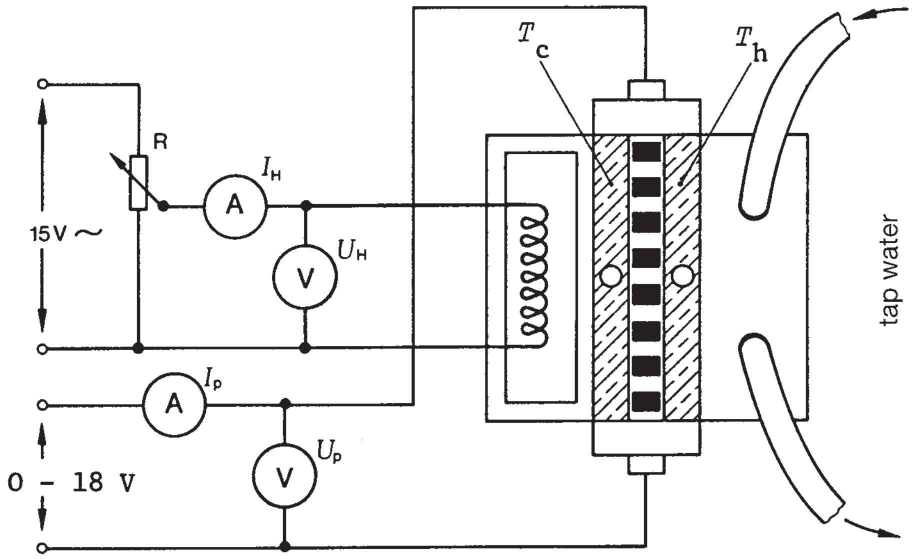


Fig. 2: Set-up for determining cooling capacity.




**Set.up and procedure**

1. Fit a water bath on the cold side and a heat exchanger through which tap water flows on the hot side. A heating coil (resistance approx. 3 ohms), operated on AC, dips into the water-filled bath. For each current value $I_p$ set the heating capacity $P_H = U_H \cdot I_H$ with the rheostat $R$ so that the temperature difference between the hot and the cold side is approximately zero. The power supplied then exactly corresponds to the cooling capacity $P_c$. Measure the heater current $I_H$ and voltage $U_H$, the operating current $I_p$ and voltage $U_p$ and the temperatures of the hot side $T_h$ and the cold side $T_c$.
2. Remove the heating coil as it is no longer required. Reverse the operating current so that the water in the bath now heats up. Measure the rise in the temperature of water $T_w$ at constant current $I_p$. Measure also $I_p$, $U_p$ and $T_c$. Calculate the heat capacities of a copper block $C_{Cu}$, of the water $C_w$ and of the brass bath $C_{Br}$ from their dimensions or by weighing.
3. Fit water baths to both sides of the heat pump and fill them with water of the same temperature. With the current $I_p$ constant) measure the changes in the temperature of the two water baths) i.e. $T_h = f(t)$, $T_c = f(t)$, $I_p$ and $U_p$.
4. For this fourth experiment we have a water bath on the cold side, an air cooler on the hot. Measure the temperature of the cold side as a function of time, with the cooler
   a) in static atmospheric air, and
   b) force-cooled with a blower.

**Theory and evaluation**

When an electric current flows through a circuit composed of two different conductors, heat will be liberated at one junction and absorbed at the other) depending on the direction in which the current is flowing (Peltier effect). The quantity of heat $Q$ liberated per unit time is proportional to the current $I$:

$$\frac{Q}{t} = P_p = \pi \cdot I = \alpha \cdot T \cdot I$$

where $\pi$ is the Peltier coefficient, $\alpha$ the Seebeck coefficient and $T$ the absolute temperature.

If an electric current $I$ flows in a homogeneous conductor in the direction of a temperature gradient

$$\frac{dT}{dx},$$

heat will be absorbed or given out, depending on the material (Thomson effect):

$$P_T = \tau \cdot I \cdot \frac{dT}{dx}$$

where $\tau$ is the Thomson coefficient.

The direction in which the heat flows depends on the sign of the Thomson coefficient, the direction in which the current flows and the direction of the temperature gradient.

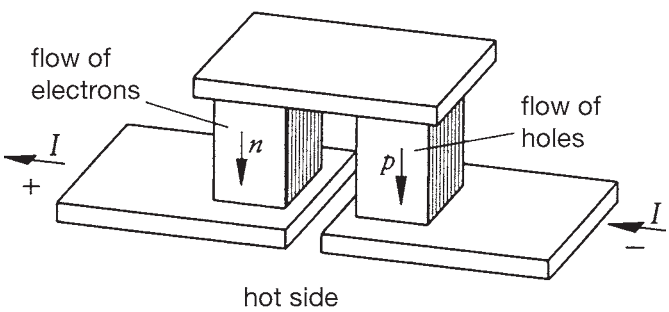
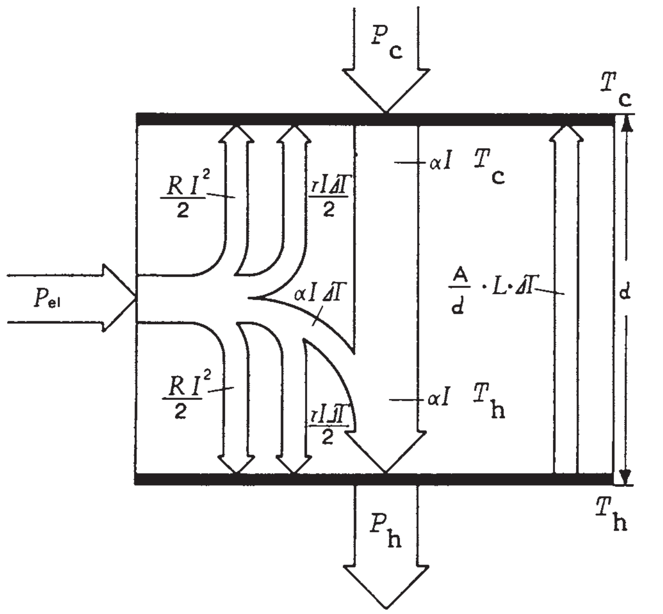



Fig. 3: Construction of a Peltier semi-conductor element. In practice several elements are generally connected in series (electrically) and in parallel (thermally).

Fig. 4: Power balance flow chart in a Peltier component. (The example illustrated is for the case where $P_T > 0$).




If an electric current $I$ flows in an isothermal conductor of resistance $R$, we have the Joule effect:

$$P_J = R \cdot I^2$$

Because of heat conduction, heat also flows from the hot side (temperature $T_h$) to the cold side (temperature $T_c$):

$$P_L = L \frac{A}{d} (T_h - T_c)$$

where $L$ is the conductivity, $A$ the cross-sectional area and $d$ the thickness of the Peltier component.

Writing $\Delta T = T_h - T_c$, we obtain for the heat capacity of the pump on the cold side (the cooling capacity):

$$-P_c = \alpha T_c I \pm \frac{\tau I \Delta T}{2d} - \frac{1}{2} I^2 R - \frac{L \cdot A \cdot \Delta T}{d}$$

and, for the heat capacity of the pump on the hot side (the heating capacity):

$$+P_h = \alpha T_h I \pm \frac{\tau I \Delta T}{2d} + \frac{1}{2} I^2 R - \frac{L \cdot A \cdot \Delta T}{d}.$$

The electric power supplied is

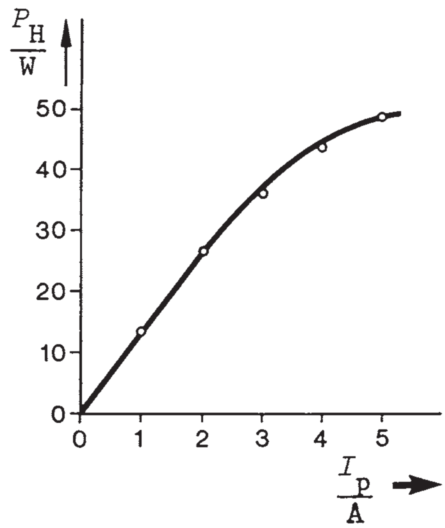
$$+P_{el.} = \alpha I \Delta T + R I^2 + \frac{\tau I \Delta T}{2d} = U_p \cdot I_p$$

1. The pump cooling capacity $P_c$ was found to be 49 W when $I_p$ = 5 A and $P_H = P_c$

   The efficiency rating

   $$\eta_c = \frac{P_c}{P_{el.}}$$

Fig. 5: Pump cooling capacity as a function of the operating current.




becomes, for the measured values
$I_p$ = 5.0 A and $U_p$ = 14.2 V,
$\eta_c$ = 0.69 ($\vartheta_h = \vartheta_c$ = 20°C)

2. From the slope of the curve in Fig. 6 (where the curve starts off as a straight line) we can calculate the pump heating capacity

$$P_h = \frac{C_{tot.} \cdot \Delta T_h}{\Delta t}$$

and the corresponding efficiency rating

$$\eta_h = \frac{P_h}{P_{el.}},$$

where $P_{el.} = I_p \cdot \overline{U}_p$

as follows:

$m_w$ = 0.194 kg, $c_w$ = 4182 $\frac{\text{J}}{\text{kg K}}$

$m_{Br}$ = 0.0983 kg, $c_{Br}$ = 381 $\frac{\text{J}}{\text{kg K}}$

$m_{Cu}$ = 0.712 kg, $c_{Cu}$ = 383 $\frac{\text{J}}{\text{kg K}}$

$$C_{tot.} = m_w \cdot c_w \cdot m_{Br} \cdot c_{Br} + m_{Cu} \cdot c_{Cu} = 1121 \frac{\text{J}}{\text{kg K}}$$

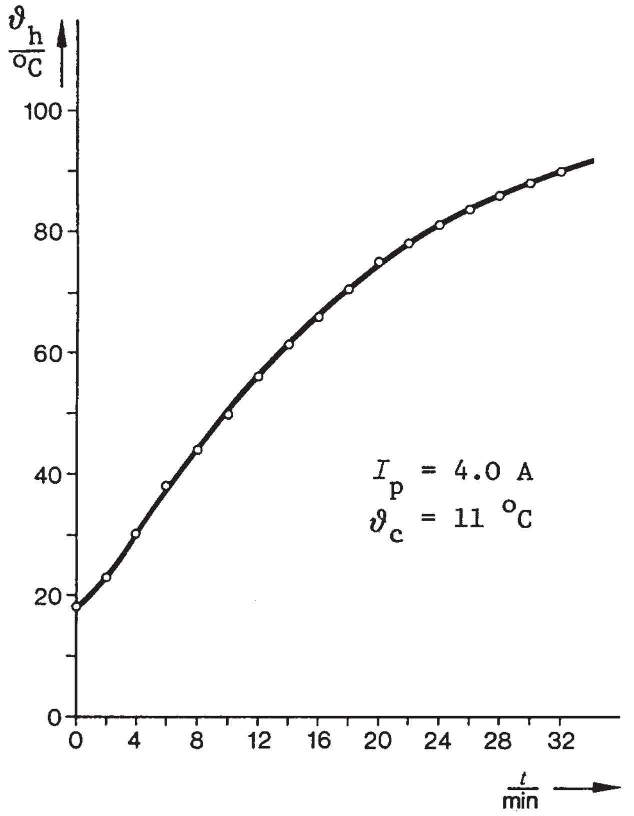
where $m_w$ is the mass of the water, $c_w$ the specific heat capacity of the water, $m_{Cu}$ the mass of a copper block, $c_{Cu}$ the specific heat capacity of copper, $m_{Br}$ the mass of the brass bath, $c_{Br}$ the specific heat capacity of brass, $I_p$ the pump current, and $\overline{U}_p$ the mean pump voltage.

With the slope

$$\frac{\Delta T_h}{\Delta t} = 6.7 \times 10^{-2} \text{ K/s}$$

we obtain a value $P_h$ of 75 W.

Fig. 6: Temperature of the hot side as a function of time.




With values for $I_p$ of 4.0 A and $\overline{U}_p$ of 12.5 V (average value) we obtain an efficiency rating

$\eta_c = 1.5$

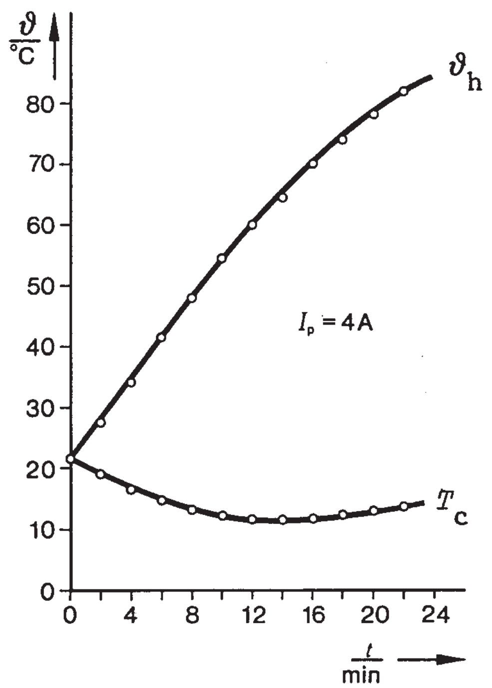
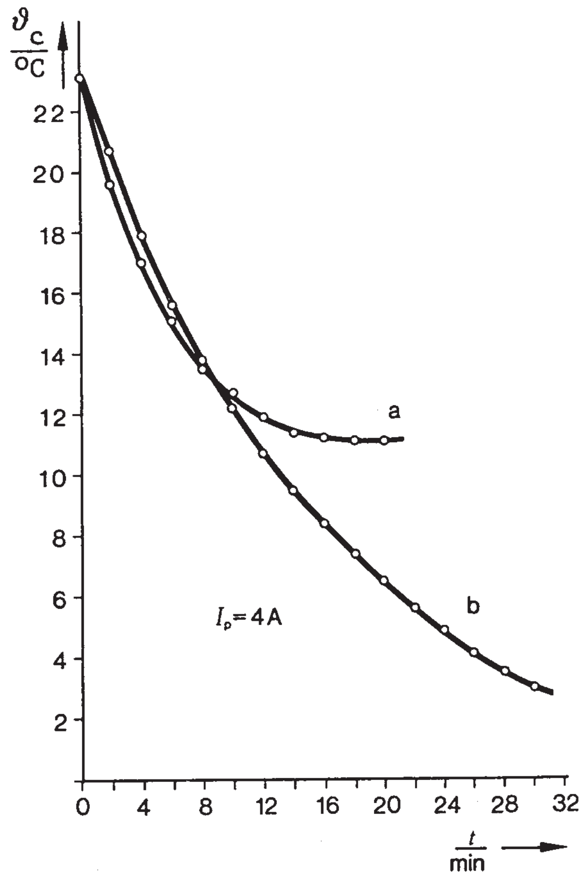



Fig. 7: Water temperature as a function of time.

Fig. 8: Water temperature when the hot side is cooled with an air cooler
a) cooling by convection
b) forced cooling.




3. $P_h$ and $P_c$, and $\eta_h$ and $\eta_c$, can be calculated from the slopes of the curves $\vartheta_h = f(t)$ and $\vartheta_c = f(t)$ and the relevant heat capacities.

   With $\frac{\Delta\vartheta_h}{\Delta t}$ = 0.056 K/s (start of curve) and

   $\frac{\Delta\vartheta_c}{\Delta t}$ $c$ = – 0.023 K/s and with $C_{tot.}$ = 1121 J/K, we obtain:

   $P_h$ = 63 W;  $P_c$ = 26 W.

   In the range considered, the voltage $\overline{U}_p$ (average value) was 12.4 V, so that we obtain the efficiency ratings $\eta_h = 1.3$ and $\eta_c = 0.52$. ($I$ = 4 A, $T$= 22°C).

4. Fig. 8 shows the course of temperature in the water bath on the cold side when the hot side was cooled with the air cooler. The temperature $\vartheta_h$ of the hot side was approx. 72°C after 20 minutes (no blower). The maximum temperature difference $\vartheta_h - \vartheta_c$ = 60 K is thus attained and the pump output of the Peltier component is zero. When the blower was used, $T_h$ remained constant at approx. 45°C after 20 minutes.