2005-03-04

Thermoelectric effects

Why do this experiment?

Thermoelectric effects are rapidly becoming more important. Thermoelectric cooling is a standard method used in many electronic instruments and other devices, as well as in small refrigerators for mobile use. With the rapid development of new advanced thermoelectric materials, thermoelectric power conversion may soon become a valuable addition to increase the efficiency of existing power production units. This motivates a closer study of these materials.

Aims of the experiment:

After doing this experiment you should

- have an increased understanding of heat and energy flow in thermoelectric circuits,
- understand thermoelectric conversion and cooling circuits,
- be able to estimate the best possible power conversion efficiency or cooling power of a thermoelectric device.

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!!! WARNINGS !!!

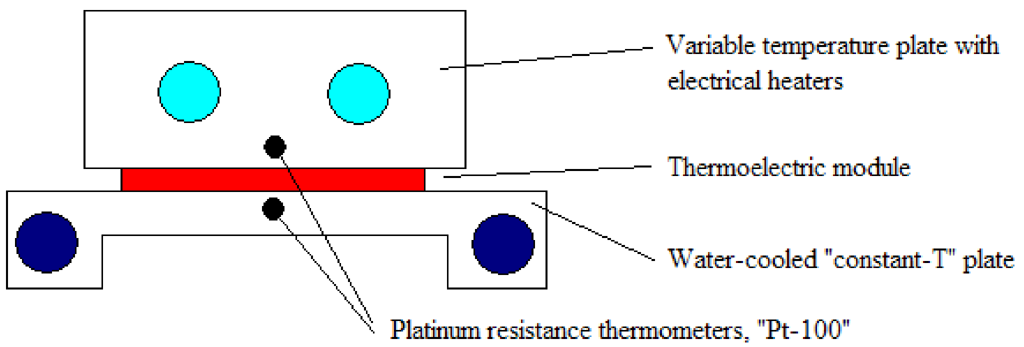
Please read this first!

Thermoelectric devices are semiconductors and are sensitive to overheating. You will also handle large heater powers, exceeding 100 W in a very small volume. Therefore,

you must always have both thermometers (platinum resistances) connected to ohmmeters, and you should always keep an eye on these, checking that no part of the circuit is ever heated to a temperature above 70ºC, corresponding to a platinum resistance of 127 Ω !

Experimental equipment

The experimental equipment is very simple: It consists of a thermoelectric module CP1.4-127-045L manufactured by Melcor, Inc., sandwiched between two metal plates as shown below.



Each metal plate contains a platinum resistance thermometer, and the temperatures on both sides of the thermoelectric module can be measured at any time.

- One of the plates has channels for cooling water which will be kept running throughout the experiment, such that the temperature of this plate is kept nominally constant.
- The temperature of the other (upper) plate can be varied, either by electrical heating using the built-in electric power heaters, or by thermoelectric heating or cooling.

The equipment is thermally insulated by a large expanded polystyrene box, and we shall assume that there is no heat exchange with the surroundings. This is a good approximation.

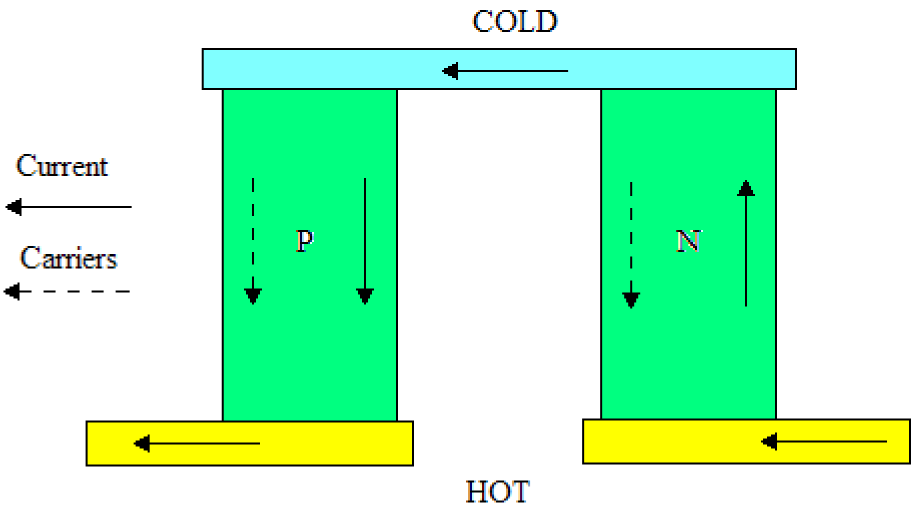
Theory

Thermoelectric materials have three important parameters,

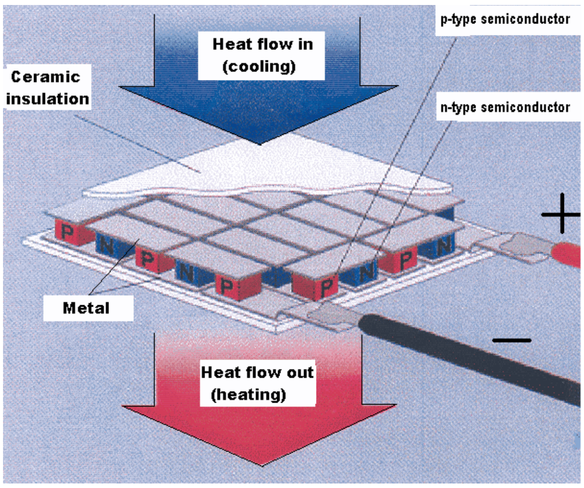
- the **Seebeck coefficient S**, defined from $U = S\Delta T$, with $I = 0$,
- the **Peltier coefficient** Π, defined from $\frac{dQ}{dt} = \Pi I$, with $\Delta T = 0$,
- and the **Thomson coefficient** μ.

These definitions assume linearity and very small differences in T and U;
U is the thermoelectric voltage, I the current, dQ/dt the heat flow and ΔT the temperature difference between the junctions. In this experiment we will not consider the Thomson effect.

The three parameters are related by the expressions $\Pi = ST$ and $\mu = T\frac{dS}{dt}$.



The thermoelectric module consists of 127 small thermocouple units of the type shown in the figure above. These modules are connected electrically in series, but thermally in parallel (i.e. they all transport heat between top and bottom):



We can define a **total electrical resistance R** and a **total thermal conductance K** as

$$R = \sum \left(\frac{L_n \rho_n}{A_n} + \frac{L_p \rho_p}{A_p} \right) \quad \text{and} \quad K = \sum \left(\frac{\kappa_n A_n}{L_n} + \frac{\kappa_p A_p}{L_p} \right),$$

where L is the length, A the cross-sectional area, ρ the resistivity, and κ the thermal conductivity, and subscripts n and p indicate the n-type and p-type branches, respectively. The summation is, of course, over all 127 individual units.

- If the <u>current I is zero</u> there is no heat dissipation and no Peltier effect, but if the temperature difference $\Delta T \neq 0$ we have two effects:
  1. there will be a *Seebeck effect*, giving a thermoelectric output voltage $U = S\Delta T$ to be summed over all 127 units,
  2. there will be a *heat flow due to thermal conduction*, $\frac{dQ}{dt} = K\Delta T$.

- If we <u>apply a current I</u> through the circuit, heat will also be transported by the Peltier effect. However, there will also be a temperature difference and thus several effects:
  1. The *Peltier effect* will absorb heat on one side and release the same amount on the other, giving a net heat flow $\frac{dQ}{dt} = \Pi I = STI$,
  2. there will be *Joule heating*, and from the superposition principle we can assume that one half of this will flow to each side, $-\frac{RI^2}{2}$,
  3. there will be *heat conduction* from the hot to the cold side, $\frac{dQ}{dt} = K\Delta T$.

If we use the Peltier element for COOLING, it will transport heat from the cold to the hot side; the total **heat flow from the cold side** is then

$$\left. \frac{dQ}{dt} \right|_{cold} = \Pi I - \frac{RI^2}{2} - K\Delta T .$$

This parabolic equation will have a maximum for one particular value of the current, corresponding to maximum cooling in the circuit.

Since we cannot use the definition valid for a single material, the **Figure-of-merit** for the thermoelectric module will be defined as

$$ZT = \frac{S^2}{KR} .$$

This expression is temperature dependent.

TASK 1:
Identification and set-up of equipment

Take a close look at the experimental equipment supplied. You may lift the insulating lid and look at the actual plate-and-module assembly.

- Make sure that you understand how the wires and tubes are connected, and why. There will be thick power wires for the resistive heater and for the thermoelectric module, and very fine (insulated) copper wires for the platinum resistance thermometers.

Be careful with the thin wires - it is very easy to tear off a wire or a contact!

- You need at least three digital multimeters and two power supplies. Make sure you understand how to handle these.
- If necessary, connect the cooling water to the taps. Switch on the cooling water and let it run.
- Connect the two platinum resistance thermometers to digital multimeters as described in the instructions (Appendix B). Switch the multimeters first to two-pole resistance measurements, then to four-pole measurements. Note that there is a significant difference between the readings!

Read the platinum resistances and calculate the temperatures in the two metal plates.
Make sure that the values are reasonable!

Note the warning text on page 3:
keep an eye on the resistance values throughout the experiment!

TASK 2:
Thermoelectric power and thermal conductance

Your first task is to measure the **Seebeck coefficient S** and the **thermal conductance** K.

By definition, in the measurement of S the current through the Peltier module should be zero.

- Connect a power supply to the resistive heater. Apply a reasonable power (5-10 W) and wait until approximate thermal equilibrium is obtained.

MEASURE
1. the applied power,
2. the temperatures on the two sides of the module,
3. the voltage over the Peltier module.

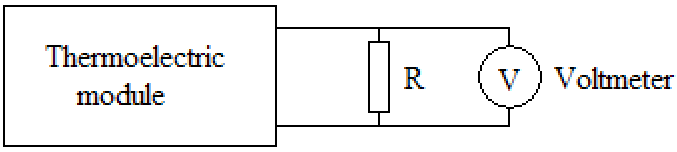
Repeat the measurement at double or half the applied power; check that the results are reasonable.

CALCULATE
1. the thermoelectric power S of the module,
2. the thermal conductance K of the module,
3. the thermoelectric power for a single thermocouple unit in the module.

Task 3:
Thermoelectric power conversion and efficiency.

In this Task, the circuit will produce electric power, on contrary to the case in Task 2, when the circuit produced a thermoelectric voltage but very little power ($I \approx 0$).

- Use the same set-up as in Task 2 and continue to use a similar heater power.
- Measure again the output voltage from the thermoelectric module.
- Connect a high power, variable resistor of 10 Ω over the output from the module, as shown in the Figure below. Note the new output voltage, which must be lower than before because of the voltage drop of the output current over the internal resistance.



- Decrease the power resistor to 5 Ω and again note the output voltage.

Calculate

1. the internal resistance of the thermoelectric module,
2. the maximum output power from the module under the experimental conditions used,
3. the maximum efficiency of the module as a thermoelectric power source.

Task 4:
Peltier coefficient

Task 4 is to measure the Peltier coefficient. By definition, this should be done using $\Delta T = 0$.

To make $\Delta T = 0$, you must heat the "variable temperature" plate and use the Peltier element to cool away this power to the "constant temperature" plate to equalize the temperature. This is done as follows:

- First apply a power of about 10 W to the resistive heater.
- Then connect the Peltier module to another power supply. Apply power and observe the two measured temperatures. **If the temperature difference increases, you probably have the wrong polarity to the thermoelectric power module!** In this case, reverse the voltage to the thermoelectric module.
- Increase the power applied to the thermoelectric module until the two temperatures are constant and as equal as possible.

Measure

1. the heater power,
2. the current through the Peltier module,
3. the voltage applied to the Peltier module.

Calculate

1. the Peltier coefficient
2. the internal resistance of the Peltier module.

TASK 5 (OPTIONAL):
Lowest possible cooling temperature

In this Task, you test the maximum capabilities of the Peltier module under test: what is the largest temperature difference between the hot and cold sides you can reach with this module?

- Switch off the power to the electrical heater, and connect the Peltier element to cool the "variable temperature" side.
- Increase the current through the Peltier module from zero to 6 A in steps of 1 A.
  At each step, MEASURE:
  1. the temperatures on the two sides,
  2. the voltage and current applied to the Peltier module.

Make sure you are cooling the correct side! The water cooled side should now be the warmer one!

Plot the temperature difference as a function of the current through the Peltier module and fit a second order function to the data.

CALCULATE

1. the maximum temperature difference that the module can create,
2. the effective cooling power at maximum temperature difference.

TASK 6:
Some relations and comparisons.

COMPARE

- the different values obtained for the internal resistance,
- the values of the Peltier coefficient obtained by direct measurements and calculated from the Seebeck coefficient,
- the measured maximum temperature difference and the value calculated from the measured Peltier coefficient, the measured internal resistance, and the measured thermal conductance.

CALCULATE

- the Figure-of-Merit for this thermoelectric module.

APPENDIX A: Data sheet for the thermoelectric module

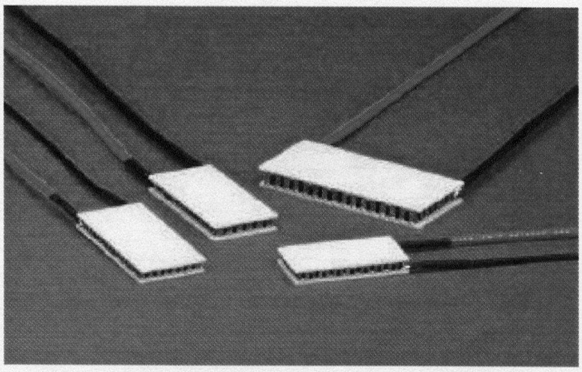
MELCOR

Thermoelectric Cooler

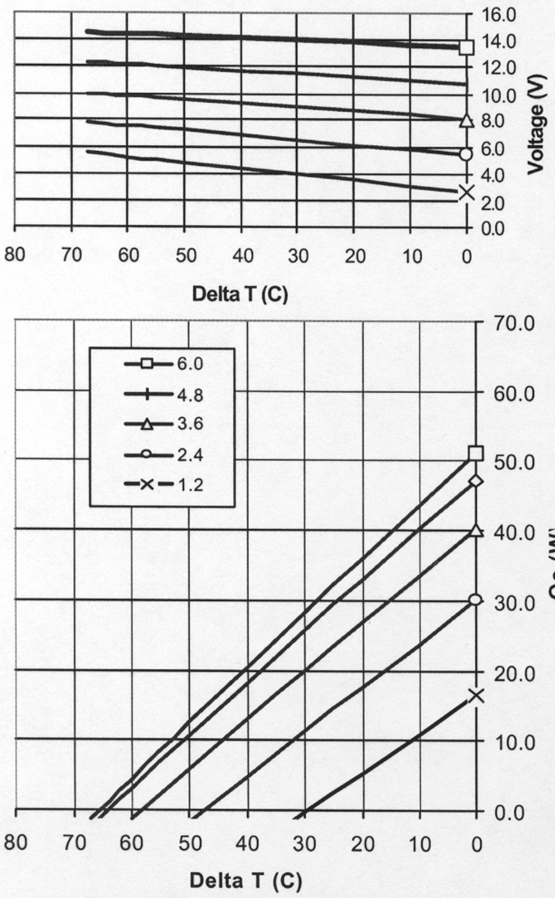
CP1.4-127-045

Performance Specifications

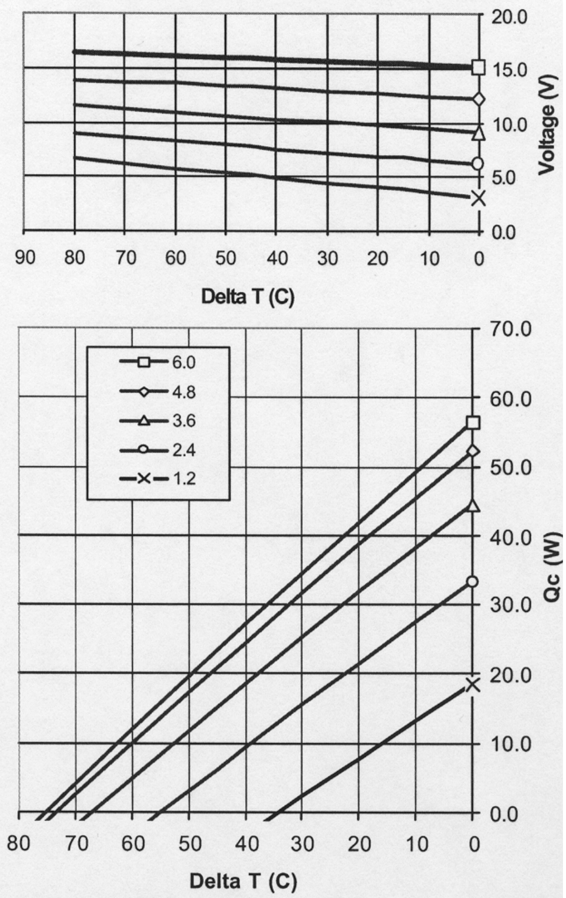
Hot Side Temperature (°C)	25°C	50°C
Qmax (Watts)	72.0	56.2
Delta Tmax (°C)	65	74
Imax (Amps)	8.5	8.5
Vmax (Volts)	15.4	16.4
Module Resistance (Ohms)	2.25	2.53



Performance Curves – Th = 25°C



Performance Curves – Th = 50°C

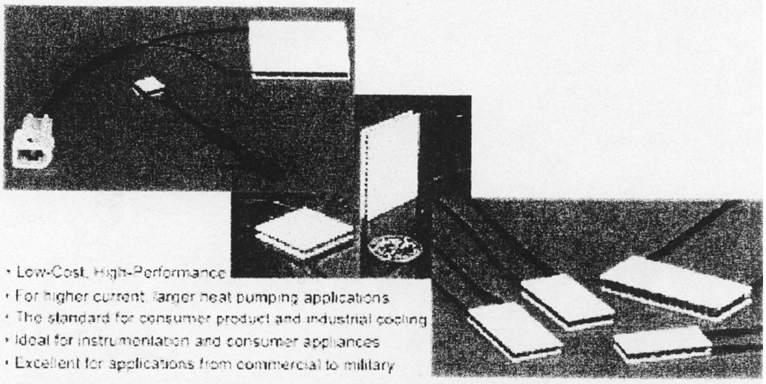


 Rev 1.01

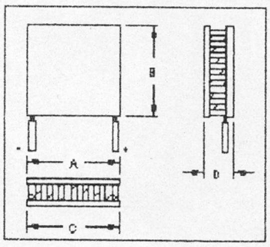
CP1.4-127-045

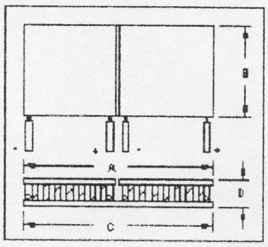
Mechanical Drawing

CP Series



Mechanical Characteristics





Ceramic Material: Alumina (Al_2O_3)
Solder Construction: 138ºC, Bismuth Tin (BiSn)

Thickness and Surface Finish Specifications

Suffix	Thickness	Flatness & Parallelism	Hot Face	Cold Face	Lead Length
L	0.131" ± 0.010"	0.0015" / 0.0015"	Lapped	Lapped	4.5"
-1	0.131" ± 0.001"	0.001" / 0.001"	Lapped	Lapped	4.5"
-2	0.131" ± 0.0005"	0.0005" / 0.0005"	Lapped	Lapped	4.5"
ML	0.135 ± 0.010"	0.002" / 0.002"	Metallized	Lapped	4.5"
LM	0.135 ± 0.010"	0.002" / 0.002"	Lapped	Metallized	4.5"
MM	0.139 ± 0.010"	0.002" / 0.002"	Metallized	Metallized	4.5"

Operating Tips

- Max. Operating Temperature: 80°C
- Do not exceed Imax or Vmax when operating module.
- Please consult Melcor for moisture and
- corrosion protection options.
- Solder tinning also available on metallized ceramics.

 Rev 1.01

Appendix B: Platinum resistance thermometers

The resistance of a platinum wire is a secondary standard for temperature and can be used to interpolate temperature to within about 1 mK over a very wide temperature range. Because of their high stability, platinum resistance thermometers are widely used in industry. The standard thermometer has a resistance of exactly 100 ohm at 0ºC and is thus called a **Pt-100 sensor**. Its resistance varies with temperature according to the curve shown at the bottom of the page.

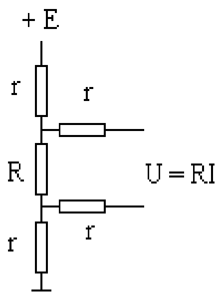
Because of the low resistance and the small variation with temperature it is necessary to measure the resistance with very high accuracy, and the resistance of the connecting leads must be eliminated from the measurements. For this reason Pt-100 sensors usually have four leads instead of two, connected as shown below. The resistance between the two connection points is the true resistance (100 Ω at 0ºC). In use, a current I is supplied through the two "current" leads and the resulting voltage drop RI is measured using a high impedance voltmeter connected to the two "voltage" leads. Because of the high impedance, no current flows through the "voltage" leads and the measured voltage corresponds exactly to U = RI. Most modern digital voltmeters are supplied with four input terminals and can measure resistances in either two-wire or four-wire mode.

Voltage source, supplying current:

Current lead

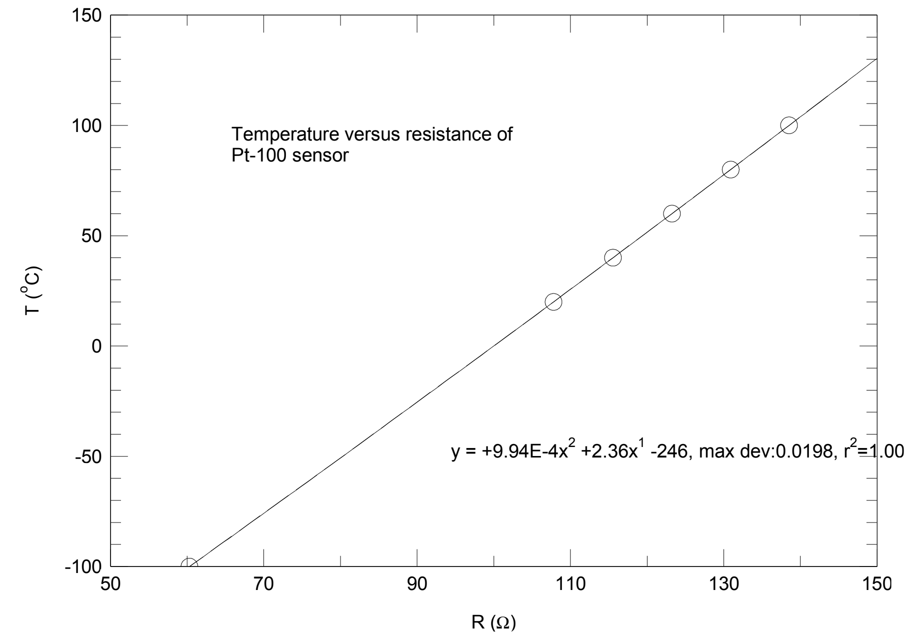
Actual Pt-100 resistance, R

Current lead



No current in the voltage leads, so no voltage drop; high input impedance voltmeter measures the true resistance as R = U/I.

Calibration curve:



T (ºC) CAN BE CALCULATED FROM **R (Ω)** USING THE FORMULA:

$$T\left[{}^{\circ}C\right] = 9.938\cdot 10^{-4}\left[\frac{{}^{\circ}C}{\Omega^2}\right]R^2 + 2.3592\left[\frac{{}^{\circ}C}{\Omega}\right]R - 245.87\left[{}^{\circ}C\right]$$