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Simple experiments with a thermoelectric module

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Abstract
The Seebeck and Peltier effects are explored with a commercially available thermoelectric module and a data-acquisition system. Five topics are presented: (i) thermoelectric heating and cooling, (ii) the Seebeck coefficient, (iii) efficiency of a thermoelectric generator, (iv) the maximum temperature difference provided by a thermoelectric cooler and (v) the Peltier coefficient and the coefficient of performance. Using a data-acquisition system, the measurements are carried out in a reasonably short time. It is shown how to deduce quantities important for the theory and applications of thermoelectric devices.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

The Seebeck effect consists in the generation of an emf between two junctions of dissimilar metals or alloys when they are kept at different temperatures. For any thermocouple and a given mean temperature, the emf is proportional to the temperature difference between the junctions, ΔT:

$$E = S\Delta T, \tag{1}$$

where the coefficient of proportionality S is called the thermoelectric power, or the Seebeck coefficient. For metals and alloys used for thermocouples, the thermoelectric power is usually in the range 10–60 μV K^{-1}. For semiconductor compounds, this figure may be several times larger. The Seebeck effect is widely used for temperature measurements and for producing electric energy when other sources are inaccessible. A thermopile serves in such cases to increase the generated voltage.

The Peltier effect is inverse to the Seebeck effect: when a dc current passes through a junction of two dissimilar materials, a heat additional to that produced by the Joule heating is generated or absorbed in the junction, depending on the direction of the current. The power of the additional heat is proportional to the current: $Q = \Pi I$, where Π is called the Peltier coefficient. The effect is used for cooling elements of electronics, such as lasers and infrared detectors. Using thermodynamic arguments, Kelvin has deduced a simple equation that relates the Seebeck and Peltier coefficients to one another:

$$\Pi = ST, \tag{2}$$

where T is the absolute temperature.

Thermoelectric phenomena constitute a part of theoretical and laboratory university courses, and several papers in this field have been published. Gross [1] considered the efficiency of thermoelectric devices and its dependence on the characteristics of the available thermoelectric materials. Mortlock [2] described an experiment in which the coefficient of performance of a thermoelectric device was determined and compared to that of an ideal heat engine. In measurements at liquid helium temperatures, Guénalt *et al* [3] achieved a reasonably good agreement with the theory. Gupta *et al* [4] used a thermoelectric module for verifying the second law of thermodynamics. The reversible and irreversible parts of the phenomenon were separated, and the results appeared to be in close agreement with theoretical predictions. Cvahte and Strnad [5] repeated this experiment achieving a better accuracy. Taking the thermoelectric generator as an illustration, Gordon [6] considered the efficiency of heat engines.

In the experiments reported [4, 5], the measurements were carried out when temperatures of the sides of a thermoelectric module were kept constant. The cold plate of the module was maintained at a constant temperature by using cooling water. A regulated heater ensured a constant temperature of the hot plate. In the first measurement, the emf of the unloaded module was determined along with the temperature difference between its sides. Then the module was loaded, and the current and voltage across the load resistor were measured. In the third case, a current was passed through the module from an external dc supply causing an additional heating of the hot side. In all three cases, the heater on the hot plate was adjusted to compensate for changes due to different modes of operation of the module. The changes in the power supplied to the hot side were determined and used in the calculations. Combining the results of the three measurements, the reversible and irreversible parts of the phenomena were separated. The only disadvantage of the experiment is the long time necessary for establishing a stationary state of the set-up. According to Cvahte and Strnad [5], the experiment takes about 5 h, so in one laboratory session the students carry out only one part.

2. Thermoelectric devices

The quality of a thermoelectric material depends on three properties, namely, the thermoelectric power S, the electrical conductivity σ and the thermal conductivity κ. The electrical conductivity defines the internal resistance of a thermoelectric device and the related Joule heating, whereas the thermal conductivity governs the heat flow through the device leading to a decrease in the temperature difference between its sides. Quantitatively, the efficiency of a thermoelectric device depends on the so-called thermoelectric figure of merit, Z:

$$Z = S^2\sigma/\kappa. \tag{3}$$

For metallic systems, the Wiedemann–Franz law shows the relationship between σ and κ:

$$\kappa/\sigma = LT, \tag{4}$$

where L is the Lorenz number equal to $2.45 \times 10^{-8}\ \mathrm{V^2\ K^{-2}}$.

The efficiency of a thermoelectric device is given by two characteristics. The thermoelectric efficiency of a thermoelectric generator is the ratio of the electrical energy produced to the amount of thermal energy absorbed from a heat source. The coefficient of performance of a thermoelectric cooler is the ratio of the heat removed from one side of the device to the amount of electric energy consumed. The Joule heating and thermal conductance inside a thermoelectric device cause irreversible energy losses.

An ideal thermoelectric device is considered to have an infinite electrical conductance and zero thermal conductance. For such a device, the second law of thermodynamics governs the thermoelectric efficiency and the coefficient of performance. When the temperature difference between the sides of the device is ΔT, the Seebeck emf equals $S\Delta T$. If the current through the loaded device is I, the total electric power developed is $IS\Delta T$. On the other hand, the power of the Peltier heat equals ΠI, and the thermoelectric efficiency is $S\Delta T/\Pi$. Taking into account equation (2), the efficiency equals $\Delta T/T_h$, i.e., the efficiency of an ideal heat engine, where T_h is the temperature of the hot side of the device. When the coefficients S and Π are determined independently, the validity of equation (2) can be considered as the verification of the second law of thermodynamics.

For a real thermoelectric device, the thermoelectric efficiency and the coefficient of performance depend on the figure of merit and the temperatures of the two sides of the device [7]. Using mixed crystals, substitutional point defects and radiation-induced damage, it is possible to reduce the thermal conductivity of a semiconductor material. The above factors also influence the electrical conductivity and thermopower, but the Z value may become more favourable. Nowadays, the most efficient thermoelectric materials are Bi_2Te_3 and PbTe. In a typical thermoelectric device, many thermocouples are joined together and sandwiched between two isolating plates of high thermal conductivity. Commercially available thermoelectric modules are based on p- and n-doped Bi_2Te_3 alloys configured to contain many junctions arranged in parallel thermally and in series electrically.

Thermoelectric devices made from even the best available materials have the disadvantages of relatively low efficiencies and concomitant high cost per unit of output. Their use is restricted to situations in which these disadvantages are outweighed by their small size, low maintenance, quiet performance and long life. When employing a thermoelectric device, one should take measures for reducing temperature differences due to relatively high heat flow through the system. The temperature of the hot side of a thermoelectric device should be as close as possible to that of the heat sink (or source), and the temperature of the cold side of the device as close as possible to the cold sink.

3. Measurements and results

A simple set-up described below is aimed at performing the experiments in a reasonably short time. Reducing the thermal inertia of one side of a thermoelectric device and employing a data-acquisition system help us to reach this goal. The *ScienceWorkshop* data-acquisition system with the *DataStudio* software from PASCO scientific [8] accumulates and displays the data. A thermoelectric module from Melcor Corporation [9], CP1.0-31-08L, is sandwiched between a thin electrical heater (upper side) and a massive aluminium block (underside). The module is pressed to the block by a plastic plate and two screws (figure 1). The block is placed in a glass filled with water at room temperature or in an ice bath. The temperatures of the sides of the module are measured by two *Thermistor sensors* (PASCO, CI-6527) pasted to its plates and connected to the inputs of the data-acquisition system. Due to the high thermal inertia of the down part of the set-up, its temperature changes are small but also measured and taken into account.

The experiments to be carried out are presented schematically in figure 2. The first experiment is a demonstration of the thermoelectric heating and cooling. A separate run

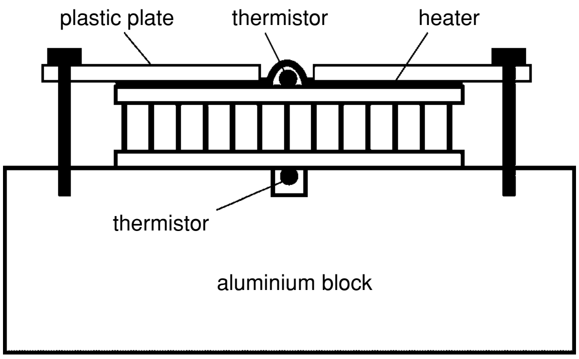

Figure 1. Arrangement for teaching thermoelectric phenomena with a thermoelectric module. The module is pressed to the aluminium block by a plastic plate and two screws.

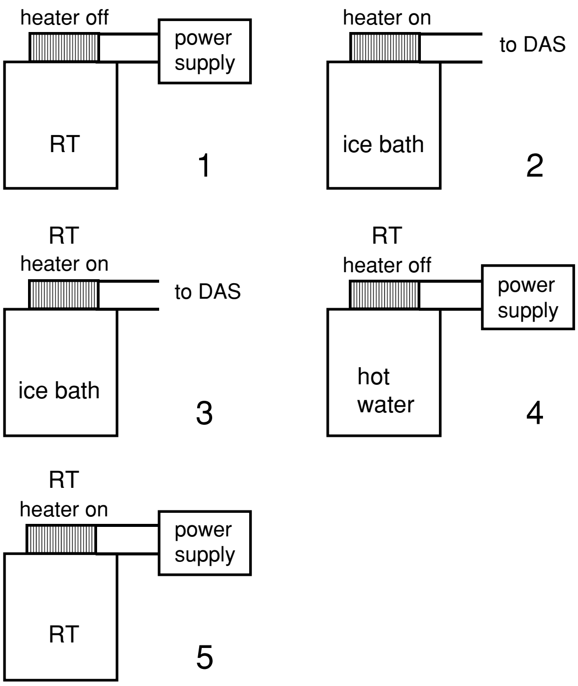

Figure 2. General scheme of the experiments with a thermoelectric module. 1–demonstration of the thermoelectric heating and cooling, 2–determination of the Seebeck coefficient, 3–thermoelectric generator, 4–measurement of the maximum temperature difference, 5–determination of the Peltier coefficient. Temperatures of both sides of the module are measured by thermistors and displayed by the *DataStudio*. RT = room temperature, DAS = data-acquisition system.

employing ac currents shows the role of the Joule heating. The goal of the second experiment is the determination of the Seebeck coefficient of the module. In the third experiment, the efficiency of the thermoelectric generator and the figure of merit are evaluated. Then the maximum temperature difference provided by the Peltier cooler is determined. From these data, the figure of merit is also available. Lastly, the Peltier coefficient of the module is measured and the coefficient of performance of the device is calculated.

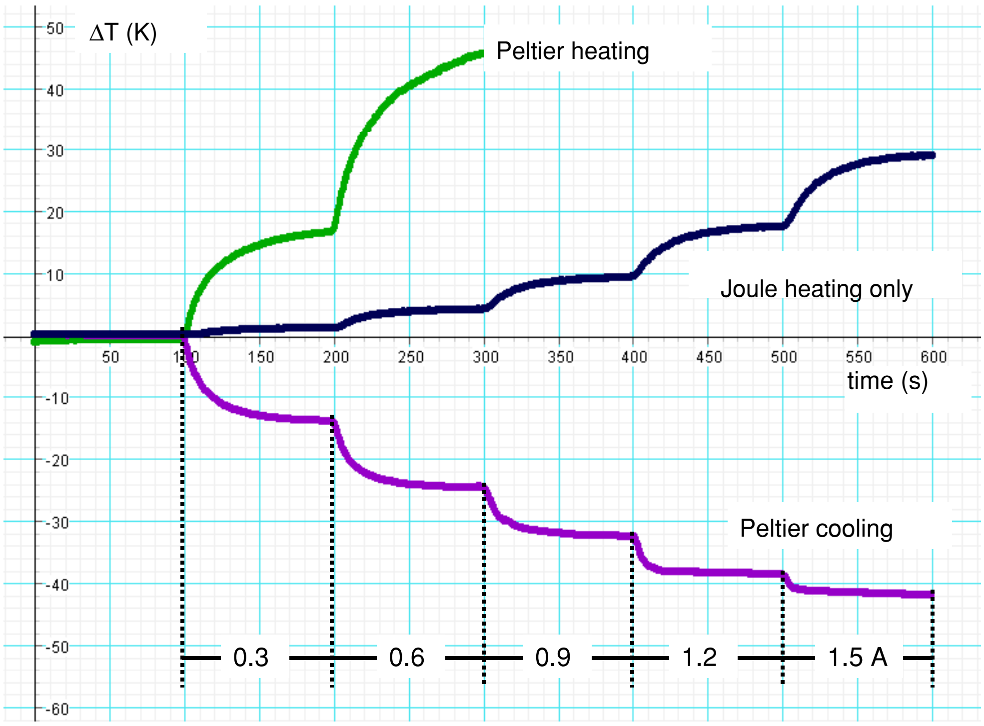

Figure 3. Temperature difference between the sides of the module versus time when the current passing through the module is changed by steps of 0.3 A. The Joule heating is demonstrated using ac currents.

3.1. Demonstration of thermoelectric heating and cooling

With a data-acquisition system, it is easy to demonstrate the thermoelectric heating and cooling. The module is connected to a power supply and operates in the regimes of cooling or heating its upper side. The temperature of the aluminium block is close to room temperature. The *Graph* tool displays the temperature difference between the sides of the module for different currents passing through it. With ac currents (50 Hz), the role of the Joule heating becomes evident (figure 3).

3.2. Determination of the Seebeck coefficient

In this experiment, the *Voltage sensor* (CI-6503) measures the voltage generated by the thermoelectric module, and the *Graph* tool displays it versus the temperature difference between the sides of the module. The electrical heater attached to the upper side of the module controls its temperature. The measurements are carried out while gradually changing the temperature difference between the sides of the module. From the data obtained (figure 4), the Seebeck coefficient of the module equals 8.5 mV K^{-1}.

3.3. Efficiency of thermoelectric generator

The efficiency of a thermoelectric generator cannot exceed the efficiency of an ideal heat engine (Carnot efficiency), $\eta_C = \Delta T/T_h$. The efficiency of a real thermoelectric generator is

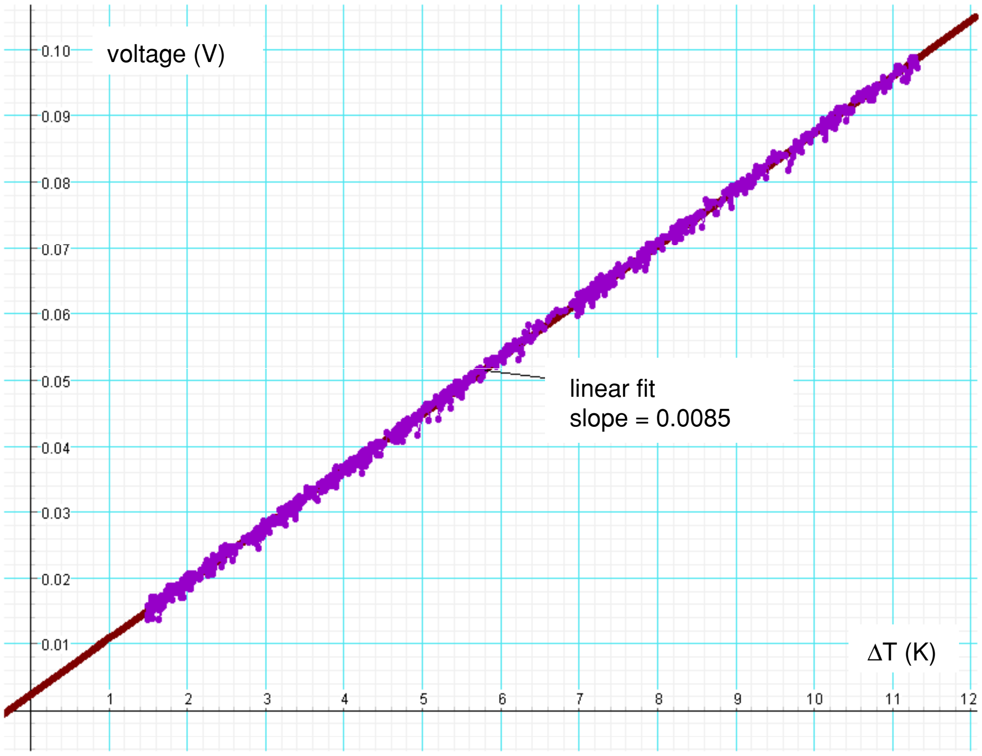

Figure 4. Voltage generated by the thermoelectric module versus the temperature difference between its sides. From the data, $S = 8.5$ mV K^{-1}.

much less than this value. The heat delivered by a heat source to the hot side of the generator, Q_{in}, is balanced by the heat conducted through the module, $K\Delta T$, and the Peltier heat, ΠI, developed at the hot junction due to the flow of current. In addition, the Joule heat dissipated in the module is assumed to flow equally to both its sides [7]. Hence,

$$Q_{in} = \Pi I + K\Delta T - \tfrac{1}{2}I^2R, \tag{5}$$

where K is the thermal conductance of the module, and R is its electrical resistance.

For determining the maximum electric power delivered by the thermoelectric module, the underside of the module is cooled by an ice bath, and the electric power supplied to the heater is adjusted to make the temperature of the upper side equal to the room temperature. Under such conditions, the heat exchange between the upper side of the module and the surroundings is excluded. The maximum electric power is delivered to the load when its resistance equals that of the module. In this case, $I = E/2R$, and $P_{out} = E^2/4R$, where E is the emf generated by the module. The efficiency of the generator, η, equals the ratio of this power to the electric power supplied to the heater, Q_{in}. The resistance of the module equals $R = 1.3\ \Omega$.

With a load equal to the resistance of the module, $\Delta T = 20.5$ K, $Q_{in} = 1.1$ W, and $P_{out} =$ 5.8 mW, so that $\eta = 0.53\%$. The thermal conductance of the module, K, is available from the measurements when $I = 0$. For the same temperature difference, Q_{in} $(I = 0) = 0.93$ W, so that K equals 0.045 W K^{-1}. The Carnot efficiency is $\eta_C = 6.9\%$.

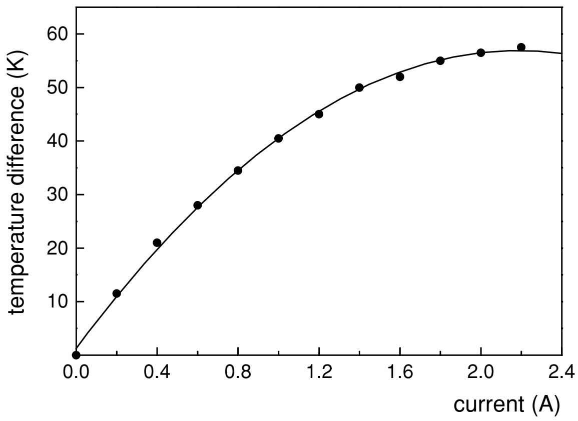

Figure 5. The temperature difference provided by the Peltier cooler versus the electric current. In the measurements, the underside of the module is heated by hot water, while the upper side is kept at room temperature. From the quadratic fit, $\Delta T = 1.3 + 50.9 \times I - 11.6 \times I^2$, the maximum temperature difference is achieved at $I = 2.2$ A, and $\Delta T_{max} = 57$ K.

The η_C/η ratio can be used for calculations of the figure of merit of the thermoelectric module. From the general expressions for P_{out} and Q_{in}, it is easy to see that [7]

$$\eta_C/\eta = 2 + 4/ZT_h - \tfrac{1}{2}\eta_C. \tag{6}$$

In our case, $\eta_C/\eta = 13$. With this value and $T_h = 298$ K, the figure of merit deduced from equation (6) is $Z = 1.2 \times 10^{-3}$ K^{-1}, somewhat lower than today's best values.

3.4. Maximum temperature difference provided by a Peltier cooler

For an ideal Peltier cooler, the rate of heat removal from its cold side is ΠI. In real thermoelectric coolers, additional heat is delivered to the cold side of the device. The power of this heat equals $\frac{1}{2}I^2R + K\Delta T$, where the term $\frac{1}{2}I^2R$ is due to the Joule heat generated inside the module. Therefore, the rate of heat removal, Q_{rem}, becomes

$$Q_{rem} = \Pi I - K\Delta T - \tfrac{1}{2}I^2R. \tag{7}$$

The temperature difference provided by a thermoelectric cooler thus increases with decreasing the heat to be removed. The maximum temperature difference, ΔT_{max}, is achievable when this heat vanishes. The temperature difference provided by the module is determined when the module operates in the regime of cooling its upper side, while the underside is heated by hot water. The data are taken when the temperature of the upper side becomes equal to that of its surroundings. The heat removal from the upper side thus vanishes, and the term $K\Delta T$ attains its maximum value. The temperature difference depends on the current (figure 5). From a quadratic fit to the experimental data, $\Delta T_{max} = 57$ K. This value is valid when the cold side of the module is kept at 25 °C. The manufacturer [9] gives two values for ΔT_{max}, 67 K when the temperature of the cold side is −42 °C and 77 K when it equals −27 °C.

The value of ΔT_{max} can be used for calculations of the figure of merit of a thermoelectric device (e.g., [7]):

$$Z = 2\Delta T_{max}/T_c^2, \tag{8}$$

where T_c is the temperature of the cold side of the device. Using $\Delta T_{max} = 57$ K and $T_c = 298$ K, the figure of merit appears to be $Z = 1.3 \times 10^{-3}$ K^{-1}.

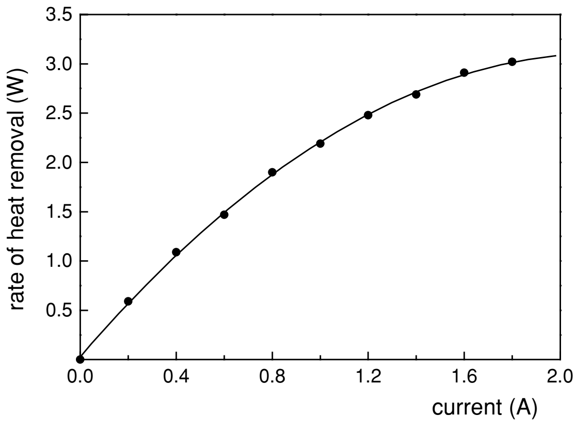

Figure 6. The rate of heat removal versus the current through the module when $\Delta T = 0$. From the fit, $Q_{rem} = 0.03 + 2.83 \times I - 0.65 \times I^2$, $\Pi = 2.83$ V.

3.5. Determination of the Peltier coefficient

For the determination of the Peltier coefficient, the module operates in the regime of cooling its upper side, while the underside is kept at room temperature. The electrical heater on the upper side serves to compensate for the heat removal by the Peltier cooling. The electric power supplied to the heater is adjusted to nullify the temperature difference between the two sides. After the compensation, the temperatures of both sides of the module become close to room temperature. The term $K\Delta T$ vanishes, and the electric power produced by the heater equals the power of the Peltier cooling less the Joule term. Therefore, the electric power should be a quadratic function of the current. From the data obtained (figure 6), the Peltier coefficient of the module is found to be $\Pi = 2.83$ V. According to the value of the Seebeck coefficient obtained in the second experiment and equation (2), it should be 2.53 V.

The cooling ability of a Peltier cooler is given by the coefficient of performance, β, which is the ratio of the rate of heat removal, Q_{rem}, to the power consumed, P. The latter is the sum of the Joule term and the power required for overcoming the Seebeck emf:

$$P = I^2R + SI\Delta T. \tag{9}$$

The coefficient of performance thus equals

$$\beta = \frac{\Pi I - I^2R/2 - K\Delta T}{SI\Delta T + I^2R}. \tag{10}$$

The coefficient of performance depends on the current through the module and the temperature difference. The Seebeck term, $SI\Delta T$, which is of minor importance under normal operational conditions, becomes significant at low currents. When $I^2R \ll SI\Delta T$, and $\Delta T = 0$, the coefficient of performance equals $\beta = \Pi/S\Delta T$. With equation (2), the coefficient of performance, under such conditions, equals that of an ideal heat engine, $T_c/\Delta T$.

Using equation (10), the coefficient of performance of the module employed was calculated as a function of the current, for several values of the temperature difference between its sides (figure 7). This graph is similar to those given by manufacturers of thermoelectric coolers. Under normal operational conditions, the coefficient of performance of thermoelectric

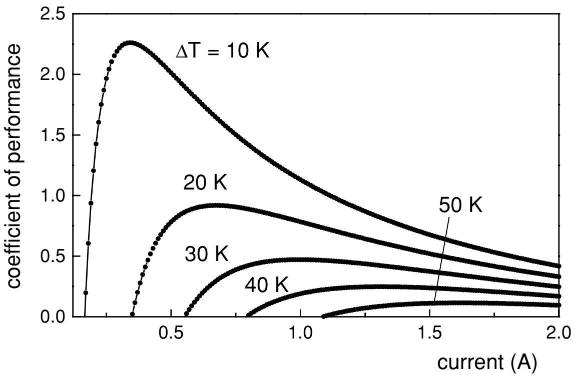

Figure 7. Coefficient of performance of the thermoelectric module versus the electric current calculated using equation (10) for different values of ΔT.

coolers equals several tenths of unity, i.e., an order of magnitude less than that of refrigerators employing the vapour-compression cycle.

4. Conclusion

The experiments described provide good opportunity for teaching the basic thermoelectric phenomena and their applications. Due to the low thermal inertia of the upper side of the thermoelectric module and the use of a data-acquisition system, the measurements are possible in a reasonably short time. To exclude the influence of the heat exchange with the surroundings, the measurements are performed under conditions where the temperature of the upper side of the module is close to the room temperature. The experiments show simple ways for determining quantities important for the theory and applications of thermoelectric devices.

Acknowledgment

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