Thermoelectric Effect and Laws of Radiation

Natan Szczepaniak

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Abstract

In this report we investigate the transfer of heat and the associated phenomena namely The Thermoelectric effect and Black Body Radiation. We find the Seeback coefficient of a thermoelectric module $S = 55.6 \pm 1.3\ mVK^{-1}$, test the First Law of Thermodynamics and aim to find the dependence of load on the efficiency of a heat engine. Additionally, we use a brass cylinder inside an electric oven, simulating a black body to obtain the Stefan-Boltzmann constant $\sigma_E = (2.9465 \pm 0.0085)\ 10^{-8}\ \ Wm^2K^4$

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1 Introduction

In this set of experiments we explore how temperature and temperature differences of objects and devices affect their other physical properties justifying our theories and conclusions using constants and the laws of thermodynamics. Using a thermoelectric module consisting of 142 Peltier cooling elements combined with a power supply we investigate the Seeback and Peltier effects both classified under the general Thermoelectric Effect. We find the Seeback coefficient which tells us about the thermo-power of a device and test the First law of Dynamics on it by showing energy conservation using various integration and fitting methods. We also demonstrate how to find how efficient a heat engine is and how its efficiency behaves under different loads using a rheostat attached in parallel to this device. Moreover, we validate a method of finding the Stefan-Boltzmann coefficient and compare it to relevant literature to assess the soundness of the method.

2 Theory

Thermoelectric effect is the phenomenon of a temperature difference being converted to an electromotive force and vice-versa. This happens as a result of a temperature gradient causing causing charge carriers diffuse from the hot side to the cold side in obedience with the second law of thermodynamics. To investigate and utilise this exchange of ΔT and emf we look at a thermoelectric module which consists of a number of elements shown in $Figure$ 1.

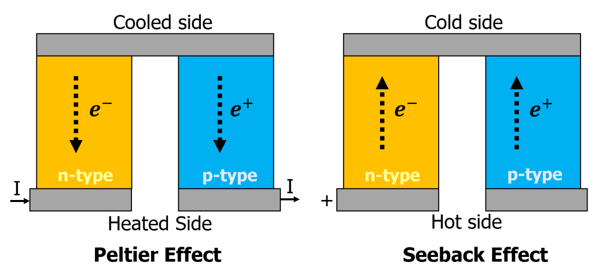

Figure 1: An example of a Peltier cooling element consisting of n-type and p-type semiconductors connected in a series circuit

The elements are made from n-type and p-type semiconductors connected in series where the junction between them is in thermal (not electrical) contact with the two (copper) 'hot' and 'cold' sides allowing for a temperature gradient as mentioned previously. As p-type semiconductors are doped with atoms that have fewer electrons than necessary to complete the atomic bonds inside the lattice and n-type are doped with atoms with more electrons than necessary. Therefore when a voltage is applied between the two terminals of a module, the electrons flow in the opposite way of the conventional current in the p-type semiconductor and electron 'holes' (which behave like positive charge carriers) flow in the direction of conventional current. Because electrons move much more freely in the copper blocks than the semiconductor, when an electron moves from the p-type semiconductor over to the copper block it jumps to a higher energy level (to match the electrons already flowing in the copper) and creates a 'hole' in the p-type semiconductor. The energy that lets the electrons make this transition is obtained by absorbing heat essentially creating a 'cold' side. Then when the electron moves from the hot side of the n-type semiconductor, it drops to a lower energy level when it is free to move in the copper again in process releasing heat creating a 'hot' side. [8]

The Thermoelectric effect covers two separate effects: Seeback effect and Peltier effect which can both be demonstrated using the thermoelectric module described above. The Seeback effect is where a temperature difference between the two sides results in a potential difference between the two terminals of a module. The equation associated with the coefficient describing the thermopower of the module is:

$$S = \frac{dV}{dT} \tag{1}$$

The Peltier effect is essentially the reverse of the Seeback effect. For a module with two of the copper sides at the same temperature (no gradient) an emf. is applied to the two terminals creating a current which then in essence creates a temperature different.

Additionally to these phenomena, if a load (resistor) is attached between the two terminals of a module, the efficiency of the 'heat engine' created will depend on the resistance applied. Thus, we can theoretically find the internal resistance of the module by finding what load gives the highest resistance.

A blackbody is a body which absorbs all incident electromagnetic radiation regardless of wavelength of angle of incidence. The more heat a body radiates, the better it can absorb that radiation. The total radiation emitted by a black body is directly proportional to its temperature to the fourth power. In other words, the rate of emission of radiant energy (called the irradiance) of unit surface area of the object is equal to:

$$M = \epsilon\sigma(T^4 - T_0^4) \tag{2}$$

Where ϵ is the emissivity of the object, T and T_0 are is the temperature of the object and the temperature of the surroundings respectively and σ is the theoretical Stefan-Boltzmann's constant. The T_0 term accounts for the energy absorbed by the object.

3 Method

3.1 Thermoelectric Effect

To investigate the Thermoelectric effect we used a thermoelectric device consisting of 142 thermoelectric elements described in Section 2 as shown in Figure 1.

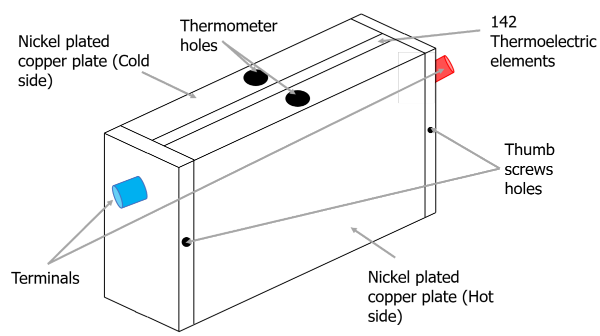

Figure 2: Thermoelectric device consisting of 142 thermoelectric elements with two copper nickel plated blocks on each side

In addition to this, we used 4 thermometers of two different ranges: -10^oC to 50^oC and 0^oC to 100^oC combined with thermal paste for taking the temperature of the two nickel plated copper blocks. To create a temperature difference between the two sides we utilised two water baths fitted to each side with rubber sealing held on with thumb screws.

Firstly, we investigated the Seeback coefficient to establish a thermo-power of the device. We started by measuring the potential difference between the terminals using a hand-held voltmeter as well as taking the temperature of both using the -10^oC to 50^oC thermometers and waited until it settled to a constant in the position it was going to remain in for the rest of the experiment. With the voltmeter connected and thermometers in place, we attached the two water baths and placed the thermometers in the holes of the device. We used a kettle to boil water and filled two beakers with hot and cold water. We then proceeded to pour the water into the two baths to the brim simultaneously and started taking measurements from the voltmeter and two thermometers. We took measurements every 10 seconds and stopped when the temperature difference was relatively small.To ensure a high degree of accuracy when measuring several variables simultaneously, we used a camera fixed in one position to take pictures in the time intervals which greatly reduced the random parallax error of reading analog thermometer scales. This allowed us to create a plot of output voltage against the temperature difference where the gradient of the slope is the Seeback coefficient of the thermoelectric device.

We then set up the thermoelectric device in a circuit (Figure 3) connected to a power supply in parallel on one side and a rheostat on the other side with a switch in the middle. This lets us switch between two modes of the device: the heat pump [Where power supply creates potential difference between terminals establishing a temperature difference (Peltier)] and the heat engine [The temperature difference creates an emf. between the terminals (Seeback)]. The current and voltage in the engine mode was read using the voltmeter and ammeter placed in corresponding sections and the power supply was used to determine the power supplied.

We then went onto investigate the energy conserved by the device ie. how well it stores heat. Using the circuit shown in Figure 3 firstly in the heat pump mode with the rheostat at 5Ω, we turn on the power supply set at a constant 2.5A and immediately start taking measurements of the pd. across the thermoelectric module (giving us power when multiplied by 2.5A) and the two temperatures for 60 seconds. Once again we used the camera technique of recording precise data. After the 60 seconds, we changed the circuit to the heat engine mode and proceeded to take readings of the pd., current and the temperatures simultaneously in 10 second intervals until the potential difference became relatively constant. This let us find the total energy supplied to the module over a 60 second time period using:

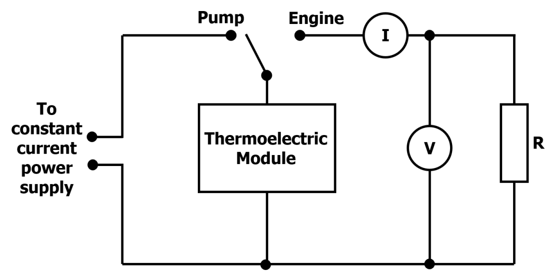

Figure 3: Circuit with the interchangeable modes of heat pump and engine

$$W = \int_0^t I_P V_P dt \tag{3}$$

The heat current due to a temperature change of one of each of the blocks of dimensions l (length), w (width) and d (depth) with density ρ specific heat capacity c is:

$$Q = \rho lwdc\Delta T \tag{4}$$

Therefore, using this we used the data to satisfied that the energy put into the system equalled the energy output by the system (First Law of Thermodynamics):

$$Q_C + W = Q_H \tag{5}$$

We then worked out the efficiency of the heat engine by dividing the work done by the load (W) by the heat extracted from the hot side.

$$\eta = \frac{W}{Q_H} \tag{6}$$

As we expected the efficiency to be low, we went to find the correlation between the value of the load (rheostat) and the efficiency of the module to find the resistance at which the heat engine is most efficient at. We did this by repeating this process however this time we solely focused on the heat engine part of the previous experiment only changing the value of the rheostat for each repetition. In this case, we also decided to only measure the initial and final temperature of the 'hot' block as well as the current and pd every 10 seconds as this was the only data required to determine the efficiency for each value of resistance.

3.2 Laws of Radiation (Oven)

To create a virtual black body we used a brass cylinder inside an oven powered by a constant power supply. After setting up and connecting the thermopile and temperature sensor (thermocouple) as shown in Figure 4, we removed the glass of the thermopile. Next we recorded the ambient room temperature T_0

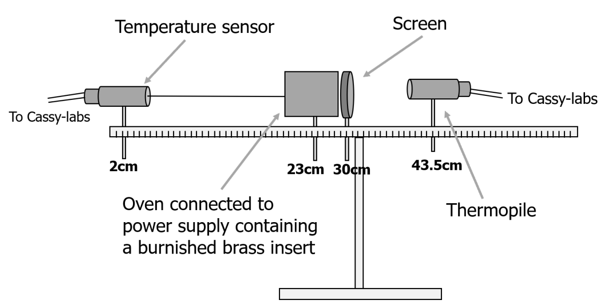

Figure 4: Experimental set up for experiment to find the Stefan Boltzmann constant

(thermocouple reading) and the associated output voltage of the thermopile via the Cassy-lab interface. Inside the program we chose the 0^oC to 1200^oC option to make sure we collect the whole range of data between our desired range of 25^oC to 450^oC in 30 second intervals(which corresponds to roughly a $2-6^oC$ temperature change interval). We recorded the average temperature obtained by the thermocouple and voltage from the thermopile. After the temperature reached the desired 450^oC we turned off the power supply to the oven and kept taking half minute readings until the temperature dropped to around 100^oC We then repeated this two more times for extra reliability. From the documentation of the thermopile we found that the sensitivity of the device was $S = 20 - 40\mu V/W/m^2$. This allowed us to find the net irradiance of the brass cylinder which is given by:

$$M_B = \frac{V}{S} \tag{7}$$

After converting all of the collected voltages from the thermopile to the corresponding irradiance, we plotted irradiance against T^4 to extract the gradient and therefore the Stefan Boltzmann constant.

4 Results and Analysis

4.1 Thermoelectric Effect

To obtain the Seeback coefficient of the device in question we simply worked out the difference in temperature for each reading for each of the repetitions and found and an average for each output voltage.Then we plotted the output voltage against the temperature difference. The gradient of this graph, which we obtained using the least squares fitting method, is equal to the Seeback Coefficient Equation (1).

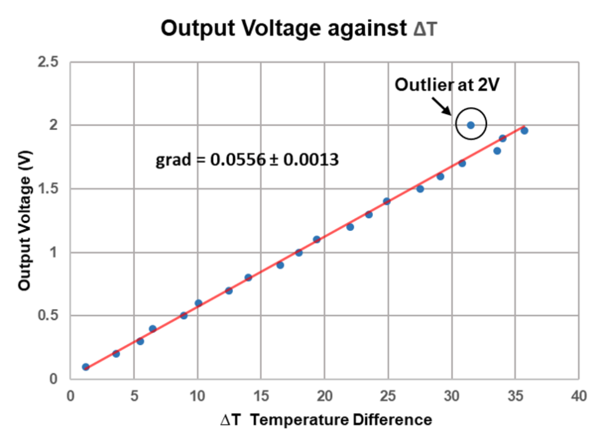

Figure 5: Plot of output Voltage against temperature difference

Unsurprisingly, we found an outlier positioned at 2V which is also the potential difference at which we started recording the data (as we took recordings every 0.1V). This is very likely due to the initial temperature being inaccurate as the thermometers have not reached a thermal equilibrium with the thermoelectric module giving us a lower temperature difference. Luckily, this issue did not carry on for long due to the low specific heat capacity of the copper as we can see from the 1.9V reading. We decided to discard this point from the line fitting. The final value of the Seeback coefficient we obtained was $S = 55.6 \pm 1.3\ mVK^{-1}$. For a device with 142 Thermoelectric elements, the theoretic Seeback coefficient should be $S = 57mVK^{-1}$ which is just outside of our uncertainty but generally lower. Our experimental value is subject to limitations such as the fact we did not consider much the environment around the device itself. A lower value of S supposedly means that the difference in temperature of the two sides was bigger than it should have been which may be caused by a systematic error in our setup. We started off with measuring the dimensions of one of the blocks allowing us to find Q from Equation (5). The dimensions were 8.0x9.5x1.0 cm. Using appropriate literature we found the density of copper $\rho = 8.96\text{x}10^3\ kgm^{-3}$ and the specific heat capacity of $c = 384Jkg^{-1}K^{-1}$. To test for the conservation of energy we rearranged Equation (6) to have the W term on the RHS both of the Q terms on the other and found each side of the equation individually as they required different methods. To find $Q_H - Q_C$ we simply used Equation (5) and the constants mentioned above. We found W by fitting a straight line (first-order polyfit) and integrating from 0 to the 60 for the heat pump mode and fitted a curve to the heat engine data set. We expected that the LHS would be lower [As the thermal energy of the block should not be higher than what was supplied (accounting for initial energy)] and that we would have to add an extra term to account for the energy lost to the environment. However, we found that the $Q_H - Q_C$ term was higher than the work done on the block. The average values we got for the two terms were $Q_H - Q_C = 1202.84J$ and $W = 1028.64J$. If we were to account to the heat lost to the surroundings, this term would be negative $Q_{Lost} = -174.2J$. In other words, the system gained energy from its surroundings. This is of course possible if the 'cold' side is absorbing energy from the environment at a higher rate than the 'hot' side is radiating it out. The energies however seem to be in the right order of magnitude with only a relatively small energy difference (1% of the total energy supplied) and if we could account for the additional energy or isolate the system completely we believe that the two sides of the equation would be equal satisfying the First Law of Thermodynamics. We then used our values of Q_H and W to find the efficiency of the device. Using Equation (7) we calculated an efficiency of the device to be $\eta = 0.347\%$.

Next, we investigated how the 'load' or resistance on the device affects the efficiency of the heat engine and looked for the highest efficiency. We used a similar data analysis sequence from the previous experiment however after taking the first few measurements and plotting them on an efficiency against load graph we saw no correlation in the points. In addition to this, the power at $t = 0$ was very difficult to measure accurately as the engine started working immediately changing the pd. and current values too quickly to measure. Due to this we took a different approach of calculating the energy dissipated by the rheostat.

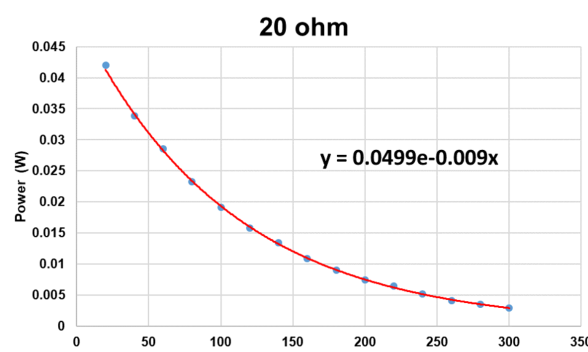

Figure 6: An example of a power-time plot with a fitted exponential

As seen in Figure 6 we fitted an exponential curve to our data omitting the reading at $t = 0$ and extrapolated the curve to fit the time range for which we measured the temperature for and simply integrated it in that region. When we used this method for the tests we did previously for different resistance values we finally got precise values of energy dissipated by the rheostat. Next, we once again used Equation (7) to find the efficiency for each corresponding resistance finally giving us a vague peak at around $2 - 5\Omega$. We also got 3 anomalous readings at 10Ω (magenta, not included in the fitting of curve), these did not fit the trend of the other data points we assumed this was the fault of the equipment but did not reject the possibility that this may be another peak when taking the rest of our data.

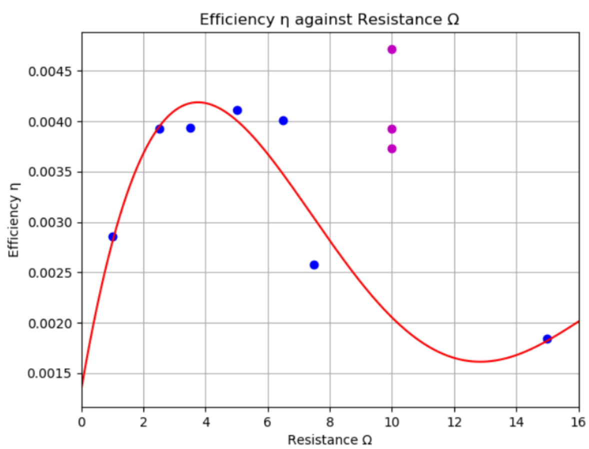

Figure 7: Plot of Efficiency against Load (Resistance) (polyfit method) magenta data points are outliers

Initially we intended to fit a normal curve Figure 8 to the data allowing us to find the sigma and assess this peak in efficiency properly however due to the lack of data points (caused by time constraints) the plot was extremely flat and sigma was very high.

Although the peak was generally at $R = 2.8\Omega$ (The accepted value of the heat engine from literature), the uncertainty was too high to consider it as a value. Instead we plotted a polynomial which had a peak at $R = 3.68\Omega$, went through zero and had the general skeweness we would have expected if we had more data points to plot a normal distribution.

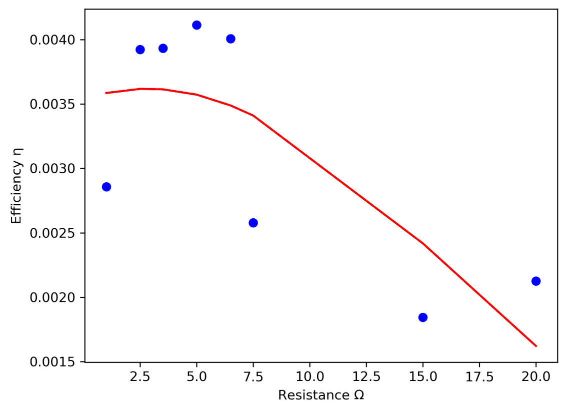

Figure 8: Plot of Efficiency against Load (Resistance) Gaussian fit of our data which we did not consider as precise enough

4.2 Laws of Radiation

After collecting the data, we split it into two data sets, one where the the oven was on, and the other where it was turned off. Using Equation (8) we converted the voltage from the thermopile ($S = 20\mu V/W/m^2$)into net irradiance and divided it by the emissivity $\epsilon = 0.03$ (for polished brass) [5] to get the irradiance of the object. Then we plotted the irradiance against the temperature in kelvin to the fourth power. Following Equation (3), this gives us the Stefan-Boltzmann's constant.

The 'Heating up' graphs showed us a very strong correlation with $R^2 = 0.999$ and a 0.3% uncertainty. Our averaged experimental value taking into account the readings we took was $\sigma = (2.9465 \pm 0.0085) * 10^{-8}$ Wm^2K^4 which is slightly more than a half of the expected value $\sigma = (5.67) * 10^{-8}$ Wm^2K^4. Due to the minimal random error in our data and the deviation from the accepted value we concluded that the values of sensitivity of the thermopile given in the documentation are inaccurate or that the thermopile has become less sensitive over time of use in the lab. Because the irradiance and the sensitivity are inversely proportional, the lower the sensitivity of the thermopile the greater the gradient of

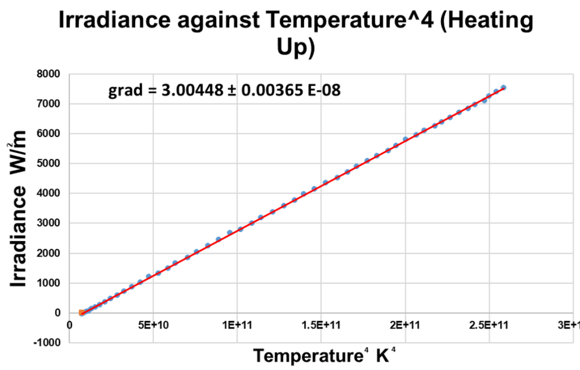

Figure 9: Plot of output Voltage against temperature difference

our graph giving us a higher value for the Stefan Boltzmann constant. The cooling down plot exhib-

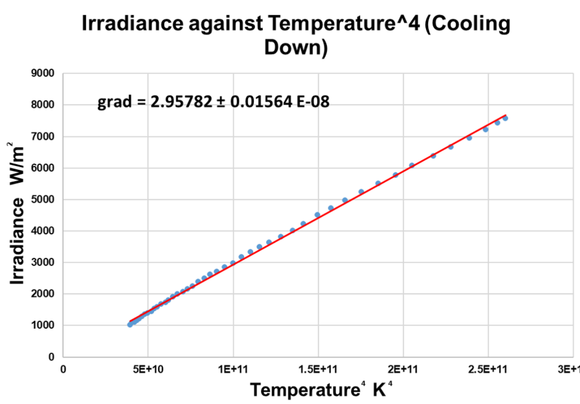

Figure 10: Plot of output Voltage against temperature difference

ited strange behaviour as the data seemed to bow out into the positive y direction meaning higher irradiance for the same temperatures in the high temperature range. We assume this could have been to the thermopile picking up radiation from objects other than the brass object and hypothesized that we would see more of this effect if we heated the oven to an even higher temperature. Due to this phenomenon, the gradient of the graphs lower which made us consider only using the 'Heating Up' data sets but we found that all of our values were within each other uncertainties meaning the average value remained the same.

5 Conclusions

In hindsight, there was a number of limitations in the experiments we conducted. I believe the Seeback coefficient investigation was successful in determining a reliable value. Looking back on Figure 5, the uncertainty could have been reduced in more controlled conditions such as isolating the device from surrounding temperature or at least creating a uniform temperature environment. The same solution may have improved the thermodynamic relation in the second experiment. For the heat engine experiment however, the only way to put us on track to find the reason for the outliers would be to take more data, repeating it several times and finding an average to obtain a high resolution plot. Unfortunately, we were limited by the time-frame we needed to conduct all of the experiments in as well as let others use the equipment. Another way of streamlining the process would be to reduce the time in between subsequent measurements. Although we did this by attempting to cool down the block by fanning it, this wouldn't be a sustainable solution. Ideally we could have a system that resets the temperature difference between the block to zero after finishing the readings. The problem of not being able to take the reading at t = 0 may have been addressed with a more advanced setup using a video camera or a multimeter with inbuilt memory, however our method of extrapolating the exponential worked well and definitely did not cause major error such as the outliers. In the Stefan-Boltzmann constant investigation we relied on a approximate sensitivity given in the documentation of the equipment to base our value for the S-B constant. When we were figuring out what value of the sensitivity we want to use we explored various options including high and low numbers, we found that if we simply half the sensitivity of the thermopile our value for the Stefan-Boltzmann constant would be $\sigma = (5.893 \pm 0.017) * 10^{-8}\ Wm^2K^4$ (). It is likely that the sensitivity of thermopile deteriorated over time of its use in the lab. This however was a systematic error caused by the use of false documentation and the only way to find out the real reason for this would be to test the sensitivity of the thermopile and the emissivity of the brass cylinder.

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