STYDING THERMOELECTRIC GENERATORS.

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Abstract

This project is a study of the thermoelectric generators. The main purpose of the project was to analyze thermoelectric generators, so someone who is developing application for the TEGs could use this material. The theory of the Seebeck effect, thermoelectric generators and heat transfer is discussed in the paper. Out of the available materials, the best possible design for the electricity generating using TEG was created. While working on the design, heat transfer in the system was analyzed. It was discovered that TEG transfers heat from one side to another at the rate of $5.64\Delta T$ W. Therefore, TEG requires more effective cooling system than it was expected. The outputs of the TEG were studied and analyzed under various conditions such as different loads, temperature differences, average temperatures and arrangements of the TEGs.

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Introduction

Nowadays, many resources that we use for the energy are not renewable, for example, nuclear or fossil fuels such as coal, petroleum and natural gas. However, overall consumption of the energy keeps increasing because society uses more equipment that require a lot of energy such as cars, computers, planes and others. Therefore, at some point, the earth population will run out of fossil fuels and other not renewable energy resources or these resources will become too costly to harvest. In addition, using fossil nuclear fuels for the energy does a lot of damage to our earth environment. Everything mentioned above lead to the use of the renewable energy resources such as sunlight, wind, tides and waves. The electrical energy is one of the main energy that people are utilizing. Using the renewable energy sources to generate electrical energy is also more environmentally safe then using fossil or nuclear fuels. However, producing electricity from the fossils is more efficient than from renewable energy sources, so we need much more renewable sources to replace the fossils that we are using now. That would be great if the society could go hundred percent green and renewable energy and be independent of the not renewable and earth damaging energy resources.

Unfortunately, a big part of the energy that is being produced is wasted. According to the Science Daily website, more than 60% of the energy produced by fossil fuels burning or by fission nuclear power plants is lost, most in the form of waste heat [1]. Another simple example is that when we are cooking, we use energy to heat up our food, but most of the heat is just going out to the atmosphere unused. In addition, there is an enormous amount of heat wasted at the power plants. Waste heat energy discharged into atmosphere is one of the largest sources of clean, fuel-free, and inexpensive energy available [2]. Therefore, the recovery of the lost thermal energy can increase the energy system efficiency. Increasing the efficiency of the energy systems would lower the overall consumption of the energy therefore making it possible to be independent of the non-renewable energy resources.

Since there is so much heat wasted in the world, waste heat recovery question is getting more and more popular nowadays. There are many waste heat technologies developed and improved by the scientists around the world. One of the most popular technologies is thermoelectric generator (TEG). This device uses the Seebeck effect phenomena, where the main idea is that from the temperature difference we can get electric potential difference. There are many different types of TEGs that differ in sizes, operating temperatures and applications. TEGs are already used for many applications including the power plants, airplanes (to power wireless sensors) and vehicle exhaust pipes [3, 4].

Even though, TEGs are already used in the industry, I wanted to study the TEG more closely and see how it behaves under different circumstances. My study might be helpful for someone who is working on developing new applications for TEGs. In addition, I wanted to design simple and effective setup for generating electricity with the TEGs, so the idea of the setup could be applied for the real world applications. Further, I wanted the design to be simple and affordable, so everyone can make it and use it at home.

Theory

Even though, this project involves a lot of experimental practice, before doing any kinds of experiments one has to understand all the theory behind the experiment. My project is mostly based on the physics phenomenon – Seebeck effect. Thermoelectric generators use Seebeck effect to produce electricity from the temperature difference. For the successful experiment, I have to know what output I should expect form the TEG under different circumstances, as well as, I have to know the intrinsic properties of the TEG. Material physical properties are also important for this project, because for different applications, I need materials with specific physical properties, for example, electric and thermal conductivity. Knowing the material properties one can better understand the heat transfer happening in the system, which is important when we want create high and stable temperature difference across the TEG for efficient electricity generating.

Seebeck Effect

The German physicist Thomas Johann Seebeck discovered Seebeck effect in 1821. First, he found out that when two ends of the conductor are held at the different temperatures there is an electromotive force produced between those two ends [5]. This happens because electrons defuse from the hot side of the conductor to the cold side. Then Seebeck was experimenting with different junctions and he found out that when two dissimilar materials are electrically connected and the junctions are held at different temperatures that would deflect a compass needle [6]. He thought that he discovered that temperature difference induces magnetism. In fact, from the electron diffusion in the conductors the potential difference occurs that can drive an electric current in the closed loop. The magnetic field that made the compass needle to deflect was the consequence of the Ampere's law. Therefore, the Seebeck effect is the phenomenon when temperature difference between two junction of dissimilar electrical conductors produces emf (voltage). The voltage produced is directly proportional to the temperature difference as shown in the equation 1. The proportionality constant is called Seebeck coefficient (α) and it is an inherent property of the conductor material [7].

$$V = \alpha * \Delta T \quad [1]$$

Seebeck coefficient is often called a thermopower because we can think of it as the amount of heat per carrier over temperature or as an entropy per carrier. Equation 2 represents the Seebeck coefficient on terms of specific heat and charge [7].

$$\alpha \approx \frac{C}{q} \quad [2]$$

If we look at the classical gas, we know its energy; therefore, we can find the specific heat. “The thermopower of a classical electron gas is then approximately k_B/e, which is about 87 µV K^{-1}” [7]. For metals, not all electrons are involved in the conduction process. Valance electrons need some energy to leave the orbital and be a charge carrier and the energy we give is the thermal energy k_BT [8]. Equation 3 represents the formula for the thermopower of a metal, where ($k_B T/E_f$) is the fraction of the electrons that participate in the conduction process [7].

$$\alpha \approx \left(\frac{k_B}{e}\right)\frac{k_BT}{E_f} \quad [3]$$

From the equation 3, we can observe that metals’ thermopower is lower than gas thermopower and it decreases as the temperature decreases. As we can observe from the formula, the amount of electrons involved in the charge carrying process depends on the temperature and the fermi energy (E_f). Fermi energy is a material property, so materials with lower fermi energy will have higher thermopower. In the semiconductor, for the particle to be a charge carrier it must be first exited across the energy gap. Equation 4 represents the formula for the thermopower of the semiconductor [7].

$$\alpha \approx \left(\frac{k_B}{e}\right)\frac{E_G}{k_BT} \quad [4]$$

Since energy gap is much greater then k_BT value, semiconductor thermopower is much greater then gas thermopower. Semiconductors can have electron conduction and negative thermopower (n-type) or hole conduction and positive thermopower (p-type). Therefore, semiconductors are a good choice for the Seebeck phenomenon.

In the tables in Figure 1 we can observe Seebeck coefficients for different metals and semiconductors. Metals’ Seebeck coefficient is expressed as it is compared to platinum because it is much easier to measure relative Seebeck coefficient. The real value for platinum is 5 µV/K [9]. The values given in the tables can be slightly for different measurements because seebeck coefficient can vary depending on the circumstances. Therefore, these should be used only for comparing different materials.

Metals	Seebeck Coefficient
	μV/K
Antimony	47
Nichrome	25
Molybdenum	10
Cadmium	7.5
Tungsten	7.5
Gold	6.5
Silver	6.5
Copper	6.5
Rhodium	6.0
Tantalum	4.5
Lead	4.0
Aluminum	3.5
Carbon	3.0
Mercury	0.6
Platinum	0
Sodium	-2.0
Potassium	-9.0
Nickel	-15
Constantan	-35
Bismuth	-72

Semiconductors	Seebeck Coefficient
	μV/K
Se	900
Te	500
Si	440
Ge	300
n-type Bi_2Te_3	-230
p-type $Bi_{2-x}Sb_xTe_3$	300
p-type Sb_2Te_3	185
PbTe	-180
$Pb_{03}Ge_{39}Se_{58}$	1670
$Pb_{06}Ge_{36}Se_{58}$	1410
$Pb_{09}Ge_{33}Se_{58}$	-1360
$Pb_{13}Ge_{29}Se_{58}$	-1710
$Pb_{15}Ge_{37}Se_{58}$	-1990
$SnSb_4Te_7$	25
$SnBi_4Te_7$	120
$SnBi_3Sb_1Te_7$	151
$SnBi_{2.5}Sb_{1.5}Te_7$	110
$SnBi_2Sb_2Te_7$	90
$PbBi_4Te_7$	-53

Figure 1: Reference tables for Seebeck coefficients for metals and semiconductors. [9]

Two dissimilar materials that are used to observe Seebeck effect are called thermocouples. One of the applications of the simple thermocouple is to measure temperature with a good precision. I will call those industrial thermocouples. Figure 2 represents a great schematic picture of the Texas Instruments industrial thermocouple structure that is made of copper and constantan.

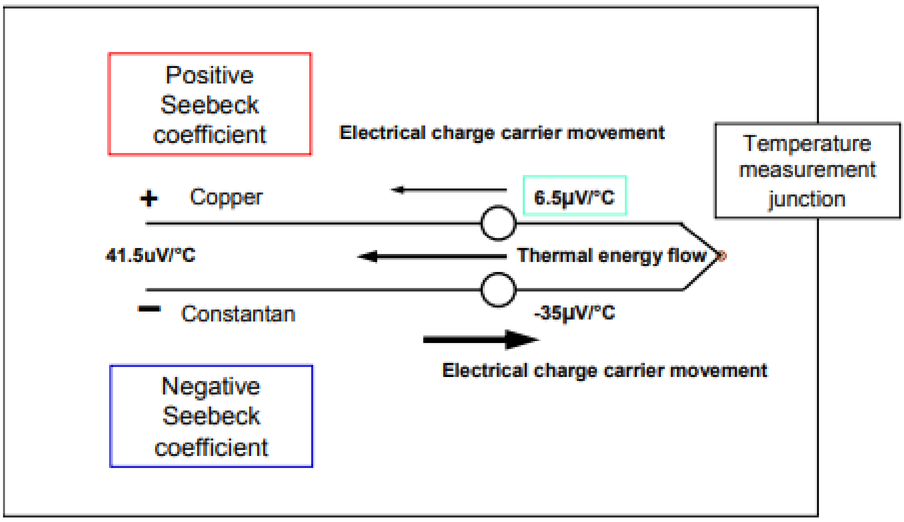

Figure 2: Structure of the industrial thermocouple [10].

From the picture, we can see that to have the best thermocouple we want to have one conductor with the highest positive thermopower and second conductor with the lowest negative thermopower. As we can see from the tables in Figure 1, best choice would be semiconductor. However, for the industrial thermocouple, we need thin wires and semiconductors cannot be fabricated in such a form, therefore, metals are used for the industrial thermocouples [5]. The thermocouples that are used for the TEG does not have to be in the form of a wire, therefore semiconductors are used for the TEG.

The schematics of the semiconductor thermocouple look different from the industrial thermocouple. We use n-type semiconductor for the negative thermopower and p-type for the positive thermopower. Those two semiconductors have to have a metal junction on one side and are connected with the wire on the other side to complete the loop, so the current can run through. Figure 3 is a very good representation of the semiconductor thermocouple.

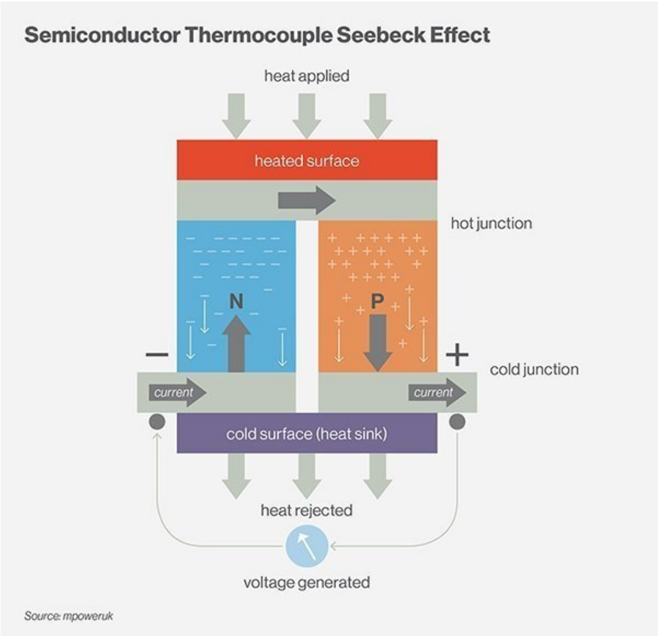

Figure 3: Semiconductor thermocouple schematics [11].

The junction is usually made of the material with a high electrical conductivity, for example, copper or gold. As we can observe from the picture, the side that has a “short” junction is called hot junction because heat should be applied on that side. The side with the wire junction is a cold junction. If the temperature difference is reversed, then the current will go other direction and the generated voltage will be negative.

The Figure of Merit (ZT)

Even though Seebeck coefficient shows the most efficient material for the Seebeck effect, when we choose the material for the thermoelectric applications there are more factors that we have to take care about to choose the most effective material. The dimensionless figure of merit (ZT) shows how effective a specific material is for the thermoelectric performance. The most trivial dependence that ZT has is the temperature dependence. As we also already observed, higher Seebeck coefficient means more voltage produced with the same temperature difference, therefore higher Seebeck coefficient results in higher ZT. In addition, we want to have a material with high electric conductivity, so electric charge has less resistance while traveling through the material, therefore increasing the voltage and power output. Since Seebeck effect depends on the temperature difference between the two sides of the material, we want the material have minimal thermal conductivity to avoid the heat transfer from the hot side to the cold side because it would reduce the temperature difference which would lead to reducing the efficiency of the thermoelectric system. Keeping the above stated dependencies in mind, scientists preformed the experiments to measure the ZT and came up with the following formula:

$$ZT = \frac{\alpha^2 \sigma\, T}{k} \qquad [5]$$

In Equation 5, α is a Seebeck coefficient, σ is the electrical conductivity and k is the total thermal conductivity (thermal conductivity has lattice and electronic contributions so we have to add them up). Since Seebeck coefficient is squared, it affects the thermoelectric efficiency the most.

In order to make a loop where the current is flowing, thermocouples are used, so it is worth looking at the ZT for the couple of the materials, specifically n-type and p-type couple. Equation 6 represents the ZT for the couple.

$$ZT = \frac{(\alpha_p - \alpha_n)^2 T}{[(\rho_n k_n)^{\frac{1}{2}} + (\rho_p k_p)^{\frac{1}{2}}]^2} \qquad [6]$$

Since α_n is negative, two Seebeck coefficients just add up. The value ρ is the electrical resistivity and it is inversely proportional to the electrical conductivity σ.

It is considered that the most efficient materials are should have ZT in between 2 and 3 and be thermally stable over the range of the temperatures it is used for [7]. However, interrelationships among the quantities that make ZT figure make it challenging to find the material that has ZT at above 1, therefore most common nowadays materials have ZT around 1 [8]. The Wiedemanne-Franz law relates thermal conductivity k and electrical conductivity σ with the following equation [12]:

$$\frac{k}{\sigma} = LT \qquad [7]$$

The constant L is the Lorenz number. From Equation 7, we can observe that for the specific temperature the ratio of k and σ has to stay constant, therefore thermal conductivity and electrical conductivity have to be directly proportional to each other. In addition, Pisarenko relation studies thermopower as a function of charge carrier concentration (n) and it implies that α is inversely proportional to the $n^{3/2}$, while the electrical conductivity is directly proportional to the charge carrier concentration (n). Therefore, an increase in n increases σ but decreases α [12, 13]. Everything in the world has to follow the laws of physics; therefore, these two limits bring a challenge for the scientists to find the best and most effective material for the thermoelectric applications.

Because of the Pisarenko relation limitation and the fact that ZT includes the ratio of electric and thermal conductivities, scientists are looking for the materials with the highest σ over k ration. Such a material should have relatively few carriers with a very high mobility. Another big reason why semiconductors are the most efficient materials for thermoelectric applications is that with their crystal, especially diamond and zinc blend, structures they have high mobilities and "highly covalent intermetallic compounds and alloys of the heavy elements" reduce the lattice thermal conductivity (k). I will take Be_2T_3 as an example because it is one of the most-studied TE materials. Both n-type and p-type Be_2T_3 have ZT around 0.6. However if we use alloying to reduce lattice thermal conductivity the optimum compounds of n-type and p-type can reach ZT of around 1 in the room temperature [7]. Nanostructures of semiconductors are also effective to reduce the lattice thermal conductivity [12]. Another way to increase ZT is to enhance Seebeck coefficient by band structure engineering. Some of the band structure engineering techniques include density-of-states distortion (for example for PbTe through TI doping) and tuning the energy offsets between light and heavy valence bands [12].

The efficiency (η_p) of the thermocouple depends on the ZT and is expressed in the following equation:

$$\eta_p = \frac{T_h - T_c}{T_h}\left[\frac{\sqrt{1+ZT_{ave}}-1}{\sqrt{1+ZT_{ave}}+T_c/T_h}\right] \qquad [8]$$

ZT_{ave} is the average ZT value for the both n-type and p-type materials over the temperature range. To find ZT_{ave} one has to integrate ZT over the temperature range from T_c to T_h and divide it by the temperature range. ZT_{ave} is expressed in the equation 9.

$$ZT_{ave} = \frac{1}{T_h - T_c}\int_{T_c}^{T_h} ZT\,dT \qquad [9]$$

It is also worthwhile noticing that the efficenty of the thermocouple is directly proportional to the well known from thermodynamics Carnot efficiency ($\Delta T/T_H$). Just by looking the Equation 8 we can see that the proportionality variable is always <1, therefore thermocouple efficiency is always lower then efficiency of the heat engine. Not the most promising conclusion, however thermoelectric applications have a lot of advantage over the heat engines that will be discussed later.

The efficiencies for different values of ZT_{ave} for different temperature differences are represented on the plot on Figure 4. As it was mentioned earlier, widely used nowadays materials have ZT value around 1 and we can observe from the graph that these materials result in around 5%-10% efficiency. However, modern materials might have ZT above 2 and using these kind of materials for TE applications might increase the efficiency up to 20% or even 25% if we can create temperature difference up to 400K and the material of TEG can be used for such a high or low temperatures.

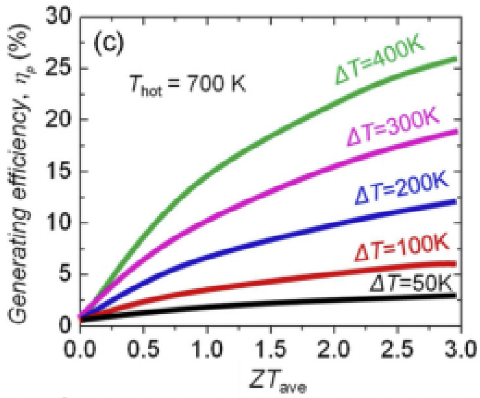

Figure 4: Thermocouple efficiency versus ZTa_{ve} plots for different temperature differences [12].

The efficiencies for the thermocouples are actually pretty low, that is why scientists are doing a lot of research to increase the dimensionless figure of merit ZT, therefore increasing the efficiency of the thermoelectric couples.

Thermoelectric Generator (TEG)

Thermoelectric generators are getting more and more popular and can be used for various applications. Main part of the TEG is the TE module and it can work two ways: generating electricity from the temperature difference through Seebeck effect, or producing temperature difference when the power is applied through Peltier effect. The Seeback effect was already discussed, so I want to briefly explain the Peltier effect. In 1834, The French physicist Jean Charles Athanase Peltier discovered that if there is a current in the loop that is made of the two dissimilar conductors, one junction of the conductors will heat up and the other junction will cool down. The phenomena of getting the temperature difference across the junctions of two dissimilar materials in the loop if the voltage is applied has a name Peltier effect [5].

The device that uses TE module to generate electricity is called Thermoelectric generator (TEG) and the device that uses TE module for cooling/heating is called Thermoelectric cooler (TEC). Often the same device can be used for generating electricity and cooling, that is why TEG and TEC generally defines the same devise. Since my project focuses on the generating electricity, for now on I will refer to TE module as to the Thermoelectric generator (TEG).

The structure of the TEG is simple because we already know what a thermocouple is. TEG is made out of many thermocouples connected electrically in series. Therefore, according to Kirchhoff's voltage law, the total emf one can get from the TEG is the sum of the thermocouples emf's. Figure 5 shows how the thermocouples are connected in series in TEG and how the current if flowing through it.

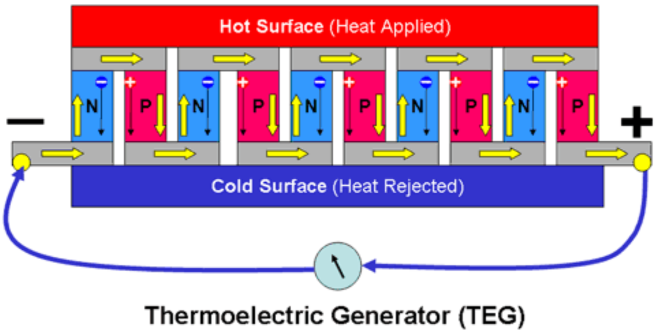

Figure 5: Representation of the current flow through the thermocouples in series in TEG [14].

To get maximum possible emf we want to make sure each thermocouple gets maximum temperature difference, therefore, thermocouples are arranged thermally in parallel. The arrangement of the thermocouples in the TEG is shown in Figure 6. From that picture, we can observe how positive and negative wires are connected to the first and last thermocouple in the series. Across these two wires we are getting the total generated voltage from the module.

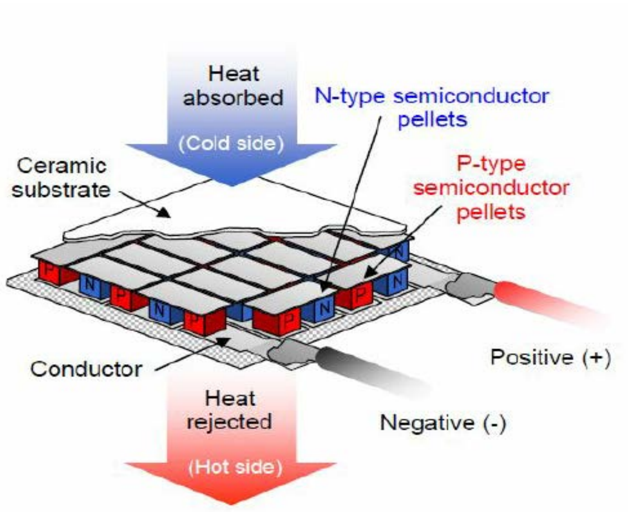

Figure 6: The structure of the thermoelectric generator [14].

The support structure material for the TEG are chosen to maximize the efficiency of the TEG. The internal part of the structure has to absorb most part of the heat and act as a conductor at the junctions. Aluminum, steel, cooper and other metals with similar properties are a good choice for the internal structure. The external structure should be a good insulator, so the emf produced by the thermocouples stays inside the TEG. In addition, we want the outer shell to be resistive to high temperature and mechanical impacts. Ceramics is the best choice for the external structure of the TEG because in addition to be a good insulator, it has high melting points, great hardness and strengths, high durability and chemical inertness [15]. Most popular ceramic material used for the TEG is Aluminum oxide (Al_2O_3) because it is not expensive and cheap in production [16].

Different TEG's can have different operating temperature limits. Those limits depend on the TEGs size and the materials that are used in the production. The thermoelectric-generator.com website has a classifications for TEGs depending on the semiconductors that are used. The most popular material is Bi_2Te_3, which allows temperature up to 320 degrees Celsius. In addition, bismuth telluride and its alloys are considered the best thermoelectric materials for refrigeration and power generation applications [17]. The second class is the hybrid of PbTe-BiTe, which allow temperature up to 360 degrees Celsius. The last two classes involve calcium manganese oxide materials (CMO) allow the temperature up to 800 and 900 degrees Celsius, however, these TEGs are expensive ($300-$400 each).

Manufacturers produce TEGs in all kinds of forms and shapes, as well as TEGs for different temperature ranges, which can be used for different applications. Marlow and TegTec are some of the the big TEG manufacturing companies. On their website, one can find the variety of different shapes for TEGs. In addition, these manufacture and cell final products made out of TEG or TEC for some applications. However, those products are expensive, so I want to come up with simple and affordable solutions for generating electricity with the TEG.

We can classify TEG's depending on their figure of merit (ZT). First generation: ZT<1.3 and efficiency between 4% and 6%. These TEG are most popular nowadays because, as it was discussed earlier, getting ZT>1 is a challenge and requires special materials and methods. Second generation: 1.3<ZT<1.8 and efficiency between 11% and 15%. Not very common nowadays but these definitely exist, just they are very expensive. Third generation: ZT>1.8 with efficiency above 15%. Most likely, these TEG's are not made of semiconductors, but new generation materials are used. For example graphene or nanomaterials, such as carbon nanotubes.

As we see, most TEG's have a very low efficiency, only about 5%-10%. However, TEG have many advantages over other power producing devices. TEG does not have any moving parts, has no noise or vibration and it is very compact. Therefore, it can be used in places where the space is limited. In addition, TEG's are environmentally friendly and have high reliability. TEG's work rate depends mostly on the temperature difference; therefore, as long as we have heat we can get power. Different materials (for example phase change materials, like paraffin) can be used to store the heat energy form the heat source therefore increasing the efficiency of the TEG.

Even though TEG's are just starting to get popular in the world, there are already many interesting applications designed. For example, TegTec company in cooperation with Osprey Labs are working on bringing thermoelectric power to under privileged families in the villages in Pakistan, India, Africa, Middle East, and South America. The power created from the waste heat allows these families to have light at night so kids can do their homework and women can work on their crafts and knitting. In addition, this power can be used to use some simple electronic devices that they have [16]. Other examples of TEG applications are: TEG on the airplanes to power wireless sensor networks or recovery of the waste heat in cars, for example form the exhaust pipes [3, 4].

Thermoelectric Generator Outputs (V, I, R, P)

For an engineer working on the application that involves TEG it is important to know what the outputs of the TEG are and how those outputs depend on the load. Just by looking at the Equation 1, we can see that TEG produces voltage that depends on the temperature difference applied to the TEG. Since TEG produces voltage, we can measure it even for the open circuit by simply measuring potential difference between positive and negative ends of the TEG. There is no current in the open circuit; therefore, the internal resistance of the TEG does not affect the potential difference of the open circuit. However, when we close the circuit the potential difference causes electrons to move, therefore, we have current running in the circuit. The total voltage of the closed circuit will be smaller than the voltage of the open circuit because of the internal resistance of the generator. Since TEG is producing voltage, adding the load to the circuit does not affect total voltage. Generally, we can treat TEG as a special type of battery does charge separation and produces voltage through Seebeck effect rather than chemical reactions.

However, while internal resistance of the battery stays constant, the resistance of the TEG varies with the temperature difference applied to it. Good news is that the difference between upper and lower limits or R that are obtained by measuring R at low and high temperature difference is not as big comparing to the upper and lower limits of voltage produced. As an example, I want to take data from the experiment that was made by the group of scientists from Transilvania University of Brasov, Romania.

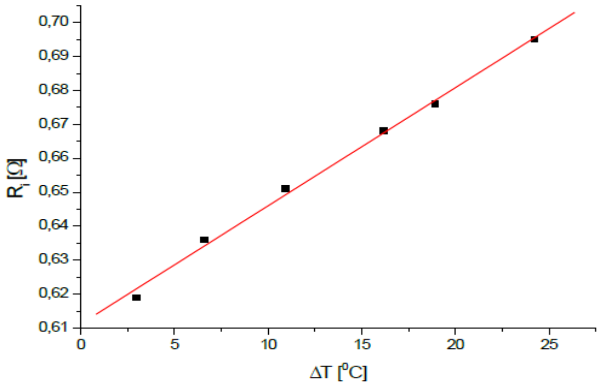

Figure 7: The internal resistance Ri vs ΔT for the Bi_2Te_3 thermoelectric generator [18].

From Figure 7, we can see that resistance increases linearly as the temperature difference increase. In the article, there is also a similar plot for the open circuit voltage versus temperature difference. Delta R for the given range is about 0.08 Ohms, while delta V is about 0.23V [18]. Depending on what is the purpose of the calculations that are preformed, one might need different level of uncertainty for the total current. If high uncertainty is not an issue, we can take average R and treat it as constant (keeping in might though that uncertainty increases towards the limits). If the allowed uncertainty for the experiment is very small then one can express the internal resistance as a function of the temperature. Every TEG will have different values for resistance and voltage output, therefore the uncertainty depends on the model of TEG that one is using. Therefore, the scientist has to make decisions based on the numbers he or she is getting from the specific TEG. Researching over multiple data sheets for the similar TEG, gave me a good understanding of what internal resistances TEG might have. For example, TEG with SnSb semiconductor is said to have only 0.5 ohm internal resistance [19]. While the examples of internal resistance for Bismuth telluride TEG are 3ohms and 7ohms [20].

Measuring the resistance of the TEG is not the same as measuring the resistance of the resistor because TEG itself is generating potential difference that drives the current. We are usually measuring the resistance of the resistor with the multimeter but multimeter does not directly measure the resistance. Multimeter makes resistance by supplying constant current to the resistor and measures the voltage across that resistance. Form the Ohm's law multimeter calculates the resistance [21]. When we are trying to measure resistance across the TEG, we are actually making a circuit and current runs through the multimeter. However, there is already some voltage potential across the TEG created form the temperature difference across the TEG. Therefore, when multimeter is applying current and measuring the voltage across the TEG it measures both TEG generated potential and potential from the applied current. Consequently, when multimeter calculates the resistance, we see a much bigger number than the actual internal resistance. However, we can measure the internal resistance indirectly. We have to measure the voltage generated by TEG in the open circuit. Then without changing temperatures across the TEG connect the resistor to the TEG and measure the voltage across the resistor. From the ohm's law I derived an Equation 10, where r is the internal resistance of the TEG, R is the resistor resistance, V_{TEG} is the open circuit generated voltage and V_R is the voltage across the resistor.

$$r = \frac{R*(V_{TEG}-V_R)}{V_r} \quad [10]$$

As we observed earlier, the internal resistance increase as the temperature difference increase. Indeed, the internal resistance increases as the average temperature of the TEG increases. Resistance represents how hard it is for the electrons to flow through the material. Higher temperature of the material means that atoms of that material have more kinetic energy and they vibrate on the bigger amplitude in the lattice (for solids) or have higher average speed (for gases). The increased movement of the atoms increases the probability that electron will hit an atom on its way while going through the material. Therefore, it is harder for the electrons to flow through the material, which means that resistance is higher for the higher temperatures. The data sheet for one of the TEGs has a very good data that represents such a behavior and it is shown on Figure 8 [22]. We can observe from the graphs on the plot that there is higher resistance when TEG has higher average temperature (higher cold side for the same hot side). Also by looking at the plot, we can see that often for bigger temperature difference we might have lower resistance, just because the average temperature on the TEG is lower. Therefore, the internal resistance indeed depends on the average temperature of the TEG.

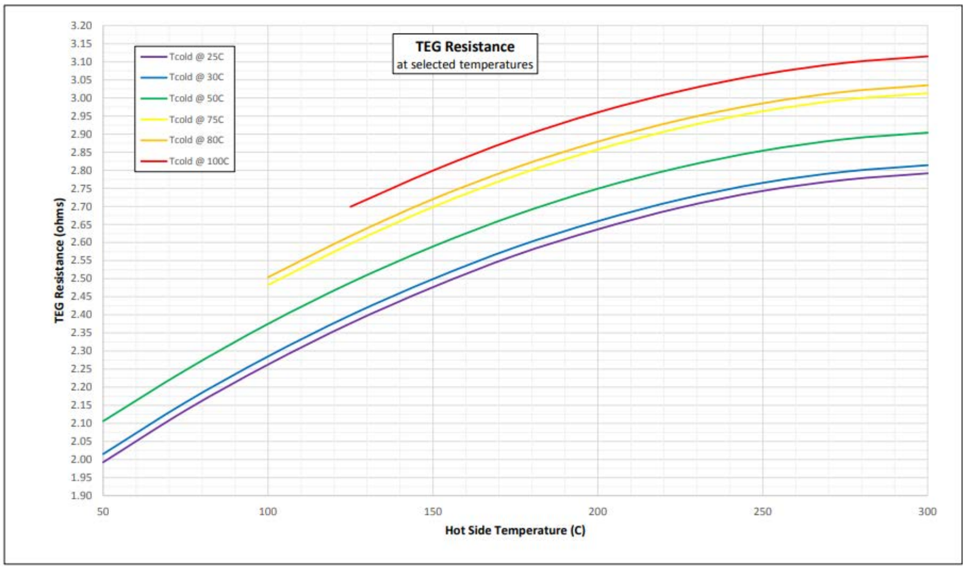

Figure 8: Internal resistance of the TEG for different values of the cold and hot side temperatures [22].

The total current depends on the internal resistance of the TEG but it also depends on the resistance of the load in the circuit and the voltage produced by the TEG. Those relationships come from the ohm's law and the formula for current can is expressed as:

$$I = \frac{\alpha * \Delta T}{R_i + R_l} = \frac{V}{R_i + R_l} \qquad [11]$$

In Equation 11, R_i stands for the average resistance of the TEG and R_l is the total load resistance in the circuit. Same as in Equation 1, α represents Seeback coefficient.

Different applications require specific amounts of supplied power, current and/or voltage to the load. If we keep the temperature difference constant, then voltage should stay constant, therefore total power depends on current. By increasing the load, we decrease total current and therefore decrease total power of the system. However, an engineer is more interested not in total power but how much power is dissipated on the load. Since TEG has an internal resistance, some fraction of the total power is dissipated inside the TEG. To maximize the power transfer to the load we want to do impedance matching, which means we want the load resistance to match the internal resistance of the voltage supply (TEG). If load resistance is lower than internal resistance then most of the power is dissipated inside the TEG. If load resistance is higher than internal resistance then the total resistance is big, therefore total power in the system reduces. The maximum output power of the TEG can be expressed as: [23]

$$P_{max} = \frac{1}{4} * \frac{(\alpha * \Delta T)}{R_i} = \frac{1}{4} * \frac{V}{R_i} \qquad [12]$$

Single TEG has a limit to the maximum power it can deliver to the load. To increase power output, we can just increase the number of TEGs. We also have to keep in mind that to get maximum power we have to match total internal resistance of the generators to the load resistance. In addition, series connection increases voltage output with same current, while parallel connection increases current with same voltage. Therefore, different application require different amounts of TEGs in different arrangements. I want to introduce new useful variables. NS is the number of TEGs connected in series. NP number of parallel lines of TEG. NT total number of TEG and can be expressed in terms of NP and NS as follows: NT=NP*NS. Usually, designs involve equal number of TEG's in each parallel line, because having different potential differences in the parallel lines can even damage the TEG. The line with more TEGs will discharge into the TEGs on the other line and current during that process might be too high and can damage TEGs. Therefore, we will limit our conversation with having equal number of TEGs connected in series in each parallel line. Figure 9 is a good representation of how we count TEG's in series and parallel.

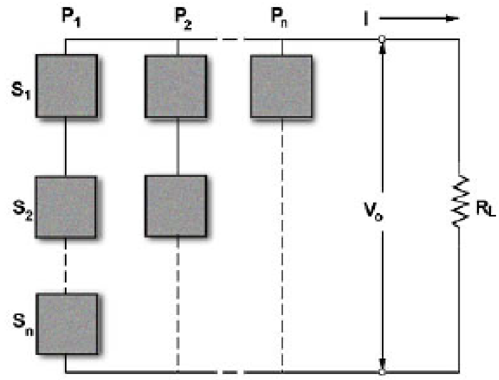

Figure 9: schematic picture of the circuit with series/parallel arrangements of TEGs [23].

When we have some combined arrangement of TEG, we can calculate total current using the following formula:

$$I = \frac{NS*(\alpha*\Delta T)}{\frac{NS}{NP}*R_i+R_l} = \frac{NS*V_{1teg}}{R_{itotal}+R_l} \quad [13]$$

From equation 13, we can also see how to calculate total voltage and total resistance of the system of TEG [23].

If we know the thermal conductance (K_c) of the TEG in watts/K, we can calculate the total heat input (Q_h) to the couple through the formula represented in the equation 14 [23], where T_h is the temperature of the hot side in Kalvin. The ratio of the total power dissipated in the system (V*I) and total heat input gives us the efficiency of the thermoelectric generator (E_g).

$$Q_h = (\alpha * T_h * I) - (0.5 * I^2 * R_i) + (K_c * \Delta T) \quad [14]$$

All the formulas provided above assume that we take average internal resistance of TEG, which sometimes may cause a big uncertainty in the calculations. The same group from Transilvania University of Brasov measured maximum power on the load for different temperature differences. They observed the expected parabolic dependence, however, the equation they obtained from the fit has a polynomial with terms ΔT^2, ΔT^1 and ΔT^0 [18]. While according to Equation 11, we expect only quadratic term. As we can see, real measurements do not exactly match simplified formulas. Assuming that we can just use average internal resistance for TEG is main reason for the mismatch we observe. However, assuming that TEG has constant internal resistance is still a good approximation that we can use for calculations.

Heat Transfer

Since this project is dealing with creating and controlling a temperature difference, I find it important to go over what is heat and what are the ways of the heat transfer. The word heat defines a process of transferring an energy from one system to another due to the temperature difference. If a system has higher temperature, then it has higher thermal energy, therefore molecules of the system have higher kinetic energy. Consequently, we can say that heat is a transfer of the thermal kinetic energy. Heat always flows spontaneously form higher temperature to lower until the total system is in thermal equilibrium. Total energy is always conserved, therefore in the result of energy exchange through heat, the change of the internal energy of the systems is equal and opposite amount. There are three ways of heat transfer: conduction, convection and radiation.

The conduction heat transfer is a result of the neighboring particles, like molecules, atoms and electrons, exchanging the kinetic energy through collisions. Conduction between two systems can accrue only through direct contact, so the molecules from these two systems can collide with each other. Solids are denser and have molecules closer together; therefore, conduction is mainly the property of the solids. Some materials are better conductors then others. Metals are great conductors because metal ions are packed close in the lattice and metals have free electrons that can carry the energy around fast. Non-metallic materials do not have free electrons, therefore the only way they can transfer energy between lattices is a vibration, which is slow and inefficient process. Conduction also appears in liquids and gasses, but on the very small rate compared to the solids.

There is a very useful law to calculate the time rate of the heat transfer through the material – Fourier's law [24]. The integral form of the Fourier's law states that the rate of the heat transfer is proportional to the materials thermal conductivity and the integral of the negative temperature gradient over the total material surface. Negative sign comes from the fact that heat flows from hot to cold. If we limit our observations to the homogenous material and a constant temperatures between two endpoints Fourier's Law ca be approximated as shown in the Equation 15 [25].

$$q = \frac{-k*A*\Delta T}{\Delta x} \qquad [15]$$

The rate of the heat transfer q is in the units of watts (W) or joules per second (J/s). The constant k represents the material thermal conductivity in W/(m*K). Constant A is the cross sectional area of the material, Δx is the distance between the two ends of the material (material thickness) and ΔT is the temperature difference between two ends of the material. If our temperature difference is changing over time, we have to use time dependent temperature gradient (ΔT(t)). Therefore, our heat transfer will be a function of time. Integrating heat transfer rate as a function of time over the total time results in the total heat transfer over that time period.

The convection is the result of the movements of the fluid. There are two types of convection: forced and free (natural). Free convention happens because the warm fluid is less dense thank cold fluid (because molecules have more energy, so they are more spread out), therefore hot fluid rises. More dense cold fluid drops, replacing the hot fluid then went up. Such a circular motion is called convention current. These fluid movements spread the heat around the system until the system reaches thermal equilibrium. Forced convection happens when the flow of the fluid around the system or over the surface is caused by the external source such as a fan or a pump resulting in an artificially induced convention current. Convention is dominant in liquids and gases.

Same as for conduction, we can calculate the rate of heat transfer from the surface to the fluid. Equation 16 is also derived from the Fourier's law. Variables q, ΔT and A represent the same things as in the Equation 15 [26].

$$q = -h * A * \Delta T \qquad [16]$$

The constant h is called the convective heat transfer coefficient, and it depends on the type of media and the flow properties, such as viscosity and velocity. For air h is in between 10 to 100 W/(m^2*K) [26]. Similar to conduction, if temperature of the surface is changing over time, we get time dependent rate of heat transfer.

Radiation does not require particles to transfer heat. Instead, it transfers heat through electromagnetic waves. Each body that has temperature above absolute zero emits thermal radiation. According to the Wien's displacement law, higher surface temperature results in the shorter dominant wavelength of the electromagnetic wave. Humans and animals radiate mostly in infrared, while from the sun we are getting ultraviolet radiation. The heat transfer through Radiation is weak comparing to the conductive and convective heat transfer, so we can neglect it for TEG applications.

Each medium and material has a property named specific heat capacity, which represents the amount of heat per unit mass required to raise the temperature by one degree kelvin. The temperature change in the material is directly proportional to the heat added to the material, where mass and specific heat capacity are the proportionality constants. This relationship is expressed in Equation 17.

$$Q = c * m * \Delta T \qquad [17]$$

Q is the amount of heat added, ΔT represents the rise of the temperature in Kelvin, c – specific heat capacity and m – total mass. If the heat is taken away from the material, then Q is negative and the temperature of the material is decreasing.

The relationship described above results in another useful law in thermodynamics - the Newton's law of cooling that states that "rate of temperature of the body is proportional to the difference between the temperature of the body and that of the surrounding medium" which yields in exponential decline of the body temperature over time [27]. Equation 18 represents the Newton's law of cooling, where T_s is the temperature of the surroundings, T_i is the initial temperature of the body and k is a positive constant.

$$T(t) = T_s + (T_i - T_s) * e^{-kt} \qquad [18]$$

The constant k characterizes the system and can be expressed as a product of convective heat transfer coefficient (h) and Area of the body (A) divided by the product of the specific heat (c) and the total mass of the body (m). Very often, we do not know the body mass, but we know its dimensions. If the body is made out of the uniform material, we can express mass in terms of density and the body volume.

Equipment and Software

For my project, I was choosing the equipment that would give me the pest possible results for the relative low cost. For every piece of equipment, I was doing some research, so I can choose parts that fit best for my purposes. In this section, I provide the list of the hardware and software I used for my experiments and in my final design with the specifications, purposes, as well as, description of why I choose this particular product.

Hardware

TEG (Model: SP1848-27145): This model of thermoelectric generator is made out of ceramic and bismuth telluride (Bi_2Te_3). Ceramic material is used on the surfaces, because ceramics is a great insulator, has high melting points and chemical inertness, as well as, it has very high durability [15]. The stated above properties make ceramics the best choice for the surface of the TEG to make it safe and long lasting. Bismuth telluride is a semiconductor that has a high electrical conductivity and low thermal conductivity. There parameters increase the dimensionless figure of merit ZT, which makes bismuth telluride an efficient material for the thermoelectric generator. In addition, according to AZO materials website article, when bismuth telluride it is alloyed with selenium or antimony, becomes a very efficient thermoelectric material, which is perfect for the power generation applications [28]. The ceramics that is used for the surfaces is white color, which is perfect because white reflects all the light, so we do not get any extra energy from the light, therefore we have cleaner experimental data.

There is no data sheet for this particular TEG model, but on the website where I purchased it, there is small description of the TEG properties. The operating temperature for this particular model should not exceed 150 degrees Celsius. The specifications for this TEG model give reference values of current and voltage for different temperature differences [29]:

- 20 degree temperature difference: open-circuit voltage 0.97V, generated current: 225mA
- 40 degree temperature difference: open circuit voltage 1.8V, generated current: 368mA
- 60 degree temperature difference: open circuit voltage 2.4V, generated current: 469mA
- 80 degree temperature difference: open circuit voltage 3.6V, generated current: 558mA
- 100 degree temperature difference: open circuit voltage 4.8V, generated current: 669mA

However, those are reference numbers and all the wiring and load would decrease the current.

This TEG model is also small, only 40mm X 40mm X 4mm, and relatively light (25 grams) [30]. Therefore, this TEG is very compact, so it is easy to use for small household applications. In addition to all the good properties of this TEG, it has a relatively low cost. One can purchase 10 pieces of TEG for $25.

Geekcreit UNO R3 board (with USB wire, breadboard and wiring): Geekcreit board is a microcontroller, where the user can upload the code that this microcontroller will run. Geeckreit board has a set of analog and digital pins that are used to get input from various sensors and equipment. Geekcreit UNO R3 board is an analog of the more popular Arduino UNO R3 board and it has similar hardware and can be used with the Arduino software, which everyone can download for free on the Arduino website. I choose Geekcreit board over the original Arduino board because the Geekcreit analog is much cheaper.

The microcontroller board is very flexible because the user can upload any code to the board, which can be downloaded from the internet or written by the user. The user can write the code that not just collects the data but also analyzes it. Therefore, one can get raw and analyzed data at the same time. Such an approach saves a lot of time, which is always useful for any research. On the Arduino website, there is a library of the sample codes that is free for everyone. I used those codes to build my own codes to make data collection as efficient as it can get. In addition, since Arduino is very popular, there are many codes and build examples on different websites and forums where people share their ideas and use of Arduino for different applications.

There is a lot of data that I had to collect for my project. In addition, this data is mostly continuous, so it is more effective to collect as much data as possible in the period of time to get smaller uncertainties on the data. Therefore, I choose Geekcreit board to collect the data for my experiments. Geekcreit board is very useful for data collection, because one can connect multiple sensors and get multiple collections of data on the same devise, which reduces the systematic error. In addition, it is very convenient to let the program gather data instead of the person writing it all down, which reduces human error. As one can conclude, using Geekcreit board for data gathering reduces many errors; therefore, I know that the data I collected is reliable.

Temperature sensor (LM35): To measure the temperature for my project I used the precision integrated circuit (IC) temperature devise LM35 made by Texas Instruments. This IC device gives an output in voltage that is linearly proportional to the Centigrade (directly calibrated in Celsius) temperature. The linear scale factor is 10mV/°C. Since LM35 is already calibrated, there is no need in any external calibration. The specifications provided by the company are: accuracy - 0.5°C, rated to operate from -55°C to 150°C, operating voltage – 4V to 30V. Further, this device has a very low self-heating; only 0.08°C in still air [31]. I chose this device over others because it is very cheap (only few dollars each), compact, compatible with Arduino and it has good accuracy.

3D printer (uPrint SE Plus): The design for some of my experiments required 3D printing. I used the Le Moyne makers StrataSYS uPrint SE Plus 3D printer. This printer has an amazing property that allows printing the support in the separate soluble filament. Le Moyne maker zone has a special chamber WaveWash that in combination with special chemicals dissolves the support filament. This feature allows to print complicated designs with high accuracy [32].

Fisher Sciencific Stirring Hotplate (11-500-16SH): Le Moyne Chemistry department provided me with the hotplate for this project. This model has 4x4 inches size top ceramic plate. This hotplate has 10 increments on the heat control knob and operates in the 150°C (302°F) - 590°C (1094°F) temperature range [33]. I used this hotplate as a heat source for TEG and I used metal bar to conduct heat energy from the top of the plate to the TEG. The heat control knob allowed me to control the heat energy delivered to the TEG.

Software

***Arduino software (IDM) 1.8.7*:** Arduino integrated development environment is a software that is used to write and compile the codes for any Arduino board. In addition, this software is used to upload the code directly to the board and it has the window where we can see the printed output (data) from the code that is running on the board. The environment is "written in Java and based on Processing and other open-source software" [34]. I used this software to write the code for data collection and upload it to my Geekcreit UNO R3 board.

PLX-DAQ 2.11V: Data that I get from the board is printed in the Arduino window, however transferring it to the Excel, where I do all my analysis, is very time consuming. Therefore, I found this software add-on for Microsoft Excel – PLX-DAQ [35]. This software is made to send data from the board directly to the Excel. I had to add additional lines to my code, which PLX-DAQ software reads to put specific data in the specific columns with labels. To get data in Excel I need to have code uploaded to the board. Then I open Excel with PLX-DAQ add-on, where I can see a window that lets me choose the port and start, pause or stop data collection.

Solidworks Education Edition 2016: Solidworks is published by Dassault Systems and it is a 3D solid modeling computer-aided design (CAD) software. My second setup required special design and I wanted the case for the second setup to be 3D printed. Therefore, I had to make my own 3D design of the case. Le Moyne makers club has a license for Solidworks education edition software that students can borrow for their laptop. In addition, I already had experience with Solidworks that is why I choose this CAD software over others options.

GrabCAD: This software was used to read and understand the CAD file and prepare the model for the 3D printing. I choose this software because it makes 3D printing easy, accessible, and connected for Stratasys 3D Printer that I used for the printing [32].

Maple 2017: Part of the analysis for this paper includes computations. I used this math software to create and plot the functions of variables to observe the predicted behavior of the variables.

Preparation Tests

Before doing actual experiments with the thermoelectric generator, I had to make sure that all my equipment works the way I expect it to work, so I be confident that my data is correct. In addition, I had to make sure that the precision of my measurement is good enough for the accurate readings and data. In order to successfully get my data on the Excel I had to follow this procedure:

1. Upload the code to the microcontroller. In the Arduino software check if the code runs well and I am getting data I am supposed to get.

2. Unplug the board from the computer. Then open Excel with the PLX-DAQ add-on and plug the microcontroller back to the computer.
3. Put the number of the com port that my board is connected to in the PLX-DAQ window (I always used the port 3).
4. Click connect to start collecting data. To finish collecting data click disconnect.

I use this simple procedure for all the experiments where I used the microcontroller board for data collection.

Temperature Sensor Accuracy Test

The first test I made on the temperature sensor was just measuring the temperature of the room. For the temperature measurement, I used LM35 temperature sensor connected to the microcontroller. The sensor returns a 10-bit number, which is read by the analog pin on the board. The program converts the analog reading to the temperature using the following equation:

$$(5.0 * temp * 1000.0) / (1024 * 10) \qquad [19]$$

AnalogRead function reads the number in between 0 to 1023, which corresponds to the input voltages from 0V to 5V. Each degree rise results in a 10-millivolt increase, therefore we have to multiply the voltage reading by 1000 to convert it to millivolts and then divide that number by 10 to get temperature reading in Celsius. I was measuring the temperature for 105 seconds and I got a very stable data of 21.48 degrees Celsius or 21.97 degrees Celsius. I am getting discrete data because this is the way the board and code work. Sensor is sending 10-bit number and it is an integer, so for that particular code I cannot get a number between 21.48 and 21.97, because those two numbers correspond to the 44 and 45 integer numbers that a sensor is sending to the board. For the copy of the code for this experiment, see Appendix A. Since temperature measurements are within small voltage range, I can increase the precision by setting analog reference to 1.1V, which is an internal board reference. This means that the integer number from 0 to 1023 correspond to the voltages between 0V and 1.1V. This little trick helps to get measurement that is more precise for the smaller voltage readings.

Using the new reference, I did another test on the sensor. I measured the temperature of the ice cubes and my warm breath. Cubes are frozen water and they are melting, so water undergoes phase change from solid to liquid and during this phase, change water has the temperature of 0 degrees Celsius. This is a good reference to test the sensor. I was holding those two cubes tight together with sensor in between them to ensure a good mechanical contact with the sensor. I put the sensor in between the cubes on the 7th second of the test and I observed the temperature reading to go down, however, it was happening relatively slow.

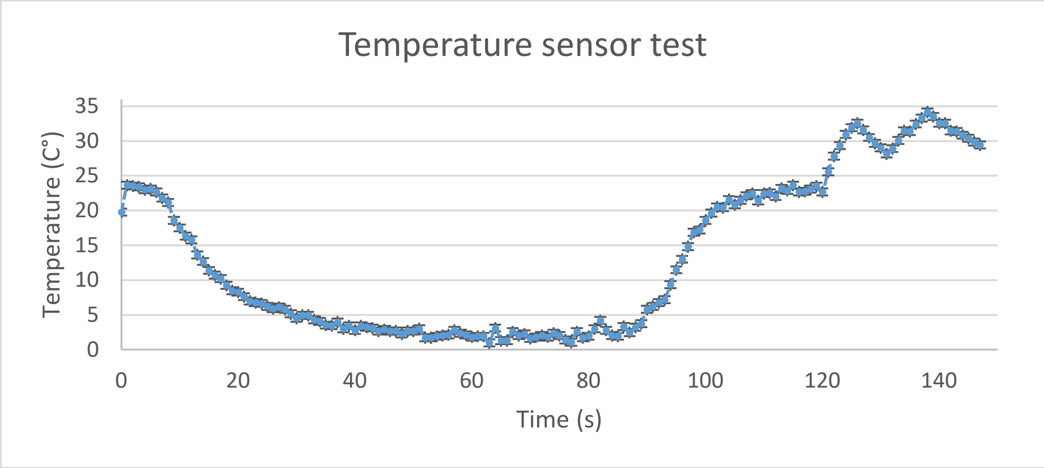

Figure 10: Graph for the temperature sensor second test. Since the sensor has 0.5 degrees precision, my data points have 0.5 degrees absolute uncertainty.

As we can observe from the data on the graph above, it took about 25 seconds for the temperature to drop down to 5 degrees Celsius and 45 seconds to drop to about 2 degrees Celsius. The temperature then was fluctuating in between 1 and 3 degrees Celsius (mostly around 2 degrees). The lowest reading I got was 0.97 degrees Celsius. I could not achieve 0 degrees because the sensor did not have perfect physical contact with the cubes on all its sides, but I still got a good result. At the 80th second I took the sensor out of the ice and the temperature starting rising. I was using the warmth of my hand to warm up the sensor faster. At around 110th second the reading went back to the room temperature. Then I exhaled towards the sensor with the warm breath twice. We can see two spikes and the end of the graph that correspond to those two exhales.

This test proved that the temperature sensor is working correctly. However, it takes some time for the measurement to adjust to the new temperature, which is because it takes some time for the sensor to warm up or cool down. That will not be an issue during my actual experiments, because no measurements in my project will have sudden temperature changes. Therefore, I can state that this sensor is good to use for my experiments.

Microcontroller Voltage Readings Tests

According to Seebeck effect and Equation 1, TEG voltage output depends directly on the temperature difference. I am measuring temperatures with microcontroller board and I want the data I am getting for the voltage to be simultaneous with the data I get for the temperature. In addition, I want to have many data points, so my plots are more informative. Because of the above stated reasons, I decided to measure voltage output with microcontroller board as well.

I have never measured the voltage with the microcontroller, so I wanted to check how accurate those measurements are. I used GW INSTEK GPS-18500 power supply to generate voltages that I can measure. I also used FLUKE 8845 6-1/2 digit precision multimeter for the reference, because power supply does not provide accurate readings for the potential.

Measuring voltages with the board is very similar to the temperature measurements but we do not have to convert input voltage to the degrees. I just use the formula to convert the analog reading (number from 0 to 1023) from the pin to the corresponding voltage. By default, the analog reading corresponds to the voltages between 0V and 5V. However, if I know that my input is small, within the 1.1V, I can set the internal reference and analog reading will correspond to the voltages between 0V and 1.1V. Changing the reference to internal for the small measurements results in the better precision. The board cannot take more than 5V, so if I know that my input exceeds 5 volts I make a voltage divider circuit to measure the voltage safely. See Appendix B1 for the code that I used for the regular voltage reading test.

Voltage divider circuit consists of the two resistors. See Appendix B3 for the photo of experimental setup for the voltage divider circuit measurements. First resistor (R1) is bigger than the second one (R2), so most of the voltage drop is across the R2. I used R1=0.996kΩ and R2=10.04kΩ. I measure the voltage across the second resistor – V2. We can calculate the voltage across the first resistor (V1) by multiplying the ratio of the two resistors by V2. Therefore, the total voltage is just the sum of V1 and V2. See Appendix B2 for the code that I used for the voltage divider circuit measurements readings.

For the voltage measurement accuracy test, I decided to test two extremes: low voltages and high voltages. For low voltages, I use internal reference in my code. For high voltages, I use voltage divider circuit and default reference. I set power supply for the specific output and record the measurement from the multimeter, while Excel collected the data for the board. Then I just compared two data sets. For my plots I call voltage that I measured with miltimeter a reference voltage.

Graph on Figures 11 and 14 represent the plot of the reference voltage (orange) and measured voltage (blue) versus time. Arduino took measurmets every second. For the reference voltage I just used one constatn number that I recorded from the power supply. I chose to represent my data this way, becasue I can see all the data on just one graph. First I anylize the measurments for the small voltages. On the plot we can see how reference voltage is just on top of the measured voltage. For the smallest voltage that I measured the fluctuation on the multimeter were so big, that I decided not to use it for the analysis. The points for the measured voltages that are off the sets are just measurement that Arduino took while I was changing the supplied voltage on the power supply.

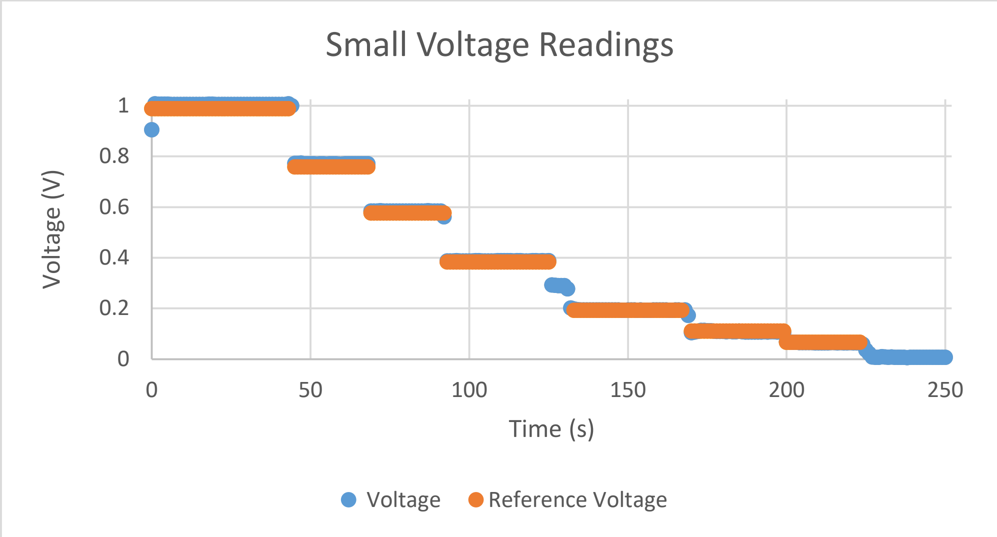

Figure 11: Graph of reference voltage and measured voltage versus time for the small voltages (0V-1.1V)

To get a better understanding on how accurate my data is, I found an average discrepancy for each set. These discrepancies are shown in the table in Figure 12. As we can see from the table, discrepancy is different for different voltages.

Average Discrepancy	Reference Voltage (V)
1,70%	0,989
1,62%	0,759
1,42%	0,5762
1,09%	0,384
0,32%	0,1928
1,89%	0,11
2,70%	0,067

Figure 12: Table of average discrepancies for the sets of the small voltages.

We can observe the pattern, how the discrepancy is dropping as the voltage gets smaller until the certain point, then it rises quickly. However, the only measurement where discrepancy exceeded 2% is the smallest measurement.

Set	**AV D**
3,64	3,36%
6,24	1,45%
8,47	0,82%
10,78	0,85%
12,18	0,07%
14,39	0,24%
16,82	0,38%
18,96	0,54%

Figure 13: Table of average discrepancies for the sets of the high voltages.

On the plot below, we again see similar behavior as we observed with the small voltages data. Again, to better see how accurate the data from the board is comparing to the reference data I made a table of discrepancies for the sets of voltages that is represented in figure 14.

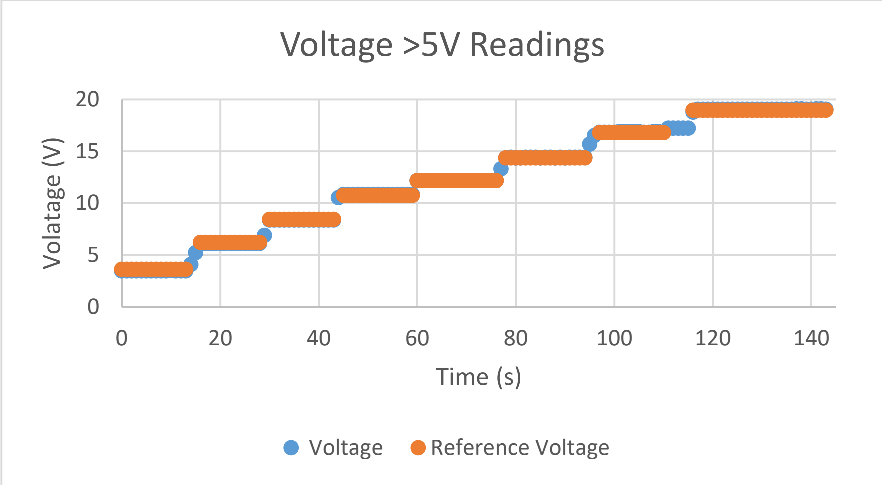

Figure 14: Graph of reference voltage and measured voltage versus time for the high voltages

On Figure 13, for the high voltages, we can observe similar patterns we saw for the small voltages. Discrepancy drops to some minimum up to the certain point and then it rises back. My conclusion from that behavior is that the board is not very reliable source of voltage readings, because it has this interesting behavior of being precise on one spot and then getting less precise as we go further away from that spot.

Since I expect the output from the single TEG to be lower than 5V, most of my measurement I will do with default reference without voltage divider circuit. Therefore, I made another data collection, with more data, for the voltages in between 0V and 5V, so I can have an idea of the uncertainties for the measurements I make in my future experiments.

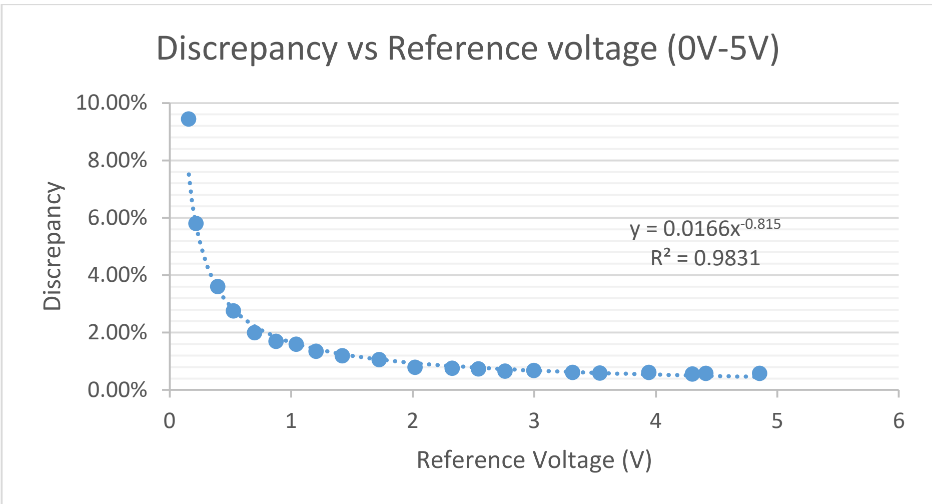

Figure 15: Discrepancy versus reference voltage and power fit on it.

Figure 15 shows that I got a very nice data, where for the smaller voltages I get bigger discrepancy. I made a power fir and got the equation for the discrepancy that is shown on the graph. R^2 number is 0.9831, which means that the fit is very good.

Overall, I think that results are good and I can use the board for my measurement. Although, I have to include the uncertainty for my measurement in my further analysis. I can use the discrepancies represented in the table as a reference to estimate the uncertainty for the future measurements. In addition, I can use the equation from the plot to calculate the uncertainty for the future measurements that lie within 0V and 5V and were taken with default reference.

Simple TEG Test:

I have never had any experience with TEG before, so once I got them I wanted to do a simple test to see approximately what voltages am I getting from some temperature differences. In addition, I just wanted to see how it behaves overall. To measure the output of the TEG I used Fulke 115 multimeter.

Since my setup was not done yet, I could not maintain temperature difference for long time. In addition, I did not measure a temperature difference on the TEG. This experiment was meant to just understand how TEG works and what to expect from it. First, as I was playing with the TEG, I found out which one is the cold side and which one is the hot side. If I apply heating on the cold side, I just get negative voltage. For all my data collections and test, I want to have positive voltage, so I get current always the same direction. Therefore, I label that side with the serial number on it is a cold side. After figuring out the sides, I did a set of measurements under different circumstances that gave me different temperature differences. I recorded the maximum voltage output I got for each measurement and organized my measurements in the table represented in Table 1.

TEG cold side	TEG hot side	# of TEG in series	Max V output (V)
Table surface	Hand palm	1	0.13
Ice Cube	Table surface	1	0.301
Ice Cube	Heat stove(increment of 2)	1	0.957
Plastic cup with ice	Heat stove(increment of 4)	1	1.3
Plastic cup with ice (TEG cooled down in ice)	Heat stove(increment of 4)	1	2.3
Plastic cup with ice (did not cover whole surface)	Heat stove(increment of 2)	2	5.5

Table 1: Data for the simple TEG test

For all the measurements, I found the same behavior of the output. In the beginning, voltage output increases fast but goes up to a certain point and then start dropping slowly. The reason for the voltage output to increase is that it took a couple seconds to transfer heat to the TEG and make the potential difference. The reason for the voltage to drop is that it did not have a sufficient cooling on the cold side. Therefore, the heat that was conducted from the hot side of the TEG to the cold side was in a faster rate than it was conducted from cold side to the ice in the cup. Therefore, the temperature difference decreases between the two sides of the TEG, therefore voltage output drops as well. In addition, in Appendix C there is a picture where one can observe how I was performing some of the measurements for the simple TEG test.

As we can see from the table, the highest voltage output I got for one TEG was 2.3V. The heat stove on the increment of four is very hot, approximately 120 degrees. Since plastic is not a good conductor of heat, temperature of the bottom of the cup was around 7-10 degrees. According to the data I have for my TEG, I should get around 4.8V for 100-degree difference. The conclusion is that I did not have good enough physical contact with the surfaces, therefore TEG did not get all the heat energy from the surfaces, which resulted in the efficiency lose.

With this experiment, I found out multiple things about the TEG. I need to have strong enough cooling on the cold side of the TEG, so it does not overheat. As well as, I have to have good physical contact between the TEG and the cold/hot surfaces, because bad physical contact results in the big efficiency loses.

Developing the Most Effective Setup

The "Master" Setup

In order to get good results of the TEG outputs, I have to create and maintain the highest possible temperature difference across the TEG. In addition, I have to keep a good physical contact between the cold/hot surfaces and the TEG.

The main idea of my setup is that I am using metal bars to conduct heat from the heat source to the TEG and from TEG to the cold source. I use hotplate as my heat source and bucket with ice as my cold source. I use the temperature sensors that are connected to the microcontroller to measure the temperature difference across the TEG. To measure voltage output from the TEG, its wires are also connected to the microcontroller. The code that is uploaded to the microcontroller converts the analog inputs from the sensors and the TEG to the degrees and volts in the similar way as it was described in the preparation experiments. Data collected by the microcontroller goes directly to excel spreadsheet. For all the following experiments the measurements were performed and recorded every five seconds. I used the breadboard to organize the wiring system, so I have only one ground and one 5V wire going to the microcontroller. Figure 16 shows the schematic representation of my setup with all the wiring. The described setup is a base for all the experiments. Therefore, I call this the “master” setup. Updating this setup by using specific metal bars and adding elements to the circuit or the setup itself makes a unique setup for each experiment. Such an approach gives me an opportunity to compare my results for the TEG output under different circumstances.

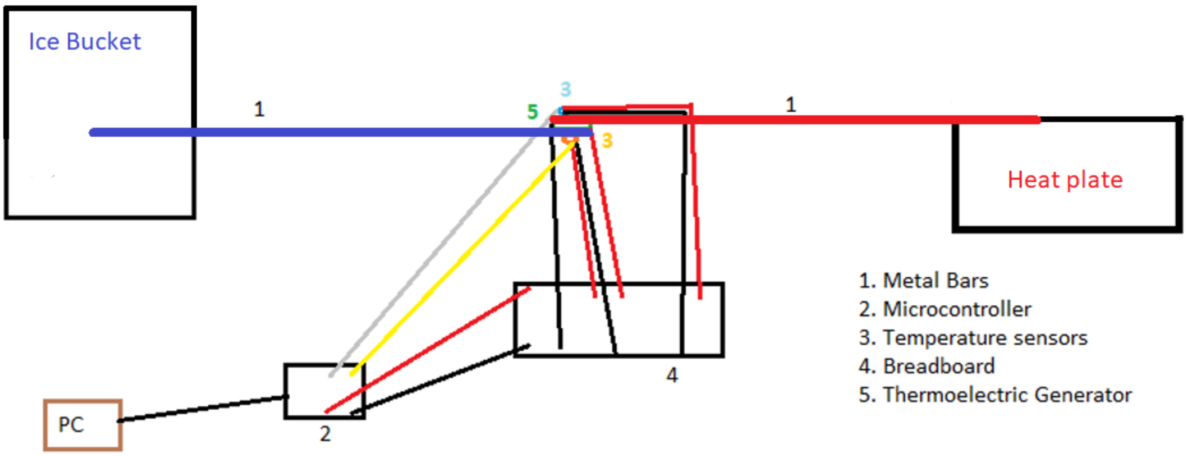

Figure 16: schematic representation of the “master” setup and wiring.

Since I did not have a chance to get a metal bar of the specific shape, I had to cut the hole in the ice bucket, so I can insert the cold metal bar inside the bucket. The hot metal bar is just sitting on the hotplate. I use plastic clamp on the area where TEG is locates to ensure a good physical contact between the bars and the TEG. The clamp must be plastic, or other insulating material to prevent heat exchange between the bars through the calmp. The plot in Appendix D shows how the use of the metal clamp results in the fast heat exchange in between the bars, which dramatically decreases the efficiency of the setup. For the setup wiring, I used the combination of male/male and female/female jumper wires to connect sensors to the board and microcontroller. The wires that are going from the TEG did not have male or female connectors on them, so I soldered them to the wire with female connector and used male to male wire to connect TEG to the breadboard.

The temperature sensors are attached to the surface of the metal bars directly above/below the area where the TEG is in between two bars, as shown on Figure 16. Therefore, the measurement I am getting is the surface temperature of the bar on the other side of the bar that is touching the TEG. The bar is only a few millimeter thick, so the temperature on the surface that is touching the TEG is almost the same as the surface temperature that I am measuring. Another thing worth mentioning is that the hot bar should be on the bottom and cold bar on the top. The reason for that is that heat is rising, so the heat from the hot bar might heat up the cold bar above it. The effect would be small because the conductive heat transfer has much more effect on the bar that convective heat transfer. Anyways, I want to minimize any heat exchange in between the bars.

Studying Heat Convection Effect on the Bars Temperature

Before making any actual experiments with different bars and resistors, I wanted to see if the convective heat transfer has a big impact on the heat exchange between the bars. To study that I had to update my “master” setup with something that would prevent any airflow between the bars. I came up with the design that involves the insulators and the plastic case to create heat and cold sinks, where the air from the sinks does not interact. The heat and cold thinks should help maintain the constant temperature on the bars.

Figure 17 illustrates the cross section of my design. Since my setup required specific case, I design it in Solidworks and 3D printed in the Lemoyne Makers Lab on uPrint SE Plus 3D printer. The case consists from the two parts, top and bottom. I used the snap fit design on the front and rare sides of the box, so I can close the box tightly and open it for disassembly of the setup when the measurements are done.

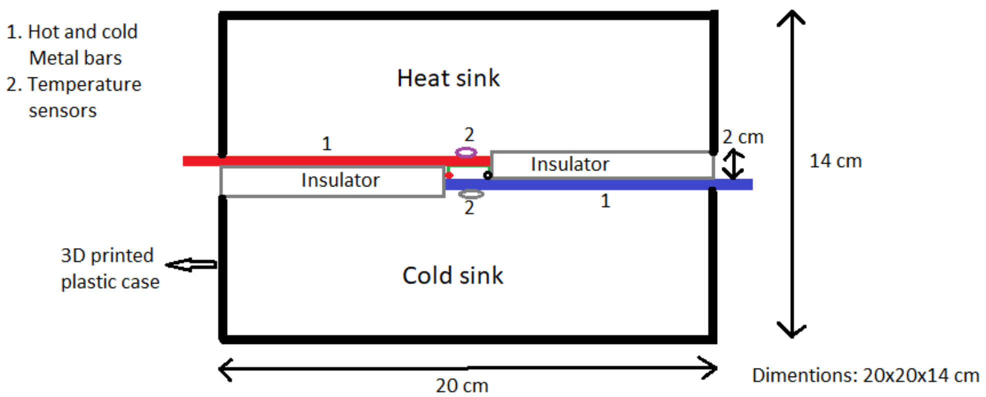

Figure 17: Cross section of the sink separation design.

For the insulator, I used the regular 2 cm thick Styrofoam that I cut so it fits in the box dimensions. The insulator on each side goes through the whole box width from the front to the rare side of the box. See Appendix E1 for the photo of the setup for this experiment. With such a design, the only place where bars can exchange the heat energy is through the TEG itself. One big disadvantage of that design is that if I want to avoid any air exchange between the sinks, I cannot use the clamp to keep the good physical contact between the bars and the TEG. The snap fit design ensures that bars are sitting tight where they should be, however, such an approach does not ensure as good physical contact between the bars and the TEG as the clamp does. The code that I used for the data collection for this experiment is attached in the Appendix E2.

Figure 18 represents the plot of the hot and cold bar temperature as well as ΔT versus time. As we can see, the hot bar is giving off a lot of heat energy to the cold bar, which makes the cold bar to heat up together with the hot bar.

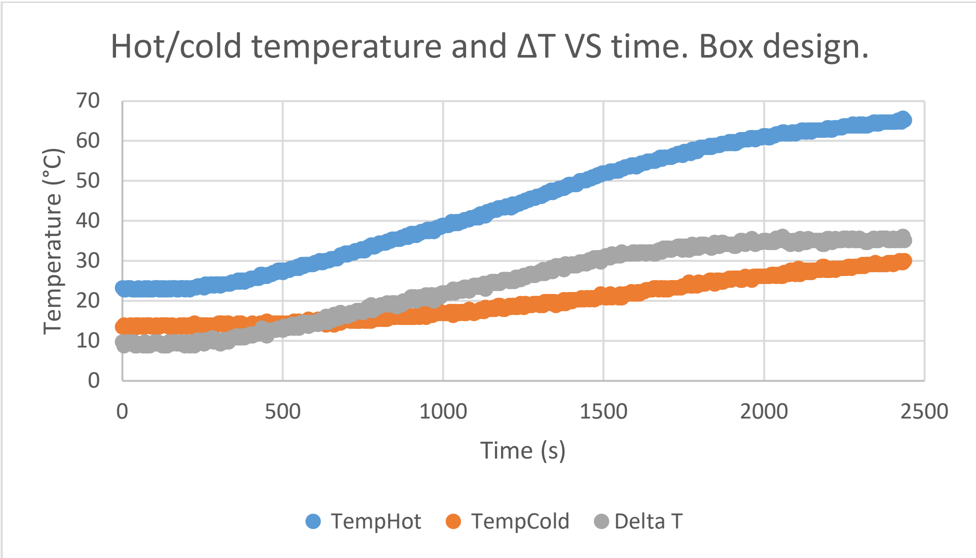

Figure 18: Plot of hot/cold temperatures and ΔT versus time for the box design.

As I mentioned earlier, the only place where heat can flow from hot bar to the cold bar is through the conduction across the TEG. The data from this experiment proves that convective heat transfer through the air does not have a big effect comparing to the heat transfer through the conduction across the TEG.

The voltage output from the TEG was in the order of 0.1-0.2V, which is much smaller than I expected. The main reason for such a low output is that I did not have a good physical contact between the bars and the TEG, therefore even a very thin layer of air acts as an insulator and decreases the heat energy that is exchanged between the bars and the TEG. However, the voltage increases along with the increase of the temperature difference. Therefore, it follows linear relationship shown in the seebeck effect Equation 1. See Appendix E4 for the voltage output and temperature plot. The "seeback coefficient" that I get for this data is almost constant with a slight increase (slope only $1*10^{-6}$) an it is in the order of 0.004-0.005. The real seebeck coefficient for this TEG is much higher. I did not have good physical contact, so TEG itself had lower ΔT across it than measured ΔT, which is the reason why I keep calculated "seebeck coefficient" in quotation marks. See Appendix E3 for the "seebeck coefficient" vs time plot.

Calculation for the heat transfer can support and prove the result I got from the experiment. First, through the Newton's law of cooling represented in the Equation 18, I want to show how long it takes to heat up the air in the hot sink if the bar is held at some constant temperature. For the initial temperature I choose the room temperature of 20 degrees. The surrounding temperature the hot bar temperature that I set to be 50 degrees. The k constant involves several parameters. Convective heat transfer coefficient, which is equal to 10 $W/(m^2*K)$ in the free convective practically still air. Area of contact of the bar with the air. Since only one side of the bar is in contact with air the area is just the length times the width of the bar. The width of the bar that I used is 5 cm and the length of the bar in the box is approximately 12 cm, which results in the area of $0.006m^2$. The specific heat capacity of the air is 1005 J/(kg*K) [36]. Density of the air is 1.225 kg/m^3 [37]. The volume of the heat sink is 20cm x 20cm x 6cm, which yields in $0.0024m^3$. Putting all the numbers in the formula and plotting it with respect to time produces the following graph shown in Figure 19. See Appendix F for the Maple spreadsheet for the plot in Figure 19.

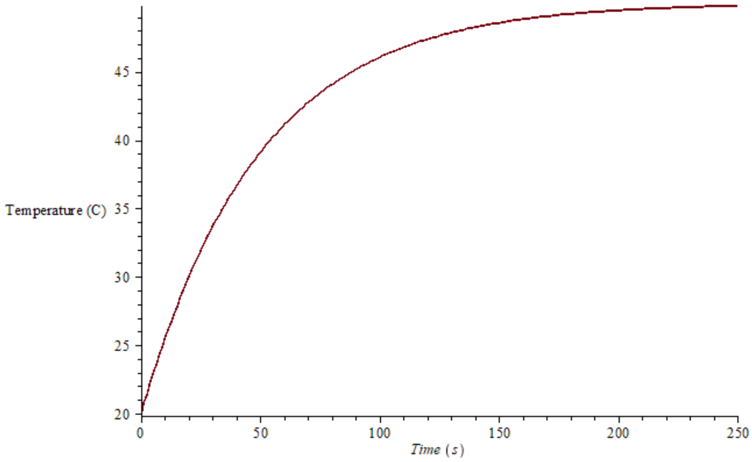

Figure 19: Plot of the predicted air temperature in the heat think versus time.

As we can observe from the plot, it takes about 200 seconds (3.3 min) for the air to heat up in the perfectly isolated heat sink. However, my heat think is not perfectly isolated from the outside air, so in reality heating would take longer than 3 min. My experiment is not running longer than 40 minutes (to avoid overheating of the TEG). That means that there is enough time for the heat think to heat up and help maintain the temperature on the bar. However, the effect of the surrounding temperature on the bar is not big, because it takes long time for the bar to heat up/ cool down as we will see further in the paper.

In addition, we can calculate at what rate the heat is given off by the bar through the convention versus the heat that is transferred to the cold bar through the conduction across the TEG. The convention heat loss rate is calculated by using the Equation 16. The h constant, the area and the temperature difference stay the same as in the previous calculations, which gives us only -1.8 W (J/s). For the conduction heat transfer rate, we use the Equation 15. The thermal conductivity for TEG can be approximated by looking at the thermal conductivities of the materials that TEG is made of: Aluminum oxide (Al_2O_3) with thermal conductivity of 18-36 W/(m*K) (I take average of that, so 27 W/(m*K)), and bismuth telluride (Bi_2Te_3) with thermal conductivity of 1.2 W/(m*K) [38,39]. Ceramic takes a about the half of the thickness of the TEG, so I approximate my TEG thermal conductivity to be the average of two thermal conductivities and it is equal to 14.1 W/(m*K). The area of contact is just the area of the TEG, which is equal to $0.0016m^2$. The thickness of the TEG is 0.004m. I set temperature difference between the bars to be 25 degrees. The numbers above result in -141 W heat rate transfer from hot to cold bar, which is 78.3 times higher than the heat loss rate through the convention. Therefore, we proved that the heat exchange with air is negligible comparing to the heat exchange through the conduction across the TEG. With that conclusion, I can perform the experiments without any special equipment to prevent heat convection.

Studying Materials for the Bars

Different material have different properties that affect the heat transfer. Shape and size of the material affects the heat transfer as well. I want to choose the best material or a combination of the materials for the most effective setup that would produce highest temperature difference across the TEG. My limitations were that I had only two options for the material: aluminum and steel. I had long but narrow aluminum bar, which was not wide enough to cover the whole area of the TEG, which would drop the electricity generating efficiency. I also had a shorter aluminum bar that was 5 cm wide (TEG is 4 cm), 3mm thick and about 25cm long. Le Moyne physical plant provided me with two steel bars both 2.5mm thick and 5cm wide. One bar was 50cm long and the other one 30cm long. Aluminum and steel are very different metals, so it was interesting to compare them. My hypothesis was that even though aluminum has higher thermal conductivity, since it is less dense it would cool off and heat up faster than steel. Therefore, aluminum would not hold constant temperature as good as the steel bar and might be more affected by the warm air around it, which might make it less efficient then steel.

To compare these types of the bars I made three runs with different combinations of the bars. For each run, I followed the same procedure:

1. Place TEG in between the bars and put the plastic camp on the area where the TEG is located to ensure good physical contact between the bars and the TEG. Make sure it is as tight as it can get.

2. Place the cold bar in the bucket and put the hot bar on the hotplate. Measure the distance from the TEG to the heat/cold sources: ~10cm from the middle of the TEG to the beginning of the hotplate and ~5cm from the TEG to the ice bucket.
3. Do the wiring as shown in figure 16 and then turn on the hotplate on the increment 2.
4. Get microcontroller ready for data collection as described before. The code for these runs is the same as for the Box design experiment (see Appendix E2)
5. Turn the hotplate on the increment 5 and start taking data.
6. Increase the temperature as the time goes by.

First run had both hot and cold bars made of steel. I used the longer bar for the cold side, to increase surface that is covered with ice in the bucket, therefore it is able to take out more heat from the TEG. I name this run Steel vs Steel. Figure 20 represents the plot of the temperatures of the hot and cold sides as well as temperature difference versus time. On the plot, we can see areas of the fast temperature increase and some flat regions. The temperature on the bar depends on the heat supply temperature. I would increase the heat on the hotplate and the bar heats up to a certain maximum point (flat region). Then I increased the temperature of the hotplate again and the bar temperature continued to increase.

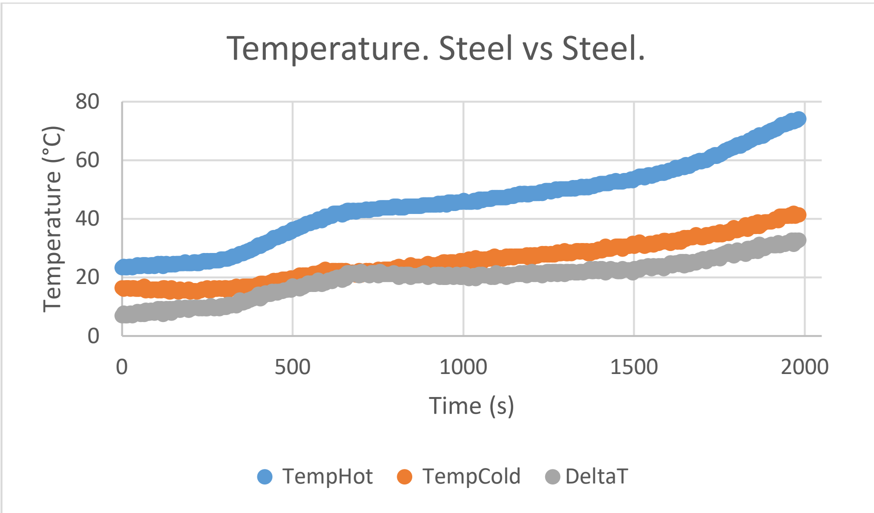

Figure 20: Plot of the hot and cold temperatures and their difference versus time for the Steel vs Steel run.

The highest temperature difference I got was around 40 degrees and it happened when the hot bar was at around 75 degrees. As we can observe from the graph, the cold bar temperature keeps increasing along with the hot bar temperature. The temperature on the hot bar is increasing faster; therefore, the temperature difference is also slowly increasing. From the previous experiments, we know that heat is transferred between the bars primarily through the

TEG. From these observations, I make a conclusion that the cold bar is not conducting the heat fast enough from the TEG, comparing to how much heat it conducted from the hot bar to the cold bar through the TEG. Such an observation means that I need a better heat conductor for the cold side.

Based on the result of the first experiment, for the second experiment I added the narrow long aluminum bar to the steel cold bar. Theoretically, aluminum bar should increase the rate at which the heat is conducted from the TEG to the ice bucket. I name this run Steel vs Steel + Aluminum run. The plot for this run is represented in figure 21 and it has same parameter graphs as the plot on figure 20.

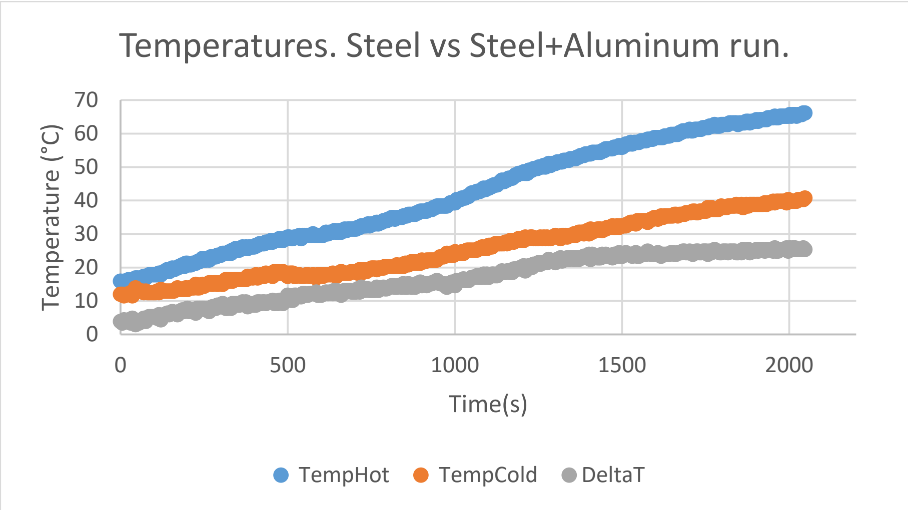

Figure 21: Plot of the hot and cold temperatures and their difference versus time for the Steel vs Steel + Aluminum run.

This plot is smoother then plot on Figure 20 because I increased the hotplate temperature before the temperature of the bar got constant. Comparing this run's data to the data I got from the Steel vs Steel run, the temperature of the cold bar during the Steel vs Steel + Aluminum run is less affected by the hot bar. I was able to get ~40 degrees temperature difference when the hot bar was at around 65 degrees, which is a better result than during the Steel vs Steel run. Such an observations prove that aluminum increases the effectiveness of the setup.

The third run has a name Steel vs Aluminum. This run has steel bar on the hot side and aluminum bar on the cold side. I could not use the narrow long aluminum bar because it is not wide enough for the TEG, so I had to use the short 5cm wide aluminum bar. The problem with the short bar is that only about 10cm of the bar is immersed in the ice bucket. Therefore, there is not big area that is in contact with the cold source, which could affect the effectiveness of the setup. The results for the Steel vs Aluminum run are shown on the plot in Figure 22.

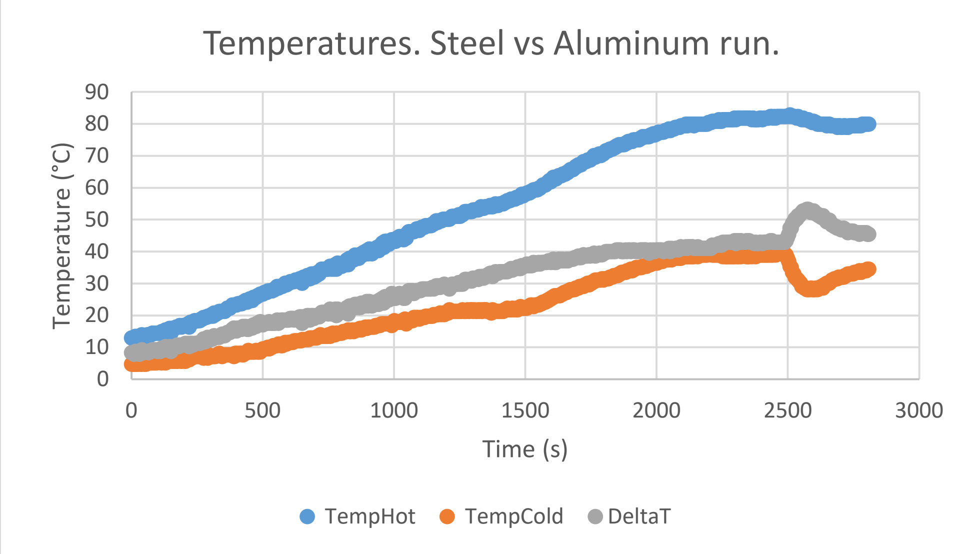

Figure 21: Plot of the hot and cold temperatures and their difference versus time for the Steel vs Aluminum run.

The “bump” on the plot of the cold bar temperature is a representation of one of the disadvantages of the small area of the bar in the bucket. During the experiment, the ice in the bucket is melting because of the warm room temperature and it is melting even faster around the cold bar, because of the heat that the cold bar is transferring to the ice. The ice I am using is in the chunks and some of these chunks stick together. When the ice is melting around the bar, some chunks of ice stay attached to the rest of the ice and do not touch the bar anymore. Since the bar is not touching that chunk of ice anymore, it does not conduct heat to it, so the bar does not get sufficient cooling. Ice keeps melting and at some point, the ice shifts and chunks of ice fall on the bar again and provide the cooling. This “bump” towards the end of the graph is when the ice shifted in the bucket (I heard it shifting during the experiment) and for some time I had a very good cooling on the bar. Later ice kept melting and the cooling efficiency was dropping again.

For the Steel vs Aluminum run, I got a temperature difference slightly over 40 degrees, while the temperature of the hot was in the range of ~70 to ~83 degrees. As we can see this run was slightly better than the Steel vs Steel + Aluminum run but not as much as I would want to. Theoretically, having a longer aluminum bar would increase the area of the ice and bar contact, which would increase the heat transfer rate from the TEG to the ice bucket. Unfortunately, I was not able to test this hypothesis because I did not have a piece of aluminum that would be wide enough and long enough. Another thing that I observed from the data for this run, is that at some point the temperature difference reached the constant value, which means that at that point the rate at which the cold bar temperature was increasing was the same as the rate of the hot bar temperature increase. I observe similar behavior for some of my other longer runs (Box design runs 1 and 2, 10000 resistor long run and Parallel vs series and different load run, which all can be found later in the text or in the appendix). I discuss the reason for such a behavior further in the paper.

There is one parameter that shows how much more efficient the aluminum bar is for cooling. As I mentioned in the procedure, the cold bar is already in the bucket for some time before I turn the hotplate on. During this time, it cools down the bar outside the bucket. The bar that is more effective for cooling should cool down to the lower temperature when heat is not applied yet. We can look at the initial temperature of the cold bar. For the Steel vs Steel run initial temperature was 16 degrees Celsius, for Steel vs Steel + Aluminum run - 12 degrees Celsius and for Steel vs Aluminum run – 5 degrees Celsius. As we would expect aluminum bar cools down to the lowest temperature and the difference is very big comparing to the other two runs. We observe such a good efficiency in the beginning because those few chunks have not started melting yet and are still touching the bar, so I have a good thermal conduction happening between the bar and the ice. This shows that if the aluminum bar was longer, so it had bigger area of connection with ice, so I always have multiple spots where ice is touching the bar, my setup would have been much more effective.

Since my data did not agree with my hypothesis, calculations are useful to check the validity of the data. For these calculations, I compare the steel bar and the wide (5cm) aluminum bar in the role of the cold bar. These two bars have the same width and almost the same thickness (2.5 mm for steel and 3mm for aluminum). The length parameter is the distance from the TEG to the ice bucket, which is constant for both – 5cm. The properties of the steel are: thermal conductivity (k) - 16 W/(m*K), specific heat capacity (c)- 490 J/(kg*K) and density (ρ) – $7.82*10^3$ (kg/m^3). The properties of the aluminum are: thermal conductivity (k) - 205 W/(m*K), specific heat capacity (c) - 897 J/(kg*K) and density (ρ) – $2.7*10^3$ (kg/m^3) [27,36,37]. Just by looking at these properties, we can see that aluminum is a much better heat conductor than steel. Therefore, according to the Equation 15, for the exact same geometry of the bars, aluminum bar transfers 12.8 times more heat energy per second then the steel bar. According to the Equation 16, the amount of heat that is exchanged with air through the convection does not depend on the material, but depends only on the fluid around it and the area of the bar. Since both bars have nearly the same area, the amount of heat is lost through the convection is the same for both bars. As I mentioned earlier, I expect the aluminum bar to cool down and heat up faster than steel. Newton's law of cooling is used to compare the cooling of the two metal bars that have the same shape and size from 50 °C to the room temperature (23 °C). Putting the metal bar properties into the Equation 18 and plotting it results in the two graphs represented in Figure 22. However, I want to mention the approximation that I did in the equation.

$$k = \frac{h*A}{c*\rho*V} = \frac{h*(2*w*l*+w*th*2)}{c*\rho*w*l*th} = \frac{2*h}{c*\rho*th} \quad [20]$$

Equation 20 represents the approximation I have done when computing the constant k. The parameters w, l and th correspond to the width, length and thickness of the bar. Since the thickness of the bars is very small comparing to the length and the width, I choose to omit the "w*th*2" term, which simplifies the equation for the k a lot. In addition, such an approximation makes k independent of the width or the length of the bar. However, one has to keep in mind that this approximation is valid only for a very small thickness of the bar. See Appendix F for the Maple spreadsheet for the plot in Figure 22.

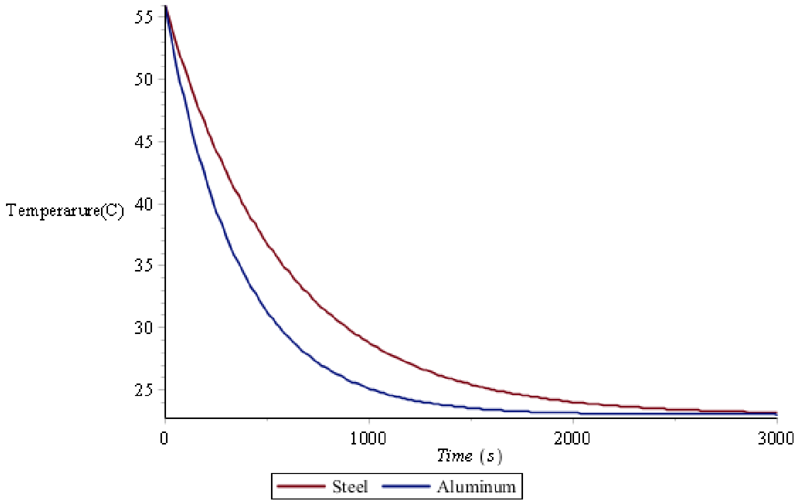

Figure 22: Plot of steel and aluminum bars temperature versus time. Newton's law of cooling.

The plot from the Figure 22 indeed proves that aluminum cools down faster than steel. However, the difference in the cooling of the two materials is not as big as the difference in the heat transfer rate. Therefore, aluminum is more effective material than steel for the heat conduction. The experiment observations and calculations lead to the conclusion that Steel vs Aluminum bar setup is the most effective setup I can make out of the materials that I have.

The Limit of the Maximum Temperature Difference Across the TEG

I mentioned earlier, that I made an interesting observation on the temperature difference across the TEG over time. Such a behavior is very easy to observe on the data from the Box design run 2 because I got a very clear data on the temperatures that were not interrupted with anything external. The plot of the temperatures for the Box design run 2 is represented in the Figure 23.

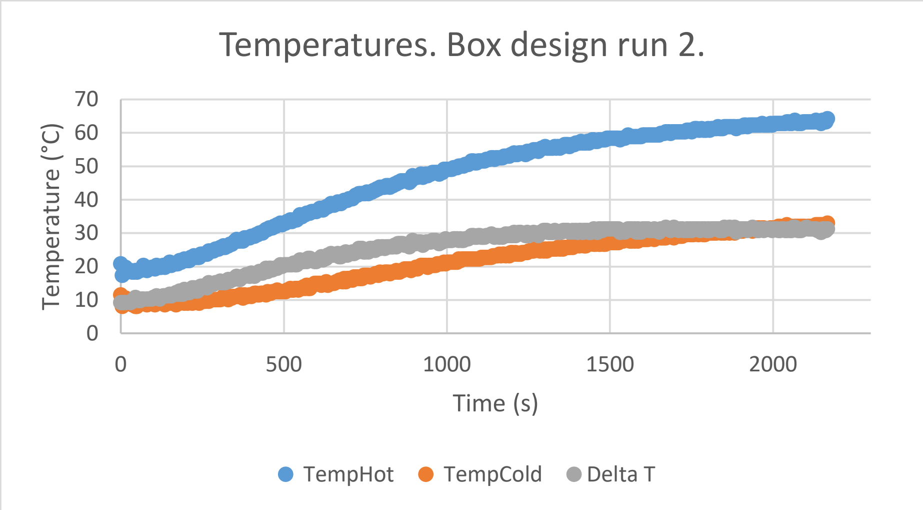

Figure 23: Plot of the hot and cold temperatures and their difference versus time for the box design run

As we can observe form the plot, at some point temperature difference reaches its maximum and stays constant, even though the temperature of the bars keeps increasing. That means that the rate at which cold bar temperature increase is the same as the rate of the hot bar temperature increase. To understand why there is that limit for the maximum temperature difference, I compare the heat transfer rate across the TEG to the heat transfer rate from the TEG to the ice bucket. I use Equation 16 to calculate the heat transfer rate as a function of ΔT. Putting the properties of the TEG and aluminum bar I get the following relationships: $q_{teg}=5.64* \Delta T_{teg}$ and $q_{c.bar}=0.615* \Delta T_{c.bar}$. From these relationships, we see that TEG transfers heat from hot bar to cold bar roughly nine times faster than cold bar is transferring heat from TEG to the ice. This is the reason why the temperature of the cold bar keeps increasing. To achieve and maintain the high temperature difference across the TEG one can choose the bar with better properties or decrease the cold sink temperature. In my case, at some point the temperature difference across the TEG is so high which yields in the very high heat transfer rate to the cold bar. Theoretically, this rate would be equal to the rate of the heat transfer from the one hot bar end to the other end and cannot be greater than that rate. Therefore, the cold bar is heating up at the same rate as the hot bar, so we reach the maximum temperature difference across the TEG.

Studying the Outputs of the TEG

During all the experiments mentioned before, along with the temperatures I was also measuring the open circuit generated voltage. I performed multiple experiments to collect data for the voltage measurements for the open and closed circuits with different loads as well as different arrangements of the TEG. Temperature measurements were performed simultaneously with voltage measurements, so I can use these data to analyze how voltage depends on the ΔT and average temperature.

For all the voltage measurements I used build in reference (5V) in the code for the microcontroller, because I expected that for high temperatures I might get voltage over 1.1V (internal reference limit). Since I am using the 5V reference, referring to figure 14, I have to keep in mind that the measurement close to 1V have uncertainty around 1-2%. However, the uncertainty is rapidly increasing with the decrease of the measured voltage. Therefore, all the analysis is better to do when I have higher voltages.

"Seebeck coefficient" and Voltage Dependence on the ΔT

From the data for the measured voltage and temperatures, I calculate the "seebeck coefficient", using the Seebeck effect Equation 1. In this paper, when I refer to the calculated seebeck coefficient from my data I keep it in quotation marks because it shows the ratio of my measured voltage to my measured temperature. While the real seebeck coefficient is the internal property of the material used in the TEG. I refer to the calculated ratio as a "seebeck coefficient" for my setup. Since I am not measuring temperatures directly on the TEG surface, I do not want to confuse it with my calculated ratio with the actual seebeck coefficient of the TEG, because those quantities might be different. However, the calculated "seebeck coefficient" is very useful in the analysis.

Figure 24 represents the plot of open circuit voltage output and ΔT over time. On this plot it is easy to see that the plot shape voltage output is exactly the same as the shape on the ΔT plot. This shows that my data is good and follows the seebeck effect.

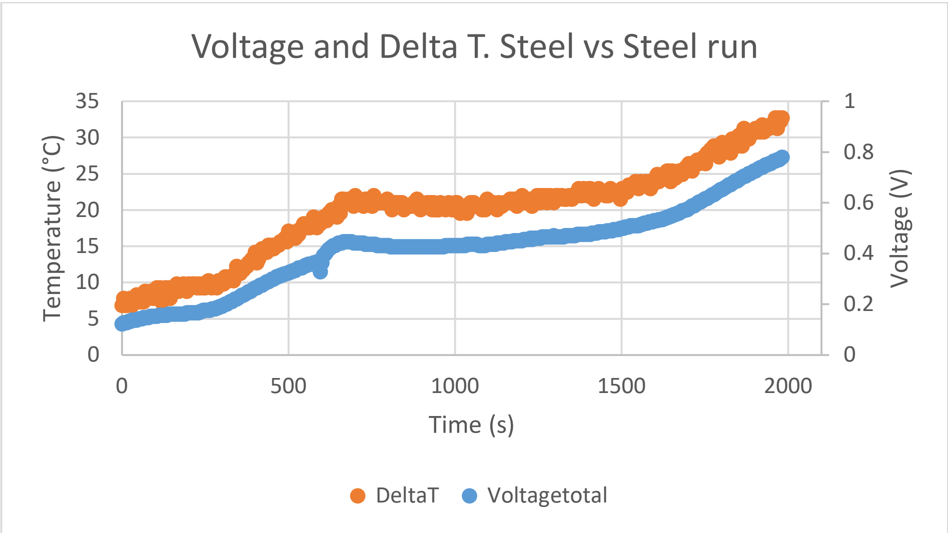

Figure 24: Plot of the voltage output and temperature difference versus time for the Steel vs Steel run.

The plots of the voltage output and ΔT from the rest of the runs show the same behavior. To observe the plots of the voltage and Delta T that are not in the text see Appendixes D, E4, G2.a and G3.a.

For each run, the plots of the voltage output verusus ΔT were made. Such a plot for the Steel vs steel run is represened in Figure 25.

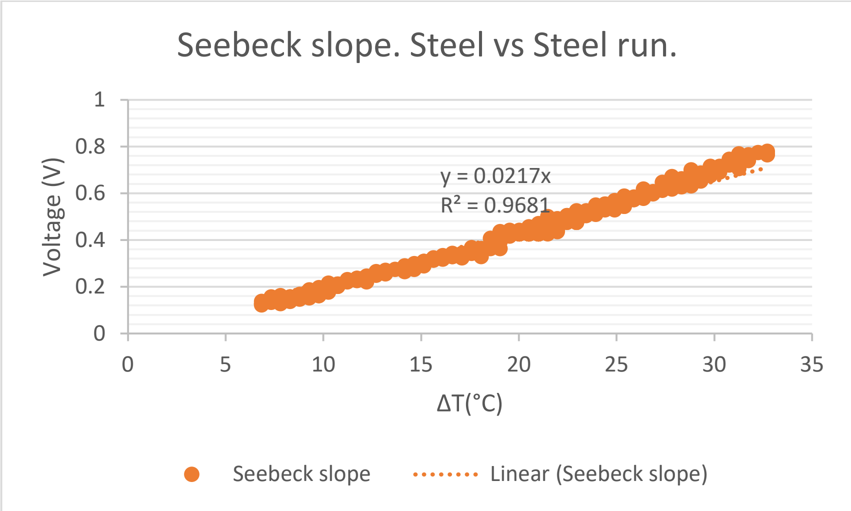

Figure 25: Plot of the voltage output versus temperature difference for the Steel vs Steel run.

Seebeck implies linear relationship between the voltage output and temperature differnece. The oserved data indeed follows the linear relationship. I made a linear fit on the data and I got R^2 value to be 0.9681, which means that the linear fit fits the data very good. If there is not temperature difference, there is no voltage output, so I set linear fit to intercept x axis at zero. The slope of the lenar fit is the “seebeck coeficient” and for this particulat plot is is equal to 0,0217 (V/K). For all the runs I squeeze the clamp as tight as I can, so I get the highest “seebeck coefficient”. If we look at the other plots of the voltage output verus ΔT from the different runs, we observe that the “seebeck coefficient” for almost all runs with a plastic clamp (not box design) is about the same (around 0.021 to 0.025 V/K). This means that I was able to maintain the same physical contact for all the runs. If the “seebeck coefficient is around the above mentioned range that means that some of my data are not valid or I have the clamp is not tight enough. For example, for the Steel vs steel + aluminum run we get a “seebeck coefficient” of 0.0453, which is much higher than I expect. This tells me that something went wrong during that data collection; therefore, I do not consider these measurements valid.

“Seeback coefficient” is a constant, so I expect it to stay the same throughout the whole measurement time. Figure 26 shows the plot of he “seebeck coefficient” over time for the same Steel vs steel run. From the data, we observe that “seebeck coefficient is slightly increasing over time. The same trend is observed for all the runs. See Appendixes E4, G2.b, G3.b, H5 and

I1 for the plots of the Seebeck slope or "seebeck coefficient" vs time that are not shown in the text.

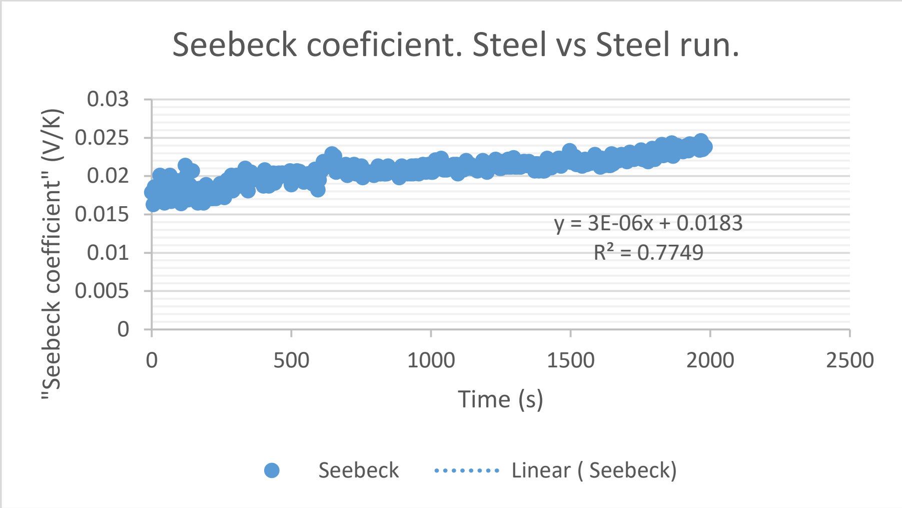

Figure 26: Plot of the "seebeck coefficient" versus time for the Steel vs steel run.

I used tape to attach the temperature sensors to the bars. My hypothesis on why "seebeck coefficient" is increasing over time is that on the high temperatures tape loses its grip, so I do not get a good physical contact between the sensor and the bar. Therefore, the measured temperature is lower than the actual temperature, which increases the "seebeck coefficient".

Since better physical contact results in the higher voltage, I consider the setup with higher "seebeck coefficient" to be more effective and closer to the "ideal" setup.

Voltage Dependence on the Load and TEG's Arrangements

To study the closed circuit TEG outputs I made the following two runs: Parallel vs series with different loads run (PvsS run) and 10000 Ohm long run. Some of the plots for the both runs are missing few points of data. I deleted the data that were completely out of the range (for example 0 for voltage measurement) or were affected by me (for example changing the circuit). For the PvsS run I use the setup similar to the "master" setup but there are two TEG's in between the bars: TEG1 closer to hot side and TEG2 closer to cold side. The photos in Appendixes H1, H2 and H3 show the setup for the PvsS experiment. Each TEG has its own hot and cold temperature sensors and plastic clamp. I choose to measure temperature difference on the two TEG's separately because from the previous experiments I learned that heat conductance might produce a big difference in temperatures over the small distance. The code that I used for the data collection for this experiment can be found in Appendix H4. Indeed, the results show that temperatures across the TEG1 and TEG2 are significantly different. Figure 27 shows the plot of the temperatures for the full PvsS run.

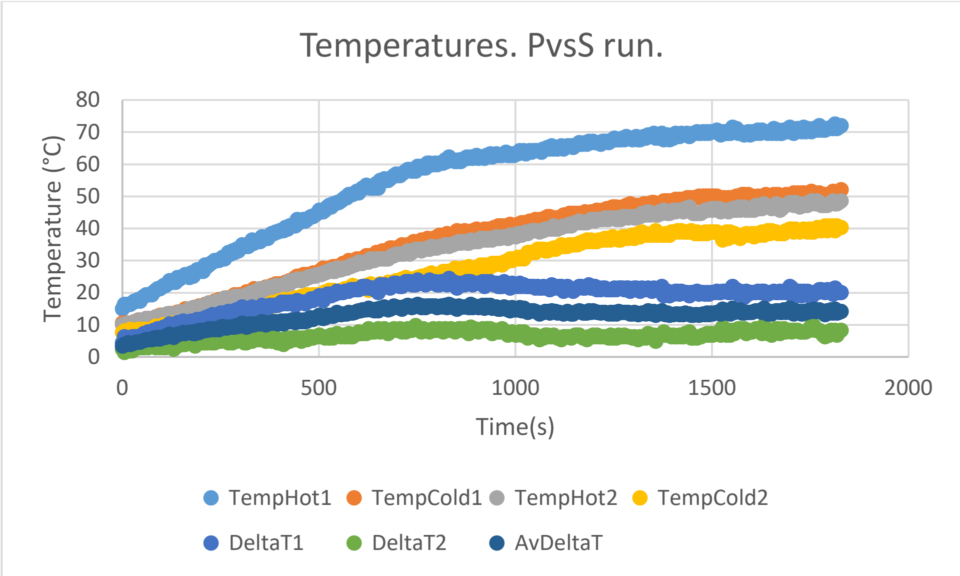

Figure 27: plot of the hot/cold and delta temperatures for TEG1 and TEG2 versus time for PvsS run.

From the plot above, we can observe that the hot side of the TEG2 has even lower temperature than the cold side of the TEG1. This is a very big difference; therefore, measuring temperatures for two TEG's separately was a right decision. Since I am getting the total voltage output from both TEG's, I use the average of the two temperature differences for the "seebeck coefficient" calculations. Since I have to measure ΔT for each TEG, I cannot measure data for more than two TEG's because my microcontroller board has only six analog pins. When I have two TEG, I use four analog pins for temperature sensors and one for voltage measurement. If I wanted to measure data for three TEG's I would need seven analog pins. In addition, we observe that when I have two TEG's I get very small temperature difference, because there is twice more heat conducted from hot bar to cold bar through the TEG's. Adding the third TEG to my setup would dramatically decrease the efficiency of my setup in terms of creating the temperature difference across the TEG's. Therefore, my analysis is limited to studying of maximum two TEG's connected together.

I measured both open circuit generated voltage as well as voltage across the resistor for the closed circuit. When I am measuring the open circuit voltage, I just measure the potential difference between the positive and negative sides of the TEG. During open circuit measurements positive and negative sides are not connected, so there is no current flowing. Some generators are generating current that creates potential difference. However, it is important to understand that TEG is generating voltage that drives the movement of the electrons in the circuit when the loop is created. TEG can be treated like a battery which potential is dependent on the temperature.

The PvsS run has several blocks of data. Over time, I was changing the configuration of the circuit, to get multiple data collections for different loads and TEG's arrangements. The data for this run can be divided in two sets: TEG's in series and TEG's in parallel. The closed circuit consists of the two TEG's in series or in parallel and the resistor. I measure the voltage across the resistor and I expect it to be less than the open circuit measured voltage because the total resistance consists of the TEG internal resistance and the load resistance. Therefore, the voltage across the resistor should be the some fraction of the open circuit voltage. The bigger the load resistance the bigger fraction of the open circuit voltage I expect to measure, which means that I am getting lower total current. As it was discussed in the theory section, when I put two TEG's in series, I double the total generated voltage, while total current stays the same and when I put two TEG's in parallel, I double the total generated current, while voltage stays the same.

The TEG's in series set has blocks of open circuit (2x) and the closed circuit with 220ohm (2x), 10kohm and 1kohm resistors. I start with getting data of the open circuit voltage output. For this set of data, I extract the "seeback coefficient" from the slope of the voltage versus average ΔT plot and I got 0.0569 V/K. See Appendix H5 for the Seebeck slope plot. Since two TEG's are in series, I expect to get double the voltage comparing to the measurement I did with only one TEG, therefore I expect double the "seebeck coefficient". For one TEG, I usually get the "seebeck coefficient" around 0.023 V/K and the "seebeck coefficient" for this run is bigger than the double of that. I think that the reason for this increase is that I have two clamps holding the structure together, so I might get better physical contact between the bars and the TEG's, what increases the efficiency of my setup (I get more voltage for the same ΔT). Therefore, I decide that using the average ΔT for my further calculation is reliable.

Figure 28 represents the plot of voltages for multiple blocks of data versus time. Voltage depends not only on the resistance but also on the ΔT across the TEG. Therefore, I added the graph of the ΔT versus time on the same plot, so we can observe both resistance and ΔT voltage dependence on the same plot. I made a plot of the "seebeck coefficient" for the series set of data (located in appendix), which implies both ΔT and resistance changes on one graph, but on that plot it is harder to observe the places where I changed the resistors. Each color graph represents the data for voltages for different blocks of measurements. On the plot we can observe that while I was getting data for voltage output, the ΔT was slightly decreasing, therefore voltage generated by the TEG was also degreasing. I collected data for the 220ohm resistor twice, in the beginning and at the end of the series set measurements. On the plot, we can observe that the second block of data for 220ohm resistor has lower voltage than the first block of data.

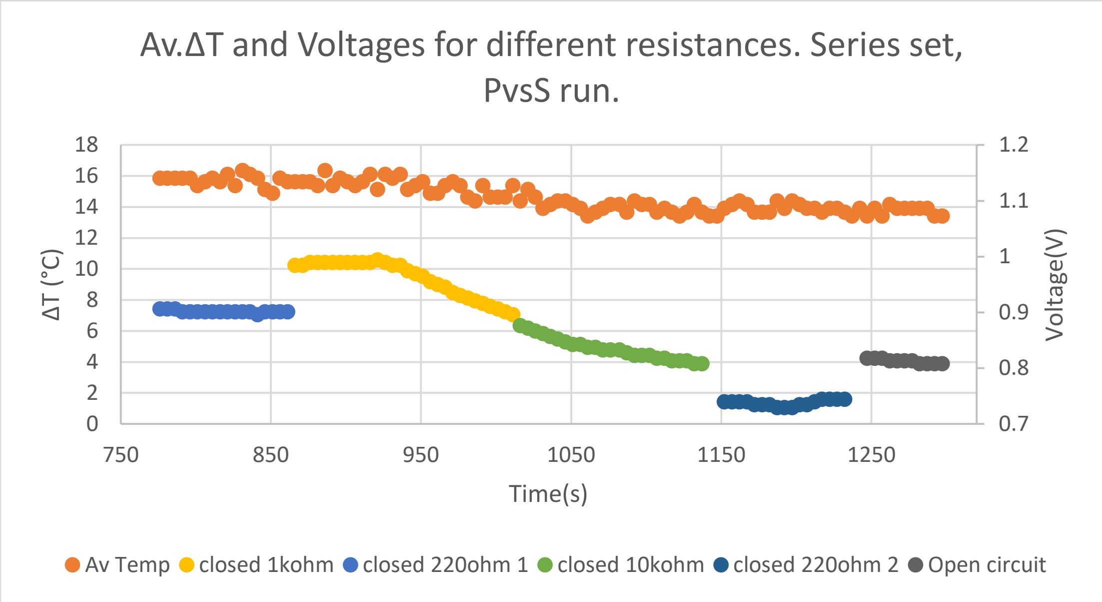

Figure 28: plot of the closed circuit voltages for different resistances, open circuit voltage and ΔT versus time for the series set of measurements of the PvsS run.

By looking at the ΔT graph, we can conclude that this difference is caused by the decrease of the ΔT across the TEG. The most important observation for the data on this plot is that we can see sudden changes in voltage output when I change the resistance of the load. Since the total generated voltage is decreasing over time, we can compare only consecutive blocks of data. There are clear "jumps" between 220ohm blocks and its consecutive blocks. Between the 10k and 1k blocks, we cannot see a clear jump, because at this time total generated voltage was also relatively rapidly decreasing. However, we can still see a small "jump" down after I switched 10kohm resistor to 1kohm resistor. The voltage output for 220ohm blocks was always lower than voltage output for higher resistances or open circuit voltage measurements.

For the parallel set of measurements, I gathered data only for 3 blocks: 220ohm resistor, 10kohm resistor and open circuit. The photo in the Appendix H6 shows the wiring on the breadboard for two TEGs connected in parallel. The plot of the ΔT and voltage outputs for parallel set of measurements over time is shown on Figure 29. It is important to mention that since I am getting low voltages for the parallel configuration of the TEG's I have a much higher uncertainty for these voltage measurements. According to the Figure 14, for the 0.35-0.4 measured voltage, the uncertainty is around 3-4%. Therefore, the data for the parallel arrangement is not as accurate as for the series arrangement. For the 220ohm block there is a weird rapid increase of voltage. There is no big change in ΔT, so this rapid change should be caused either by increase of physical contact between the TEG's and the bars (clam applied more pressure), or change in the resistance of the load (something external affected the resistance of the resistor).

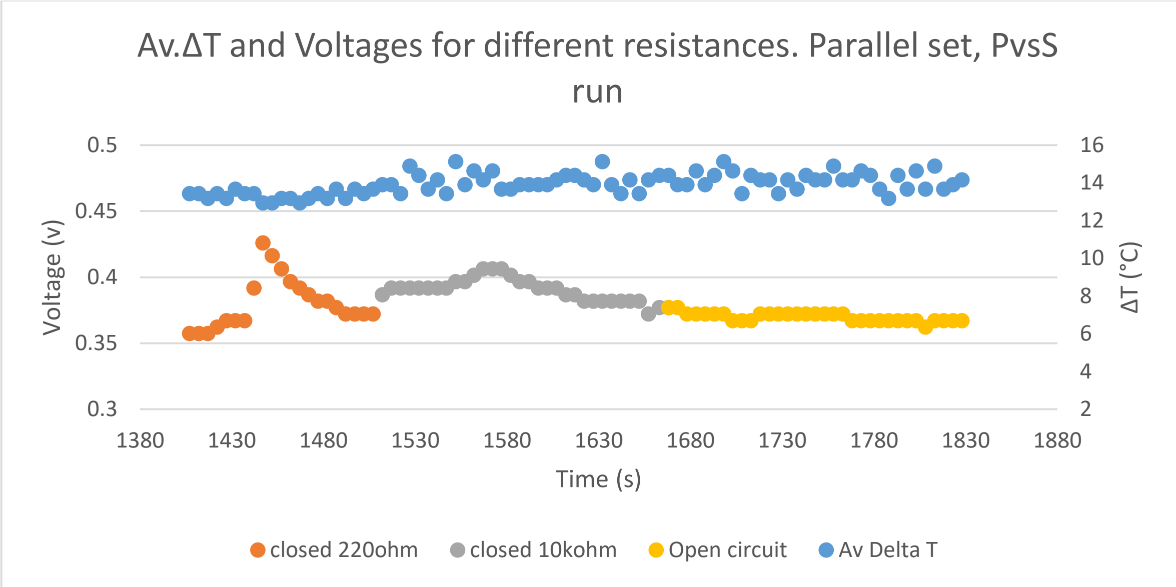

Figure 29: plot of the closed circuit voltages for different resistances, open circuit voltage and ΔT versus time for the parallel set of measurments of the PvsS run.

However, we can still observe a "jump" up at the time when I changed the 220ohm resistor to the 10kohm resistor. The "jumps" of the voltage outputs for the parallel set of measurements are harder to see, because the generated voltage from the TEG's is lower. There is no "jump" obsereved in between 10kohm closed circuit and open circuit voltage measurements and the reason for that is explained later in the paper, when I talk about the internal resistance of the TEG.

The data from the PvsS set is useful to compare generated voltage of the TEG's in series and in parallel. Since total generated voltage depends not only on the arrangements of the TEG's but also on the ΔT across the TEG's, I compare "seebeck coefficients" for both sets of data. In other words, I compute the ratio of the average generated voltage over the average average ΔT across the TEG. I calculate the average "seebeck coefficients" of the open circuit measurements for the two TEG's connected in series and in parallel. The average "seebeck coefficient" for the series arrangement is 0.0579 V/K, while for parallel arrangement I got 0.0261 V/K. The ratio of the two average is 2.22, which is higher that the expected ratio of 2. However, we discovered earlier that over time the "seebeck coefficients" for my data is increasing over time due to the decrease of the physical contact between the temperature sensor and the hot bar. The series set measurements were done before the parallel set measurements.

Therefore, the fact that computed ratio is bigger that 2 makes sense because of the gradual increase of the "seebeck coefficient" for my measurements over time.

The observations of the voltage outputs for different loads for both series and parallel arrangements support my theoretical expectations. In addition, the computed ratio of the "seeback coefficient" for the series and parallel sets of measurements agrees to the expected ratio. Therefore, I conclude that TEG's are operating the way the theory predicts and my collected data is valid.

TEG's Average Temperature Effect on the Generated Voltage

In the theory section of the paper, I discussed that the increase of the average temperature of the TEG causes the internal resistance of the TEG to increase. I preformed data collection for the 10kohm long run to observe how is voltage output changing over time and comparing it to ΔT change and average temperature change. For this run, I made a closed loop with 10kohm resistor connected to the TEG. I choose a bigger resistor for this run because it is easier to observe changes in the bigger voltages than in the smaller voltages. Towards the end of the run, I switched 10kohm resistor to 220ohm resistor for some time and then I also got some data for the open circuit. I did it, so I can get more data on how voltage is dependent on the load resistance. The code for this run is the same as the code for the all the measurements with one TEG (see Appendix E3). I made plot of the open circuit voltage, closed circuit voltages for 10kohm, 220ohm and ΔT versus time for 10kohm long run. I indeed observed the same "jumps" as I observed for the PvsS run.

After a certain time since I started getting the data I noticed that I am not getting as much voltage as I usually do and I my "seebeck coefficient" was in the range on 0.011-0.013 V/K, which is smaller than it is supposed to be (around 0.023 V/K). Therefore, I tightened the clamp on the bars and I observed higher voltage measurements. On the plot of the "seebeck coefficient" versus time, which can be found in the Appendix I1, there is a place at around 950 seconds when the "seebeck coefficient" rapidly increased. This is when I tightened the clamp. I am not doing data analysis on the data for the time range in between 900 and 1200 seconds, because data is affected by me touching the setup, so this data is not valid.

In order to see whether the average temperature affects the voltage output I create the graphs of the average temperature, measured voltage and ΔT over time on the same plot. I have to include ΔT in the plot because measured voltage always depends on the ΔT across the TEG. I choose three blocks of data to plot: increasing, steady and decreasing ΔT and average temperature. It would be great to look at the area where ΔT stays constant, while average temperature is still increasing, but unfortunately this is exactly the area where I said data is not valid. Indeed, the plots for this area are not informative because voltage readings are not consistent. Figure 30 shows the plot for the area where ΔT and average temperature are both increasing.

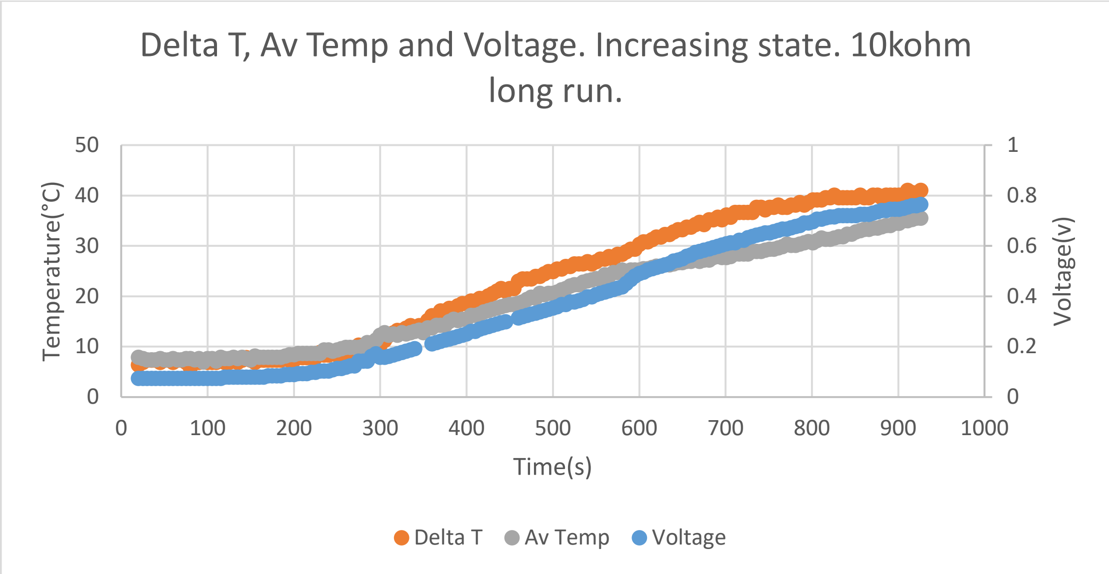

Figure 30: plot of ΔT, average temperature and voltage versus time for the increasing state of the 10kohm long run.

Up to around 600 seconds ΔT, average temperature and voltage graphs are correlated. However, after 600 seconds we observe that average temperature started to increase on the slower rate, while the rate of the ΔT stayed the same. Exactly at the same point the voltage started to increase faster. Therefore, from this plot we can observe that when the average temperature is smaller, I get more voltage generated by the TEG. This data agrees with the theory, because lower average temperature means lower internal resistance of the TEG, therefore it is easier for the electrons to flow through the TEG and I get higher potential difference. Figure 31 shows the area of the somewhat steady ΔT and average temperature measurements. I adjusted the scaling of the temperature and voltage axis so there is an area of the plot where the voltage graph is superimposed on the ΔT graph. The part of the plot where voltage and ΔT graphs are superimposed clearly shows that voltage is directly dependent on the ΔT. Graph of the voltage has all the same little “bumps” that ΔT graph has. The average temperature for this set of data is higher on one side of the plot and smaller on the other side of the plot. On the right side of the plot, ΔT and voltage graphs are superimposed. On the left side of the plot, average temperature is higher, and the voltage graph is below the ΔT graph; however it still follow ΔT graph pattern. The data agrees with the theory, because for the higher average temperature we observe lower generated voltage

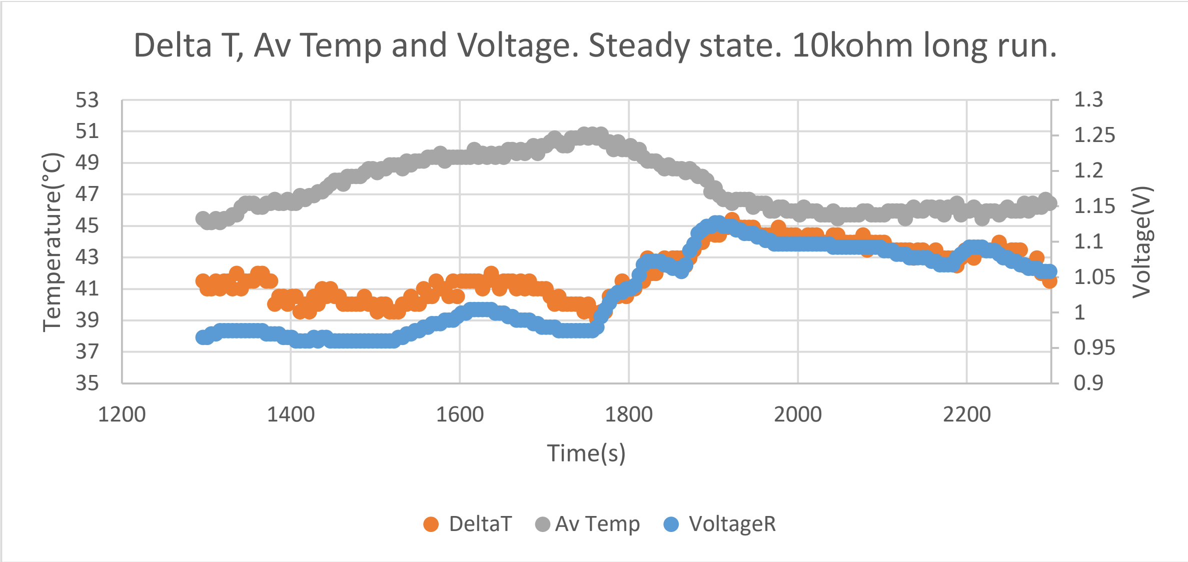

Figure 31: plot of ΔT, average temperature and voltage versus time for the steady state of the 10kohm long run.

. Form the plot we can say that ΔT determines the shape of the voltage graph, while average temperature acts as a scaling factor on the voltage graph. The fact that voltage measurements changes have a strong correlation with the ΔT measurements shows that voltage is mostly depended on the ΔT, which is what we expect from the Seebeck effect. The plot for the third block of data (decreasing state for 220ohm) is located in the Appendix I2. The data for this set of measurements is very clear and does not have any "bumps". This plot clearly shows how the increase of the average temperature makes the voltage decease on the faster rate than the decrease of the ΔT.

All three blocks of data prove that TEG's generated voltage is affected by the average temperature of the TEG. Therefore, TEG is more efficient when it is operated in the lower temperatures than in the higher temperatures for the same ΔT.

Calculating the Resistance of the TEG

In the theory section, I mentioned that we cannot measure the resistance of the TEG with the multimeter. However, I introduced the way to calculate the internal resistance of the TEG, if we know the open circuit generated voltage and the closed circuit voltage across some resistor. Since voltage is always dependent on multiple factors like ΔT and average temperature, ideally the measurements of the voltages for the calculations should be taken when there is constant ΔT and average temperature. However, it is hard to achieve with my setup. Therefore, I chose to take of the data where the voltage measurement of the open circuit and voltage measurement across the resistor are within a short amount of time (5-20 seconds). Such an approach is good, because even if there is a change in the average temperature or ΔT it is very small and we can neglect it. The data from the PvsS and 10kohm long run has places where I switched from the closed circuit measurement with the resistor to the open circuit measurement and vice versa. I can use the last measurement of the voltage before the switch and the first measurement right after the switch to calculate the internal resistance. The Equation 10 is used for the calculations of the internal resistance. During the PvsS run, when I had two TEG's connected in series, at 1240's second I switch from measuring the voltage across the 220 ohm resistor to measuring the open circuit voltage. The voltage across the resistor right before the switch was 0.7493 V and the voltage of the open circuit voltage right after the switch was 0.8179 V. These numbers result in the 20.14 ohm calculated total internal resistance of the TEG's. Since I have TEG's connected in series, the internal resistance of one TEG is half of the total internal resistance – 10.07ohm. The average temperature at the time of these measurements was 48.27 °C and ΔT was 13.92°C. During the 10k ohm long run, where I had only one TEG connected, at 2678's second I switched from measuring the resistance across the 220ohm to measuring the open circuit voltage. The voltage across the resistor was 0.9354V and open circuit voltage was 0.9697V. These numbers result in the 8.06ohm calculated internal resistance of the TEG. The average temperature at the time of the measurements was 50.83 °C and ΔT was 36.62°C. Two calculated internal resistances of the TEG have a discrepancy of 20%. Even though both analyzed measurements had almost the same average temperature, the measurements from the 10kohm long run had almost three times higher ΔT across the TEG, so the generated voltage is smaller therefore it has higher uncertainty, which may have caused such a high discrepancy.. In addition, those the measurements are from the two independent runs, which do have different strengths of the physical contact. As it was mentioned earlier, 10kohm long run had two claps holding the setup, and we observed that "seebeck coefficient" for this run was higher than for the other runs. Higher pressure on the TEG's might have increased the resistance of the TEG's.

During the PvsS run, when I had TEG's in parallel, I also had a spot when I switched from measuring the voltage across the 10kohm resistor to measuring the open circuit voltage. However, there the voltage output did not change. I calculated that the resistance of one TEG during that run was 10.07ohm. When TEG's are connected in parallel, the total resistance is halved, so the total internal resistance was 5.04ohm. If I say that we know the open circuit voltage, which for that run right after the switch was 0.3771V, I can use equation 10 to calculate the expected voltage across the 10kohm resistor and I get 0.3767V. The difference in the voltages is very small, and during these measurements the temperature was not very steady and had fluctuations. The voltage might have been affected by the temperature change, so it was hard to observe such a small temperature change.

Since the internal resistance is small, having the bigger load resistance would decrease the effect of the internal resistance change to the generated voltage. The calculations and observations of the internal resistance of the TEG show that if the application requires steady voltage output, but there are big average temperature differences with constant ΔT, one has to put bigger load to reduce the effect of the changing internal resistance.

TEG's Generated Current and Power Dissipated on the Load

Since microcontroller cannot measure current, I did not measure the generated current directly. However, I measured the voltage across the known resistances, so I calculated the current. I use measured voltage and calculated current to compute the dissipated power across the resistor. In the theory section, I mentioned that in order to have maximum power dissipated across the load, I have to match the load resistance with the TEG internal resistance. We calculated the resistor to be 8-10ohms, which means that 220 ohm resistor is closer to the impendance matching than 10kohm resistor, therefore I expect more power dissipated across the 220 ohm resistor.

For the calculations, I take data form the 10kohm long run at the time when I switched from the 10k ohm resistor to the 220 ohm resistor. The measured voltage across the 10kohm resistor right before the switch was 1.053V and the calculated current was 0.1053mA. The measured voltage and calculated current for the 220 ohm resistor right after the switch were 0.991V and 4.541mA. I calculate power using the P=VI formula and I get 0.1109mW across the 10kohm resistor and 4.5mW across the 220 ohm resistor. Indeed, I get higher power dissipated across the load that has closer resistance to the TEG's internal resistance.

It would be very interesting to make measurments with the higher, lower and same load resistance as the internal TEG resistance, to observe the maximum power dissipated. However, I would have to either use a very small resistor (below 20ohms) and the potential across that resistor would be very small, which would involve high uncertainty and would be just hard to measure precise with the microcontroller. Alternatively, I would have to add more TEG's in series to increase the total internal resistance, but my setup is not design for many TEG's.

Improvements

This project consisted of the two main areas of analysis – heat transfer/setup design and TEG's outputs. In this section of the paper, I am introducing the ideas of improvement for data collection and setup design as well as what other experiments could have been performed to do get a better data for the TEG's outputs

Improvements of the Setup Design

Computational analysis of the heat transfer for my setup showed that my setup did not have an efficient cooling for the cold side of the TEG. As I mentioned earlier, the bar that I was using was not long enough, so just using a longer bar would already increase the efficiency of my setup. There are several more ways to increase the rate of the heat transfer from the TEG. I used ice that was in the chunks, therefore most of the time not all area of the bar had a physical contact with ice. If I used smaller pieces of ice that should increase the heat transfer rate. Decreasing the "cold bath" temperature would also increase the heat transfer rate. For example, liquid nitrogen would be a very effective for the cooling. In addition, according to the conductive heat transfer equation, increasing the cross sectional area of the bar, also increases the rate of the heat transfer. Therefore, a thicker metal bar would increase the efficiency of my setup. If I had thick metal bar, I would be able to drill a hole in the bar, so I can place the temperature sensor inside the bar. Such an approach would increase the accuracy of the temperature readings. Another way to increase the efficiency of the setup is to use the thermal grease in between the TEG and the bars, to increase thermal contact between the TEG and the bars.

Experiments that Would give More Data:

Looking at my analysis for the TEG's internal resistance, I think that that would be beneficial to perform an experiment where I measure temperature and keep switching between measuring open circuit voltage and voltage across different resistor. Such an experiment would provide me with a data from which I could perform multiple calculations of the internal resistance of the TEG. That would be interesting to see graphs of internal resistance and average temperature of the TEG versus time on the same plot. In addition, preforming multiple runs like the one described above with different pressure applied to the TEG would answer the question if the internal resistance depends on the pressure applied to the TEG. In addition, the collection of multiple calculated internal resistances for one TEG, would give me an opportunity to get a precise estimate of the TEG's internal resistance.

If I had more efficient setup, I would be able to get higher and more precise measurements of the voltage output; therefore, I could have more reliable data for the measurements of the parallel arrangements of the TEG's. In addition, higher total generated voltage would allow me to measure resistance across the small load resistances, so I could perform the impedance matching experiment and more closely study the power dissipated across the various resistors. Impendence matching implies that I should get highest power dissipated across the resistor equivalent to the internal resistance of the TEG. Therefore, the data from the impendence matching experiment could be used to compute the internal resistance of the TEG, which could be compared with the internal resistance data that I got using an open/closed loop technique.

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Conclusion

Originally, I wanted to study the thermoelectric generator depending on the outputs design an application of the TEG for everyday life. However, I faced the problem even creating an experimental setup for the TEG is a challenge, because it is hard to create high and steady temperature difference across the TEG. I had to perform an additional research on the heat transfer and discovered that the heat conduction through the TEG is much higher than I expected, therefore I need much better cooling system for the TEG’s cold side. Based on the heat transfer observations and calculations I created the most effective setup from the materials that I had. The measurements of the voltage outputs under different circumstances like different load, TEG’s arrangement and temperature equipped me with data to perform the analysis on the TEG’s outputs. I found out that total generated voltage depends not only on the temperature difference across the TEG, but also the average temperature of the TEG. In addition, I learned that physical contact between the TEG and the hot/cold source influences the generated voltage a lot; therefore, it affects the effectiveness of the setup. I used the data to calculate the internal resistance of the TEG I also observed an expected voltage measurements and dissipated power for the different loads and TEG’s arrangements, so I conclude that my setup works properly and the technique I use for the data collection is reliable. This paper is a great guide for someone who wants to learn about TEG’s and or consider using TEG’s for their applications.

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Appendix A: Temperature Sensor test code

This appendix includes the code that was used for the data collection for the temperature sensor test.

```
//assigning pin for the temperature sensor
int temppin=0;

void setup() {
Serial.begin(9600);
Serial.println("CLEARSHEET"); //setup so PLX-DAQ receives data.
Serial.println("CLEARDATA"); //aka talking to PLX-DAQ
Serial.println("LABEL, TimeElappsed, TempC, TempF"); //Label the columns in the Excel spreadsheet
Serial.println("RESETTIMER");
}

void loop() {
Serial.print("DATA,"); //PLX-DAQ knows that it will receive data

unsigned long ElapsedTime=millis(); //Reads how much time has elapsed since the beggining of he experiment
ElapsedTime=ElapsedTime*0.001; //convert milliseconds to seconds

int temp=analogRead(temppin); //Readiag data from the hot sensor. Stored as a 10bit number
float voltage = temp * 5.0/1024;
float tempC=(voltage - 0.5) * 100; //Converting 10bit number to the temperature.

float tempF=((tempC*9/5)+32); //Convert to Fahrenheit
//print data. Separate data print outs with by comma, so PLX-DAQ recognizes it as separate data
Serial.print( ElapsedTime ); //print how much time elapsed since the beginning of the experiment
Serial.print(",");
Serial.print( tempC ); //print the temp in Celsius
Serial.print(",");
Serial.println( tempF ); //print temp in Fahrenheit

delay(1000); //repeat the loop every second (take data every second)

}
```

Appendix B: Voltage readings tests codes and pictures

This appendix includes the codes that were used for the data collection for the voltage readings tests as well as pictures of the experimental setup.

1. The code for the regular voltage reading

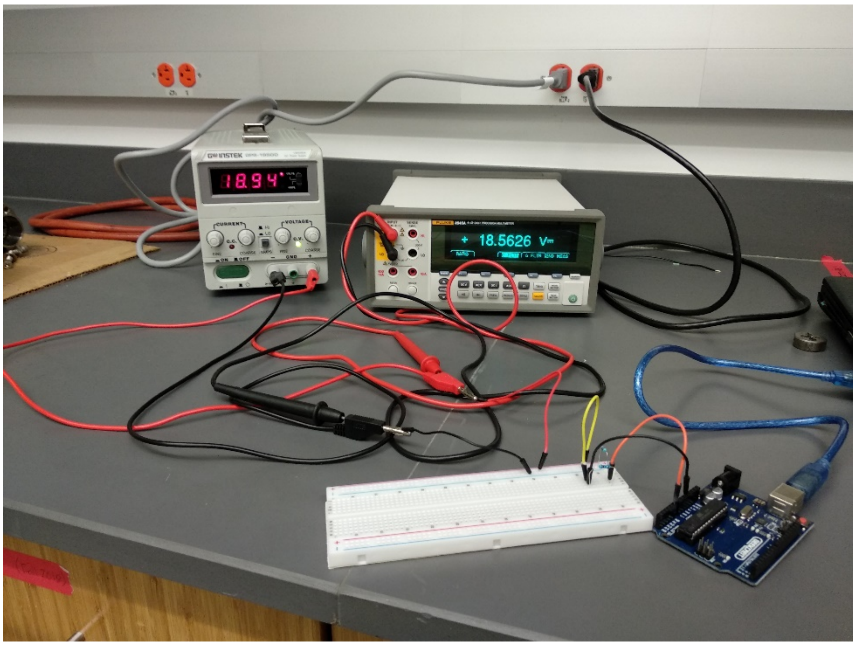
```
void setup() {
// initialize serial communication at 9600 bits per second:
Serial.begin(9600);
Serial.println("CLEARSHEET");//setup so PLX-DAQ receives data.
Serial.println("CLEARDATA");
Serial.println("LABEL, Time, Voltage,");//Name labels for columns in Excel
Serial.println("RESETTIMER");
}
void loop(){
Serial.print("DATA,"); // //PLX-DAQ knows that it will receive data
int sum = 0;
for (int i=0; i<30; i++) {
sum=sum+analogRead(A2); //for loop to sum 30 measurements
}
float average=sum/30; //get average of the 30 measurements (better precision)
float Vs = average * (5.015 / 1024); //voltage reading from the TEG
// Convert the analog reading (which goes from 0 - 1023) to a voltage (0 - 5V):
unsigned long Time=millis()/1000; //how much time has elapsed
// print out the value you read:
Serial.print(Time); //print time elapsed
Serial.print(",");
Serial.println(Vs,5); //print total voltage with 5 decimals
//separate data print outs with by comma, so PLX-DAQ recognizes it as separate data
delay (1000);//repeat the loop every second (take data every second)
}
```

2. The code for the voltage reading with the voltage divider circuit

```
void setup() {
// initialize serial communication at 9600 bits per second:
Serial.begin(9600);
Serial.println("CLEARSHEET");//setup so PLX-DAQ receives data.
Serial.println("CLEARDATA");
Serial.println("LABEL, Time, Voltage,");//Name labels for columns in Excel
Serial.println("RESETTIMER");
}
void loop(){
Serial.print("DATA,"); //PLX-DAQ knows that it will receive data
int sum = 0;
for (int i=0; i<30; i++) {
sum=sum+analogRead(A2); //for loop to sum 30 measurements
}
float average=sum/30; //get average of the 30 measurements (better precision)
float voltageR2 = average * (5.015 / 1024); //voltage reading across R2
// Convert the analog reading (which goes from 0 - 1023) to a voltage (0 - 5V):
float Vs =( voltageR2 * 10.2)+voltageR2; //Total voltage calculations
//R1 and R2 ratio is 10.2, therefore V across R1 is V for R2*Ratio
//Total voltage is the sum of voltages across both resistors
```

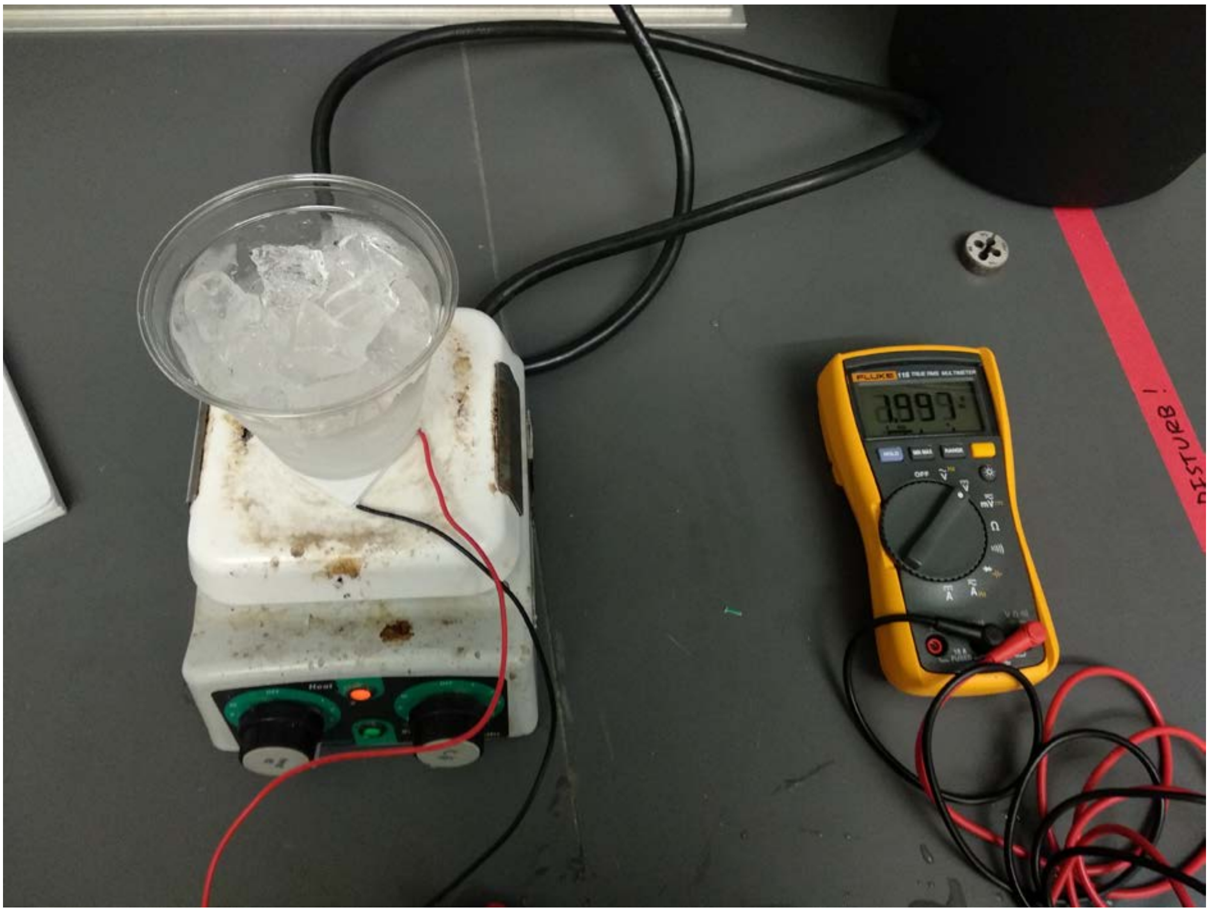
```
unsigned long Time=millis()/1000; //how much time has elapsed
// print out the value you read:
Serial.print(Time); //print time elapsed
Serial.print(",");
Serial.println(Vs,5); //print total voltage with 5 decimals
//separate data print outs with by comma, so PLX-DAQ recognizes it as separate data
delay (1000);//repeat the loop every second (take data every second)

}
```

3. **The picture of the experimental setup for the voltage readings with the voltage divider circuit**



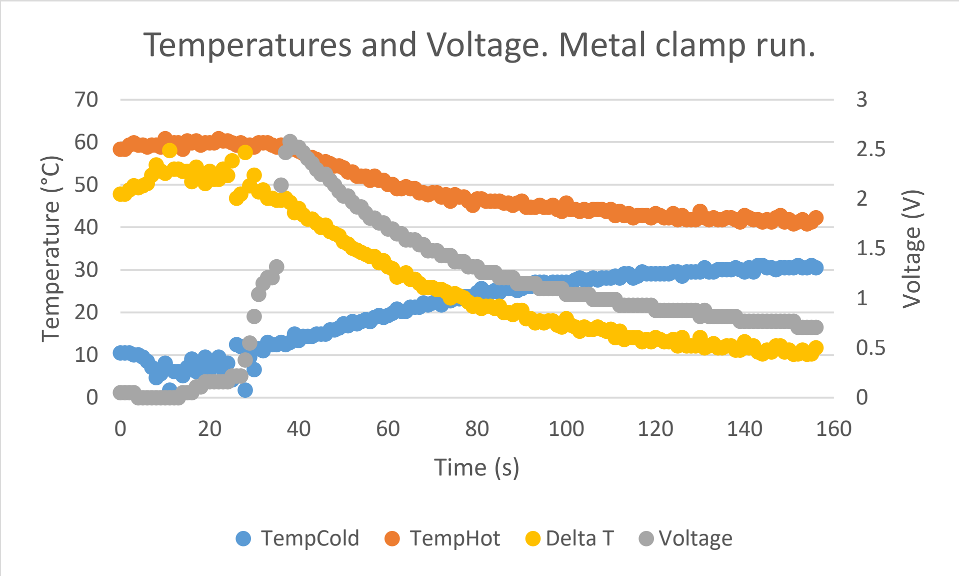
Appendix C: A photo of the Simple TEG test.

This photo was taken during preforming the measurements when I had plastic cup with ice on the cold side of the TEG and hotplate on the increment of four on the hot side of the TEG.



Appendix D: Metal clamp run graph

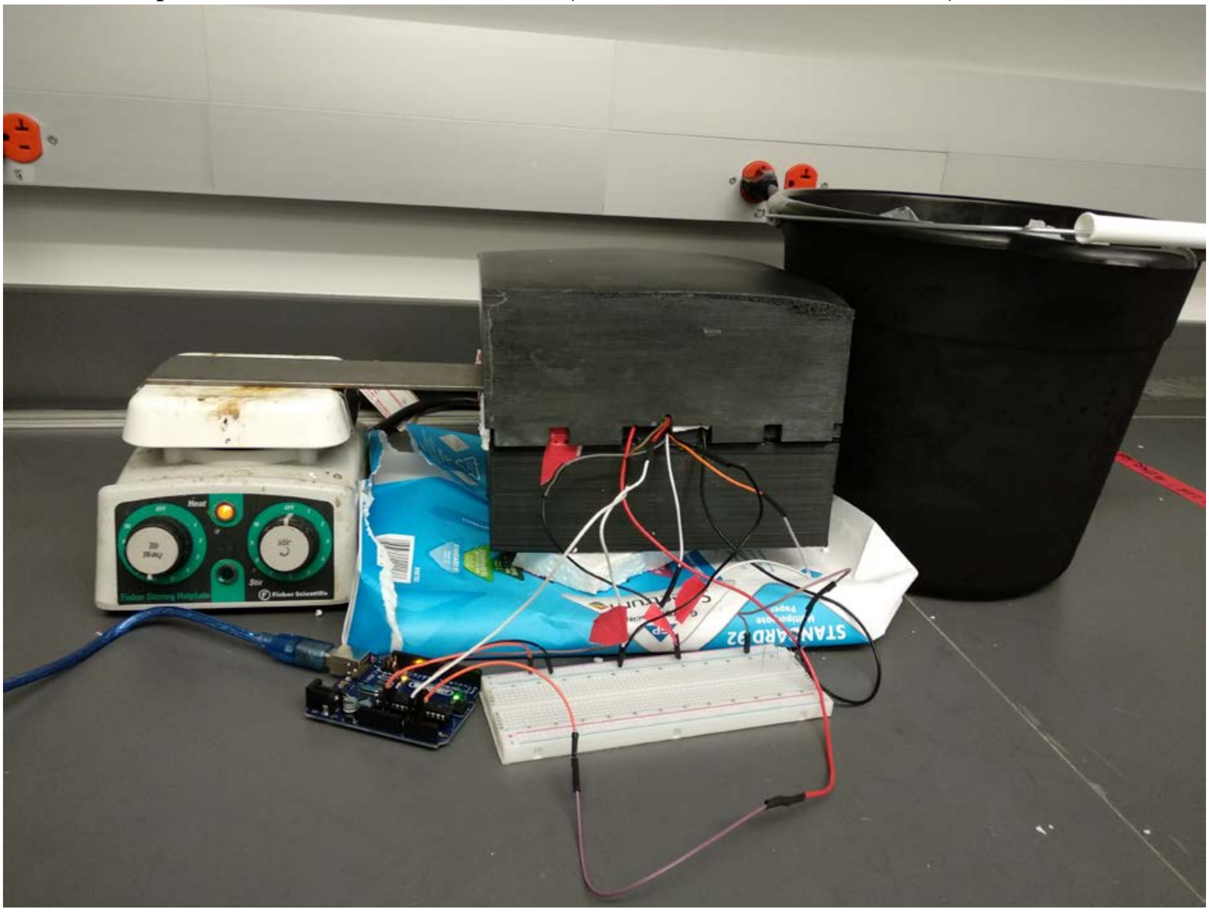
This plot shows how fast the heat was exchanged in between the bars through the metal clamp. This resulted in fast decrease in the temperature difference, which resulted I the fast decrease of the generated voltage. Therefore, metal clamp dramatically decreases the efficiency of the setup.



Appendix E: Supplementary materials for the Box design run.

1. **3D rendering**
2. **Photo of the setup**

   This photo shoes the setup for the box design run. I have the setup as close as possible to the ice bucket, so I ensure the best cooling I can make for the setup. I also had to put paper stack and Styrofoam block under the box, to level up the TEG in the box with the hotplate and the hole in the bucket (to insert the bar in the bucket).



3. **The code for the Box design run**

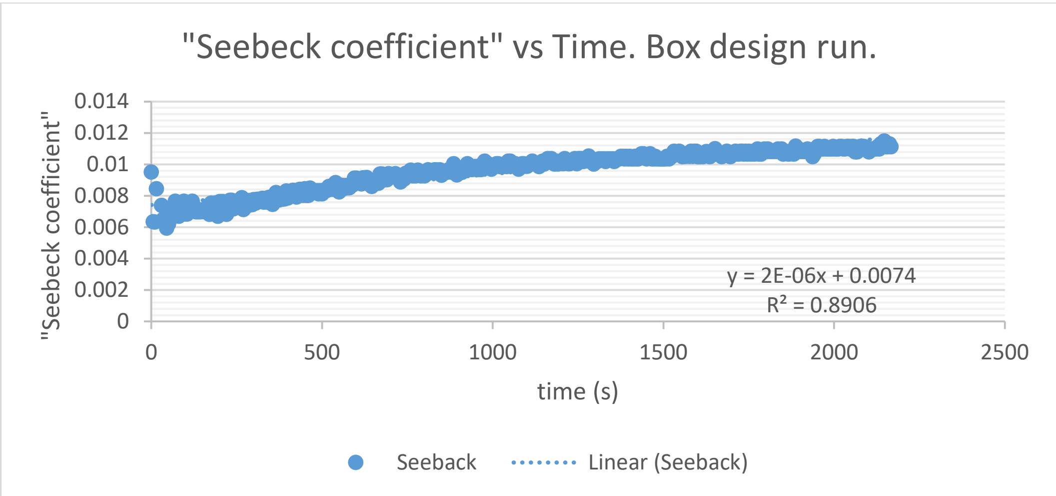
This code was used for all the measurements that involved only one TEG.

```
//assigning variables
int temppinhot=0;
int temppincold=1;

void setup() {
Serial.begin(9600);
Serial.println("CLEARSHEET"); //setup so PLX-DAQ recieves data.
Serial.println("CLEARDATA"); //aka talking to PLX-DAQ
Serial.println("LABEL, TimeElappsed, TempHot, TempCold, Voltagetotal, DeltaT, , Seebeck");
Serial.println("RESETTIMER");
}

void loop() {

Serial.print("DATA,"); //PLX-DAQ knows that it will receive data
```

```
unsigned long ElapsedTime=millis(); //Reads how much time has elapsed since the beginning of the experiment
ElapsedTime=ElapsedTime*0.001; //convert milliseconds to seconds

int temphot=analogRead(temppinhot); //Reading data from the sensor on the hot bar. Stored as a 10bit number
float voltagehot = temphot * 5.0/1024; //Converting 10bit number to voltage ant then to the temperature.
float tempChot=(voltagehot - 0.5) * 100;
int tempcold=analogRead(temppincold); //Reading data from the sensor on the cold bar. Stored as a 10bit number
float voltagecold = tempcold * 5.0/1024; //Converting 10bit number to voltage and then to the temperature.
float tempCcold=(voltagecold - 0.5) * 100;

int sum = 0;
for (int i=0; i<30; i++) {
sum=sum+analogRead(A2); //for loop to sum 30 measurements
}
float average=sum/30; //get average of the 30 measurements (better precision)
float voltagetotal = average * (5.015 / 1024); //voltage measured from the TEG
float DeltaT=tempChot-tempCcold; //Computed delta temperature
float Seebeck=voltagetotal/DeltaT; //Computed seebeck coefficient
// print out the value you read:
Serial.print( ElapsedTime);
Serial.print(",");
Serial.print( tempChot );
Serial.print(",");
Serial.print( tempCcold);
Serial.print(",");
Serial.print(voltagetotal, 4);
Serial.print(",");
Serial.print( DeltaT );
Serial.print(",");
Serial.println( Seebeck, 4);
//separate data print outs with by comma, so PLX-DAQ recognizes it as separate data

delay(5000); //repeat the loop every second (take data every second)
}
```

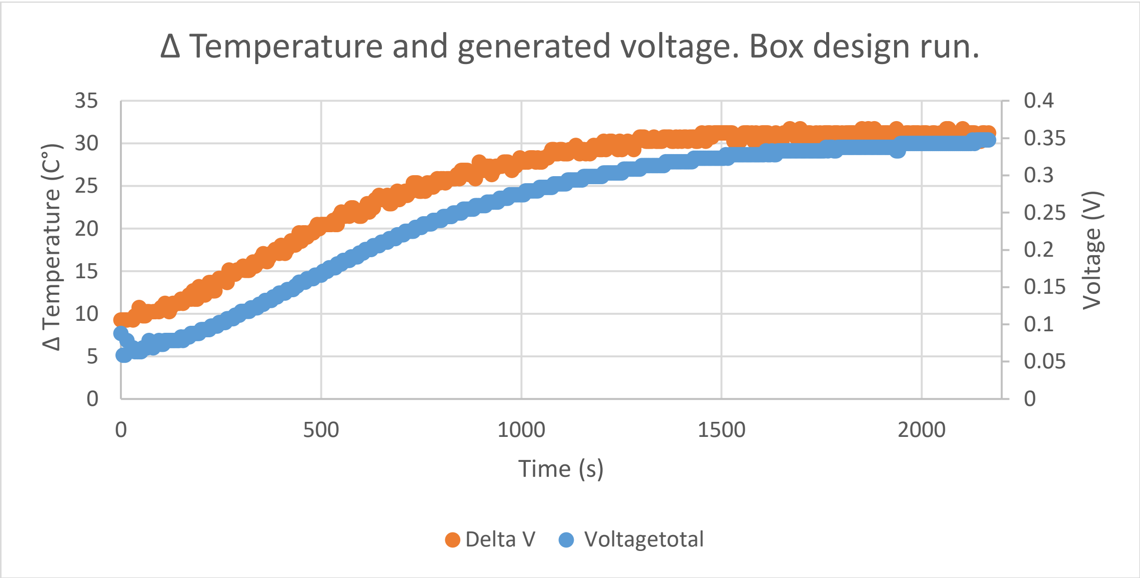
4. "Seebeck coefficient" plot versus time

Even though the seebeck coefficient is expected to be constant, it is slightly increasing over time.



5. Plot of temperature difference and generated voltage versus time.

Generated voltage is perfectly correlated with temperature difference during the first half of the experiment. However, during the second half of the experiment generated voltage was increasing faster than the temperature difference measurement.



Appendix F: Maple spreadsheet

This maple spreadsheet shows the calculations and plots I did for the Newtons Law of cooling.

$$k := \frac{10 \cdot 0.006}{1005 \cdot 1.225 \cdot 0.0024}$$

0.02030663011

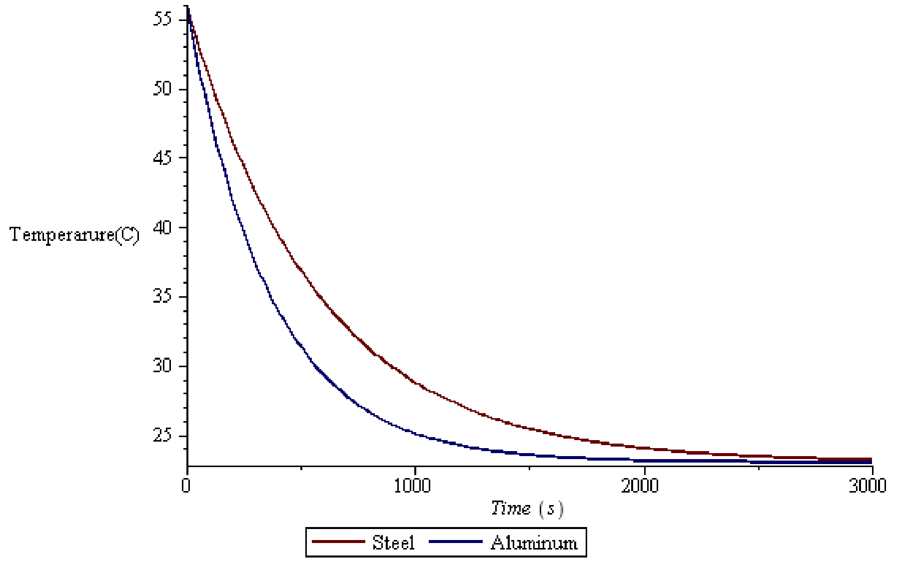
$$kl := \frac{10 \cdot 2}{490 \cdot 7820 \cdot 0.003}$$

0.001739826365

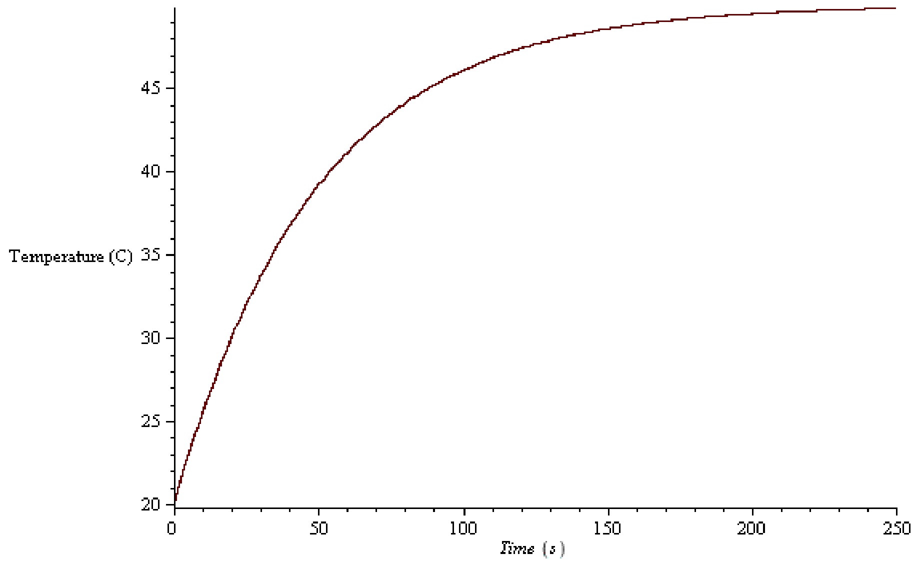
$$ka := \frac{10 \cdot 2}{897 \cdot 2700 \cdot 0.003}$$

0.002752659757

$plot\left(\left[23 + 33 \cdot e^{-kl \cdot x}, 23 + 33 \cdot e^{-\mathrm{ka} \cdot x}\right], x = 0..3000\right)$



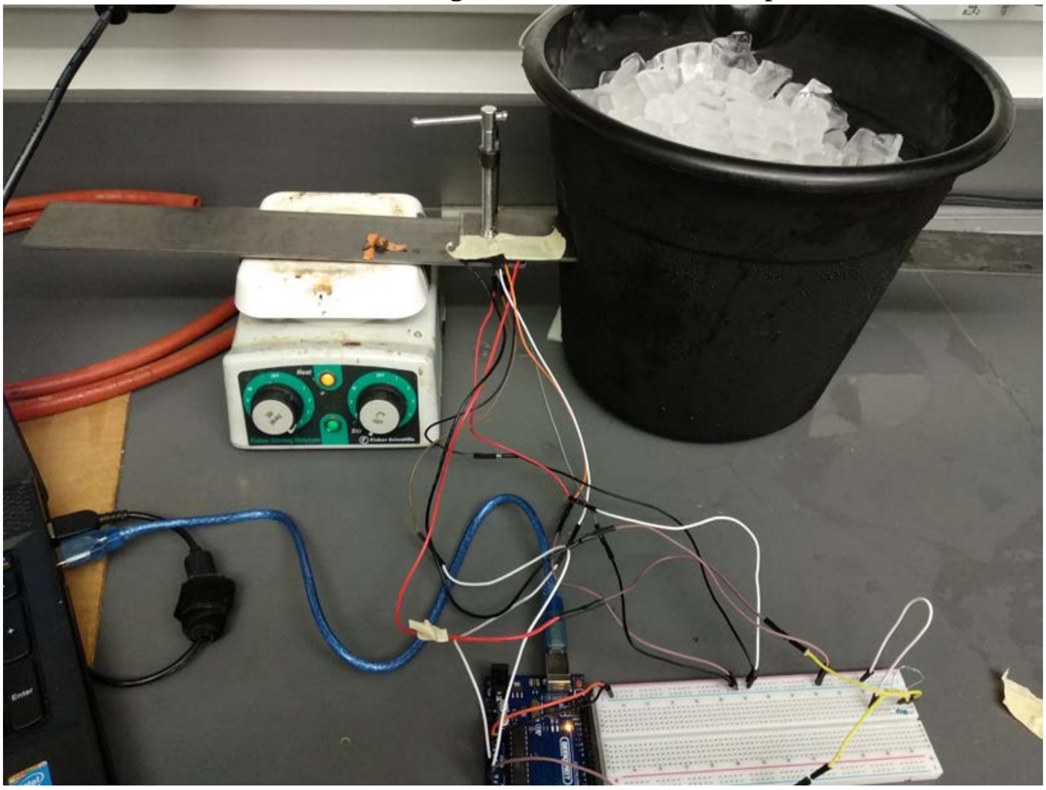
$plot\left(50 - 30 \cdot e^{-k \cdot t}, t = 0..250\right)$



Appendix G: Supplementary materials for the runs with the different bars configuration

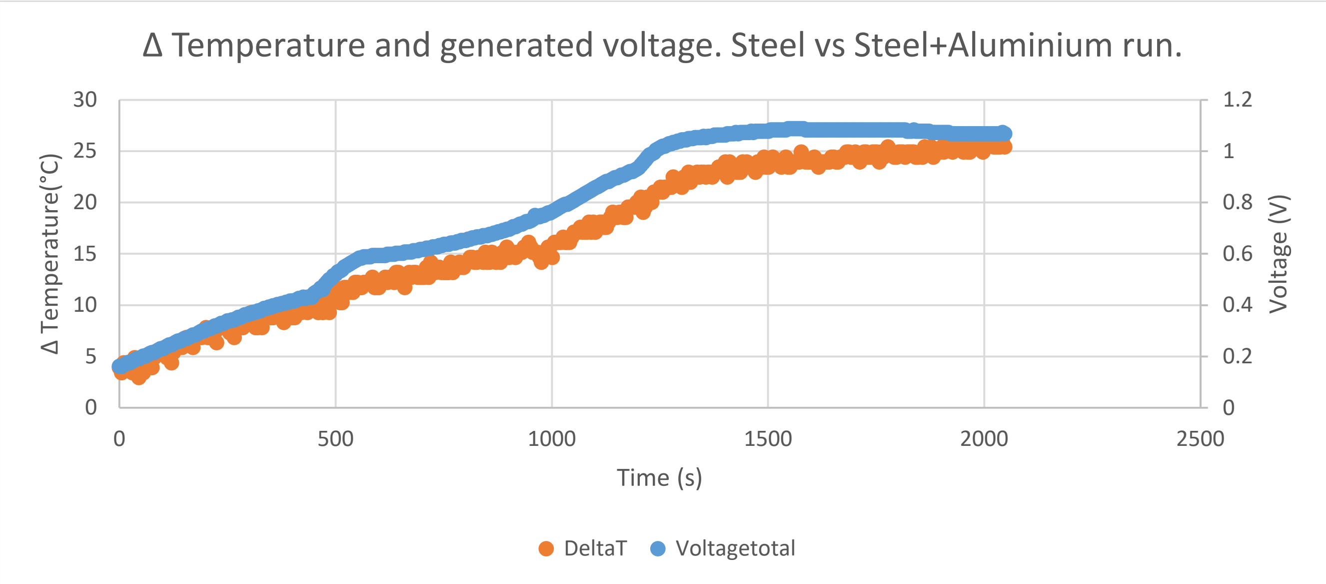
1. **Steel vs Steel run**
   a. **Photo**

This photo shoes the setup for the Steel vs Steel run. I have the setup as close as possible to the ice bucket, so I ensure the best cooling I can make for the setup.



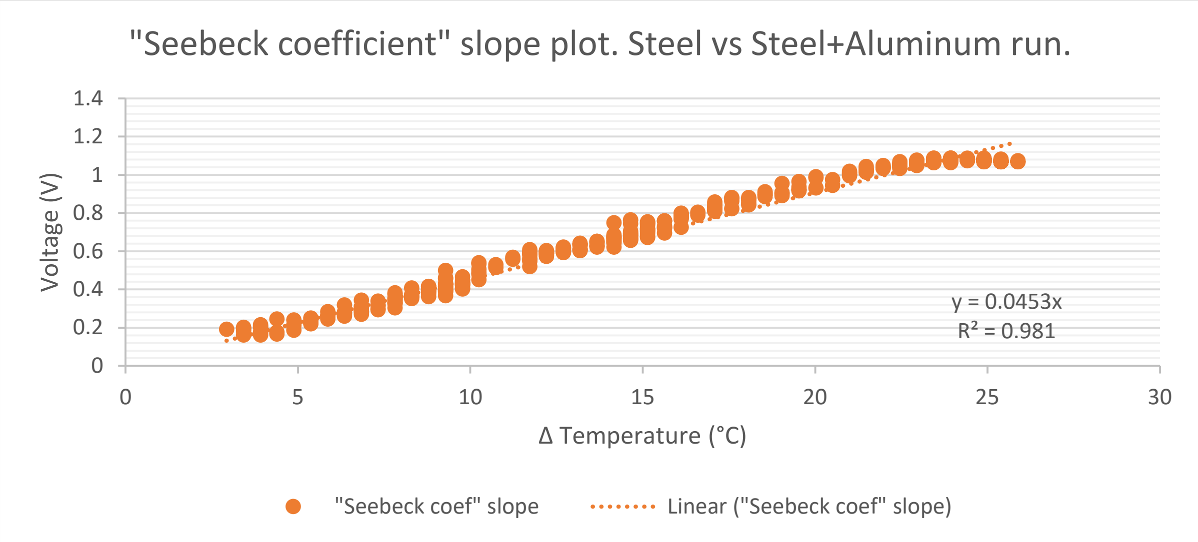
2. **Steel vs Steel + Aluminum run**
   a. **Plot of temperature difference and generated voltage versus time.**

The plot shows that generated voltage is closely correlated with the temperature difference across the TEG. This is the expected behavior from the Seebeck effect.



b. "Seebeck coefficient" slope plot

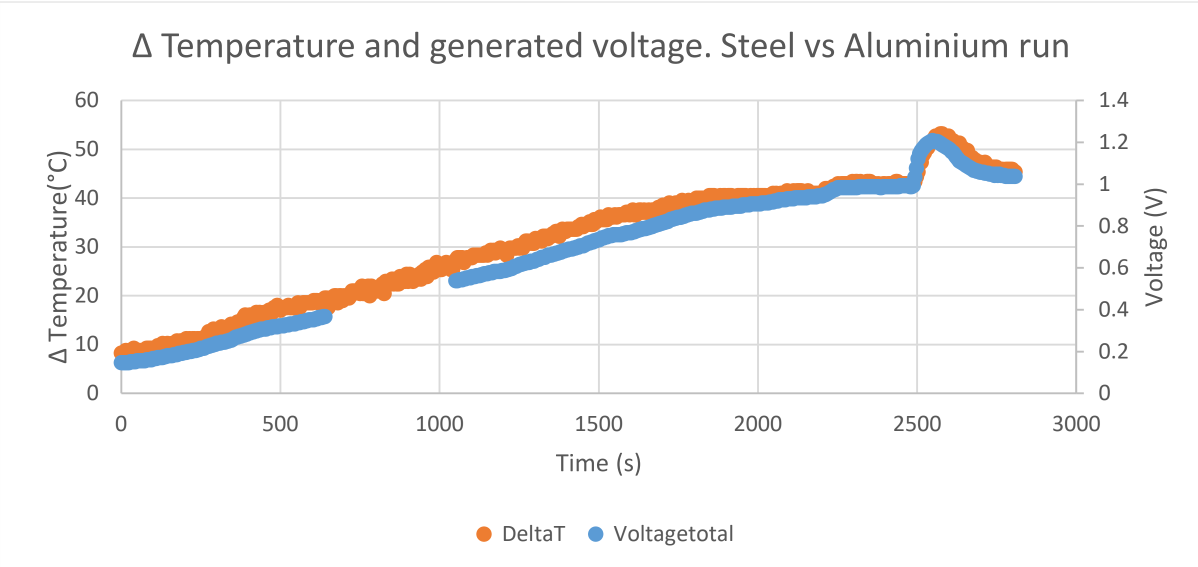
The slope of this plot represents the "seebeck coefficient" for this run. The "seebeck coefficient" for this run is 0.0453, which is about twice more than usual, therefore expected, "seebeck coefficient" for this kind of setup.



3. Steel vs Aluminum run

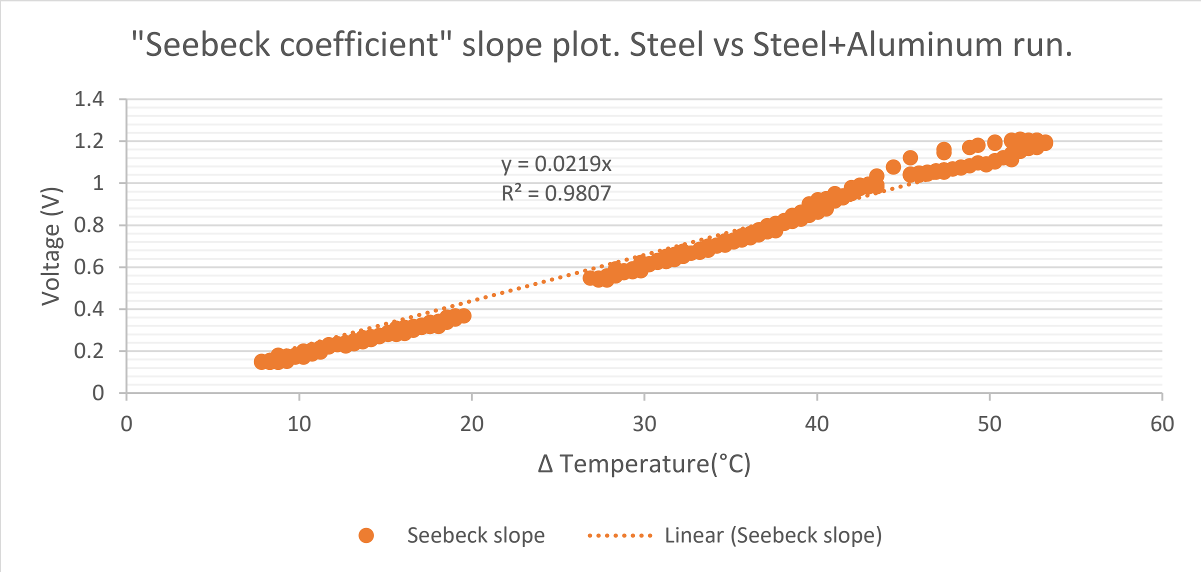
a. Plot of temperature difference and generated voltage versus time.

The plot shows that generated voltage is closely correlated with the temperature difference across the TEG, which is an expected behavior from the Seebeck effect. There are some data missing for the voltage measurements, because during that time the measurement was affected by me, therefore these data is not valid, so I took it out.



b. "Seebeck coefficient" slope plot

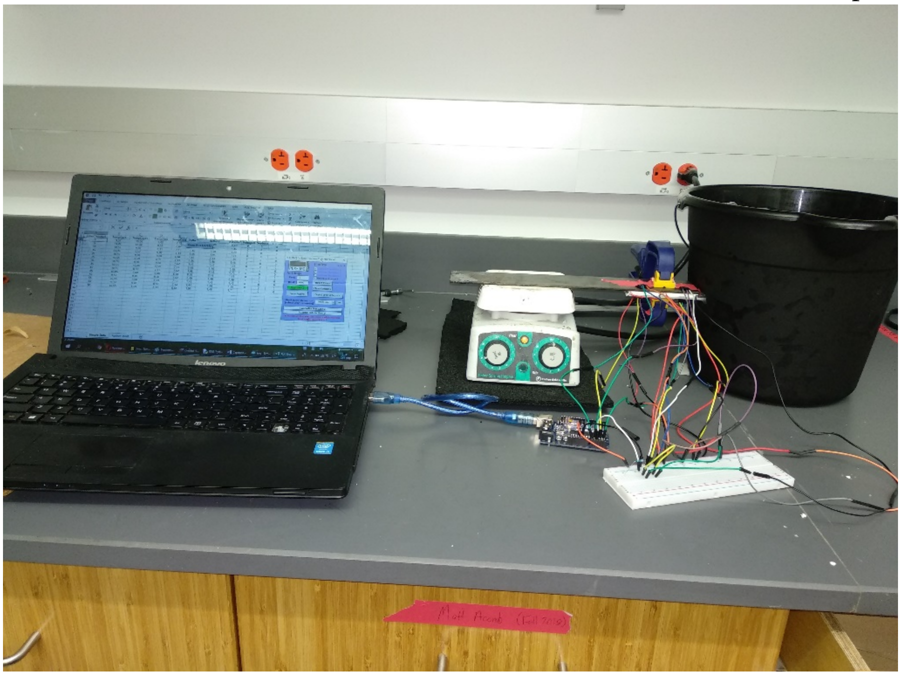
The slope of this plot represents the "seebeck coefficient" for this run. The "seebeck coefficient" for this run is 0.0219, which is in the range of the usual, therefore expected, "seebeck coefficient" for this kind of setup. There are some data missing for the voltage measurements, because during that time the measurement was affected by me, therefore these data is not valid, so I took it out.



Appendix H: Supplementary materials for the parallel vs series with different loads run

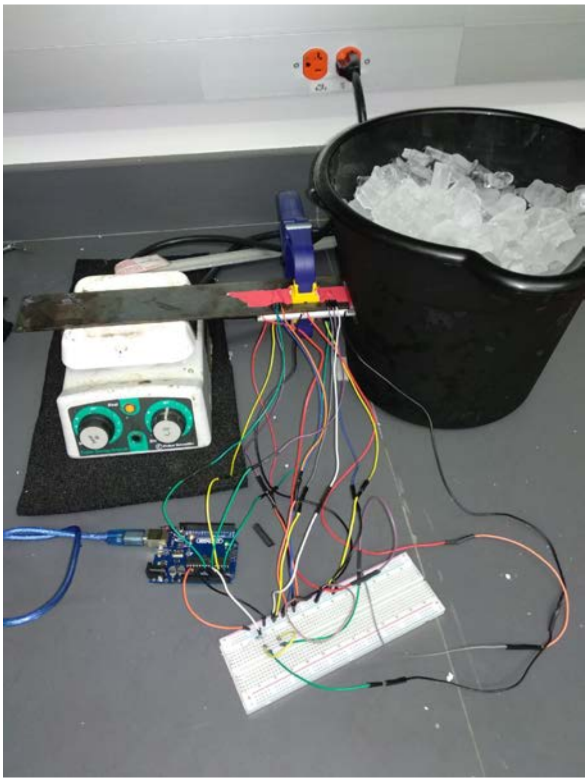
1. **Picture big**

This photo shoes the setup for the PvsS run run. I have the setup as close as possible to the ice bucket, so I ensure the best cooling I can make for the setup. There is arunf 5 cm from the middle of the TEG to the ice and 10 cm from the middle of the TEG to the hotplate.



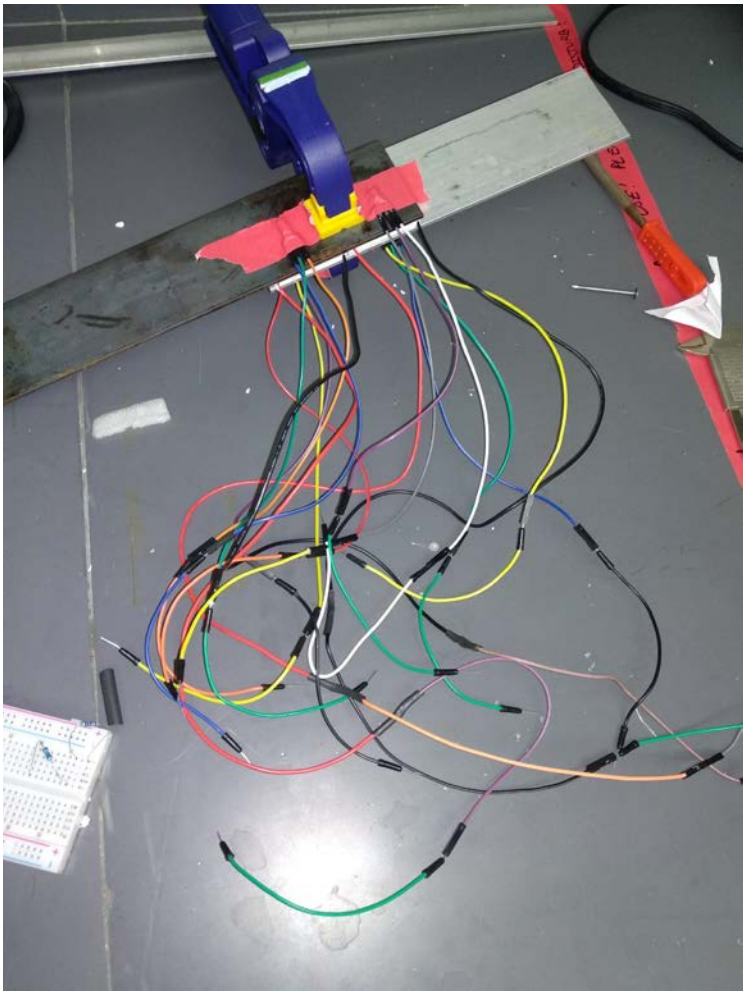
2. **Picture closer**

This photo show the PvsS setup closer, where one can see that there are two TEG's and each has a pair of temperature sensors.



3. Picture TEGs and bars

This photo shows closely hot two TEG's are compressed in between two bars by the plastic clamp. In addition, on this photo one can see how I attach the temperature sensors to the hot bars. The sensor on the cold bar are attached the same way. I assembled the part shown on the picture first and then I just put the bars to their cold/heat sources.



4. Code

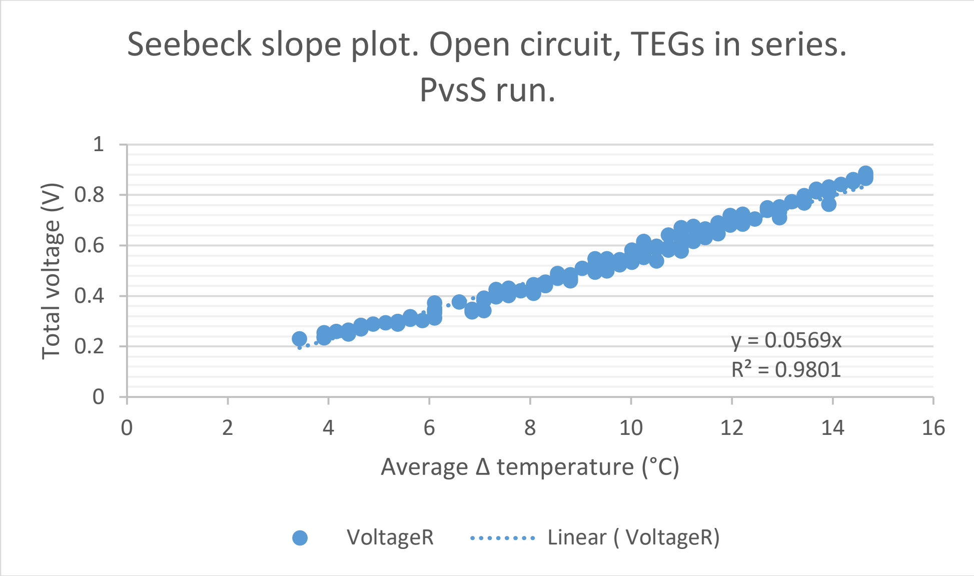
The voltage measurement in this code is not any specific to open or closed loop. It just reads data for voltage measurement. To know what exactly the measurement represents, during the experiment I reported times in my notebook when I switched to a different kind of measurement (different resistor or different TEG's arrangements).

```
//assigning variables to analog pins
int temppinhot1=0;
int temppincold1=1;
int temppinhot2=3;
int temppincold2=4;

void setup() {
Serial.begin(9600);
Serial.println("CLEARSHEET"); //setup so PLX-DAQ receives data.
Serial.println("CLEARDATA"); //aka talking to PLX-DAQ
Serial.println("LABEL, TimeElappsed, TempHot1, TempCold1, TempHot2, TempCold2, DeltaT1, DeltaT2, AvDeltaT, VoltageR, Seebeck, Current");
```

```
Serial.println("RESETTIMER");
}

void loop() {
Serial.print("DATA,"); //PLX-DAQ knows that it will receive data
unsigned long ElapsedTime=millis(); //Reads how much time has elapsed since the beggining of he experiment
ElapsedTime=ElapsedTime*0.001; //convert milliseconds to second

int temphot1=analogRead(temppinhot1); //Reading data from the sensor on the hot bar for TEG1. Stored as a 10bit number
float voltagehot1 = temphot1 * 5.0/1024;
float tempChot1=(voltagehot1 - 0.5) * 100;//Converting 10bit number to the  temperature.
int tempcold1=analogRead(temppincold1); //Reading data from the sensor on the cold bar for TEG1. Stored as a 10bit number
float voltagecold1 = tempcold1 * 5.0/1024;
float tempCcold1=(voltagecold1 - 0.5) * 100;//Converting 10bit number to the temperature.
int temphot2=analogRead(temppinhot2); //Reading data from the sensor on the hot bar for TEG2. Stored as a 10bit number
float voltagehot2 = temphot2 * 5.0/1024;
float tempChot2=(voltagehot2 - 0.5) * 100;//Converting 10bit number to the temperature.
int tempcold2=analogRead(temppincold2); //Reading data from the sensor from the cold bar for TEG2. Stored as a 10bit number
float voltagecold2 = tempcold2 * 5.0/1024;
float tempCcold2=(voltagecold2 - 0.5) * 100;//Converting 10bit number to the temperature.

int sum = 0;
for (int i=0; i<30; i++) {
sum=sum+analogRead(A2); //for loop to sum 30 measurements
}
float average=sum/30; //get average of the 30 measurements (better precision)
float voltageR = average * (5.015 / 1024);// Measured voltage (for whatever I am measuring)
//Computations from the measured data
float DeltaT1=tempChot1-tempCcold1; //temperature difference on the TEG1
float DeltaT2=tempChot2-tempCcold2; //temperature difference on the TEG2
float AvDeltaT=(DeltaT1+DeltaT2)/2; //Average temperature difference
float Seebeck=voltageR/AvDeltaT; //calculated Seebeck coefficient
// print out the value you read:
Serial.print( ElapsedTime);
Serial.print(",");
Serial.print( tempChot1 );
Serial.print(",");
Serial.print( tempCcold1 );
Serial.print(",");
Serial.print( tempChot2 );
Serial.print(",");
Serial.print( tempCcold2 );
Serial.print(",");
Serial.print( DeltaT1 );
Serial.print(",");
Serial.print( DeltaT2 );
Serial.print(",");
Serial.print( AvDeltaT, 2 );
Serial.print(",");
Serial.print( voltageR, 4);
Serial.print(",");
Serial.println( Seebeck, 4 );
//separate data print outs with by comma, so PLX-DAQ recognizes it as separate data
delay(5000); //repeat the loop every second (take data every second)
}
```

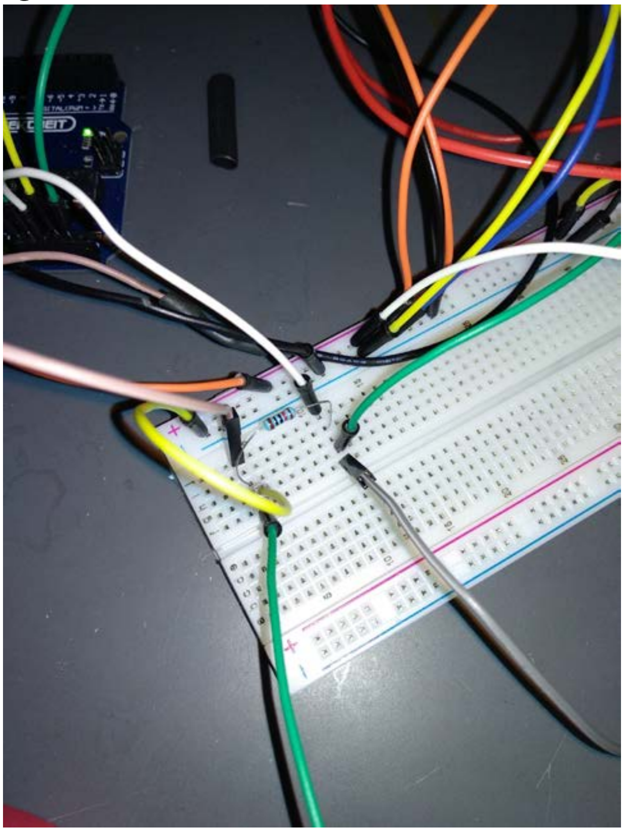
5. **Seebeck slope for series plot**

The slope of this plot represents the "seebeck coefficient" of the two TEG's connected in series. The slope is 0.0569, which is higher than expected ~4.5 measures seebeck coefficient for two TEG's in series.



6. **Breadboard picture for parallel**

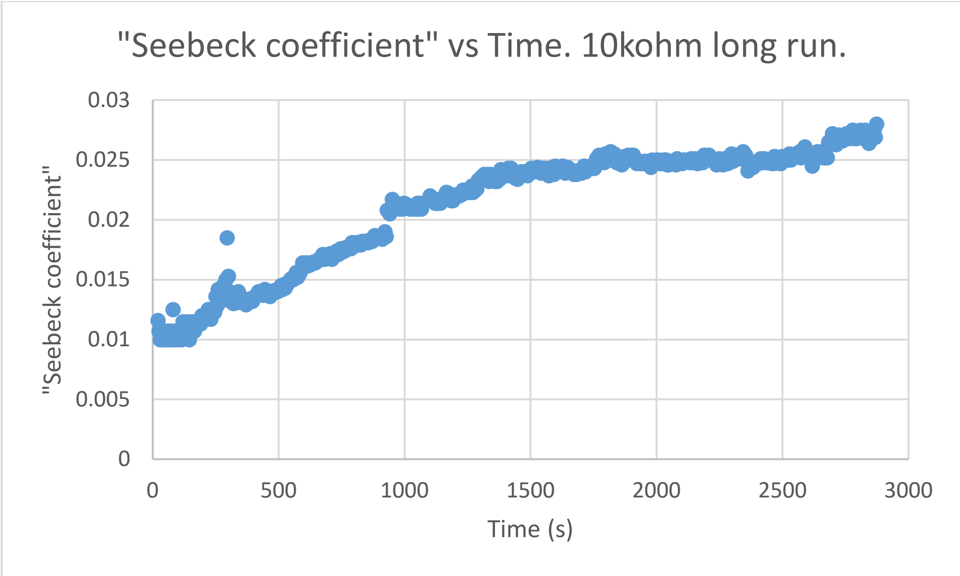
This photo shows an example of how I did the wiring for measuring voltage. This specific example is the measurement of the voltage across the resistor that is in series with the two TEG's connected in parallel. On the right side of the resistor, green and gray wires are the positive ends of the TEG's, and the white wire goes to the analog pin of the microcontroller. On the left side of the resistor, green and purple wires are the negative ends of the TEG's and yellow wire goes to the ground.



Appendix I: Supplementary materials for the 10kΩ long run

1. **"Seebeck coefficient" vs time plot**

This plot represents how the calculated "seebeck coefficient" changes over time. There is a spot around 950 seconds, where the "seebeck coefficient" rapidly increased. This rapid increase happened when I tightened the clamp to get better physical contact in between the TEG and the bars.



2. **Plot of delta T, av T and voltage vs time for 220ohm.**

This plot shows how average temperature, delta temperature and voltage change over time. From this plot we can see that voltage depends not only on the temperature difference, but also on the average temperature of the TEG.