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Thermoelectrics and Thermoelectric Devices

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Thermoelectrics and thermoelectric devices

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Thesis Acceptance

Linfield College

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1. INTRODUCTION

1.1 Background history

Interest in thermoelectrics began around 1822 when Thomas Johann Seebeck observed a compass needle being deflected by a closed loop formed by two different metals with two different temperatures. We know now that this is due to be a conversion of heat energy directly into electricity at the junction, or thermal contact, of the different metals [2]. French physicist Jean Charles Peltier studied these thermal electric properties and discovered that the reverse effect also occurs, and so applying a voltage at the junction of two different metals will cause heating or cooling at the junction. Thomson issued a comprehensive explanation of the Seebeck and Peltier Effects and described their interrelationship, known as the Kelvin relations. These relations showed that the Seebeck and Peltier effects, which are most pronouced to particular metal alloys, are related to each other through thermodynamics. These thermodynamic derivations lead Thomson to predict a third thermoelectric relationship; heat is absorbed or produced when a current flows in a material with a temperature gradient [2]. Thomson's derivation predicted that the heat moved is proportional to both the electric current and temperature gradient.

1.2 Peltier Modules

At an atomic scale, an applied temperature gradient causes charge carriers in the material to diffuse from one side to the other. To observe thermoelectric effects, testing a Peltier device was chosen because it is used as a well-known thermoelectric device (TED) inside computer and refrigeration systems. The Peltier device uses two unique doped semiconductors, one n-type and one p-type, due to their different electron densities. The n-type semiconductor has negatively charged electrons as its charge carriers and the p-type semiconductor uses positively charged holes. When these semiconductors are lined parallel to each other, the charge carrier differences between the materials help promote the flow of charge when the metals are heated [7]. Inside the tested Peltier module the p-type semiconductor is thermally joined with the n-type, touching the conducting plates on each side as shown in Figure 1.1

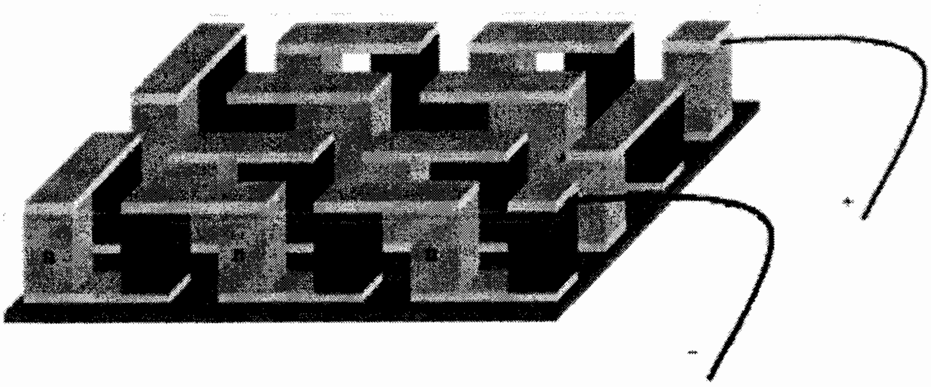

Figure 1.1 A transparent diagram of the thermal construction of a Peltier module, reproduced from reference 5.

The devices tested in this experiment were designed for applications of the Peltier effect to either heat or cool a surface. However, due to the thermodynamics, these devices can also be used to generate power with the seebeck effect. When testing these devices, the Peltier effect applications are expected to perform better, due to moving heat being the primary motivation for the construction of the devices.

1.3 Peltier effect

When a voltage is applied to the free ends of the semiconductors, there is a flow of DC current across the junctions of the semiconductors[6]. This will cause a charge to flow between the conducting plates and the charge carriers inside the material will carry heat from one plate to the other, effectively heating or cooling the conducting plates (seen in figure 1.2). This effect is amplified by the choice of doped p and n-type semiconductors and alignment of the semiconductors inside the module seen in figure 1.1.

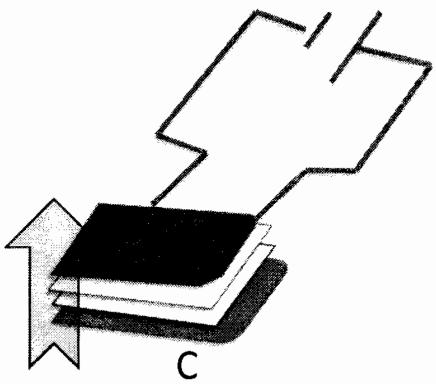

Figure 1.2: The Peltier effect in which a DC voltage causes heat to move from the cold plate to the hot plate.

1.4 Seebeck effect

When one plate is heated and the other is cooled, a flow of charge will move around the circuit from the 'hot' plate to the 'cold' plate, as seen in figure 1.3.

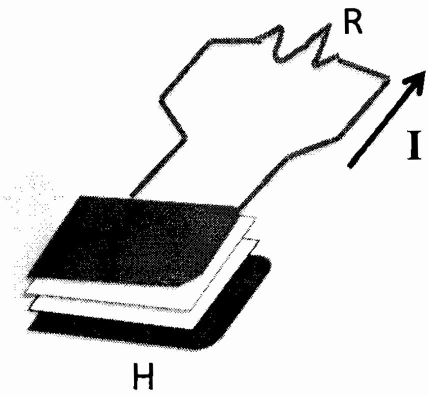

Figure 1.3 The Seebeck effect in which charge carriers promote the flow of charge around the circuit towards the cold plate.

Heat energy applied to the device causes the charge carriers inside the semiconductors to become excited. These carriers naturally want to move toward a lower energy, thus they diffuse toward the cold side, creating a current inside the device.

1.5 Figure of merit zT

In 1909, Edmund Altenkirch was the first to derive the maximum efficiency of a thermoelectric generator and the performance of a thermoelectric cooler in 1911. This study later developed a quantity called the 'figure of merit' zT, which defines a good thermoelectric material. This quantity zT predicted that good thermoelectric materials have high electrical conductivity to minimize Joule heating due to electrical resistance, and low thermal conductivity to minimize heat loss[2]. The Seebeck coefficient is unique to individual metal alloys and determines the magnitude of voltage (ΔV) generated from an applied temperature difference (ΔT)[6].

$$S = -\frac{\Delta V}{\Delta T} \quad (1)$$

This study prompted thermal conductivity measurements by A Eucken on solids that quickly revealed point defects found in alloys significantly reduce lattice thermal conductivity. A strategy of manipulating these defects to raise the figure of merit zT quickly became important for thermoelectric material production.

Many thought that thermoelectrics would replace conventional heat engines and refrigeration in time and it became a significant area of research till the 1960's. However, studies on the upper limit of zT showed it wouldn't surpass other forms of power generation. Around this time, Abram Ioffe developed a modern theory of thermoelectricity using semiconductors to improve the zT figure of merit. His studies promoted the use of semiconductor physics to optimize the performance of these devices by reducing lattice thermal conductivity with point defects. These materials, with high figures of merit zT , due to their lower thermal conductivity, are typically heavily doped semiconductors known as the tellurides of antimony, bismuth and lead. These materials are still used in devices today and are present in the Peltier modules being tested in this experiment.

1.6 Current Thermoelectric Study

The importance of thermoelectrics in its applications can be seen more in its utility than its effectiveness. Even with these significant improvements in the technology, the typical efficiencies are on the order of 1-10% with temperature differences being below 500°C. However, Thermoelectric devices have no moving parts and thus require low maintenance. Low maintenance means low cost and long life spans, which can be seen in its selection for systems that require longevity such as satellites [6]. The Peltier effect is considered a fast feedback control mechanism and can be sensitively controlled at minute levels. These qualities, in addition to the size control that manufacturing allows, makes these devices ideal for applications in electrical systems. The direct cooling of circuits plays a large role in superconductors, DNA sequencing, and satellite cooling [6].

Thermoelectric devices are scalable to the nanoscale where they continue to work under the same principles. Studies in nanoparticle engineering have shown that small one-dimensional lattices and Nano-silicon wires can be utilized in novel thermoelectric devices to improve zT [6]. These improvements have also allowed for the capture of small energy levels that could produce power from minute ambient temperature differences. However, this technology is premature, expensive for now, and hard to produce.

Most applications of these devices revolve around waste heat that can be found in common systems. VW and BMW announced 24 Bi_2Te_3 modules added in their 2008 engine model that reduced 5% of its fuel consumption through powering the alternator [3]. The NASA radioisotope thermoelectric generator uses a Pu^{238} isotope source paired with a thermoelectric generator to generate enough electricity to power satellites for 33 years [6]. Seiko produced a wristwatch that produces 22μW of electrical power just from the waste heat off a human wrist[1]. Coal based power accounts for almost 41% of the world's electricity generation and is done by the Rankin Cycle, which only has an efficiency of 32%-42% [6]. Many power plants have utilized thermoelectrics to recover power lost to the waste heat involved in the Rankin cycle. The same theory can be applied to steam and nuclear power plants that produce mass amounts of waste heat.

The field of thermoelectrics has many applications and more are found in everyday systems. From its current studies, it is apparent that improving the figure of merit zT is important in the effectiveness of power generation. Another important part of thermoelectrics is the duality of these devices. They can both move heat and generate power, depending on their role in the system. In this thesis research, a process was made to test these thermoelectric relationships for a few Peltier devices in order to understand their efficiencies and what systems they can be applied too.

2. THEORY

As discussed in the introduction, the thermoelectric effect is a direct conversion of heat energy to electric voltage and vice versa. In this project, the efficiency of both the Peltier and Seebeck effects were measured within the same device, so that they could be compared to each other. This section describes the classical thermodynamic theory that allows our measured data to be converted to energies and efficiencies.

2.1 Peltier Effect

When a voltage is applied to the Peltier module, heat absorbed by one of the conducting plates is moved by charge to the other plate, each plate being called the 'cold' and 'hot' side respectively. The heat transfer will be measured by melting a reservoir of ice placed on the hot plate that all the heat is directed to. As the reservoir is heated up, the ice will change states and the heat added can be found from the resulting liquid water. The total heat energy, Q, added to the reservoir can be found from,

$$Q = m_w c \Delta T + m_i c_f \quad (1)$$

m_w is the mass of the resulting water, c is the specific heat of liquid water, m_i is the mass of the ice melted, c_f is the specific heat of fusion, and ΔT will be the change in temperature. This allows for the calculation of the heat it takes to melt the ice into water and the heat absorbed by the water itself. The heat flux is estimated by $\frac{Q}{t}$ where t is the total heating time.

To calculate the power supplied to the device, Joule's law can be used,

$$P = IV \quad (2)$$

Where I is the current through the device and V is the voltage across the device. This way a relationship can be found between the power supplied to the device and the temperature flux produced from the Peltier effect.

2.2 Seebeck Effect

This effect is observed by holding the conducting plates of the device at different temperatures. Heat will be maintained by a heater on the 'hot' side and ice water will keep the 'cold' side at a constant temperature of 0°C. When connected at the free ends of the semiconductors, a circuit can be powered by the resulting flow of charge. To calculate this temperature difference, equation 3 will be used. In the connected circuit, the voltage applied across the resistor can be found by Ohms law, equation 4.

$$\Delta T = T_h - T_c \quad (3)$$

T_h and T_c are the temperatures of the hot conducting plate and cold plate respectively.

$$V = IR \ (4)$$

Where I is the current produced by the device and R is the resistance of the resistor placed inside the measurement circuit. Using equation 2 the power produced by the device can be determined with,

$$P = I^2R \ (5)$$

This way a relationship between the temperature differences between the plates and output power of the device can be found. For the Seebeck effect, a DC heater will supply the input heat that will cause the charge carrier flow through the circuit to the other conducting plate. Looking at the power supplied to the heater, equation 2, and comparing it to the output power of the device, equation 5, will give us device efficiency using equation 6.

2.3 Efficiency

Efficiency is the ratio of power output and power input.

$$Efficiency = \frac{P_{output}}{P_{input}} (6)$$

For this device, power input and output will be given in Watts, Joules per second. To compare this to the heat input or output, the energy flux will need to be in watts. Equation 1 will give heat in joules and equation 5 can be used with equation 6 to calculate efficiency for the Peltier effect.

3. EXPERIMENT

3.1 Experiment Introduction

The goal of this experiment is to observe the duality of the Peltier effect with the Seebeck effect. To do this, the power generation and efficiency of a Peltier module will be observed by using the Seebeck effect. Then the heat efficiency of its Peltier effect will be measured by applying a voltage to the module. As mentioned in the introduction every Peltier device is essentially a thermoelectric generator when set up differently. Thus, I will have two experiment set ups around the same device in order to observe the duality of its application.

Two different TE technology Peltier devices were tested with dimensions; 8.3 x 8.3 x 3.62mm, and 23 x 23 x 4.68mm. The 23mm device is a standard low cost Peltier module whereas the 8.3mm device is a higher performing module. This high performance module has more heat pumping capacity for any given size through the use of shorter thermoelectric elements and higher element packing densities when using the Peltier effect.

3.2 Heat sink

In order to do these tests a heat sink was constructed. This heat sink was constructed from a aluminum reservoir of ice and a box made from Styrofoam, for insulation. For the experiments, a heat source was needed, so a variable heater was placed at the bottom of the box where the Peltier device will sit (see fig 3.2). A resistance thermometer was be placed on the bottom surface of the device so that the temperature of the heater could be measured accurately. After the device was placed, an aluminum bowl was put on top of the cold side and any holes was be filled with Styrofoam. The aluminum bowl held a reservoir of ice water so that the top surface of the Peltier device could be kept at a constant temperature of 0°C.

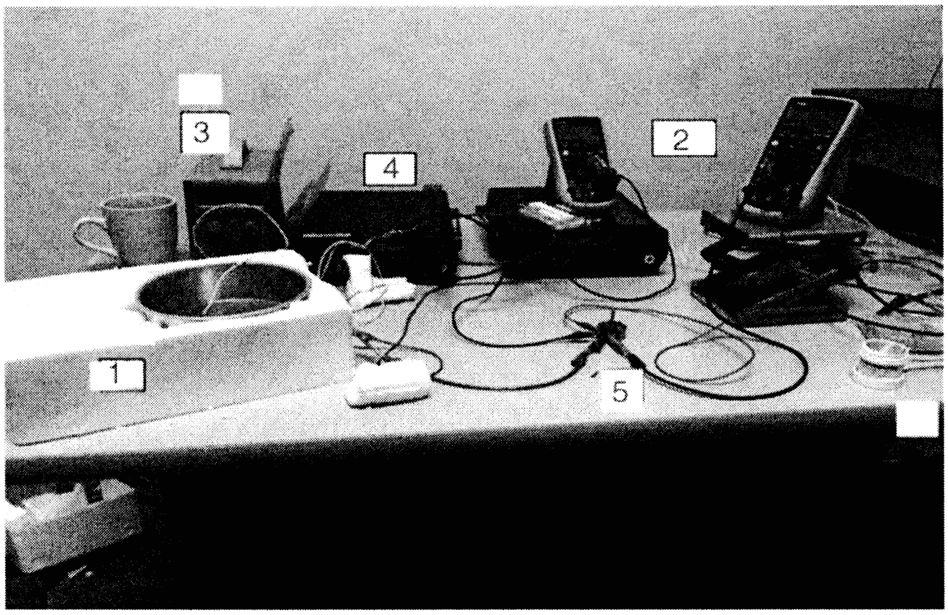

Figure 3.1 This is the full setup for the experiment; the Styrofoam surrounding the heat sink(1), the measurement circuit (2) is on the right, variable resistor (3). A separate voltmeter for the resistance thermometer (4), and the DC voltage supply for the heater is on the left side (5).

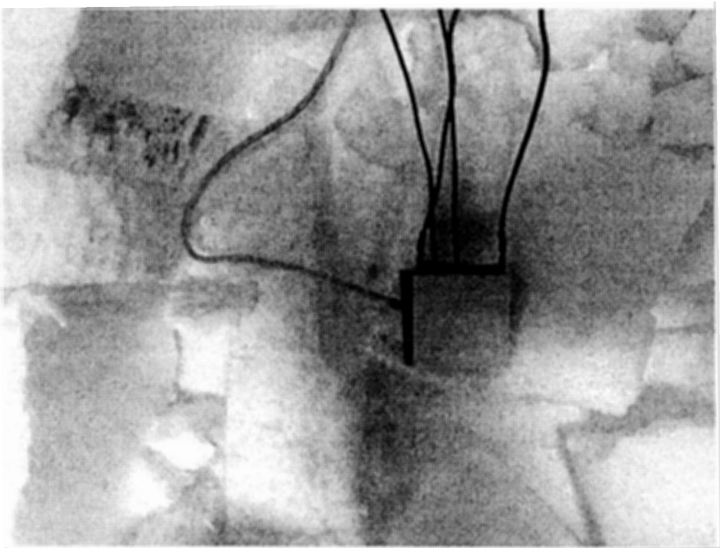

Figure 3.2 The heater placement on the bottom of the heat sink. The white RTD wire is placed between the heater and peltier device with thermal adhesive to keep in place.

3.3 The Peltier Effect

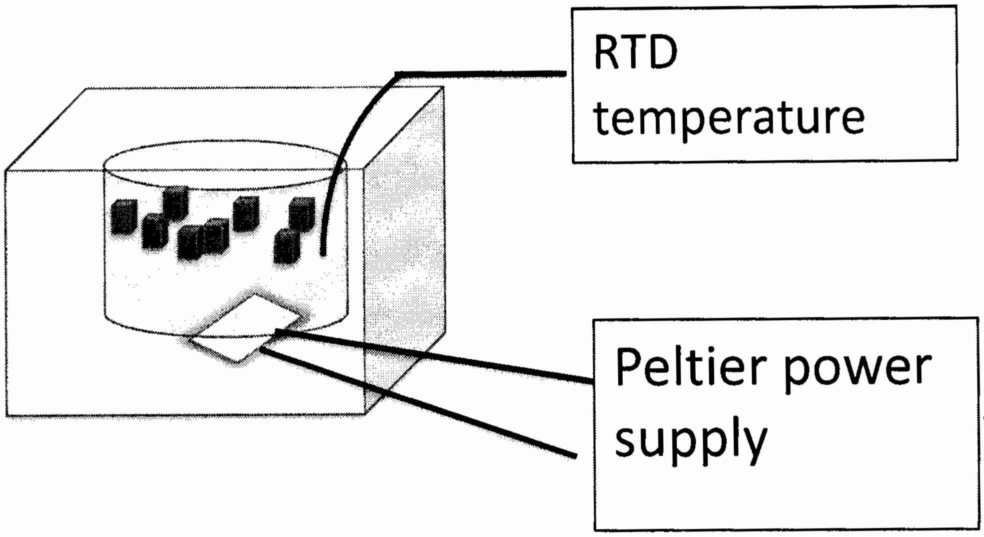

Figure 3.3 Experimental setup for experiment 3.4. The Peltier device is applied a voltage and the resistance thermometer is placed inside the ice to measure the temperature when it is melted.

Voltage was applied to the Peltier device and the resulting heat flux was measured by the amount of heat moved into the reservoir of ice (Figures 3.1 and 3.3). Once a voltage was applied, the device was allowed to sit till the ice melted. The melting time for the ice was then recorded. The amount of resulting heat moved was determined from the equations in the theory section. Power and voltage applied to the Peltier device was measured so that it could be compared using equation 6.

3.4 The Seebeck Effect

To observe the Seebeck effect, a variable heater was set to different temperatures and the aluminum bowl was filled with ice to supply a constant source of 0° C (Fig 3.1 shows the full set-up).

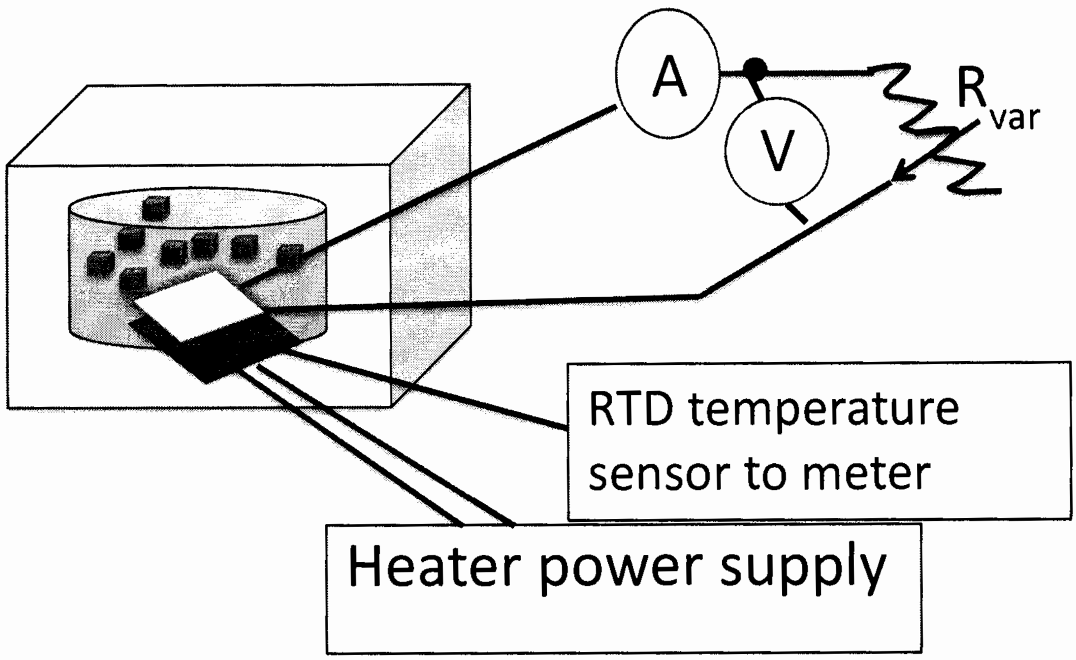

Figure 3.4 The experimental setup for experiment 3.3 with the measurement circuit consisting of an ammeter, and voltmeter across the variable resistor.

A resistance thermometer at the base of the heat sink gave the temperature of the bottom plate and thus the temperature difference between the plates since the cold plate was 0 °C due to the ice. The Peltier device was wired in a measurement circuit so that the power output of the device could be found. This measurement circuit consisted of an ammeter and a voltmeter across the variable resister (see figure 3.3). When the heater is turned on and the ice is placed in the aluminum bowl, the measurement circuit recorded the power output of the device as well as the power at different resistances using equation 2 from the theory section.

4. Results and Analysis

4.1 The Peltier effect

To look at the Peltier effect the relationship between power supplied to the device and the heat transferred to the hot conducting plate was observed. Figures 4.1, and 4.2 depict the data for the 23mm and 8mm devices respectively. The linear trend between power supplied and heat moved can be seen in each figure and matches what was expected from the theory. The 23mm device, powered at 2.11J/s, moved 1.59mJ/s. The 8.3mm device, powered at 0.344J/s, moved 2.637mJ/s. As mentioned in the before, the 8.3mm device is higher performing and this is apparent when comparing it to the 23mm device. The 8.3mm device only needed 5.9% of the power supplied to the 23mm to move around the same amount of heat. This shows the effect of shorter thermoelectric elements and higher element packing densities on performance of these devices when used as heat pumps.

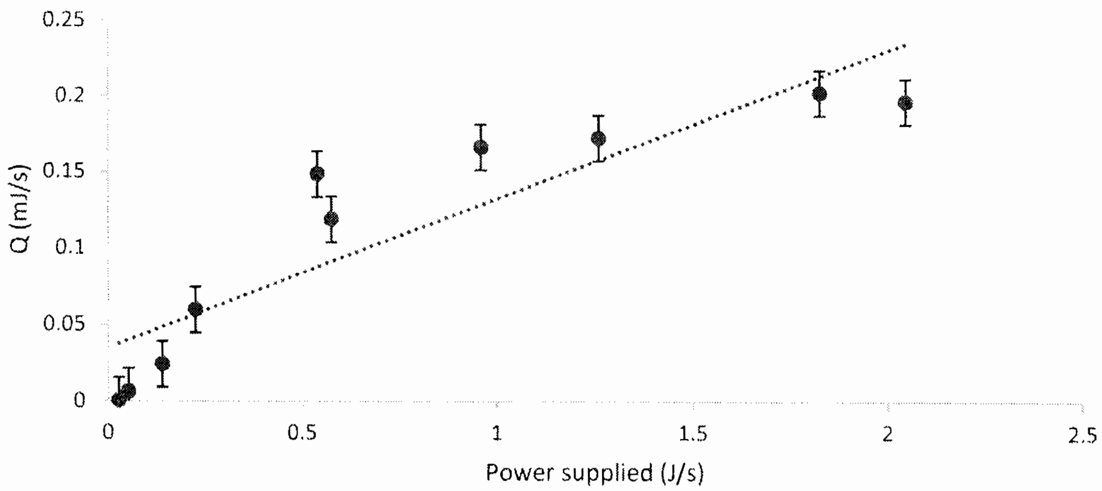

Figure 4.1 Data for the power supplied to the 23mm Peltier device and heat transferred to the hot conducting plate.

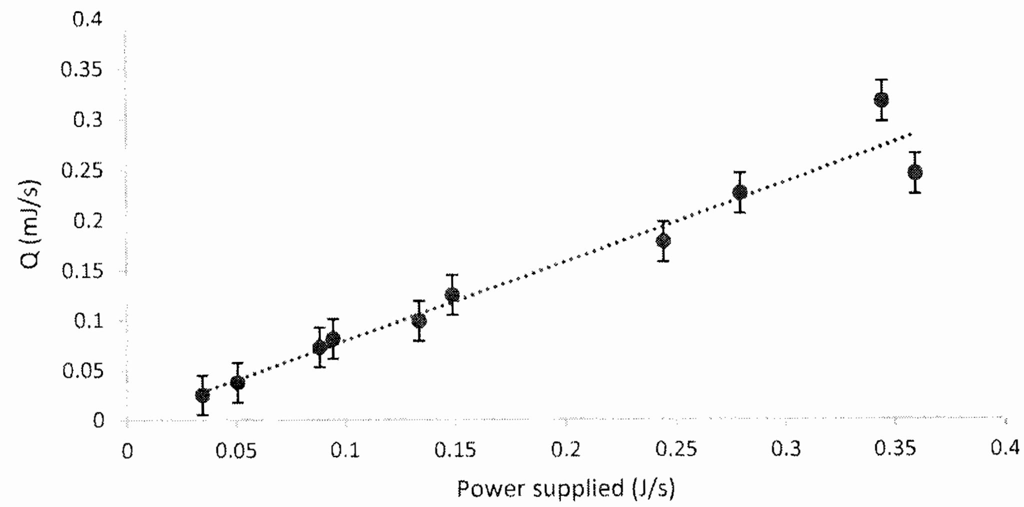

Figure 4.2 Data for the power supplied to the 8.3mm Peltier device and heat transferred to the hot conducting plate.

4.2 The Seebeck Effect

Figures 4.1 and Figure 4.2 show the data collected for the 23mm and 8.3mm devices respectively. Both graphs show the power generation for the Peltier circuit for two different resistances, one being the lowest resistance setting 0.3 Ohms and another at a resistance closer to the internal resistance of the device given by the manufacturer, 1.1 Ohms and 1.5 Ohms for each device respectively. Initially, a positive, roughly linear trend can be seen between the applied heat difference and power generated. We hypothesized this relationship to be linear and it can be seen that increasing the applied heat difference will generate more power. For both devices, the initial 0.3 Ohm load produced less power than the load that matched the internal resistance. This agrees with the theory that max power is produced when resistance in the circuit is closer to the internal resistance of the Peltier device. The initial curve in the plots was unexpected. Possibly the heater wasn't high enough to generate a large enough heat difference with the heat sink. Omitting the first few data points where this might have happened, a linear relationship can be seen. This follows the expected relationship between the applied heat difference and power generated. At 1.1 Ohms resistance, the 8.3mm device at a 26°C heat difference generated $6.5 * 10^{-4}W$ of power. At 1.5 Ohms resistance, the 23mm at a 18.5°C heat difference generated $25.6\ 10^{-4}W$ of power. For both devices this generation is enough to power small LED lights or other small electronic devices with the right set up.

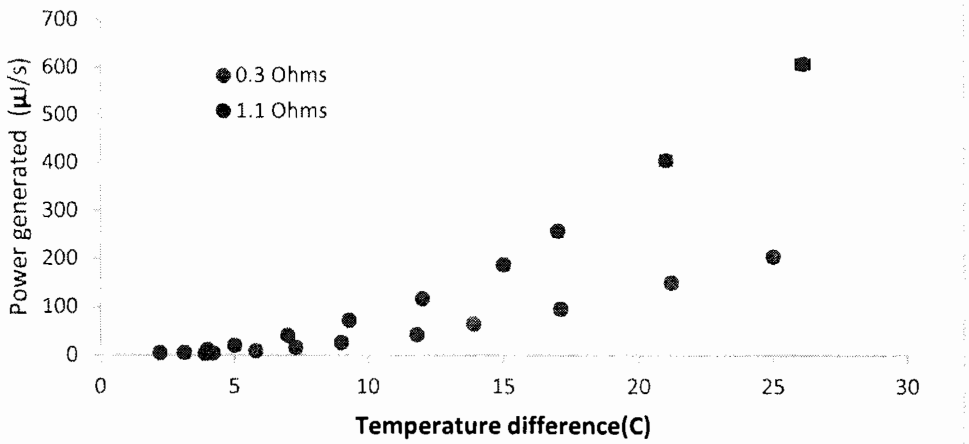

Figure 4.3 Power generated vs. difference in temperature between the conducting plates for the 23mm Peltier device with resistor of 0.3 and 1.1 Ohms.

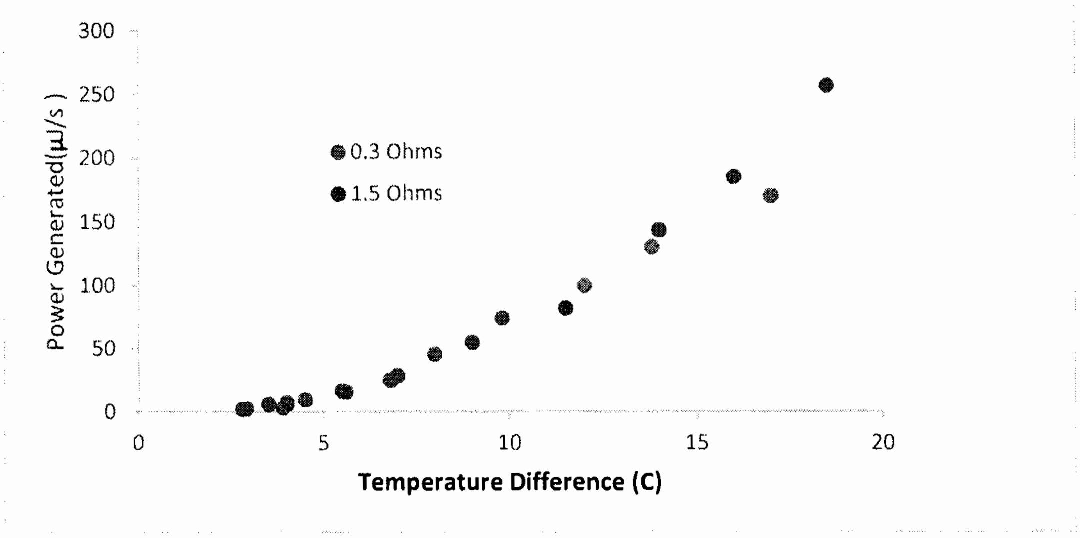

Figure 4.4 Power generated vs. difference in temperature between the conducting plates for the 8.3mm Peltier device with resistor of 0.3 and 1.5 Ohms.

4.3 Efficiencies

To investigate the Peltier effect efficiencies further, the output heat energy and input power will allow for efficiency to be found. Figures 4.5, and 4.6 depict the percent efficiency for energy moved at different input powers for the 23mm and 8.3mm device respectively. These graphs are expected to be constant and for both modules they are relatively linear and fluctuate around a constant efficiency. The efficiency of the 23mm device was measured to be around $0.08 \pm 0.01\%$ and is much less than the 8.3mm efficiency of $0.651 \pm 0.012\%$. The uncertainty will be discussed later in the section.

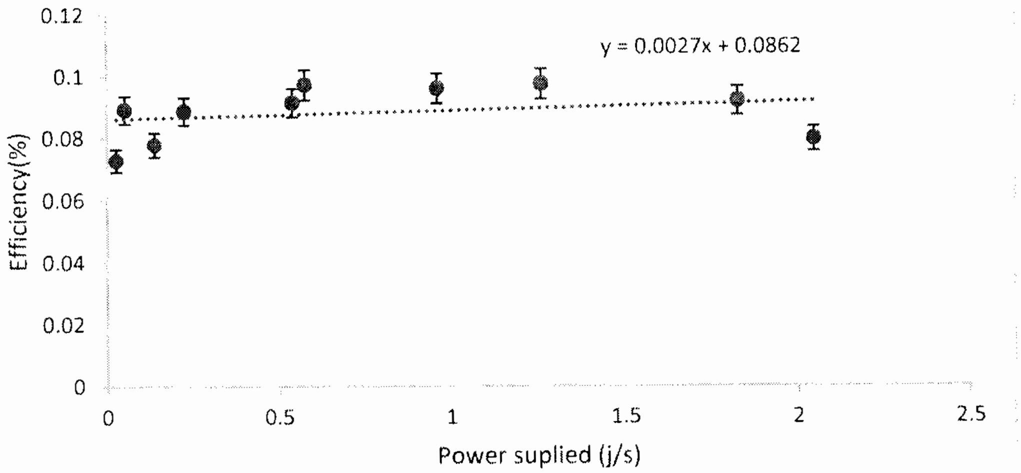

Figure 4.5 The heat pump efficiency of the 23mm Peltier device at different supplied powers.

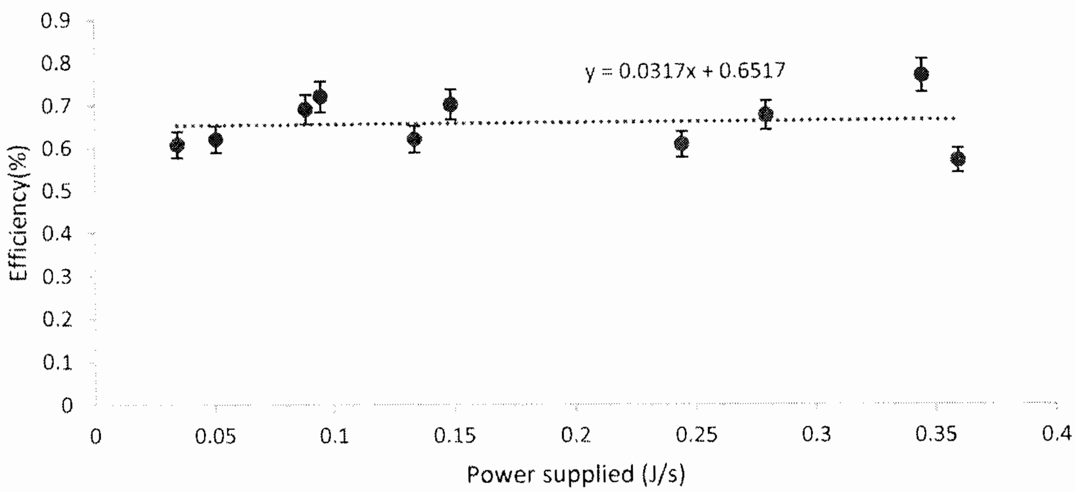

Figure 4.6 The heat pump efficiency of the 8.3mm Peltier device at different supplied powers.

To represent Seebeck effect efficiency, Figure 4.7 and Figure 4.8 show the relationship between power generated and the power to the heater supplying the heat difference in the system. In both figures, the same unanticipated curve in the first few data points can be seen and with the same reasoning a linear relationship can be observed as the heater power is increased. When fit with a trendline to the points following the unanticipated curve, the linear trend can be observed as the efficiency of the devices. For the 23mm device, a max power of 0.7mJ is generated from an input of 0.8J to the heater, 0.009% efficiency. Similarly, the 8.3mm device generated a max power of 0.256mJ was generated from an input of 0.624J to the heater. This is a significantly small efficiency of 0.001%, which was expected from the mechanics behind the device.

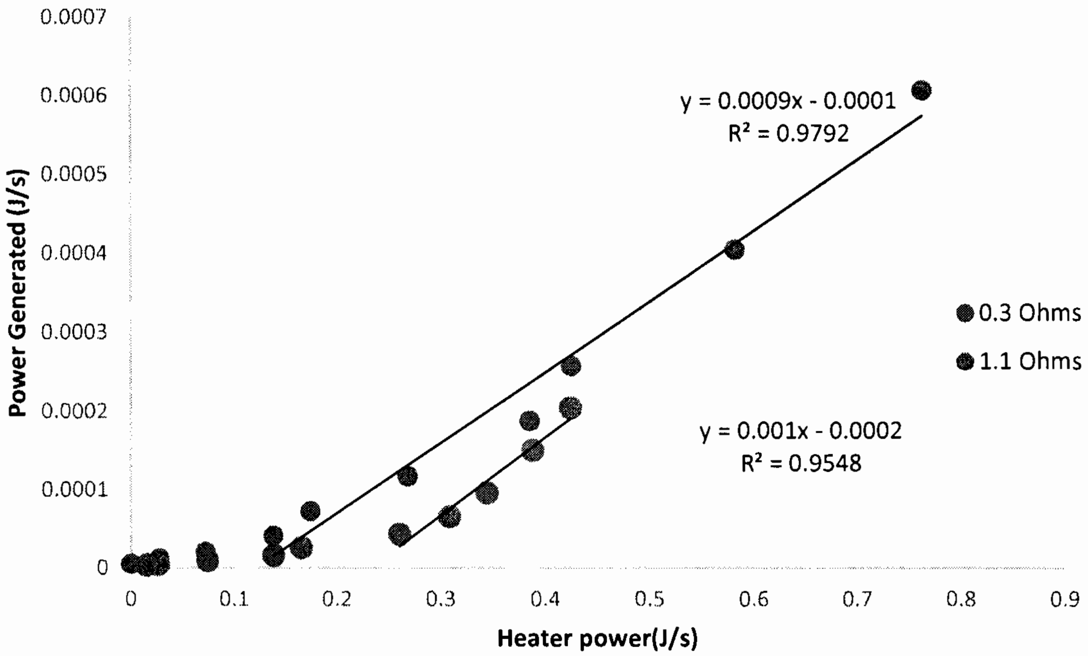

Figure 4.7 The relationship between power generated and power applied to the heater for the 23mm Peltier device with resistor of 0.3 and 1.1 Ohms.

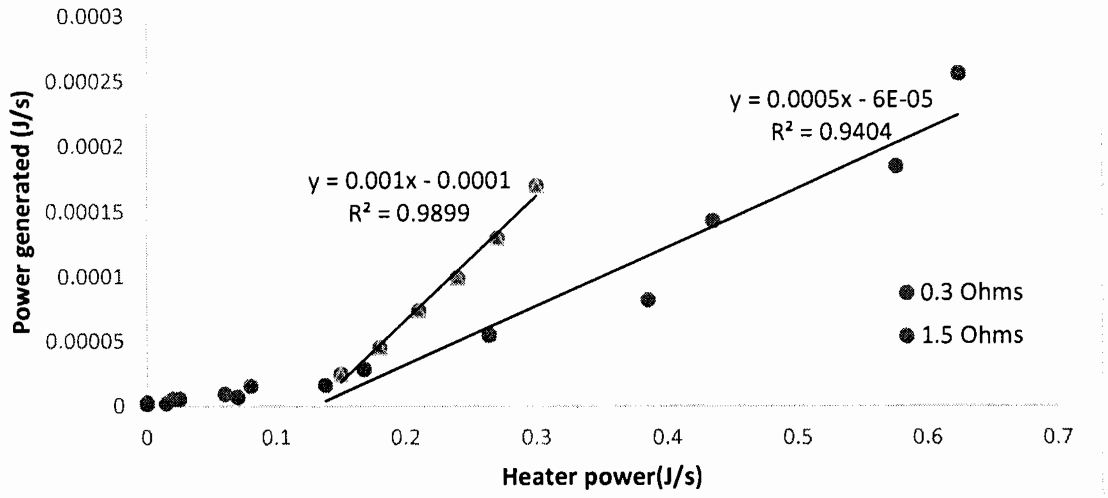

Figure 4.8 The relationship between power generated and power applied to the heater for the 8.3mm Peltier device with resistor of 0.3 and 1.5 Ohms.

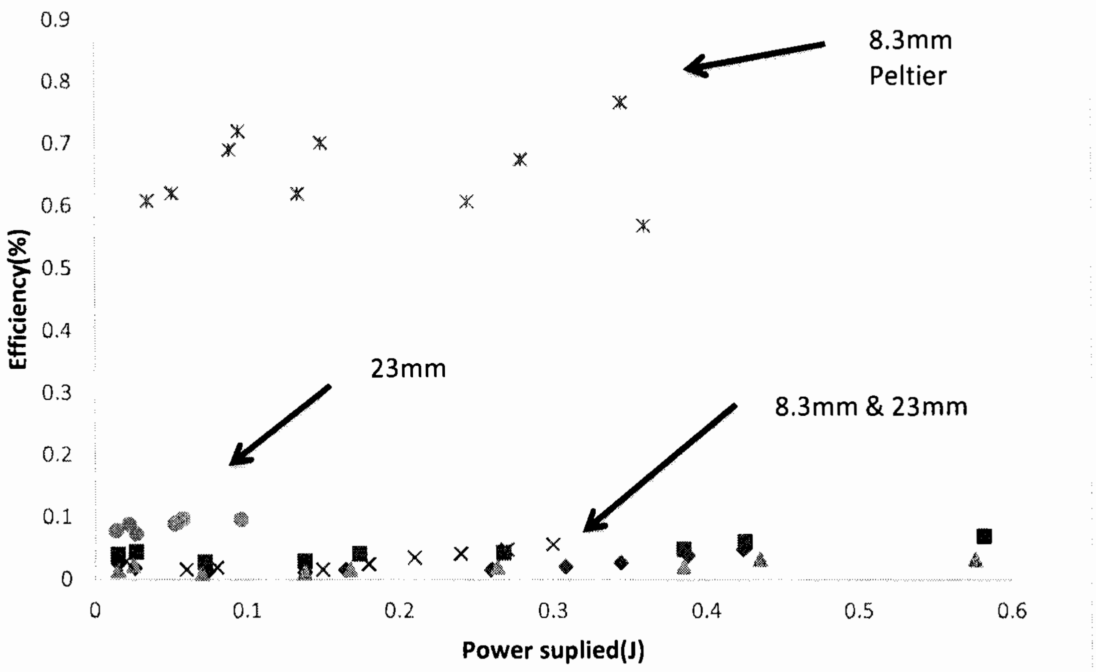

Figure 4.9 Graph that shows the efficiencies of the 8.3mm (x-symbols) and 23mm(circles and squares) devices, with results for both the Seebeck (purple, blue, and green) and Peltier (blue and orange) effects.

When comparing the efficiencies of both effects, it is clear that the Peltier effect is more efficient, as seen in Figure 4.9. This was somewhat expected due to the modules being made for the purpose of using the Peltier effect in applications and not the Seebeck effect. However it is known from theory that the Peltier effect will generally be more efficient due to a larger supply of charge carriers and this data supports that as well. Also from Figure 4.9, the 8.3mm high performance module was significantly more efficient then the 23mm device. This result supports the hypothesis that efficiency is improved by the shorter elements and higher packing densities that this device has.

4.3 Uncertainties

I hypothesize that uncertainty in these experiments is dominated by additional heat flow to and from the environment due to the inadequacy of the insulation. To account for this uncertainty, ice was left in the apparatus for the same amount of time as the tests without the device being turned on. This way the amount of ice that melts would give a value of heat absorbed by the ice from the environment. This was calculated the same way using $Q=mc\Delta T$ and added as error bars to the respective figures. This uncertainty was found as 0.2mJ/s and was added to the graphs as error bars. The uncertainty is significant however the linear trends can still be seen for the efficiencies that were tested.

5. Conclusion

From this study, a working experimental setup was created to allow for the measurement of Peltier and Seebeck efficiencies. The results of the experiment confirm the low efficiencies for the 8.3 and 23mm thermoelectric devices from their manufactures data sheets, less than 1% for Peltier applications. The 8.3mm device had 0.008% efficiency for the Seebeck effect and 0.6% for its Peltier effect. The 23mm device had 0.03% efficiency for the Seebeck effect and 0.08% efficiency for its Peltier effect. This data shows that the 23mm device was better at generating power then the 8.3mm. This follows the trend that more surface area contact will improve the amount of charge moved from applying heat energy. Also the 8.3mm device was better at moving heat with the Peltier effect than the 23mm device. This was somewhat expected due to the device being a higher performance module, and confirms that the properties of shorter thermal electric elements and higher packing densities improve the amount of heat moved from an applied voltage. The Seebeck tests showed a positive trend between the amount of heat changed into electricity and the increase in the amount of incident heat. This seems rather trivial but studies involving high temperature differences, $\Delta T > 500°C$, have shown to improve efficiency of power generation by 10-20%. These results also show the validity for adding thermoelectrics into large systems that that involve waste heat, in order to recapture a percentage of lost energy with a large surfaced thermal electric generator. The Peltier effect data also reflects the use of a thermoelectric cooler to cool small areas such as circuits or DNA samples. This can also be observed from the devices' properties of moving heat quickly in small areas.

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