An Investigation of Thermoelectric Element Power Generation

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Abstract

The purpose of this research project was two fold: to first quantify the cooling ability of a CPU cooling unit and then to characterize the power generation of a Peltier device in the context of a model CPU and CPU cooling unit. A Peltier device is a thermoelectric device that can act as a power supply when the two sides of the device are at different temperatures. Along with that, the goal of the research project was to automate the data collection processes. This was accomplished with prototype circuits on a breadboard that were controlled by a Raspberry Pi 3. Python was the language used for the automation programs. This included for data acquisition as well as data analysis. Studying the cooling ability of the CPU cooling units resulted in Temperature vs. Time plots that showed how the well the cooling units could stabilize temperature when an aluminum block (model CPU) was heated over a range of power levels. Then, using the ability to develop stable temperature differences between the metal block and cooling unit and placing a Peltier device in between the two allowed I-V curves of the Peltier device to be produced by creating a programmable variable resistor.

Contents

1 Introduction

This project consists of experiments that are conducted in the context of the thermal environment of computers. One of the main components of a computer is the CPU. The CPU acts as the ”brain” of a computer handling literally billions of instructions per second. When running at its maximum capacity, otherwise known as overclocking, CPU’s will heat up from thermal power dissipation of the electronic circuitry that makes them up. If this heating is not handled then you risk damaging or even destroying the CPU. A traditional CPU cooling unit, consisting of a heat sink with a fan attached, is the traditional approach. However, the market for these cooling units is abstract in its description of how well they can cool. The initial inspiration for this project was to quantify cooling abilities of these units to see whether or not the price difference between after market cooling units really makes much of a difference.

This first part of the project was the work of Austin Rutelege. His work was repeated to verify his results, but then was extended to include examination of the Peltier device. The Peltier device is an exaggerated version of the thermoelectric effect. It’s a grid of thermoelectric elements that effectively multiplies the usual electric output of a single thermoelectric element. This grid is contained between two ceramic plates and there are two lead wires that extend from it. If there is a difference in temperature between the top and bottom plates, then the device looks like a ”black box” power source. Characterizing how well this power source works in this context of a CPU and CPU cooling unit was the goal of this project.

In carrying out the experiments, it becomes clear that manually measuring and recording data would be tedious and time consuming. Instead, experiment control, safety, data acquisition, and data visualization can all be automated. Raspberry Pi was the choice for use due to their low cost and easy access to general purpose input output (GPIO) pins.

2 Theory

The following principles represent the physics that was applied to the experiments carried in the project.

2.1 Conservation of Energy

During a state of thermal equilibrium, we know that the total energy of the system is constant. Also, if there is energy flowing in to the system, then there must be the same amount of energy flowing out of the system. Since power is a rate of energy, then the power pumped into the system is also equal to the power being dissipated by the system. Expressed mathematically:

$$\Sigma E = constant$$

$$E_{in} = E_{out}$$

$$P_{in} = P_{out}$$

2.2 Active Circuit Elements

In Electronics, to study the DC behavior of an active circuit, one that acts as a power source, we make I-V plots. This is done by connecting various loads to the circuit and measuring the current through the load (I) and the voltage across the load (V). Active circuits have I-V curves that are related to their output resistance by the following equation,

$$I = \frac{-1}{R}V,$$

where R is the output resistance of the circuit.This is of course derived from Ohm's Law:

$$V = IR$$

3 Experimental Design

To model a CPU, a 100W thermoelectric heater was jammed in the middle of an small aluminum block. Using a Pulse Width Modulation (PWM) object to control a power relay that the heater was plugged into, the power level of this model CPU could be controlled and changed from a range of 0W to the maximum 100W of the heater. By keeping the principles stated above in mind, the following designs were used for each experiment.

3.1 Testing CPU Cooling Units

Basically, each cooling unit was tested by seeing how well it could stabilize the temperature of the aluminum block, the model CPU, when the block was being heated at varying power levels. To convincingly say that all (or nearly all) of the energy that is provided by the heater is being pumped out by the cooling unit during temperature stability, heat dissipation to the ambient air had to minimized. By surrounding each side of the block in an insulating foam except for the side that was in contact with the metal block, this was accomplished. Also, a thermal paste was used to ensure good thermal contact between the block and cooling unit. A typical stock Intel cooling unit and an after-market Hyper cooling unit were tested.

For each test, the CPU was run at power levels ranging from 10W to 100W in 10W increments. The temperatures of the metal block, the cooling unit, and the ambient air temperature were recorded for five minutes at each power level. There were two test parameters also in play. Since this is modeling a computer system, a limit of 70°C was set as a maximum for the aluminum block. If the block was ever measured to be 70°C or more, then the run at that power level ended and the block would cool down before going to the next power level. The other parameter was a safety parameter for piece of mind in letting the experiment carry on itself un-monitored. An error was thrown if the block ever got above 100°C and this would cause the whole experiment to end.

3.2 Characterizing the Power Output of a Peltier Device

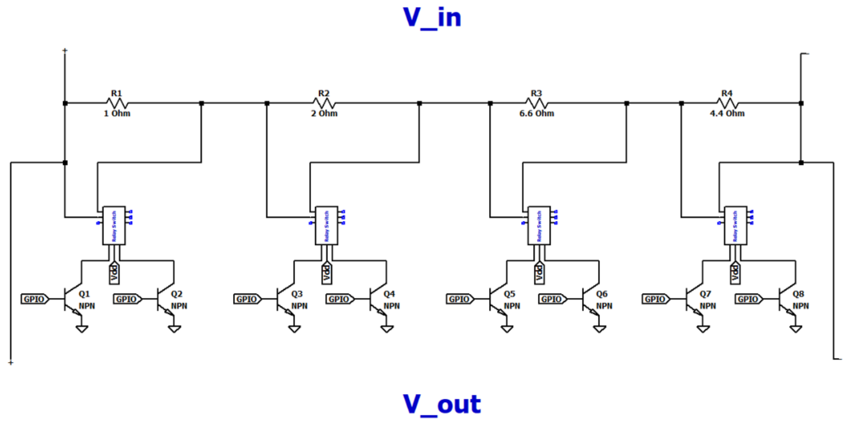
In this experiment, the Hyper cooling unit was used because it was found to be the better cooling unit. The modification to the system was to place the Peltier device in between the hot metal block and the cold cooling unit in order to generate electricity. A preliminary trial was performed using a hot plate as the hot side instead of the metal block and manually loading resistors while taking voltage and current measurements with multimeters. This was to get an idea of what values of resistors would be a good choice for a reasonable spread of data points and to get an approximate idea of power output of the device to know what power rating the resistors needed to be rated for. In order to automate the experiment, a programmable variable resistor was made. Once this was accomplished, the leads of the Peltier device were connected to the input terminals of the programmable variable resistor and the the voltage was measured across the output terminals via an

Analog to Digital Converter (ADC) chip. The current was calculated using Ohm's Law, $I = \frac{V}{R}$, where R was a known, measured value from the variable resistor.

The parameters were different for this experiment. The Peltier device acts an insulating layer between the metal block and the cooling unit since the plates are made of ceramic and there are small pockets of air in the spaces of the grid of thermoelectric elements that make up the Peltier device. Thermal paste was still applied to contact points. Therefore, the power levels ranged from 10W to 50W because the cooling unit could not as effectively pump heat from the metal block. Also, instead of using an arbitrary 70°C as the stopping point, 100°C was chosen because this was closer to the maximum hot temperature operating point of 138°C which was set as the error-throwing/program-ending maximum temperature. This strays from the original context of a CPU environment, however; the goal was more focused on examining the operation of the Peltier device.

3.2.1 Building a Progammable Variable Resistor

The basis of developing a programmable resistor was to control switches. Relay switches which could be opened or closed by a pair of transistors operated by GPIO pins from the Raspberry Pi were the choice candidate. The relay switches were used as a way to by-pass each of the chosen set of resistors. Four resistors were placed in series and and each one had a relay switch that could open or close a path that would by-pass one of the resistors. By combining the values of resistors in every possible combination, the variable resistor could make 16 different resistances. This is because each resistor has two states: either on (added to the total resistance) or off (not added to the total resistance). The number of combinations of four two-state objects is simply $2^4 = 16$. Below, in Figure 1, is a circuit diagram of the variable resistor and a table that summarizes the performance of the variable resistor using $R_1 = 1\Omega$, $R_2 = 2\Omega$, $R_3 = 6.6\Omega$, and $R_4 = 4.4\Omega$. As the switches were closed and the resistance reached its lowest expected values, the actual resistance would not be as low. This was attributed to non-negligible resistance of the jumper wires and breadboard.



Index #	Combination Switches	$R_{predicted}$ Ohms (Ω)	R_{actual} Ohms (Ω)	$R_{predicted} - R_{actual}$ Ohms (Ω)	% Difference %
1	blank	14.2	14.4	0.2	1.39
2	1	13.1	13.7	0.6	4.38
3	2	12.1	12.8	0.7	5.47
4	3	7.6	8.7	1.1	12.64
5	4	9.8	11	1.2	10.91
6	12	11	12.1	1.1	9.09
7	13	6.5	8	1.5	18.75
8	14	8.7	10.2	1.5	14.71
9	23	5.5	6.6	1.1	16.67
10	24	7.7	9.1	1.4	15.38
11	34	3.2	4.9	1.7	34.69
12	123	4.4	5.8	1.4	24.14
13	124	6.6	8.5	1.9	22.35
14	134	2.1	4.3	2.2	51.16
15	234	1.1	2.9	1.8	62.07
16	1234	0	2.1	2.1	100.00

Figure 1: Programmable Variable Resistor Circuit Diagram and Performance Results

4 Results and Analysis

4.1 How Well Do the Cooling Units Work?

Figure 2 shows plots of the temperature of the aluminum block (model CPU) over time at different power levels for each of the cooling units. The Intel plot shows how at 100W, the program kicked into an early cool-down before the five minute mark because the block reached a temperature above 70°C. It is clear that the Hyper unit performs better because of how even at 100W input the unit can still stabilize the temperature 20°C below the maximum allowed temperature.

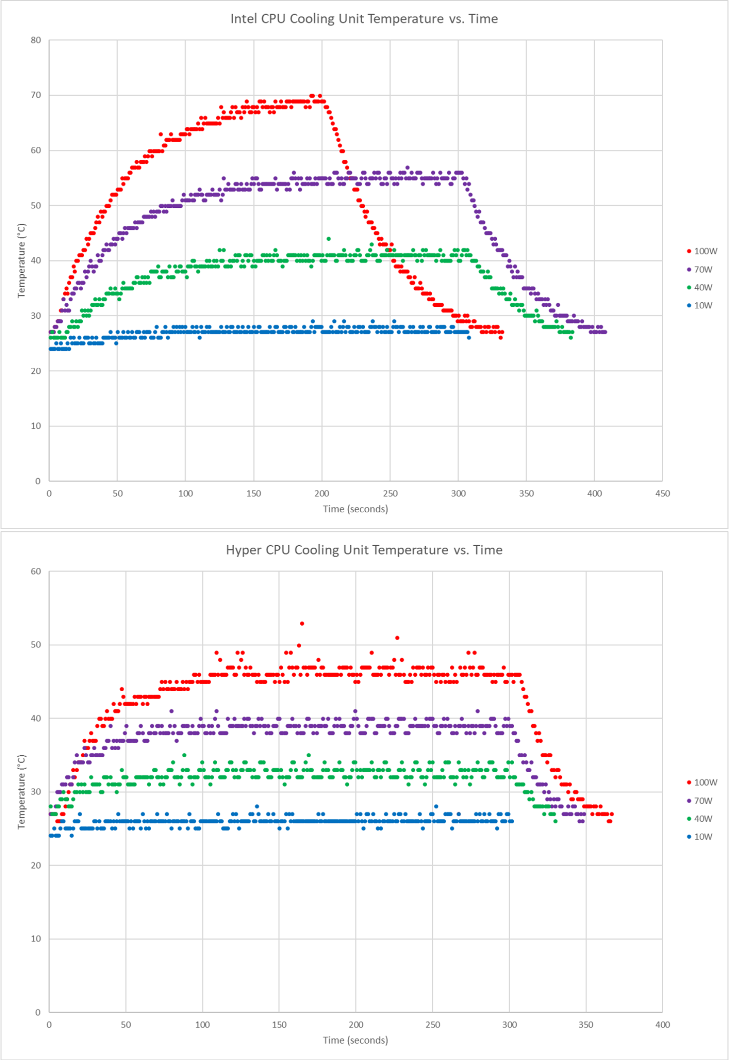


Figure 2: Cooling Unit Performance

For the Intel cooling unit the following calculations were made to determine cooling effectiveness. The measured ΔT values are an average of difference in temperature measured by the metal block temperature sensor and the CPU cooling unit temperature sensor during the time when the metal block was holding at a stable temperature.

$$\text{stable } \Delta T = 21.5°C \text{ at 70W}$$

$$\text{stable } \Delta T = 13.5°C \text{ at 40W}$$

By conservation of thermal energy,

$$Power_{in} = Power_{out}$$

Once the temperature has stabilized, the above equation can be equated to the following equation where G is a proportionality constant.

$$Power = G\Delta T$$

Based on the two measurements above, the proportionality constant for the Intel Cooling Unit averages out to be

$$G_{Intel} = 3.1\frac{W}{°C}$$

The same calculations were made for the Hyper cooling unit based on the measured ΔT values below.

$$\text{stable } \Delta T = 12.2°C \text{ at 70W}$$

$$\text{stable } \Delta T = 16.8°C \text{ at 100W}$$

Based on the two measurements above, the proportionality constant for the Hyper Cooling Unit averages out to be

$$G_{Hyper} = 5.8\frac{W}{°C}$$

The Hyper cooling unit has a higher value for the cooling coefficient which means that it can cool better than the Intel cooling unit. Quantitatively, the Hyper cooling unit can pump nearly $3\frac{W}{°C}$ more than the Intel cooling unit can. Because of this, the Hyper unit was chosen as the cooling unit to use for studying the power output of the Peltier device.

4.2 What kind of Power Output Can the Peltier Device Produce?

Even though this experiment was run over a range of power inputs of 10W to 50W in 10W increments, only the first three power inputs could be used. At both 40W and 50W, the cooling unit could not stabilize the temperature of the metal block below a temperature of $100°C$ with the Peltier device in between the metal block and cooling unit. Figure 3 shows the resulting I-V curves that were attained. Linear regression was applied to the data to form straight-line fits. These fits show the maximum current and voltages, otherwise known as the equivalent Norton current, I_N, and Thevenin voltage, V_{Th}, of the Peltier device at each power input. Also, the equivalent output resistance of the device, R_{Th}, was determined from I_N and V_{Th} by Ohm's Law, $R_{Th} = V_{Th}/I_N$. Refer to Figure 4 for depiction of the equivalent circuits and a table summarizing these maximum currents and voltages.

To determine what the power output of the device is, the linear-fit equations were used which are in the following form:

$$I(V) = \frac{-1}{R_{Th}} V + I_{max}$$

We also know that $P = IV$, so the equation for power output is

$$P(V) = \frac{-1}{R_{Th}} V^2 + I_{max} V$$

Since the linear fits had good R^2 values, the coefficients could be used for the power equation and then the equations plotted to visualize the power output. Figure 5 shows these results.

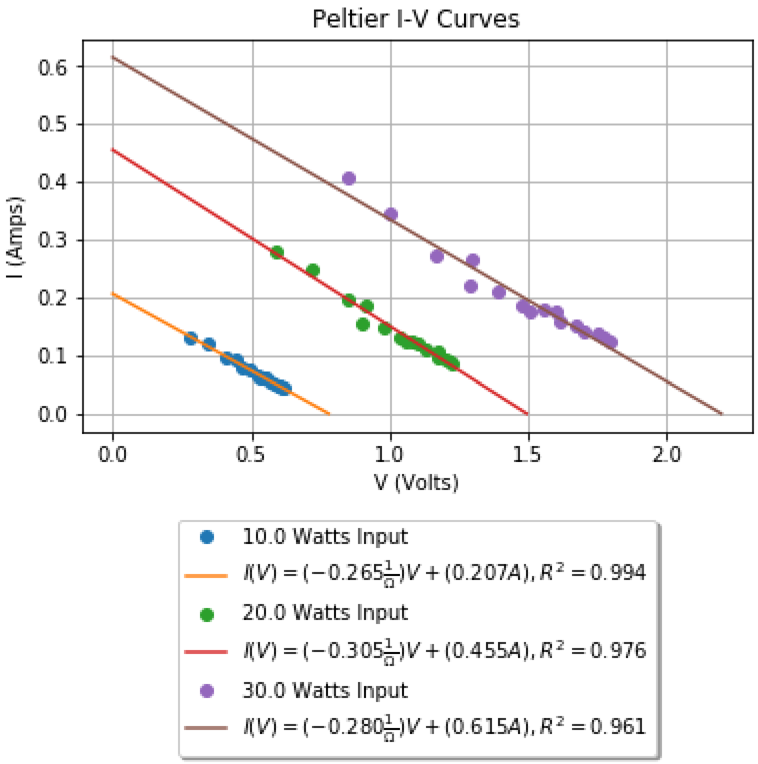
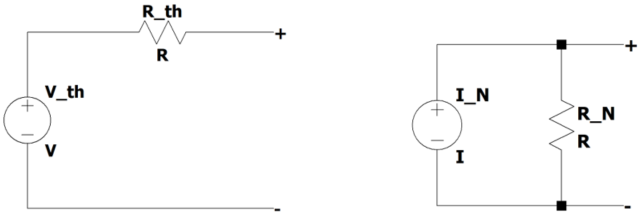


Figure 3: I-V Plots and Linear Fits of the Peltier Device



Power Input (W)	V_{Th} (Volts)	I_N (Amps)	R_{Th} (Ω)
10	0.781	0.207	3.77
20	1.492	0.455	3.28
30	2.196	0.615	3.57

Figure 4: Thevenin and Norton Equivalent Circuits

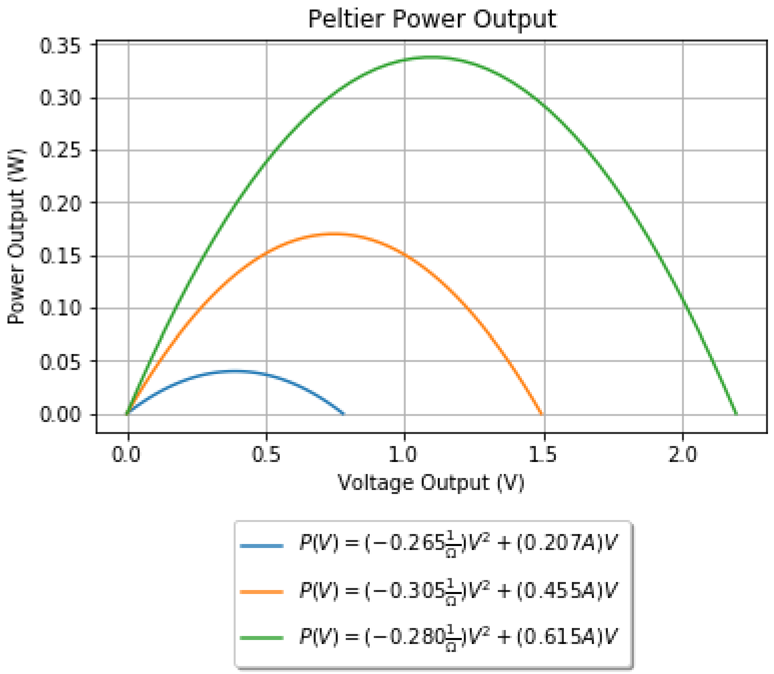


Figure 5: Power Output Curves Determined from Linear I-V Plot Fit Lines

5 Conclusion

A Peltier device is an interesting device. While this project was done in the context of a computer environment, these devices can operate anywhere there is difference in temperature as self sustaining power sources. They do not have any moving parts and can continue to operate as long as the temperatures they are subject too are under the maximum operating temperature of the device. Being able to output over 200 mW by using what would normally only be waste heat makes these useful devices with many possible applications.

A Software Design

Python was the language used for writing the automation programs. The diagram below in Figure 6 shows the packages used and what scripts were written. The key functions and data of each script is included and the relationships of each of the files is also depicted.

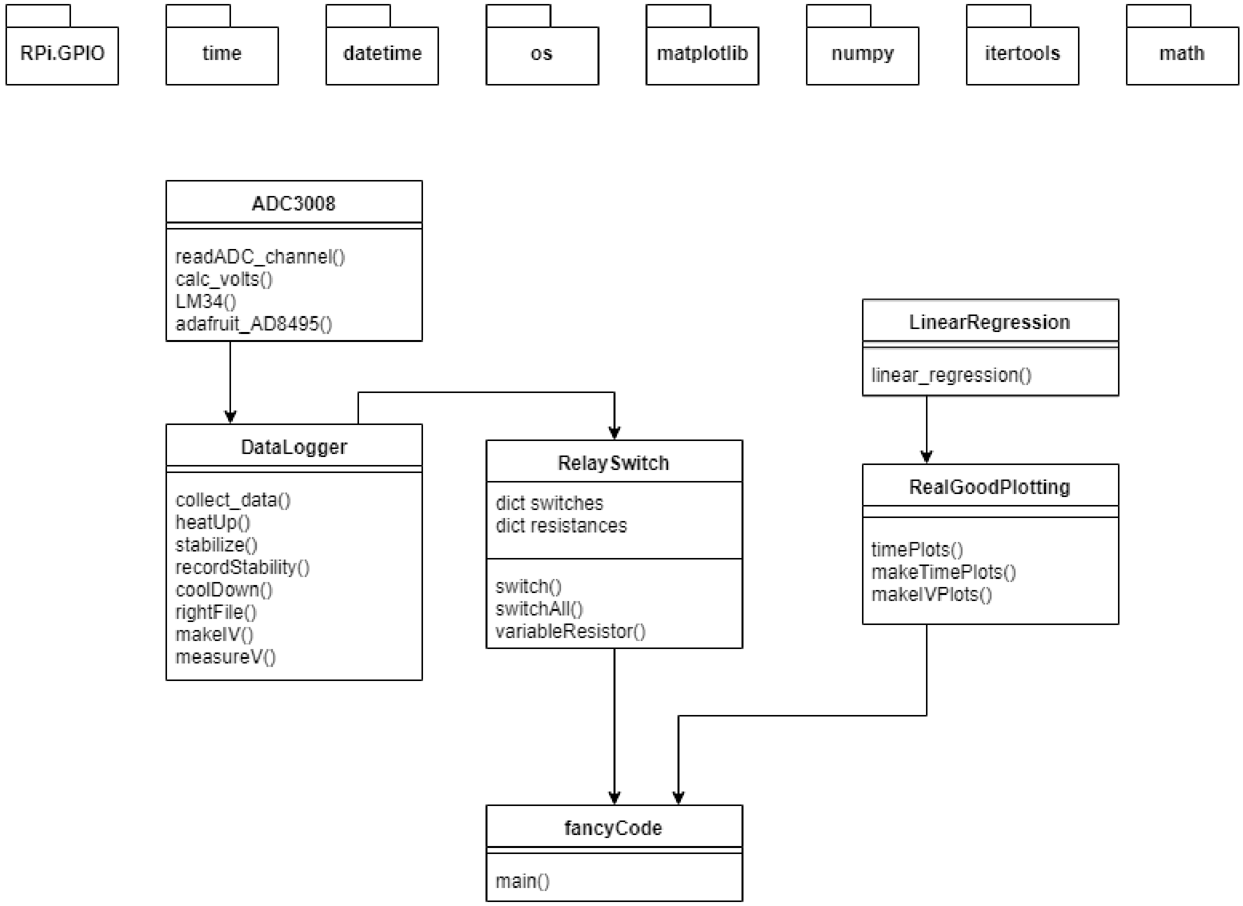


Figure 6: Software Design Schematic