THE PENNSYLVANIA STATE UNIVERSITY
SCHREYER HONORS COLLEGE

DEPARTMENT OF MECHANICAL ENGINEERING

CHARACTERIZATION OF A PELTIER COOLER USED IN A SMALL-SCALE DISTRICT HEATING NETWORK

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Spring 2019

A thesis
submitted in partial fulfillment
of the requirements
for a baccalaureate degree
in Mechanical Engineering
with honors in Mechanical Engineering

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ABSTRACT

Cogeneration is the combined production of heat and power within the same system for improved combined efficiency. When electricity is generated, hot water is typically a byproduct of component cooling. In these systems, rather than discarding the hot water, a secondary loop is implemented where it can instead be used to heat buildings within a District Heating Network (DHN). The delivery of hot water to the buildings in the network occurs through large underground pipes that are subject to energy losses and transport delays. Once the hot water is delivered to a building, a heat exchanger is used to deliver the requested heating power.

To study the heat losses experienced by a DHN, a small-scale DHN was built using a water heater, a pump, Pex piping, and thermal masses to represent the buildings within the network. To mimic the effect of heat losses to cold air outside these buildings, the thermal masses include a Peltier cooler that uses thermoelectric cooling and the Peltier effect to remove heat. This experiment studies the heat removal capabilities of these Peltier coolers and the impact of the desired temperature on the cooler's performance, which has been identified as the limiting design factor of the small-scale DHN.

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ACKNOWLEDGEMENTS

I would to thank everybody who helped me in every step of this thesis writing process. First, the constant willingness of Dr. Stephanie Stockar to meet with me and answer any questions made this whole thesis so much less stressful. To Stephen Boyle, Brian Block, and Brian Huynh I'd like to say thank you for your input and feedback on my content and your guidance whenever I brought questions to lab meetings. To Melissa Krieger, I am proud of all that you accomplished with starting this experiment, and I know that I owe this whole project to you and the work you put in to set me up for this year. I'd also like to thank Dr. Hosam Fathy for believing in me for the past four years and making sure I stayed on track with both my thesis and all my other Honors College requirements. Finally, to Dr. Stephen Peluso, I'd like to express my sincerest gratitude for all that you have done for me and our lab in general. You were always available for help whenever it was needed, and I can honestly say you personally saved us all from many potential disasters.

Chapter 1 : Literature Review

Existing Use of Cogeneration in District Heating Networks

The concept of a district energy system is not new, however recently a new possibility of cogeneration was introduced. Cogeneration involves the production of heat and electricity for users within a network at one location, referred to as combined heat and power (CHP). This process is also able to produce increased efficiency when compared to individual heat and electricity production. Up until the 1980s the sources of energy within district energy systems were almost solely coal and oil, until the introduction of infrastructure that allowed for energy production from biomass and waste [1]. U.S. energy consumption in 2014 is displayed in Figure 1, which clearly shows the recent push towards renewable energy sources and natural gas, especially when compared to the energy consumption in 2005.

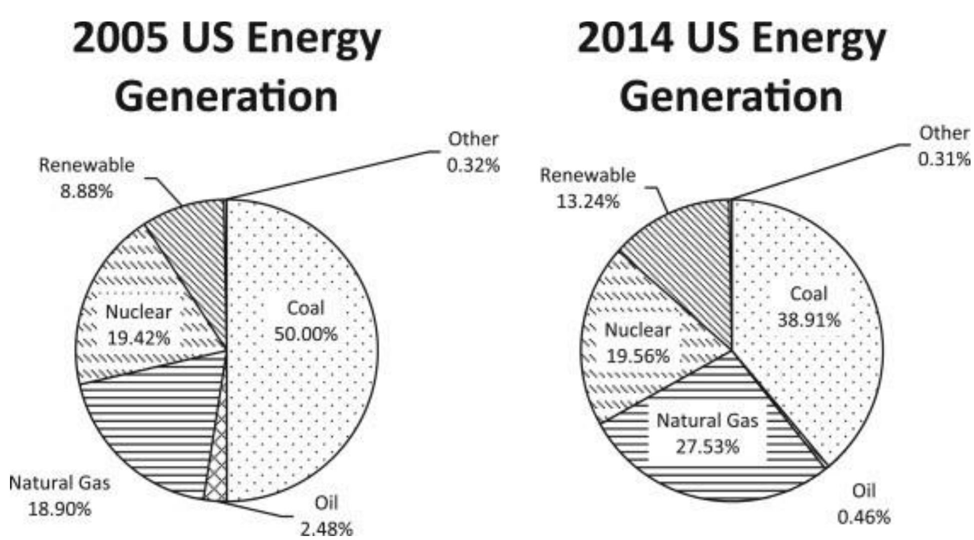

Figure 1 US energy consumption in 2005 and 2014, with visible push towards renewable resources [1]

The recent push for energy sources that are more environmentally friendly makes the district energy system a competitive technology for limiting the environmental impact of electricity generation and heating demands. Cogeneration can utilize many different primary energy sources, and studies have shown the design feasibility of district energy systems that use solely renewable sources and biomass incineration. This produces sufficient heat and electricity for the demand of a medium sized network while drastically reducing the CO_2 emissions, which plays a large role on the environmental impact of an energy system [1]. Research and development surrounding district energy systems, for both heating and cooling, needs to be completed if they are to run primarily on renewable energy sources, as the existing infrastructure in modern networks stands in the way of this goal. The existing infrastructure, however, does provide opportunities for dramatic improvement even with the use of common non-renewable energy sources.

There are several district heating network installations in operation today and they are studied in literature extensively with the objective of improving their energy efficiency and limiting operating costs. One such example is the case study of the DHN in Göteborg, Sweden. Göteborg is a city on the western coast of Sweden and their DHN is managed by Göteborg Energi (GBE). This case study observes the effects of three types of heat sources within the DHN [2]. The three sources are combined heat and power, heat from industries, and waste incineration. These sources are limited by certain policies, including energy taxation and emissions regulations (primarily for waste incineration). The study also simulates optimization of this DHN using a system called MODEST (model for optimization of dynamic energy systems with time-dependent components and boundary conditions). Upon simulation, the lowest cost to GBE comes from a DHN that features more heat from waste incineration at 360 million euros over ten years. The study shows that using more waste incineration reduces the global CO_2 emissions, which is due to the combined heat and power generation possibilities. Incinerating the waste provides heat to the DHN but also provides electricity to the network, thus reducing the need to generate electricity through other methods that traditionally contribute to CO_2 emissions. This entire study, however, uses a constant price for electricity. Further research will be performed on the optimization of different primary energy sources to the network for heat and electricity based on the fluctuation of electricity prices. As prices increase or decrease it could become more efficient to burn more or less waste.

A study on an existing network in Narva, Estonia, shows the indisputable importance of infrastructure quality. The network uses combined heat and power from the Balti and Eesti power plants, but due to poor insulation on existing piping the heat losses are as high as 18-19% [3]. These losses are much higher than typical Swedish DHNs with similar heat demand, which typically have losses of 7-9%. With these existing losses resulting from the poor infrastructure of the central heat network the local residents of Narva elected to keep localized heating. The case study of Narva has shown that heat losses must be reduced as a priority to keep DHNs feasible, especially considering returns on initial capital investments. Several different energy inputs for cogeneration are considered, however due to the existing infrastructure within the power plants a method of cogeneration with oil shale would be the most cost effective. Return on investment breaks even at 9 years, and the availability of this type of fuel will remain stable.

Energy and Exergy Analyses in Literature

Within any real DHN there will be energy and exergy losses. To study these losses, Hongwei Li and Svend Svendsen of the Technical University of Denmark designed a small-scale, low temperature DHN to provide heat for 30 low energy houses [4]. In this study a low energy house is considered a one story, single family house. Thermal bypasses are placed at the critical user of the network to assist in the prevention of heat loss due to low flow rates in seasons of lower heat demand. The study shows that the most efficient DHN is one featuring smaller pipe diameters and lower temperatures. Low temperature networks and medium temperature networks were both considered, and they yielded overall energy efficiencies of 85.6% and 79.2%, respectively. Heat loss also increases for the medium temperature network, but decreased pipe diameter decreases heat loss. The annual exergy loss for the low and medium temperature systems are 43.5% and 27.1%, respectively. A large portion of this exergy loss is due to heat loss within the pipeline, especially because the study does not consider heat loss within the houses. The effects of using a thermal bypass at the consumer end are increased heat loss in the return pipe and increased exergy loss as the bypass water mixes with the supply water. However, overall energy and exergy efficiencies can be increased with a decrease in bypass temperature. Heat loss increases as the ambient temperature decreases, as displayed in Figure 2. Thus, the overall efficiency decreases as the ambient temperature decreases.

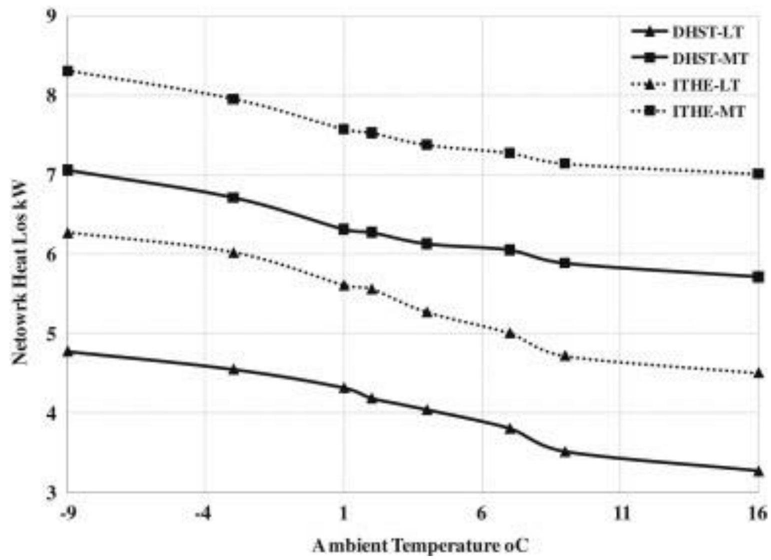

Figure 2 Effects of Ambient Temperature on Heat Loss [4]

When studying the efficiency of a DHN it should be noted that energy and exergy efficiencies may differ drastically. Exergy is an important measure because it accounts for the systems interaction with the outside environment as well. This displays a more true efficiency than solely energy [5]. For example, a case study was performed on a DHN in Edmonton, Canada that utilizes cogeneration. In one scenario the case study determined the energy efficiency of the system to be 94%, implying an incredible efficiency. Exergy analyses of the same scenario warranted a value of 28%, which is much lower and shows a lack of overall thermodynamic efficiency [5].

Economic Considerations of a District Heating Network

While the efficiency benefits of a DHN that features cogeneration are clear, the economic cost of implementing this technology should also be considered. A study of DHNs performed by Rezaie Behnaz and Marc A. Rosen at the University of Ontario Institute of Technology [6] gives a strong consideration to the economic cost. European networks were considered, primarily single-family homes using district heating. The economics of a heating network were narrowed down to three main factors: production cost of thermal energy, the cost of the thermal energy distribution network, and customer connection costs. Unfortunately, the customer connection costs are highest when adding a DHN to a preexisting community, and are only minimized when added during community development. This brings attention to the cost of fitting this technology into major cities that have existing infrastructure. Small towns with low population density are not worth the cost of installing of a DHN, rather it is most economical for larger buildings with high heat demand or areas with high population densities and thus a higher heat demand. DHNs have proved most profitable when the overall cost is lower than heat production by other means. For example, if the cost of delivering the heat to customers increases it may be compensated by lower costs of recycled energy. When installing a DHN, the capital costs and energy efficiencies are optimized with the use of smaller pipe diameters [7]. Pipe costs for this conclusion were based on insulated steel pipes, placed in conditions similar to the case study performed in South Wales. The equivalent annual cost, which includes the cost of energy consumption, calls for different pipe sizes based on the style of DHN used. These styles, analyzed in [7], use both constant and variable flows and temperatures. Pump size and pipe diameter are very dependent on the temperature regime of the DHN.

Another study exists that performs analyses of a DHN using a Clustering Pareto Evolutionary Algorithm (CPEA) [8]. Applying this algorithm shows that there are different optimal solutions based on the consideration of pollution. The pollution considered is CO_2 emissions, which typically increase as price decreases. For example, when considering a two-objective approach with the CPEA, the model producing the least pollution involves one central heat pump covering the entire heat demand. This is based on a network with consumers requiring relatively low heat demand. Within this two-objective model, however, the most cost efficient involves the use of a heat pump, gas turbine, and an auxiliary boiler. The environmental and economic impacts must be weighed against one another in determining the feasibility of any DHN design, and it should also be noted that the results of the CPEA were based solely on the two-objective approach. When considering three objectives (electricity costs, gas costs, and investment costs), the optimization is not as clear and thinning of the algorithm occurs.

Governmental policies, while not solely economic, will play a massive role in the continuation of research and eventual installation of DHNs with cogeneration. Cogeneration is particularly effective at reducing CO_2 emissions when bioenergy is a fuel source, however installing the necessary infrastructure for bioenergy is expensive. The cost is significantly larger than the cost to continue fossil fuel consumption, so enticement will need to come from the government in the form of taxes [9]. Finland and Sweden already charge taxes on fossil fuel consumption and are committed to policies that will help the growth of DHN technology. Installing the infrastructure poses a risk to private companies, and also opens the possibility for monopolies to develop. It is critical that governments regulate the prices of energy grids for DHNs to reach their potential.

Chapter 2 : Methodology

Objective

District heating networks offer ample opportunity to increase the efficiency of electricity and heat generation. With a growing push towards reducing environmental impact, research surrounding DHN's has gained importance. For this reason, a small-scale DHN experiment was built, giving the capability to simulate the heat losses featured in a full-size system and to verify simulation and control design models. A key component of this model is a Peltier cooler, which is used to simulate the effect of the cold air outside of a building that needs to be heated. The objective of this experiment is to size the Peltier cooler, and determine the maximum rate at which it can remove heat from the system. This will allow the rest of the experiment to be scaled based on the capabilities of the cooler.

Experimental Set Up

The experiment features a water heater, a pump, two thermal masses, bypass valves, and a closed network of Pex piping, see Figure 4.

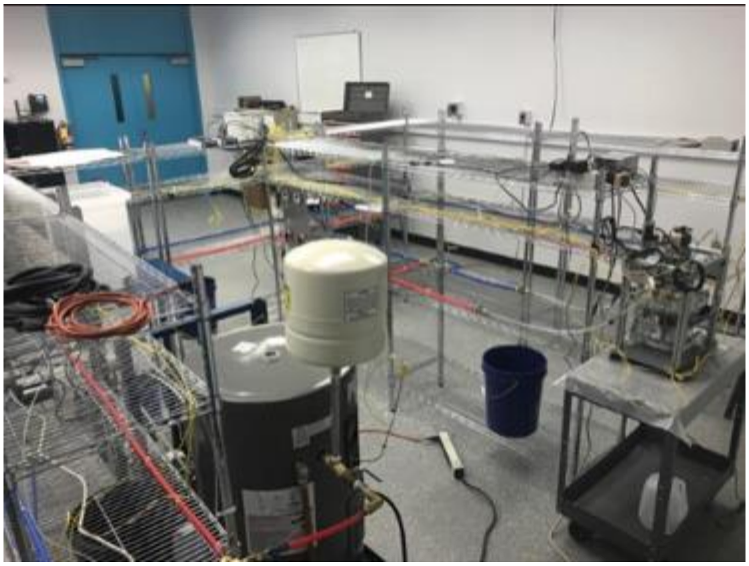

Figure 3 DHN Experiment

The red Pex piping delivers the hot water from the water heater to the thermal masses. The water goes through a copper pipe in the thermal mass, and exchanges heat to warm the water inside the thermal mass which represents the temperature of a building. Then, the water returns to the heater through the blue Pex piping. Each of the thermal masses have a Peltier cooler mounted on the outside, pictured in Figure 5.

Figure 4 Thermal mass with mounted Peltier cooler

Within the experiment, the Peltier cooler is used to represent the effect of the outside temperature on the temperature dynamic of the building.

The Peltier Effect

Peltier coolers are a key part of this experiment. They can extract heat from the thermal masses through the simulation of a desired outside temperature. Peltier coolers are able to extract heat by creating a temperature gradient, while using no moving parts. This separates them from devices that use a fan, rather these thermoelectric coolers use current and something called the Peltier effect. Discovered in 1834 by Jean Peltier [9], this effect states that when two semiconducting materials (one positively doped and one negatively doped) are placed together and a current is run through them, the charge carried from both materials moves with the current and removes heat from the system. Should the current be applied in the opposing direction, Peltier coolers can also be used to add heat to a system.

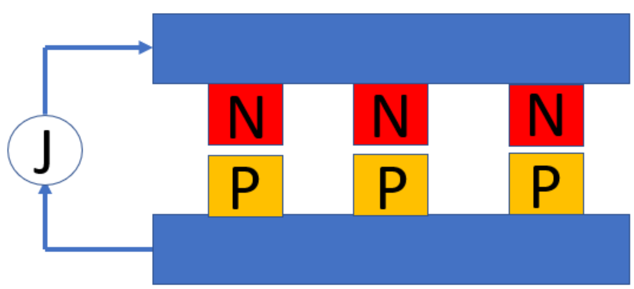

Figure 5 Diagram of a Peltier cooler

The elements of a typical Peltier cooler are pictured above in Figure 3. The cells labeled “N” represent the negatively doped material and the cells labeled “P” represent the positively doped material. These cells are connected electrically in parallel, and when current flows from the negatively doped material to the positively doped material it creates the cooling effect that is used in this experiment to remove heat from the thermal masses [10].

Data Acquisition and Sensor Placement

To understand the energy losses and cooling performance of the system, temperature, mass flow rate, and pressure data at different locations are collected with a DAQ and viewed in LabView. The program allows users to set the outdoor temperature that the Peltier cooler will simulate. The cooler has a hot and cold side, and the cold side is pressed against the thermal mass. The hot side is cooled using a heat sink. Temperature for the hot side, water inside the thermal mass, and the ambient temperature are all monitored with thermocouples. The temperature of the cold side of the Peltier junction is monitored through a built-in sensor, and the power delivered to the Peltier junction is recorded as well. All of this data, as well as temperatures and pressures in other parts of the system, can be seen in real-time with the use of a Labview program. A screenshot of the Labview VI is shown below.

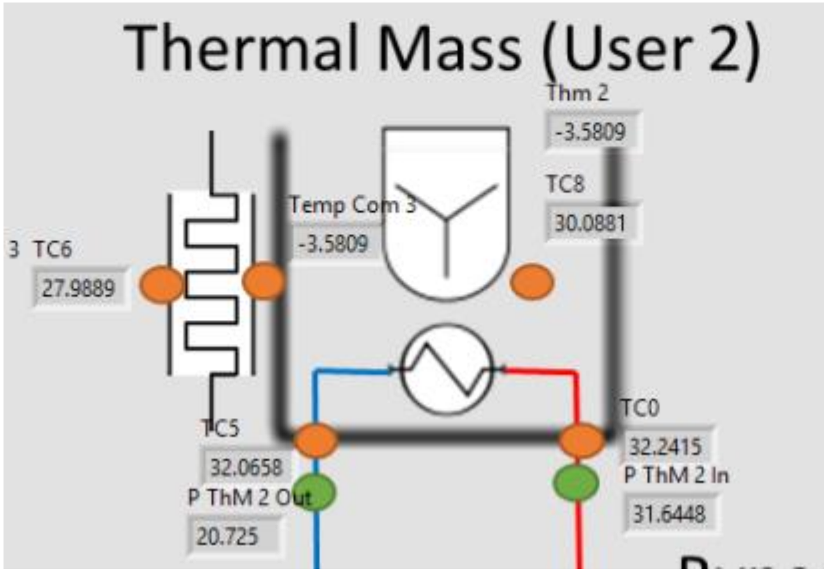

Figure 6 Labview VI

When in use and powered on, the Peltier cooler is controlled with a separate Labview VI that allows users to choose a specific outdoor temperature to simulate, or a specific percentage of its total power to use. The Peltier cooler is the limiting factor of this experiment. The water heater and pump are able to deliver hot water, and thus heat the thermal mass, at a rate much higher than the cooler's heat removal capabilities. Therefore, these results will allow the rest of the experiment to be scaled based on the performance of the Peltier cooler. The water inside the thermal masses is bound to experience heat transfer with the solid walls [11]. Therefore, since the water is not in direct contact with the Peltier cooler, this is not an ideal heat transfer system. This explains some of the difficulty faced by the Peltier cooler in removing heat from the system, as heat transfer must occur between the cooler, the wall of the thermal mass, and then the water inside the mass. It should also be noted that this experiment features a much higher heating capability than a real DHN, which again makes the Peltier cooler the limiting factor. This experiment does not feature the same geometric ratios that a real network would have. The flow area of the copper pipes within the thermal masses compared to the volume of the water they are heating is much larger proportionally than a real DHN. Meeting these geometric similarities is very important to ensuring accuracy of an experiment [12].

Since the objective of this work is to characterize the maximum heat rejection capacity of the Peltier cooler, the following sensor data are recorded: the temperature of the water entering the thermal mass, the temperature of the water leaving the thermal mass, the temperature of the water inside the thermal mass tank, the temperature of the hot side of the Peltier cooler, the temperature of the cold side of the Peltier cooler, and the ambient temperature.

Sensor Verification

Before collecting experimental data, the readings from the thermocouples to be used in the experiment had to be verified. Specifically, thermocouples for the water inside the thermal mass and the ambient temperature needed to be compared while the Peltier cooler was turned off. Any major discrepancy between the temperature readings of these two thermocouples would need to be addressed moving forward. This was done by running the Lavbiew VI for 30 minutes to collect temperature data from the two thermocouples, and plotting the data to check for differences. The plot is shown below.

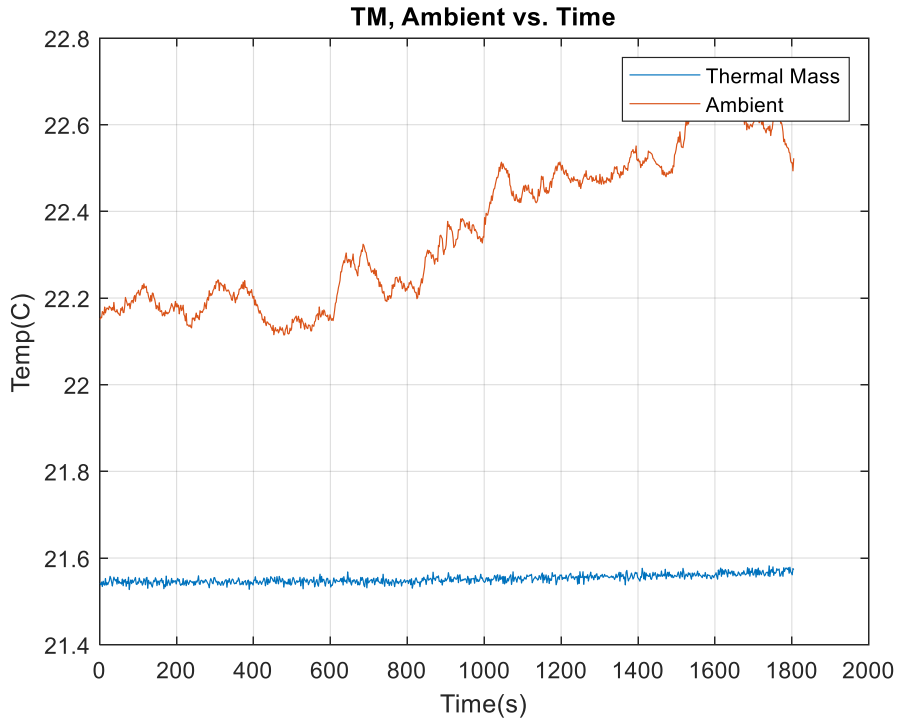

Figure 7 Testing thermocouples

The ambient temperature shows values hovering from just below 22.2 C to just over 22.6 degrees C. These are reasonable values for ambient temperature, and the slight increase in temperature throughout the test could be attributed to heat given off by the persons or equipment in the room. The water inside the thermal mass stayed at just under 21.6 degrees C, which is within 1 degree C of the ambient temperature. This was a small enough discrepancy to continue data collection with the same equipment.

Experimental Procedure

In order the determine the maximum heat extraction power of the Peltier cooler, the system must first be heated to a predetermined starting temperature. All sets of data analyzed featured a starting temperature of 30 degrees Celsius. This is done by turning on the water heater and pump, and allowing hot water to flow to the thermal mass. Data is recorded using the Lavbiew VI mentioned in the previous section. When the water inside the thermal mass reaches the designated temperature the pump is turned off and the inlets and outlets of the thermal mass are closed. This isolates the thermal mass from the rest of the system. The Peltier cooler is then turned on with a starting desired temperature that matches the temperature within the thermal mass. The desired temperature is then lowered by increments of 4 or 2 degrees depending on the experiment. When the temperature inside the thermal mass reaches the desired temperature, it is dropped again by 4 or 2 degrees. With data for the ambient temperature, Peltier cooler temperature, and temperature within the thermal mass, the rate that the Peltier cooler removes heat can be calculated using the heat loss equation.

$$Q = C_v \cdot m \cdot \Delta T$$

In this specific case, Q can be reduced to solely Q_{out} because when the bypass is opened and flow to the thermal mass stops, there is no longer any heat being added to the system and thus Q_{in} is equal to zero. The goal is to find the maximum rate that heat can be removed, so the equation needs to show rate, thus $\dot{Q}$. Therefore, the equation becomes:

$$\dot{Q}_{out} = \dot{Q}_{pelt} + \dot{Q}_{amb}$$

In this equation, $\dot{Q}_{pelt}$ represents the heat loss due to the Peltier cooler and $\dot{Q}_{amb}$ represents the heat loss through the rest of the thermal mass to the ambient temperature. The heat loss to ambient temperature is assumed to be negligible in this experiment, and thus $\dot{Q}_{amb}$ is assumed to be zero. Adding in constants representative of the Peltier cooler the final equation can be expressed as such:

$$\dot{Q}_{out} = C_v \, m \frac{dT}{dt}$$

In this equation, C_v represents the specific heat of water, which is 4.12 kJ/kg-K in the temperature range used in this experiment. The mass of the water is represented by m, and with a volume of 0.0035 m^3 and a density of 995.65 kg/m^3 the mass of the water in the thermal mass is 3.485 kg.

Chapter 3 : Results and Recommendations

For characterizing the limitation of the Peltier junction, a number of experiments have been conducted at different initial temperatures and at different resolution in the desired temperature. The first experiment performed featured a starting temperature of 30 degrees Celsius with the desired temperature decreasing by increments of 4 degrees.

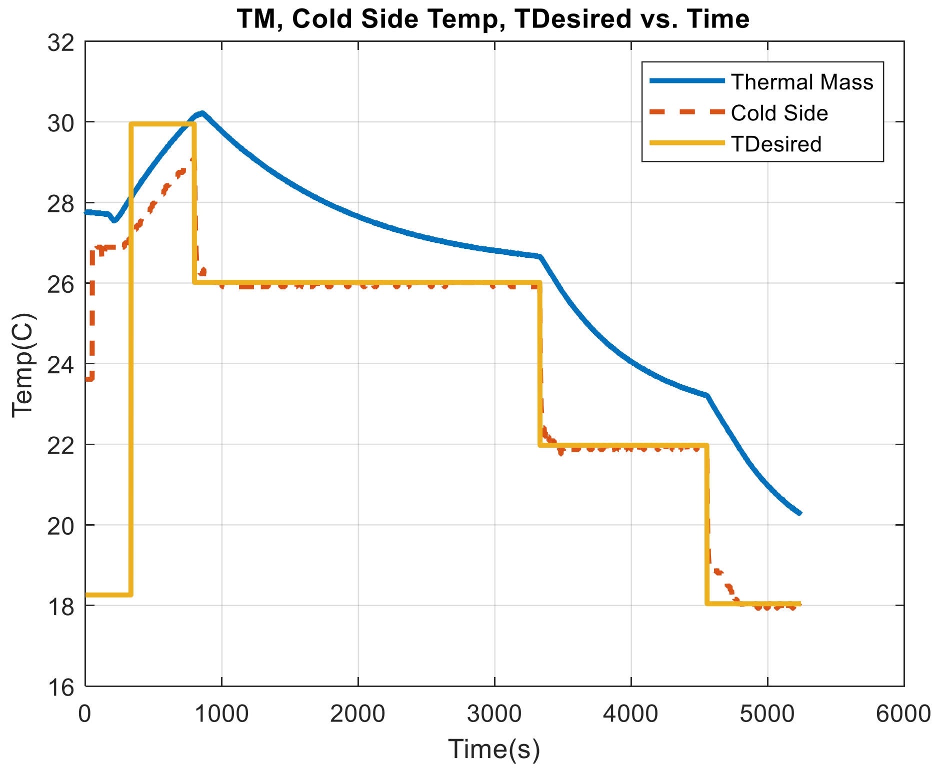

Figure 8 Start temp of 30 C with increments of 4 degrees

Figure 8 shows the desired temperature starting at 30 degrees, and then decreasing by 4 degrees when instructed on the VI. The experiment ran for about 1.5 hours. The blue line in Figure 8 shows the temperature on the cold side of the Peltier cooler. This is the side pressed against the wall of the thermal mass, and it is responsible for removing heat from the system. The plot of the cold side temperature is almost identical to the plot for the desired temperature meaning that the Peltier cooler is very quickly able reach the temperatures needed for the experiment. This means that under these conditions it is possible to instantaneously control the equivalent ambient temperature. Once the cold side reaches the desired temperature, the plot shows that it remains at that temperature and continues to cool down the thermal mass until the command is given to decrease the desired temperature. This is shown in Figure 8 in the step-like behavior of the desired temperature.

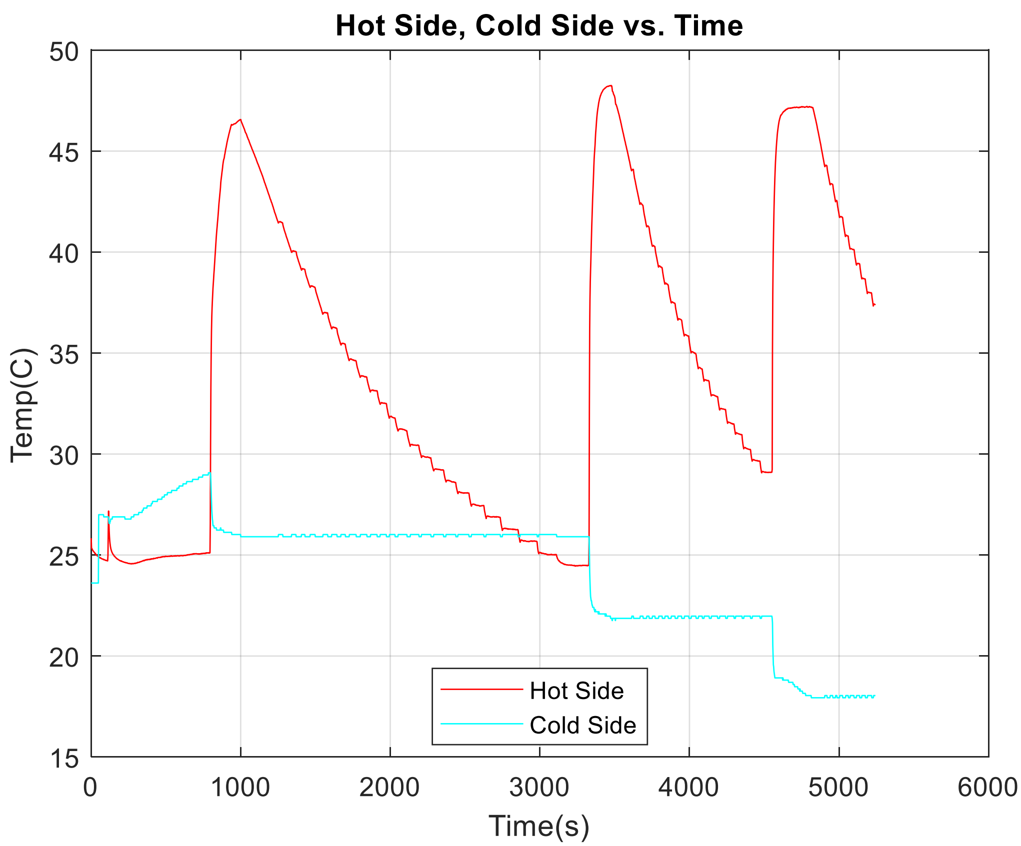

Figure 9 Hot side and cold side with increments of 4 degrees

Figure 9 shows the hot side and cold side temperatures of the Peltier cooler. When the desired temperature is decreased, the cold side immediately begins dropping its temperature, which is shown in the step-like behavior. The hot side temperature spikes upwards in a similar manner, but with a much larger value. This behavior explains the manner in which the Peltier cooler consumes power, shown below. This system is limited by the cooling performance of the hot side. Once it reaches a certain temperature, the Peltier junction is unable to reject heat, no matter the power supplied to the system.

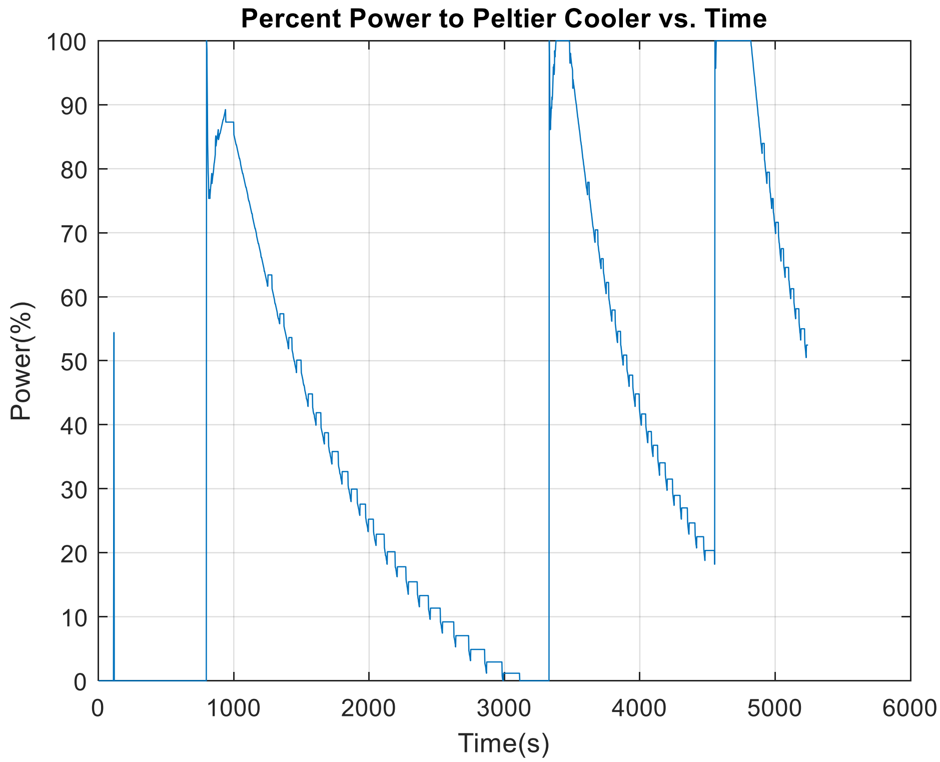

Figure 10 Percent power to cooler with increments of 4 degrees

Figure 10 shows the percent of the total possible power of the Peltier cooler being used. The jumps in percent power coincide directly with the reductions in desired temperature. They also coincide directly with the large increases in temperature on the hot side of the Peltier cooler.

Each interval was analyzed using the equation mentioned in Experimental Procedure to find the heat removal rate, and then an average for the whole experiment was found. These results are displayed in Table 1 below.

Table 1 Analysis results for 4 degree increments

Desired Interval (C)	T Start (C)	T Fin (C)	ΔT	t start (s)	t fin (s)	Δt	Q (kW)
30-26	30.22	26.62	3.6	861	3335	2474	0.020892
26-22	26.62	23.2	3.42	3335	4557	1222	0.040182
22-18	23.2	20.27	2.93	4557	5241	684	0.061501

The average heat removal rate for the experiment with intervals of 4 degrees was 0.0409 kW.

The experiment with a starting temperature of 30 degrees Celsius and desired temperature increments of 2 degrees showed similar results. Featured in Figure 11 below, the plots for the desired temperature and the cold side of the Peltier cooler show almost identical behavior.

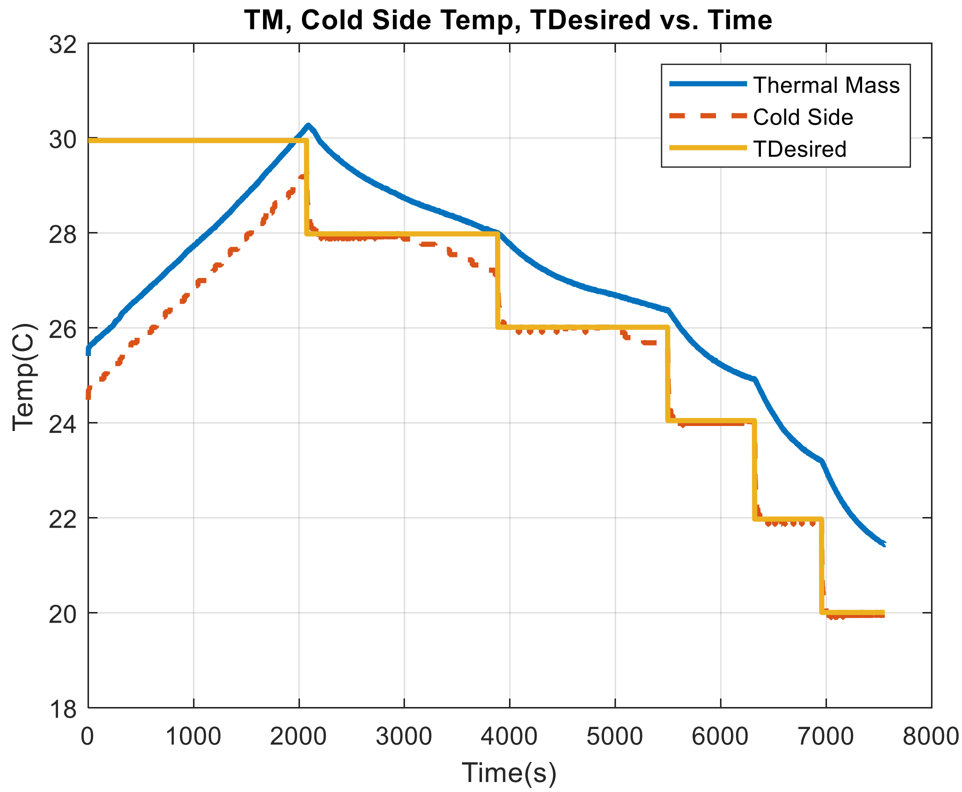

Figure 11 Start temp of 30 degrees C with increments of 2 degrees

Once again, the hot side temperature jumps up at the same time that the cold side temperature decreases, which is a result of the desired temperature decreasing. This is illustrated below in Figure 12.

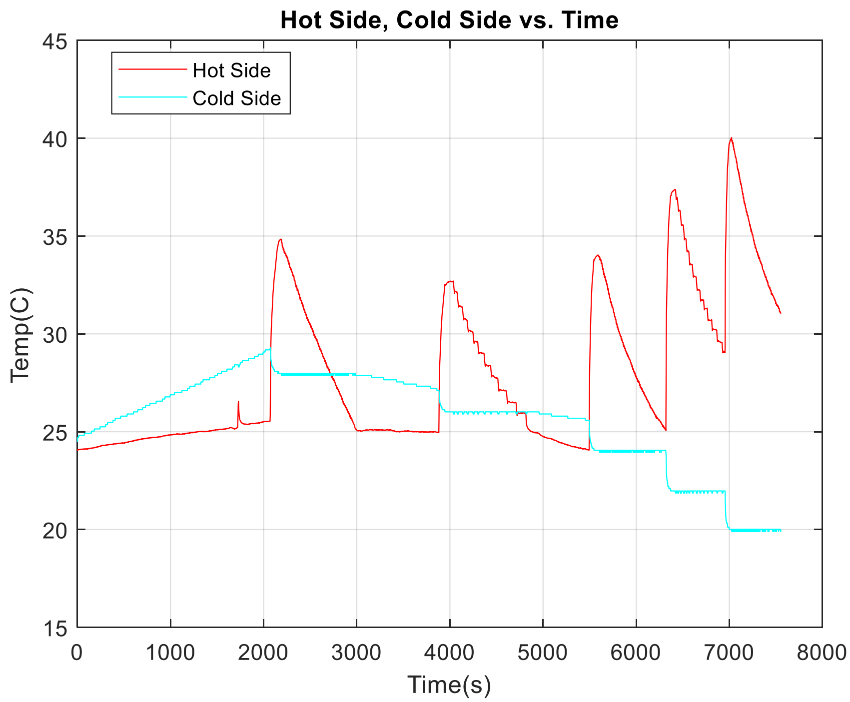

Figure 12 Hot side and cold side of cooler with increments of 2 degrees

The jumps in percent power used also coincide with the decreases in desired temperature, just like the experiment with 4 degree increments. This is shown below in Figure 13.

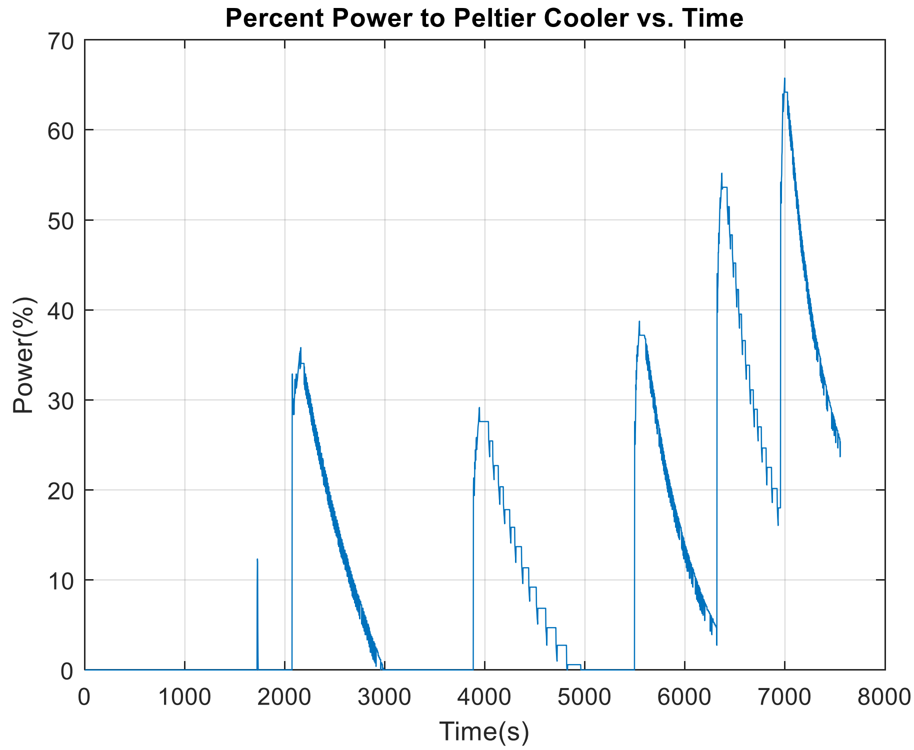

Figure 13 Percent power to cooler with increments of 2 degrees

The difference between using increments of 2 degrees and increments of 4 degrees becomes more evident when analyzing the heat removal rates, shown below in Table 2.

Table 2 Analysis results for 2 degree increments

Interval	T Start (C)	T Fin (C)	ΔT	t start (s)	t start (s)	Δt	Q (kW)
30-28	30.25	28.02	2.23	2085	3865	1780	0.017987
28-26	27.98	26.36	1.62	3883	5507	1624	0.014322
26-24	26.36	24.92	1.44	5507	6319	812	0.025461
24-22	24.92	23.18	1.74	6319	6961	642	0.038912
22-20	23.18	21.48	1.7	6961	7533	572	0.04267

These intervals produced significantly lower heat removal rates when compared to the 4 degree increments, with an overall average of 0.0279 kW. This value is slightly more than half of the value produced by the 4 degree increments. The difference seems to come from less power supplied to the Peltier cooler. When the desired temperature is only dropped by 2 degrees, the necessary change of the cold side is less drastic, so the Peltier cooler does not work as hard. Therefore, in order to achieve the maximum possible heat removal rate with the Peltier cooler, there needs to be a large difference between the desired temperature and the current temperature of the cold side of the cooler.

Chapter 4 : Conclusion and Future Work

Based on the results of this experiment, it is clear that the Peltier cooler best removes heat when the desired temperature is much lower than the current temperature of the cold side of the cooler. This was seen whenever the desired temperature was dropped in the experiment with 4 degree increments. Figure 10 shows that the percent power to the cooler jumps to almost 100% every single time the desired temperature is lowered. During the experiment with 2 degree increments, this sudden spike in power was not achieved and the heat removal rate reflected this. Figure 13 shows that the maximum power delivered to the cooler during that entire experiment was only 60%. The smaller difference between the cold side temperature and the desired temperature did not call for as much power. It is also consistent with the equations mentioned in Experimental Setup to see this behavior. If the difference between the cold side temperature and the water inside the thermal mass is not as large, the resulting heat removal rate will be much smaller.

Should future work surrounding the application of Peltier coolers in a district heating network experiment be performed, it would be helpful to understand whether or not the cooler's ability to remove heat is impacted by the hot side temperature. The hot side jumps up to high temperatures as soon as the desired temperature is decreased, as seen in Figures 9 and 12. Also, Figure 12 shows that as the desired temperature gets lower, the jump in hot side temperature reaches higher peaks in temperature. Future work includes sizing of the system components and parameters to match the scaled response of a full system. Hence, operating temperatures, pressure losses and flow rates will be scaled based on the maximum heat rejection performance determined in this study. If these heat rejection performances are not matching the full system, improvement on the cooling mechanism for the Peltier junction hot side will be introduced, such as liquid based cooling.

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ACADEMIC VITA

Dylan T. Stecklair

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EDUCATION

The Pennsylvania State University, Schreyer Honors College
University Park, PA
May 2019 (Expected)
Bachelor of Science in Mechanical Engineering
-Minor in Engineering Entrepreneurship

The Pennsylvania State University, Smeal College of Business
Master of Professional Studies in Management and Organizational Leadership
May 2020 (Expected)

EXPERIENCE

Arconic Mill Products – Process Engineering Intern *May 2018 – August 2018*
Lancaster, PA

- Completed optimization projects on raw material dryers that will decrease cycle time by 16%, increasing output by 28.8 million more pounds per year and 235 more cycles per year.
- Trained and assisted operators on implementation of new technology to eliminate traceability issues.
- Updated and created standard operating procedures to ensure proper execution of daily processes.

First Quality Retail Services – Process Engineering Intern *May 2017 – August 2017*
Lewistown, PA

- Completed optimization projects on production lines that will save 116,800 products per year and several hours of auditing per day.
- Designed and built a testing device that First Quality aims to make a company-wide standard.
- Selected and implemented coating options that will become standard for production lines.

Undergraduate Research Assistant *August 2016 – May 2019*
University Park, PA

- Assisting Dr. Stephanie Stockar with the calibration of a small-scale district heating network.

Penn State Engineering Orientation Network – President *October 2017 – December 2018*
University Park, PA

- Responsible for the oversight of all operations, as well as directors, head mentors, mentors and mentees.

Penn State Lion Ambassadors – Director of Internal Affairs *April 2018 – May 2019*

- Organizing social and professional events for current members and appropriating organizational funds.