

6-2018

# Applications of Latent Heat Storage using Phase Change Materials

Daniel Giroux

Follow this and additional works at: <https://digitalworks.union.edu/theses>



Part of the [Energy Systems Commons](#)

---

## Recommended Citation

Giroux, Daniel, "Applications of Latent Heat Storage using Phase Change Materials" (2018). *Honors Theses*. 1647.  
<https://digitalworks.union.edu/theses/1647>

This Open Access is brought to you for free and open access by the Student Work at Union | Digital Works. It has been accepted for inclusion in Honors Theses by an authorized administrator of Union | Digital Works. For more information, please contact [digitalworks@union.edu](mailto:digitalworks@union.edu).

# Applications of Latent Heat Storage using Phase Change Materials

Thermal Energy Storage for a Solar Thermal Collector

Dan Giroux

\* \* \* \* \*

Submitted in partial fulfillment  
of the requirements for  
Honors in the Department of Mechanical Engineering

UNION COLLEGE

June, 2018

## Abstract

ADVISOR: Richard Wilk, PhD.

Thermal Storage Systems are gaining more attention in recent years with the increased emphasis on more renewable energy sources. Energy storage is necessary whenever there is greater amounts of energy being produced than is required. Various improvements to the conventional heat storage system can be made by integrating latent heat storage into the conventional heat storage system. Latent heat storage can be utilized for thermal storage applications by using phase change materials, materials that will undergo a change in their physical state in the temperature range desired for heat storage.

Analysis was conducted on four different waxes considering the waxes for use in a latent heat storage unit. Benchmark experiments analyzing the cooling curves of the waxes were conducted. In addition, data was collected using a differential scanning calorimeter to measure the latent heat of the phase change material as well as the onset temperature of melting in the waxes. The latent heat value of paraffin wax was found to be approximately  $186 \text{ kJ/kg}$ . Based on the analysis, palm wax was chosen as the phase change material to be used in a prototype latent heat storage.

A small prototype latent heat storage unit was constructed using a 1 gallon steel can with copper tube coils in the container. The container was then filled with palm wax, which serves as the heat storage medium in the system. Based on some initial testing, it was found that when operating between  $21^{\circ}\text{C}$  and  $75^{\circ}\text{C}$ , the palm wax was able to store approximately  $1.266 \text{ MJ}$  of energy.

## Table of Contents

Abstract	ii
List of Figures	v
List of Tables	vi
Introduction	1
Background	4
Method	9
Benchmark Experiment Procedure	9
Reproducibility of Wax Properties during Heating and Cooling	12
Measurement of Latent Heat Value	14
Numerical Model Method	16
Results	21
Benchmark Experiments Results	21
Reproducibility of Wax Properties during Heating and Cooling Results	30
Differential Scanning Calorimeter Results	31
Discussion	33
Prototype Design	39
Prototype Design Analysis	41
Prototype Testing	42
	iii

Conclusion	45
Appendices	49
Appendix A-Paraffin Wax Literature Properties [13]	49
Appendix B-Derivation of Overall Heat Loss Coefficient Calculations	49
Appendix C-MATLAB Code for Numerical Simulation	50
Appendix D- Plot of DSC data of Paraffin and Beeswax	51
Appendix E-Bill of Materials for Prototype	52

## List of Figures

Figure 1. Classification of Energy Storage Materials [3].....	5
Figure 2. Benchmark experimental testing configuration for the paraffin wax.....	10
Figure 3. Experimental Configuration for heating the wax using a water bath .....	12
Figure 4. Pyris Differential Scanning Calorimeter and refrigeration unit.....	15
Figure 5. Plot to find overall heat loss coefficient .....	19
Figure 6. Plot of Temperature versus time of Paraffin Wax.....	22
Figure 7. Temperature versus Time of Paraffin Wax with two thermocouples, one in the center of the wax and one at the edge of the beaker .....	23
Figure 8. Three experimental trials conducted with the paraffin wax .....	24
Figure 9. Plot of Experimental Data of Paraffin, Palm, Soy and Beeswax.....	25
Figure 10. Comparison of cooling curves of Paraffin Wax and Palm Wax .....	27
Figure 11. Comparison of Palm Wax experimental data and Simulated data .....	28
Figure 12. Comparison of Paraffin Wax experimental data and simulated data .....	29
Figure 13. Paraffin Wax Heating Curve in a hot water bath.....	30
Figure 14. Plot of heat rate vs temperature for the palm wax.....	31
Figure 15. Plot of heat rate vs temperature of soy wax.....	32
Figure 16. Prototype Palm Wax heat exchanger .....	40
Figure 17. Plot of the rate of heat leaving the water vs time in the prototype .....	44
Figure 18. Paraffin Wax plot of heat rate vs temperature .....	51
Figure 19. Beeswax plot of heat rate vs temperature .....	51

## List of Tables

Table 1. Melting Temperature of Waxes as measured by benchmark experiments..... 25

Table 2. Latent Heat Values and Melting Temperature as measured by DSC ..... 33

## Introduction

Thermal Energy storage is essential in many heating and cooling systems. It is beneficial to have energy stored and ready for use when needed rather than producing the energy at the time which it is needed. Energy is often naturally produced in many different forms such as wind and solar energy. However, most of these energy sources do not provide a steady stream of energy, as they only produce energy periodically in short periods of time. Despite the non-continuous production, there is often excess unharnessed energy to be collected at the times at which these sources are producing. To make full use of these energy sources, the excess energy should be stored for use at a later time. And so, it is important to have effective storage systems for these types of energy, specifically thermal energy storage.

Conventional heat storage systems make use of water as a heat storage medium. Water's high specific heat and high thermal conductivity in combination with being inexpensive and readily available make it an obvious option as a heat storage medium. Although effective there are several ways in which the conventional heat storage system can be improved.

The majority of thermal storage applications require temperatures at which water remains in the liquid state. The water therefore, stores the energy as sensible heat. This means that any energy that is added or removed from the system causes a change in the temperature of the material. As a result, the system can reach high



temperatures. The conventional heat storage system can be improved by making use of latent heat storage, energy exchange that occurs with no change in temperature.

Although presenting concern for many years, climate change is now exhibiting many of the effects it is having on the environment. This is resulting in greater support for more sustainable and environmentally friendly energy options as well as making existing energy systems more environmentally friendly. Phase change materials present a viable option for improving upon an existing thermal storage design. In addition, phase change materials are recyclable with many of the materials being sustainable.

Thermal Energy storage is an important topic when discussing solar thermal systems. Solar Energy is only produced a few hours out of each day, however, the times at which the energy is being produced are often the warmest parts of each day and therefore there is little need for thermal energy at that time. As a result, this excess energy must then be stored for use at a later time. This provides the ideal thermal storage application to explore the possibilities of improving the storage system with the use of phase change materials.

Latent Heat Storage can be integrated into conventional heat storage systems using phase change materials. These materials make use of the melting or freezing of a material for energy storage rather than simply storing the energy as sensible heat. A great deal of energy is required to melt a given mass when compared to the amount of energy required to increase the temperature of that same mass by one degree [1]. These materials are more suitable for energy storage than water because their thermal density is greater than water's. The use of these materials allows for comparable thermal

energy storage to traditional heat storage systems at lower temperatures and a physically smaller system.

In an attempt to consider the most environmentally friendly system possible, sustainable phase change materials will also be considered. Paraffin wax is often used as a phase change material; however, this wax is derived from fossil fuels which are limited. As a result, the paraffin wax is recyclable but not renewable. Several other naturally produced phase change materials are also available, including beeswax, palm wax and soy wax. Several of these materials possess many of the same properties as the paraffin wax but have the benefit of being naturally produced and renewable.

The goal of the project will be to research several properties, including the melting temperature, density, thermal conductivity, and specific heat of several different phase change materials and compare these properties to determine which material provides the greatest potential as a thermal storage medium for a latent heat storage system. The properties will be analyzed and compared using experimental tests, numerical simulations and data and literature values found in other sources. Once the phase change material has been chosen, research will be conducted to develop a working prototype of a latent heat storage system. The system will make use of the chosen phase change material that has been selected through the initial tests.

This report will examine and survey existing research that has previously been conducted on phase change materials. The report will discuss the methodology that was used to conduct the benchmark experiments, the development of the numerical model, as well as the steps taken when operating the differential scanning calorimeter. Using

the data that has been collected in the various experiments and modeling, an analysis will be conducted. After analyzing the data for each of the waxes, one of the four waxes will be chosen to be used in a prototype latent heat storage unit. Finally, the design and analysis of the prototype design will then be discussed.

## Background

The conventional thermal storage system stores energy as sensible heat, meaning energy that is added to the heat storage medium causes the temperature of the material to increase. There are many ways in which this system can be improved, one option being the use of latent heat storage. Unlike sensible heat storage, latent heat storage does not change the temperature of the material, rather it changes the phase of the material [2]. This leads to the material absorbing or releasing energy while remaining at a constant temperature.

Many conventional heat storage systems, such as a domestic hot water heater, use water as the thermal storage medium. Water serves as one of the best heat storage mediums at low temperatures due to its high specific heat and high thermal conductivity. Water however does not function as well at high temperatures, requiring high quality insulation and containers capable of high pressures due to the high vaporization pressure [1]. Most heat storage applications require a temperature between 50 and 100°C. Therefore, water does not make use of latent heat storage, all of the energy that the water absorbs is stored as sensible heat, meaning the water has a significant increase in temperature.

Phase change materials provide an option to make use of latent heat when storing thermal energy. The definition of a phase change material is broad and requires further classification. All materials have a phase change temperature at which the material will change from one state to another, i.e. solid to liquid. Often phase change materials receive the title by having melting temperatures in the desired temperature ranges for heating and cooling applications. Figure 1 presents the standard classification of energy storage materials with an emphasis on phase change materials.

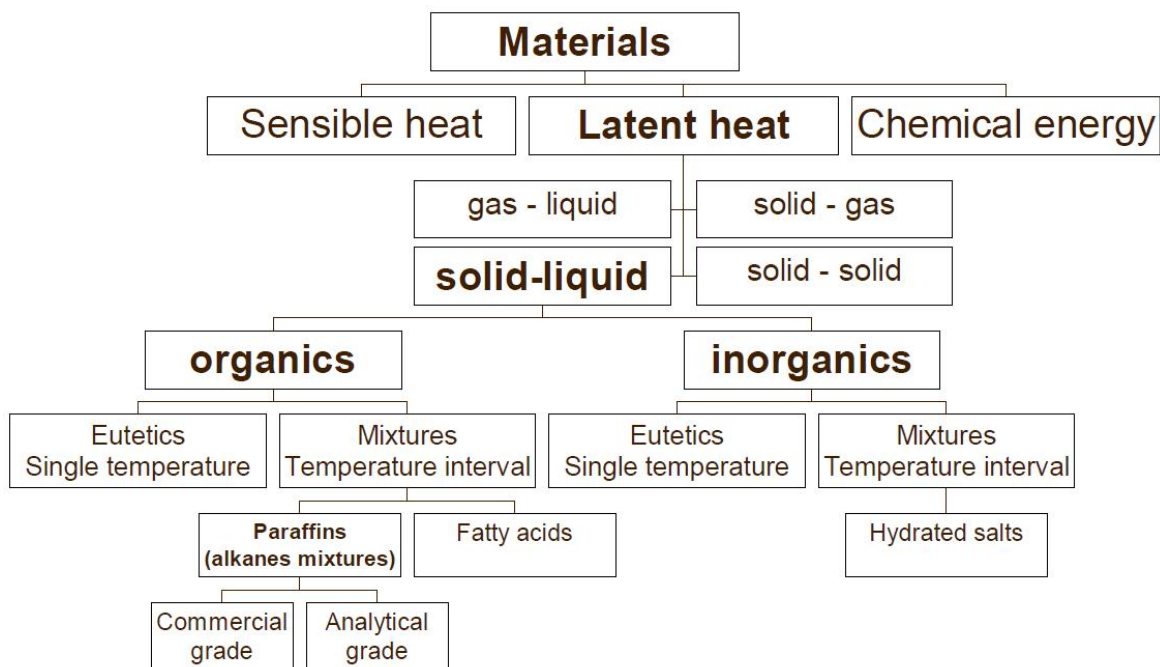


Figure 1. Classification of Energy Storage Materials [3]

Although latent heat occurs during all phase changes, phase change materials typically refer to the solid-liquid phase change due to their ability to store a great deal of heat in a small temperature range [1]. Within the solid-liquid phase change category there are two categories, organic and inorganic materials. Inorganic phase change

materials include salt hydrates, while organic materials are waxes and fatty acids. There are advantages to both organic and inorganic phase change materials. The inorganic materials have a large heat of fusion; however, they lead to undercooling, corrosion and phase separation. The organic materials are non-corrosive, low undercooling and chemically and thermally stable, unfortunately these materials have a low thermal conductivity and lower heat of fusion [3].

There are several properties that make for a good phase change material. Some of these properties include a phase change temperature in the temperature range of the heat storage application, large specific heat values, large latent heat values and a high thermal conductivity. In addition, it is beneficial for the material to have a high density and to be chemically stable [3]. Phase change materials tend to be more expensive than simple water storage systems. However, phase change materials have a greater storage density than water, meaning that the same amount of energy that is stored in water could be stored in a significantly smaller storage tank with the same thermal capacity [4]. In addition, phase change materials can result in energy being stored at lower average temperatures and therefore decrease the temperature difference between the thermal storage medium and the ambient air temperature.

There are several ways to improve the thermal conductivity of the organic phase change materials, often involving the use of materials that have a higher thermal conductivity. One option for improving thermal conductivity would be the introduction of metallic nanoparticles into the waxes. Another frequently used technique is to have a

metal lattice in the material which will also help exchange energy within the material more quickly.

Research has been conducted on the use of phase change materials as thermal storage mediums many times, investigating different properties and applications. The most commonly researched materials include salt hydrates and paraffin wax [5]. As this project focuses on organic phase change materials, we will specifically look at the use of waxes.

Paraffin waxes are a general category which consists of hydrocarbons originating from fossil fuels. These are typically straight chain hydrocarbons [6]. These materials therefore have a large range of properties including a very large range of melting temperatures. Paraffin wax is chemically and thermally stable at the operating temperatures for most heating applications [6]. Several studies have been conducted using paraffin wax as the thermal storage medium with the conclusion that incorporating the wax into the heat storage system has several advantages over the conventional heat storage system [7] [8]. This includes decreasing the size and weight of the thermal storage system as well as decreasing the maximum temperature that the system reaches.

In addition to paraffin waxes, there are several sustainable waxes such as beeswax, palm wax and soy wax, which could potentially be used as a phase change material. These materials share many of the same properties as paraffin waxes, yet they are actively being produced naturally. These materials have the ability to be applied in

many different thermal storage applications, however significant testing must be conducted on these materials.

Energy storage systems are necessary whenever there is a difference in the amount of energy being produced and the amount of energy needed. It is often the case that the times at which energy is being produced is not when it has the greatest need, this is specifically true for energy sources that have natural production, such as wind and solar energy. Solar energy can only be collected when the sun is visible, during the day. The greatest amount of thermal energy is produced by the sun in the middle of the day when the sun is directly overhead. However, this is not the point in the day when the most thermal energy is required with that time being later at night when the temperatures are coldest. Therefore, it is necessary that a solar thermal system have an energy storage system which can collect excess energy from the sun during the day and save the energy for when it is needed.

Large scale concentrated solar collectors are being used in regions that often experience high amounts of sun exposure, notably deserts. These solar collectors make use of mirrors to direct the solar energy to a central solar thermal receiver located on top of a tower. The solar thermal receiver absorbs the energy, transferring the energy into a heat transfer fluid. This system uses molten salts as both the heat transfer fluid and heat storage medium. This system can reach temperatures greater than  $500^{\circ}\text{C}$ . The thermal energy is then used to create steam, which spins a turbine, creating electricity [9].

This project will focus on residential solar thermal systems, including stationary solar collectors such as flat plate collectors and evacuated tube collectors. These solar collectors typically operate at temperatures between  $30 - 100^{\circ}\text{C}$ , however they can reach temperatures up to  $200^{\circ}\text{C}$  [10]. Heat storage for these types of solar collectors typically use water as the storage material [11]. The introduction of phase change materials into the thermal storage system should allow for noticeable improvements in the storage of the energy produced by the solar thermal collectors. The latent heat storage system should allow for the thermal energy to be stored in a smaller container at lower temperatures [12].

## Method

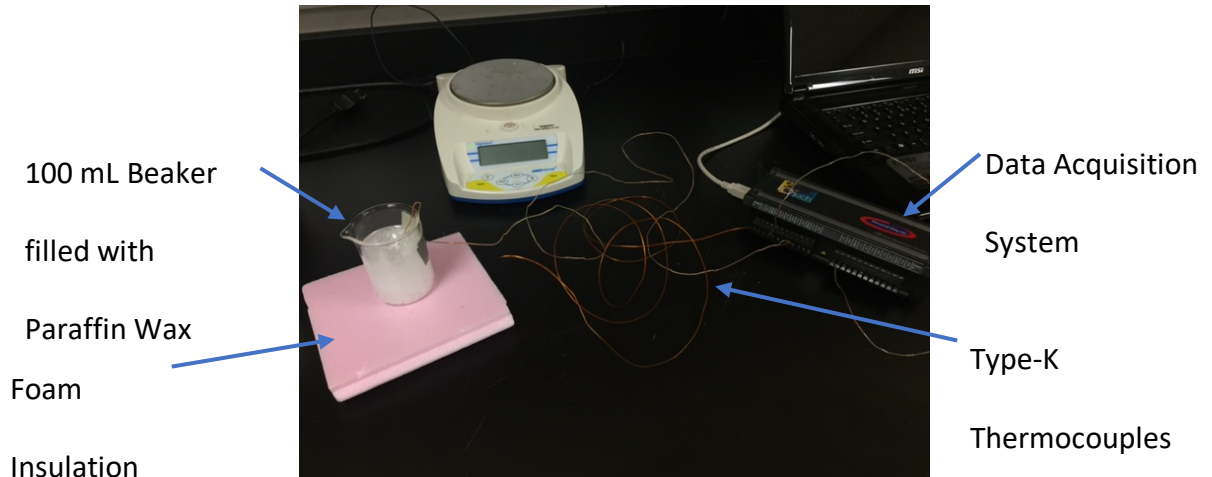
### Benchmark Experiment Procedure

Several exploratory benchmark experiments were initially conducted on paraffin wax to test the melting point and temperature curve of the paraffin wax in question as well as to determine the best testing configuration for comparing the different waxes in future data collection. Two thermocouples were used for all of the benchmark experiments in consideration, with the purpose of being able to identify any temperature gradients throughout the waxes.

A 100 mL beaker is used to represent a thermal storage tank. The mass of the empty beaker is measured. The beaker is filled with solid paraffin wax that was cut from a large block of wax. Then a hot plate is used to heat and melt the wax. Once all of the wax has melted, the overall mass of the system is collected using the scale. The hot



plate is turned off and the beaker is placed on a piece of foam insulation. The system is left to cool to room temperature.



*Figure 2. Benchmark experimental testing configuration for the paraffin wax*

The temperature of the wax and the temperature of the surroundings is measured using K-type thermocouples. One thermocouple is placed in the center of the beaker to collect the temperature change of the center of the wax, a second thermocouple is placed near the edge of the beaker, and finally a third thermocouple is used to collect the ambient air temperature. The thermocouple measuring the ambient air should be placed away from the heated system so as to not be affected by the changing temperatures near the system. In total three thermocouples are used for this configuration each of which is connected to the io Tech Personal Data Acquisition System 56 (DAQ System).

The DAQ System begins collecting data once the beaker is removed from the heat source and begins to cool. The DAQ System is configured to collect one reading per

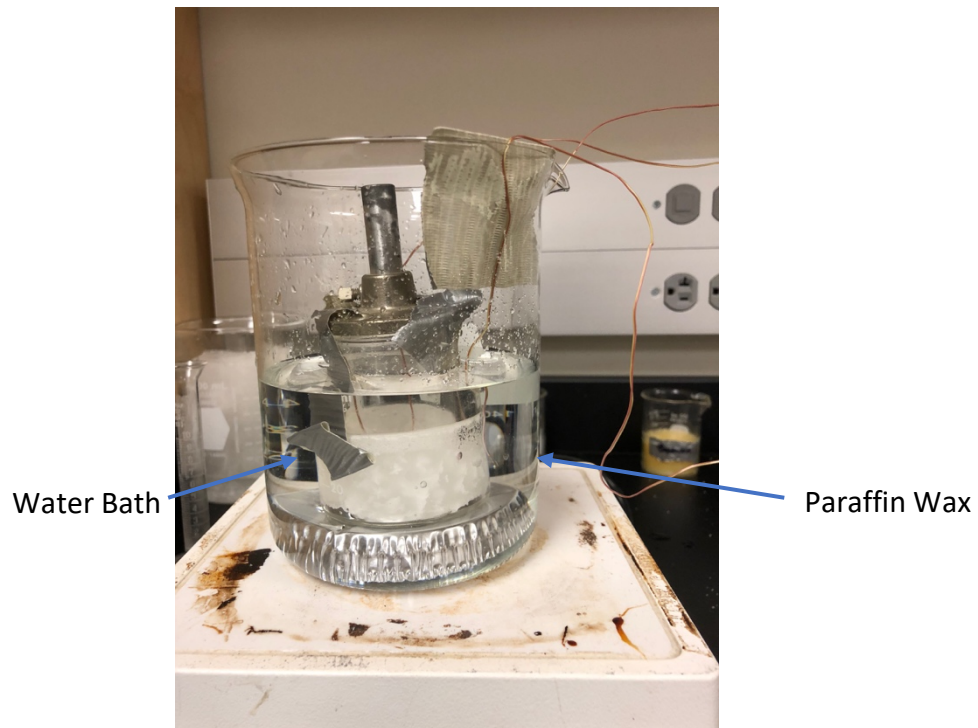
second. It is allowed to run overnight so as to allow enough time for the wax temperature to return to the ambient air temperature.

The main goal of these benchmark experiments was to provide data to be used for comparison of the waxes. In order to ensure proper comparison, independent variables should be controlled, making the wax the only changing variable in the tests. Four samples, paraffin wax, palm wax, soy wax, and beeswax, were prepared for testing in the benchmark conditions. Each sample was measured to be exactly  $40.0g$ . The samples were each placed in a  $100mL$  beaker. Masses were calculated by measuring the mass of the beakers prior to being filled with the wax sample and a second measurement after the beaker had been filled with the sample. Two thermocouples were then placed in each wax sample, one thermocouple in the center of the beaker and the second thermocouple along the edge of the beaker. In addition, a third thermocouple was used to measure the ambient air temperature throughout the experiment.

A hotplate was used to heat each of the samples to approximately  $100^{\circ}C$  using a hotplate. Once the wax sample reaches the desired temperature for data collection, the sample is removed from the hotplate and placed on a piece of foam insulation. The sample is then allowed to cool to ambient temperature. The DAQ System is launched at the commencement of cooling, recording data points at a rate of one measurement each second. In order to ensure that the collected data is reproducible, the experiment is repeated three times for each sample being tested.

## Reproducibility of Wax Properties during Heating and Cooling

When considering a material to be used in heating and cooling applications, data should be collected for the material experiencing both of these processes. A simple experiment was conducted with the goal of showing that the paraffin wax had similar properties in both the heating and cooling of the material. The experimental setup for the system can be seen in figure 3.



*Figure 3. Experimental Configuration for heating the wax using a water bath*

The experiment aimed to heat the wax from all sides rather than heating from solely the bottom of the beaker. The following experiment was conducted only on the paraffin wax. The experiment was conducted for both the heating of the wax as well as the cooling of the wax. The 40.0g sample of paraffin wax that was previously prepared was used for this experiment.

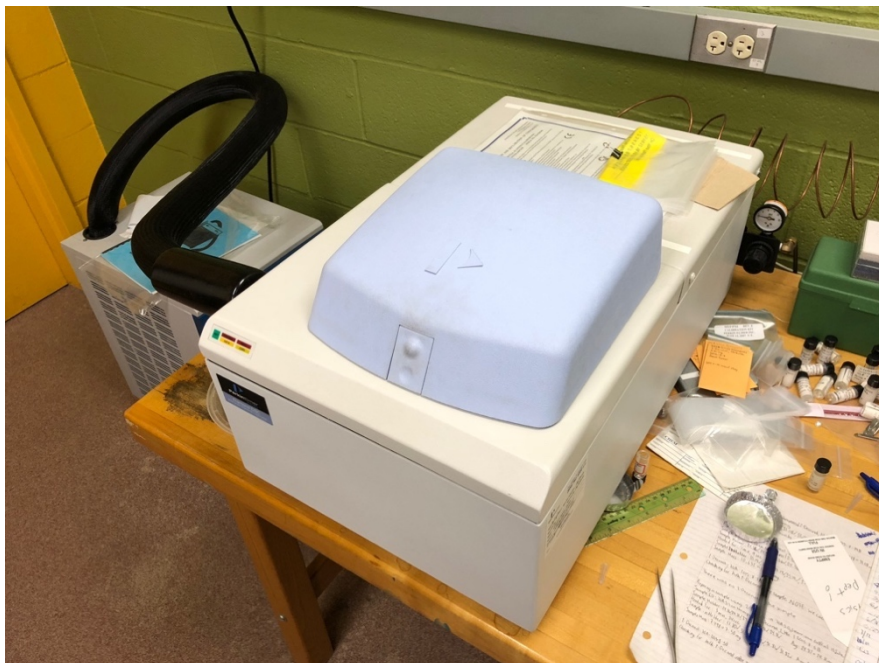
The wax sample should be heated using a water bath in order to provide more uniform heating throughout the sample. A 1000mL beaker was used to prepare the hot water bath to be used when heating the wax sample. The water bath was filled to approximately the 300mL point, to ensure that all of the wax would be submerged in water without the water overflowing into the wax beaker. The water was then heated to approximately 70°C. This temperature was chosen in order to heat the wax barely over the melting temperature of the wax, this was done with the goal of heating the wax at a slow rate. By heating the wax at a slower rate, the phase change should be more noticeable for the heating of the wax. Once the water had reached the desired temperature a metal tray with several holes was placed in the bottom of the beaker. This was done with the goal of raising the wax beaker off of the bottom of the water beaker so as to ensure that all of the heat that the wax was receiving was coming through the water rather than directly from the hotplate.

The wax filled beaker was then placed in the water bath on top of the metal tray. Due to the wax having a lower density than water, the wax must be weighed down in order to prevent the beaker from floating on top of the water. Similar to the previous tests, two thermocouples were placed in the wax beaker, as well as one thermocouple in the water and an additional thermocouple to measure the ambient air. The wax was then left in the hot water bath, allowing all of the wax to increase temperature and melt. The hot plate was left on through the heating phase of the experiment, therefore ensuring that heat was being added to the wax until the heating was completed. Once all of the wax has melted, the hot plate is turned off and unplugged. The wax, along with

the water is allowed to cool to room temperature. The DAQ system was used to collect data at all points of heating and cooling of the wax.

### Measurement of Latent Heat Value

The latent heat of fusion of the various waxes was determined using the PYRIS Diamond Differential Scanning Calorimeter (DSC) by Perkin Elmer, as seen in figure 4. All four waxes in consideration were tested using the machine. In order to perform the experiment each sample must first be prepared. Each wax sample must be contained in a small tray. A small aluminum tray and cover was weighed to find the mass of the empty container. The tray was then filled with a sample of wax, filling the tray with as much wax as possible with the goal of having a sample with a large mass. At which point the cover was placed on the tray and sealed shut using a small screw press. Once the container is sealed, the mass of the container is measured again to the nearest hundredth of a milligram. The difference in mass is the mass of the sample being considered.



*Figure 4. Pyris Differential Scanning Calorimeter and refrigeration unit*

Prior to commencement of experimentation, the DSC must be prepared for testing. Baseline calibration of the DSC has already been completed due to the fact that the physics department maintains and operates the machine. The pyris software must be started on the computer. The purge gas supply must be turned on. Control valves were previously installed to ensure the proper flow rate of the gas. The Perkin Elmer refrigeration unit must also be turned on in order to extract heat from the calorimeter. Once all of the systems are running, the sample is loaded into the DSC. There are two trays present in the DSC, the one contains the reference material, sapphire, while the other contains the sample that is in question. The entire aluminum tray and seal is loaded into the sample side of the DSC. The DSC lids are closed. The starting temperature is then set for the calorimeter, and the refrigeration system must cool the

calorimeter to that temperature. Using the pyris software a program is set up for the wax to be tested at. This experiment consisted of six steps:

1. Hold the sample for 1 minute at a temperature of  $30^{\circ}\text{C}$
2. Increase the temperature of the sample to  $70^{\circ}\text{C}$  at a rate of  $1^{\circ}\text{C}/\text{minute}$
3. Hold the sample for 1 minute at a temperature of  $70^{\circ}\text{C}$
4. Decrease the temperature of the sample to  $0^{\circ}\text{C}$  at a rate of  $1^{\circ}\text{C}/\text{minute}$
5. Hold the sample for 1 minute at a temperature of  $0^{\circ}\text{C}$
6. Increase the temperature of the sample to  $70^{\circ}\text{C}$  at a rate of  $1^{\circ}\text{C}/\text{minute}$

This procedure was conducted on each of the wax samples. The software then plots the heat flow into the sample vs the temperature of the system. The plots show peaks in the heat flow at the temperatures at which phase change occurs. The latent heat value for each sample was then calculated considering the area under the peaks. The melting temperatures of the DSC have an uncertainty of  $\pm 0.5^{\circ}\text{C}$ , while the latent heat values have an uncertainty of  $\pm 10\%$ .

### Numerical Model Method

A numerical model was created using algebraic equations that were derived from the basic differential equations, to model the temperature curve for the system iteratively. The model will be used to predict the temperature curve of other materials based on their thermal and physical properties. In addition, the model will be used to aid in the analysis of the experimental data. The numerical simulation was created using MATLAB.

Due to the fact that the results of a simulated model will vary with the amount of wax that is being tested, it is necessary to determine an overall heat loss coefficient (UA) for each specific system that is tested. The overall heat loss coefficient refers to how

well the energy is transferred through the materials. A UA value must be calculated for both the solid and liquid states of the wax due to the material having different properties depending on the physical state. Verified literature values and variables specific to the system must be used to calculate the UA value. To start we must first look at the rate at which heat is being lost in the system, this is shown in equation 1.

Equation 2 defines  $\theta$  as the difference in temperature of the current temperature and the ambient air temperature. Equation 3 states that  $\theta_i$  is the temperature difference of the starting temperature of the system and the ambient air.

$$Q_{out} = UA(T - T_{\infty}) \quad (1)$$

$$\theta = T - T_{\infty} \quad (2)$$

$$\theta_i = T_i - T_{\infty} \quad (3)$$

Where  $T_i$  is the initial temperature and  $T_{\infty}$  is the ambient temperature. Based on these equations it can be assumed that the change in  $\theta$  is equal to the change in  $T$ .

Equation 4 represents the energy that is stored in the system. Due to the law of conservation of energy (equation 5) it can be stated that the rate at which energy is stored in the system is equivalent to the energy that is put out by the system because no energy is being added to the system and no energy is being generated by the system, resulting in equation 6.

$$Q_{stored} = mC_p \frac{dT}{dt} \quad (4)$$

$$\dot{E}_{stored} = \dot{E}_{in} - \dot{E}_{out} + \dot{E}_{generated} \quad (5)$$



$$mC_p \frac{dT}{dt} = -UA(T - T_\infty) \quad (6)$$

Where  $C_p$  is the specific heat of the material,  $m$  is the mass of the material.

Equation 7 is the result of using equation 2 in equation 6, simply making the temperature difference one term. Equation 6 is rearranged to provide equation 8.

$$mC_p \frac{d\theta}{dt} = -UA\theta \quad (7)$$

$$\frac{d\theta}{\theta} = -\frac{UA}{mC_p} dt \quad (8)$$

We must now take the integral of equation 8 which results in equation 9. The natural log of  $\theta$  must then be plotted versus time. A straight line must then be fitted to the plot. The plot is shown in figure 3. The magnitude of the slope of the fitted line is equivalent to the coefficient of the time dependent component, shown in equation 10. An equation for the overall heat loss coefficient of the system is found by rearranging equation 10, resulting in equation 11.

$$\ln\theta = -\frac{UA}{mC_p} t + \ln\theta_i \quad (9)$$

$$|slope| = \frac{UA}{mC_p} \quad (10)$$

$$UA = mC_p |slope| \quad (11)$$

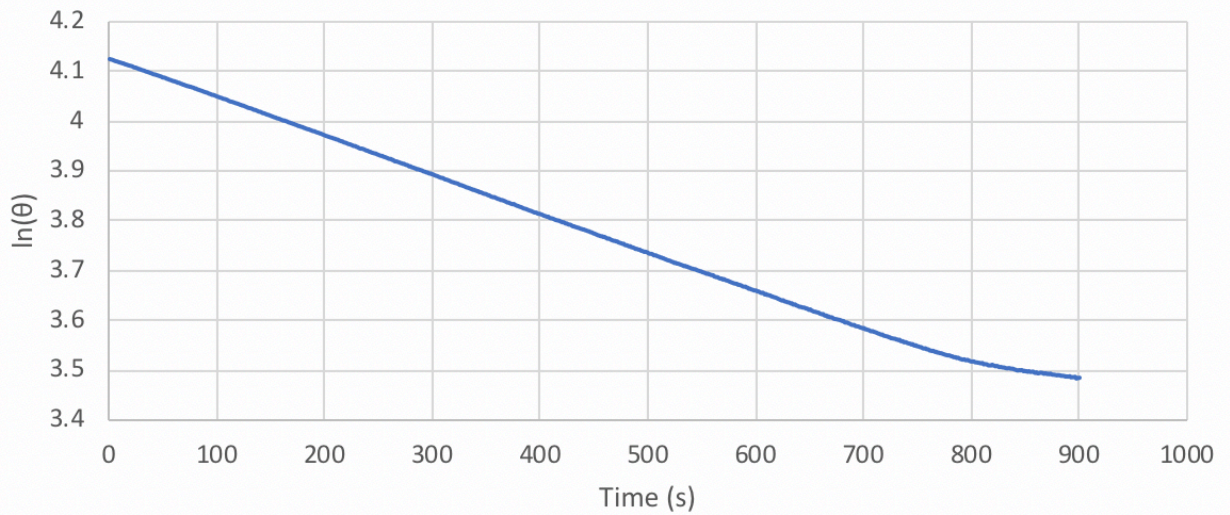


Figure 5. Plot to find overall heat loss coefficient

The algebraic equations that will be used to conduct the simulation must now be derived. To begin, a differential equation must be found representing the energy transfer of the system. This equation was previously derived in the calculations of the UA, equation 6. We must then manipulate equation 6 to produce an algebraic equation, equation 12.

$$T_{t+1} = T_t + \frac{UA}{mC_p} \Delta t (T_{\infty} - T_t) \quad (12)$$

Where  $T_{t+1}$  is the new temperature a time step away,  $T_t$  is the current temperature, and  $\Delta t$  is the time step. Equation 12 can then be used in MATLAB to simulate the sensible temperature curve for the system.

The phase change portion of the temperature curve must also be simulated using algebraic equations. Equation 13 represents the energy stored in the system during the phase change while equation 14 represents the energy put out by the system

during the phase change region. Using the conservation of energy law, it is assumed that the energy of the system is constant therefore equations 13 and 14 can be combined to come up with equation 15.

$$Q_{stored} = h_i \frac{dm_s}{dt} \quad (13)$$

$$Q_{out} = -UA(T_{melt} - T_{\infty}) \quad (14)$$

$$h_i \frac{dm_s}{dt} = UA(T_{melt} - T_{\infty}) \quad (15)$$

Where  $h_i$  is the latent heat of fusion,  $m_s$  is the mass of the solid,  $T_{melt}$  is the melting temperature of the phase change material, and all other variables remain the same from the previous equations. Using the differential equation 15 we are able to derive an algebraic equation that can be used for simulating the data.

$$m_{s_{t+1}} = m_{s_t} + \frac{UA}{h_i} \Delta t (T_{\infty} - T_{melt}) \quad (16)$$

Where  $m_{s_t}$  is the mass of the solid portion of the material at that time,  $m_{s_{t+1}}$  is the mass of the solid predicted at a time step away from the current time.

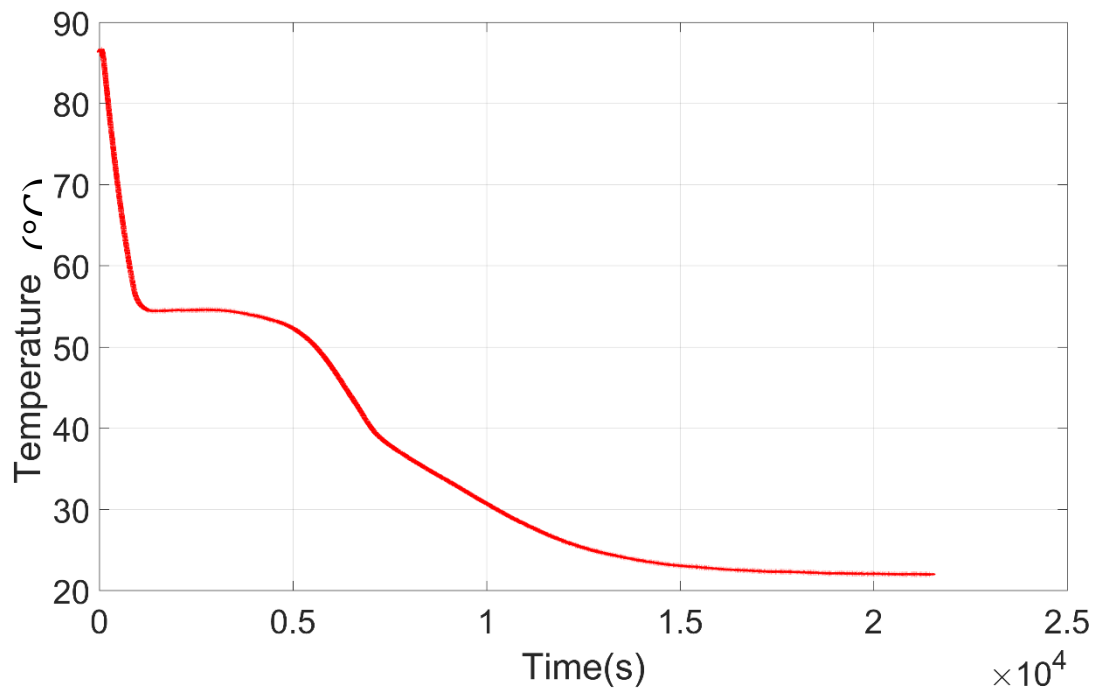
Using equations 12 and 16 we are able to develop a MATLAB code which is able to simulate the predicted temperature curve given certain values. The model will make use of the overall heat loss coefficient of the system that was previously calculated. Using equation 12 and the UA value of the liquid wax, the initial temperature decrease can be calculated, this is run until the temperature of the system reaches the melting point of the material.

Once the simulation reaches the melting point, equation 16 is used to simulate the phase change of the system. It is assumed when generating the model that all of the wax solidifies before the temperature of the wax begins to decrease. This is done by using the value calculated with equation 9 and the overall mass of the material to calculate what percent of the wax has solidified at each time. Once one hundred percent of the wax is solidified the temperature begins to decrease again, now using the UA value that was calculated for the solid wax portion.

## Results

### Benchmark Experiments Results

In order to investigate the paraffin wax as a potential phase change material, experiments must be conducted to determine the properties of the materials. This was done to determine the temperature curve of the paraffin wax, the melting temperature, as well as to ensure that the paraffin wax reacted the same through many melting solidification cycles.



*Figure 6. Plot of Temperature versus time of Paraffin Wax*

Figure 6 shows the change in temperature of the paraffin wax over time. As the liquid wax begins to decrease temperature it follows a linear curve until it reaches the freezing temperature. At this point the temperature remains constant as the liquid wax solidifies. The freezing temperature was found to be approximately 54.5°C. The transition from the liquid wax cooling to freezing is rather sudden and well defined. However, the transition to continue decreasing in temperature is more gradual. The temperature of the wax continues to decrease until the entire sample of wax returns to the ambient temperature of the air.

In an attempt to observe the temperature gradient of the system, data was observed both in the center of the wax as well as near the edge of the wax, figure 7 shows the results of this system. The temperature of the wax in the center of the beaker

follows the expected cooling curve. However, the temperature profile at the edge of the beaker follows a significantly different curve. Based on this plot it appears as though the wax along the edge of the beaker spends little to no time in the phase change range. There is still a noticeable change in the slope of the curve at the melting temperature, however the wax at the edge of the glass begins to immediately decrease in temperature, eventually reaching the ambient air temperature around the same time as the wax in the center of the beaker.

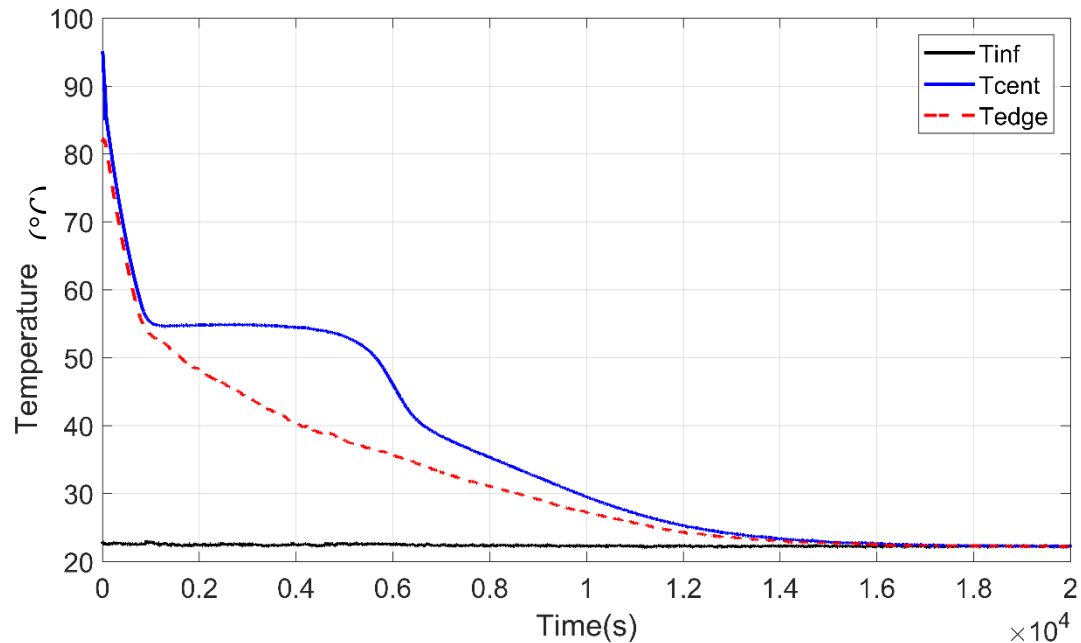
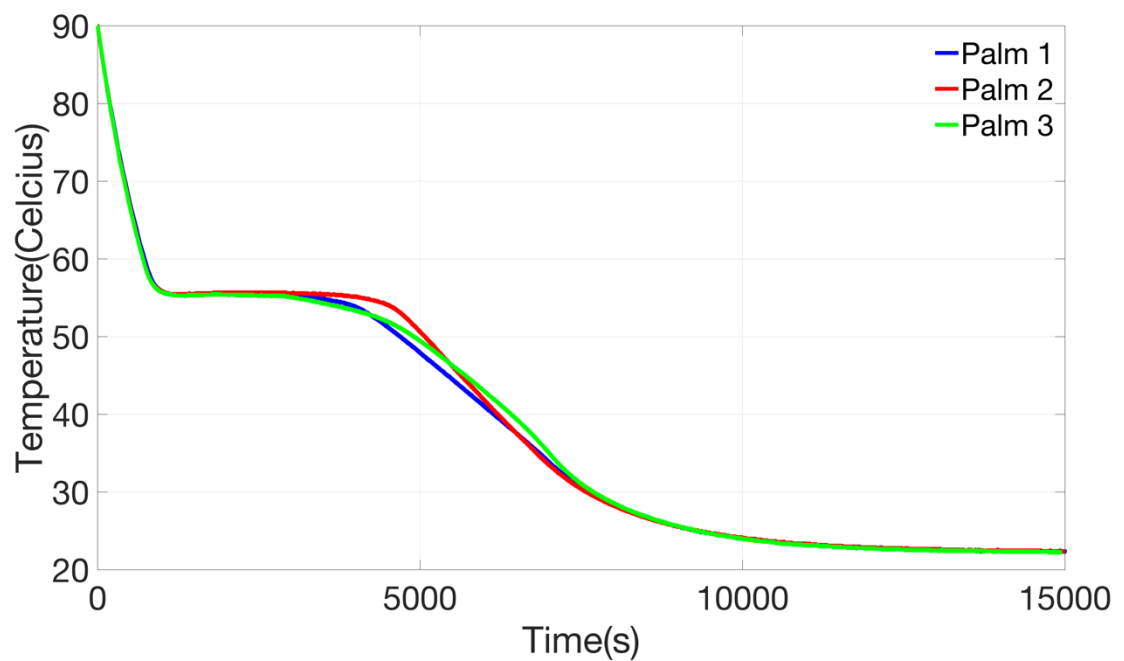


Figure 7. Temperature versus Time of Paraffin Wax with two thermocouples, one in the center of the wax and one at the edge of the beaker

Following these initial benchmark experiments, several other experiments were conducted on the four waxes in consideration for use in a thermal energy storage unit, including paraffin wax, palm wax, soy wax, and beeswax. The benchmark experiments were found to be reproducible for each of the waxes. Figure 8 shows the cooling curves

of the three trials that were conducted for the palm wax. The three trials appear to follow similar cooling curves, all three trials have approximately the same liquid cooling rate and clearly melt at the same temperature. The difference in the trials can be observed in the amount of time the wax spends solidifying, each of the waxes transitions back to the temperature decreasing at slightly different temperatures.



*Figure 8. Three experimental trials conducted with the paraffin wax*

Table 1 shows the melting temperatures measured using the benchmark experiments of the waxes. The melting temperatures for these experiments were measured using the average temperature of the flat portion of the plot when possible and when there was an inflexion in the cooling curve for the beeswax and soy wax which did not clearly go through a phase change. Figure 9 presents the cooling curves of the four waxes which are being considered for use in the prototype heat storage unit.

Table 1. Melting Temperature of Waxes as measured by benchmark experiments

	Melting Temperature ( $^{\circ}\text{C}$ )
<b>Paraffin Wax</b>	54.5
<b>Palm Wax</b>	55.4
<b>Beeswax</b>	60.5
<b>Soy Wax</b>	45.2

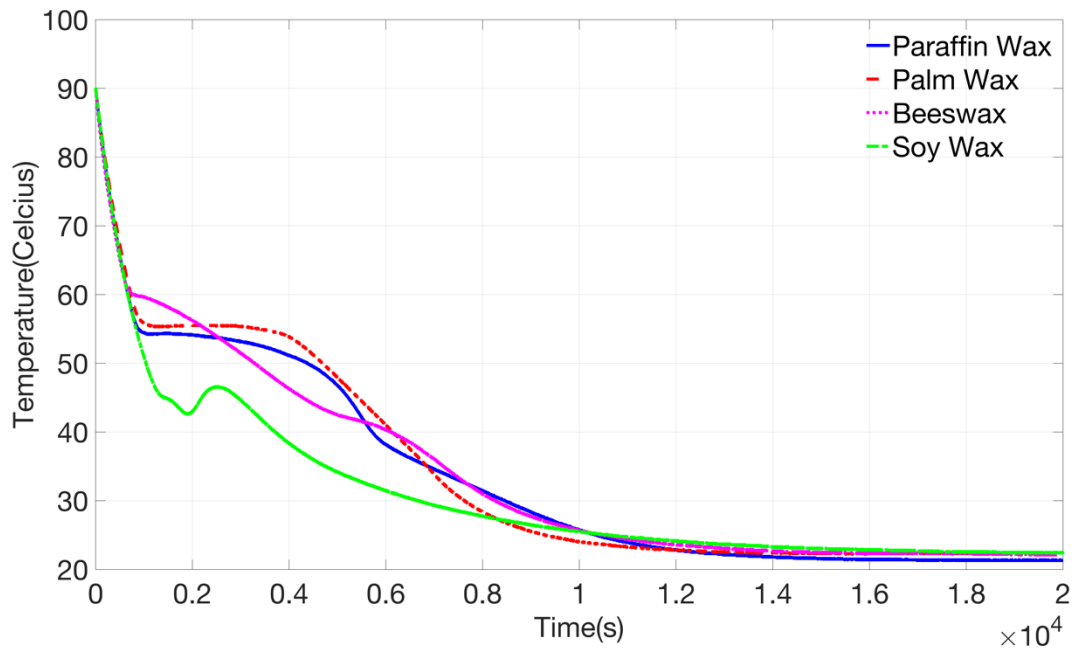


Figure 9. Plot of Experimental Data of Paraffin, Palm, Soy and Beeswax

Figure 9 clearly shows the comparison of how the waxes act when cooling over time. The paraffin wax and palm wax have very distinct freezing portions in the cooling curve. These two waxes reach the freezing temperature and then remain at that temperature while the wax is solidifying. After the majority of the wax has solidified, the temperature of the solid wax begins to decrease again until it returns to room temperature.



It is important to note that the cooling rate of the four samples is approximately the same for the liquid wax cooling. The difference in properties becomes clear when the waxes begin to solidify.

Unlike the Paraffin and Palm Wax, the beeswax does not appear to remain at a single temperature for any duration of time, an inflexion occurs in the plot at approximately  $60^{\circ}\text{C}$ , after which point the wax begins to cool at a significantly different rate.

The Soy wax differed significantly from the other three waxes in consideration. The soy wax did not experience a clear melting temperature. It is important to note that no external heat sources were applied to the waxes throughout data collection. The soy wax appears to cool to a temperature of  $42^{\circ}\text{C}$  and then temperature begins to rise again to a temperature of  $46^{\circ}\text{C}$  before it then continues to cool until it reaches ambient temperature.

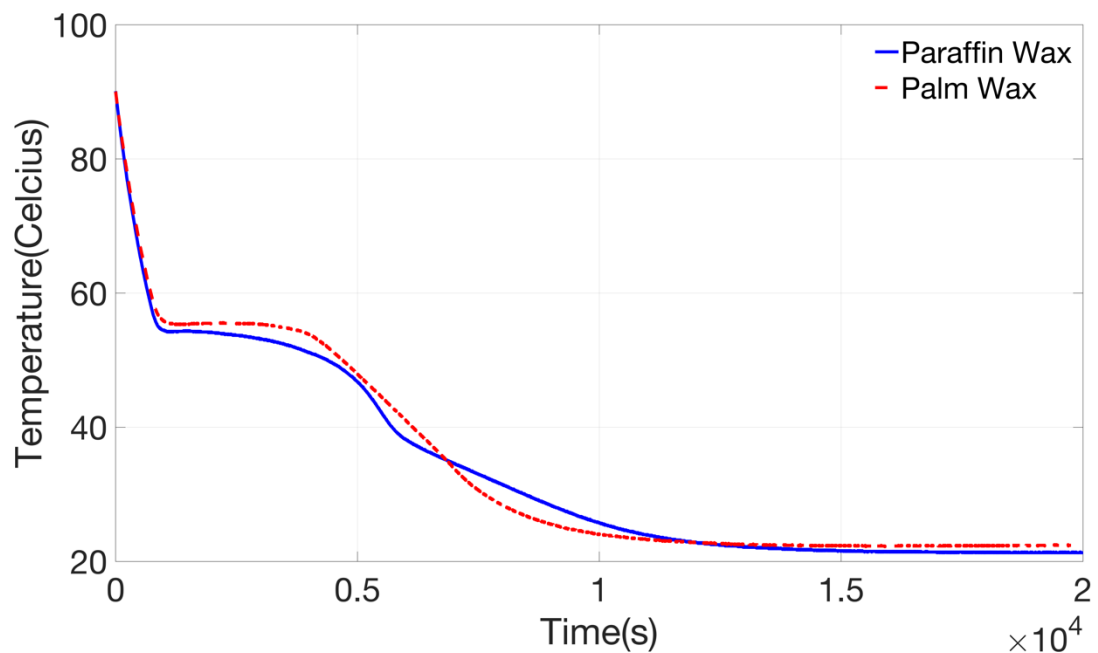
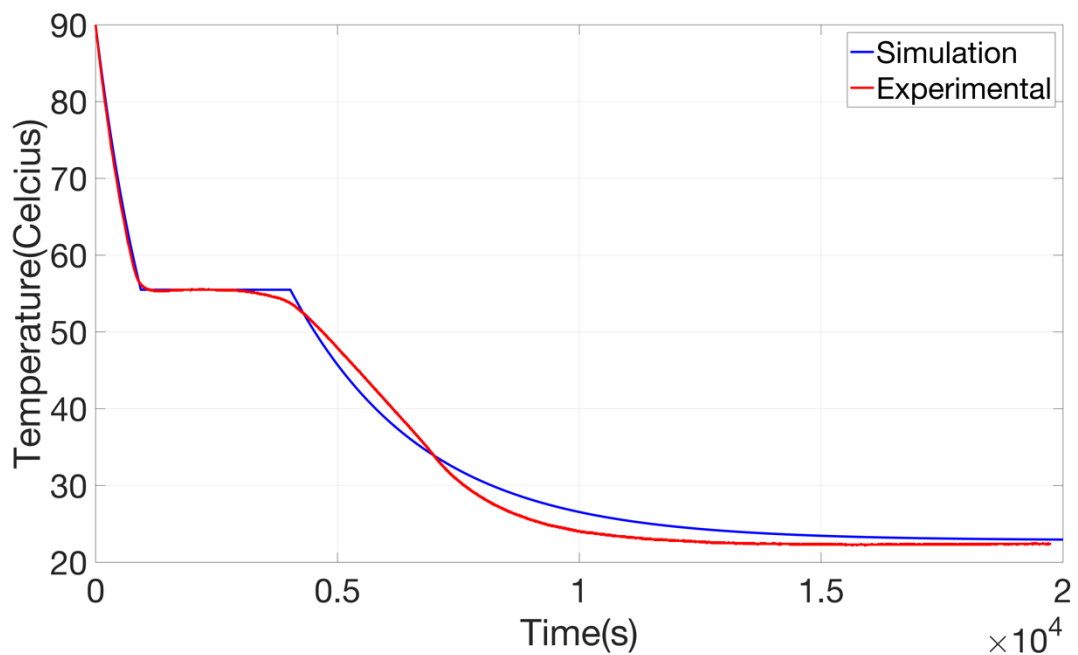


Figure 10. Comparison of cooling curves of Paraffin Wax and Palm Wax

Figure 10 shows a direct comparison of the palm and paraffin waxes. It can be seen that both waxes in the liquid state cool at almost identical rates. Both waxes transition into the freezing point rather abruptly, shown by a sharp turn in the graph. The palm wax begins to solidify at approximately 1°C higher than the paraffin wax. The palm wax appears to solidify almost entirely before the temperature begins to decrease again. The transition of the palm wax from solidifying to decreasing temperature has a rather sharp transition. The paraffin wax however, appears to slowly begin to decrease temperature while it is solidifying. The transition of the paraffin wax from solidifying to the temperature decreasing has a more gradual change in comparison to that of the palm wax. In addition, the rate at which the paraffin wax is cooling appears to change at approximately 39°C.

Using the numerical model that was previously developed, it was possible to simulate the cooling curve of the palm wax to use for comparison of the experimental to the predicted data. The numerical model was performed on the paraffin wax and palm wax. The palm wax numerical model is compared to the experimental data in figure 11 and the paraffin wax numerical model is compared to the experimental data in figure 12.



*Figure 11. Comparison of Palm Wax experimental data and Simulated data*

The numerical model of the palm wax appears to follow the experimental cooling curve of the data rather closely. The transition of the wax from decreasing temperature in the liquid phase to solidifying is rather sharp under both conditions, therefore the numerical appears to be quite accurate through the transition. The point where the difference is seen is the transition from the solidifying of the wax to the

temperature of the wax continuing to decrease. The model's transition is immediate as this is how it was programmed, whereas the experimental data experiences a slightly more gradual transition.

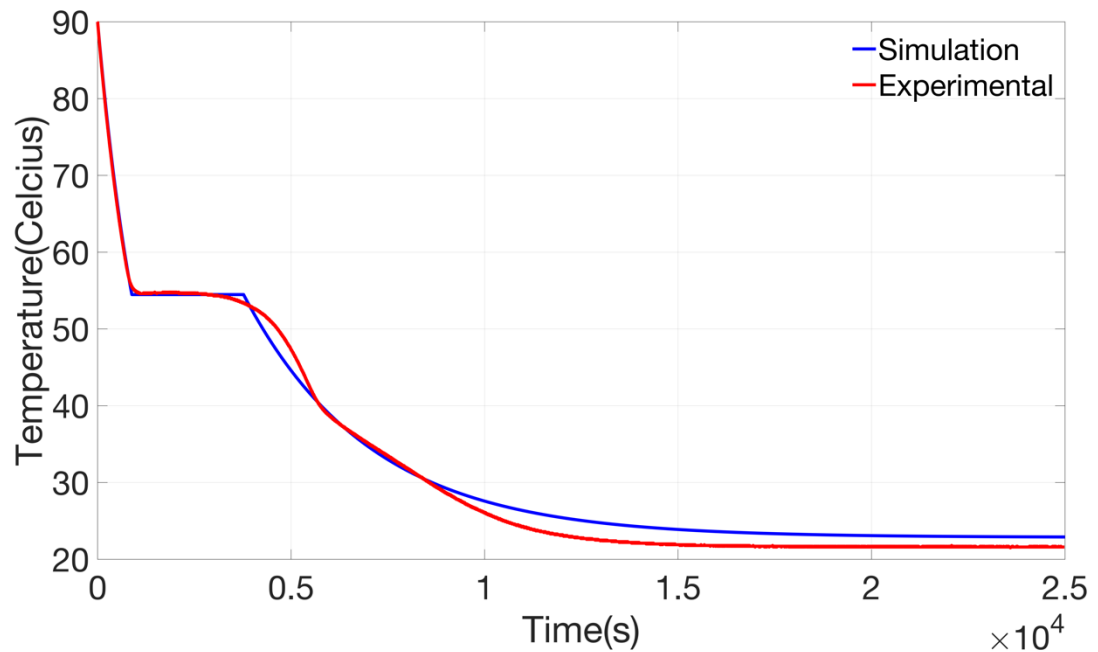


Figure 12. Comparison of Paraffin Wax experimental data and simulated data

Similar to the palm wax, the paraffin wax simulation follows the experimental data rather closely. Although the experimental data for the paraffin wax shows a gradual transition back to the temperature decreasing, the numerical model eventually matches up to the simulated model and cools at exactly the same rate for a period of time.

## Reproducibility of Wax Properties during Heating and Cooling Results

The plot of the paraffin wax being heated at approximately  $70^{\circ}\text{C}$  can be seen in figure 13. The purpose of this plot is to compare some of the properties of the wax while the wax is being heated.

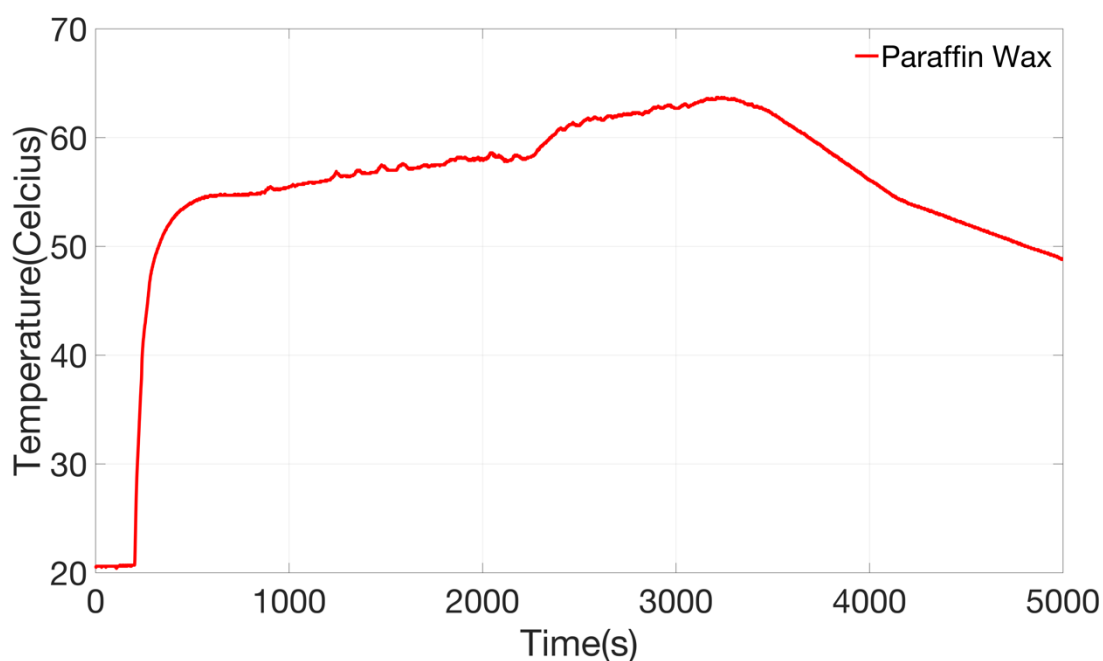


Figure 13. Paraffin Wax Heating Curve in a hot water bath

The graph above shows the same  $40.0\text{g}$  paraffin wax sample being heated and melting all of the wax in the beaker. Once the wax sample has been placed in the hot water bath, there is a clear and fast increase in temperature. A rather sudden change in the heating rate is observed at approximately  $54^{\circ}\text{C}$ . This differs from the cooling curve of the wax by not experiencing a very prolonged period at the same temperature. The change in the heat rate appears to occur at approximately the same temperature that the wax melts at, suggesting that the wax reacts the same in both the heating and

cooling conditions. After experiencing the change in heating rate, the wax continues to slowly increase temperature until it reaches the temperature of the water.

### Differential Scanning Calorimeter Results

The DSC continuously reads measurements of the temperature of the sample as well as the amount of energy that is being added or removed from each of the samples. As a result, the DSC software provides two main plots for each run, a plot of heat rate into the sample vs time and a plot of heat rate into the sample vs temperature.

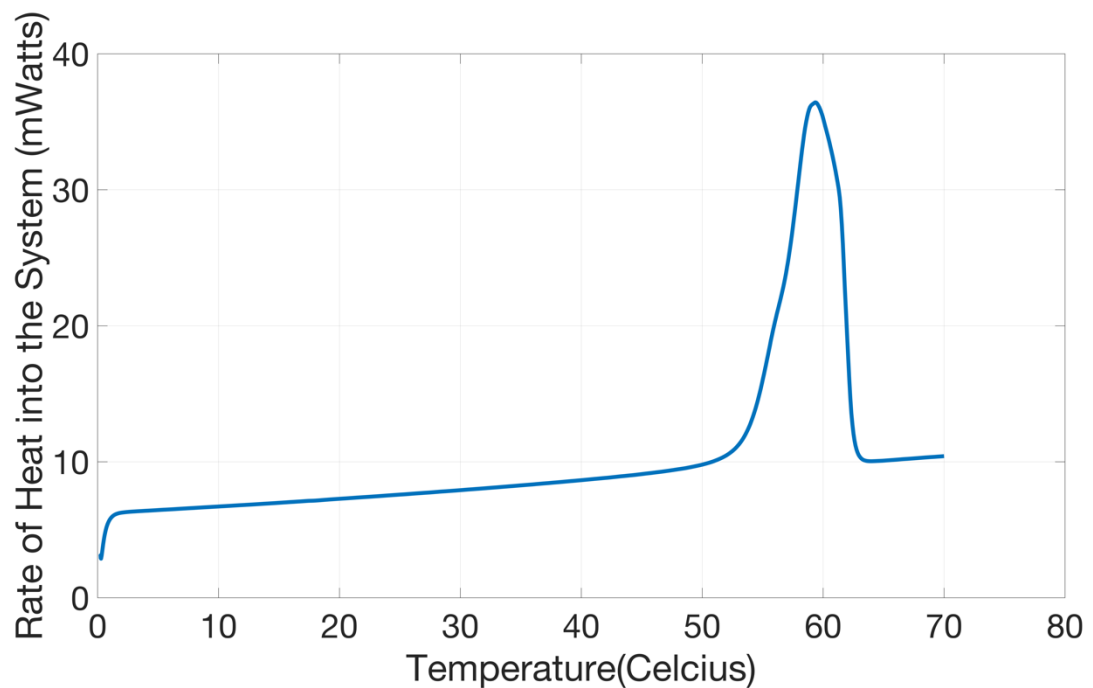


Figure 14. Plot of heat rate vs temperature for the palm wax

Figure 14 shows the plot of the rate of heat being provided into the system vs the temperature of the sample, as the sample is heated from 0°C to 70°C. The plot clearly shows the amount of heat being added to the sample is relatively constant for most of the temperatures. A clear spike begins to occur shortly after the sample reaches

50°C. This suggests that the melting temperature of the wax occurs at the location of the peak and the latent heat of the sample can be calculated from the area under the spike. All Latent Heat values can be found in table 2.

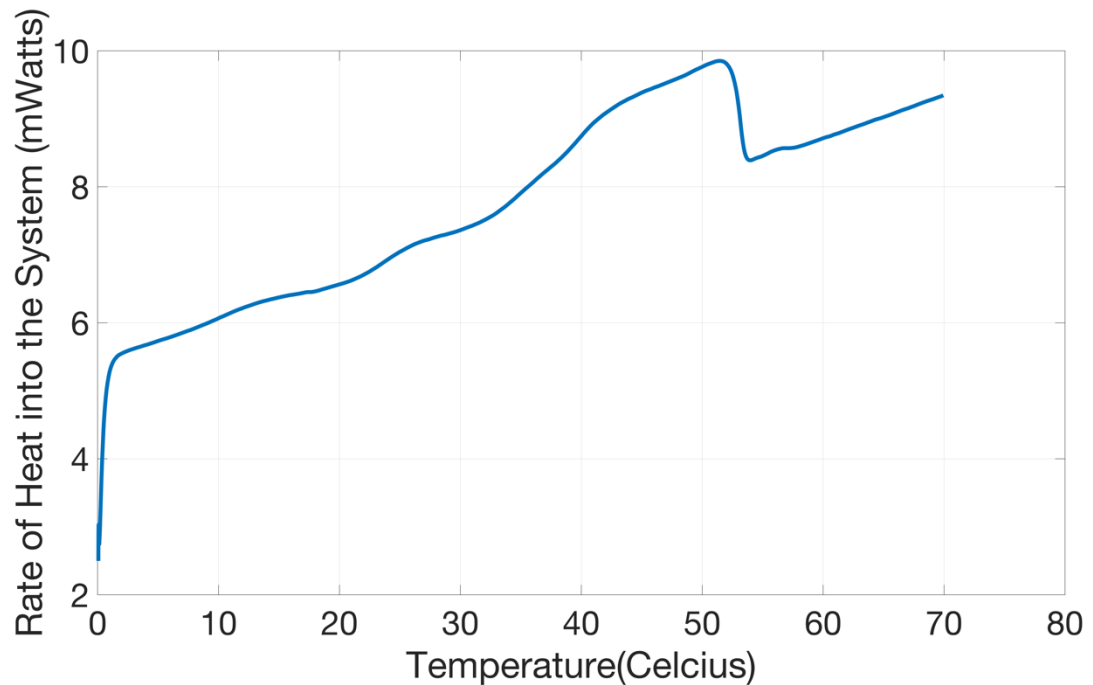


Figure 15. Plot of heat rate vs temperature of soy wax

The soy wax plot, figure 15, however did not have a clear spike in the curve, rather the soy wax seemed to have a more gradual increase in the amount of heat supplied to the system, with various small peaks occurring along the temperature increase. Therefore, it appears as though the latent heat of fusion occurs at several different temperatures, making it rather difficult to determine a clear melting point.

Similar graphs were produced for both of the other waxes in consideration, the paraffin and beeswax (Appendix D). Using the graphs of each of the waxes, the latent

heat of fusion values as well as the onset temperature of melting were calculated from the graphs provided. This information can be found in table 2.

*Table 2. Latent Heat Values and Melting Temperature as measured by DSC*

	Latent Heat ( $\text{kJ/kg}$ )	Melting Temperature ( $^{\circ}\text{C}$ )
<b>Paraffin Wax</b>	172.9	54.3
<b>Palm Wax</b>	186.2	53.7
<b>Beeswax</b>	137.8	59.1
<b>Soy Wax</b>	84.6	38.4

The table above helps the reader to see that the paraffin wax, palm wax and beeswax all have rather similar melting temperatures according to the DSC. The melting temperatures were found using the cooling information of the DSC for the waxes due to the fact that when referring to the melting temperatures of these waxes, the temperature of interest is when the majority of the wax is melting. Therefore, although the paraffin and beeswax begin to melt gradually, they do seem to have a spike at which the majority of the melting occurs. Based on this information it appears as though the soy wax clearly had the lowest melting point of the four waxes. In addition, the palm wax was found to have the greatest latent heat value of the four waxes.

## Discussion

When analyzing the collected data, it is assumed that there is uniform heating throughout the system and that the temperature is the same everywhere in the sample, in practice this is not true. The experimental data suggests that there is a temperature gradient present in the system. This means that the wax at the edges of the beaker cool



more quickly than the wax in the center of the beaker. This can be seen in figure 7. The liquid temperature of the wax appears to cool at the same rate at both the edge of the beaker and the center of the beaker, however the data differs when the wax begins to solidify. The wax at the edge of the beaker continues to decrease in temperature, spending little to no time solidifying unlike the wax at the center of the beaker which remains at the melting temperature for a significant duration of time. This is likely due to its position, suggesting that the wax closer to the edge will spend less time solidifying than the wax in the center of the beaker.

The wax appears to follow the same temperature curve for the three trials displayed in figure 8. This suggests that the data is reproducible and should continue to have the same reaction, regardless of how many times the system is run.

In order for the waxes to be considered for use in latent heat storage applications, information must be known on how the waxes perform both under heating conditions as well as under cooling conditions. It is expected that these waxes will perform similarly under both conditions as they are materials that allow for continuous heating and cooling cycles. Provided the equipment available and the amount of time available for conducting experiments a simple analysis was done to look at the paraffin wax under the heating conditions. The curve shown in figure 13 suggests that the wax does in fact melt at approximately the same temperature as it freezes. Unfortunately, even heating the wax at temperatures just above the melting point, heat is applied to the wax at a rather fast rate, therefore not allowing for the heating curve to be as clear as the cooling curve.

Based on the simple experiments that were performed to test the waxes, a comparison was able to be conducted for the four waxes in consideration. When testing the waxes, there were several unexpected results in the way that the waxes reacted under heating and cooling conditions. Based on previous experiments, it was assumed that all three sustainable waxes in consideration would perform similarly to the previous experiments conducted on the paraffin wax. Although this was the case for the palm wax, this did not occur for the beeswax or the soy wax.

The beeswax had an interesting cooling curve due to the fact that the wax did not experience a very clear melting point. There was clearly a change in the rate of cooling of the wax, however the beeswax did not appear to remain at a single temperature for any extended period of time. Rather, based on the benchmark experiments it appears as though the beeswax experiences an almost immediate phase change. The differential scanning calorimeter provides data that could support the previous evidence. The plot from the calorimeter shows multiple heating peaks for the beeswax, suggesting that the beeswax melts at different temperatures. In addition, the calorimetry data supports the melting temperature found in the benchmark experiments. The benchmark experiments found a melting temperature of approximately  $60.5^{\circ}\text{C}$  while the calorimetry data found a melting temperature of  $59.1^{\circ}\text{C}$ , this is slightly more than a 2% difference in the melting temperatures.

The soy wax provided the most unexpected data. The cooling curve of the soy wax provided the most different shape in comparison to the other waxes. The soy wax cooled and then experienced a rise in temperature before finally cooling to ambient

temperature. As no external heat source was being applied during this data collection this reaction is rather obscure. It is also important to note that this reaction was observed on three separate trials. Further analysis into this reaction could be interesting to research in future work under more strictly controlled conditions.

The soy wax was found to have both the lowest melting temperature of the waxes being considered, in the range of  $40^{\circ}\text{C}$ , as well as the lowest latent heat value, measuring approximately  $84.64 \text{ kJ/kg}$ . Similar to the beeswax, the DSC data, provided data with multiple small peaks, and an overall gradual curve, again suggesting that the soy wax did not melt at a single temperature, but melted slowly at several different temperatures, causing the cooling curve to have the obscure shape that was found. In comparison to the difference in melting temperatures measured in the DSC versus the benchmark experiments, the soy wax differed significantly. This is likely due to the wax melting at a more gradual rate throughout the cooling process. The DSC calculates the cooling curve by determining when cooling first begins, whereas the benchmark experiments will observe the melting at the temperature which is absorbing the most energy.

The paraffin wax has become a rather common heat storage medium for latent heat storage applications. The paraffin wax has a clearly defined melting point which occurs at a temperature of  $54.5^{\circ}\text{C}$  according to the benchmark experiments. The wax almost entirely solidifies before the temperature begins to decrease again. The DSC data for the paraffin wax showed two peaks in the heat being supplied to the sample. This suggests that not all of the sample melts at the same temperature. This idea is

supported in the cooling curve graph, once the solid wax is again decreasing temperatures there is a sudden change in the cooling rate of the wax, this could be due to the remainder of the liquid wax solidifying at this temperature. In addition, the reasoning behind the gradual transition from the solidifying to the temperature decreasing could likely be caused by the sample solidifying at multiple temperatures.

The palm wax became the focus of the analysis, it was clear from the benchmark experiments that the palm wax possessed many of the same properties as the paraffin wax which made it a viable option for a sustainable phase change material. The palm wax provided the most distinct transitions in the cooling curves, showing a clear change in the wax entering the solidifying stage and returning to the temperature of the wax decreasing. The benchmark experiments found the melting temperature of the palm wax to occur at  $55.4^{\circ}\text{C}$  while the DSC data found the melting temperature to be located at  $53.7^{\circ}\text{C}$ . The difference in the two measured temperatures was found to be approximately 3% difference. In addition, the melting temperature of the palm wax was found to be almost the same melting temperature as the paraffin wax in question, meaning that the palm wax would be a viable option in basically the same temperature range that the paraffin wax operates at.

In addition to the melting temperature, the DSC was able to measure the latent heat of the palm wax. This value was found to be  $186.2 \text{ kJ/kg}$ . The palm wax was found to have the greatest latent heat value of the four waxes in consideration. Based on some simple comparisons, this makes a valid argument that out of the four waxes being considered, palm wax may be the best option.

Unlike the other waxes that were being considered, the palm wax did not appear to have several melting points, evidence of this can be seen in both the DSC data as well as the cooling curve for the palm wax. The DSC data clearly shows a single spike in the amount of heat being supplied to the sample, suggesting that the melting all occurs at this one temperature. In addition, the cooling curve appears to have rather sharp transitions from the solidifying regions and after the wax temperature levels out at the melting temperature, the wax appears to cool at a rather standard rate until the wax reaches ambient temperature.

Palm wax was chosen to be used for constructing a prototype system for several reasons. As paraffin wax has many of the desired properties for a phase change material, such as a high specific heat and latent heat of fusion, it is beneficial to choose a sustainable material with similar properties. In addition, the fact that the latent heat value for the palm wax was the greatest was the final deciding factor in choosing the material to consider. This provides that not only would this option be sustainable but could also be more energy dense than the paraffin wax which it was being compared to.

Another important value to consider when analyzing these waxes is the specific heat of each of the waxes. Although this information would be valuable for further analysis of the system, time would not allow for the specific heat of all waxes in consideration to be tested.

## Prototype Design

The final prototype design consists of a 1 gallon volume steel can with a lid.

Figure 16 shows the prototype heat exchanger that has been constructed for testing.

Approximately 10m of 1/4" copper pipe has been bent into coils and inserted into the storage container. Through wall connections allow the copper pipe inside the container to be attached to the lid of the container, providing both the inlet and outlet for the water being transferred through the pipe. A bill of materials for the prototype can be found in Appendix E. Thermocouples were placed at the inlet and exit of the heat exchanger to measure any changes in temperature of the water through the heat exchanger. Valves were also placed at the inlet and exit of the container, so as to allow for the heat exchanger to be easily removed from the system. While operating the system, the can would be surrounded by a flexible closed cell insulation.

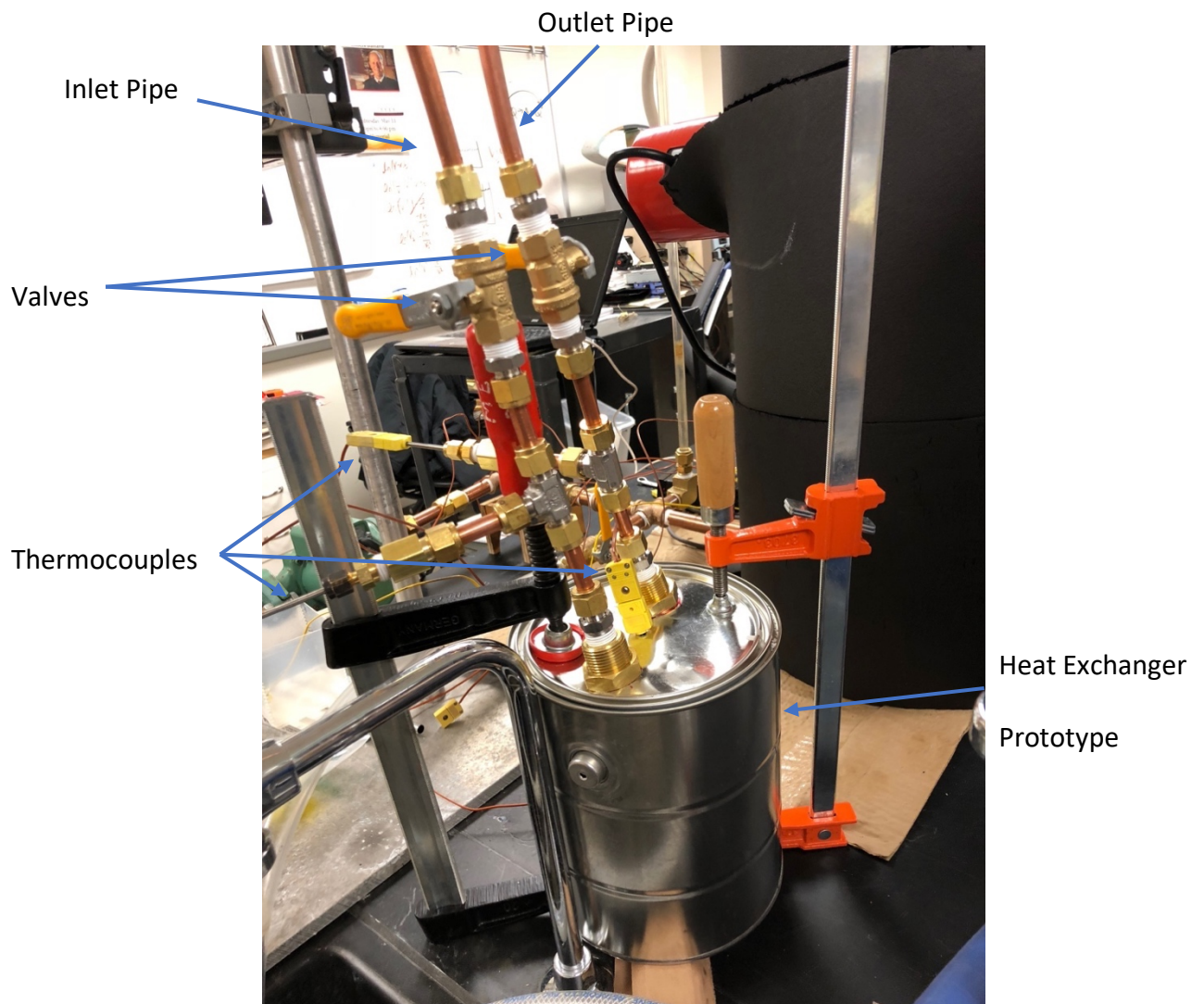


Figure 16. Prototype Palm Wax heat exchanger

The container was then filled with 2.636 kg of palm wax. The palm wax will serve as the latent heat storage medium for the prototype. A thermocouple was placed in the center of the wax to monitor the temperature of the wax while the system is operating.

A solar thermal source was simulated using a hot water tank with an electric heater. The water is heated to near boiling before it circulates through the system. The simulated solar thermal collector is connected to the heat exchanger using 3/8" copper tubing.

A small sump pump was installed in the system, located between the hot water tank and the inlet of the heat exchanger prototype. The pump was required to provide enough head to overcome the approximately 10m of pipe in the prototype, as well as several sharp bends in the prototype. The flow rate provided by the pump was controlled by several ball valves located through the length of pipe.

### Prototype Design Analysis

The overall goal of the research is to develop a physical system in which the phase change materials can be applied. The design was constructed with the purpose of being a heat storage unit for a solar thermal collector. The initial concept being considered included developing a heat storage unit that would make use of latent heat. An actual storage system would seek to make use of not only the latent heat storage that is available but also sensible heat storage in both the wax and a traditional water heat storage. As a result, water would be used as the working fluid and would be heated by the solar collector and then pumped through two heat exchangers to transfer the heat energy to the storage mediums.

In order to transfer the energy into the heat storage mediums heat exchangers must be used. Therefore, the design portion of this project was largely based around designing and constructing a small heat exchanger prototype that makes use of the phase change materials. Analysis was conducted on four different waxes, paraffin wax, palm wax, soy wax and beeswax. Based on this analysis, palm wax was chosen as the



phase change material to be used in the prototype due to its high latent heat value as well as the fact that it is sustainable.

The initial concept for the storage system that was being considered was a hybrid storage system having two separate heat storage units, a water storage unit, storing all of the absorbed energy as sensible heat, and a wax storage unit, storing the absorbed energy as latent heat. The focus of the design was on the wax storage unit. Due to the low thermal conductivity of the wax, the heat exchanger must have a means of successfully transferring heat throughout all of the wax in the container. A metal lattice was considered for improving the heat transfer through the wax. The lattice would be placed in the wax and surrounded by wax. The greater thermal conductivity of the metal would increase the overall thermal conductivity of the system. However, the container used for the prototype is small, therefore the metal lattice was unable to be used in the prototype. Instead, the copper pipe was tightly coiled together and consisted of one coil being placed inside another coil, this provided a great deal of copper surface area in contact with the wax, which in theory should heat the wax rather evenly.

### Prototype Testing

The prototype palm wax heat exchanger was constructed, and some initial tests were conducted to analyze the performance of the small heat exchanger. A solar thermal collector was simulated using a hot water tank and an electric heater. The water in the tank was heated to approximately  $90^{\circ}\text{C}$  prior to the start of the testing.

The heat exchanger prototype was then connected to the hot water tank, the inlet of the heat exchanger received water from the hot water tank and the outlet of the heat exchanger returned the water back to the tank. The latent heat storage prototype was tested by itself in order to identify the energy storage capabilities of heat storage system of this size.

The temperature of the water was measured inside the hot water tank as well as at both the inlet and exit of the prototype container. In addition, the thermocouple in the wax was also monitored to observe the state of the wax through the experiment. A flow meter was placed in the pipe length leading up to the prototype, allowing the average flow rate of the water through the pipes to be measured. The volumetric flow rate of the water was set to  $0.3\text{ gpm}$  using the ball valves that were installed in the system. Knowing the density of water to be approximately  $1000\text{ kg/m}^3$  the mass flow rate was found to be  $0.01893\text{ kg/s}$ .

The rate at which heat was being transferred out of the water can be determined by the temperature loss through the prototype, using equation 17.

$$\dot{Q} = \dot{m}C_p\Delta T \quad [17]$$

Where  $\dot{Q}$  is the heat rate,  $\dot{m}$  is the mass flow rate of the water,  $C_p$  is the specific heat of the water, and  $\Delta T$  is the temperature difference of the water across the prototype. The rate at which heat is being taken out of the system was calculated for the entire length of time the system was operating, using the temperature difference at each point. Although slight variation may occur, the average heat rate should approximately remain constant throughout testing. This can be seen in figure 17.

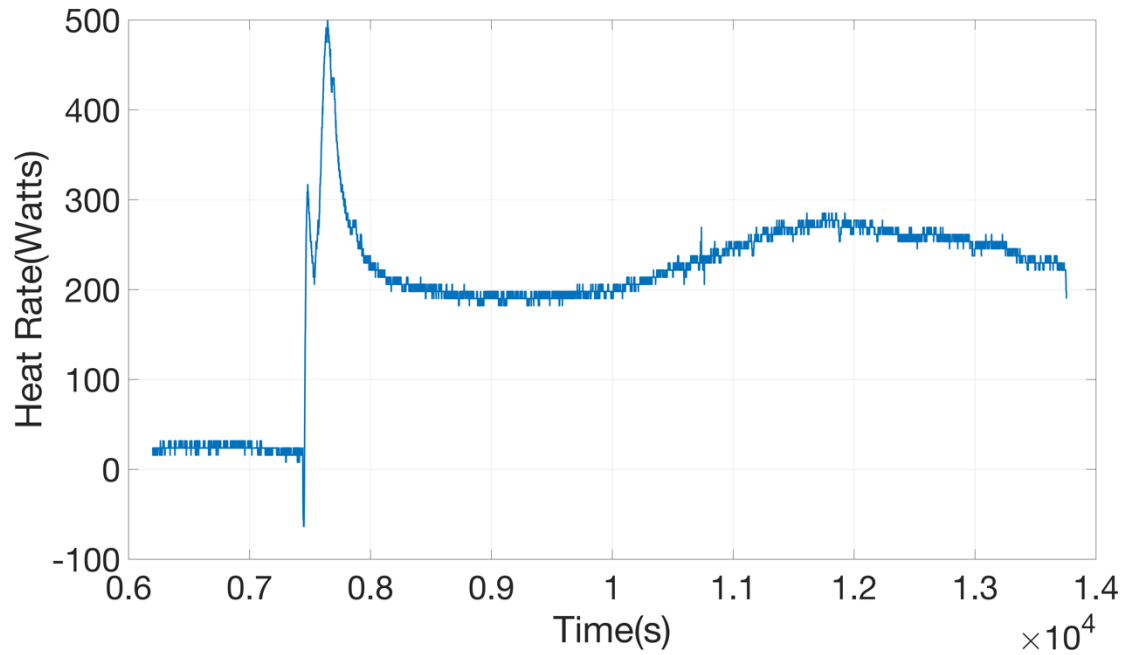


Figure 17. Plot of the rate of heat leaving the water vs time in the prototype

Using the calculated heat rates found over the operating time of the system an average heat rate was calculated for the full operating time. The average heat rate was found to be 201.1 W. In addition, it can be clearly observed the point at which the system was turned on, due to the sudden jump in the heat rate of being applied to the system. Using the average heat rate of the system and the amount of time the system operates, the overall energy into the system can be calculated using equation 18.

$$Energy = Power * time \quad [18]$$

The prototype is found store approximately 1.266 MJ of energy over the time which it operated. However, it is important to note that in reality, some of this heat was lost to the environment and did not remain in the latent heat storage unit. The temperature of the wax as measured by the thermocouple placed into the heat storage unit, started at ambient temperature at 21°C and was heated to a temperature of 75°C. Based on the melting temperature of the palm wax being around 55°C, it can be assumed that all of the wax in the system was melted. This means that the prototype successfully stored energy in the forms of both sensible heat and latent heat.

## Conclusion

Analysis was performed on four waxes, paraffin wax, palm wax, soy wax, and beeswax. The goal of analyzing these waxes was to determine the best sustainable phase change material to use in a latent heat storage unit. Benchmark experiments were conducted on the four waxes in question to determine the cooling curves of the waxes, as well as the melting temperatures of the waxes. As paraffin wax is already in use in several applications as a heat storage medium, the goal was to find a sustainable wax that shared several similar properties. The beeswax and soy wax acted unexpectedly, not exhibiting a clear melting temperature for either of the waxes. The palm wax however, appeared to follow the cooling curve of the paraffin wax extremely closely, exhibiting a similar melting temperature as well as a similar length of time spent cooling.

Following these initial benchmark experiments, data was collected using a differential scanning calorimeter (DSC). The DSC was able to measure the latent heat of fusion of each of the waxes in consideration, as well as the temperature at which phase change occurs in the material. The data was not quite as ideal as previously expected. The analysis of the DSC data suggested that several of the waxes had multiple melting points, not all of the wax experienced phase change at the same temperatures. This was the case for paraffin wax, beeswax and soy wax that was being tested. Each wax appeared to have multiple melting points, with the soy wax having the most obscure results. The soy wax did not appear to experience a clear melting temperature, rather the melting occurred over a range of temperatures.

The values found for the palm wax differed from the DSC data found on the other waxes in consideration. The palm wax was the only wax tested which appeared to have a clear distinct melting temperature. The melting temperature of the palm wax was found to be approximately  $55^{\circ}\text{C}$ . The palm wax was also found to have the greatest latent heat value of the four waxes in question, with a latent heat of  $186 \text{ kJ/kg}$ . Due to having the highest latent heat value and following a similar cooling curve to the paraffin wax, the palm wax was chosen as the latent heat storage medium to be used in the prototype system.

Finally, using palm wax as the latent heat storage medium, a prototype latent heat storage unit was designed and constructed for some initial tests. The prototype consisted of a steel can filled with wax as well as copper tube coils in the can with water flowing through the coils. The prototype functioned as a heat exchanger, with the heat

of the hot water being transferred into the wax. Based on an initial test of the prototype, the latent heat storage unit was able to store approximately  $1.266 \text{ MJ}$  of energy, with the wax temperature increasing from  $21^{\circ}\text{C}$  to  $75^{\circ}\text{C}$ . In reality, some of this energy was lost to the surroundings. However, this initial test provides evidence that the heat storage unit was able to store energy as both sensible and latent heat.

This project easily lends itself to future research. Although this project focused on heat storage in waxes, there are several other phase change materials that could be considered for use in a heat storage system. Further research could be conducted with the physics department, making use of their differential scanning calorimeter to measure values such as the latent heat of the waxes in consideration. Further research could be conducted on using the prototype heat storage unit in a larger system, which makes use of sensible heat storage. The applications of phase change materials are very large, being used in many different ways. It is an important topic that could have a significant impact on future environmentally friendly energy systems.

## Works Cited

- [1] J. J. Tomlinson and L. D. Kannberg, "Thermal Energy Storage," *Mechanical Engineering-CIME*, 1990.
- [2] S. M. Hasnain, "Review on Sustainable Thermal Energy Storage Technologies, Part I: Heat Storage Materials and Techniques," *Energy Conversion and Management*, vol. 39, no. 11, pp. 1127-1138, 1998.
- [3] B. Zalba, J. M. Marin, L. F. Cabeza and H. Mehling, "Review on thermal energy storage with phase change: materials, heat transfer analysis and applications," *Applied Thermal Engineering*, vol. 23, no. 3, pp. 251-283, 2002.
- [4] S. A. Khot, "Enhancement of Thermal Storage System using Phase Change Material," *Energy Procedia*, pp. 142-151, 2013.
- [5] S. Canbazoglu, A. Sahinaslan, A. Ekmekyapar, G. Y. Aksoy and F. Akarsu, "Enhancement of solar thermal energy storage performace using sodium thiosulfate pentahydrate of a conventional solar water-heating system," *Energy and Buildings*, vol. 37, no. 3, pp. 235-242, 2005.
- [6] A. Sharma, V. V. Tyagi, C. R. Chen and D. Buddhi, "Review on thermal energy storage with phase change materials and applications," *Renewable and Sustainable Energy Reviews*, pp. 318-345, 2009.
- [7] A. Kurklu, A. Ozmerzi and S. Bilgin, "Thermal performance of a water-phase change material solar collector," *Renewable Energy*, vol. 26, no. 3, pp. 391-399, 2002.
- [8] D. Vikram, S. Kaushik, V. Prashanth and N. Nallusamy, "An Improvement in the Solar Water Heating Systems by Thermal Storage Using Phase Change Materials," in *ASME 2006 International Solar Energy Conference*, Denver, 2006.
- [9] "Concentrating Solar Power," Solar Energy Industries Association, 2017. [Online]. [Accessed 19 11 2017].
- [10] S. A. Kalogirou, "Solar thermal collectors and applications," *Progress in Energy and Combustion Science*, pp. 231-295, 2004.
- [11] S. A. Kalogirou and Y. Tripanagnostopoulous, "Hybrid PV/T solar systems for domestic hot water and electricity production," *Energy Conversion and Management*, vol. 47, no. 18-19, pp. 3368-3382, 2006.
- [12] Y. Tian and C. Y. Zhao, "A review of solar collectors and thermal energy storage in solar thermal applications," *Applied Energy*, pp. 538-553, 2013.

## Appendices

### Appendix A-Paraffin Wax Literature Properties [13]

Density	798 kg/m <sup>3</sup>
Specific Heat (Liquid)	2.3179 kJ/kg*K
Specific Heat (Solid)	1.905 kJ/kg*K
Latent Heat of Fusion	255 kJ/kg

### Appendix B-Derivation of Overall Heat Loss Coefficient Calculations

Calculation of Overall Heat Loss

$$Q = -UA(T(t) - T_{\infty})$$
$$\Theta = T(t) - T_{\infty} \quad \Theta_i = T_i - T_{\infty}$$
$$d\Theta = dT$$
$$\rho VC \frac{d\Theta}{dt} = -UA \Theta(t)$$
$$\frac{d\Theta}{\Theta} = -\frac{UA}{\rho VC} dt$$
$$\ln \frac{\Theta}{\Theta_i} = -\frac{UA}{\rho VC} t$$
$$\ln \Theta = -\frac{UA}{\rho VC} t + \ln \Theta_i$$

plot  $\ln \Theta$  vs.  $t$

$$\text{slope} = \frac{UA}{\rho VC}$$
$$UA = \rho VC |\text{slope}|$$



## Appendix C-MATLAB Code for Numerical Simulation

```
%Dan Giroux
%Senior Project Code
clear;clc; close all;

%Constants
rho=798; %kg/m^3
Volume=1e-4; %m^3
Cpl=2.3179; %kJ/kg*K
Cps=1.905;
h=255;

%Temperatures in Celcius
Tstart=86.67;
Tinf=22.86;
Tmelt=54.5;

UAL=0.000141479; %Liquid
UAs=3.03131e-05; %Solid
mass=rho*Volume;

deltat=1;
t=0:deltat:25000;

T=[Tstart];
ms=0; %Mass of the Solid

for k=1:length(t)-1

    if T(k)>Tmelt

        T(k+1)=T(k)+deltat/(mass*Cpl)*(UAL*(Tinf-T(k)));
        ms(k+1)=ms(k);
        ps(k+1)=ms(k)/mass; %Percent of Mass that has frozen

    elseif T(k)<=Tmelt && T(k)>=Tmelt-1

        T(k+1)=T(k);
        ms(k+1)=ms(k)+deltat*UAL/h*(Tmelt-Tinf); %Percent Solid
        ps(k+1)=ms(k)/mass;
        if ps(k)>=1 %Once the entire mass freezes then restart temp change
            T(k+1)=T(k)+deltat/(mass*Cps)*(UAs*(Tinf-T(k)));
        end

    else

        T(k+1)=T(k)+deltat/(mass*Cps)*(UAs*(Tinf-T(k)));
        ms(k+1)=ms(k);
        ps(k+1)=ms(k)/mass;

    end

end

%Experimental Data
Exp_Temp=load('Triall.txt','ASCII');
Exp_Time=1:length(Exp_Temp);

%Plot Experimental Data and Modelled Data
plot(t,T,'b','LineWidth',2)
hold on
plot(Exp_Time,Exp_Temp,'r','LineWidth',2)
xlabel('Time(s)')
ylabel('Temperature(Celcius)')
legend('Simulation','Experimental')
```

## Appendix D- Plot of DSC data of Paraffin and Beeswax

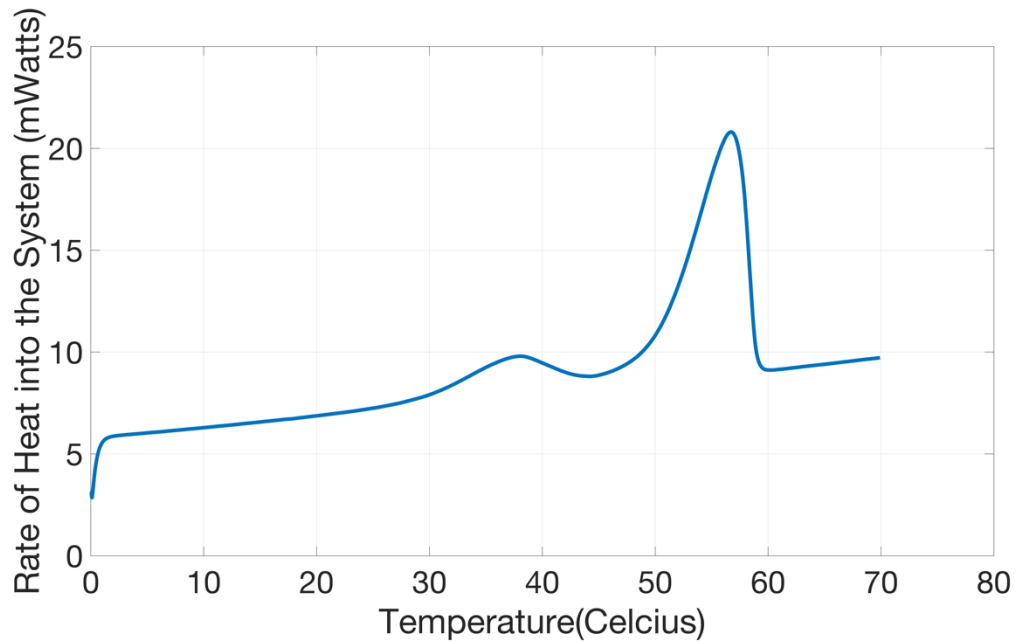


Figure 18. Paraffin Wax plot of heat rate vs temperature

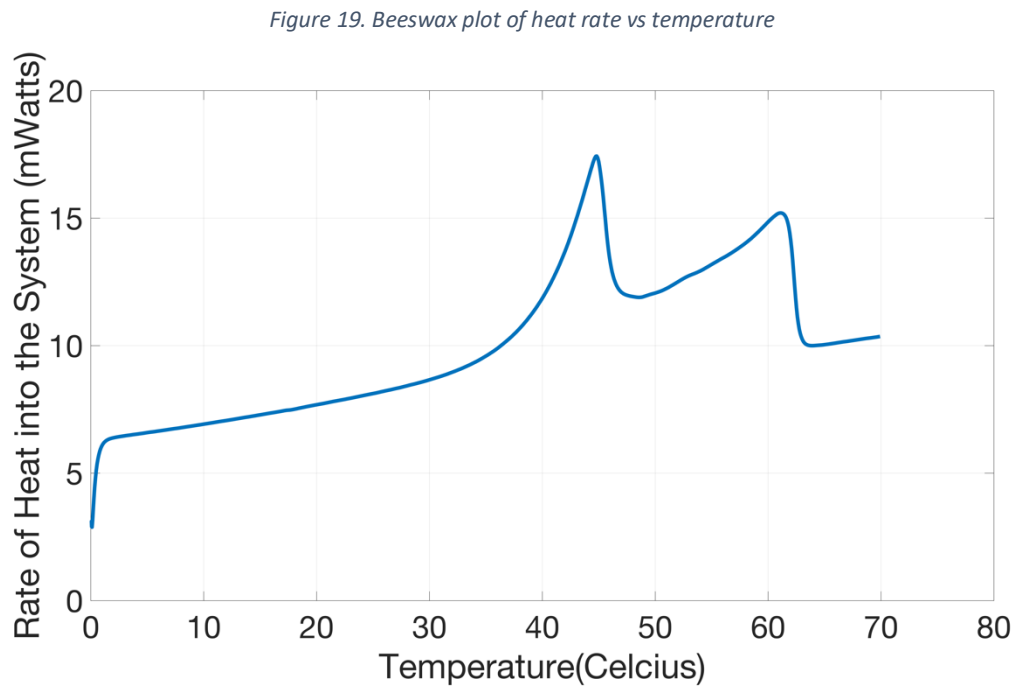


Figure 19. Beeswax plot of heat rate vs temperature

## Appendix E-Bill of Materials for Prototype

Part #	Description	Supplier	Qty	Unit	Cost/unit
60689	Steel Can, 1 gallon	Lowes	1	unit	\$4.98
8967K88	¼" Copper Tubing	McMaster	30	ft.	\$1.26
8967K94	3/8" Copper Tubing	McMaster	20	ft.	\$3.20
KQXL-18U-6	Type K Thermocouple Probe	Omega	4	Unit	\$36.50
4629K12	Brass Ball Valve	McMaster	2	Unit	\$10.83
5220k139	Brass Tee Connectors	McMaster	2	Unit	9.52