Phase Change Energy Storage Implementing Recycled Materials

A Major Qualifying Project to be submitted to the faculty of
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Abstract

This project involved the development and design of a hybrid thermal energy storage system to reduce financial and environmental costs of thermal energy. Energy storage is achieved in the form of latent heat, primarily using solar energy collected during peak hours. Phase change materials were chosen for their high energy density across small temperature increments, increasing efficiency and product lifetime. Utilization of waste and recycled products was a focus of this project affecting material choices resulting in the choice of P-116 paraffin wax as the phase change material. Computational thermal simulations were conducted to provide insight to help optimize the storage system design; based on this a prototype was experimentally tested with promising results. A dynamic system was designed with scaling possible for home or industrial scale systems.

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Acronym Reference Table

HDPE	High-density polyethylene
HX	Heat exchanger
LHTS	Latent heat thermal system
PCM	Phase change material
TES	Thermal Energy Storage

Chapter 1: Introduction

The engineering world revolves around creating new technologies in order to improve the efficiencies of existing systems. Whether that involves minimizing the mass of a car to make room for new technologies, improving efficiency of energy generation systems, or improving the yield of a manufacturing system, this idea of improving efficiencies is everywhere within the field of mechanical engineering. In order to concentrate on increasing efficiencies, our goal was to suggest a home-scale supplementary heating system using thermal solar panels as a form of heating, a paraffin wax-based latent heat storage tank which would be used to store collected heat, and a compact heat exchanger between the solar working fluid and the air entering a furnace to transfer the collected heat at a desired time. In order to supplement this goal, we conducted background research on energy storage and concentrated on the different methods of energy storage. We then focused on thermal energy storage and its classifications. Next, we elaborate on the chemistry of material phase changes, phase change materials (or PCMs), and the material properties of the grade of paraffin we planned our design around. Finally, we discussed common designs of the cell encasement.

The project's primary objective was to design, simulate, and build a proof-of-concept latent heat thermal system that uses available recyclable materials such as paraffin wax. In order to accomplish this first objective, we designed a system that would include a heat source, a storage tank full of paraffin cells, and a heat exchanger to interface between the supplementary system and the home heating system. For our project, we decided to use solar thermal cells as our heat source. We chose a sunny location to base our simulations on (Phoenix, AZ) and used the solar data from a week in January in Arizona in order to simulate “worst-case” energy collection based on an estimate of usable home roof area for the solar cells. We were able to determine that our model had workable cycle times and temperatures. Our secondary objective was to design the cell and cell arrangement of encased paraffin wax within a tank. Through intense background research and iterative design, we decided on a four loop plastic mesh shelving system in our insulated container. The values obtained during the experiment closely matched the data from the cell simulations conducted. The values also confirmed the theory and workability of our thermal energy storage system.

Chapter 2: Background

In this section we will discuss various topics related to the foundation and design of our project. We will discuss what energy storage means for our project and why it is necessary, what thermal energy is and its specific applications, and the three main types of thermal energy. In addition, we will be discussing the necessary materials and equipment for latent heat energy storage and use.

2.1 Introduction to Energy Storage

Since the industrial revolution, mankind has been working on developing methods of storing energy. The broad applications of storing energy has pushed engineers to find innovative and effective methods of storing energy. Energy storage is a crucial component of manufacturing, the service industry, and even portable electronics [Whittingham]. In the last decade, the surge to develop renewable energy sources has drawn increased attention towards energy storage methods, due to their irregular levels of energy generation. The intermittency of solar, wind, and hydroelectric power makes it necessary to store energy in order to meet peak power demands. Therefore, in order to make renewable energy a more prevalent component of modern-day power grids, methods of energy storage must be improved. Currently, there are many applications of energy storage that can help to offset this peak power demand.

2.2 How Energy is Stored

Electric grids around the world experience vast fluctuations in the amount of energy necessary to supply business and homes. Some systems require more energy in the daytime, when businesses are open. Homes, especially those with solar cells, require more energy at night. In order to deal with this complication, energy is stored via different solutions. Batteries, hydroelectric pumps, and compressed gas are all different examples of how energy can be stored. In order to meet the goals of reduced grid energy consumption, we investigated creative energy storage solutions.

2.2.1 Energy Storage using Potential Chemical Reactions

One way in which energy can be stored is by taking advantage of certain chemical properties. One of the most common chemical energy storage systems is the battery. Batteries rely on chemical reactions to generate energy in the form of electricity. While chemical energy storage is very applicable for portable electronics, it is not always the most effective resource for larger systems [Aho et al.].

2.2.2 Energy Storage using Mechanical Properties and Systems

With our knowledge of physical properties we can store energy via its inertia and gravitational/potential energy. Pumping water and releasing it at a later time in order to harness hydroelectric power is a great example of mechanical energy storage. Another system of energy storage with growing usage is compressed air storage [Luo, X., Wang, J., Dooner, M., & Clarke, J.].

2.3 Thermal Energy Storage

We will be implementing a thermal energy storage system, for it is the most synthesizable with regard to solar thermal cells. Thermal energy storage can also be treated as heat and cold storage via sensible and latent heat. Typically, thermal energy storage is divided into sensible and latent heat storage, which are subdivided into different phases.

2.3.1 Thermal Energy Storage and Applications

One main application of energy storage can be found in home heating systems. With home temperature regulation costing homeowners significant amounts in colder climates, there has been a large push to integrate energy storage systems into home heating. In January 2018, approximately 43% of retail electricity sold in the United States was used in residential applications [U.S. Energy Information Administration]. Although not all of this electricity was used for heating, this statistic highlights an influx of residential electricity usage that must be decreased in order to maintain a functioning electrical grid.

One example of energy storage for home use is underground thermal energy storage. Underground thermal energy storage has increased in popularity in Europe (Sanner, 2003). This is not the only example of heat storage applications in use today. Water and air storage systems exist both with the goal of storing heat energy in a medium that allows for the distribution of heat throughout a residential building. The goal of these thermal storage systems is to reduce electricity or fuel consumption by making heat more accessible to the entire building. This decreases peak energy demands and enables home heating systems to have a decreased environmental impact.

Energy storage is not limited to residential use, as it is also prominently used in industrial applications as well. A subsection of industrial applications of thermal storage is industrial waste heat recovery [Miró, L., Gasia, J., & Cabeza, L. F.]. When there is a difference between heat produced and heat demand for an industrial process, waste heat is created. There exists economic and environmental gain when this waste heat can be stored using thermal storage for future utilization. An example of an industry in which waste heat is stored for later use is metal manufacturing. In this process, exhaust temperatures from these processes can be very high. Other examples of industrial applications of thermal storage include chemical, paper, and food and beverage industries.

2.3.2 Types of Thermal Energy Storage

Thermal energy storage can be broken down into three main categories: sensible heat, latent heat, and chemical energy storage. Chemical energy storage is not as commonly found in thermal energy storage applications. Sensible and latent heat energy storage are both storage methods that take heat energy into the system which can be released at a later time. Sensible heat refers to the storage of heat energy in the form of temperature change. Whereas sensible heat can be represented by either a temperature or an enthalpy differential, latent heat can only be represented by an enthalpy differential. This is because in latent heat, the energy stored in the system is stored during a phase change. While a material undergoes a phase change its temperature does not increase.

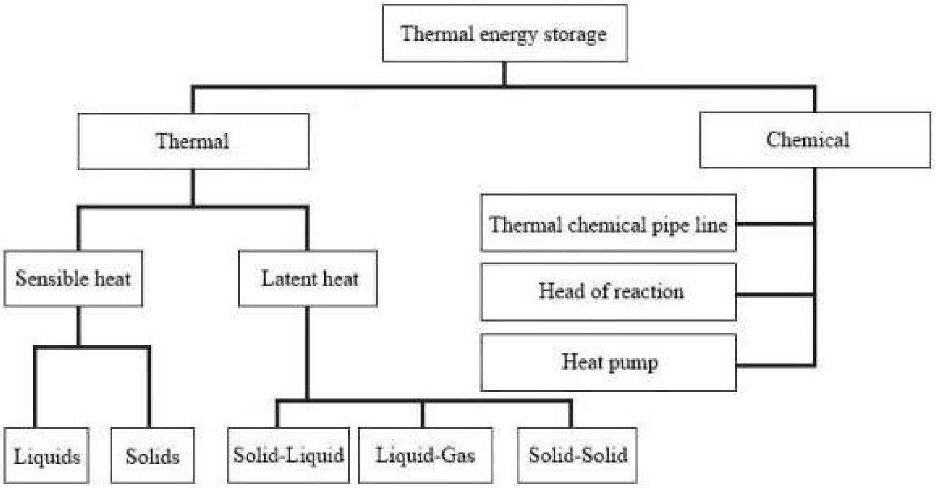


Figure 1: Forms of thermal energy storage [Zalba]

These three types of thermal energy storage and their applications are pictured above in Figure 1.

2.3.3 Sensible Heat Storage

Energy stored in a medium as a temperature differential and not a phase change is known as sensible heat storage (e.g., water, sand, molten salts, or rocks). Sensible heat storage is typically used to smooth out heat transfer between insulating walls, but cannot store the amount of energy needed to supplement heating in a reasonable way. Typically they are concrete walls that slow the rate of heat loss or gain [Velez]. The amount of heat stored is represented by the following equation if there is no phase change:

$$\mathbf{Q = m*cp*(t_f - t_i)}$$

Where m is the mass in kg, cp is the specific heat capacity of the material in kJ/kg*K, t_i is the initial temperature, and t_f is the final temperature.

2.3.4 Latent Heat Storage

The energy density for a latent heat storage system is typically 50-100 times larger than that of sensible heat [Velez]. Latent heat is defined as the heat energy stored in any phase change transition, most commonly from solid to liquid, liquid to gas, solid to solid, or liquid to solid. Phase change can be caused by conduction or convection from the other heat transfer material to the phase change material, or can be an exchange of heat between two phase change materials [Velez]. The thermal energy stored by latent heat can be calculated using the equation:

$$\mathbf{Q = m*L}$$

where m is the mass in kilograms and L is the specific latent heat in kilojoules per kilogram [Velez]. Another advantage that latent heat exchange systems have over sensible heat storage systems is that the temperature differences between charging and discharging are much smaller due to the zero temperature change when undergoing latent heat exchange [Johnson].

A temperature range between 20 and 100 degrees Celsius is considered appropriate for low-temperature storage (thermal energy storage, or TES) systems. These systems are useful for applications such as home heating, space heating, bathing, and laundry. Between 100 and 250 degrees Celsius is considered medium heat; this range is useful for drying, steaming, boiling, and sterilizing using phase change materials such as sugar alcohols and chemical absorption storage materials. Finally, high temperature heat storage applications above 250 degrees Celsius use storage materials such as salts, concrete, and metals; these are mostly used in industrial applications [Shchukina, E. M., et al.].

2.3.5 Chemical Energy Storage

Chemical energy storage includes fuels and batteries which are the most prevalent forms of dense energy storage. Currently, many systems rely on fuels for mechanical energy (eg cars), thermal energy (eg home heating), or electrical energy (eg coal power plant). This form of chemical energy is very useful but is the type of energy storage we are trying to reduce the use of with our project. Batteries have been optimized to store energy in a way that they can release as electrical energy, but this type of energy storage is expensive, especially when being used in an application such as home heating.

2.3.6 Thermal Energy Storage

It is important to state foremost that the main reason TES does not see more widespread use internationally is due to its high initial capital cost requirements. We find that the sensible heat storage requirements for materials are simple and well-researched; cement is typically the most useful and cost-effective form of TES available commercially. The biggest drawback of sensible heat storage is the lack of temperature stability during the discharge of heat.

2.4 Phase Changes

Phase change materials have two main uses: as thermal inertia and as a form of energy storage. According to the 33rd Lunar and Planetary Science Conference, thermal inertia is a material’s resistance to changing temperature [Presley, 2002]. Materials undergoing a phase change require an enormous amount of energy to change the amount of heat stored in the materials relative to when they remain in a single phase. Phase changes can be used to efficiently maintain the temperature of a volume for long periods of time. For example, ice melts at 0°C and is used to keep drinks cold for a relatively long time–even in warm environments.This is because all of the heat that enters the drink melts the ice, rather than heating the drink. The high thermal inertia of phase change materials is especially useful in situations where ambient temperatures change from too warm to too cold very quickly. The energy entering the system could be stored in the PCM, preventing the insulated volume from getting too warm, while energy leaving the system can be replaced by energy stored in the PCM, rather than allowing the insulated volume to become too cold. The applications of PCM's vary from keeping a space station at livable temperatures to keeping donated organs cool or airplane meals warm.

2.4.1 Types of Phase Changes

There are several ways materials can change phase including from liquid to gas, solid to liquid, solid to solid, and solid to gas. All of these phase changes have properties that make them more or less advantageous for specific applications. The most advantageous phase change for a given application is also determined based on the material being used and the optimal working temperature for the system. These different types of phase changes will be discussed in greater detail in this section.

Solid-solid phase store thermal energy through a change in crystal structure in the material. These materials are advantageous because they do not expand noticeably, are easy to contain due to their constant solid state, and do not experience supercooling since they are not a fluid in either state. However, because they store energy in crystal structure instead of a full phase change, the energy density is lower than other phase change conversions and only specific and often expensive materials can be used for this form of energy storage.

Solid-liquid phase changes are advantageous for energy storage. The melting temperature of materials can vary greatly between near absolute zero to thousands of degrees which allows them to be used in a variety of applications depending on the desired storage temperature. Additionally, the latent heat of fusion is high resulting in energy density five to fourteen times greater than non-PCM material [Solid]. The density of materials often does not change greatly between solid and liquid meaning there is not huge variations in volume which cause containment issues. Since almost any material can be used for solid-liquid phase change, very cheap materials can be used as the PCM depending on the application. The problems with solid-liquid phase change is that liquids are more difficult to contain than solids and liquids can undergo the phenomenon, supercooling, which will be described in the following section.

Liquid-gas phase change has many of the same advantages as solid-liquid including high energy density and wide range of temperatures and materials is widely used. However, the massive expansion, often on the order of 10^3, that occurs requires large systems that are unrealistic for energy storage.

Solid-gas phase change, also known as sublimation, has extremely high energy density because it is the enthalpy of fusion plus the enthalpy of vaporization. Sublimation occurs when a solid is at a pressure below the triple point, where conditions allow a material to be a solid, liquid, and gas simultaneously. This concept is shown in Figure 2.

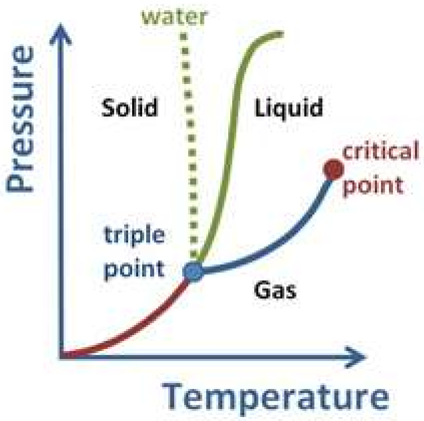


Figure 2: Phases of water on a P-T diagram [Velez]

However, there are some major drawbacks; first, only certain materials are feasible for sublimation because they must have a reasonable triple point. Second, an expensive vacuum system must be incorporated to keep the pressure below the triple point, and third there is massive expansion between solids and gases.

Supercooling and Phase Separation

Supercooling is a phenomenon where a material can remain a fluid below its freezing temperature. This occurs when the crystallization (or nucleation) temperature of a material is below the freezing temperature. As a result, the material can exist below its freezing temperature until a crystal forms. Once this occurs, it triggers a chain reaction which allows the entire material to freeze. The temperature of the material drops below the freezing temperature, and then when it freezes the temperature actually rises as shown in Figure 3.

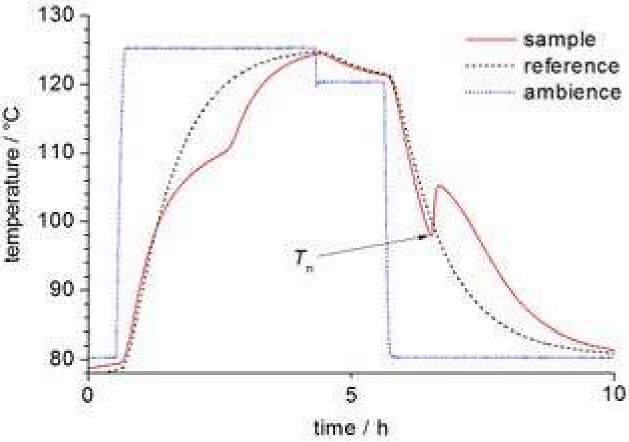


Figure 3: An experiment showing the temperature of a material through supercooling [Velez].

Supercooling causes two effects detrimental to ideal phase change energy storage. First, supercooling reduces the effectiveness of the PCM because the energy is stored as sensible energy instead of latent energy. Second, supercooling can cause phase separation in PCMs that are a blend of materials with different freezing temperatures. This will lead to material destabilization which can hamper the thermal cycle associated with energy storage.

PCM supercooling results in an undesirable difference in charging and discharging temperature. Nucleating agents are useful for testing a PCM like Polyethylene glycol, which has a high supercooling degree.[Alva]. Polyethylene glycol is a low volatility and anhydrous organic PCM. Fatty acids, fatty acid derivatives, and paraffins all fall into this category [Khudhair] Initial latent heat storage research was focused on salt hydrates, but researchers moved on because of their tendency to supercool, especially not congruently. Paraffin escapes both of these problems [Khudhair].

Among these four types of phase change, solid-liquid provides the best combination of properties for thermal energy storage [Agyenim]. This is because the latent heat of fusion is high and the expansion/contraction coefficient is low. Additionally, there are many materials available for solid-liquid phase change which results in a wide range of available temperatures that can be selected depending on the application. However, as explained in the following section, not all materials are suitable for use as phase change materials.

2.4.2 Phase Change Materials

Phase change materials are usually broken down into subcategories to help classify them by their characteristics. Solid-liquid PCMs can be organic or inorganic which each have their own strengths. Inorganic PCMs generally have higher energy densities than organic PCMs. However, organic PCMs melt congruently and have self-nucleation [Alva]. This means that they will remain stable throughout subcooling, which is one of the major drawbacks of liquid-solid phase change. As well, inorganic materials like salts can often corrode container material [Velraj]. Now, PCMs are just often mixtures of chemicals which can melt at a single temperature (eutectics) or over a range [Alva].

Characteristics of Effective Phase Change Materials

There are many characteristics that make certain PCMs better than others that have been listed by many scientists and researchers who have studied PCMs. The ones pertinent for thermal energy storage include[Mishra][Agyenim][Johnson][Sharma]:

Thermophysical

- High latent heat of fusion per unit volume and mass to store more energy in a given volume and mass.
- Reversible freeze/melt cycle

- Melting Temperature in the desired range
- High specific heat to provide additional significant sensible heat storage effects.
- High thermal conductivity to assist charging and discharging of energy.
- Exhibit little or no subcooling during freezing to provide good stability during extended thermal cycling / or high nucleation rate
- Low changes in volume during phase change and low vapor pressure to avoid containment problems.
- Congruent melting with each cycle

Chemical

- Possess chemical stability, no chemical decomposition.
- Does not react with and/or act as a solvent for packaging materials.
- Contain non-poisonous, non-corrosive, non-flammable, non-explosive, and non-carcinogenic elements/compounds.

Economical and Environmental

- Landfill disposable and/or waterway disposable.
- Available in large quantities at low cost.

These characteristics are objective, but one of the most important characteristics depends on the application it is being used for. Melting temperature must be selected based on the temperature of the heat source to optimize the system. While the melting temperature of the PCM must be below the temperature of the heat source for heat transfer to occur, higher melting temperatures of the PCM results in higher quality heat storage.

Based on these desirable characteristics for PCMs, some of the key challenges presented by PCM energy storage include [Johnson]:

- Material Compatibility
- Material Properties and Thermal Performance
- Packaging for Use
- Conditioning for Use
- Cost and Availability

Alkane Phase Change Materials

Organic PCMs are often selected for thermal storage since they have much better stability than inorganic materials. Among these organic materials, linear alkanes (following the chemical formula C_nH_{2n+2}) provide a good combination of characteristics making them attractive for solar energy storage [Velez]. “An exhaustive evaluation by Cold Chain Technologies did not uncover the “perfect” PCM but alkanes exhibited the best combination of attributes.”[Formato] They have high latent heat of fusion, good chemical stability, melt congruently, and are relatively non-reactive.

2.4.3 Paraffin Wax as a Phase Change Material

Linear alkanes generally have higher melting temperatures as the number of carbon atoms increase. For example, at STP, alkanes between n=1 and n=4 are gases, alkanes between n=5 and n=17 are liquids, and alkanes above n=18 are solid [Esir]. When different ratios of alkanes are mixed, the resulting material has a reversible melting point that ranges over a few degrees over a central temperature that depends on the ratio and melting points of the alkanes added. Alkanes between carbon numbers between n=12 and n=40 are classified as paraffin [Velez]. The chemical change in the paraffin is the crystallization of the CH3- chain of the paraffin at the freezing point. This crystallization releases a large amount of latent heat, relative to other materials. Because of the long chain length of paraffin, the melting point and latent heat of fusion are high relative to other materials [Velez].

Paraffin wax is a byproduct of crude oil refining and is created in such high quantities, that uses such as chewing gum and candle making cannot keep up with production. This causes commercial paraffin to be very cheap since its surplus is often burned off as waste. Paraffin can be separated into its specific alkanes which is known as analytical grade paraffin. However, this separation is costly and is mostly used for research since blends of paraffin are equally effective for most applications. Paraffin is also non-polar and forms an “oil in water” emulsion, which helps the microencapsulation process. Paraffin has a high heat of fusion, low supercooling temperature, chemical stability, and does not undergo phase segregation. All of these aspects are advantages. The low supercooling temperature is a small plus in the low melting temperature ranges we already have. The chemical stability and lack of phase segregation enables long-term use possibilities for thermal storage. However, the drawbacks include low density, low thermal conductivity, and large volume change during phase change [Velez] [Velraj].

Certain phase change materials can be enhanced with filler material. Filler materials allow for fine-tuning of PCM’s and increase thermal conductivity and viscosity while decreasing natural convection and heat transfer rate. Possible materials include various carbon, ceramic, and metallic fillers [Alva].

According to Velraj, paraffin wax can remain stable after approximately 1,500 cycles. However, wax can also infiltrate and soften plastic containers, while metal remains compatible. Aluminum honeycombs was one suggested way to avoid the lack of stability of wax [Velraj]. According to Güçeri, metal containers were used on one of his past experiments and the volume change lowered the latent heat energy actually stored. However, we decided early in this project that the manufacturing cost should be excluded this from the scope of the project.

2.5 PCM Cell design

Phase change materials that exist as a fluid in either or both states must be contained to prevent them from mixing with the working fluid that transfers heat from one location to another. When the PCM exists at a liquid in both states, such as a liquid-gas system, the ability for the material to flow regardless of the state allows a relatively simple heat exchanger and storage tank design. However, solid-liquid phase change is not able to utilize this technology because as the material forms a solid, it can clog fluid flow. Thus the PCM must be stored in self-contained units to prevent mixing with the working fluid. These PCM storage units will henceforth be defined as storage cells.

Thermal Cycle

Each application of thermal energy storage has its own thermal cycle which impacts the storage cell design. Some of the constraints derived from the thermal cycle include: maximum positive and negative heat flux, inlet and outlet temperatures, cycle period, and maximum energy storage. These constraints are important and designing around them will increase the efficiency of the system, but often realistic constraints such as cost and volume will require some design compromises.

How Cell Storage helps Heat Transfer

High surface area increases heat transfer which allows thermal systems to operate more efficiently as it decreases thermal resistance. This is especially important when using materials with low thermal conductivity. Although decreasing the volume of the storage cells will increase the cell heat flux, it also decreases the energy density of the system because there is less PCM and more packaging. Also, it will increase cost of packaging as well as the likelihood of the storage cell leaking. To optimize the design, the storage cell size should maximize storage cell volume while still meeting the thermal cycle demands.

Containment of Solid-Liquid Phase Change Materials

One of the most challenging aspects of PCM storage is containing the fluid within the storage cell [Solid]. PCMs often expand and contract during phase change which causes them to pull away from rigid containment. Contraction during solidification causes a gap between the PCM and the cell wall which creates a huge thermal barrier which prevents efficient use. Flexible containment can prevent this issue, but sealing flexible cells presents a formidable challenge. PCMs have lower surface tension than water which allows them to easily leak out of seals that are water tight, and expansion and contraction cycles can cause leaks to form over time.

2.6 Case material

Material Compatibility

The most important characteristic of the cell casing is compatibility with the PCM it will be containing. Most materials, especially PCMs, are reactive with certain materials which will cause serious issues immediately or over time. Even if the PCM and cell casing material are chemically stable with each other, they must also have compatible working temperatures. The PCM selected will have a phase change temperature and usually an additional temperature range owing to sensible heat storage; the casing material must retain acceptable chemical and thermophysical properties through this range.

Flexibility of Cell Material

As mentioned before, most PCMs expand and contract upon phase change, even between solid and liquid. This expansion and contraction prevents rigid containment from being a feasible option. Materials that stretch could account for the fluctuation in volume, however, stretching can increase permeability and after many cycles cause fatigue and eventually failure. The best option is materials that are flexible and designed in a way that allows the volume to change while the surface area remains constant. For example, a rectangular cuboid can have the same surface area but less volume than a cube.

Thermal Conductivity of Casing Material

The storage cell design is centered around heat transfer, so the casing material also must be selected with this in mind. Minimizing thermal resistance is a goal of the design, but impact greatly depends on the thermal conductivity of the PCM inside. A very low thermal conductivity casing used with a high thermal conductivity PCM will reduce the efficiency of the system, but a very high thermal conductivity casing will not greatly impact the efficiency if used with a low conductivity PCM. Increasing the thermal conductivity of the casing will become less impactful as it passes the thermal conductivity of the PCM [Formato].

Many things are necessary to keep in mind when designing a system around containers of PCM's to ensure proper heat transfer and cycling. There are many processes that can and will go wrong and things that need to be kept in mind during design. Heat loss in a TES for example is accelerated by a multitude of factors. The higher the operating temperature means a higher rate of heat loss, which should be appropriately considered when designing the process of waste heat leaving the system, or insulation thicknesses. That same insulation can also become wet or damaged in certain designs, resulting in extra heat loss. Additionally, piping length and design must be carefully watched in heat loss contribution to the thermal network. What is also good to consider is a cascaded storage system; if possible, different PCM's could be arranged to store heat at different temperatures. This improves solar collecting efficiency when the lower T at the bottom of the tank is connected to the inlet of the heat transfer medium. Even if the container is not cascaded, care can be taken in the system design to stratify and mix the storage. A proper thermal gradient has influence over the aspect ratio (ratio of height to width/diameter), inlet/outlet locations in the storage tank, and the operating parameters such as inlet velocity and temperature of the heat transfer fluid. The inlet location has a noticeable effect on thermal stratification [Alva].

Chapter 3: Methodology

This section will discuss the methodology developed to achieve the goal of suggesting a sufficient home-scale system using thermal solar panels, a paraffin-based latent heat storage tank, and a compact heat exchanger between the solar working fluid and the circulating air. The objectives were created in order to achieve this goal:

1. To design, simulate, and build a proof-of-concept latent heat thermal system (LHTS) that uses available recyclable materials such as paraffin wax
2. To design the cell and cell arrangement of encased paraffin wax (which will be used as our phase change material) within a tank

A full-scale system can be suggested based on a smaller version of the home heating supplementary system if the experimental and simulated results show that it is able to store and release sufficient energy.

3.1 Home Heating System Design

Our team chose to design our supplementary heating system for a home-scale system due to the standardization of hot air heating systems. Because of this, we were able to suggest a system that could be refined and used for many homes in order to better distribute heat energy throughout the day. We were able to achieve this by designing a system which includes: solar thermal panels as a method of collecting heat, a paraffin wax storage tank as a means of storing thermal energy in the form of latent energy, and a heat exchanger between the heated working fluid and the air entering a furnace. The main aspects of this design will be covered in this section (solar heating, storage tank, heat exchanger).

3.1.1 Heat Source Development

There are many heat sources that we could have design our system around, but we chose solar thermal panels as a renewable but variable heat source. Solar thermal panels are large collectors that take advantage of the sun's radiative heat to heat a fluid flowing through the panels and a much higher efficiency than photovoltaic cells. We designed our project around using flat plate collectors on the roof of a house. A diagram of a flat plate solar collector can be seen in figure 4 below:

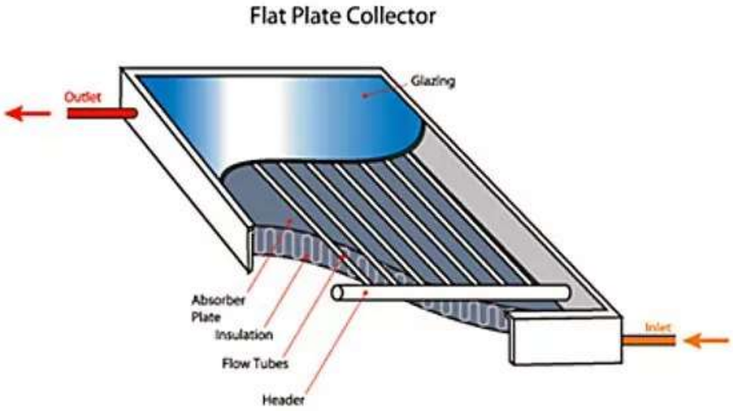


Figure 4: A flat plate solar thermal collector [Abdelhamid]

3.1.2 Storage Tank Design

The concept for this project was originally developed by our advisor, Selcuk Güçeri, as a thermal storage unit using paraffin wax stored in aluminum cans. The project was unsuccessful because the wax shrunk and separated from the can wall as it solidified in the cans. This resulted in a layer of low density air, which created a large thermal resistance [Güçeri]. This past failure lead to implementation of flexible HDPE cells.

Our design for a phase change material storage tank included an encapsulation for the phase change material, a method of securing the cells in place, and a method of controlling the direction of flow of water past the cells.

3.1.3 Heating System Integration

The interface between our heat collecting/releasing system and a home heating system is a heat exchanger located at the entrance to a hot air furnace. This is represented in figure 5 below.

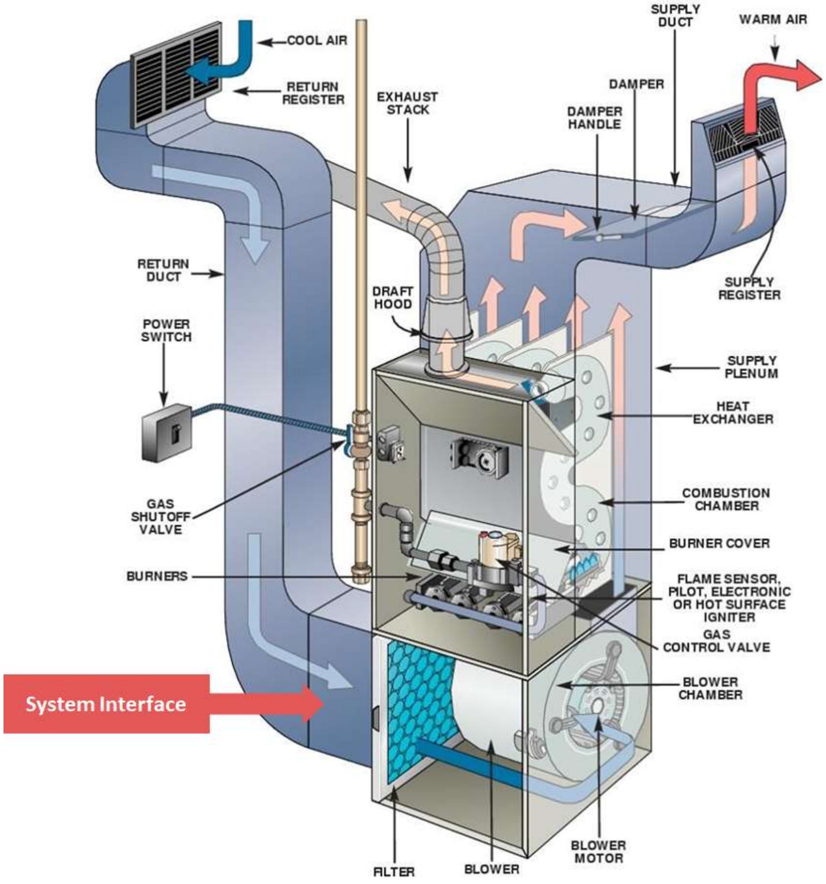


Figure 5: Schematic of an existing furnace design with the hybrid system integrated [UGI]

We chose to add our system before the furnace as a “preheat” for the air coming into the furnace. Our system would heat the air entering the furnace while the furnace burners are on in order to reduce the amount of time that the burners need to run.

3.2 Cell Design and Simulation

Simulations were conducted to determine how the wax would melt with many different conditions. This helped determine the optimal conditions for the system to operate and thus the size the wax cells could be with the desired cycle time. The simulations were conducted using Solidworks thermal simulations with transient analysis. Paraffin phase change was simulated by setting the heat capacity of the material as temperature dependent. Solid material properties were used for temperatures below the melting point and liquid properties were used above the melting point. The phase change was simulated by using a short temperature range with very high heat capacity where the integral of the heat capacity curve equals the latent heat. This approach resulted in much quicker simulation iterations with similar accuracy as complex programs such as COMSOL Multiphysics.

The first set of simulations was designed to determine optimal operating conditions and the characteristic length of paraffin cells. It was a one-dimensional analysis using different liquid temperatures and convection coefficients to help decide the optimal balance of fluid temperature and mass flow rate. Simulated sensors at regular locations provided temperatures over an eight hour day showing how the paraffin melted.

The second set of simulations used the three dimensional model of the paraffin cell to verify that it melted as the one dimensional simulation predicted. Additionally, the thermal load applied to the simulation varied over the eight hour simulation time to model how using solar energy would impact the melting conditions. The solar data provided in figure 6 was sourced from the NREL. It came from Phoenix, AZ and was the average of the first two weeks in January, 2017 [National Solar Radiation Database].

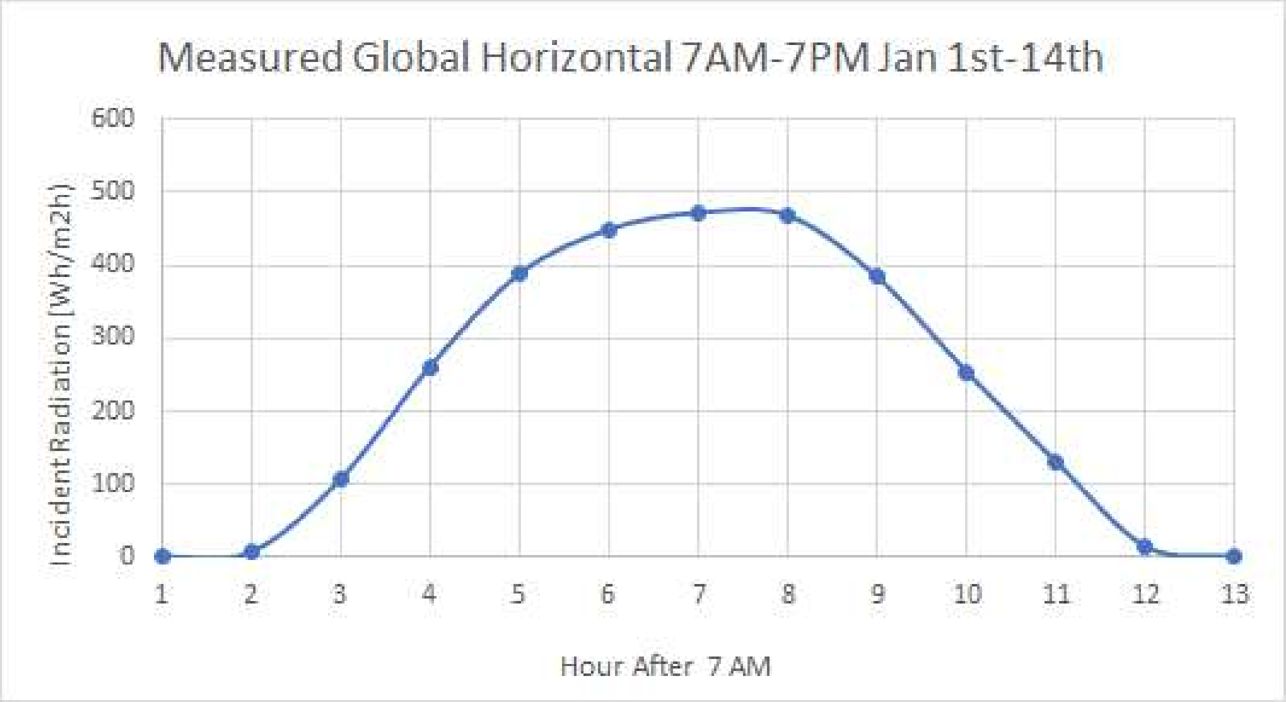


Figure 6. Measured global horizontal 7AM-7PM Jan 1st-14th

The third set of simulations replicated the conditions of the second set of simulations except that it included a series of cells in succession. This was to simulate how the cells nearer the hot liquid inlet melt faster than those nearer the cool outlet to determine the maximum number of cells that could be placed in succession while still melting.

3.3 Proof of Concept System

An experiment was necessary to verify the theoretical feasibility of the system and confirm the simulation results. The goal of our model was to melt paraffin with hot water and then heat air. An experimental prototype and system for data collection were designed and produced in the following way.

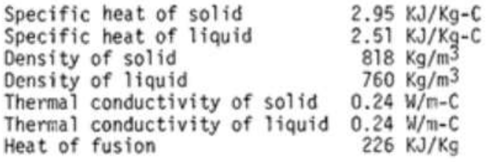
3.3.1 Design of Proof of Concept System

The system that was simulated at full scale would be costly and time consuming to build and test. It was determined that a small scale test would validate our previous work and would scale up to a full sized product accurately. The experiment was designed and the following components, seen in Figure 8, were determined necessary for testing.

1. Thermal Collector: A sous vide heater in a five gallon reservoir tank simulated a thermal solar collector. This sous vide was programmable to set temperatures and ensured that the reservoir was always the desired temperature. It compactly and accurately controlled the system input temperature with a premade device.
2. Water pump: The only electrically powered device in the full scale system would be a water pump to ensure proper flow of the working fluid. The pump used had a flow rate of 19 liters (5 gallon) per minute.
3. Insulated containment vessel: A 100 liter Coleman© cooler was used as the thermal storage tank to store the paraffin cells. It is important for the system to be as close to adiabatic as

possible and waterproof, and the cooler provided a premade system designed to fit these needs.

4. Heat Exchanger: The system used only one heat exchanger which served both for the charging and discharging phase. The full scale system would have two heat exchangers and a valve system to control the charging and discharging, but this was unnecessary to test the device.
5. Shelving system: Three shelves made of acrylic were used to hold the paraffin cells in place using a plastic mesh to ensure even exposure to the water flow. The shelves were held in place by threaded rods and additional weights were required to keep the buoyant paraffin submerged.
6. Insulated Rubber Hose: The control volume system was connected using rubber insulated hose.
7. Paraffin Cells: The paraffin was contained in 2mm thickness 50x300mm HDPE bags that were heat-sealed to prevent leakage. Melting point was confirmed upon arrival to be between 46.1 and 47.8 centigrade.
8. Paraffin: Recycled paraffin wax was purchased with the following properties.



Specific heat of solid	2.95 KJ/Kg-C
Specific heat of liquid	2.51 KJ/Kg-C
Density of solid	818 Kg/m^3
Density of liquid	760 Kg/m^3
Thermal conductivity of solid	0.24 W/m-C
Thermal conductivity of liquid	0.24 W/m-C
Heat of fusion	226 KJ/Kg

Figure 7. Thermophysical properties of paraffin wax. [Haji-Sheikh]

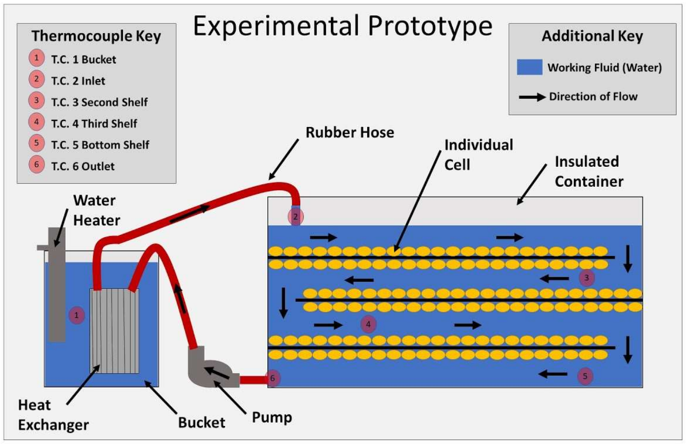


Figure 8. Schematic of experimental prototype system.

These components presented a controllable system to simulate the charging and discharging of energy into the storage cells. The results required a data acquisition method and it was determined the easiest way to do this was by measuring temperature change using thermocouples.

3.3.2 Method of Analysis for Testing

It was determined that temperature should be known at six points in the system to understand the heat transfer occurring in the system. LabVIEW was used to translate the voltages generated by the thermocouples into accurate temperatures and record the values over an extended period. An example program provided by Peter Hefti was modified to fit the specific needs of this experiment. The original program was short-term and any experiment that ran over an hour would crash due to technical difficulties. That program was modified to include six inputs for T-type thermocouples and the timing system was optimized for extended experiments. The thermocouples were connected to the ground and power. This program allowed thermocouples to be placed in their appropriate locations as seen above in figure 8.

3.3.3 Methodology for Building the System

Once the system schematic and individual components were finalized, they were purchased. Upon the arrival of the materials we assembled the setup as described below:

- Cells were assembled by melting paraffin below the damage point of HDPE and pouring the liquid into the bags
- Bags were filled to the top of the bag, leaving room for sealing
- Bags were then submerged in cool water to solidify
- Once solid, the cells were sealed with a heat sealer

The system was assembled according to the schematic on Figure 8. and caulking was used to ensure that the system was as watertight as possible. Shelves were created out of acrylic with threaded rod spacers. Metal weight was added to the top of the cooler to counteract the buoyancy of the paraffin in water. Open and closed configurations are visible in figures 9 and 10.

Figure 9. Open configuration of the insulated container

Figure 10. Closed configuration of the insulated container

3.3.4 Testing Procedure

A standardized experimental procedure was determined and can be found in appendix A.

Chapter 4: Results and Analysis

In this section we will discuss our simulation results, our experimental results, and our home-scale design. As discussed in the prior chapter, our simulation results were used to determine the specifications of our paraffin cells. Whether our final recommended design is feasible or not was partially determined by how well our experimental design functioned.

4.1 Simulation Results and Analysis

The simulations provided many insights into the conditions that would optimize our system. The data was analysed to determine certain properties and then would lead to more complex simulations. Perhaps the most important of the simulations was the first group that altered the temperature of water flowing over a block of paraffin at different convection coefficients. As seen in Figure 11, increasing the convection coefficient has little effect above 100 W/m2K. However, As seen in Figure 12, increasing the temperature of the water does increase the melting capability of the system.

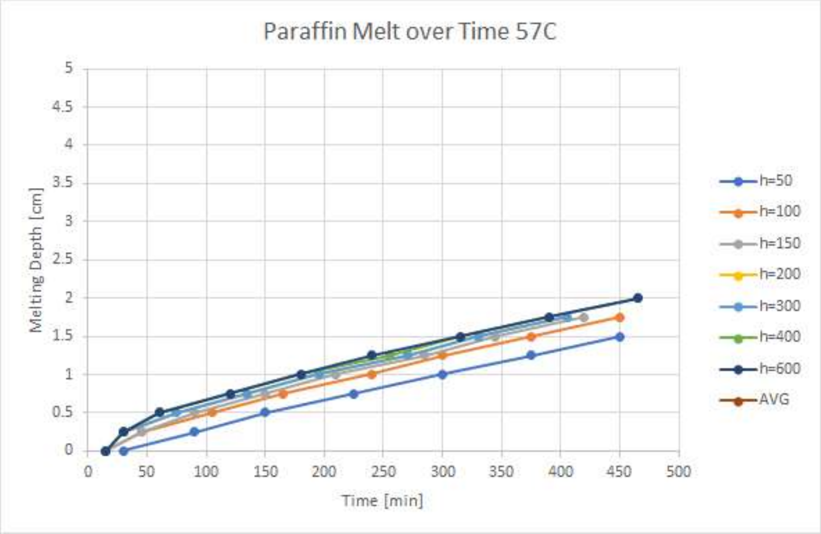


Figure 11. How far into a block of paraffin could water at 57C melt at different convection coefficients

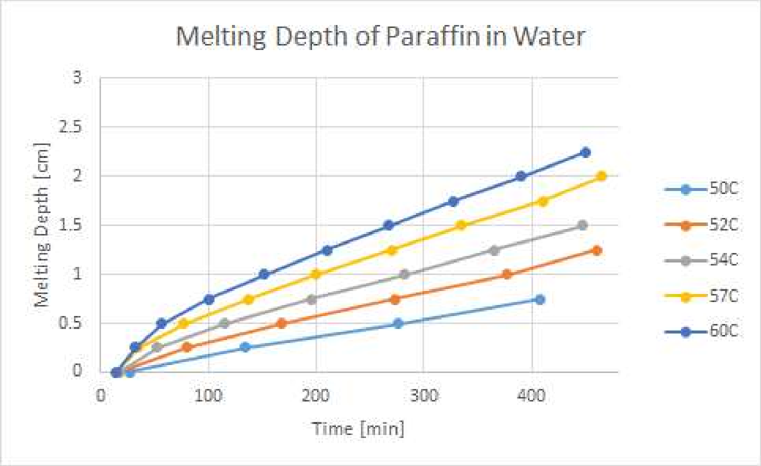


Figure 12. How far into a block of paraffin could water at different temperatures melt using an averaged convection coefficient

This translated to the project by using the highest temperature available while maintaining materials' working temperatures and by running a relatively slow water flow rate. This data also provided the maximum characteristic length of the paraffin cells based on the temperature used and charging cycle.

The second group of simulations were three dimensional to verify that the cells would melt completely based on the radius found using the previous simulations' data. The cells were intended to melt fully during a cycle, but only just so which increases the energy density of the system. The data provided showed that the cells would melt fully, even with the temperatures provided by a variable energy source such as the sun. Towards the end of the day as the solar intensity dropped, the cells actually started to cool while continuing to melt which shows a clear advantage that phase change materials hold over sensible heat storage.

The final group of simulations was to show how the final cells would melt much slower than the initial ones because the water cools as it flows over many cells. This resulted in the reduction of cell size to allow all the cells to melt over a full cycle time, not only the initial few that are exposed to inlet conditions the entire cycle.

4.2 Experimental Results

The experiment was designed to verify the thermodynamic benefit of the system over an entire cycle. The test was run for 19 hours to simulate a full heating cycle, and then most of the discharging cycle. This was the culmination of all aspects of this project and yielded results that suggested the system could reduce home heating costs.

4.2.1 Design Results

Our experimental setup was a key component in order to collect accurate data. The following is an account of the performance and limitations of our experimental design. The experimental design allowed for programmable temperature control of water being pumped into our storage container. The hose connections served duly to transport as well as insulate the working fluid. The hoses were warm to the touch during the experiment indicating that they were not ideally insulated or adiabatic. The cooler served as a sufficient storage container due to its insulation.

One large system drawback came from a leaky pump that lost approximately 2 liters of water from the system while our experiment took place. Additionally approximately 5% of the paraffin cells leaked during the experiment. While considerable, these failures were not deemed significant enough to invalidate our results and were a result of the low budget nature of our production procedure.

4.2.2 LabVIEW Program

The program worked as designed and provided us with high quality data. One limitation of the program was that over the course of our experiment our cold junction sources were not constant. This caused our data to be limited to the first 15 hours of the experiment, but this was not detrimental, as the significant data occured in the first 15 hours.

Our program performed well over the extended time frame. This project pioneered new LabVIEW techniques at WPI, and this was an added success of this project. The next section details the results obtained by this program during our experiment.

4.2.4 Testing Results and Analysis

The following section describes the experimental results achieved as measured by LabVIEW.

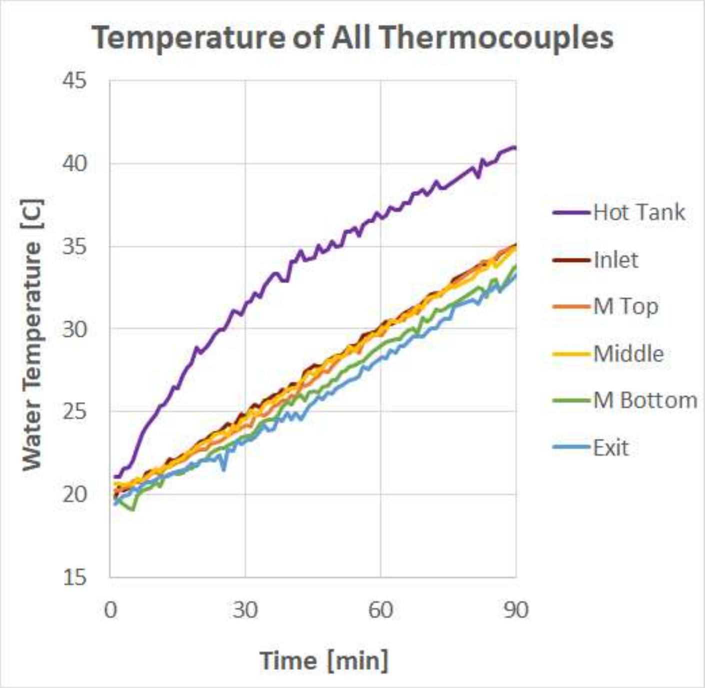


Figure 13. Temperature of all thermocouples

By design, we expected that our experimental setup would have the highest temperature in the hot tank and decrease in temperature from the inlet to the system exit prior to the heat exchanger. Figure 13 illustrates that this design came to fruition as each layer descends in temperature. Since the cooler is semi-adiabatic and the temperature is decreasing along the direction of flow we can conclude that thermal energy is being stored in the paraffin cells.

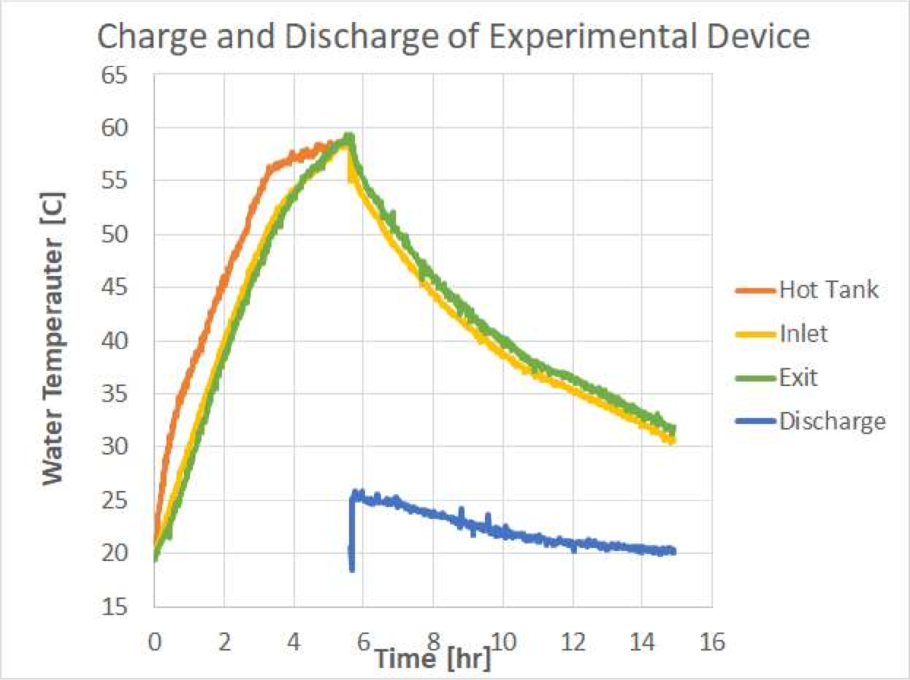


Figure 14. Charge and discharge of an experimental device

The expected charging time of our system was approximately 6 hours. Our system plateaued as observed in Figure 14 at approximately 5.5 hours. Our discharge time was also comparable to our charge time which would indicate that our system could be useful to collect at the period of the day with peak radiation and release at the minimum temperature.

4.3 Home Heating System Design

We designed a system that would incorporate the thermal storage system into an existing furnace with only minor modifications. During the day, when the system is charging, the solar working fluid flows through the storage unit and melts the paraffin. This is shown in figure 15 on the right side of the schematic. During the night or when there is not enough sun to continue heating the storage unit, a series of solenoids diverts the flow away from the solar collectors and into the heat exchanger to allow the heat to flow from the paraffin to preheat the air entering the furnace. This is shown in figure 15 on the left.

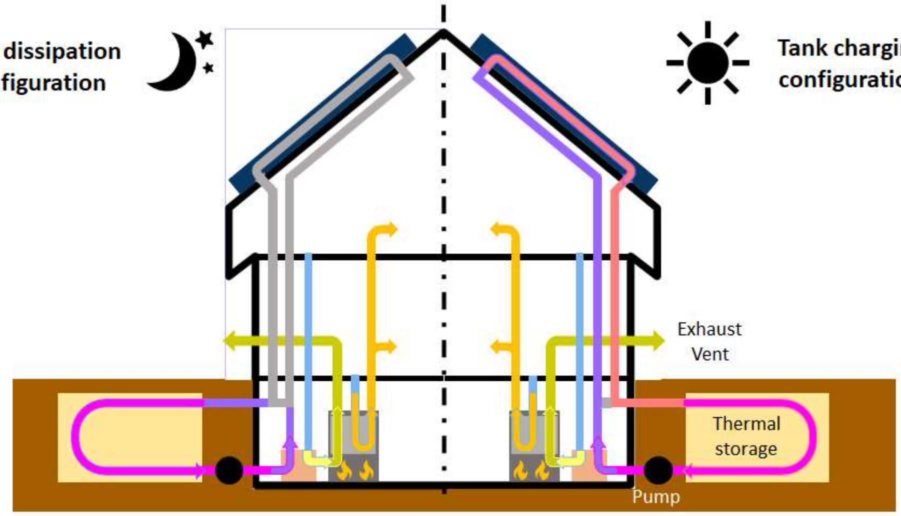


Figure 15: A schematic showing the flow of fluids through the house system mirrored to show both the charging and dissipating configurations in a single figure

The success of the prototype showed that the system has potential if it was scaled up. The charge time and thus cell size would be comparable to the prototype and solar thermal cells are an existing technology. Because this system relies on mostly existing technology rearranged in a new way, it would require a relatively small development cost and timeline. Additionally, since the materials are mostly waste or recycled, the system could prove to be economically advantageous since the production costs could be low. An industrial scale process would be necessary to produce paraffin cells in much higher quantity and quality to create systems at a home scale that could stand thousands of thermal cycles, and thus a reasonable product lifetime.

Chapter 5: Conclusions and Recommendations

This section will serve to summarize the findings of our work. Due to project constraints such as funding and time frame we are left with recommendations for future work on this project.

1. **The experimental data indicates feasibility of the proposed technology**

   Due to our teams limited time frame we needed to make procedural sacrifices to ensure that we obtained experimental data. For this reason our group chose to define project success simply by being able to obtain data that supports that storing and releasing energy in phase change materials could be achieved for a 6 hour cycle time. As outlined in section 4.2.4 we determined this to be the case graphically. This suggests that on a large scale our technology could be implemented to increase the efficiency of existing home heating systems. We recognize that a limitation of our work is that we are unable to sufficiently address the efficiency, benefits, and feasibility of implementation. This will be addressed in the following section.

2. **These results confirm that further research should be conducted for the following aspects:**

   a. **System efficiency**

      We recognize that in order for our supplementary heating system to be viable it will require a reasonable positive impact. In order to access the system efficiency we would need to refine our experimental prototype and improve data collection as well as analysis techniques. One way we could do this is by applying conservation of energy principles to deduce efficiency. Another is to run a control setup with water only and compare the results over the paraffin. Additionally, in order to maintain optimal melting temperature rate with respect to the changing ambient outside temperature, one could program a change in HTF flow rate. This would reduce cost of putting the storage system underground and would lead to a decrease in maintenance and installation costs [Velez].

b. Cost analysis

In order for the implementation of such a system to be useful it must pay back its costs in a reasonable timeframe. This was initially a project goal, but due to time constraints it went unaccomplished. Paraffin and storage tanks are cheep which would lead us to believe that the limiting factors would be the solar thermal collectors and pumps. A cost benefit analysis must be performed before this product can be deemed commercially viable.

c. System scaling

Our team performed our experiment on a much smaller scale than the implementation scale. We designed our home system with this in mind, but if we were to build a large scale system it would come with its own implementation challenges. These would need to be researched before a full scale prototype could be built.

d. Life cycle analysis

A key feature of this project was our attention to detail with regards to paraffin cell material selection. HDPE was selected for its ability to hold up over time due to its relatively high thermal conductivity, chemical resistance, and low water absorption/permeability rate. However due to the nature of the system ruptured paraffin cells would inhibit the working of the system. This is why attention must be paid to study the life cycle of the cells.

In addition it would be important to make sure that the system can last longer than the financial pay back period. It would also be beneficial to see how these systems would be disposed of and recycled when they reach the end of their lives.

3. **This technology could be used for a variety of thermal storage applications on various scales**

Although the focus of our project was on home heating systems this technology is applicable to many different scales and fields. One of the largest applicable fields in on an industrial scale. Any system that produces waste heat could be used in place of a solar thermal collector to recycle and reduce heat therefore providing a dual service of removing excess heat that would need to be removed with AC and allowing this heat to be reused at another point.

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Appendix A: Experimental Test Procedure

I. Pre-run
   A. Monitor system for 1 hour
   B. Determine perfect running temp
   C. Check for data recording
   D. No leaks
   E. Begin run at room temperature and increase to 60 centigrade
   F. Begin trial if no issues arise
II. Setup
   A. Fill bucket and system with water
   B. Run pump at highest setting, start heater set to 60 centigrade, and start program
III. Charging configuration
   A. Heat exchanger and sous vide in bucket
   B. Thermocouples at 6 locations
   C. HX → cooler → pump → HX
   D. Run for 6 hours, recording data every 1 min
IV. Discharge configuration
   A. Empty bucket and cool HX
   B. HX in box with fan
   C. Thermocouples at 6 locations (heat source changes to box)
   D. Same configuration otherwise
   E. Run for 15 hours