MODELING A HOT WATER STORAGE TANK FOR THERMAL ENERGY STORAGE USING ENCAPSULATED PHASE CHANGE MATERIALS (PCMs)

by

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A thesis submitted to the School of Graduate Studies

in partial fulfillment of the requirements for the degree of

Master of Engineering

Department of Mechanical Engineering

Faculty of Engineering and Applied Science

Memorial University of Newfoundland

May 2018

St. John's Newfoundland and Labrador Canada

Abstract

Over the past few decades, there has been a steady increase in the use of solar water heaters in areas of the world that have large amounts of solar energy. However, as the sun can only provide energy for a portion of each 24-hour solar cycle, there is a need to augment the solar-powered water heaters with thermal energy storage systems. These systems feature Phase Change Materials (PCMs) that can store extra energy in order to provide sufficient power to, for instance, offset potential shortages which might occur due to low production times such as occur at night or on a heavily clouded day. PCMs can experience phase changes from solid to liquid (i.e., melting solidification) when heated to a temperature that accords with the thermal application being used. The present thesis study will investigate ways to enhance thermal efficiency in hot water tanks by applying potential numerical simulations using PCMs that incorporate paraffin wax. Finding the most expedient PCMs for the finite element model includes finding changes in thermal conductivity and enthalpy across different temperatures. Elements which enhance efficiency (e.g., raise the thermal conductivity level in paraffin wax) potentially include utilizing encapsulated PCMs for spheres on the heat exchanger and changing the time needed in the melt/solidification process. The present study also includes an overview of the latent heat energy storage system (LHESS) and the theory underlying it.

Acknowledgements

Many people have contributed to the success of this thesis study. First, I would like to extend my heartfelt thanks to Dr. John Shirokoff, my supervisor, who has guided and supported me throughout the various stages of this work. His extensive knowledge and experience in his field have given me great advantages and am eternally grateful for his advice. I also wish to thank the MUNS technicians and staff for their kind assistance, and my friends, colleagues and classmates for their support. Finally, I wish to thank my parents, my brothers and my sisters for their lifelong encouragement and love. I could not have completed this work without your help.

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CHAPTER 1

Introduction

Given the current global push for countries to reduce the size of their carbon footprint, alternative energy sources that reduce greenhouse gas emissions are becoming increasingly popular. Among these alternative sources, solar energy is especially significant, particularly in areas that have abundant sunshine. However, finding cost-efficient ways to store energy for later use continues to be a challenge. Energy storage (ES) technology must be sufficient to satisfy peak demand needs while at the same time being affordable demonstrated by Nielsen et al. (2003). Thermal energy storage (TES) systems can help store extra energy from peak hours to offset lower energy production times, all the while improving the integration of generators with electricity grids. TES stores solar energy for later usage (Dincer, 1999). One of the main benefits of TES systems is their ability to store thermal energy in order for it to be applied for later use, either at the harvesting source or elsewhere (Dincer, 2002), (Dincer & Rosen, 2007). Some other benefits are listed below (Dincer & Rosen, 2002).

- Affordable maintenance costs
- Lower energy costs
- Enhanced efficiency in equipment usage
- Fewer emissions

- Improved indoor air quality
- Flexibility in operation
- Reduced size of system components.

1.1 Energy storage methods

Mechanical and hydraulic energy storage systems use compression energy, elevation and rotation derived from electrical sources. Both compressed air ES and pumped storage have shown moderate success rates and can be employed in depleted gas fields as storage reservoirs. Additionally, rotational energy has proved to be storable in flywheels; however, this option requires high-tensile materials to be incorporated into the design if the storage costs are to become affordable. In fact, the general inefficiency of the current mechanical and hydraulic storage systems has led to an energy loss of around 50% when calculated across the entire storage cycle as has been shown (Dincer & Rosen, 2002).

Thermal energy storage systems are moving to the forefront of research and development projects, considering the importance of alternative energy sources to growing global energy demand. Thermal systems can include an assortment of customized containers, as well as bricks, soils lakes and underground aquifers (Dincer & Rosen, 2002). Systems that employ bricks, for instance, store the energy in the form of sensible heat. Thermal energy is also storable as latent heat in materials that can melt (e.g., paraffin and salt). Meanwhile, electric energy is storable as a superconducting magnetic system, but the overhead for these systems is very costly.

In light of the current high maintenance fees attached to ES applications, the development of ES systems now and into the future is crucial if we are to harvest renewable energy resources at an affordable cost. More advanced solar ES systems might not be required immediately, but there is a need to apply and enhance the more promising of the cheap ES alternatives which are currently available. This will then lead to better sustainability of solar energy through its continued expansion of application.

1.2 Background

For hot water heating in domestic applications, solar thermal energy has been proven to be both efficient and cost-effective. It collects energy during times of high solar radiation (i.e., when it is clear and sunny outside), using the energy for the preheating of water for use during high-demand periods. However, there is often a significant difference between the demand for hot water and energy availability according to Liu, Wang, and Ma (2006). TES systems can help bridge the gap between energy supply and usage demand. Typical TES systems include infrastructure such as hot water storage tanks, but they can present challenges in buildings that feature smaller living spaces. Storage systems that make use of PCMs could resolve the space issue (Mehing & Cabeza, 2008).

In PCMs, which are often referred to as latent heat energy storage systems, the storage of energy occurs in the melting phase, while the stored energy can be released in the solidification phase by Fernadez et al. (2010). Thermal energy storage is generally categorized as either latent or sensible energy storage. A brief description of both storage categories is given below.

In latent heat, there is a release and/or absorption of heat if the phase change material being heated or cooled undergoes a phase change while maintaining a consistent temperature. Thus, latent heat which is stored in the PCM (Q_{latent}) and which is expressed as being in direct proportion to latent heat in the PCM's fusion (Δ_{hm}), along with the mass of material which experiences phase transition (M), can be formulated as:

$$Q_{latent} = \text{M}.\,\Delta\text{hm} \quad (1.1)$$

On the other hand, sensible energy can be stored if a material's temperature rises and can then be released if the temperature drops. The sensible heat $(Q_{Sensible})$ of a material is thus directly dependent on its heat capacity $\left(C_p\right)$, as well as any changes in the materials' temperature when comparing its starting (initial) (T_i) and final temperatures (T_F), along with the material's mass (M), which can be thus expressed as:

$$\boldsymbol{Q_{Sensible}} = \text{M.C}_\text{P}.\,(\text{T}_\text{f} - \text{T}_\text{i}) \quad (1.2)$$

1.3 Study objective

The objectives of this thesis are to find and test new approaches that,will lead to improvements in thermal efficiency in hot water tanks that incorporate phase change materials in their construction. The elements which potentially result in efficiency enhancements (e.g., increasing the size of heat transfer zones for paraffin wax during the melt/solidify phases) will be investigated. In figure 1.1, it can be seen how to use solar thermal energy in phase change material

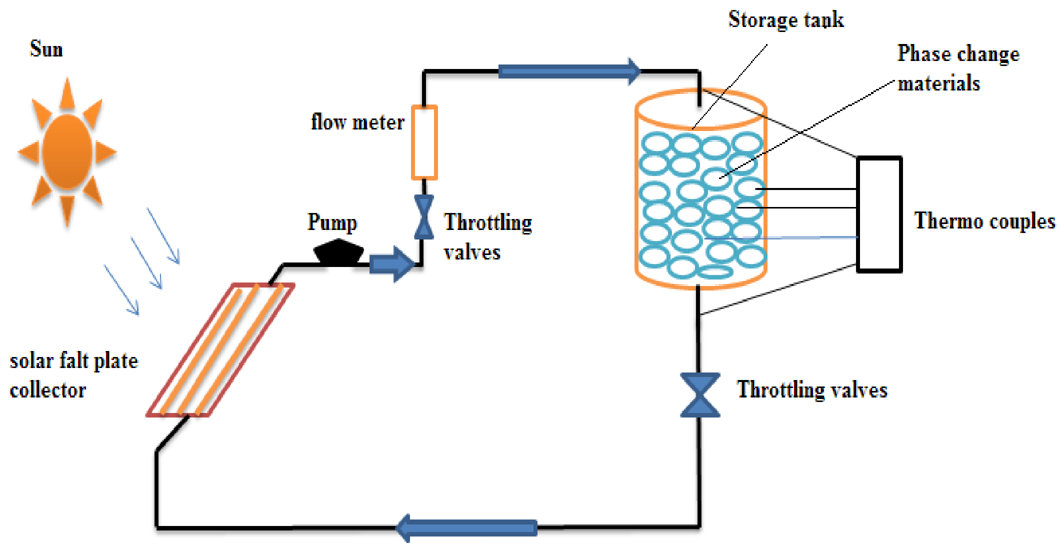

Figure 1.1: Using solar thermal energy in phase change materials

1.4 Thesis scope

The aim of this thesis project is to develop numerical simulations for storage tanks using PCMs in order to discover alternative options for enhancing the tanks' thermal efficiency. The study will focus on investigating the main elements which contribute to enhanced efficiency, including looking at melting and solidification times as well as improvements to paraffin wax thermal conductivity through encapsulating sphere-shaped wax in the heat exchanger. The study will also discuss latent heat energy storage systems.

1.5 Thesis Organizations

Chapter 2 is a literature review of thermal energy storage using phase change material, the background of thermodynamic and energy storage, phase transformations and latent heat storage, the properties of materials which used for thermal energy storage, the definition of sub-cooling, the important features of TES system, as well as advantages of PCMs and some aspects of selection, analysis of solid-liquid phase change.

Chapter 3 introduces hot water storage tank design, some calculations of a solar hot water system with paraffin wax thermal storage including collector zone, collector size, mass of PCMs used in the tank, amount of heat stored with water, energy input, time needed to release or absorb energy from paraffin wax, total value of heat from the collector and the energy storage potential of paraffin wax.

Chapter 4 shows the theoretical analysis of solar hot water heater including the problem statement with some assumption and approximations, determining the effect of paraffin wax on the thermal performance of the storage tank, determining the average efficiency of the collector and concluding with some results.

Chapter 5 conveys Numerical simulations of a solar hot water heater including the methodology of the work using ANSYS Software, the main outputs of the simulation, governing equations and energy equations, results when the tank is full of PCM and when the tank is filled with encapsulated PCM with results for each case and discussion. Chapter 6 is the thesis conclusion and future work

1.6 Software Used in Thesis

Three software packages were used in this thesis and they are described as follows:

1). **SolidWorks** is a solid modeling computer-aided design and computer-aided engineering computer program that runs on Microsoft Windows. SolidWorks is published by Dassault Systems, Waltham, Massachusetts, USA; www.solidworks.com; This Software was used in Chapter 3.

2). **HOMER** is a free software application developed by the National Renewable Energy Laboratory in the United States of America. This software application is used to design and evaluate technically and financially the options for off-grid and on-grid power energy systems for remote, stand-alone and distributed generation applications as well as solar radiation. NREL made a version publicly available for free to serve the growing community of system designers interested in Renewable Energy. Since then HOMER has remained a free software application which has evolved into a tool for modeling and applications. It was originally developed by the Department of Energy (DOE), Washington, Maryland, USA. This Software was used in Chapter 4.

3). **ANSYS** Software: ANSYS develops and markets finite element analysis software used to simulate engineering problems. The Software creates simulated computer models of structures, electronics, or machine components to simulate strength, toughness, elasticity, temperature distribution, electromagnetism, fluid flow, and other attributes; *ANSYS. Pennsylvania Technology Directory. 1999. P. 25.* This Software was used in Chapter 5

CHAPTER 2

Literature Review

2.1 Heat transfer in a latent heat storage system

Heat transfer occurs by a phase change presenting as one of three possible modes: a conduction convection-controlled phase change; a conduction-controlled phase change; and a convection-controlled phase change. Convection is the principal heat transfer mode during melting, whereas conduction is the main heat transfer during solidification. To make energy storage more efficient, it is better to use phase change materials inside a latent heat energy storage system according to Agyenim, Eames, and Smyth (2010), (Khodadadi & Zhang, 2001). Phase change occurs in the following forms: solid-solid, solid-liquid, solid-gas, liquid-gas and their inverse. In solid-solid transitions, heat which is stored as the material is transformed from one crystal to another, (Figure 2.1). These changes usually involve a smaller amount of latent heat and volume changes than solid-liquid transitions. Solid-solid phase change materials provide the advantages of having less complex container requirements and better design (Pillai & Brinkworth, 1976).

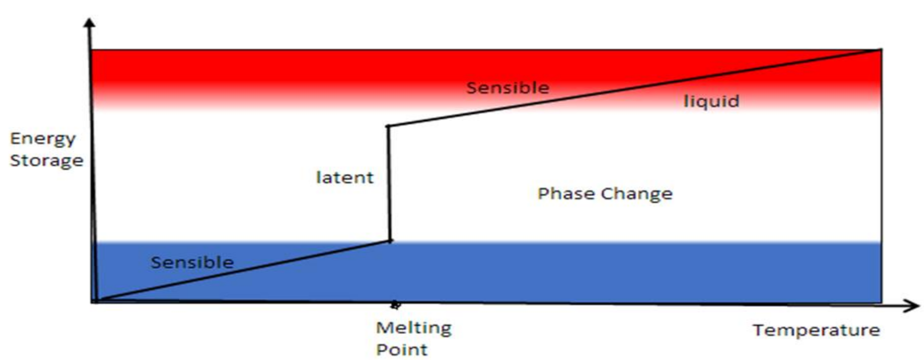

Figure 2.1: Heat storage as latent heat in solid-liquid phase change.

Solid-to-gas and liquid-to-gas transitions involve large volume changes in phase transitions at near constant pressure. These include obstacles which rule out their potential utility in thermal storage systems. However, liquid-to-gas and solid-to-gas transitions have a significantly higher latent heat phase transition. The sizeable difference in volume change makes the system more complicated (Abhat, 1983). Solid-to-liquid transformation has a relatively smaller latent heat than liquid-to-gas, though this transformation includes only slight changes in volume of around 10% or less. Therefore, solid-liquid is confirmed to be economically important in the usage of thermal energy storage systems. PCMs themselves cannot be used as a heat transfer medium. An unconnected heat transfer medium must be used with a heat exchanger to transfer energy from the source to the PCM, and from the PCM to the load (Ramlow & Nusz, 2006).

2.2 Literature Review

As discussed in Chapter 1, PCMs are used to store thermal energy in the form of latent and sensible heat. They also assist in providing greater efficiency when either using or conserving solar energy or waste heat. However, compared to storing sensible heat, storing latent heat offers higher density in energy storage while also featuring a shorter gap in temperature difference between stored and released heat. Over the years, several types of materials were tested to find the best combination of PCMs for use in a broad range of applications across several industries. Tested materials include organic compounds (e.g., paraffin and fatty acids), inorganic systems (e.g., salt as well as salt hydrates), and polymeric materials such as polyethylene glycol (Pielichowski, 2014). Specifically, the relation between energy storage qualities and material structure were investigated in order to better understand the mechanisms of the materials' heat emission and accumulation. The outcome of these studies is the development of applications of thermal energy storage which feature improvements in safety levels (e.g., flame retardants) and performance (e.g., enhanced conductivity, shape stabilization processes, and encapsulation approaches).

Today, PCMs are used in a variety of fields ranging from the automotive industry, to biomedical applications, to construction (Pielichowski, 2014). Passive processes for thermal energy storage have also been gaining in popularity recently, with the materials used in the approach being categorized as either specific or latent. In specific (or sensible) heat, "thermal energy transferred to or from a substance resulting in a change in temperature" (Sutterlin, 2015). The main characteristic in PCM encapsulation is the provision of a large area for heat transfer, which serves to reduce the response of PCMs in external environments and better deal with changes of storage sizes which can occur during phase change demonstrated by Farid et al. (2004). In their recent work, Zhou, Zhao and Tian (2012) looked at dozens of prior studies on latent thermal energy storage used for building applications. The extensive review included building applications, thermal performance analyses, impregnation strategies, and PCMs. The researchers also looked at studies involving numerical simulations of structures using PCMs. The study findings indicated that PCMs not only decrease fluctuations in interior temperatures but also help to maintain preferred temperatures consistently. Next paragraphs introduce the timeline researches that have been done.

Sari and Kaygusuz (2001) investigated the incorporation of stearic acid in PCM thermal energy storage, and they revealed the benefits of using stearic acid in heat transfer and then compared their findings with those from other research works. The main focus of their investigations was propagation in liquid-solid interfaces, transition times, and how the heat flow rate impacted phase change stability in stearic acid also found increased activity occurring in PCMs if the heat exchanger tube were set as horizontal rather than vertical. The researchers noted an increased efficiency of approximately 50.3%.

Zalba et al. (2003) examined the impact of thermal energy storage in relation to solid-liquid phase change. Their review looked at how heat transfer affects different types of materials as well as various applications involving heat transfer. In their work on PCMs, also looked at more than 150 materials, including PCMs which are currently available commercially. In related research, Khudhair and Farid (2004) investigated how building applications use energy conservation methods that incorporate thermal storage via latent heat and PCMs. Specifically, the work examined thermal storage of PCMs encapsulated in floors, ceilings, walls, etc., and listed issues caused by the PCM application in relation to type of material and the various approaches applied.

Kim and Darkwa (2004) looked for ways to enhance laminated PCM wallboard efficacy in thermal energy storage. They discussed in detail the integrated PCM wallboard system and combined different types of PCMs in their test wallboards. Their new method of PCMs integration significantly enhanced latent heat transfer, which then also resulted in more effective wallboard recycling.

Cabeza et al. (2006) has utilized a test solar pilot plant to test PCMS behaviour in real conditions. This modified conventional solar energy development by adding a PCM at the highest point of the hot-water storage tank stratification using a granular PCM-graphite compound as a PCM.

Along the same lines, Kenisarin and Mahkamov (2007) examined ways to apply PCMs in the storage of solar energy, focusing mainly on issues that are currently preventing a wider application of PCMs for that purpose

Significant experiments performed by Moosavi and Zohoor (2008) aiming to enhancing the capacity of both solar thermal energy storage systems and solar energy hybrid storage systems. The outcome of the investigations was an increase in energy gathering potential in these systems in the winter months compared to that found in individual water storage tanks.

El Qrina has applied numerical analysis to a coupled solar collector latent heat storage unit, employing different kinds of PCMs for water heating. From these investigations, also devised a model from energy equations in order to determine how a solar latent heat storage unit (LHSU) might behave. Numerical simulations of stearic acid, paraffin wax and n-octadecane were performed and a finite volume approach was used to model the LHSU's thermal behaviors in order to find the best configuration to represent summertime conditions and to determine flow rates for outlet temperatures in discharge mode, (El Qrnia, 2009).

Mazman et al. (2009) sought ways to include PCM modules in the upper level of water tanks. This modification would enable a greater level of heat loss compensation at the tank's top layers and carried out tests on heating and cooling using an entire solar heating system, finding that stearic acid (PS) and paraffin were able to deliver optimal thermal performance (~74% efficiency improvement) for solar domestic hot water tanks.

Lin et al. (2010) looked at temperature control and energy storage in packaging plates that featured microencapsulated PCMs. Their goal was to create better thermal management materials than were available at the time. They investigated the thermal behaviour in composite materials and discovered that microencapsulated MPCM structure remained consistent throughout the manufacturing process; they also found that composite materials which included MPCM took longer to achieve steady state than those without.

While Al-Hinti et al. (2010) applied real-life conditions by employing paraffin wax for a PCM while testing traditional solar water heating systems. Using natural circulation patterns in a closed-loop system, the researchers measured storage capabilities by connecting the tank and flat plate collectors. The test findings showed that brief spurts of forced circulation had little to no impact on overall system performance, also investigated simulated daily-use patterns through applying both storage behavior and recovery impacts for the PCMs using open-loop systems.

Jaisankar et al. (2011) discussed the importance of solar water heaters for industrial and domestic use, citing a number of passive techniques which can be applied to enhance convective heat transfer and thermal efficiency in solar water heaters. The shortcomings in existing research, as well as some gaps in the literature, were pointed out, along with a few suggestions for potential modifications to the technology.

Zhang et al. (2012) looked at the thermal energy storage properties for expanded graphite (EG) and paraffin as composite PCMs. They used paraffin for a PCM and produced EG at ambient room temperature using microwave radiation. Utilizing differential scanning calorimeter analysis, they found that the melt temperatures for the paraffin and the composite PCM were more or less the same. They also found that the calculated value and latent heat were the same. However, compared to the paraffin, the performance of thermal energy storage charging for the composite PCM's duration was significantly less.

According to Chong, Chay and Chin (2012) debuted a cumulative V-trough solar water heater system that employed a forced circulation system. Chong et al.'s device was essentially a solar absorber that incorporated a V-trough reverse. The device succeeded in improving the water heater system's performance. Hossain et al. (2011) investigated how the absorber plate thermal conductivity of a solar collector can impact efficiency in a thermo-siphon solar water heater. The study results showed that the siphon-assisted solar water heater had nearly 20% higher efficiency compared to traditional systems through decreases in heat loss.

Chen et al. (2012) investigated PCM behavior in foot massage devices, discovering that the inclusion of PCMs in the design led to the water staying warmer longer, which ultimately led to savings in energy and costs.

Moreover, several ways to enhance the thermal conductivity in PCMs. High conductivity has been used and fixed constant structure inserts made of various metals (e.g., nickel, aluminum, copper). As well as various kinds of types of carbon fiber materials. Additionally, they looked at storage thermal energy units, heat switches, and work status. Their findings indicated that minimizing conductive pathways which connected cold and hot ends using high conductivity inserts/structures showed promise for enhancing conductivity, (Fan & Khodadadi, 2011).

According to Liu, Saman, and Bruno (2012) conducted studying the impact of rising temperatures on thermal storage systems in order to gain a deeper understanding of strategies related to storage materials and thermal performance. The researchers compared PCMs at fusion temperatures exceeding 300°C, giving them an extensive database that will assist future research endeavours related to improving cost efficiency in phase change storage systems.

An experimental study by Souliotis et al. (2013) looked to develop three novel integrated collector storage solar water heaters (ICSSWHs), hoping to create low-cost devices that can operate using solar power and feature efficient thermal performance. Their findings indicated that the designs can be used year-round, which is an important step forward in the modifications of existing ICS-type solar water heaters.

A study of PCMs and their thermal stability in heat energy storage systems was carried out by Rathod and Banerjee (2013). looked at the thermal stability of PCMs when present in heat energy storage systems. The researchers measured the stability of the PCMs through modifying their physical properties following the repeat of the thermal cycle's number. The resultant database test findings help other researchers locate the best PCMs for their purposes when using latent heat energy storage systems.

A study of possible TES materials to be used in construction applications was conducted by Tatsidjodoung et al. (2013) examined which thermal energy storage materials were most suitable for construction applications. The researchers looked at heat storage materials and thermal energy storage technologies which could be incorporated into building applications. The outcome of their inquiries provided up-to-date information on the primary modes of thermal energy storage.

Another interesting study was conducted by Nkwetta et al. (2014) who investigated various PCMs in relation to their positioning in domestic hot water tanks and subsequent thermal performance. The researchers found that they could enhance the energy storage capacity by integrating a PCM with sensible heat, with the test results indicating that, in comparison with RT58-Rubitherm and industrial-grade granulated paraffin wax, 10% graphite and sodium acetate trihydrate gave significantly better storage potential and also required less charging time.

Nkwetta et al. (2014) studied the potential use of PCMs for improving hot water tank thermal performance in residential buildings, mainly to reduce peak power demand.

The research applied a model of PCMs and a hot water tank, along with a consumption profile for hot water in order to gauge the impact of PCMs in the system. The findings revealed that, in comparison to tanks with no PCMs, combining sensible heat and PCMs in a hot water tank notably enhanced thermal energy storage. Meanwhile, Padovan and Manzan (2014) discussed the advantages in decreasing space allotment of TES equipment while increasing a system's energy savings through incorporating PCMs. Their results showed that reducing the size allotment was not much of a factor in energy savings.

According to Chaabane, Manzan and Bournot (2014) performed a numerical study for an integrated collector storage solar water heater (ICSSWH). The ICSSWH featured a sensible heat storage unit that permitted model validation. The researchers also looked at the impact of PCMs in the thermal performance of ICSSWHs. The test outcomes indicated that, when using meristic, the latent heat storage unit (LHSU) had a higher performance level in daylight hours in comparison to the sensible one. However, the LHSU showed a higher level of effectiveness when PCMs were tested during the night.

Bouadila et al. (2014) investigated the behavior of storage systems that employ a PCM made of paraffin. They tested and measured temperature stratifications of PCM-filled cavities by creating two rectangular cavities positioned to the rear of the flat plate solar collector absorber.

Other research by Trigui and Karkri (2014) employed composite PCMs for latent heat storage to test the potential for thermophysical properties in paraffin-filled materials to enhance PCM properties. They devised a test set-up for measuring composites' thermal response to thermal collection. From these results, they discovered that the proposed system's effectiveness was impacted by the thermal effectiveness in PCMs, which led to recommendations on energy saving through the application of PCMs.

2.3 Latent heat storage system

2.3.1 Materials for latent heat thermal energy storage

Materials which are utilized for latent heat thermal energy storage should have properties such as high thermal conductivity and large latent heat. These materials are also expected to meet requirements that conform to building and engineering codes, such as:

- Having a melting temperature that is appropriate for the practical range of operation
- Exhibiting melting which conforms to minimal sub-cooling
- Being chemically stable
- Being low-cost
- Being non-toxic and non-corrosive

The idea behind using PCMs for storing thermal energy is utilizing the latent heat of a phase change, usually between the solid and liquid states, to store highly efficient energy. Since a phase change involves only a slight change in temperature, phase change materials that are used for their properties over a given temperature range become more stable and have the ability to store more heat with large energy densities collection and small changes in temperature (Heinz & Streicher, 2006).

2.3.2 Sub-Cooling

For abundant PCMs, it is important to consider the aspects of sub-cooling and its effect. Sub-cooling is a procedure of material crystallization at a temperature that can be much lower than its melting temperature. After crystallization is complete, the temperature of the PCM increases until it reaches the melting temperature, although for some materials the temperature does not rise to the melting point. The temperature differences between the crystallization and melting temperatures have an impact on the sub-cooling (Heinz & Schranzhofer, 2007).

2.4 Energy storage

Solar energy is dependent on time as an energy source. Energy requirements are also time-dependent for a very wide variety of applications but in a different way than in the solar energy supply. Therefore, during the solar process, the storage of energy or other products is necessary if solar energy is to meet a considerable portion of the energy needs.

Energy storage must be measured in conjunction with a solar process system, the major components of which are the different types of solar collectors, storage components and transformation devices (such as engines, air conditioning), as well as loads, auxiliary energy supplies, and control systems. The performance of each of these components is connected to all the others. The collector efficiency’s dependence on temperature makes the performance of the whole system sensitive to temperature. For example, in a solar-thermal power system, a thermal energy storage system which is characterized by a high drop in temperature between input and output will lead to an unnecessarily high collector temperature. Moreover, if the engine has a low inlet temperature, both systems will lead to a decrease in system performance.

In passive solar applications such as solar heating, storage units and collectors are incorporated into the building structure. The performance of storage media in heating systems is dependent on the absorption of energy. In passive solar heating, both storage components and collectors are integrated into the structure of the building. The absorption of energy depends on the storage media type used in the heating system.

The peak capacity of an energy storage system depends on the expected time of solar radiation availability, the nature of loads to be anticipated in the process, the degree of reliability needed for the process, the method in which additional energy is supplied, and the economic analysis, the latter which determines how much of the annual load should be carried by the solar source and how much by the auxiliary energy source.

2.4.1 Energy storage in solar process systems

Energy storage may occur in the form of liquid or solid sensible heat, as the heat of melting in chemical systems, or as a type of chemical energy of products in a reversible chemical reaction. Mechanical energy can be transformed to potential energy and stored in elevated fluids. Products of solar processes other than energy may be stored. So, for example, water extracted from a solar system may still be stored in tanks until needed, and electrical energy can be stored as chemical energy in batteries.

The selection of storage media depends on the nature of the process. For water heating, storing energy as sensible heat of stored water is logical. If air heating collectors are used, the different storage effects of sensible or latent heat in particular storage units are specified. In passive heating, storage is provided as sensible heat in building elements, whereas if photovoltaic or photochemical processes are used, storage is logically in the form of chemical energy.

2.4.2 Important features of thermal energy storage systems

(a) Capacity per unit of volume of the system
(b) Operational temperature range, which is the temperature at which heat is added to and removed from the system
(c) Methods of removal or addition of heat and the different temperatures connected
(d) Stratification of temperature in the storage unit
(e) Capacity requirements for the removal or addition of heat
(f) Containers, tanks, or other structural elements associated with the storage system
(g) Means of controlling thermal losses from the storage system
(h) Overall cost

These factors affect the operation of the solar collector. The gain from a collector decreases as its average plate temperature increases. The connection between the average collector temperature and the temperature at which heat is provided to the load can be written as:

T (collector) − T (delivery) = ΔT (transport from collector to storage) + ΔT (into storage) + ΔT (storage loss) + ΔT (out of storage) + ΔT (transport from storage to application) + ΔT (into application).

Therefore, the temperature of the collector, which defines the useful gain for the collector, is higher than the temperature at which the final heat is utilized by adding the f sequences of the temperature differences that drive the energy. A key objective of system design, particularly of storage unit design, is to reduce or eliminate these temperature drops within economic constraints.

2.5 Thermal energy storage using PCMs

2.5.1 Phase Change Basics

As introduced in earlier chapters, phase change materials (PCMs) are materials that undertake a liquid-solid phase transformation (known as the fusion-solidification period) at a temperature within the limits of a chosen thermal application. They absorb energy from the surroundings when the phase of a material changes from a solid state to a liquid state, while remaining at a constant or almost constant temperature. The heat of the material acts to raise the energy of the constituent molecules, and as a result their vibrational state increases. At melting temperature, the atomic bonds loosen and the material changes from solid to liquid; the inverse of this process is solidification, during which the material transmits energy to the area around it. In this phase, the molecules no longer have energy and order themselves into their solid phase.

The energy during the melting and solidification cycles that is either absorbed or released is known as the latent heat of fusion. A good example of this process can be given by melting of a cube of ice. It can be heated by exposing it to ambient temperature (such as room temperature), by raising its temperature with a hair dryer, or by blasting it with a blowtorch. The latent heat absorbed during the melting process is indicative of the latent heat of fusion. This is distinguished from the other type of latent heat – vaporization – which is characterized by a change in phase from a liquid to a gas.

The process continues as the solid transitions to a liquid through the latent heat of fusion. Its temperature then rises as sensible heat to the boiling point. Once the boiling point is reached, the liquid is converted to vapor during the vaporization of the latent heat until the phase change process is complete. Any further heating during this process will take the form of sensible heat, which acts to superheat the vapor. The steps of the process can be seen in figures 2.2 and 2.3. As can be seen in figure 2.3, the latent heat of evaporation has a higher energy process than that of fusion. Considering this, one could question why phase change materials are used for their latent heat of fusion rather than their latent heat of vaporization.

Although the condensation/boiling process absorbs and releases more energy, the density change from the liquid state to the vapour state is quite large. Moreover, working with boilers and condensers often requires a significant amount of assistance equipment, which is not always possible to install. There are many applications for boiling heat transfer, but the focus in this study is on the situations in which a liquid-solid phase change process is most advantageous.

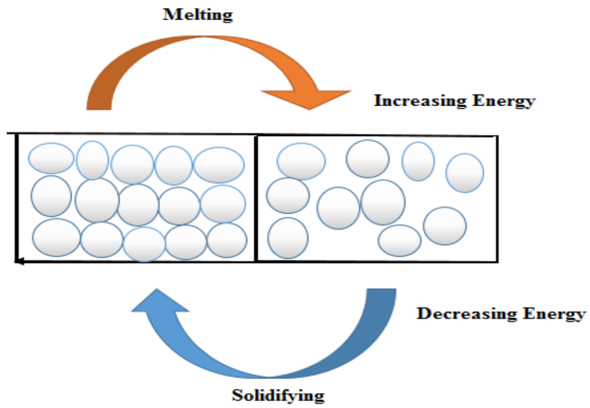

Figure 2.2: Melting/solidification process

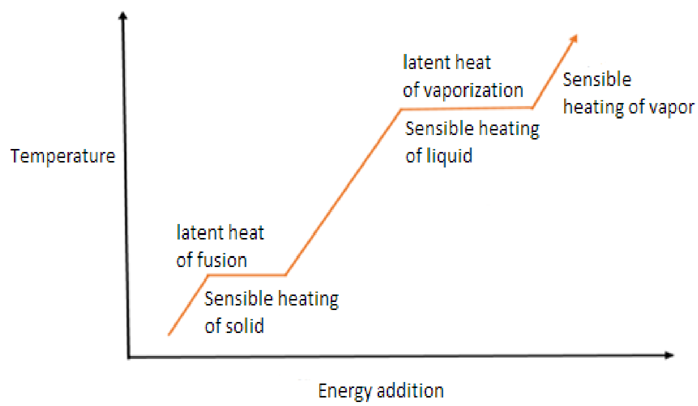

Figure 2.3: Standard heating curve

The quantity of energy absorbed or released through the melting-solidification cycle is governed by the value of the material of latent heat of melting. In general, the latent heat of fusion can be expressed in units of J/g or kJ/kg. The process is dependent on the amount of energy absorbed by the material during melting and on the mass of material present in the engineering design.

The average temperature at which the material melts is led by the operating conditions. For instance, water (ice) has about 333 kJ/kg; thus, each 1 kg of ice will require a heat input of 333 kJ to melt. The rate at which ice melts depends on the process of heat transfer. How quickly can the heat be transmitted into the ice? The heat flux used and the temperature difference from the heat source to the melting point will govern this process. Considering this, it is clear that 1 kg of ice will not increase its temperature if it is melted using a blowtorch.

2.5.2 Advantages of phase change materials

PCMs for transient thermal energy management have features which allow a constant system temperature to be maintained, especially during the melting process or in any case of applied heat flux. Phase change materials are lightweight, portable and highly reliable. Furthermore, they depend solely on the characteristics of the material itself and not on any external flow source, such as a pump or a fan.

The fundamental choices readily available for thermal energy storage include sensible heat storage and thermochemical storage. Latent heat storage has a considerably higher energy density than sensible heat storage, resulting in less required material mass and/or a smaller volume required for the size of the storage tank. Latent heat storage systems are also easier to work with than those for thermochemical storage. The outcome of solid-liquid transition occurs with only a small density change, resulting in a smaller system size and using fewer support tools than when attempting to store thermal energy for long-term use through the liquid vapour phase change.

2.5.3 Properties and selection of PCMs

PCMs are fundamental components in the design of latent heat energy storage systems and can be divided into two types: organic and inorganic. Organic materials such as fatty acids and paraffin are usually studied for energy storage use. These types of materials are known for suitable melting, as well as for frequent melting and freezing without phase division or a decrease in their thermal and material properties (Zhang & Hu, 1996).

PCM selection for LHESS depends on the desired application of the system. Some aspects for choosing a PCM are as follows (Zhang & Ke, 2002).

- Melting point in the desired temperature range for the application to ensure the storage and release of heat at a useful temperature
- High latent heat of fusion to achieve a high storage density
- High specific heat so that sensible heat storage effects may play a role
- High thermal conductivity
- Small volume changes during phase transition
- Little or no sub-cooling exhibited during solidification
- Chemical stability; no chemical decomposition and no destructive corrosion of materials used in the LHESS
- No poisonous flammable or explosive elements
- Reasonable price and easily accessible

The selection of a PCM for a solar domestic hot water system should be made carefully in order to produce hot water at an acceptable range of temperatures and to minimize safety concerns (such as the PCM leaking into the building's water supply) Chen et al. (2007).

2.6 Analysis of solid-liquid phase change

It is important to consider the mathematics that describe melting and solidification in order to fully understand the physics of PCMs. The energy storage potential of material as it melts is found by multiplying the mass of material by the latent heat of fusion because this is much simpler to quantify than the dynamic melting and solidification processes. The energy storage potential of the material is quantified using the latent heat of the material. The latent heat of fusion (hf) is the measure of how much energy can be stored in a specified mass of material as it transitions from solid to liquid, given in units of kJ/kg. However, whether the full energy storage potential of material will be utilized, and the rate at which the energy is stored, is dependent on the rate of heat transfers into and out of the PCM's mass. The rate of heat transfer is dependent on the temperature difference between the melting point and the heat source, the boundary conditions of the material, and the initial temperature of the PCM.

Using more paraffin wax in the tank will result in more energy storage, because the energy storage potential of material as it melts is found by multiplying the mass of material by the latent heat of fusion, as follows:

$$E_{stored} = M.hf \qquad (2.1)$$

where:

M: mass of paraffin wax, kg.

hf: latent heat of fusion of paraffin wax = 230 KJ/KG.

Heating material through the melting process generally occurs using these steps:

1. Initially, the PCM is raised uniformly in temperature from its initial temperature to the melt point through sensible heat.

2. Once the melt point is reached and as the heating process continues, the material no longer increases in temperature with the addition of heat. Now it will change the phase through the latent heating cycle.

3. During this time the material transitions from solid to liquid and the melt front marks the transition point from solid to liquid.

4. As the melt front crosses the material and the material enters the fully melted phase, further addition of heat raises the temperature of the liquid material through sensible heating.

5. The melt front can speed up or slow down depending on the rate of heat added and lost through the boundaries. This creates a situation where the location of the melt front at any point in time is not known in advance but must be found.

6. As boundaries interact, the temperature within the PCM takes on three-dimensionality, creating a situation where the melt front does not simply move uniformly from one side to the other across the material, but can instead move diagonally.

CHAPTER 3

Solar Hot Water Heater Design

3.1 Hot Water Storage Tank Design

The water storage tank is made from steel; all dimensions are in inches. The outer diameter is 15.75 inches, the inside diameter is 14.5 inches, with a 23 inches length and an insulation of 0.5 inches. Inside the tank, there is pipe made from copper, which works as a heat exchanger. The dimensions for the pipe are as follows: the outer diameter is 12 inches, the inner diameter is 11 inches, and the length of the pipe is about 500 inches with 14.5 revaluations. Around the pipe, there is phase change material (paraffin wax) encapsulated in a sphere shape, it can be seen in figure 3.1.

The major features of phase change materials' encapsulation are providing a large heat transfer area, downsizing the phase change materials reaction across the external environment, and managing the variations in materials' storage size that take place with the phase change. The heat transfer fluid (HTF) used is hot water, which comes from the flat plate collector. During the daytime, paraffin wax absorbs the heat from the water and stores it to use at night.

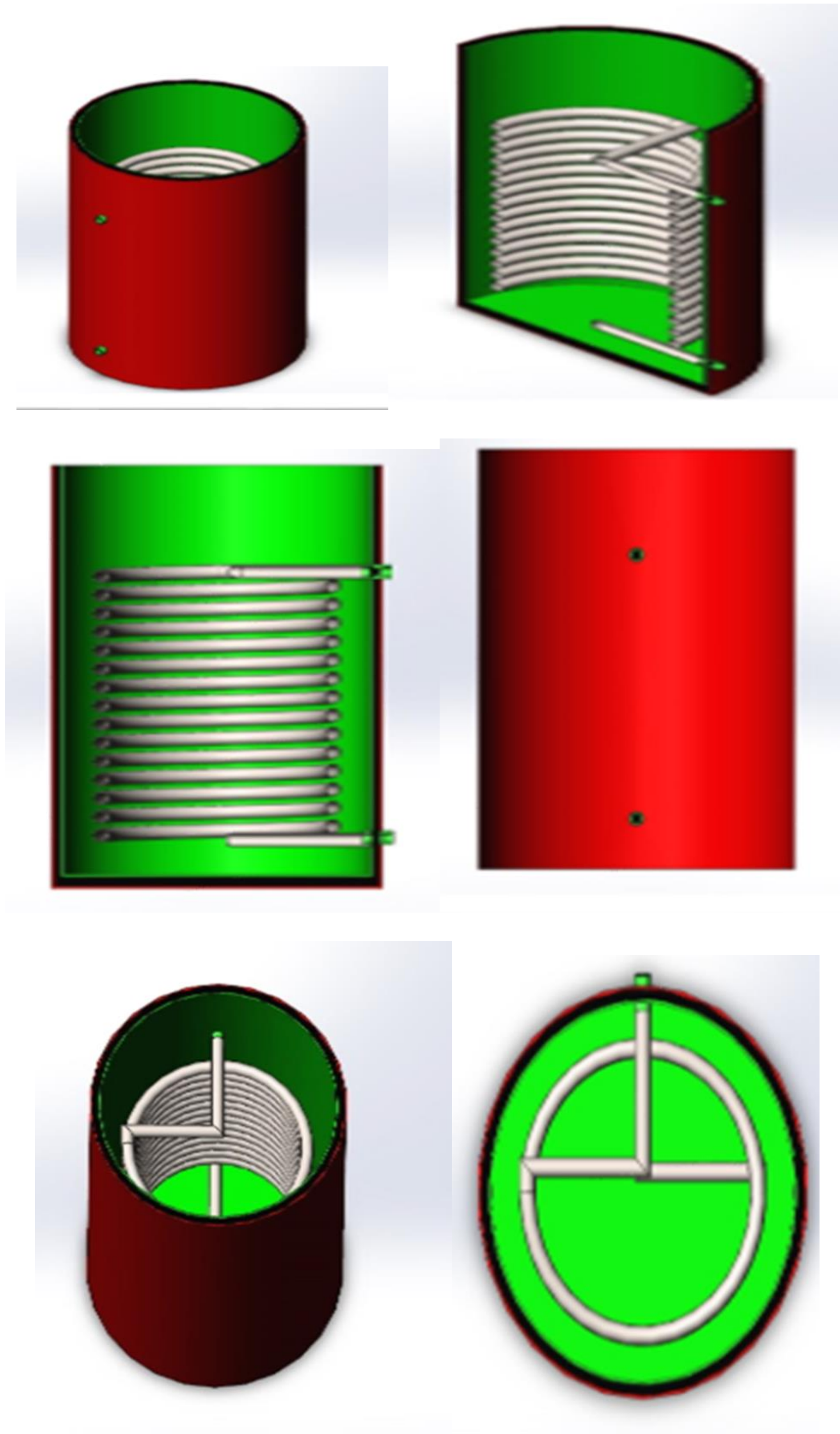

Figure 3.1: Hot water storage tank [Solid Work Software].

3. 2 Conditions for the calculation of a solar hot water system with PCM thermal storage

Solar thermal systems for domestic hot water use need a variety of storage and collector capacities depending on how many persons are using the system. So, per person, and to maintain hot water temperature at 45℃, a flat-plate collector needs a storage size of around 80-100 L and a collector size of approximately 1-1.5 m^2.

Some estimated calculations for three per-person standard usages are listed below:

1. High usage: 60-120 L / 2.4-4.8 kW/h daily.

2. Medium usage: 30-60 L / 1.2-2.4 kW/h daily.

3. Low usage: 15-30 L / 0.6-1.2 kW/h daily.

3.2.1 Storage size in relation to demand

In general, storage size ($V_{storage}$) measures approximately twice that of people (P) and their daily need (V_{person}):

$$V_{storage}=2.P.\ V_{person} \tag{3.1}$$

Depending on per-person daily hot water needs (Q), yearly hot water needs can then be formulated using Eq. (3.2) below:

$$Q_{HW}= 2.P.V_{person} \tag{3.2}$$

Hence, for a standard house with four people who consume on average 45 L / 1.8 kW/h of hot water daily, the storage size would be formulated at shown in Eq. (3.3) below:

$$V_{storage}=2.4.45 \text{ liters}=360 \text{ liters} \quad (3.3)$$

while the yearly heating needs would be formatted as shown in Eq. (3.4) below:

$$Q_{HW}= 365.4.\ 1.8 \text{ kW/h}=2628 \text{ kW/h}. \quad (3.4)$$

3.2.2 Optimal sizing of collector

The size of the storage cylinder helps to determine the optimal sizing of the collector, $A_{collector}$. Note that for this formulation, the following information is also needed: yearly solar fraction (*sf)*, a 30% average system efficiency in systems that have flat-plate collectors, yearly radiation amounts H solar, and tilt gains $f_{orientation}$, as expressed in Eq. (3.5), the average system efficiency using flat plate collectors is considered by a factor 0.3.

$$A_{collector} = \frac{sf*Q_{HW}}{0.3*H_{Solar}*f_{orientation}} \quad (3.5)$$

where:

sf : Yearly solar fraction.

H_{solar}: Yearly radiation amounts.

$F_{orientation}$: Tilt gains.

$$Q_{Sensible} = M_{cp}\,(T_F - T_i) \quad (3.6)$$

where:

M: Mass flow rate of water.

C_p: Specific heat of the material

T_f : Final temperature

T_i : Initial temperature

$Q_{latent} = \text{M}.\Delta\text{hf}$ (3.7)

where:

Q_{latent}: Amount of heat stored in the material

M: Mass of the material

Δh_f: Latent heat of fusion of the material

3.2.3 Amount of heat stored or released from a material:

$\text{Q} = \text{M}.\text{Cp}.\Delta\text{T}$ (3.8)

Table 1.3: Paraffin Wax Properties

Melting temperature, ℃	Latent heat of fusion, kJ/kg	Density, kg/m^2		Specific heat, J/kg.℃		Thermal conductivity, K	
		Solid	Liquid	Solid	Liquid	Solid	Liquid
52℃ to 60 ℃	213 kJ/kg	861 Kg/m^2	778kg/m^2	1850 J/kg.℃	2384 J/kg.℃	0.4 W/m.℃	NA

Heat stored with water (Q_{Water}):

$\text{Qwater} = V.\rho.Cp.\Delta T$ (3.9)

3.2.4 Charging speed

The speed of charging is the ratio of heat accumulated in the storage fluid and the time needed to absorb or release the heat from the fluid. The total volume of the PCM can be calculated as:

$\text{Vpcm} = \frac{Q_{coll}}{\Delta H_{pcm} \cdot \rho_{pcm}}$ (3.10)

where:

Q_{coll}: Heat collected with the solar collector, kW/h

ΔH_{pcm}: Latent heat of PCM, kJ/kg

ρ_{pcm}: Density of PCM, kg/m^3

The heat to be stored with PCM would thus be:

$$V_{pcm} = \frac{Q_{pcm}}{\Delta h_{pcm} \cdot \rho_{pcm}} \tag{3.11}$$

3.3 Calculations for a solar hot water system with PCM (paraffin wax) thermal storage

3.3.1 Calculating the mass of PCMs used in the tank:

The amount of heat required to increase the temperature of PCMs, Q_{PCM} is equal to the amount of heat stored in the water, Q_{H2O}.

$$Q_{PCM} = M\,[Cp_s.\,(T_m - T_i) + \Delta_{hf} Cp_l\,.(T_f - T_m)] = Q_{H2O} \tag{3.12}$$

where: $Q_{H2O} = V.\rho\,.C_p\,.\Delta T$

Here, different amounts of paraffin wax and quantities of heat stored in PCMs (Q_{PCM}) are used. The reason for using different amounts of PCMs (paraffin wax) is that if more paraffin wax is used in the tank, the amount of heat stored in PCMs will increase. This can be seen in figure 3.2.

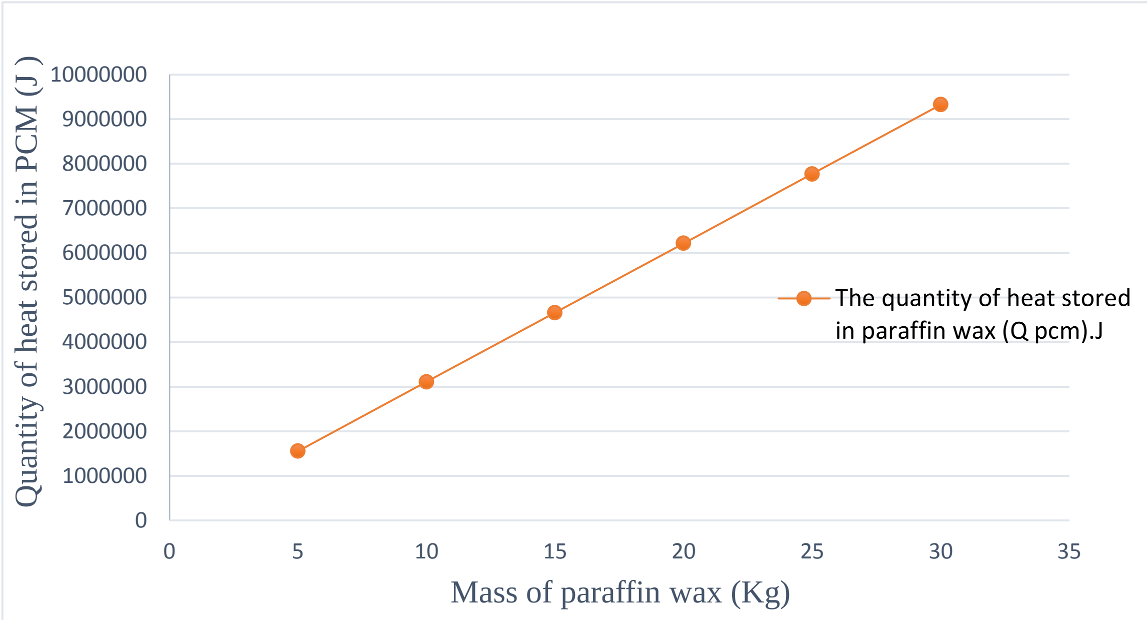

Figure 3.2: Quantity of heat stored in paraffin wax and mass of paraffin wax.

$$Q_{PCM} = M\,[C_{ps}.\,(T_m - Ti) + \Delta hf + C_{pl}\,.(T_f\text{-}T_m)] \quad (3.13)$$

where:

M: Mass of PCMs

T_m: Temperature melting of PCMs (paraffin wax)

Ti : Water temperature inlet to the tank

Δhf: Latent heat of fusion of paraffin wax =213 KJ/kg =213000 J/kg

T_f : Final temperature

C_{ps} : Specific heat capacity of paraffin in the solid state = 1850 J/kg.℃

C_{Pl} : Specific heat capacity of paraffin in the liquid state = 2384 J/kg.℃

3.4.3 Amount of heat stored in water (Q_{H2O})

$$Q_{H2O} = V . \rho . C_p . \Delta T \qquad (3.14)$$

Where:

V: Volume of water used in the tank.

ρ_{Water}: Density of water = 1000 kg/m^3.

Cp_{water}: Specific heat capacity of the water = 4.18 kJ/kg.K

ΔT: Temperature differences.

If the temperature of the inlet and outlet water with the same volume from the collector is different, the amount of heat stored in the water (Q_{H2O}) will be decreased. This is shown in figure 3.3.

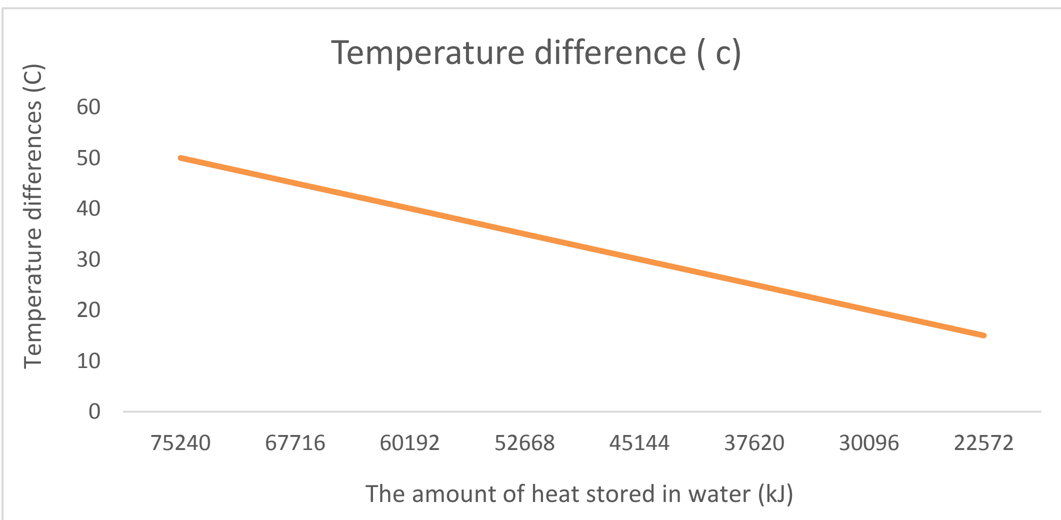

Figure 3.3: Amount of heat stored in the water and temperature difference in the heat exchange.

3.3.2 Energy input ($Q^{\blacksquare}_{input}$)

$Q^{\blacksquare}_{input}$= m$^{\bullet}$.Cp. ΔT (4.15)

Where:

m$^{\bullet}$: Mass flow rate of the water

Cp: Specific heat capacity of the water = 4.18 kJ/kg. K

ΔT: HTF inlet/outlet temperature difference of the water.

There is a relationship between the energy input and mass flow rate of water with a constant temperature difference. If the mass flow rate (m$^{\bullet}$) of water increases, then the energy input also increases, as shown in figure 3.4.

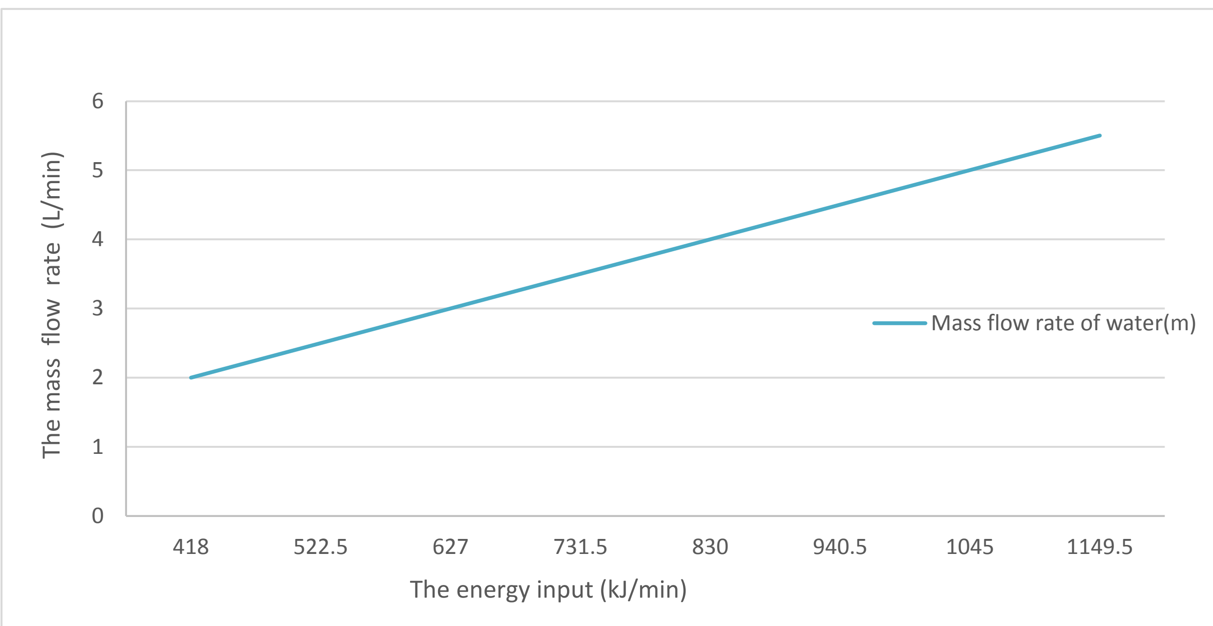

Figure 3.4: Energy input and mass flow rate.

3.3.3 Time of absorb/release energy

A critical factor for enhancing the efficiency in hot water storage tank is time. Specifically, heat transfer at a fast rate is required within a short time period. To satisfy this need, the water inlet temperature needs to rise while there is a reduction in the time needed for charging/discharging during the melting/solidification processes. As well, energy storage technology is useful in this regard for storing excess energy in peak hours. The energy storage can then supplement any possible shortages which might occur during times of lower production, such as at night. This will also help energy generators more easily integrate into local electrical grids.

To date, the potential of thermal energy storage has not yet been tapped for practical application. For instance, TES is capable to store solar energy (as heat) during the warmer months, and this energy can then be accessed during colder months. It can also store energy from sunny days and apply them on cloudy days or at nighttime. In other words, TES can be used to move heat that might otherwise be lost or wasted from one area to another and from one timeframe to another.

In terms of the present study, this means that the storage time (t) for the hot water storage tank which uses paraffin wax can be calculated by dividing the total energy stored in paraffin wax (Q_{PCM}) by the energy required to increase the temperature of the water (Q_{water}) can be expressed as:

$$t = \frac{\mathrm{hfs}.M_l}{Q^{\blacksquare}_{input}} \tag{3.16}$$

where:

hfs: Latent heat of fusion of paraffin wax = 213 kJ/kg = 213000 J/Kg

M_L: Mass of paraffin wax in the liquid phase

$Q^{\blacksquare}_{input}$: Energy input

The time (t) to release or absorb energy decreases as the energy input increases (Q_{input}) when the mass of paraffin wax in the liquid phase is a constant. This is shown in Fig. 3.5.

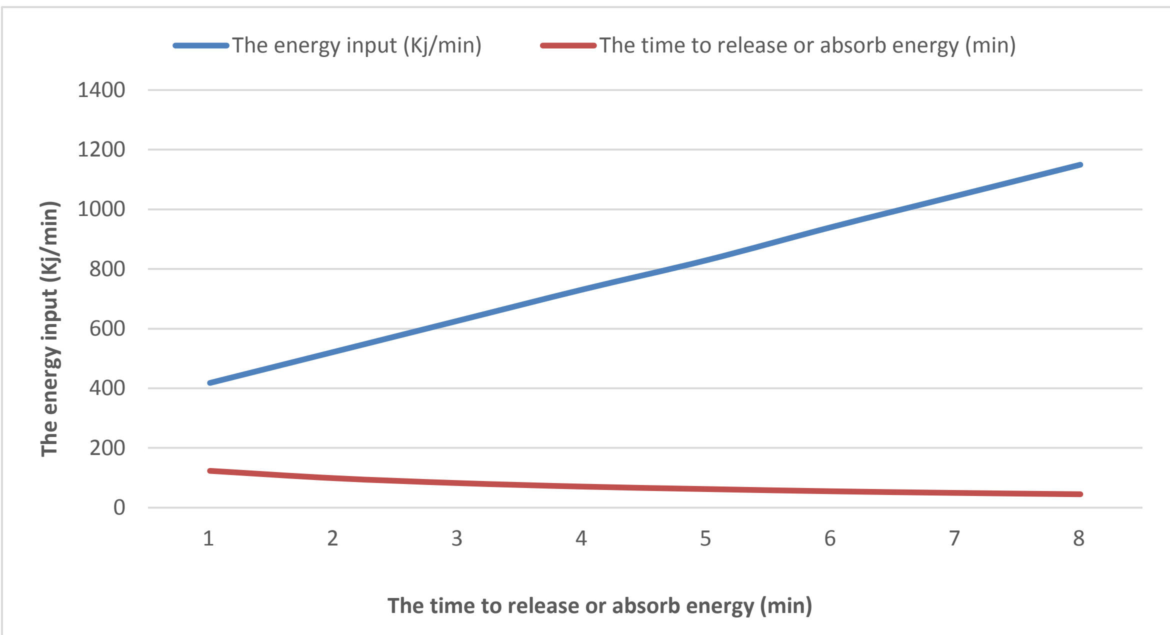

Figure 3.5: Time to absorb or release energy and energy input.

3.3.4 Energy storage potential (E_{Stored})

$$E_{Stored} = M.hf \tag{3.17}$$

where:

M: Mass of material of PCMs'

hf: Latent heat of material of fusion.

In the relationship between energy storage potential and the mass of phase change materials, the energy stored will be increased when the mass of PCMs is increased, as depicted in figure 3. 6.

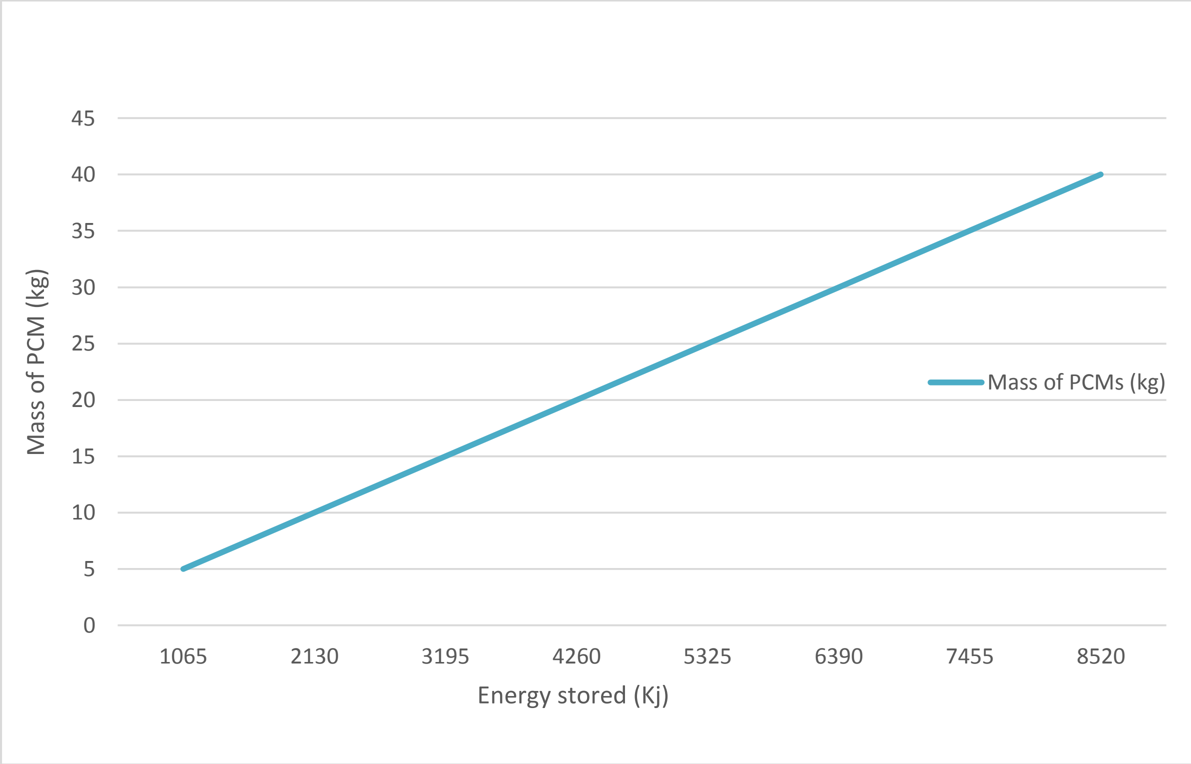

Figure 3.6: Energy stored and mass of paraffin wax.

CHAPTER 4

Theoretical Analysis of Solar Hot Water Heater

4.1 Problem statement

Solar water heaters are widely used in places where solar energy is abundant. However, thermal energy storage systems are required because solar energy is available only during the day. The solution is to design a thermal storage system with PCMs to provide hot water for domestic usage at night. The example below shows a household in Tripoli, Libya, in April:

Figure 4.1: Location of Tripoli city [HOMER Software].

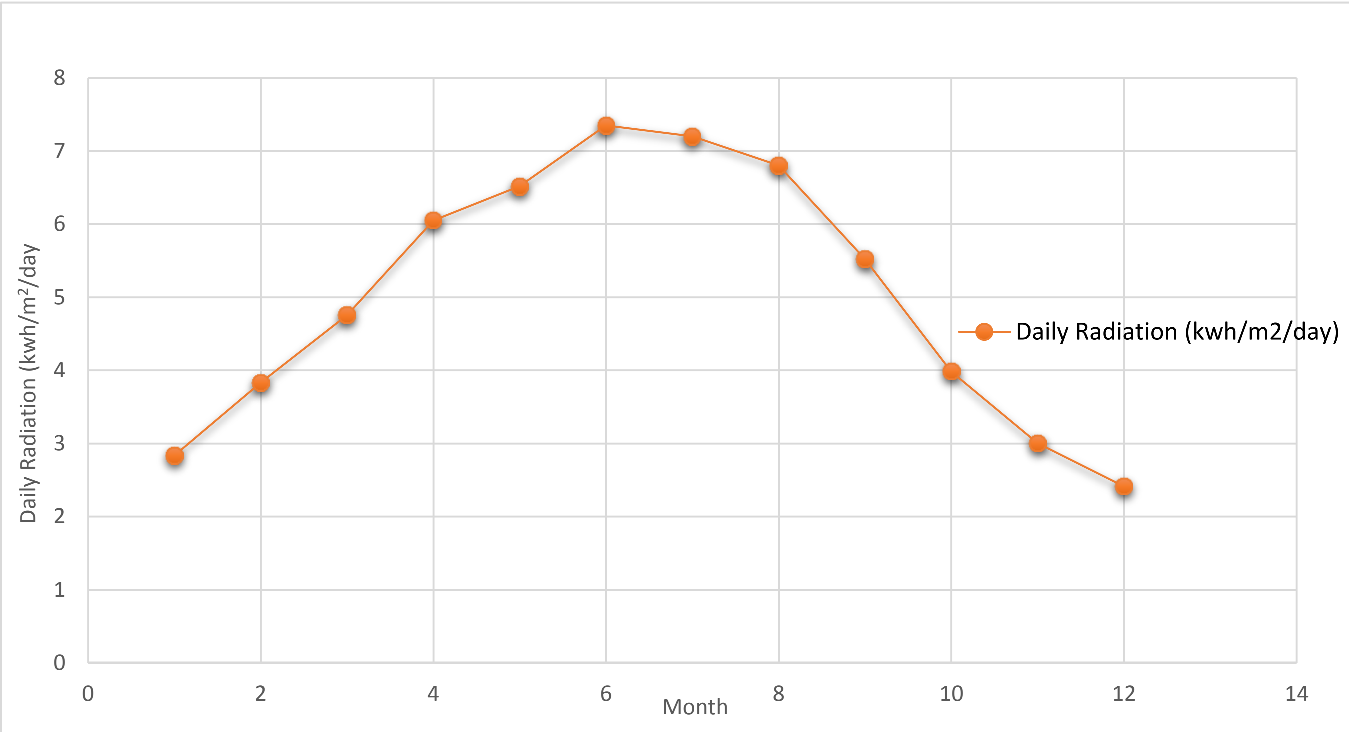

Figure 4.2: Monthly average solar radiation [Homer software].

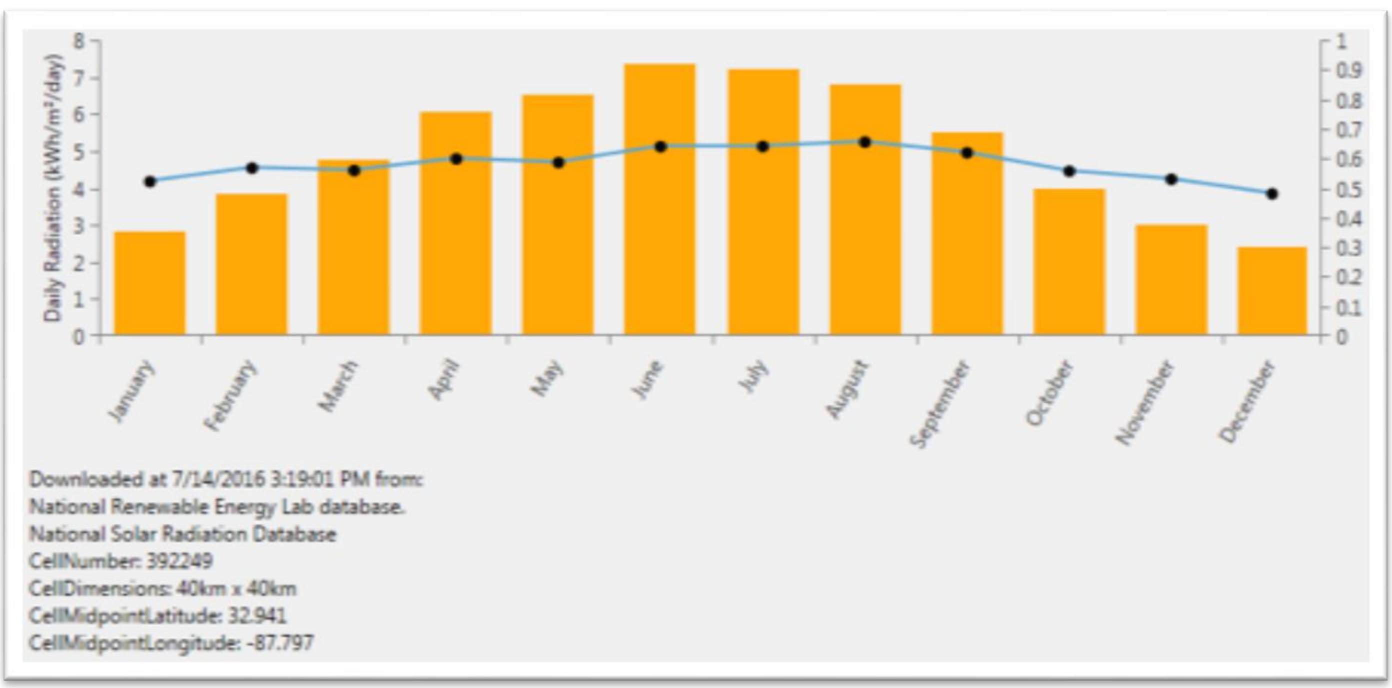

Figure 4.3: Monthly average solar radiation [HOMER Software].

The average daily temperature of the ambient air can be estimated by:

$$T = T_m + 5\ A\ Sin(\omega t) \qquad (4.1)$$

where

$$T_m = \frac{T_{max}+T_{min}}{2}$$

$$A = (T_{max} + T_{min})$$

$$\omega = \frac{2\pi}{365}\ day^{-1}$$

Here, T_{max} and T_{min} are the maximum and minimum air temperatures in April, respectively, and t is the day number (t = 0 is for the first of January). The maximum and minimum air temperatures in April are 35°C and 15°C, respectively.

The solar radiation can be computed by:

$$I_c = 17 + 100\ Sin(\omega t) \quad \frac{MJ}{m^2} per\ day \qquad (4.2)$$

The average sunshine duration for Tripoli in April is 6.14 hrs. Figure 5.4 shows a schematic of a solar water heater system. A solar collector of 2 m^2 is chosen as the flat plate collector. It has a single glass cover on top of a black surface absorption plate. The piping that allows heat transfer fluid to pass through is positioned beneath the absorption plate. The storage tank, with a volume of 151.3 L, is composed of paraffin wax and water. One hundred litres are allocated for water, considering a water consumption of 25 L per person in a household which accommodates four people.

The rest of the tank (51.3 L) contains 40 kg of paraffin. The paraffin wax is placed into aluminum cylindrical tubes that have a diameter of 0.06 m. In total, 26 tubes containing paraffin wax are positioned horizontally inside the tank (Sari & Kaygusuz, 2001). The flow rate and hot water temperature required are equal to 0.1 kg/s and 50°C, respectively.

Table 2 illustrates the properties of the solar flat plate collector.

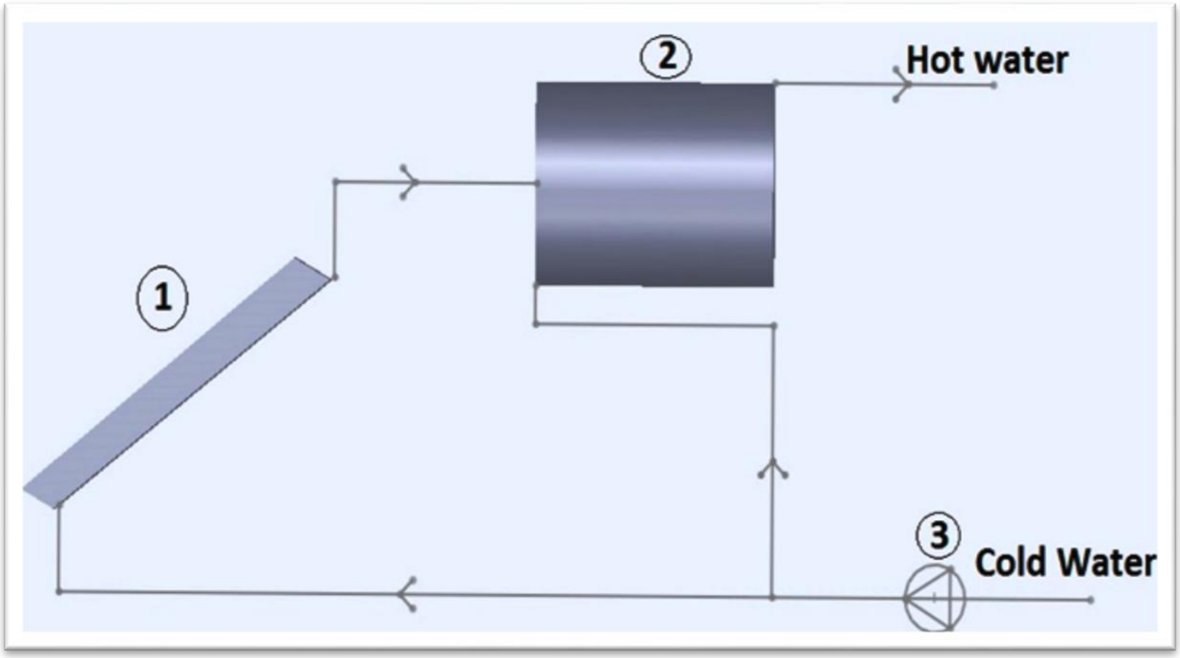

Figure 4.4: Solar water heater system

Note: (1) solar collector, (2) storage tank and (3) circulation pump

Table 2.4: Collectors Properties

Tilt angle	45°
Collector area, Ac	2 m^2
Overall surface conductance, U_c	8.0 W/m^2K
Heat transfer coefficient inside the tube for water, h_w	1500 W/mK
Cover transmittance, τ	0.9
Solar absorption of the copper surface, α	0.9
The water inlet temperature, $T_{f,i}$	65 °C

4.1.1 Assumptions and approximations

To simplify the analysis of the solar water heater system theoretically, the following assumptions are made:

- The PCM operates under ideal conditions, which implies that paraffin wax melts congruently and solidifies without super cooling at a specific temperature.
- The storage unit is assumed to be well insulated so that there is no heat loss.
- The Biot number which is the ratio of the internal thermal resistance of solid to the boundary layer thermal resistance was considered to sufficiently low to be ignore the temperature gradient in the direction normal to the flow direction.
- Only radial conduction is taken into consideration in the fluid.

The collector efficiency depends on several parameters. In order to estimate the efficiency of the collector, simplified assumptions are made for convenience, as follows:

- Flat collector is in equilibrium under a steady-state conditions.
- Temperature decrease through the absorber plate is neglected.
- Heat transfer is only in the normal direction from the cover through the back insulation.
- There is uniform flow along the tubes.
- Sky is considered a black-body source.
- Solar irradiance on the collector is uniform.

4.1.2 Determining the effect of paraffin wax on the thermal performance of the storage tank

The thermal performance of the storage tank with and without paraffin wax is compared by finding the heat stored per unit time theoretically.

1). The energy required to increase the temperature of the water from ambient air temperature (T_a), with a mass flow rate of 0.1 kg/s and a final temperature (T_f) for human usage of 50℃, with maximum air temperature (Tmax) 35℃ and minimum air temperature (Tmin) 15℃ .

$$\dot{Q_w} = \dot{m_w}\ c_{p,w}\ (T_f - T_a) \tag{4.3}$$

The average daily temperature of the ambient air can be estimated by:

$$T = T_m + 5\ A\ \mathrm{Sin}(\omega t) \tag{4.4}$$

$$T = \left(\frac{35+15}{2}\right) + 5\ (35 - 15)\ \mathrm{Sin}\left(\frac{2\pi}{365}t\right) = 25 + 100\ \mathrm{Sin}\left(\frac{2\pi}{365}t\right)$$

The first of April, t_1 = 90 day, so $T_1 = 25 + 100\ Sin\left(\frac{2\pi}{365} * 90\right) = 27.7$ °C

The 30th of April, t_2 = 120 day, so $T_2 = 25 + 100\ Sin\left(\frac{2\pi}{365} * 120\right) = 28.6$ °C

Thus, the average ambient air temperature in April, T_a, was equal to 28.15 °C

$$\dot{Q_w} = \dot{m_w}\ c_{p,w}\ (T_r - T_a) = \left(0.1\frac{kg}{s}\right)\left(4.1868\frac{kJ}{kg}.K\right)(323K - 301.15K)$$

$= 9.15$ kw.

2). Solar radiation can be computed by:

$$I_c = 17 + 100\ \mathrm{Sin}(\omega t)\quad \frac{MJ}{m^2}\text{per day} \tag{4.5}$$

3). Total heat stored in the tank containing 151.3 L water without any PCM, Tf = 65℃

$$Q_w = m_w\ c_{p,w}\ \Delta T = (151.3\ kg)\left(4.1868\frac{kJ}{kg}.K\right)(338K - 323K)$$

$$= 9501.9\ Kj \tag{4.6}$$

4). Storage time of the water flowing at a rate of 0.1 kg/s at 50℃ can be found by calculating the ratio between the total heat stored in the tank containing 151.3 L of water alone (Qw) and the energy required to increase the temperature of the water ($\dot{Q_w}$).

$$t_w = \frac{Q_w}{\dot{Q_w}} = \frac{9501.9 \text{ kJ}}{9.15 \text{ kW}} = 1038.5\text{s} \tag{4.7}$$

5). Energy stored in paraffin wax and water has two components: energy stored and latent energy stored.

$$m = \dot{m_w}\, t_w = \left(0.1\,\frac{\text{kg}}{\text{s}}\right)(1038.5\text{s}) = 103.85\text{kg} \tag{4.8}$$

6). The energy stored in paraffin wax and water has two components, sensible energy stored and latent energy stored.

Sensible energy stored is equal to:

$$Q_S = m_w\, c_{p,w}\, \Delta T + m_{PCM}\left(c_{p,PCM}\, \Delta T\right) \tag{4.9}$$

$$= (100\text{kg})\left(\frac{4.1868\text{kJ}}{\text{kg}}.\text{K}\right)(338\text{K} - 323\text{K}) + 40\left(\frac{2.4\text{kJ}}{\text{kg}}.\text{K}\right)(338\text{K} - 323\text{K})$$

$$= 7720.2 \text{ kJ}$$

The latent energy stored in paraffin wax is found using the latent heat of paraffin:

$$Q_L = m_{PCM}\, H_{SL} \tag{4.10}$$

$$= (40 \text{ kg})\left(230\,\frac{\text{kj}}{\text{kg}}\right) = 9200\text{kJ}$$

$$Q_{PCM} = Q_S + Q_L = 16920.2 \text{ kJ}$$

7). Storage time of the hot water for the storage tank with paraffin wax:

$$t_{PCM} = \frac{Q_{PCM}}{\dot{Q_w}} = \frac{16920.2\ \mathrm{kJ}}{9.15\ \mathrm{kW}} = 1849.2\ \mathrm{s} \tag{4.11}$$

4.1.3 Determining the average efficiency of the collector

1). The copper tubes have an internal diameter of 1 cm with 0.05 cm thickness. They are connected to each other with a thick plate at a center-to-center distance of 15 cm. In order to find the average total solar radiation in April, we have:

$$I_c = 17 + 100\ \mathrm{Sin}\left(\frac{2\pi}{365}t\right)\ \ \frac{\mathrm{MJ}}{\mathrm{m}^2}\text{per day} \tag{4.12}$$

The first of April, t_1 = 90 day, $I_{c_1} = 17 + 100\ \mathrm{Sin}\left(\frac{2\pi}{365} * 90\right) = 19.7\ \ \frac{\mathrm{MJ}}{\mathrm{m}^2}\text{per day}$

The end of April, t_2 = 120 day, $I_{C_2} = 17 + 100\ \mathrm{Sin}\left(\frac{2\pi}{365} * 120\right) = 20.6\ \ \frac{\mathrm{MJ}}{\mathrm{m}^2}\text{per day}$

The average solar radiation in April is equal to 20.15 $\frac{MJ}{m^2} per\ day$

Thus,

$$I_{c,ave} = \frac{20.15\frac{\mathrm{MJ}}{\mathrm{m}^2}\mathrm{day}}{6.14\ \mathrm{h}\left(3600\ \frac{\mathrm{s}}{\mathrm{h}}\right)} = 911.6\frac{\mathrm{W}}{\mathrm{m}^2}$$

2). The instantaneous efficiency of the collector can be found by dividing the useful heat gain, q_u ,by the solar irradiance that falls on the collector surface:

$$\eta_c = \frac{q_u}{I_c A_C} = F_R\left[\tau\,\alpha - \frac{U_c(T_{f,i} - T_a)}{I_c}\right] \tag{4.13}$$

3). The collector efficiency factor, F', is also required to find the heat removal factor:

$$F_R = \frac{GC_p}{U_c}\left[1 - \exp\left(-\frac{U_c F'}{GC_p}\right)\right] \tag{4.14}$$

where *G* is the flow rate per unit surface of collector, $G = \frac{\dot{m}}{A_c} = \frac{\frac{0.1kg}{s}}{2}m^2 = \frac{0.05kg}{m^2s}$, and C_p is the specific heat of the water.

4). The collector efficiency factor, F' ,is also required to find heat removal factor:

$$F' = \frac{1/U_c}{L[1/(U_c(D+w\eta_f))+1/(h_{c,i}\pi D)]} \qquad (4.15)$$

5). The fin efficiency, known as η_f, can be found using the following relation:

$$\eta_f = \frac{\frac{\tanh m(L-D)}{2}}{\frac{m(L-D)}{2}} \qquad (4.16)$$

where:

$$m = \left(\frac{U_c}{k_c t}\right)^{1/2} \qquad (4.17)$$

The thermal conductivity of the copper plate, k_c, is 390 W/mK, while the thickness of the plate is 0.05 cm. (5.5) to (5.18). The average efficiency of the collector can thus be determined as:

$$m = \left(\frac{8}{390*5*10^{-4}}\right)^{1/2} = 6.4 \qquad (5.18)$$

$$\eta_f = \frac{\frac{\tanh 6.4(0.15-0.01)}{2}}{\frac{6.4(0.15-0.01)}{2}} = 0.938$$

$$F' = \frac{1/8}{0.15\left[1/\left(8(0.01+0.14*0.938)\right)+1/(1500\pi*0.01)\right]}$$

$$F_R = \frac{0.05*4186.8}{8}\left[1-\exp\left(-\frac{8*0.92}{0.05*4186.8}\right)\right] = 0.906$$

After finding the heat removal factor, the average efficiency of the collector can be calculated.

$$\eta_{c,average} = 0.906\left[0.9 * 0.9 - \frac{8 * (338 - 301.15)}{911.6}\right] = 0.44 \text{ or } \%44$$

The water temperature of domestic water heating will increase due to solar irradiation, whereas the cold replenishment of water leads to the decrease of water temperature in the tank. The following relationships can be used to calculate the increase and decrease of water temperature:

$$\Delta T_{increase} = \frac{\eta A_c I_S}{M_w C_{p,w}} = \frac{\eta A_c I_S \Delta t}{\rho_w V C_{p,w}} \tag{5.19}$$

$$\Delta T_{decrease} = T_{previous} - \frac{Q \Delta t T_{rep.} + (V - Q \Delta t) T_{previous}}{V} \tag{5.20}$$

The temperature at each hour can be computed by:

$$T = T_{previous} + \Delta T_{increase} - \Delta T_{decrease} \tag{5.21}$$

By considering the following specifications, the water temperature can be plotted as below:

Efficiency of system, $\eta = 0.5$

Initial temperature, $T_i = 50\,^{\circ}C$

Replenishing water temperature, $T_{rep.} = -10\,^{\circ}C$

Specific Heat, Cp,w = 4186 J/kgK.

4.2 Results from theoretical calculations

The theoretical calculations revealed that a storage tank with paraffin wax can provide more than one and a half times more hot water at 50°C than the storage tank containing only water as a storage material. While this result does show the potential of PCMs for energy storage applications, it can be seen in figure 4.5. Several factors need to be taken into account in choosing the PCMs for storage material. Firstly, the phase change temperature of the material is a crucial factor, depending on the application. For domestic hot water application, a PCM that has a melting temperature above 52°C is suitable when the required hot water temperature is assumed to be 50°C. Moreover, the cost and availability of the PCMs play important roles in commercial applications.

Moreover, the collector efficiency depends on many factors, including absorption plate thickness, thermal conductivity, and the distance between the flow channels. The collector efficiency is found to be 44% with the assumed properties, but it changes hourly depending on the falling solar radiance. Therefore, the calculated average collector efficiency only provides a rough estimate of the solar collector's efficiency throughout the day. When the temperature of a system reaches the melting temperature of PCM, extra energy will be stored in the PCM to use later. The stored thermal energy can be computed by subtracting the difference between the temperature of the two curves (with PCM and without PCM).

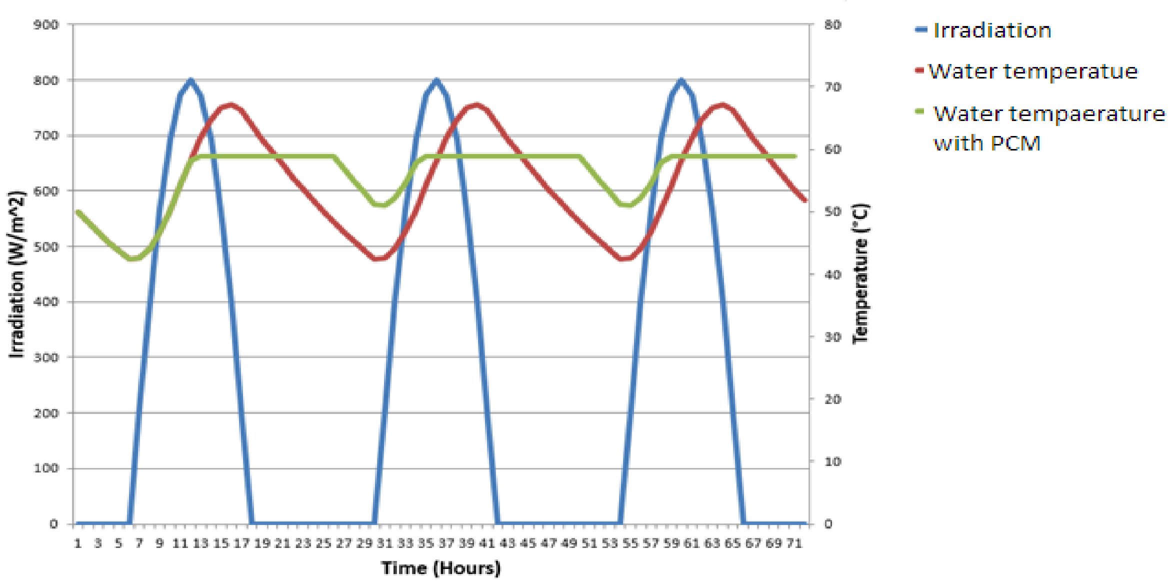

Figure 4.5: Variations in water temperature over time using phase change materials.

CHAPTER 5

Numerical Simulation of Solar Hot Water Heater

5.1 Methodology

This research has been accepted for Publication in LICEET 2018 (Libyan International Conference on Electrical Engineering and Technologies, 2018, Tripoli, Libya). Lasmar et al. (2018).

5.1.1 Finite Element Modeling for PCM effect on heat exchanger efficiency

To enhance the performance of heat exchangers, PCMs have been used to improve the thermal energy storage in the heat exchangers during the night. To simulate this problem, the following steps have been conducted:

(1). Three-dimensional (3D) models for the system are created considering two main options, as shown in Figs. (5.1a) and (5.1b). (A) Filling the tank with PCMs (Fig. 1a). (B) Encapsulated PCMs around heat exchanger (Fig. 1b).

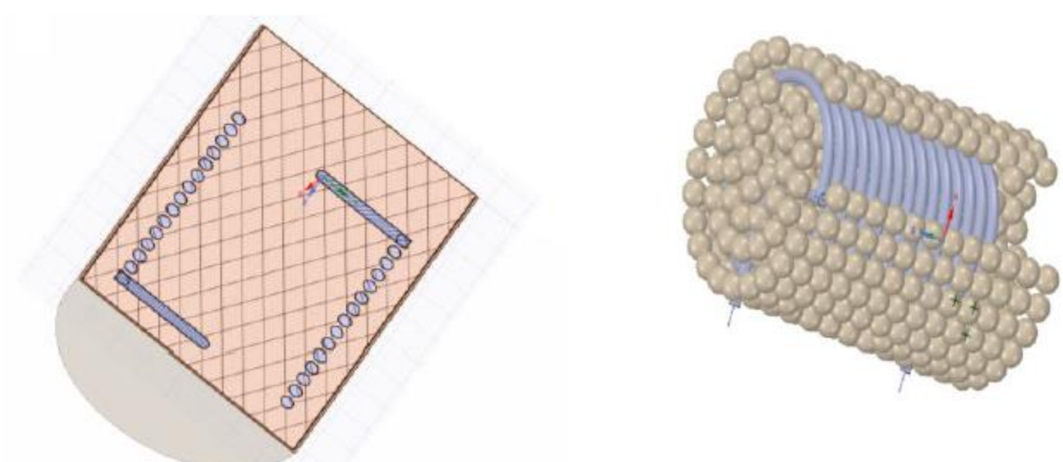

Figure 5.1: a) Filling the tank with PCMs; b) filling the tank with encapsulated PCMs [ANSYS Software].

2. A finite element model is created in the environment of ANSYS, as shown in Figs. 5.2 and 5.3.

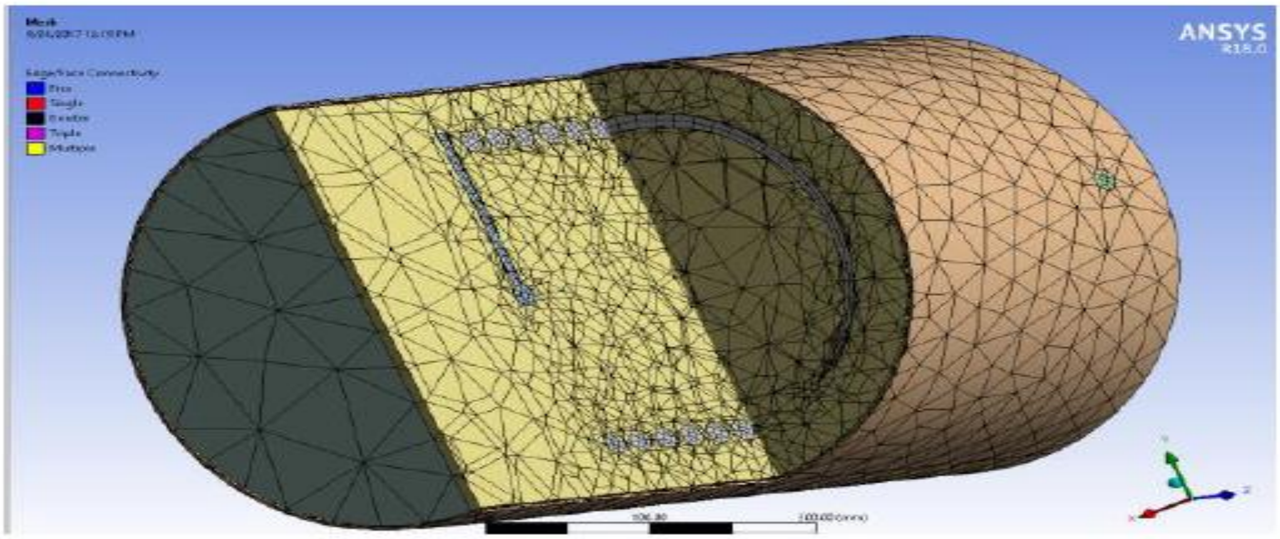

Figure 5.2: Meshing of system (a)

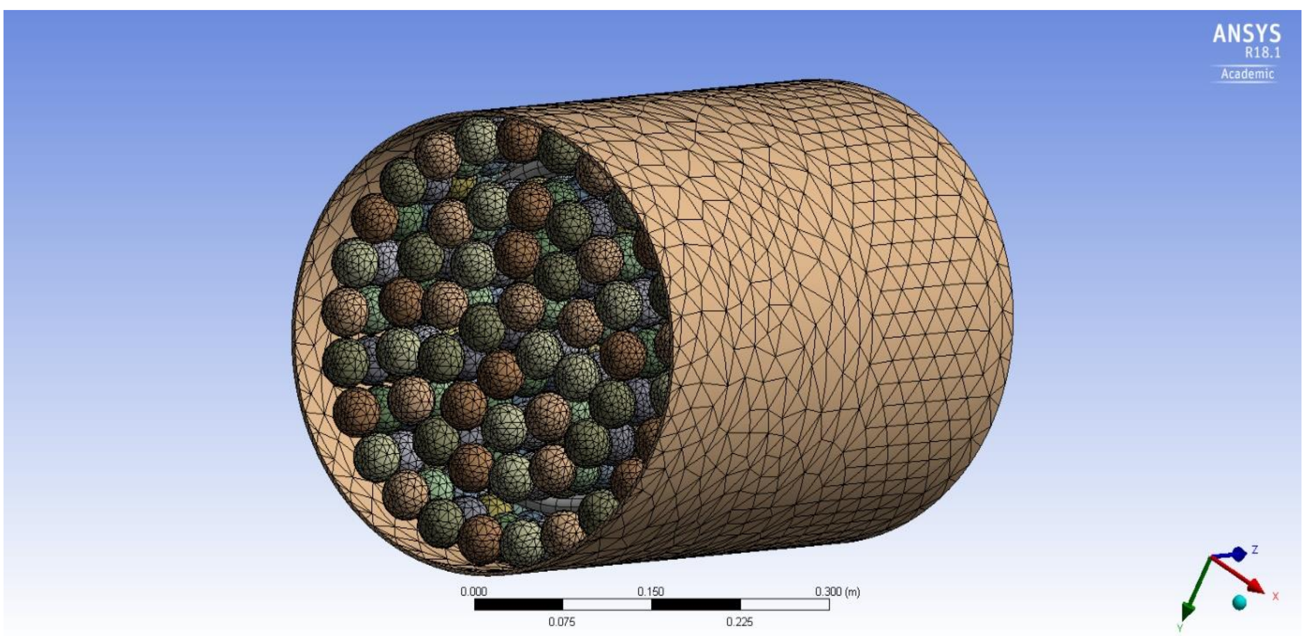

Figure 5.3: Meshing of system (b)

(3). A transient thermal module has been used to study the change of the water temperature with time, to detect the effect of the PCMs.

(4). The challenge of identifying the change in phase for paraffin wax will be addressed.

The principle requirements for identifying the PCMs in the finite element model are to define the change of the enthalpy and the thermal conductivity with temperature changes. In the model, Equations (5.1) to (5.7) have been used to calculate changes in enthalpy versus temperature:

$C_{avg} = (C_S + C_L)/2$	: Average specific heat	(5.1)
$C^* = C_{avg} + (L / (T_L - T_S))$	: Specific heat for transition	(5.2)
$H- = \rho_s C_S (T - T_0)$	: Enthalpy below solid temperature	(5.3)
$H_S = \rho_s C_S (T_S - T_0)$	: Enthalpy at solid temperature	(5.4)
$H_{TR} = H_S + \rho_L C (T_L - T_S)$	: Enthalpy between solid/liquid temperature	(5.5)
$H_L = H_S + \rho_L C^* (T_L - T_S)$	: Enthalpy at liquid temperature	(5.6)
$H+ = HL + \rho_L C_L (T - TL)$	: Enthalpy above liquid temperature	(5.7)

where C_S is the specific heat of the solid state, C_L is the specific heat of the liquid state, ρ_L is the density in the liquid state, ρ_s is the density in the solid state, T_S is solid, temperature, T_L is liquid temperature, and L is latent heat. The changes in enthalpy, thermal conductivity, density, and specific heat with varying temperatures are shown in Figs. 5.4 to 5.7.

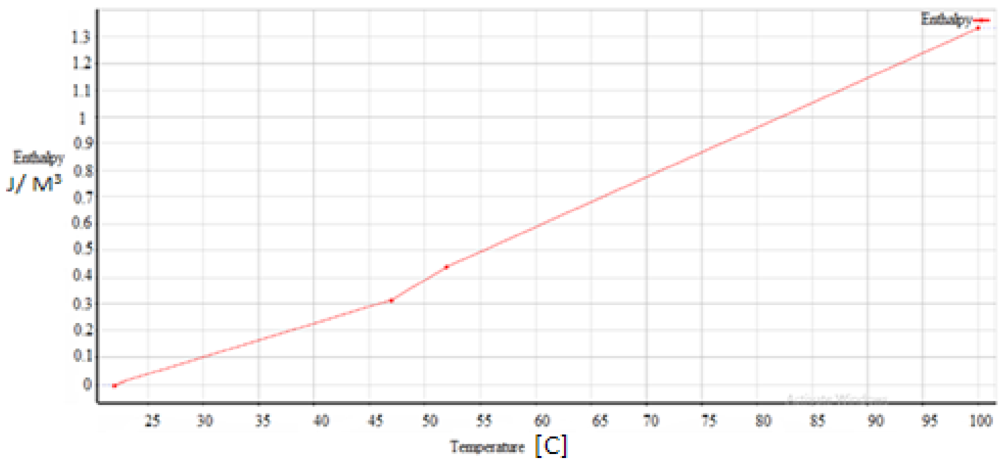

Figure 5.4: Enthalpy change with temperature of PCMs.

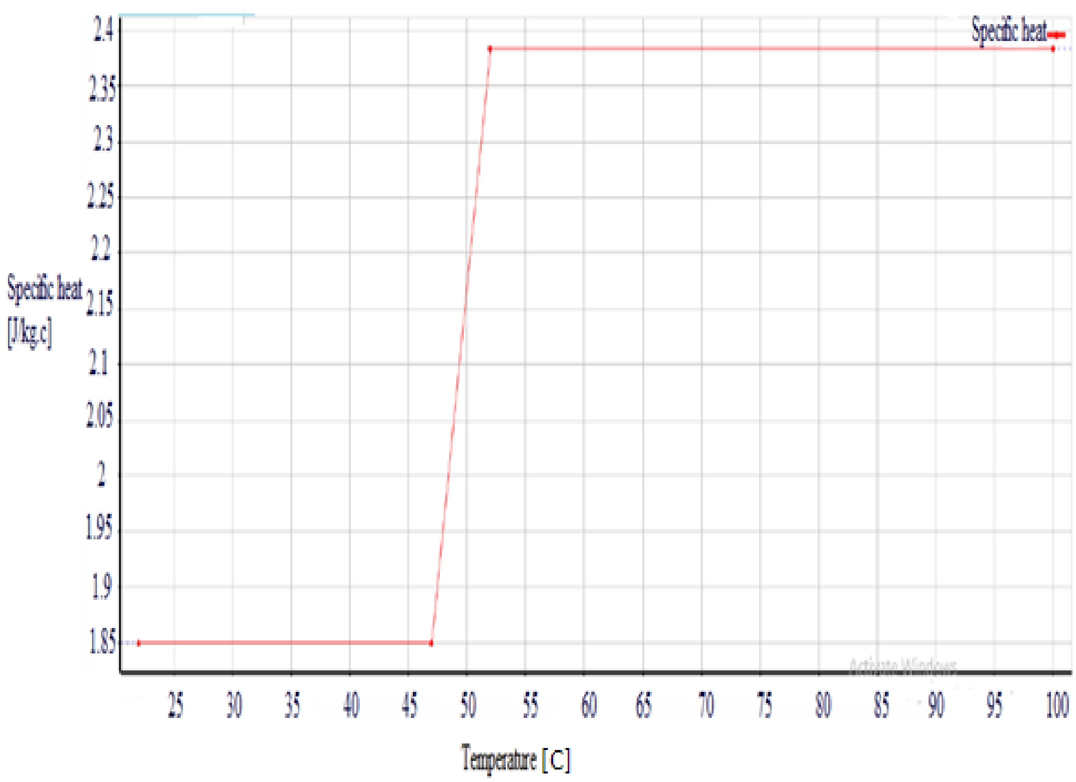

Figure 5.5: Specific heat change with temperature for PCM.

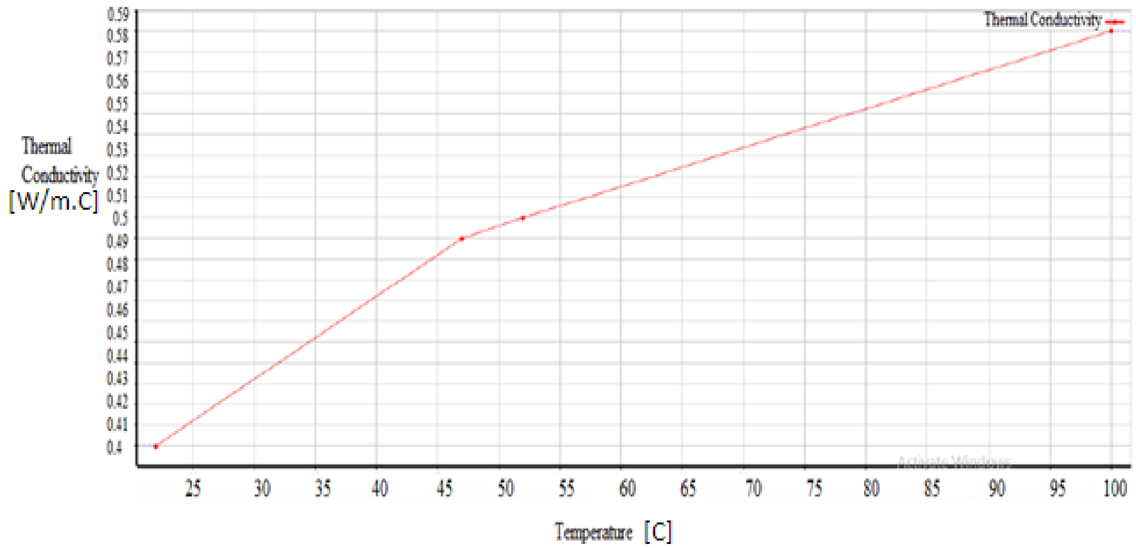

Figure 5.6: Thermal conductivity changes with temperature for PCM.

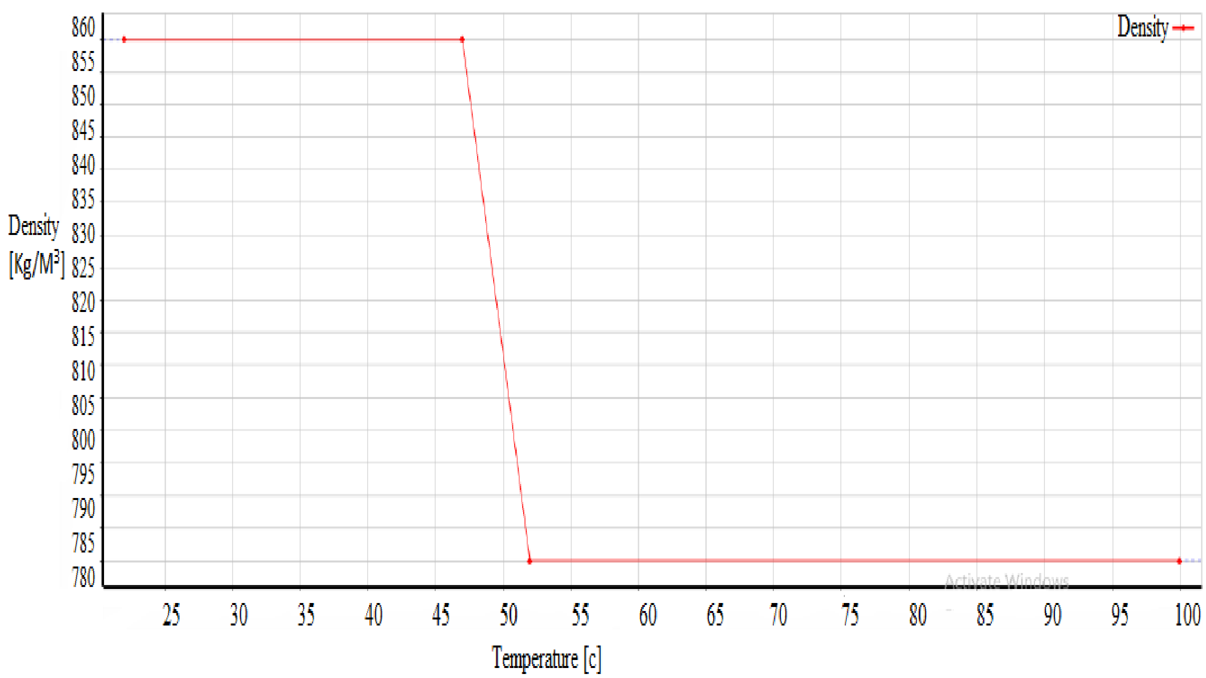

Figure 5.7: Density change with temperature for PCM.

From the previous figures, we can see the values of the thermal and physical properties of the PCM, showing the change in these properties, the liquid and solid states of the PCM, and also the transient state between the liquid and solid states.The changes in these values express the behaviour of the PCM in relatin to changes in the input temperature in the heat exchanger.

(5) The main outputs of the simulation will thus be:

(A) PCM temperature change during an entire working day (24h).

(B). The effect of the PCM is demonstrated by observing the water temperature for one day, which shows the efficiency of the heat exchanger.

5.2 Governing equations

The simplifications for the mathematical model assume the following:

- The flow is laminar.
- The fluid is Newtonian and incompressible.
- The thermophysical properties of the fluid and the PCM are assumed to be constant in the temperature range envisaged in the proposed study.
- The PCM is pure and initially solid, and the phase change process is isothermal.
- The solid PCM is motionless even when surrounded by liquid.

For incompressible water fluid, the energy equations are as follows:

$$\frac{\partial \theta}{\partial \tau} + \frac{\partial (V\theta)}{\partial y} = \left[\frac{\partial}{\partial x}\left(\alpha \frac{\partial \theta}{\partial x}\right) + \frac{\partial}{\partial y}\left(\alpha \frac{\partial \theta}{\partial y}\right)\right] \tag{5.8}$$

An enthalpy formulation of energy equation of PCM gives:

$$\frac{\partial \theta}{\partial \tau}+\frac{\partial (U\theta)}{\partial x}+\frac{\partial (V\theta)}{\partial y}=\alpha \frac{\partial^2 \theta}{\partial x^2}+\alpha \frac{d^2 \theta}{\partial y^2}-\frac{1}{Ste}\frac{\partial f}{\partial \tau} \tag{5.9}$$

The conservation mass of PCM is as follows:

$$\frac{\partial U}{\partial x}+\frac{\partial V}{\partial y}=0 \tag{5.10}$$

$$\frac{\partial U}{\partial \tau}+\frac{\partial (UU)}{\partial x}+\frac{\partial (VU)}{\partial y}=-\frac{\partial P}{\partial x}+\frac{\Pr(\partial^2 U)}{\partial x^2}+\Pr\frac{\partial^2 U}{\partial x^2}+Pr\frac{\partial^2 U}{\partial y^2}+S_X \tag{5.11}$$

$$\frac{\partial V}{\partial \tau}+\frac{\partial (UV)}{\partial x}+\frac{\partial (VV)}{\partial y}=-\frac{\partial P}{\partial y}+\frac{\Pr(\partial^2 V)}{\partial x^2}+\Pr\frac{\partial^2 U}{\partial y^2}+Pr\frac{\partial^2 V}{\partial y^2}+S_Y+S_b \tag{5.12}$$

5.3 Energy equations

1) The enthalpy of the material is computed as the sum of the sensible enthalpy, h, and the latent heat, ΔH:

$$H=h+\Delta H \tag{5.13}$$

where:

$$h=h_{ref}+\int_{Tref}^{T} CpdT \tag{5.14}$$

and h_{ref} = reference enthalpy

T_{ref} =reference temperature

C_P =specific heat at constant pressure

2) Liquid fraction, β, can be defined as:

$\beta=0 \quad if\ T<T_{Solid}$

$\beta=1\ if\ T>\ T_{Liquid}$

$$B=\frac{T-T_{Solid}}{T_{Liquid}-T_{Solid}}\ \text{ if }\ T_{Solid}<T<T_{Liquid} \tag{5.15}$$

Equation (5.15) is referred to as the lever rule:

The latent heat content can now be written in terms of the latent heat of the material, L:

$$\Delta H = \beta L \tag{5.16}$$

The latent heat content can vary between zero (for a solid) and L (for a liquid).

For solidification/melting problems, the energy equation is written as:

$$\frac{\partial}{\partial t}(\rho_H) + \nabla.(\rho\, V\, H) = \nabla.(k\nabla T) + S \tag{5.17}$$

where:

H= enthalpy

ρ = density

V= fluid velocity

S =source term

The solution for temperature is essentially an iteration between the energy equation (Equation 5.17) and the liquid fraction equation (Equation 5.15). Directly using equation 5.15 to update the liquid fraction usually results in poor convergence of the energy equation.

3) Momentum equations:

The enthalpy technique treats the mushy region (partially solidified region) as a porous medium. The porosity in each cell is set equal to the liquid fraction in that cell. In fully solidified regions, the porosity is equal to zero, representing the velocities in these regions. The momentum sink due to the reduced porosity in the mushy zone takes the following form:

$$S = \frac{(1-\beta)^2}{(\beta^3+\epsilon)} A_{mush} \text{ (v-vp)} \tag{5.18}$$

where β is the liquid volume fraction, ϵ is a small number (0.001) to prevent division by zero, A_{mush} is the mushy zone constant, and (v-vp) is the solid velocity due to the removal of solidified material from the domain.

The mushy zone constant measures the amplitude of the damping; the higher this value, the steeper the transition of the velocity of the material to zero as it solidifies. Very large values may cause the solution to oscillate.

5.4 Volume of PCM equations

For every system with a PCM model included, the volume of PCMs must be divided into cylinders, spheres or cuboids to provide more area for heat transfer. The diameter D [m] of a cylindrical PCM model is calculated using Eq. (5.19) and Eq. (5.20):

$$D = \sqrt{\frac{4V}{N\pi H}} \tag{5.19}$$

$$V = ND^2 \pi \frac{1}{4} H \tag{5.20}$$

where:

where $V[M^3]$ represents the total volume of PCM material inside the tank, N is the number of PCM models, H [m] is the height of modules. In the case of spherical models, Eq. (5.21) and Eq. (5.22) are used:

$$D= \sqrt[3]{\frac{6V}{N\pi}} \tag{5.21}$$

$$V= D^3 \pi \frac{1}{6} N \tag{5.22}$$

The diameter, D, and the number N of models, N, are changed. The values obtained for the diameter are used in the water tank model.

5.5 Results and discussion

There are a few issues that arise from the inherent characteristics of PCM. Due to the low thermal conductivity of the PCMs, it is observed that it takes a long time to charge and discharge the PCM. The low heat transfer rate between the heat transfer fluid and PCM leads to less efficient thermal systems.

Another issue is that some PCMs, particularly inorganic ones, tend to experience super cooling and phase separation, which affect the reliability of the storage systems. Super cooling occurs when a PCM melts at a temperature below its melting temperature preventing the stored energy from being released. Phase separation is also a common problem affecting inorganic hydrated salts. During melting, a PCM forms water and lower hydrated salt which has a higher density than water. Therefore, it sinks to the bottom, disrupting the repeatability of the charging and discharging.

The problems associated with PCMs have been addressed for decades. Some researchers proposed encapsulating PCMs to increase the heat transfer area between the PCM and heat transfer fluid. Encapsulation also ensures cycle stability and better performance. The location of the household is Tripoli, the research period is an April, and the monthly average solar radiation in April is 6.049 Kwh/m^2/day, with an annual average of 5.02 Kwh/m^2/day. The average sunshine duration at Tripoli in April is 6.14 hrs. The amount of paraffin wax which is melted in this process is 51.3 L, which is equal to 40 kg of paraffin wax.

5.5.1 Results when the tank is full of PCM

Simulations for different inputs and characteristics are discussed, as follows:

1) The simulation of one day's inlet water temperature is shown in Fig. 5.8. **Free convection** (slow flow of air) at the outer surface of the tank with the convection of coefficient 10 W/m^2.℃ is considered.

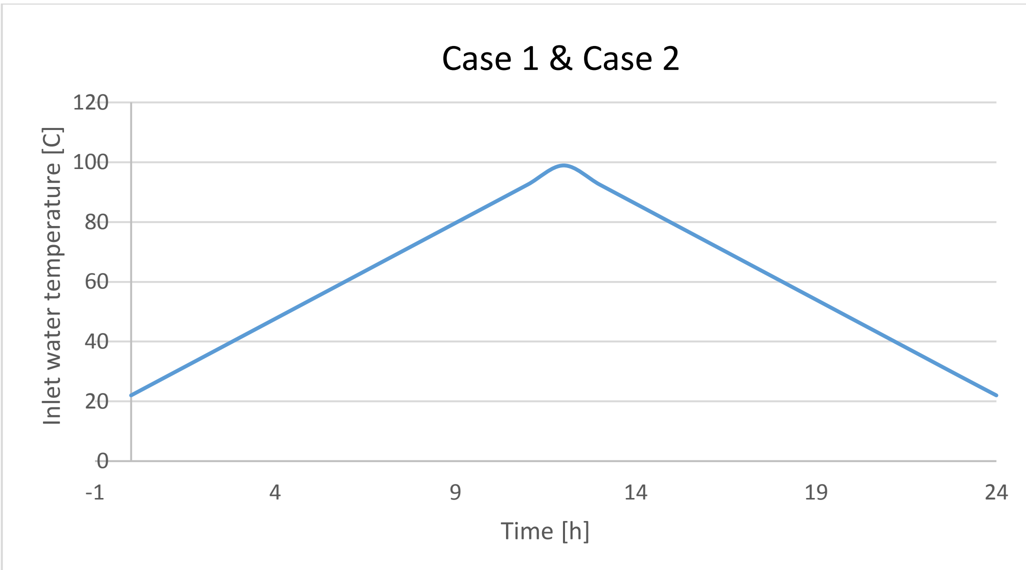

Figure 5.8: Inlet water temperature change over time.

2) A simulation of one day's inlet water temperature (the same as in Case 1) is shown in Fig. (5.8). **Perfect Insulation** at the outer surface of the tank is considered.

3) A simulation of three days' certain IR-radiation input and its related inlet temperature is shown in Fig. 5.9 and Fig. 5.10, respectively. **Perfect Insulation** at the outer surface of the tank is considered.

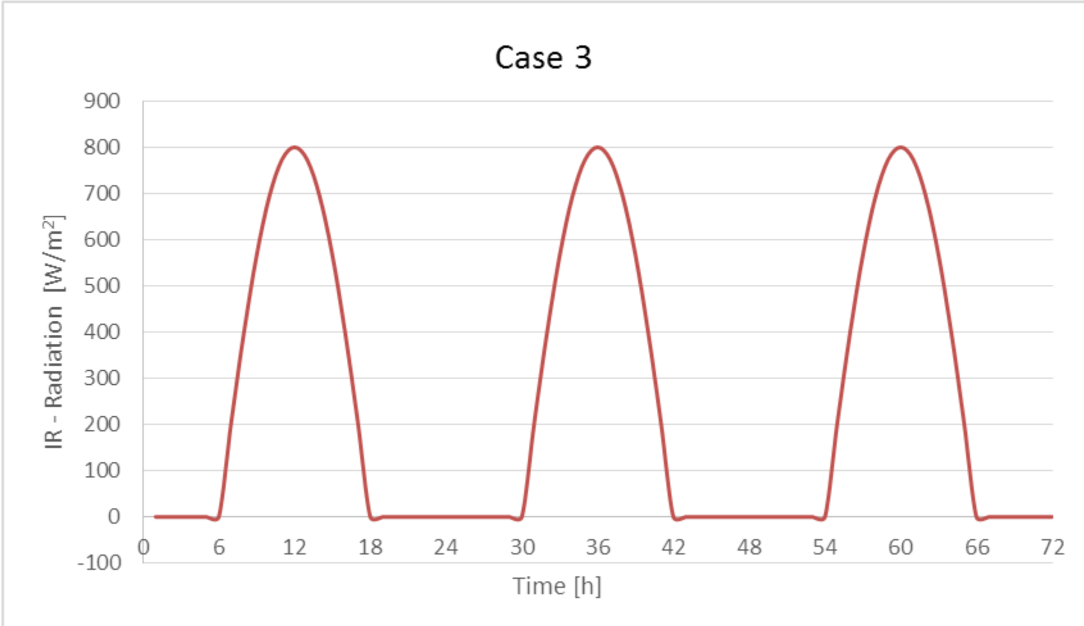

Figure 5.9: Input IR-radiation change over time.

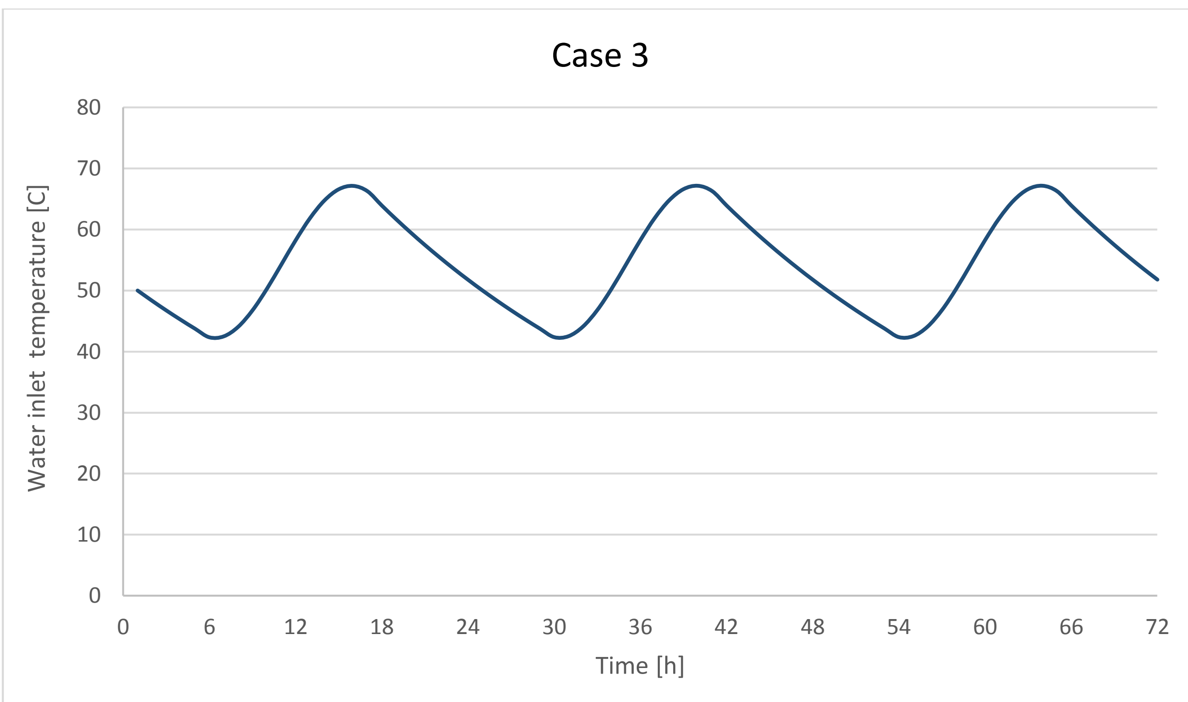

Figure 5.10: Inlet water temperature change over time.

Results for Case 1:

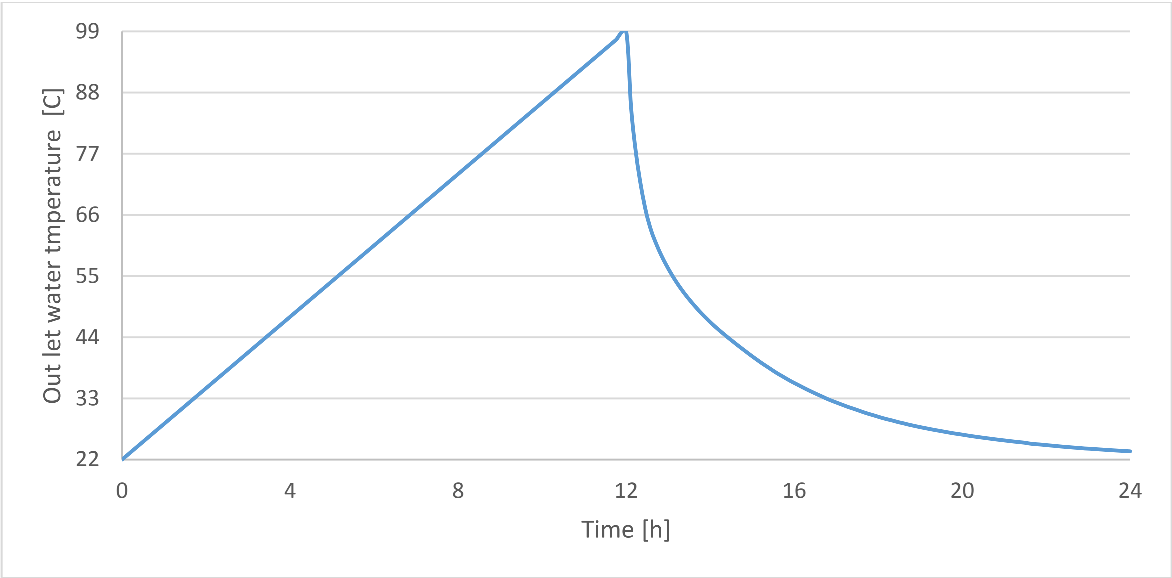

Figure 5.11: Outlet water temperature change over time.

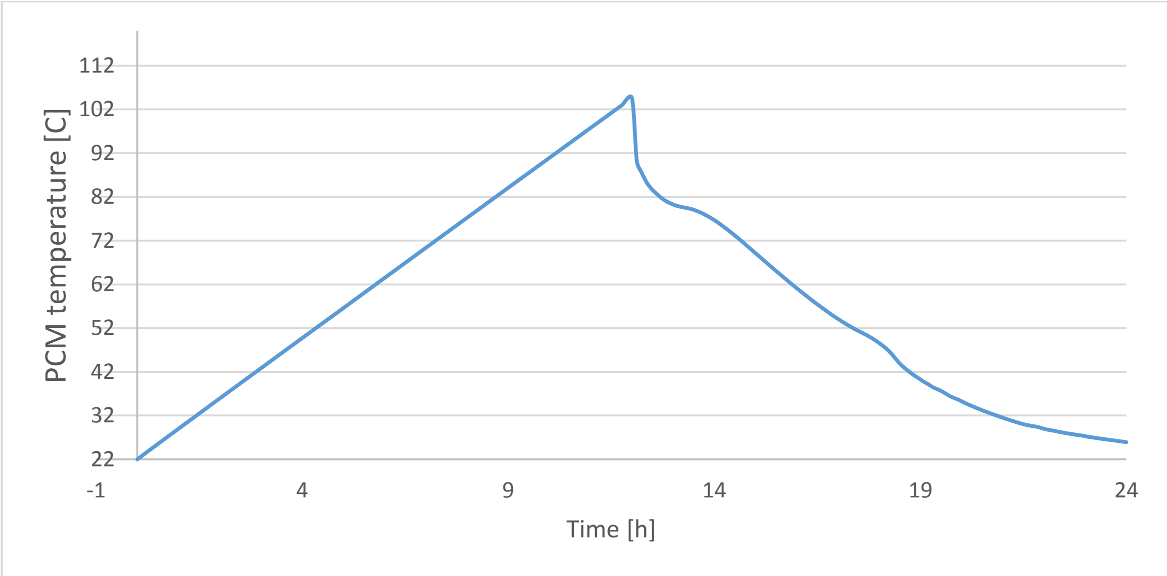

Figure 5.12: PCM temperature change over time.

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Results for Case 2:

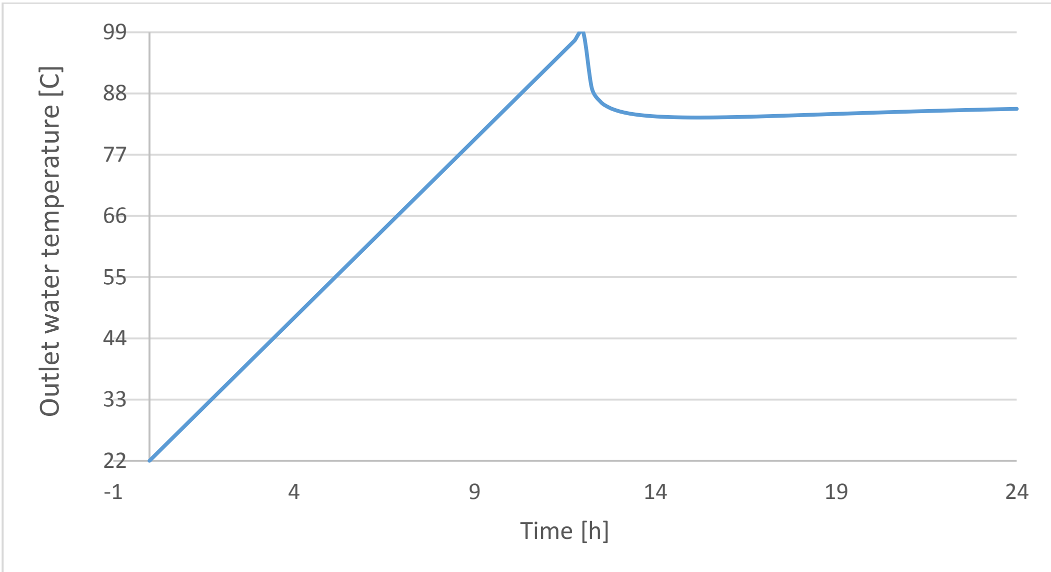

Figure 5.13: Outlet water temperature change over time.

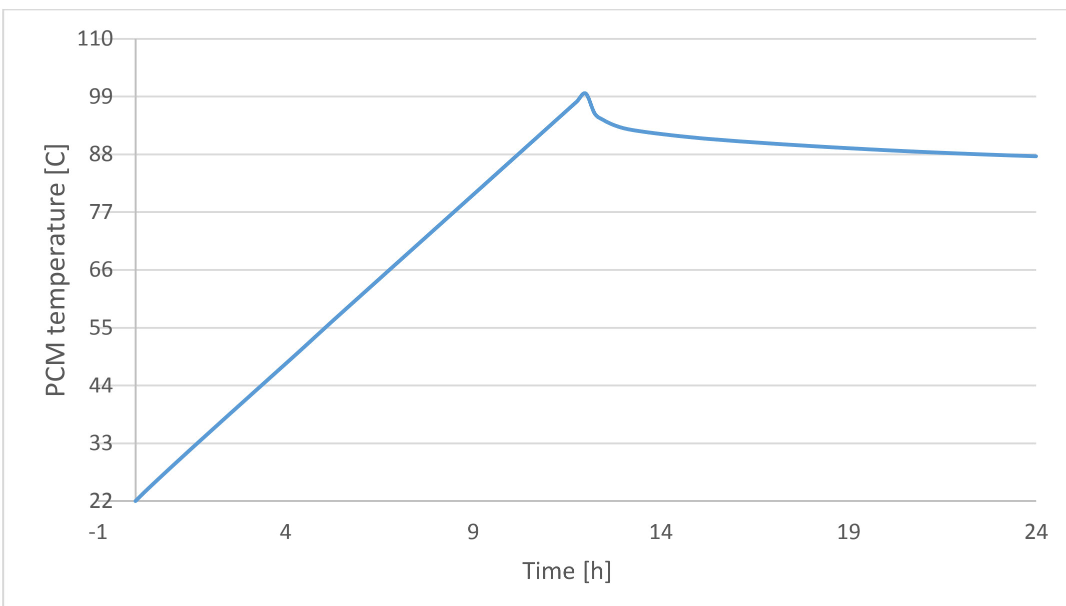

Figure 5.14: PCM temperature change over time.

Results of Case 3:

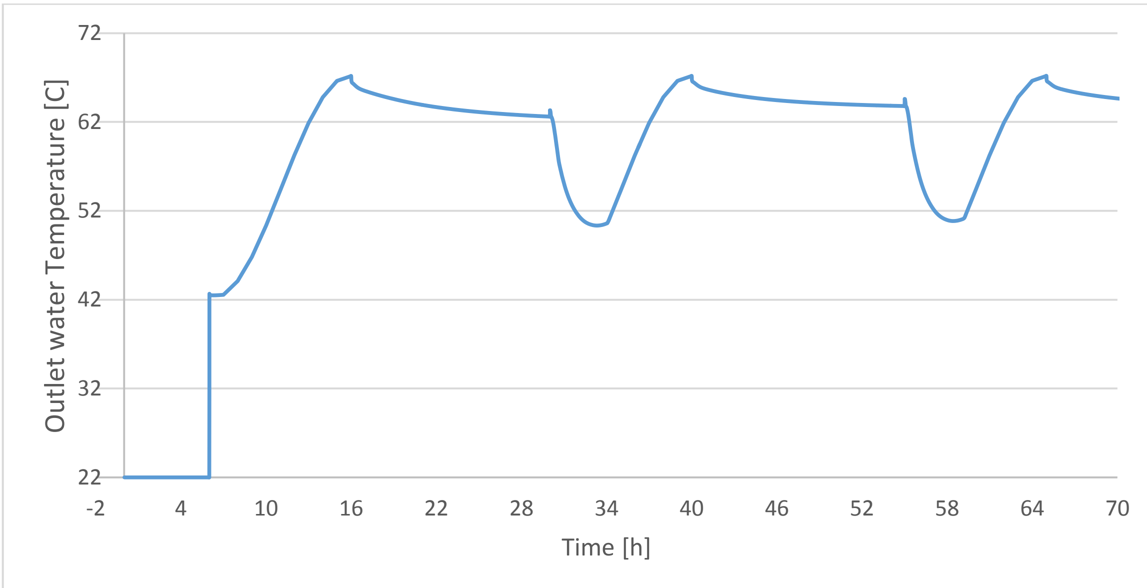

Figure 5.15: Outlet water temperature changes over time.

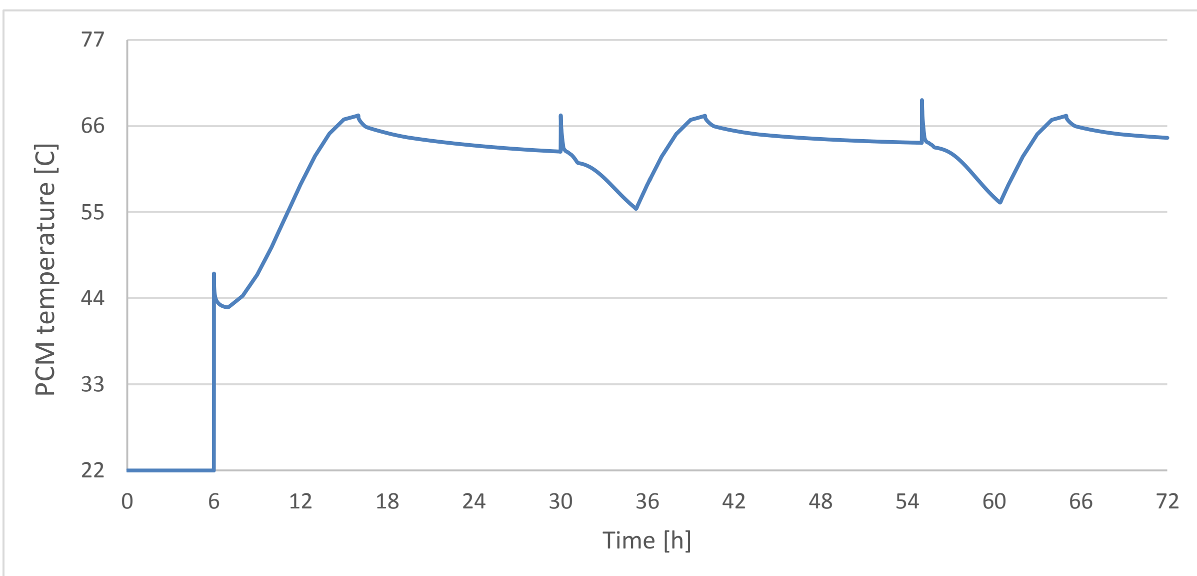

Figure 5.16: PCM temperature changes over time.

The following conclusions have been deduced from the previous results:

- A PCM can conserve the outlet water temperature, especially when the inlet water temperature is reduced during the day.
- Insulation of the tank is important in this study.
- The FEM has the ability to reflect the effect of the PCM on the heat exchanger.
- Inlet water temperature is assumed to increase during the day (12 hrs) and decrease at night for clarity and simplicity.
- Case 1 results show that the outlet water temperature and PCM temperature increased quickly during the first half of the day and after that decreased suddenly. This is because free convection has a significant effect and there is no insulation for the tank in this case.
- In Case 2 results, the outlet water temperature and PCM temperature decrease and become stable over time because there is perfect insulation in this case.
- In Case 3 results, the outlet water temperature and PCM temperature changed for 3 days due to varying variable solar radiation.

5.5.2 Results when the tank was filled with encapsulated PCM

Simulations for different inputs and characteristics are discussed as follows:

1. The simulation for one day's inlet water temperature is the same as in Case 1, as shown in Fig. 5.17. **Perfect insulation** at the outer surface of the tank is considered.

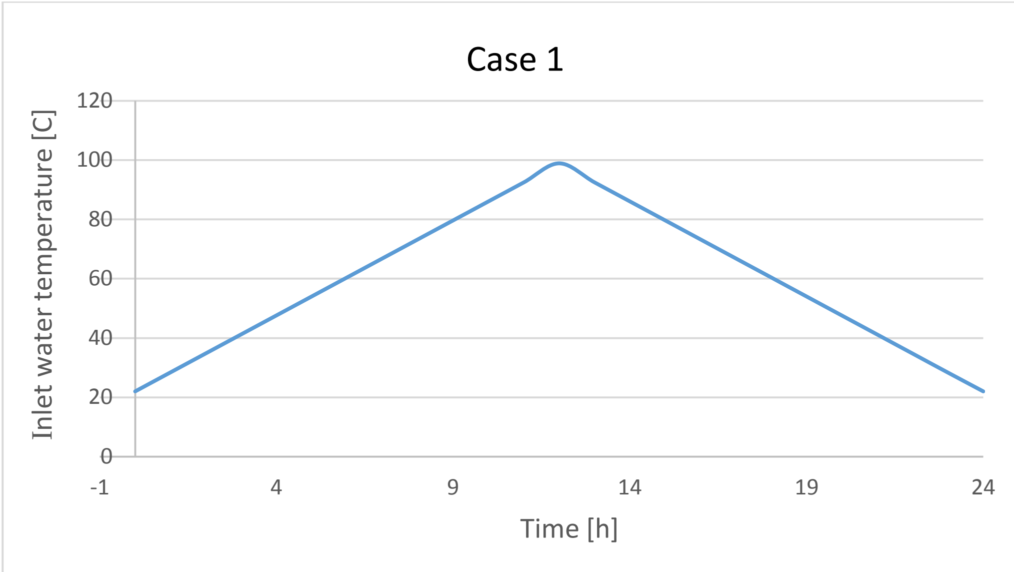

Figure 5.17: Inlet water temperature changes over time.

2. The simulation for one day's certain IR-radiation input and its related inlet temperature, as given from the analytical solution, are shown in Figs. 5.18 and 5.19, respectively. Perfect insulation at the outer surface of the tank is considered.

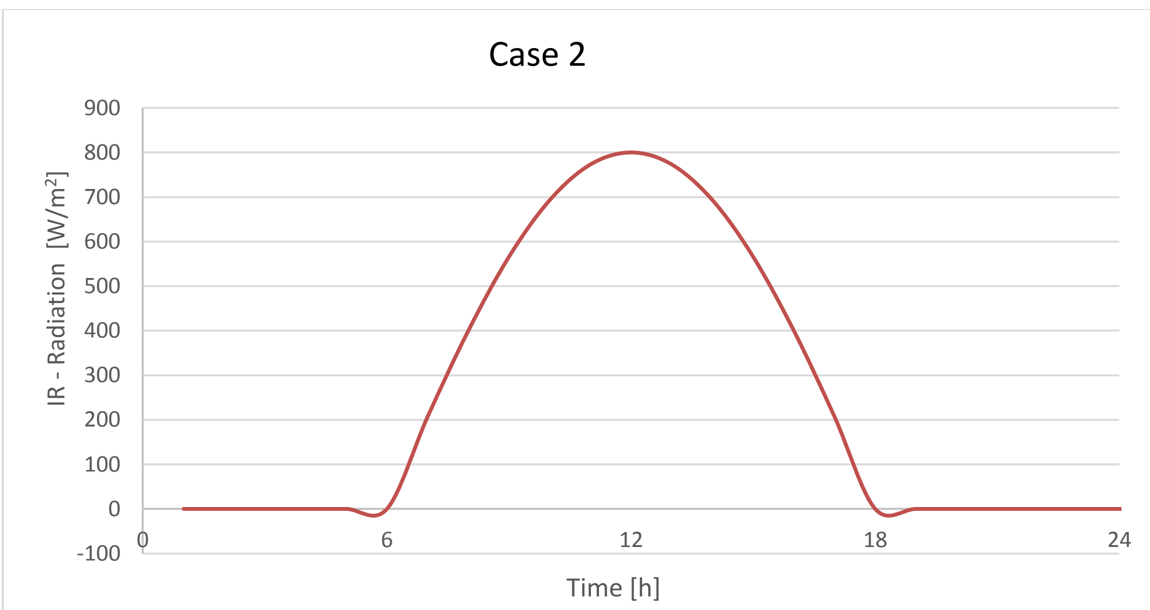

Figure 5.18: Input IR-radiation changes.

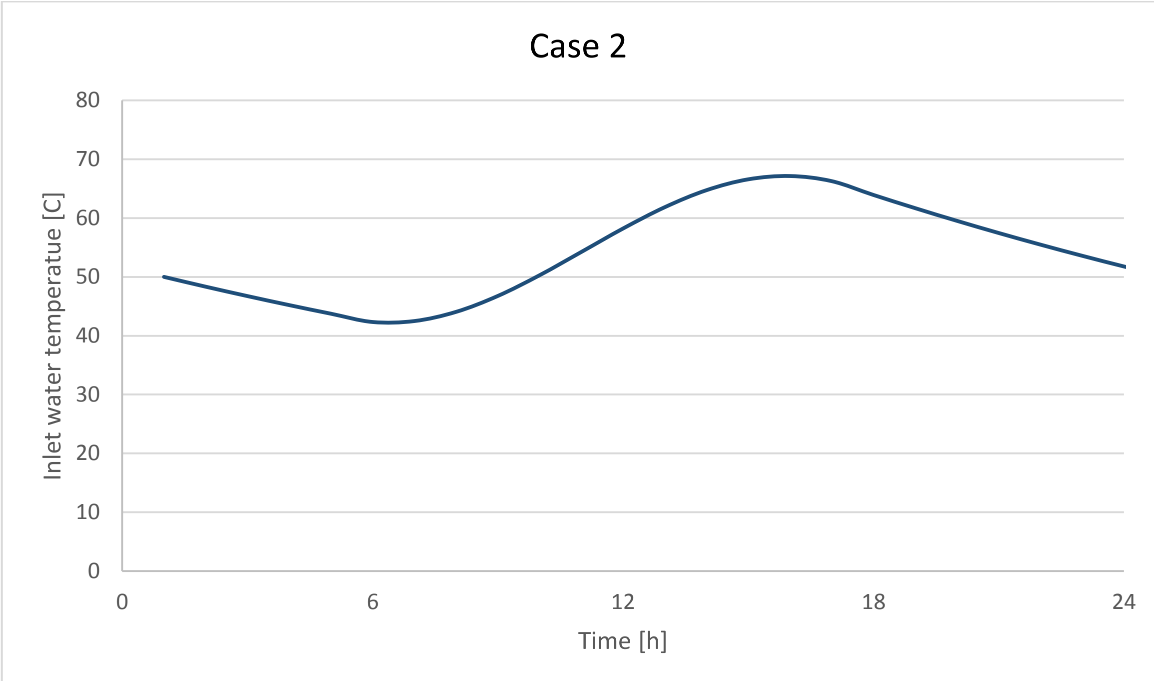

Figure 5.19: Inlet water temperature changes over time.

Because of the difficulty and the very long computational time required to find transient thermal solution for this complicated system, which has 780 different bodies, 860,000 elements, 2,500,000 nodes, and 36 h working time, the following assumptions have been considered:

1. The capsules are made of very thin PVC material with a density of 1100 kg/m^3, a specific heat of 880 J/kg.k, and a thermal conductivity of 0.12 W/m.k. It is assumed that there is no thermal effect in this simulation.
2. Only one working day has been simulated, assuming that the cycle and the results will be the same for all other days.
3. As the temperature is not so high (less than 100°C), it is assumed that there is no change in the dimensions for any part of the system. Although the PCM changes from solid to liquid and vice versa, it has been put in the same container and thus has the same dimensions.

Results for Case 1:

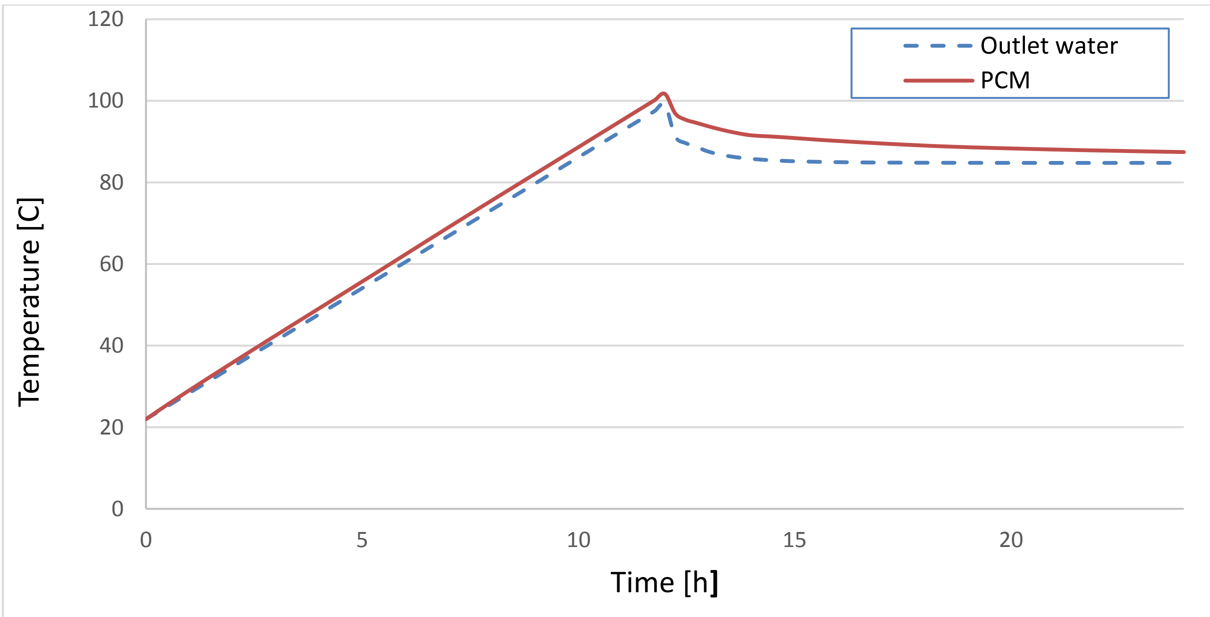

Figure 5.20: Outlet water and PCM temperatures changes over time.

Results for Case 2:

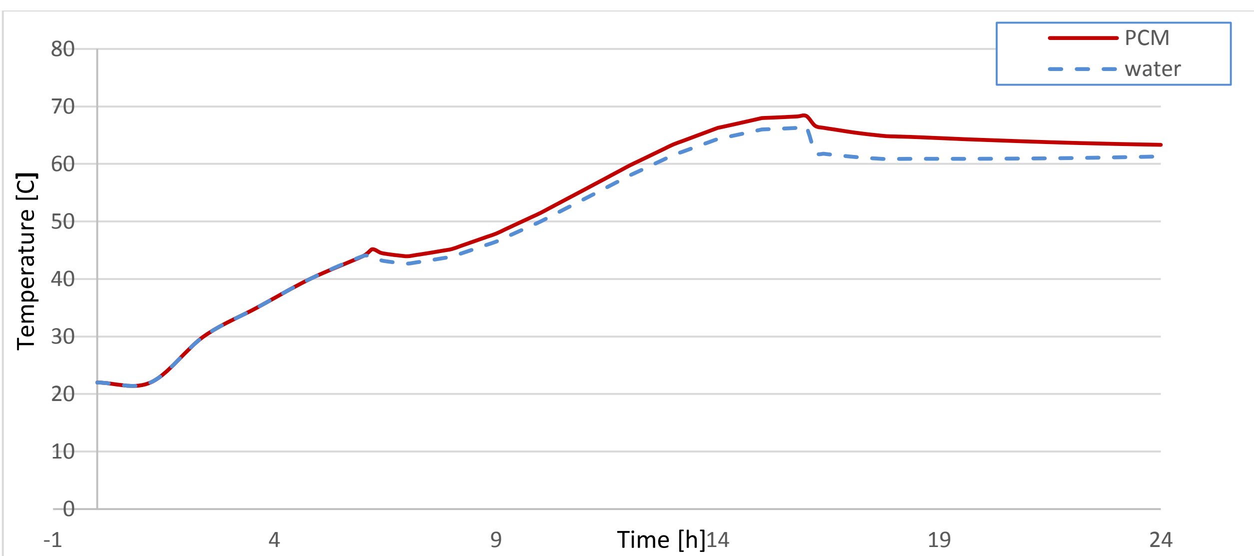

Figure 5.21: Outlet water and PCM temperature changes over time.

The following conclusions have been deduced from the previous results:

1- A PCM can conserve the outlet water temperature, especially when the inlet water temperature is reduced during the day.
2- The minimum outlet water temperature for Case 1 at the end of the working day is less than the maximum inlet water temperature by 19%. This percentage comes from the maximum inlet water temperature (99℃) minus the minimum outlet water temperature, which is 80℃, divided by the maximum inlet water temperature (99℃): $\frac{99\ ℃-80℃}{99℃}=19\%$
3- The minimum outlet water temperature for Case 2 at the end of the working day is less than the maximum inlet water temperature by 11%. This percentage comes from the maximum inlet water temperature (69℃) minus the minimum outlet water temperature, which is 58℃, divided by the maximum inlet water temperature (69℃): $\frac{69\ ℃-58℃}{69℃}=11\%$

CHAPTER 6

Conclusion

Encapsulating PCMs can conserve the outlet water temperature, especially when the inlet water temperature is reduced at night time. Additionally, insulating the tank is important when using PCMs, as the FEM has the ability to reflect the effect of PCMs on the heat exchanger. There are a few issues that arise from the inherent characteristics of PCMs. Due to the low thermal conductivity of PCMs, it takes a long time to charge and discharge them. The low heat transfer rate between the heat transfer fluid and PCM leads to less efficient thermal systems. Encapsulating PCMs have been used in this research in order to increase the heat transfer area between the PCM and heat transfer fluid. Encapsulating the PCM in a sphere shape around the heat exchanger shows cycle stability and better performance for a hot water storage tank.

Paraffin wax, which was used as the phase change material in this research, has provided the change in the values of thermal and physical properties that lead to the behavior of the PCM with a change of the input temperature in the heat exchanger. A PCM can conserve the outlet water temperature, especially when the inlet water temperature is reduced during the day.

Future Research

1. Extend the numerical analysis to simulate the charge and discharge process using different types of phase change materials such as inorganic PCM.
2. Extend the analysis of the charging process by taking the natural convection into account.

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