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Integration of Solar Domestic Hot Water System with Thermal Energy Storage Based on Phase Change Materials

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Abstract

In many processes, heat generated cannot not be used during its time of production. Thermal energy storage has the potential to store this heat energy which can later be used for different purposes. It helps in improving the process efficiency. Phase change materials are used to store latent heat. In this study, solar water heating system has been integrated with thermal energy storage based on phase change materials. Three different phase change materials namely sodium acetate trihydrate with graphite, RT60 and Paraffin56 have been taken for this study. Four different water profiles namely daily peak, multi dwelling, UK and ASHRAE have been considered to analyse the performance of phase change materials under different water withdrawal distribution. TRNSYS software has been used for carrying out simulations. ASCII files have been made by getting data from thermal analyser. Type 840 tank in TRNSYS has been used and it has the capacity to incorporate phase change material in cylindrical, spherical and slurry form. This study will help in finding out a suitable phase change material according to Lisbon climatic conditions. Cylindrical shaped modules performed better than spherical ones and out of three proposed volumes of phase change material, 20% volume was selected based on performance. Incorporating phase change materials resulted in saving electricity bills as electric heater's operation time was reduced. Moreover, carbon footprint was also reduced significantly. Results show that presence of phase change materials inside tank helps in maintaining high water temperatures for longer period of time.

Keywords: Phase change material, latent heat storage, water profiles, energy, TRNSYS.

Resumo

Em muitos processos que consomem energia térmica, o calor gerado pode não ser totalmente utilizado. O armazenamento de energia térmica tem o potencial de armazenar o excedente de energia térmica, e utilizá-la posteriormente para diferentes fins. Os materiais de mudança de fase são usados para armazenar calor latente. Neste estudo analisa-se a integração de um sistema de armazenamento baseado em materiais de mudança de fase com um sistema de aquecimento solar de água. Foi analisado o funcionamento desse sistema considerando diversos configurações: três diferentes materiais de mudança de fase, nomeadamente o acetato de sódio hidratado com grafite, RT60 e Paraffin56; quatro perfis de utilização diferentes de água - um perfil com um pico diário, um perfil de habitação múltipla, o perfil típico para o Reino Unido e o perfil da ASHRAE - foram considerados para analisar o desempenho do sistema de armazenamento para diferentes distribuições de consumo de água; duas configurações de encapsulamento de material de mudança de fase, cilíndrico, esférico; finalmente, três volumes diferentes de material de mudança de fase foram considerados. Para o caso de estudo para um sistema solar térmico na região climática de Lisboa, o armazenamento de forma cilíndrica teve o melhor desempenho, com 20% do volume de material de mudança de fase. A incorporação de materiais de mudança de fase resultou na economia da fatura de eletricidade, pois o tempo de operação do apoio elétrico foi reduzido. Além disso, a pegada de carbono também foi reduzida significativamente. Os resultados mostram que a presença de materiais de mudança de fase no interior do tanque ajuda a manter elevada a temperaturas da água por um longo período de tempo.

Palavras-chave: Material de mudança de fase, armazenamento de calor latente, perfis de água, energia, TRNSYS.

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Nomenclature

$C_{p,s}$	Specific heat capacity in solid phase
$C_{p,l}$	Specific heat capacity in liquid phase
D	Diameter
DP	Double port
D_o	Outer diameter
D_{in}	Inner diameter
E_{heater}	Heating value of electric heater
ERR	Energy recovery ratio
h	Enthalpy
hyst	Hysteresis
HX	Heat exchanger
IAM	Incidence angle modifier
kWh	Kilo Watt hour
K	Kelvin
N	Total number of nodes
p	Time step
p+1	Next time step
PCM	Phase change material
PCMs	Phase change materials
PV	Photovoltaic
Q_{stored}	Energy stored
RT	Rubitherm
sc	Subcooling
SDHW	Solar Domestic Hot Water
STA	Simultaneous thermal analyser
STC	Solar thermal collector
Temp	Temperature
TRNSYS	Transient system simulation
V	Volume
WOPCM	Without PCM
ρ	Density

1. Introduction

In the past few decades, there have been many attempts at global scale to reduce the carbon footprint by integrating the renewable sources of energy with energy production units. Sun is one of the biggest sources of renewable energy and many concentrated solar power plants are already in action in the parts of world having abundant sunshine. The biggest limitation is the duration of sunshine. So, the need of such a system was felt which is reliable and can somehow store the energy to provide following the sunset. Thermal energy storage, also known as the latent energy storage, has emerged as the top contender to add reliability to systems dependent on solar energy. From small scale solar domestic water heating systems to large scale concentrated solar power plants, thermal energy storage has shown promising results. Phase change materials (PCMs) are used for this purpose which can be either organic or inorganic. For high temperature applications, salts (e.g. sodium chloride) are used while paraffin are used for low temperature applications. Organic PCM are economical, easily available and chemically inert.

Now a days, the concept of energy zero building has emerged with a strong conviction. A zero-energy building has carbon footprint equals to zero and is energy efficient. Researches in many countries are underway to find suitable PCMs to integrate them with the buildings according to the local conditions. European countries have decided to reduce the carbon footprint by increasing the energy production from renewable resources in Paris Agreement 2016 [1]. So, lot of funds have been allocated for the research in the field of harnessing energy from renewable resources. Developed countries have been asked to take actions for emission reduction as well. This thesis is also an attempt to reduce the carbon footprint in solar domestic hot water systems (SDHW).

Having a look at energy mix globally, it is evident that countries are using fossil fuels as a major share of their energy mix for energy production which poses great threats to environment. International bodies reserved for environment protection have expressed huge concerns over increment of earth temperature, melting of glaciers, skin diseases due to emissions and environmental pollution. The solution to avoid more pollution is to find means which are clean and doesn’t cause serious health or environmental issues. Renewable energy resources such as solar, wind, hydro have shown strong potential in this regard and they can meet a big share of global energy needs also.

Portugal is one of those European countries where sufficient solar potential is present to meet energy demands. Solar market is also very strong and there are many companies working in the fields of solar PV and thermal. Conditions are also conducive to exploit energy from sun. Solar thermal collectors are used for meeting around 60-80% of hot water needs in Portugal. Rest of 20% is covered by providing energy either from electricity or gas [2].

Thermal energy storage is a promising way to reduce carbon dioxide emissions. Huge energy can be stored in a very small temperature range which can later be released. This phase where energy is stored with minimal change in temperature is called latent phase. Normally phase change materials are used for storing energy. These materials undergo sensible and latent phase to store and release energy. Different materials are meant for different purposes. Most of the time, temperature range of storage defines the type of material to be used. Most commonly available phase change material (PCM) is paraffin wax. Salts such as sodium chloride (NaCl) are used as PCM for high temperature latent storage.

In this master's thesis, a solar water heating system will be integrated with thermal energy storage based on PCMs to see if the presence of PCM affects the temperature inside water storage tank. Four different profiles of water usage have been taken in to account to assess the performance of PCMs. Performance of three PCMs will be assessed.

The main objective of this thesis is to find a suitable PCM according to the weather conditions of Lisbon which can add reliability and sustainability to domestic water heating systems. Side objectives include the investigation of behaviours of different PCM under different water usage profiles and weather conditions. Research questions are related to performance and behaviour of PCMs under different water withdrawal profiles.

It is expected that presence of PCM will help in maintaining a higher water temperature for a longer period of time thus reducing the working of electric heaters which will result in lower electricity bills and carbon footprint. PCM will help in storing heat during the day time and will act as heat source at night.

The results of thesis will be useful for the industry of solar water heating systems. Addition of PCM may lead towards increasing solar fraction of system. Moreover, the determination of suitable PCM according to the climate-based conditions will also be of great help as multiple tasks can be done with the stored heat. In the previous studies, focus was only on determining if latent storage helps in accumulating excessive heat as compared to sensible heat storage. The results of this research would also be applicable in the parts of world where solar irradiation and weather conditions match that of Lisbon and similar water withdrawal profiles are being used.

Recent developments in this field have been mentioned in the literature review section. Research articles have been mentioned regarding solar energy potential. The literature review section has been divided in five subsections. These subsections cover details about the solar potential, solar hot water systems and applications and energy storage with PCMs. Moreover, thermal energy storage is also discussed in detail and developments done in the field of integration of solar thermal and thermal energy storage have been discussed.

The instruments, techniques, software and procedure used have been discussed in detail in the chapter 3 of methodology. All the details from selection of PCMs to TRNSYS simulation parameters have been discussed in 3rd chapter. Details are given about each apparatus used and details of TRNSYS software have also been mentioned. All governing equations are also mentioned in this chapter. Moreover, the criteria made for selection of shape and volume of PCM is also stated. Results and discussion, which constitute 4th chapter, include all the results obtained through simulations via TRNSYS. All important results have been mentioned, discussed and explained. Conclusion and recommendations in chapter 5 consists of a recap of what has been done and learnt in this thesis. Recommendations have been given to improve and validate the simulation model.

2. Literature review

Various studies have been carried out to understand the integration of solar water heating system with PCMs. The researches made in this field have been thoroughly covered in this chapter.

2.1. Solar energy

According to the recent Global Status Report 2018, heating and cooling sector has the highest (48%) share of total energy consumption. Transport and power sectors are ranked second and third with 32% and 20% share respectively. In heating sector, 27% of heating and cooling demand is being met while using renewable energy resources [3]. Sun is one of the biggest sources of renewable energy. In a study carried out by Kannan and Vakeesan, solar energy was termed as a clean and promising source of energy. As energy demand is increasing because of population explosion, it is the need of hour to find cost effective and reliable sources of energy. Harnessing solar energy has become a tool for developing countries to boost and develop their economic status [4].

In general, active solar technology is divided into two more groups: photovoltaic technology and solar thermal technology. In solar PV, sun energy is converted to electrical energy via using thin film cells traditionally made of silicon and germanium. In solar thermal technology, sun energy is harnessed to thermal energy and can be used for commercial and household purposes. Concentrated solar plants have been installed in many countries to generate electricity [5].

The most common applications of solar energy for household purposes are water heating and space heating [6]. During the sunshine hours, the demands can be met easily. After the sunset time, electric heaters come in to action to keep circulating water warm to maintain the temperature at a comfortable level. Therefore, the major challenge is the mismatch of solar energy's availability. There should be an effective energy storage mechanism which absorbs the solar energy when available and dissipate when it's needed [7].

A comparison of power production from different renewable sources has been shown in Table 1 below [8]:

Table 1 Comparison of global power capacity of different renewable energy sectors[8]

Order	**Power capacity (Unit GW)**	**Year**		
		2013	**2014**	**2015**
1	Total Renewable power	1578	1712	1849
2	Hydropower	1018	1055	1064
3	Bio-power	88	93	106
4	Geothermal	12.1	12.8	13.2
5	Solar PV	138	177	227
6	Concentrating solar thermal	3.4	4.4	4.8
7	Wind power capacity	319	370	433

A volatility and uncertainty in the already increasing prices of fossil fuels, increment in greenhouse gas emissions and mismatch between energy supply and demand are the main reasons for which non-conventional sources of energy are being utilized. The main purposes of these newly built system for effectively exploiting energy from renewable resources is to improve the performance of systems, reducing emissions and storing energy to reduce the mismatch between demand and supply. Scientists from many parts of the world stated in their findings that solar radiation is a huge source of clean energy and integrating latent heat storage systems with a solar thermal system can significantly reduce greenhouse gas emissions [9].

2.2. Solar thermal hot water systems

Solar water heating system consists of a solar collector, storage tank, pump and piping for water circulation. For continuous supply of warm water, electric or gas boiler and a controller is also integrated with solar water heating system [10].

There are two main issues pertaining to solar water heating systems; a) high dependency on weather conditions and b) absence of material possessing high latent heat storage density [11], [12]. Solar collectors should have good optical properties so that they can absorb as much heat as possible. A solar collector collects the energy from solar irradiation and heats up the working fluid. The heat absorbed by working fluid can then be used for various purposes. These purposes include warming of house, warming water to meet hot water demands or to melt the PCM for storing thermal energy storage [13].

A general and most common used solar water heating system is given below in Figure 1.

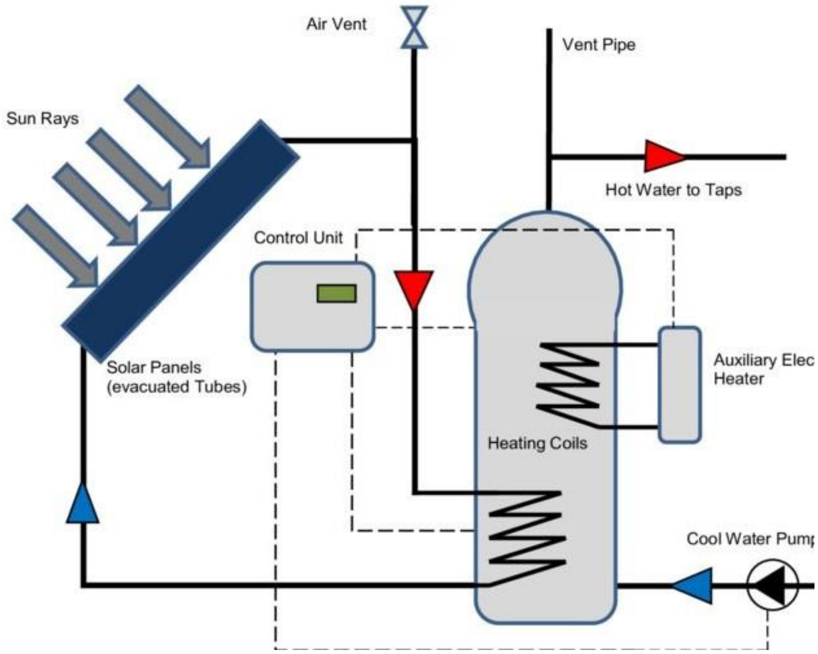

Figure 1 Solar water heating system [14]

The sun emits the energy at a rate of 3.8 x 10^{23} kW. Earth intercepts a portion of this energy which is about 1.8 x 10^{14} kW. Out of the intercepted energy, only 60% is absorbed by earth. Rest of the energy is reflected back in to environment and it is absorbed by atmosphere. In 60 minutes, energy absorbed by the earth is more than the energy consumed in whole world for 1 year. It shows that sun radiation has a lot of potential to exploit. Right now, the solar cells do not have high efficiencies. By improving the efficiencies of solar panels and cells, more energy can be exploited through sun [15].

Most of the energy systems use only water for sensible heat storage. A problem associated with sensible storage systems is their huge size. As a huge mass is required to store enormous heat so, the size of whole system gets big. On the other hand, latent storage has considerable small size as compared to sensible storage. The reason is that even small mass is enough to store a huge amount of heat [16].

2.3. Energy storage and phase change materials

In the recent years, many organic and inorganic PCMs have been discovered. These materials have been used at industrial level too and have enhanced the energy flexibility and energy supply capacity of power production sites. Inorganic salts in the molten form have been used to produce the steam which can then produce electricity by rotating the turbine. These inorganic salts have huge latent heat storage capacities. Concentrated solar power plants are used to melt these salts. During the initial recovery of PCMs, organic materials dominated most of the applications. Now, with the passage of time, inorganic materials are also being used and their use has produced promising effects [12].

Different types of energy storage methods are shown in Figure 2 below.

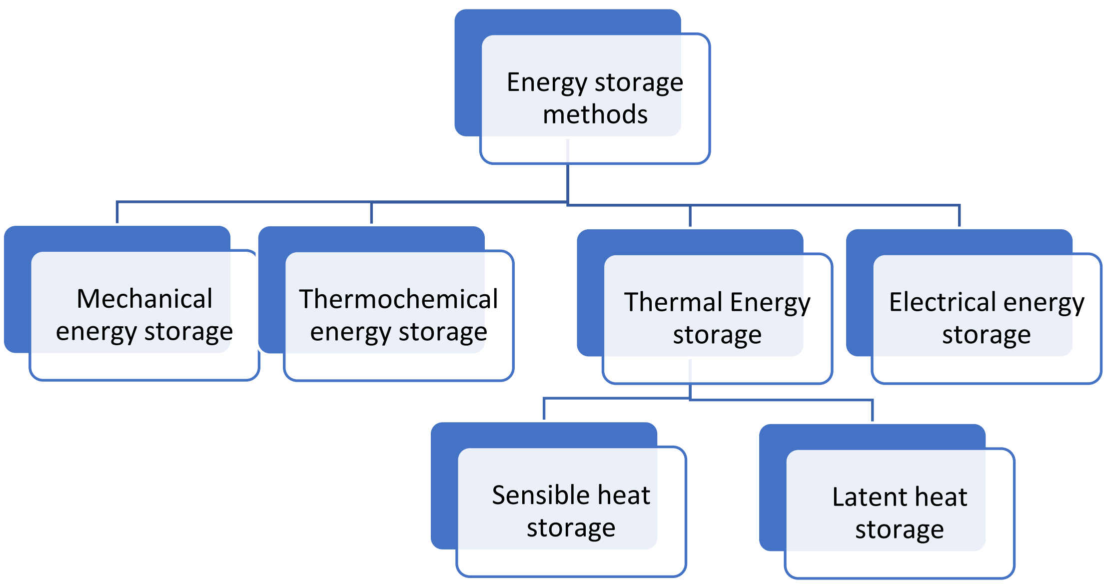

Figure 2 Types of energy storage methods [17]

A PCM is selected based on its use and application. Normally, the factors which are taken into account to determine the compatibility of PCMs are melting point, density, latent heat of fusion, specific heat, thermal conductivity, super cooling, cost and availability, thermal and chemical stability, volume change, toxicity, corrosiveness, flammability, congruent melting and vapour pressure. Selection criteria constitutes of thermodynamic, kinetic, chemical and economic properties. In order to measure thermal properties, differential scanning calorimetry, differential thermal analysis and T-history method are commonly used [17].

Ideally, materials used for latent heat storage should be non-corrosive, non-toxic and economically feasible. The melting temperature should be in the range of application for which PCM is going to be used. For example, for solar water heating system, PCMs used have melting points in the range of 55-60 ºC. Materials used in power plants for boiling water and making steam have melting points in order of 700 ºC and above. Organic salts are used for such purposes [9]. Paraffin wax is a PCM which has been extensively used for latent heat storage. It has a moderate thermal storage density which is around 200 kJ/kg or 150 MJ/m3. It has thermal reliability and stability after 1000-2000 cycles. Its melting range is from -10 C to 67 ºC [18].

PCMs are used because they store a huge amount of energy in a small temperature range. This happens during phase change which is usually between solid and liquid state. Sensible heat storage techniques involve very low cost but energy stored is low as compared to latent heat [19].

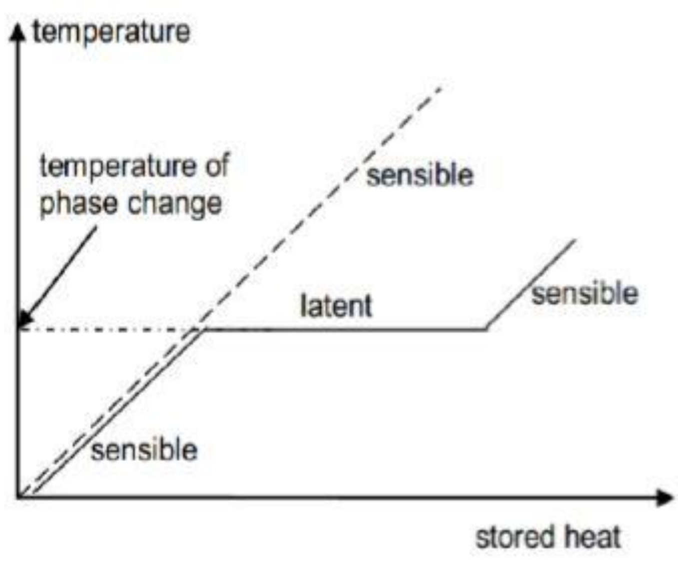

Figure 3 Sensible and latent heat storage depiction for solid-liquid phase change[20]

Pictorial view of sensible and latent heat is shown in Figure 3. Initially, a material starts absorbing sensible heat and as soon as it reaches its melting point, the phase change phenomena starts and latent heat is stored. After this phase change ends, material again starts storing heat in sensible form [20].

Based on phase change state, there are three types of PCMs: solid-solid, solid-liquid and liquid-gas. Solid-liquid PCMs are more suitable for thermal energy storage. Solid-liquid PCMs have further classifications as organic, inorganic and eutectic compounds. Organic compounds consist of paraffin and fatty acids. Inorganic compounds constitute of salt hydrates and metallic. Eutectic group of PCMs consists of organic-organic, inorganic-organic and inorganic-inorganic compounds. The above-mentioned classification is given in Figure 4 below [16].

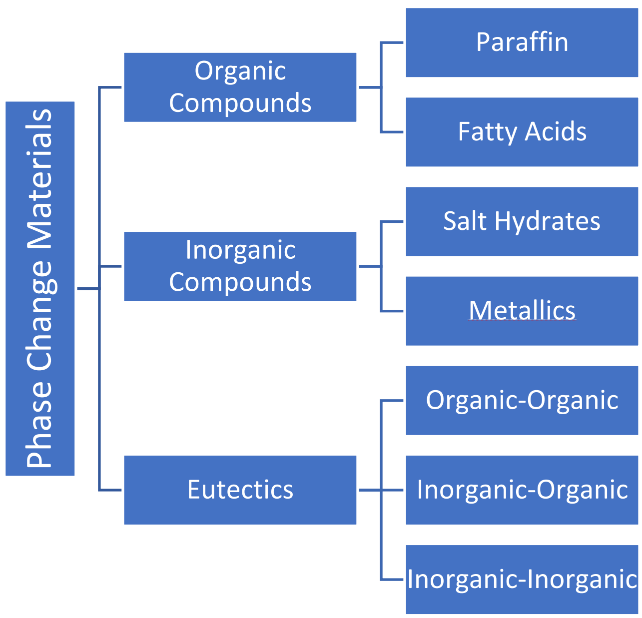

Figure 4 PCM classification [16]

2.4. Thermal energy storage

Thermal energy storage is one of the most efficient means to store solar energy. PCMs are used for this process. These materials can store a lot of energy during phase change. The crucial factors which determine the efficient working of thermal storage are the material selection and encapsulation techniques [21].

Phase change materials can be of different types. Mainly, organic and inorganic ones are used which have their own advantages and disadvantages. Paraffin are mostly used phase change materials because of their easy availability and low cost. A comparison of advantages and disadvantages of organic and inorganic PCMs are given in Table 2 below:

Table 2 Advantages and disadvantages of organic and inorganic PCMs [20]

Organic	Inorganic
Advantages • Non-toxic • Non-corrosive • Chemically and thermally stable • Little sub cooling	Advantages • High heat of fusion • High energy storage density • High thermal conductivity • Low volume change
Disadvantages • Low heat of fusion • Low energy accumulating density • Flammable	Disadvantages • Sub cooling • Corrosiveness • Low cycling stability

One of the drawbacks associated with the phase change materials is the low thermal conductivity. In order to solve this problem, metallic pieces are inserted to increase the heat transfer. Moreover, installing fins or increasing the surface area can also result in high heat transfer rates [21].

In Figure 5, different types of thermal energy storage have been shown. Thermal energy has two distinct branches which are thermal and chemical. Thermal branch has further two branches. So, heat can either be stored in sensible or in latent form.

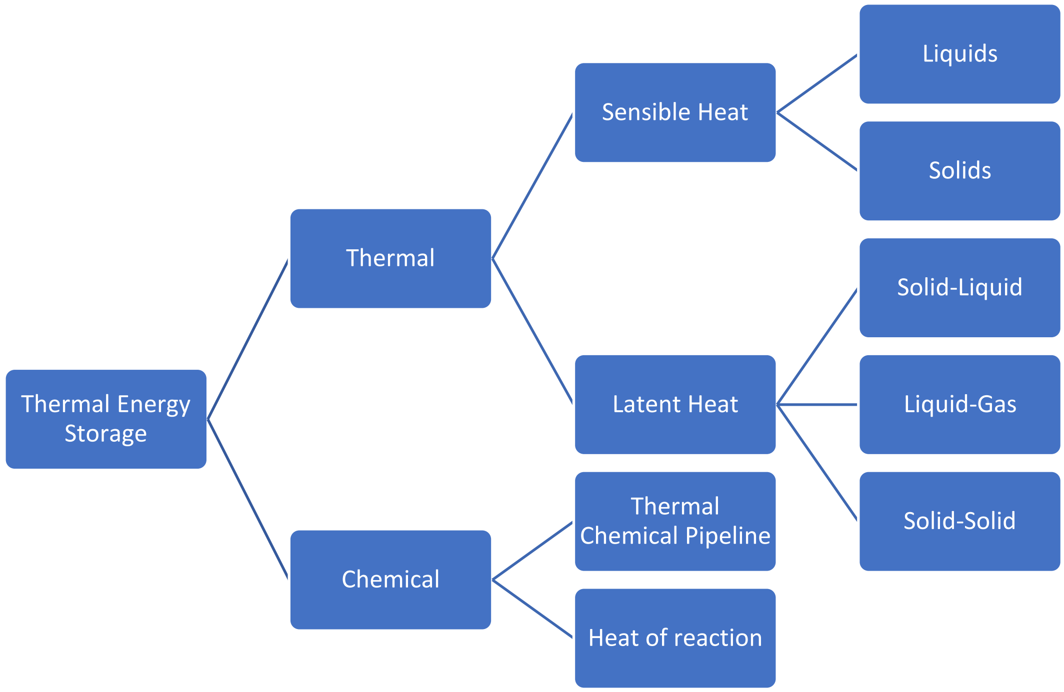

Figure 5 Types of thermal energy storage [16]

2.5. Phase change materials in solar thermal water heating systems

There can be three different ways of integrating solar thermal water heating system (STWH) with phase change materials. First way is to put PCM in flat plate solar thermal collector. The study carried out by Carmona and Palacio found that phase change materials work as a heat source at night [22].

In second design, PCM is placed in water storage tank. Various studies have been made on this design type. It was found that presence of phase change materials keeps water at a higher temperature as compared to when there was no PCM. A masters' thesis carried out by M. Trogrlic, integrated PCM with STWH system. The material used was Sodium Acetate plus Graphite. TRNSYS software was used to carry out the simulations. PCM was placed in cylindrical and spherical form and performance was noted in both cases. Cylindrical encapsulation was selected because of its easy manufacturability. Charging and discharging time was also analysed along with the quantity of heat stored. No physical experiment was made and results were explained on the basis of simulations. It was observed that time needed to charge the storage material in case of water plus PCM was greater than the time needed to charge in case of water only [20].

In third design, PCM and water are stored in different tanks. Parakash et al. conducted a study on an off grid solar water heating system in USA[23]. Three different phase change materials were used to gauge their performance when integrated with water storage tank. These materials included paraffin wax, puretemp68 and eutectic mixture of palmitic and stearic acid. The eutectic mixture of palmitic and stearic acid outperformed the other two phase change materials in terms of charging and discharging efficiency and homogeneous heat distribution in storage tank while Paraffin wax showed the significant Energy Recovery Ratio (ERR) compared to other two materials. Separate PCM and water tanks were used to carry out the experiments. Phase change materials' charging and discharging graphs have been shown in the research paper and will be of great help during conducting this masters' thesis [22].

Seddegh et al. studied the thermal behaviour of PCM in a shell tube heat exchanger. It was concluded that horizontal distribution of storage tank is superior as compared to vertical one based on the thermal performance. In horizontal orientation, convective heat transfer has the major share in melting PCM. In vertical orientation of storage tank, convective heat transfer was responsible for entire charging process. Moreover, it was also observed that increment in heat transfer fluid results in reduced charging time of PCM [24].

Asgharian and Baniasadi studied the modelling and simulating methods of integrating PCM with solar thermal. All the methods were extensively analysed through numerical, mathematical and thermodynamic approaches. It was concluded that 1D models have more accurate results as some factors such as quality and sizing of mesh, boundary conditions and assumptions made for simplifying the situation can affect accuracy in 2D and 3D models. Numerous methods of simulations were discussed along with their applications, model dimensions and maximum percentage error [25].

Manuel et al. performed an experiment along with simulation of water tank including PCM. A TRNSYS component called Type 60PCM was used for simulations. TRNSYS software was used for carrying out simulations. The results obtained from experimental and simulated results were very coherent and consistent. The results obtained showed that energy storage density increases when PCM is incorporated in the storage tank. Charging and discharging processes were done and PCM effect was very visible. In the simulation work, phase change material’s hysteresis behaviour wasn’t taken in to account. Modules used for PCM were cylindrical in shape [26].

Another similar study carried out by Luisa et al. at University of Lleida to test the behaviour of PCM in real life conditions. The PCM modules were cylindrical in shape and they were placed at the top of water tank. Hot water is present at the top of tank because of density difference and it can help in fast charging of PCMs. With the presence of PCM, a drastic increase in energy density was observed from the results. Three different volumes of PCM which were 2.05%, 4.1% and 6.16% volume of tank of tank. The results also showed that inclusion of PCM allows to have water at higher temperatures for a longer period of time [27].

3. Methodology

The work included simulations and experimental work. Thermal properties of phase change materials were obtained with the help of thermal analyser. The instructions and technique used for thermal analyser have been mentioned in detail in coming sections. All the water usage profiles taken in to account for this thesis have also been mentioned along with diagrams for better understanding. An overview of TRNSYS software is also given and important details have been stated. Simulation parameters and criteria for selecting shape and volume of PCM are also explained in this chapter. Method used to calculate financial savings and reduction in carbon footprint is also explained.

3.1. Selection of phase change materials

It is recommended to keep water at 60 ºC because Legionella bacteria can't survive and grow at this temperature. This bacterium can cause fatal pneumonia if comes in contact with human skin [28]. As the recommended temperature of domestic hot water systems is 60 ºC, so phase change materials with melting temperature around 60ºC were required [29]. Three phase change materials have been selected out of which two materials are organic while one is inorganic. These materials are RT60, Paraffin56 and sodium acetate with graphite. These materials have been selected because their melting points are in range of 55-60 ºC. Thermal properties of these materials have been given below in detail. For latent storage purposes, materials with high latent storage capacity are used. The melting temperature should lie in the range of operation. Materials should exhibit minimum subcooling and hysteresis. Moreover, phase change materials used for such purposes should be chemically stable, non-corrosive and easily available. Besides, the life and cycles for which these materials can work should also be considerably high. All these characteristics were kept in mind while selecting the phase change materials for incorporating them with domestic solar water heating system.

3.1.1. Sodium acetate trihydrate with graphite

It is an inorganic phase change material having its melting point around 58 ºC. The latent heat of fusion is almost 204 kJ/kg. Actually, latent heat of fusion for sodium acetate is as high as 260 kJ/kg but addition of graphite particles has resulted in decrease of enthalpy. Moreover, addition of graphite in the powdered form has also made this phase change material less dense as density has decreased from 1400 kg/m^3 to 1100 kg/m^3. Graphite has been added to increase the thermal conductivity. Low thermal conductivity is the biggest limitation of phase change materials. It results in slow charging and discharging. Addition of metallic particles, graphite or any other suitable materials helps in increasing the thermal conductivity. This PCM-graphite compound has 90% volume of sodium acetate trihydrate and 10% volume of graphite. This specific phase change material showed sub-cooling as evident from curve shown below in Figure 6.

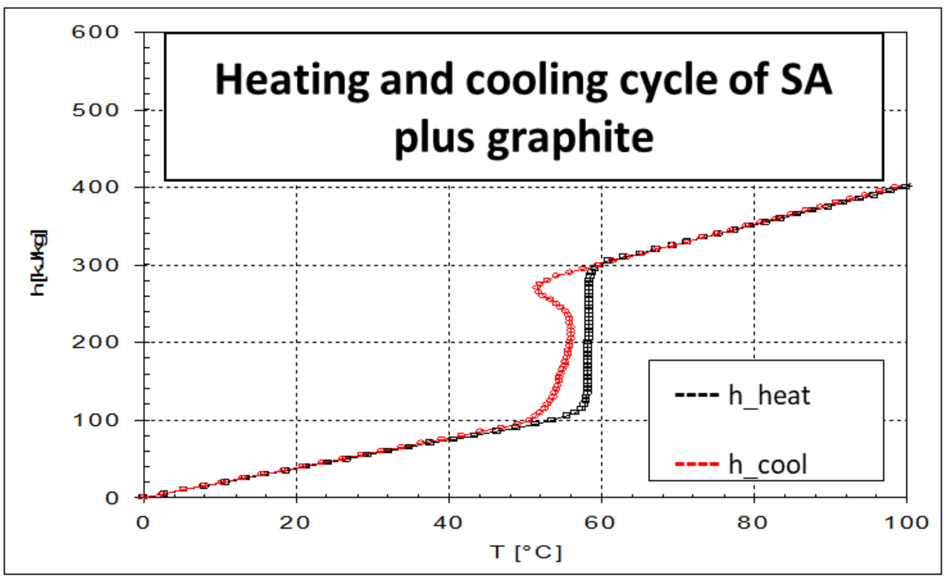

Figure 6 Heating and cooling curve of SA plus graphite [30]

3.1.2. RT 60

One of the PCMs used i.e. RT 60 has been developed by Rubitherm. Rubitherm is a company from Germany which makes PCMs for different applications. These applications include buildings, food and beverages, healthcare and medical, logistics, industry and automotive. It provides organic and inorganic PCMs based on specific product solutions. For SDWH system, latent storage should be in the range of 55-60 ^{0}C. As evident from name, the PCM melts at 60 ºC. The latent heat of fusion is almost 160 kJ/kg [31].

The heating and cooling curves have been shown below in the Figure 7. Both curves are built with the help of datasheet provided by Rubitherm. As the values of enthalpy for heating and cooling are very close to each other, therefore both curves are overlapping each other for complete temperature range. For more details of this PCM, datasheet is present in annex.

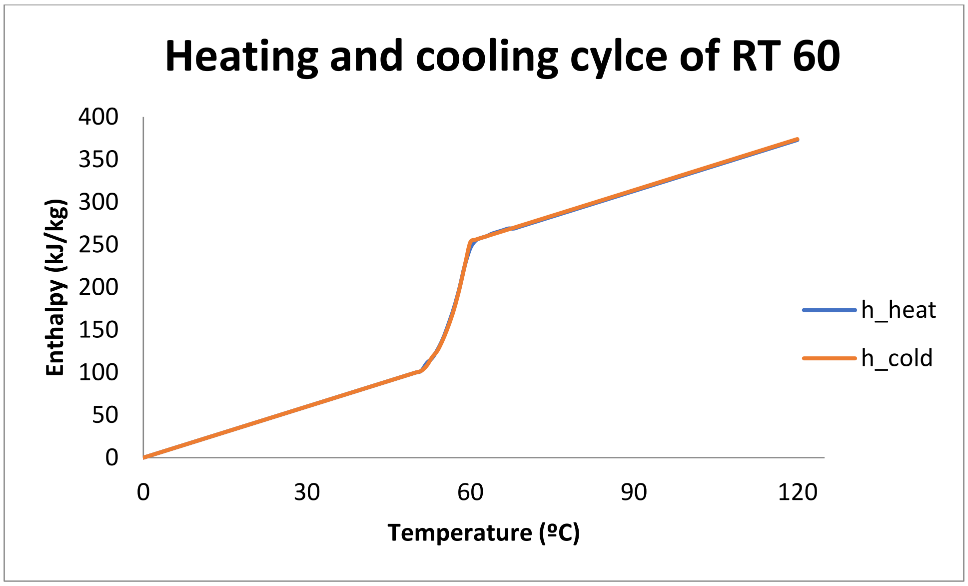

Figure 7 Heating and cooling curve of RT 60

3.1.3. Paraffin 56

Third PCM which has been used is Paraffin 56 ordered online from Gran Velada, an online store based in Spain. As evident from name Paraffin 56, its melting point is around 56 ºC. Normally, paraffins have a melting range instead of a sharp melting point. The reason is that paraffins are a mixture of a range of carbon numbers. According to the data provided, the paraffin under consideration is a complex amalgam of hydrogenated straight chain paraffinic hydrocarbons with carbon numbers approximately in the range of C20 to C50 [32]. Pure paraffins are highly expensive. It is low quality paraffin which is used to make candles or wax sculptures. Pictures of Paraffin56 are shown in Figure 8. The paraffin ordered, refer to figure 8(a), was in beads shape as shown in figure 8(b).

(a) (b)

Figure 8 (a) Paraffin 56 packaging (b) Physical beads form of Paraffin 56 [32]

Paraffin is preferred over other materials because of its easy availability and low cost. This material is non-flammable and non-corrosive. Moreover, it is chemically inert and undergo little sub-cooling.

Experiments were run in thermal analyser to obtain enthalpy vs temperature curve. Phenomena of hysteresis also occurred during melting and cooling cycles of paraffin 56. Results show that melting starts around 40 ºC up to 80 ºC. There are at least three clear melting points – around 50 ºC, around 60 ºC and around 63 ºC. These are consistent with paraffin between C20 (icosane) and C30 (triacontane). Solidification starts immediately but more significantly below 55 ºC. The latent heat of fusion is almost 244 kJ/kg. During simulations, it was observed that PCM temperature does not go above 70 ºC. Therefore, in adjusted results shown in Figure 10, melting has been considered only up till 68 ºC and it has been assumed that material will absorb sensible heat later on.

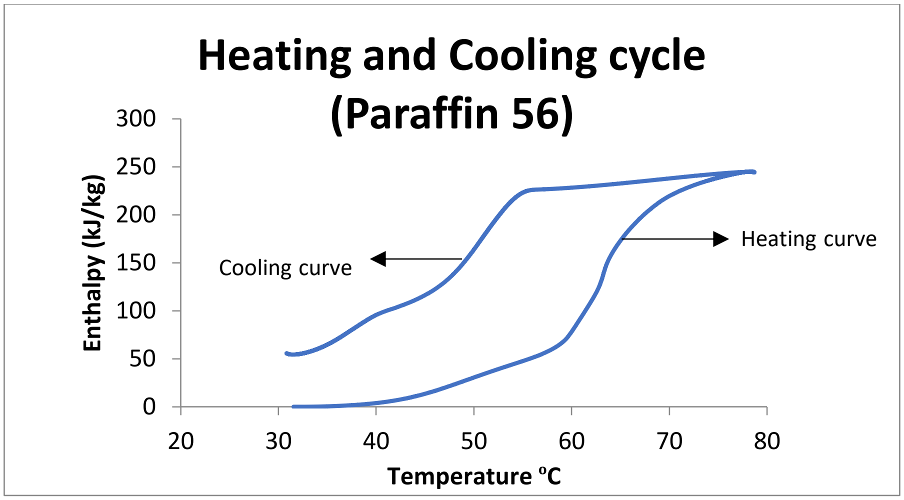

Figure 9 Heating and cooling curve of Paraffin 56

Figure 9 and Figure 10 show the heating and cooling curve of Paraffin56. For TRNSYS, an ASCII file is required for running simulations for TYPE 840 which is a PCM storage tank. For ASCII file, data range is from 0 ºC to at least 115 ºC.

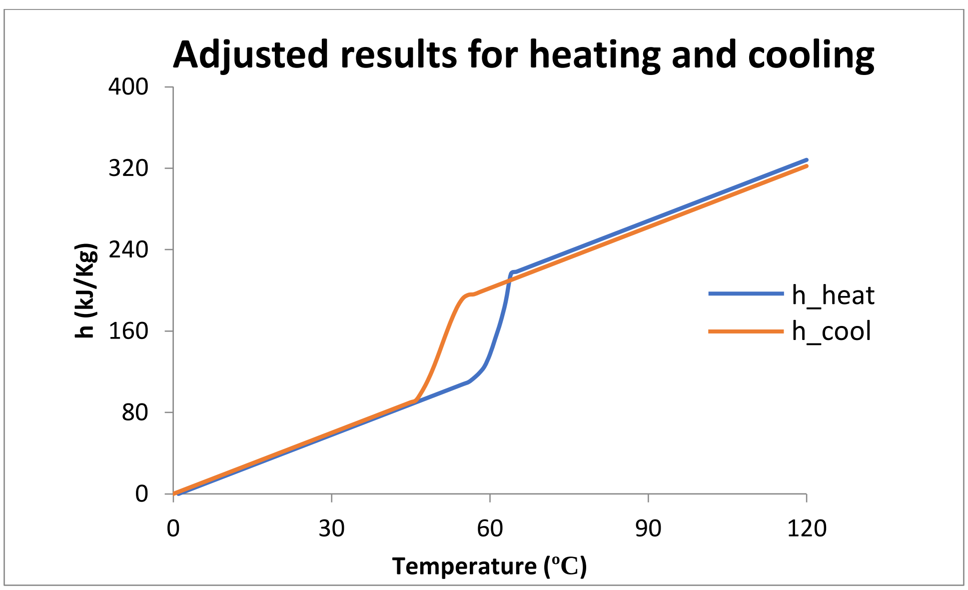

Figure 10 Adjusted heating and cooling curve of Paraffin 56

3.2. Thermal analyser

Thermal analysers are instruments that examine change in materials related to heat e.g. freezing and boiling temperatures, heat of fusion and vaporization etc. Properties of materials are studied as a function of temperature. Temperature profile is predetermined and sample is continuously measured. STA 6000 thermal analyser was used for carrying out tests on PCM. STA stands for simultaneous thermal analyser. Perkin Elmer is the manufacturer of this analyser [33]. A sample of 20 mg is taken and placed in an Alumina pan. Alumina is a ceramic material and can sustain high temperatures. Its melting point is 2000 ºC. The weight of pan used is 167.6 mg. The software associated with thermal analyser is PYRIS. The name of the file is stored by following a standard method that is “Date - Material Name - Highest Temperature - Lowest Temperature - Gas Injected”. So, the name of file is 08-05-2019-Paraffin-80-10-N2. Pictures of STA 6000 has been shown in Figure 11. Pan holder for putting sample and thermal analyser have been shown in figure 11(a) and (b).

(a) (b)

Figure 11 (a) Pan holder (b) Thermal analyser STA 6000 [33]

The features of STA 6000 have been given in Table 3 below:

Table 3 Salient features of STA 6000 [34]

Specifications	
Maximum temperature	1000 ºC
Minimum temperature	15 ºC
Model name	STA 6000
Technology type	Thermal Analysis
Portable	No
Instrument control	Pyris software
Weight	12-16 kg
Dimensions	(HxWxD) 17 x 38 x 41 cm
Accuracy of calorimetric data	±2% based on metal standard
Temperature accuracy	< ±0.5 ºC

Following instruction were given to carry out tests on thermal analyser.

1- Hold for 10 minutes at 30 ºC. Stabilization takes place while the system is on hold. During stabilization, nitrogen is injected inside and air is removed. The nitrogen is injected with a flowrate of 20 ml/min.
2- Heat from 30 ºC to 80 ºC at 10 ºC per minute.
3- Hold for 10 minutes at 80 ºC.
4- Cool from 80 ºC to 30 ºC 10 ºC per minute.
5- Hold for 10 minutes at 30 ºC.

Figure 12 shows the window of software file. All instruction can be seen.

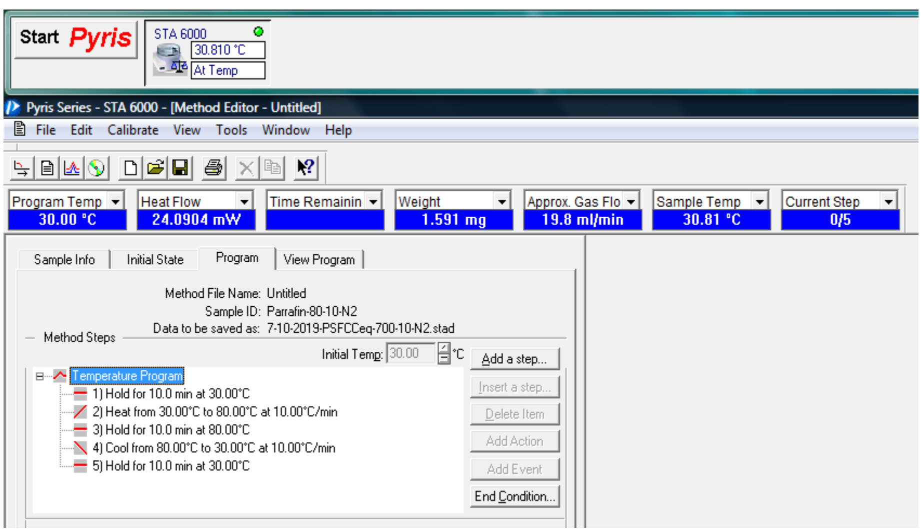

Figure 12 Operation instructions in software

3.3. Water withdrawal profiles

Water withdrawal profile is defined as a trend developed on the basis of the tendency of users to consume water. Profile depends a lot on the lifestyle of a family. Moreover, different countries have different profiles because of climatic conditions. In summer, the amount of water used for drinking and taking a bath is much higher as compared to winters. So, after years of research, these trends of using water were taken in to account and profiles were built. In this thesis, four profiles will be used to assess the performance of phase change materials (PCM). As the water withdrawal is different in different hours of the day for these profiles, so it will surely affect the charging and discharging time of PCM.

Simulations and all calculations have been done to meet the demands of a household having four people. According to European standards, a person utilizes 150 litres of water per day. It includes usage of water in drinking, laundry, cleaning purposes and in toilets. As far as hot water needs are concerned, 40 litres are used by one person on average. Here for the sake of safety factor and building a conservative design, 50 litres have been considered as daily consumption of water per person. So, a water tank with 300 m^3 has been considered. Four user profiles taken in to account for simulations are as follows:

a. Daily peak profile

b. Multi-dwelling profile

c. ASHRAE profile

d. UK profile

All of these profiles have been taken from Vela Solaris Polysun software [35]. The water withdrawal as a function of time for all these profiles has been shown in Figure 13 below.

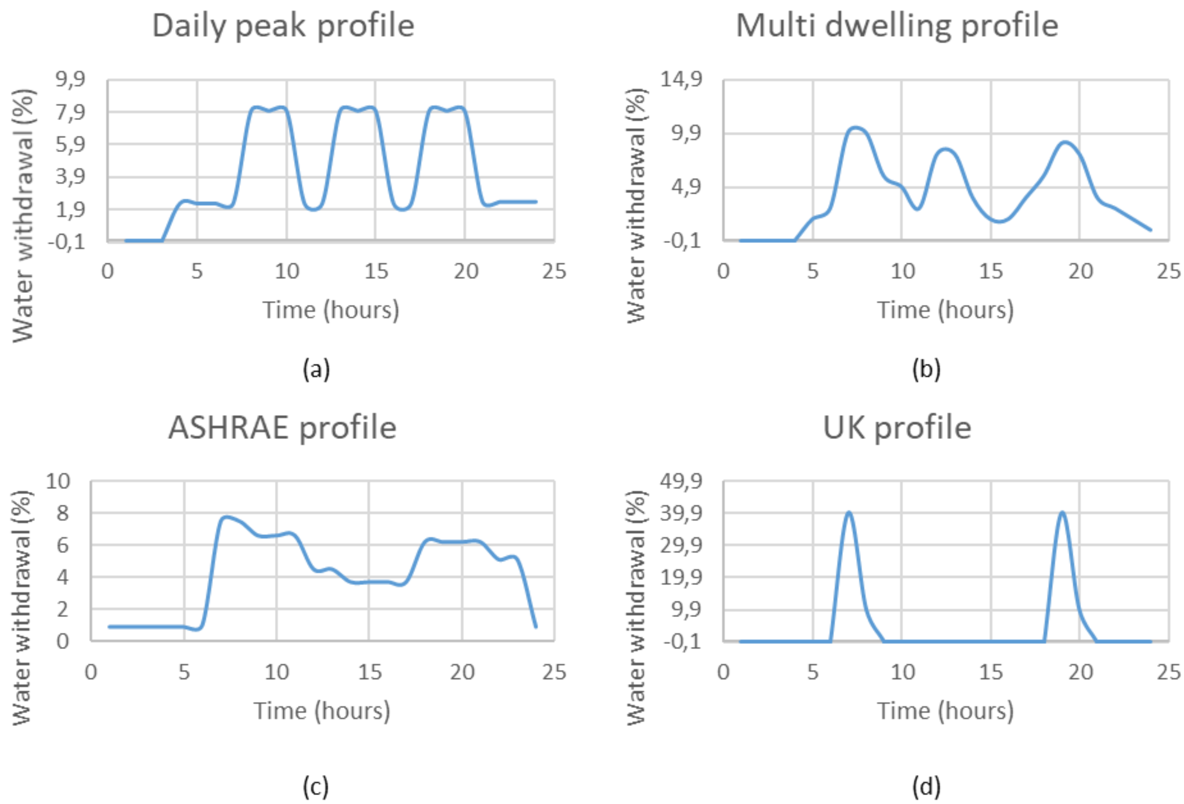

Figure 13 Water withdrawal profiles (a) Daily peak profile (b) Multi dwelling profile (c) ASHRAE 90.2 (d) UK profile

3.4. Software simulations

3.4.1. TRNSYS overview

For simulations, TRNSYS software has been used. The mentioned software is being used for different transient systems. In fact, TRNSYS word is taken from 'Transient Systems'. The major use of this software is to assess the performance of different thermal and energy systems but it can also be used for diverse purposes i.e. traffic flow or processes related to biology. It is a highly flexible software and results can be obtained graphically [36].

TRNSYS has two parts which get the job done. First part is called 'kernel' that reads the input files and solves the system iteratively. It looks for convergence of solutions and thus plots the selected system variables. The second part of TRNSYS is its library of extensive components which has models ranging from HVAC to thermal storage equipment, weather analysers to heat exchangers and pumps to multi zone buildings. The library consists of almost 150 components. Another great feature of TRNSYS is that new models can be built according to the requirement and can be integrated with it [37].

The models of TRNSYS libraries and some non-standard models are mostly written in FORTRAN language. Users can also make the models while using the languages C, C++ or any other language which has a compiler being able to make a DLL. TRNSYS has a wide users' range which includes researchers, students, consultants, engineers and simulation experts [38].

3.4.2. TRNSYS components

All important TRNSYS components have been explained below. These components include solar collector, water storage tank, controller, weather file, electric heater and load profile. Figure 14 which is given below shows the simulation setup.

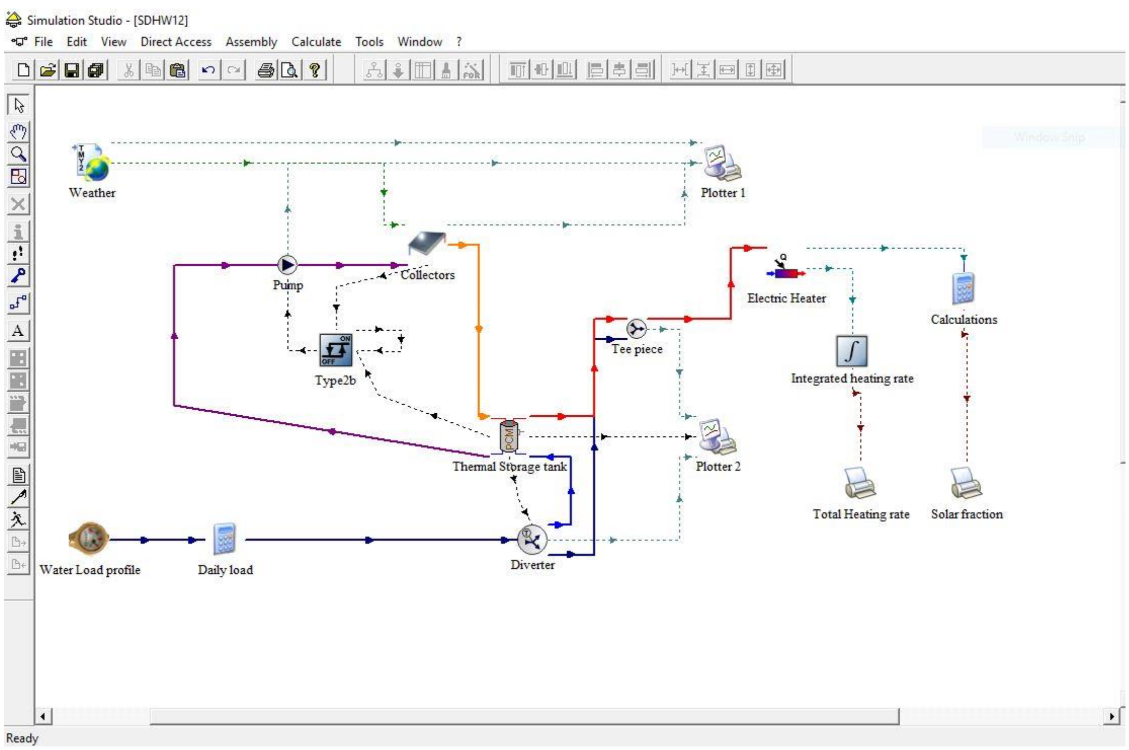

Figure 14 Schematic diagram of whole simulation setup

3.4.3. Solar collector

The used solar collector is an Insuatherm Al AP S.I.2000 with a total absorber surface of 5 m^2. The flow rate in primary circuit of the solar collector field is independent of the number of persons. The value for flowrate is usually taken as 0.02 kg/(s.m2) according to the test standard ISO 9806:2017 [39]. The parameters used for simulation in TRNSYS are given in Table 4 below.

Table 4 Simulation parameters of solar thermal collector for TRNSYS software

Parameters	Value	Units
Number of collectors	1	-
Collector area	5	m^2
Tested flow rate	0.02	kg/s.m^2
Intercept efficiency	0.78	-
Efficiency slope	4.05	W/m^2.K
Efficiency curvature	0.022	W/m^2.K^2
1st-order IAM	0.254	-
2nd-order IAM	0.029	-
Ground reflectance	0.2	

3.4.4. Water storage tank

Type 840 water tank is used for simulations of PCMs. Andreas Heinz and Hermann Schranzhofer at Institute of Thermal Engineering, TU Graz, Austria within the framework of European Project PAMELA (2004) and IEA SHC TASK 32 developed this tank called Type 840 [30]. This tank provides a model for transient simulation of water along with PCM modules having different geometries (spheres, cylinders and plates) or tanks full of a PCM slurry. The details of modules geometry include length, diameter and wall thickness of storage container and are given by user.

As the thermal properties of PCM change with temperature and a careful analysis of latent heat of fusion is required, because it is accounted for modelling, a theoretical approach has been adopted. For this storage model, enthalpy approach of Clauben and Visser is used in which enthalpy is a continuous function of temperature [40].

3.4.4.1. Governing equations

The basic equation for energy accumulation for PCM is as follows:

$$Q_{stored} = m[C_{p,s}(T_s - T_i) + X\Delta h + C_{p,l}(T_f - T_l)] \quad (1)$$

where $C_{p,s}$ is specific heat of PCM in solid phase, $C_{p,l}$ is specific heat in liquid, T_s is melting temperature, T_i is initial temperature of PCM and T_f and T_l are final and liquid temperatures of PCM. X is melting fraction and can be calculated according to formula given below:

$$X = \frac{T - T_s}{T_l - T_s} \tag{2}$$

where T_s <T <T_l and T is temperature of PCM in phase change state.

The model for water storage tank is implemented as a multi-node storage model where nodes are obtained by dividing the storage in vertical direction as shown in Figure 15. Whole storage volume is divided in to N horizontal nodes with each storage node (j) categorized by enthalpy h_j, temperature T_j and mass m_j. The energy balance equation to find temperature T_j and enthalpy h_j of any node is as follows:

$$m_j \ \frac{{h_j}^{P+1} - {h_j}^{P}}{\Delta t} = \dot{Q}_{dp}^{P} + \dot{Q}_{hx}^{P} + \dot{Q}_{aux}^{P} + \dot{Q}_{cond}^{P} + \dot{Q}_{loss}^{P} + \dot{Q}_{module}^{P} \tag{3}$$

The left side of equation 1 demonstrates the evolution of enthalpy from one time step (P) to next time step (P+1) where Δt is the size of time step. The right side of equation expresses heat flows in and out of a respective node. The term $\dot{Q}_{dp}^{P}$ denotes the heat flow through the double port of tank, $\dot{Q}_{hx}^{P}$ symbolises heat flow through internal heat exchanger, $\dot{Q}_{aux}^{P}$ represents the heat flow through inbuilt auxiliary electric heater, $\dot{Q}_{cond}^{P}$ represents the heat conduction to adjacent storage nodes, $\dot{Q}_{loss}^{P}$ denotes the losses to ambient and $\dot{Q}_{module}^{P}$ denotes heat exchange with built-in PCM modules.

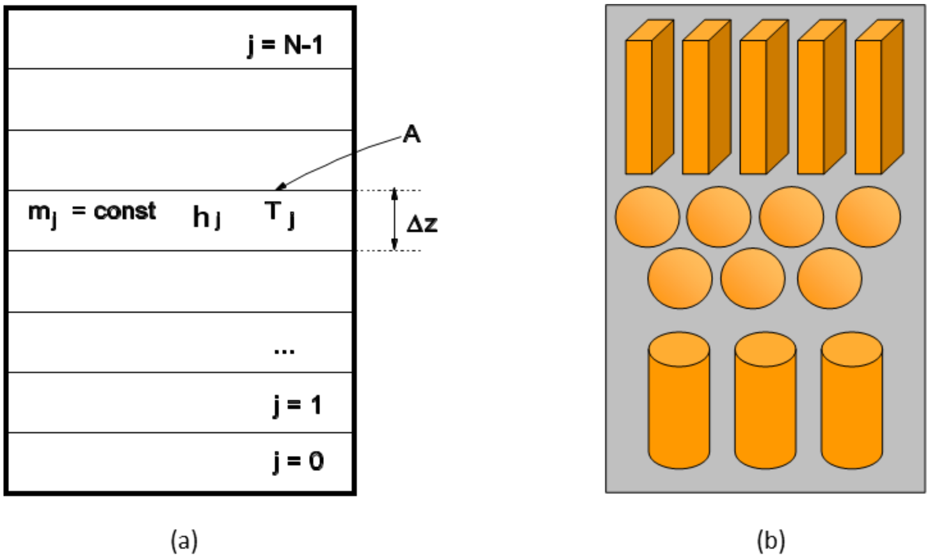

Figure 15 (a)Multi node storage model with N nodes having height Δz and top and bottom cross sectional area A; the node (j) has mass mj , enthalpy hj and temperature Tj (b) Storage tank with three possible geometries; plates, spheres and cylinders

Explicit approach is used to determine the evolution of enthalpy with the time as follows:

$$h_j^{\,P+1} = h_j^{\,P} + \frac{\Delta t}{\mathrm{mj}} \sum \dot{Q}^P \qquad (4)$$

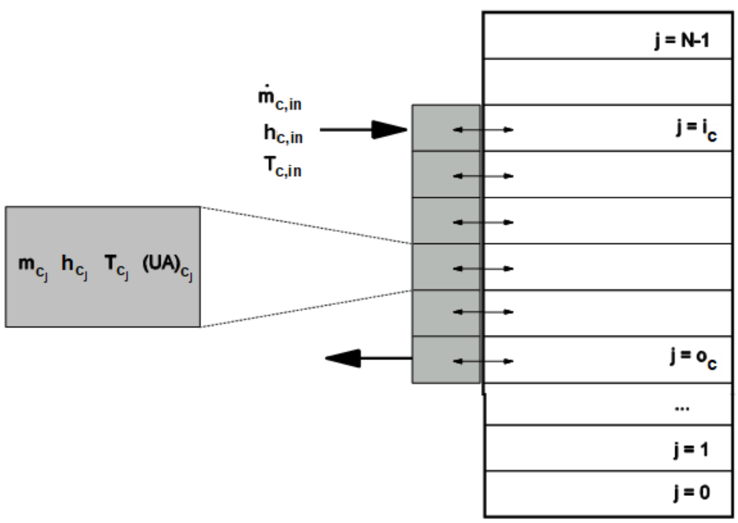

Figure 16 Nodal network of an internal heat exchanger; inlet is located at ic, the outlet at oc

The storage tank model allows up to five double port hydraulic connections. One hydraulic connection is used and cold water is withdrawn according to the water usage profile. The option for internal heat exchanger is also available as shown in Figure 16. The inlet of heat exchanger is connected with the outlet of solar thermal collector in this study. So, hot water is circulated through heat exchanger and it flows towards pump to carry on the cycle. Maximum of five heat exchangers can be used. Heat exchangers are also subdivided into several nodes with a certain temperature, mass and enthalpy.

Heat flow is calculated as

$$\dot{Q}_{hx,j} = \sum_{c} (UA)_{c,j} \, (T_{c,j} - T_j) \tag{5}$$

where heat transfer per temperature difference between the storage node (j) and corresponding node of the heat exchanger (c) is denoted as $(UA)_{c,j}$.

The model calculates the heat transfer between PCM modules and storage fluid. It also calculates the heat transfer inside PCM module by conduction and phase change process. A pictorial demonstration of a cylindrical PCM module is given in Figure 17 below.

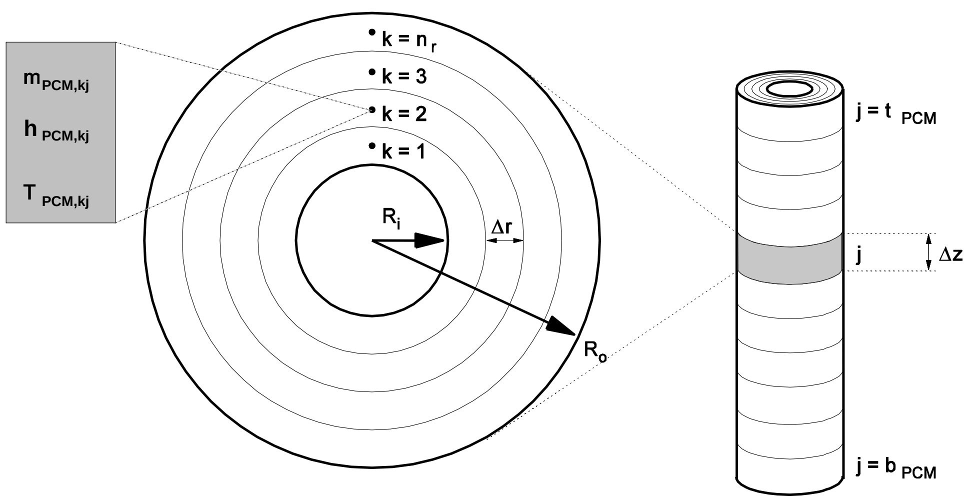

Figure 17 A cylindrical PCM module with vertical nodes (j) and radial nodes (k)

Water storage tank with PCM modules have been shown in Figure 18 below. Position of temperature sensors can also be seen.

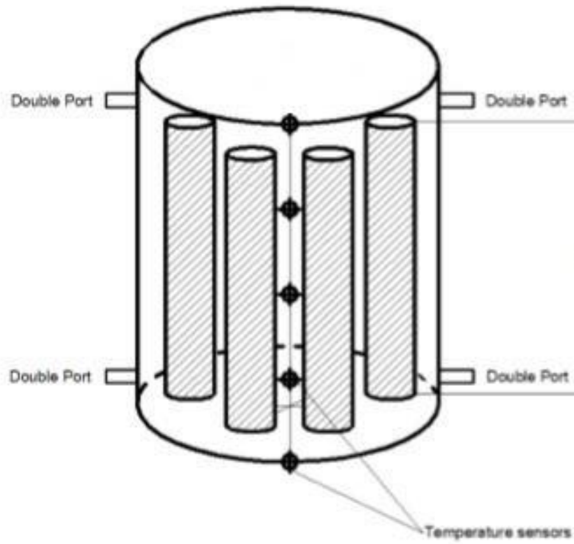

Figure 18 Type 840 storage tank with PCM modules

The geometry of tank and the height of its ports have been shown below in Figure 19. The total height of tank is 1.4 metres. The dimensions given in Figure 18 and Figure 19 are in millimetres. Two double ports have been used. One port is for heat exchanger which releases heat inside and other double port is for cold water to enter and hot water to leave.

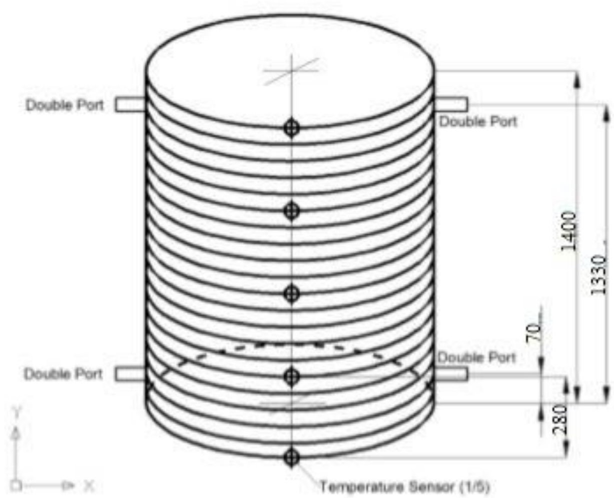

Figure 19 Storage tank with dimensions of double ports and thermocouples

In Figure 20, position of temperature sensors is mentioned. These temperature sensors can be installed along the height and radius of PCM module. A module is divided in to radial and vertical nodes. So temperature sensors can be installed in the centre and on surface of module. These sensors were installed at different heights to analyse the charging and discharging of PCM.

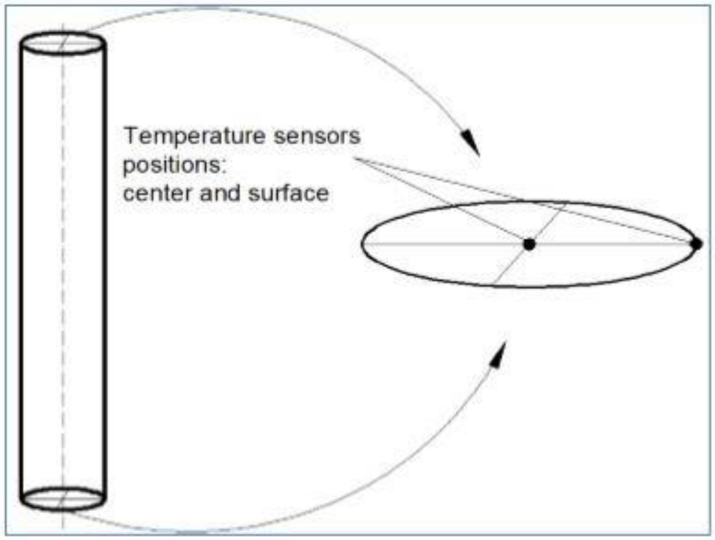

Figure 20 Thermocouples position on PCM module

3.4.4.2. ASCII data files

In order to carry out the simulations, thermal properties of PCM are first written in an ASCII file and then uploaded in the TRNSYS software. ASCII files have certain conditions which should be fulfilled in order to successfully obtain results e.g. the data should be provided from 0 ºC and must reach up to 115 ºC at least. Maximum of hundred values can be provided. Moreover, even if there is no PCM storage inside tank, these files need to be made available in order to carry out simulations. The files for heating and cooling cycles must end with an extension "_heat" and "_cool" respectively. These files contain five rows having data of enthalpy (J/Kg), density (kg/m^3), thermal conductivity (W/mK) and dynamic viscosity (N.s/m^2) as a function of temperature (ºC). An example of ASCII file is given in Figure 21.

Properties of phase change materials, taken in to account, are extensively read courtesy results obtained from thermal analyser. Sodium acetate showed sub-cooling phenomena while in RT60, sub-cooling is not so significant. Moreover, paraffin are not pure so instead of having a sharp melting point, they have a melting range. All these factors are taken in to account while making an ASCII file.

Material data (h, ρ, λ, μ)

#Temp[°C]	h[J/kg]	rho[kg/m^3]	lam[W/mK]	mu[N s/m^2]
0.00	0.0	996.0	0.25	21.4237e-3
5.00	18837.5	994.0	0.25	18.2852e-3
10.00	37675.0	992.0	0.25	15.5937e-3
15.00	56512.5	990.0	0.25	13.3047e-3
20.00	75350.0	988.0	0.25	11.3758e-3
35.07	132450.0	978.0	0.25	7.35698e-3
40.06	153440.0	974.0	0.25	6.48641e-3
45.02	175880.0	969.0	0.25	5.7955e-3
50.06	201890.0	961.0	0.25	5.25449e-3
51.06	207330.0	959.4	0.25	5.17075e-3
52.12	213010.0	957.8	0.25	5.08700e-3
53.08	218210.0	956.2	0.25	5.00326e-3
54.07	223610.0	954.6	0.25	4.91951e-3
55.04	229130.0	953.0	0.25	4.83577e-3
56.12	235610.0	950.0	0.25	4.77138e-3
57.06	241460.0	947.0	0.25	4.70698e-3
58.11	248290.0	943.0	0.25	4.64259e-3
59.05	254460.0	940.0	0.25	4.57819e-3
60.09	261700.0	938.0	0.25	4.5138e-3
61.08	269040.0	935.0	0.25	4.46408e-3
62.11	276640.0	932.0	0.25	4.41435e-3
63.15	283590.0	929.0	0.25	4.36463e-3
64.05	287960.0	928.5	0.25	4.31490e-3
65.28	292940.0	928.0	0.25	4.26518e-3
70.00	311250.0	925.0	0.25	4.06861e-3
80.00	348920.0	919.0	0.25	3.757e-3
100.00	424270.0	907.0	0.25	3.05588e-3

Figure 21 Example of a material data file [30]

3.4.4.3. Subcooling and hysteresis of PCM material

Many PCMs undergo sub cooling and hysteresis. So, considering both these phenomena is necessary to have realistic results. Subcooling means that material does not crystallize at its melting temperature but at a temperature, which is considerably low. After the material undergoes crystallization, temperature starts to increase and latent heat is set free until it reaches its melting temperature. For some materials, latent heat is set free at a temperature slightly below its melting temperature. Both the effect and temperature difference between this temperature and melting temperature are called as hysteresis. Enthalpy vs temperature graph shown in Figure 22 below depicts subcooling and hysteresis of a PCM as ΔT_{sc} and ΔT_{hyst}. [30]

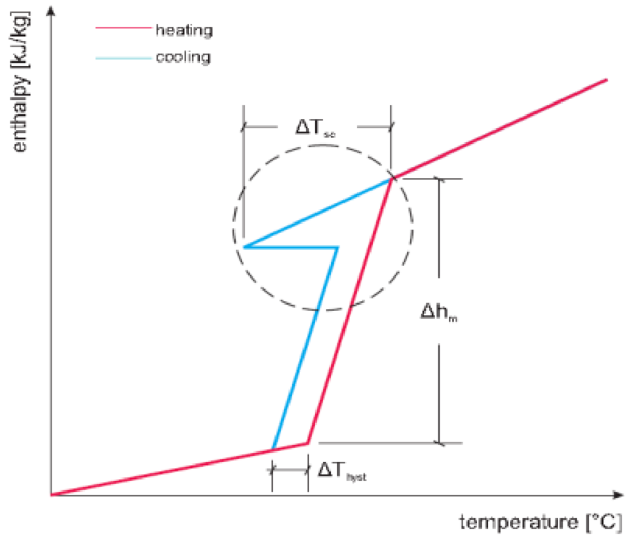

Figure 22 Example of subcooling and hysteresis of a certain PCM

The approach used to model the effects of subcooling and hysteresis is shown in Figure 23 below. If the temperatures of all nodes of PCM module is higher than $T_{critical\ 2}$, module is considered to be fully melted. If temperature of any node of a module falls below $T_{critical\ 1}$, the transition from cooling to heating function takes place. All PCM temperatures are increased to the temperature with the same enthalpy on heating function (corrected by ΔT_{hyst}) [30].

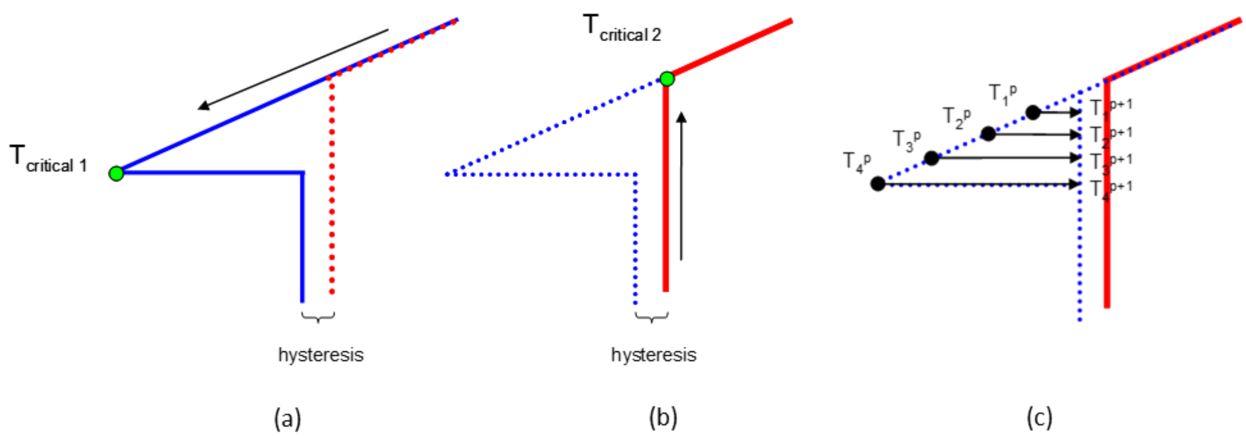

Figure 23 (a) and (b) Critical temperatures for transition between enthalpy-temperature function for heating and cooling (c) Transition from cooling to heating function (corrected by hysteresis) from time step (p) to time step (p+1)

In this thesis, three volumes of PCM are used i.e. 10%, 20% and 30%. Modules can be cylindrical or spherical. To calculate the diameter of a cylindrical PCM module, following equation is used:

$$D = \sqrt{\frac{4V}{N\pi h}} \tag{6}$$

In above equation, 'V' represents the volume of PCM, 'D' is diameter and 'h' is height of PCM module. 'N' represents the total number of modules.

In case of spherical models, the equation used is as follows:

$$D = \sqrt[3]{\frac{6V}{N\pi}} \tag{7}$$

Total number of modules are selected to be 8. The diameters of modules for different volumes of PCM are given in the following Table 5:

Table 5 Diameter of modules against respective PCM volume

Volume of PCM (10%)	Diameter of cylindrical modules (mm)	Diameter of spherical modules (mm)
10	63.1	193
20	89.2	243
30	110	278

3.4.5. Weather file

Weather file of Lisbon for Meteonorm was used. This file is available in the library of TRNSYS. The Meteonorm weather file of Lisbon, Portugal has been used for all the profiles in question. The intent is to gauge the performance of different PCMs for each profile while taking into account the weather of Lisbon. Meteornorm has a library in TRNSYS and weather files of all big cities of world are available. The type of weather file is Type109-TMY2.

3.4.6. Electric heater

Electric heater keeps water at 60 ºC which is declared as a threshold for its working in simulation parameters. If the water coming from outlet of storage tank is at or above 60 ºC, heater will remain switched off. As soon as the water temperature drops below the threshold, heater will start working again to maintain it at 60 ºC. Energy used by heater during its working throughout whole year can be obtained and it will help in finding if solar fraction of system has increased after integrating PCM with heating water system. The equation 8, given below, governs calculation for solar fraction:

$$Solar\ fraction = \frac{m\ C_p\ (Hot\ water\ temperature - Cold\ water\ temperature) * 365 - E_{heater}}{m\ C_p\ (Hot\ water\ temperature - Cold\ water\ temperature) * 365} \quad (8)$$

In equation (8), E_{heater} is annual heating value of electric heater, m is mass of water and C_p is specific heat capacity of water. Hot water temperature is 60 ºC while cold water has a temperature of 15 ºC. Based on the equation 8, savings that can be made via using PCM are also calculated. Type 6 from TRNSYS library has been used for electric heater.

3.4.7. Load profile

In order to supply water according to water withdrawal profile, Type 14b was used in which values are inserted for each hour of the day. The values are in the form of percentage of daily water withdrawal.

3.5. Simulation procedure

Now considering that we have three different PCM, four different water profiles, two different shapes and three different volumes of PCM, it can be understood that simulations reach a very big number. The total number of simulations reach 72 which are only with PCM. For making a comparison, simulations needed to be run without PCM. Moreover, simulations were required to be run for a day and for whole year also. Furthermore, simulations needed to be carried out for both charging and discharging phenomena. One simulation takes from 35 to 40 minutes. It can be understood that how hectic and lengthy this procedure would be if run for all the scenarios. In order to reduce the number of simulations, shape and volume of PCM were selected beforehand based on the preliminary results, which will be discussed in detail in upcoming chapter.

So, for selecting the most suitable PCM, simulations will be run only for cylindrical shape and 20% volume of PCM. ASHRAE profile is used for singling out a specific shape and a specific volume. The reason for selecting this profile is that it has a continuous water withdrawal throughout the day. At each hour of the day, a specific quantity of water is required which is not the case in other water usage profiles. The profile is shown in Figure 13(c). So, PCMs were put under extreme conditions and burden to meet energy demand. A criterion was defined to gauge the performance of PCMs in order to specify a certain shape and volume. The details of criteria are given below.

3.5.1. Simulation parameters

Simulation parameters are very crucial to get accurate results. A good understanding of TRNSYS models is needed to use the appropriate ones at required time. All models come with a certain set of parameters, inputs and outputs. Inputs of a certain model may be outputs of another model. For example, the outlet temperature of solar thermal collector is the inlet temperature for heat exchanger inside storage tank.

Model inputs, outputs and simulation parameters of Type 840 tank are given below in Table 6, Table 7 and Table 8. It is to be noted that there is a huge list of input and output parameters. So, a brief list is being presented here mentioning each parameter used for simulations. There are certain parameters and inputs of every model in TRNSYS that need to be given a value in order to run accurate simulations.

Some parameters have a default value so as not to obstruct the simulations. These parameters need to be given carefully as results depend on them. One should have a very clear idea of inputs and parameters of a model because large number of these parameters may cause confusion.

Table 6 Outputs of Type 840 [41]

Model Outputs		
Serial no.	**Output parameter**	**Unit**
1	Outlet temperature 1,2,3,4,5	ºC
2	Total energy of store	kWh
3	Energy of storage fluid	kWh
4	Energy in internal HX1, HX2, HX3, HX4, HX5	kWh
5	Energy in PCM module1, 2, 3	kWh
6	Energy in PCM container1, 2, 3	kWh
7	Power through double port1, 2, 3, 4, 5	kW
8	Heat loss rate to ambient	kW
9	Temperature sensor 1, 2, 3, 4, 5	ºC
10	Fluid temperature 1,2,3,…,9	ºC
11	PCM temperature 1, 2, 3,…, 9	ºC

The list of outputs of model Type 840 are given in Table 6. There is a huge list of these parameters and demand great care when choosing what to display on graphs. There is a connection window for making a link between inputs and outputs of certain model with other models. So, input parameters of one model and output parameters of other model are arranged in parallel order in this ‘connection window’ and links can be made by using a tool called ‘connect mode’.

Table 7 Parameters and inputs of Type 840 [41]

Parameters and Inputs of Type 840			
Serial no.	**Parameter name**	**Units**	**Value Range**
1	Volume of storage	m^3	-
2	Height of storage	m	[0;10]
3	Heat loss rate	W/K	[0;1000]
4	Fluid number of storage fluid	-	[0;3]
5	Number of nodes	-	[1;200]
6	Initial temperature of store	^oC	[0;100]
7	Number of temperature sensors	-	[1;10]
8	Position of top sensor	-	[0;1]
9	Position of bottom sensor	-	[0;1]
10	DP1: type	-	[0;1]
11	DP1: fluid number	-	[0;3]
12	DP1: inlet height	-	[0;1]
13	DP1: outlet height	-	[0;1]
14	DP1: height of temperature sensor	-	[0;1]
15	DP1: Length of HX pipe	m	[0;200]
16	DP1: Inner diameter of HX pipe	mm	[0;100]
17	DP1: Outer diameter of HX pipe	mm	[0;100]
18	DP1: Therm. Cond. of pipe wall	W/m.K	[0;5000]
19	PCM1: number of modules	-	[0;+Inf]
20	PCM1: fluid number	-	[0;3]
21	PCM1: geometry 0 = cylinder, 1 = sphere	-	[0;1]
22	PCM1: Inner diameter (cylinder)	mm	[0;500]
23	PCM1: Outer diameter	mm	[0;500]
24	PCM1: Number of radial nodes	-	[1;20]
25	PCM1: thickness container	mm	[0;10]
26	PCM1: therm. cond. container	W/m.K	[0;5000]
27	PCM1: Cp of container material	J/kgK	-
28	PCM1: mass density of container material	kg/m^3	-
29	Inlet temperature 1,2,3,4,5…	^oC	-
30	Inlet mass flow rate 1,2,3,4,5...	kg/hr	-
31	Ambient temperature	^oC	-
32	Electric heater power	W	-

Important simulation parameters have been mentioned below. These parameters are backbone of this simulation. A slight change in these parameters bring a huge change in obtained results. It is to be mentioned that volume of capsule is not taken into account as it is very minute as compared to total volume of tank and can be neglected. The thickness of capsules is only 1mm for both cylindrical and spherical modules. If we find the volume of capsules for cylindrical and spherical modules, they turn out to be not even one percent of total volume. Moreover, the sensible heat stored in the capsule material has also been neglected. Simulation parameters used for running all the simulations for this thesis are as follows in Table 8:

Table 8 Simulation parameters for TRNSYS

Simulation parameters	
Water tank volume	300 litres
Tank height	1.4 m
Simulation time (For charging)	24 hours
Simulation time (For discharging)	48 hours
Simulation time (For solar fraction)	8760 hours
Simulation time step	0.01 hours
Number of tank nodes	20
Initial temperature of tank (For charging)	50 ºC
Initial temperature of tank (For discharging)	65 ºC
Ambient Temperature	20 ºC
Height of inlet for HX	1.33 m
Height of outlet for HX	0.07
Outlet height for double port	1.33
Inlet height for double port	0.07 m
Set point temperature for electric heater	60 ºC
Temperature of cold water	15 ºC
PCM modules height	1.2 m
PCM module diameter	89.2 mm
Module material	Steel
Heat exchanger dimension	
Outer diameter of HX pipe (D_o)	22 mm
Inner diameter (D_{in})	20 mm
Length of HX pipe	20 m

3.5.2. Criteria for selection of PCM shape

There were two options for shape i.e. cylindrical and spherical. Simulations were run for both shapes and comparative analysis was made. Factors, which were taken in to account, are as follows:

a) Number of hours to retain water above 50 ºC temperature

To analyse this criterion, the temperature of water from the outlet of water storage tank is taken in to consideration. The inflow of cold water in to storage tank continues throughout the day according to the water withdrawal profile and temperature of water in the tank drops. So, number of hours were noted for both spherical and cylindrical shaped PCM modules while in discharging mode. The initial temperature of tank is set as 65 ºC. The connection of heat exchanger to solar thermal collector is also cut off as no heat source is provided to tank. Water discharging profile is obtained as an outcome and useful results have been shown in results section. It takes 21.38 hours to retain water above 50 ºC without the presence of any PCM. All the other values will be compared to this specific value in order to carry out a comparison.

b) Charging time

The time taken by a certain PCM module from 45 ºC till the completion of phase change is taken as charging time in this study. It is made sure that PCM enters phase change phenomena following sensible heat phase. This is why charging time is taken from 45 ºC. As all of these three PCMs have specific heat capacity value ≈ 2, so sensible heat absorbed will be same for each PCM. The difference in absorbed energy will be evident when these PCMs will undergo phase change phenomena as latent heat of fusion is different for each PCM. A question may rise here that time could have been started from 50 ºC also. It is to be noted that paraffin have a melting range instead of having a sharp melting point. Specially, the PCM paraffin 56 has a huge melting range that can be seen in Figure 9 also. The units of this parameter are 'hours'.

c) Energy accumulated

The accumulated energy refers to the maximum amount of energy that a PCM stored for this specific day just after its latent phase ends. If a PCM does not undergo latent phase completely, the maximum energy stored is taken as accumulated energy. Energy stored in a PCM module is measured to obtain values for this criterion. It is observed that cylindrical shaped PCM absorbed more energy as compared to spherical ones. This conclusion was consistent in all the water profiles used. At certain times, there were some cases when spherical shaped PCM did not melt fully because of continuous water withdrawal from the tank. Continuous withdrawal of water results in lowering the temperature of storage fluid. Therefore, PCM does not get enough time to absorb heat from water in order to fully charge. The units of this parameter are ‘kWh’.

3.5.3. Criteria for selection of PCM volume

Performance of three different volumes of PCM inside storage tank will be tested. Proposed volumes are 10, 20 and 30 percent of volume of storage tank. The volume of storage tank is 300 litres which is equal to 0.3 m^3. Volume of water left inside storage tank after excluding PCM and heat exchanger volume is given in Table 9 below.

Table 9 Volume of water in storage tank excluding PCM and HX volume

Volume of PCM (%)	Volume of water (m^3)
10	0.269
20	0.239
30	0.209

For evaluating the volume of PCM which will prove to be sufficient for heating up the water and work best according to the case under study, two factors will be taken in to consideration which are as follows:

a) Number of hours to retain water above 50 ºC temperature

This criterion has already been explained in above headings.

b) Compromise on volume of water

Incorporating PCM inside water tank means that it will occupy certain volume. Higher amount of PCM may affect the reliability of supply of water. Further details have been given in next chapter.

c) Economic and other side factors

Higher amount of PCM directs towards more cost in terms of volume and material. More material will be needed as steel modules are used to encapsulate PCM. Further details have been given in next chapter.

Percentage increase method is used to find out that which volume of PCM will be suitable. For the first criterion, values of all PCMs have been compared with a tank without PCM. The equation 9 used to calculate percentage increase is as follows:

$$Percentage\ increase = \frac{new\ number - original\ number}{original\ number} * 100 \quad (9)$$

After analysing the results, 20% volume of PCM was selected for further simulations.

3.5.4. Criteria for selecting best type of PCM

Following criteria are considered in a bid to single out the most suitable PCM. Some of these criteria are also considered while finding the best shape and suitable volume and they have been explained earlier. The details of new criteria are given below.

a) Charging time

This criterion has been explained earlier while explaining the criteria for selecting shape of PCM.

b) Charging rate

Charging rate is the ratio of amount of heat stored to the time needed for this process. The time is considered from 45 ºC until phase change completion. A suitable PCM should have a higher charging rate. The units of this parameter are kWh/hour. The equation 10 is used to calculate charging rate of a respective PCM.

$$Charging\ rate = \frac{\Delta Q_{energy\ @\ phase\ change\ completion - energy\ @\ 45\ ºC}}{\Delta \tau_{time\ @\ phase\ change\ completion\ -\mathrm{time\ @\ 45\ ºC}}} \quad (10)$$

c) Energy accumulated

This criterion has been explained earlier while explaining the criteria for selecting shape of PCM.

d) Energy recovery ratio (ERR)

As evident from name, this parameter is a ratio of amount of heat discharged to heat absorbed per unit respective times i.e. charging and discharging. This parameter is a good way to compare the performances of different PCM under consideration. For this parameter, the charging time is noted from 30 ºC until phase change completion. Same is the case with discharging. The values of energy and temperatures are also taken at the start of phase change phenomena and at 30 ºC. The equation for ERR has been shown below as equation 11. $Q_{recovered}$ and Q_{stored} represent the amount of heat discharged and absorbed. $\tau_{complete\ discharge}$ and $\tau_{complete\ charge}$ denote the time required for complete charging an discharging.

$$\text{ERR} = \frac{Q_{recovered}/\tau_{complete\ discharge}}{Q_{stored}/t_{complete\ charge}} \tag{11}$$

e) Number of hours to retain water above 50 ºC temperature

This criterion has already been explained in above headings.

3.6. Financial savings

Through TRNSYS simulation, annual working of heater and solar fraction values are also obtained. With the help of these values, it will be find out if the integration of PCM in the tank has helped in reducing electric heater's operation time. In this way, energy savings would be calculated. For solar fraction comparison, a water tank Type 60d without PCM was chosen for simulations.

Financial gain is also expected. So, savings made as a result of less electric heater's operation time will be calculated. The electricity price per kWh is taken as 0.17€. It is to be noted that energy used by heater is different for each profile. So, different amount of savings is made for each profile.

3.7. Reduction in carbon footprint

The reduction in operation time of electric heaters will not only help to make savings but also help in reducing the carbon footprint. Carbon dioxide is the most important greenhouse emission gas. Therefore, the carbon footprint of each heating technology is measured and calculated in terms of carbon dioxide. The unit used is grams of carbon dioxide equivalent per kilowatt of heat. According to a report, the carbon footprint of electric heaters is approximately 370 gCO_2eqkWh. The drop in operational time of electric heater means that carbon footprint is reduced. So, this reduction in footprint will be calculated for each water usage profile.

4. Results

As mentioned in the methodology section, first step is to decide the configuration of PCM. PCM can either be encapsulated in cylindrical or spherical form. The simulations are carried out in identical conditions for all three PCMs. The results obtained from simulations carried out in order to determine suitable shape and volume of PCM are shown in this chapter. Simulations were carried out for each criterion and a comparison was made between PCMs to determine the most suitable PCM. ASHRAE profile was used to find out the shape and volume of PCM.

4.1. Selection of shape

4.1.1. Charging time

The methodology used for measuring charging time has been already explained in sections above. Below shown are the Figure 24, Figure 25 and Figure 26 of charging curves of all three PCMs with cylindrical modules. It can be seen that increase in solar irradiance results in the increase of water temperature inside storage tank and PCM starts getting charged. Every PCM has its own distinct thermal properties and that is why the charging time is different for each PCM.

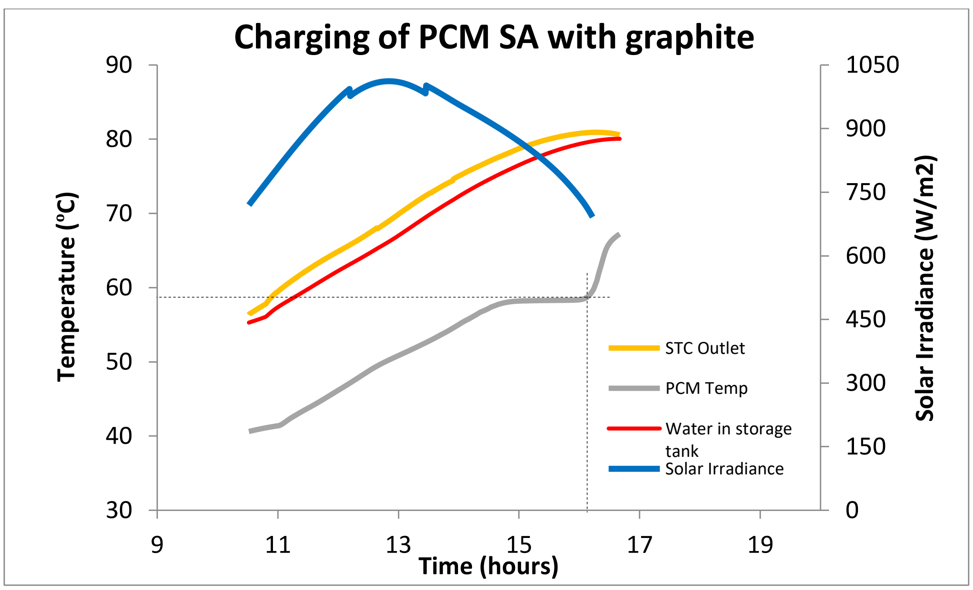

Figure 24 Charging of PCM Sodium acetate with graphite (ASHRAE profile)

Initial temperature of tank is set at 50 ºC and simulations have been performed starting from midnight. As soon as the sun rises and solar irradiation increases, the temperature of fluid circulating in solar panel starts getting higher and thus the heat is released in water storage tank through heat exchanger. PCM also starts absorbing heat from water in the tank and charging phenomenon starts.

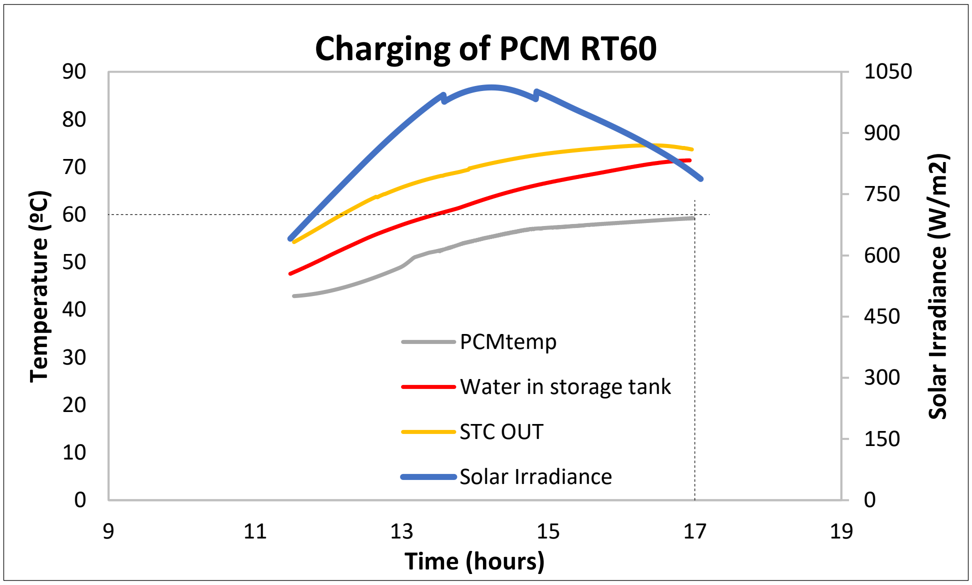

Figure 25 Charging of PCM RT 60 (ASHRAE profile)

In the figures 24, 25 and 26 shown above, it can be seen that PCM charging starts around 11 AM in the day. Initially, it is the sensible heat which is being stored until the phase change starts. Sensible heat charging rate is almost same for all three PCMs as their values of specific heat capacity are close to 2 kJ/ (kg.K). A huge amount of latent heat is stored during phase change, which will be discussed in coming sections in detail.

Figure 26 represents the charging of Pasraffin56. There is a strange noise in the curve obtained for PCM temperature curve. This noise may have been generated because of poor numerical integration.

From the figures 27, 28 and 29, it is clear that cylindrical shaped PCM takes less time as compared to spherical shaped PCM in getting charged.

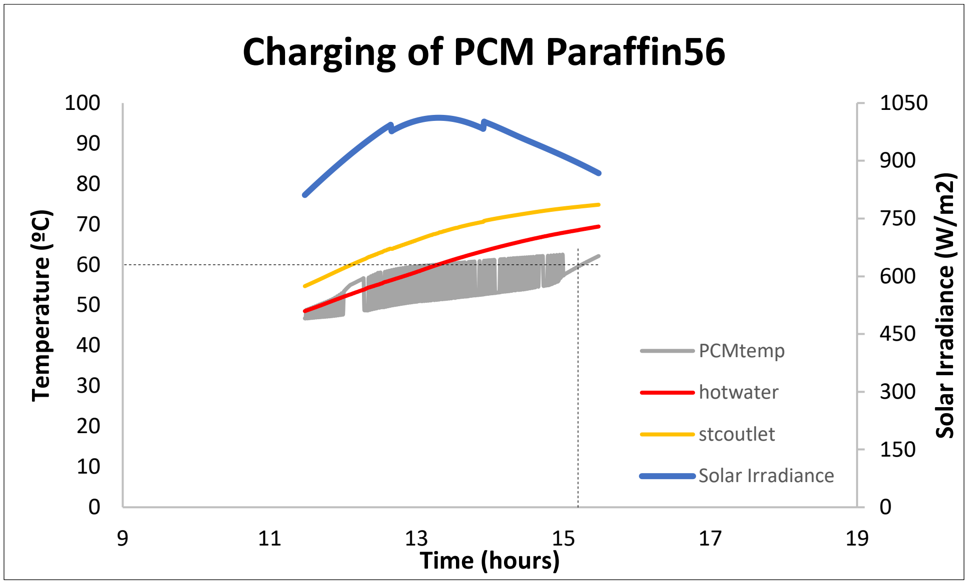

Figure 26 Charging of PCM Paraffin 56 (ASHRAE profile)

Simulations have been done for three percentages of PCM and consistent results have been obtained which prove that charging time of cylindrical shaped PCM is much faster. The time considered for charging is from 45 ºC until phase change completion. All the three PCMs used have their melting range within 56 ºC to 60 ºC.

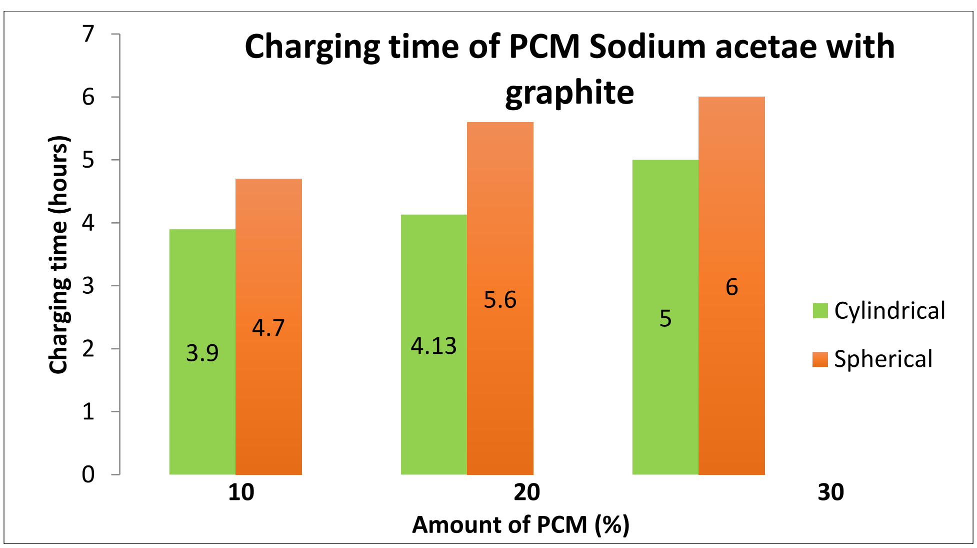

Figure 27 Charging time of SA with graphite (ASHRAE profile)

In Table 5, the diameters of PCM modules are given. It can be seen that cylindrical modules have small diameters as compared to spherical ones. This is the reason that heat penetrates in these modules comparatively easier and PCM is charged in lesser amount of time. Initially, heat is transferred through conduction. For conduction, lesser the thickness more will be the heat transfer. Moreover, the volume to surface area ratio for spherical modules is higher. Higher volume to surface area ratio results in slow rate of heat transfer. Higher surface area results in higher heat transfer rates. Cylinders have lower volume to surface area ratio and that is why the heat transfer rate is higher. Higher heat transfer rates help cylindrical modules to melt early as compared to spherical ones.

PCM inside cylindrical modules melts early and process of convection also starts at the same time. In case of spherical modules, the diameter is large and heat takes more time to penetrate inside. This results in slow melting of PCM and thus process of convection starts lately. This is the reason that in certain water withdrawal profiles, despite of having huge amount of time, spherical modules couldn't get charged fully because heat transfer process was slow. So, for the houses, offices and huge buildings where water is continually being drawn out from storage tank, spherical modules for having PCM is not a good choice.

In Figure 27, charging times of three volumes of sodium acetate plus graphite are shown. It can be seen that PCM present in cylindrical shaped module completed the charging process much earlier as compared to spherical modules. The results are consistent in all three volumes of PCM. Cylindrical modules take 21%, 36% and 20% more time in charging as compared to cylindrical modules for 10, 20 and 30 percent volume of PCM respectively.

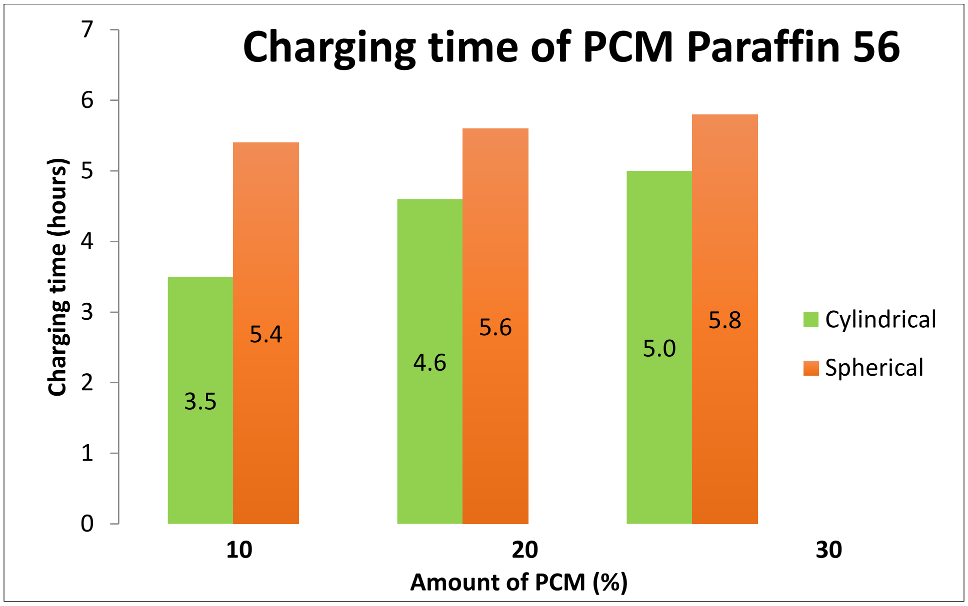

Figure 28 Charging time of Paraffin 56 (ASHRAE profile)

In the same way, cylindrical modules having PCM Paraffin 56 take 54%, 22% and 16% more time in charging as compared to cylindrical modules for 10, 20 and 30 percent volume of PCM respectively. Results are shown in Figure 28.

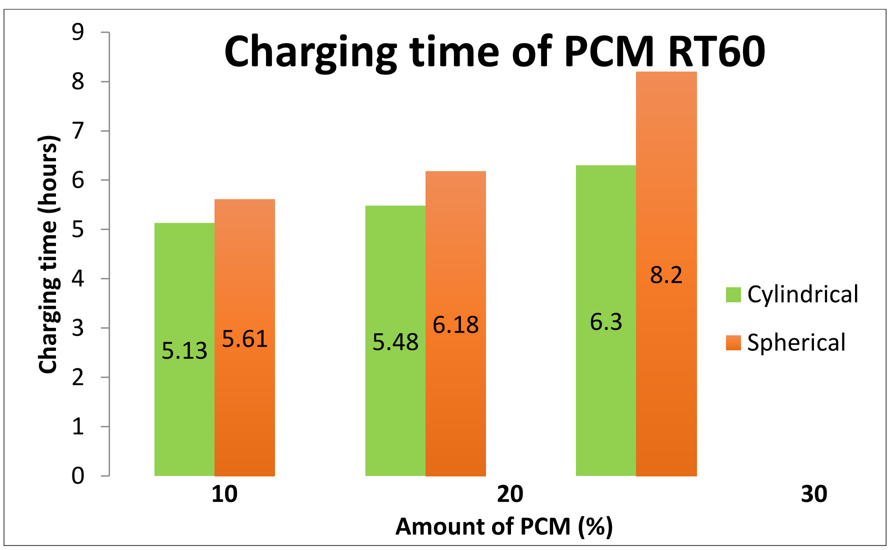

Figure 29 Charging time of RT 60 (ASHRAE profile)

The results obtained for PCM RT 60 are also consistent with the previous achieved results. Cylindrical modules take more time for charging. Time taken is extended by 9%, 13% and 30% for 10, 20 and 30 percent volume of PCM respectively. Results are given in Figure 29.

4.1.2. No. of hours taken by a certain PCM to maintain water above 50 ºC

This criterion provides an estimate that how long can be withdrawn from tank at a temperature higher than 50 ºC. There is a drastic difference between the results obtained by the two shapes namely cylindrical and spherical. The results are shown in figures 30, 31 and 32 given below and it is clear to see that cylindrical shape has better results for discharging as compared to spherical shape. A good PCM has a higher discharging rate which helps in quickly releasing heat to water.

For 10% amount of PCM, there is an increase of 9.1% in the number of hours. The percentage increase for 20 and 30% amount of PCM is 30.4 and 40.4 respectively.

For PCM sodium acetate plus graphite, number of hours for cylindrical modules to keep water above 50 ºC is extended by 2, 7 and 9.5 hours as compared to spherical modules for 10, 20 and 30 percent volumes of PCM respectively.

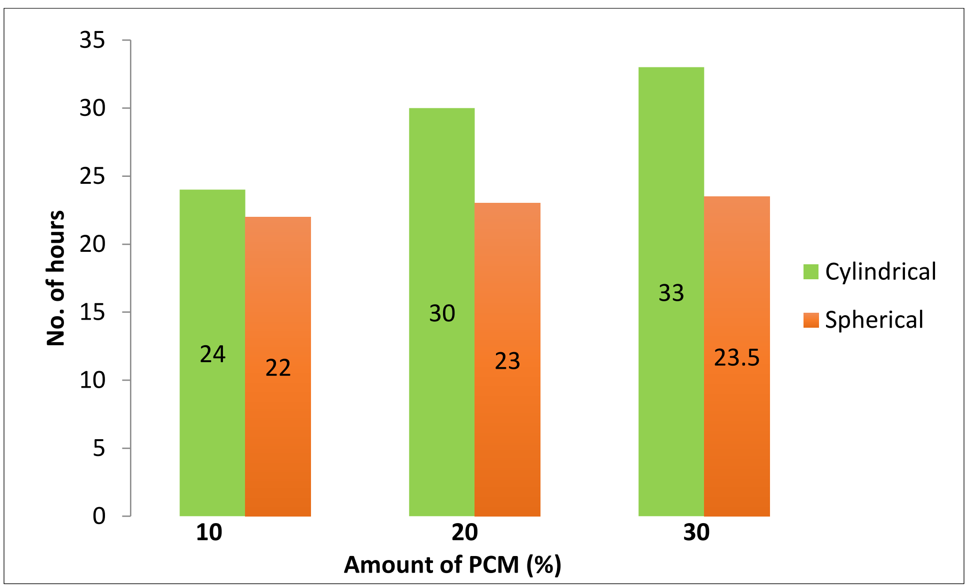

Figure 30 No of hours taken by PCM SA with graphite to maintain water above 50 ºC (ASHRAE profile)

Moreover, results show that larger the volume of PCM, longer will be the time for which water remains above 50 ºC. From calculations, it can be seen that percentage increase is 9.1, 30.4 and 40.4 percent for 10, 20 and 30 percent volumes of PCM.

Comparison of discharging profiles of water in presence of different PCM volumes for spherical modules has been shown in Figure 31 below. The PCM effect is obvious for all three volumes of

PCM. The results indicate that higher the PCM volume, longer will be the time period for which water remains at elevated temperature.

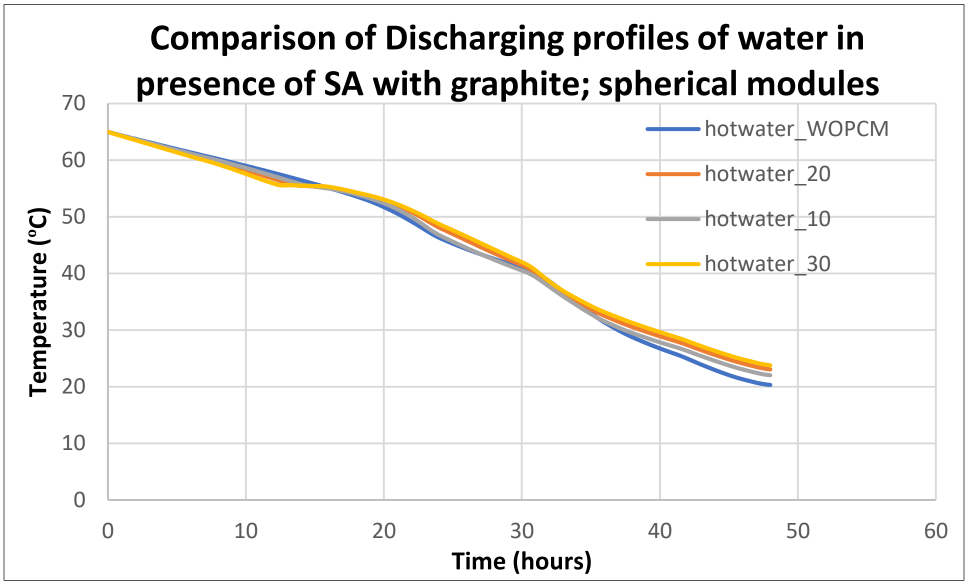

Figure 31 Discharging water profiles in presence of PCM sodium acetate with graphite; spherical module (ASHRAE profile)

In Figure 32, discharging profiles for spherical modules have been shown. It can be seen that there is no or very little useful effect of these modules. The results from figures 31 and 32 exhibit that cylindrical modules have better performance than spherical modules. The results for other two PCMs i.e. RT60 and Paraffin56 are also same.

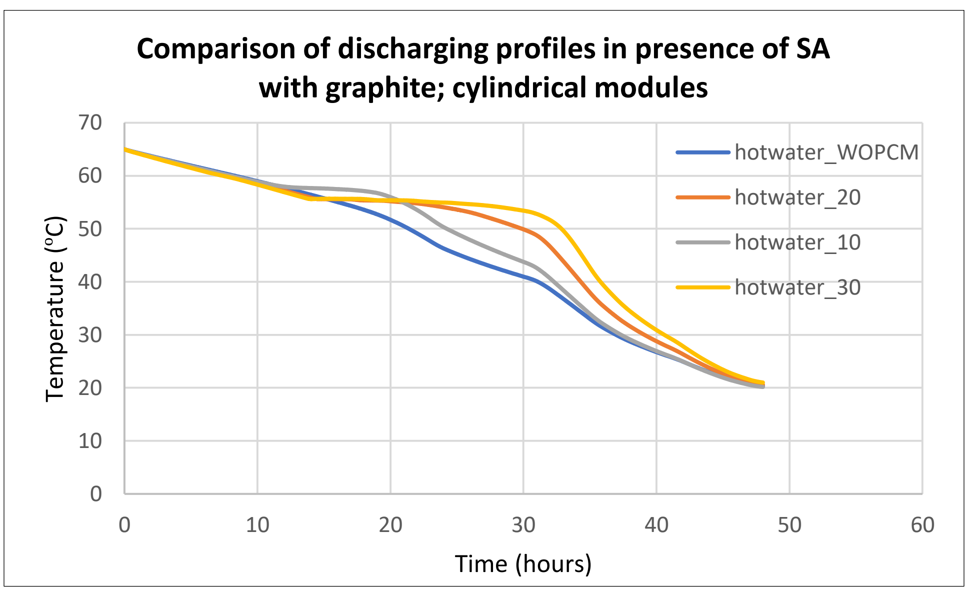

Figure 32 Discharging water profiles in presence of PCM sodium acetate with graphite; cylindrical module (ASHRAE profile)

The results being presented here are for ASHRAE water profile.

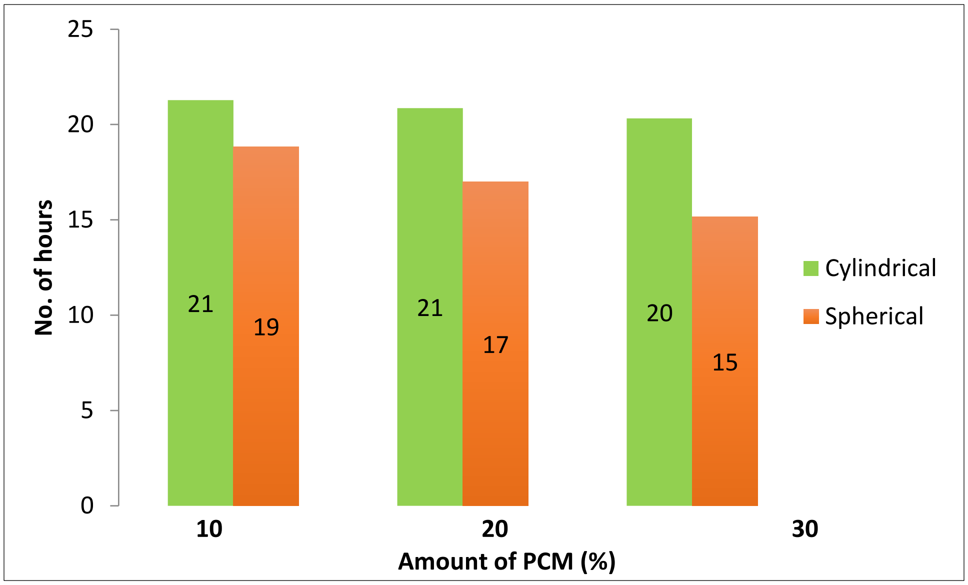

Figure 33 No of hours taken by PCM Paraffin 56 to maintain water above 50 ºC (ASHRAE profile)

For PCM paraffin 56, number of hours to keep water above 50 ºC is extended by 2, 7 and 9.5 hours for 10, 20 and 30 percent volumes of PCM respectively. The trend for both cylindrical and spherical shaped module is interesting for this PCM. The results show that increasing the volume of PCM will result in lowering of water temperature inside storage tank. This is understandable as higher volume of PCM is difficult to melt.

The results for Paraffin56 refer to low latent heat of fusion for PCM paraffin 56. Another conclusion can be drawn which is an assumption at this stage, that having PCM Paraffin 56 in tank is not serving the purpose and perhaps water alone will perform better in this criterion.

Figure 34 represents the discharging profile in presence of PCM Paraffin56. The results are not so encouraging neither for cylindrical nor for spherical modules. Cylindrical modules have barely met the criteria by keeping water at elevated temperature. The results are almost similar to water temperatures without PCM. Spherical modules have shown even worse results. It indicated that presence of Paraffin56 would decrease the performance and sustainability of system. Results are shown in Figure 35.

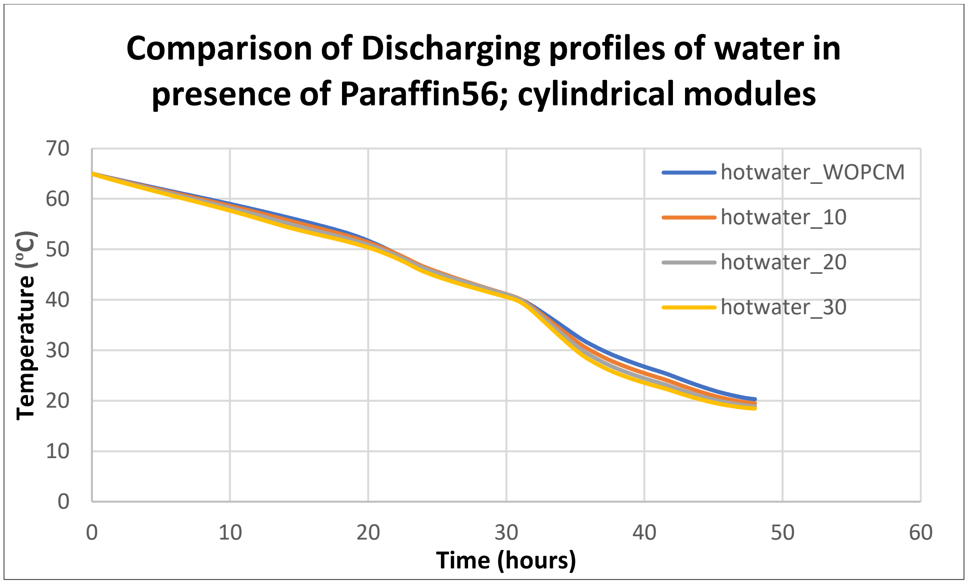

Figure 34 Discharging water profiles in presence of PCM Parafffin56; cylindrical module (ASHRAE profile)

Figure 34 and Figure 35 show the results obtained for Paraffin56 for cylindrical and spherical modules. These results indicate the performance of both cylindrical and spherical modules. The first conclusion that can be made from these results is about the comparison of performance of cylindrical and spherical modules. Cylindrical modules have performed better than the spherical ones. Secondly, it can be seen that spherical modules do not possess the ability to keep water at elevated temperatures for longer period of time when compared to cylindrical modules.

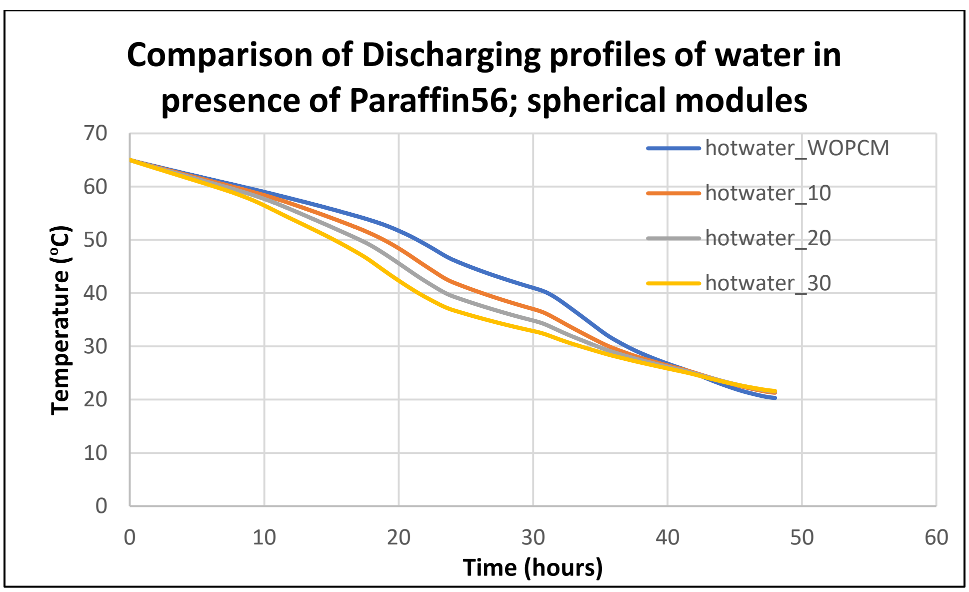

Figure 35 Discharging water profiles in presence of PCM Praffin56; spherical module (ASHRAE profile)

Figure 36, Figure 37 and Figure 38 show the results obtained for RT60 for cylindrical and spherical modules. These results indicate the performance of both modules. A comparative analysis can be drawn based on the above results.

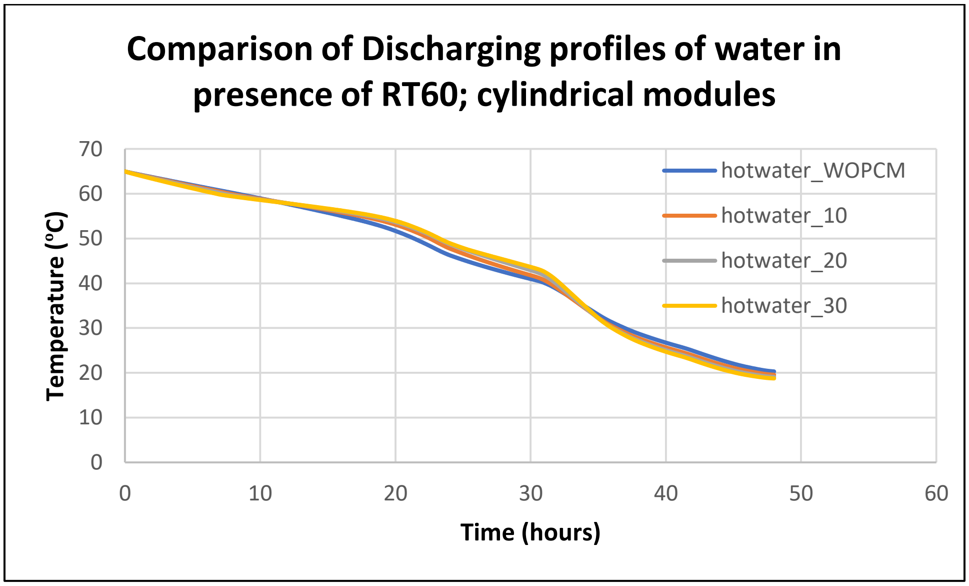

Figure 36 Discharging water profiles in presence of PCM RT60; cylindrical module (ASHRAE profile)

It can be seen from figure 37 that spherical modules failed to keep water temperature at an elevated temperature. Results show that absence of PCM will be better than having spherical modules of PCM.

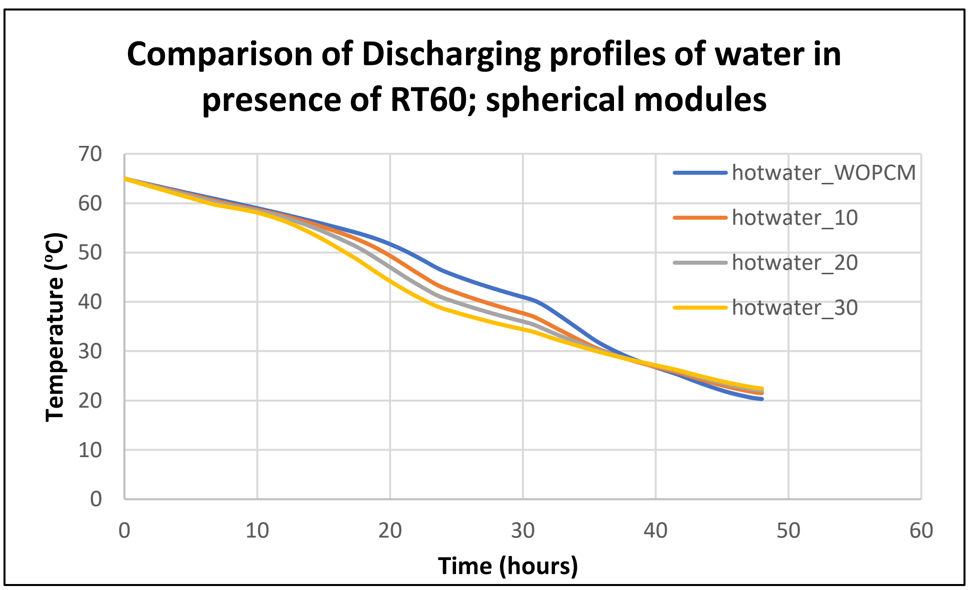

Figure 37 Discharging water profiles in presence of PCM RT60; spherical module (ASHRAE profile)

For PCM RT60, number of hours to keep water above 50 ºC for cylindrical modules is prolonged by 4.54, 4.86 and 6.59 hours as compared to spherical modules for 10, 20 and 30 percent volumes of PCM respectively. Difference between the values of number of hours for different volumes is not considerable for cylindrical shaped modules. The results depict that increasing the volume of PCM RT60 will have no considerable increment for this criterion. Same is the case with spherical modules. There is no significant difference in the results obtained by changing volume of PCM.

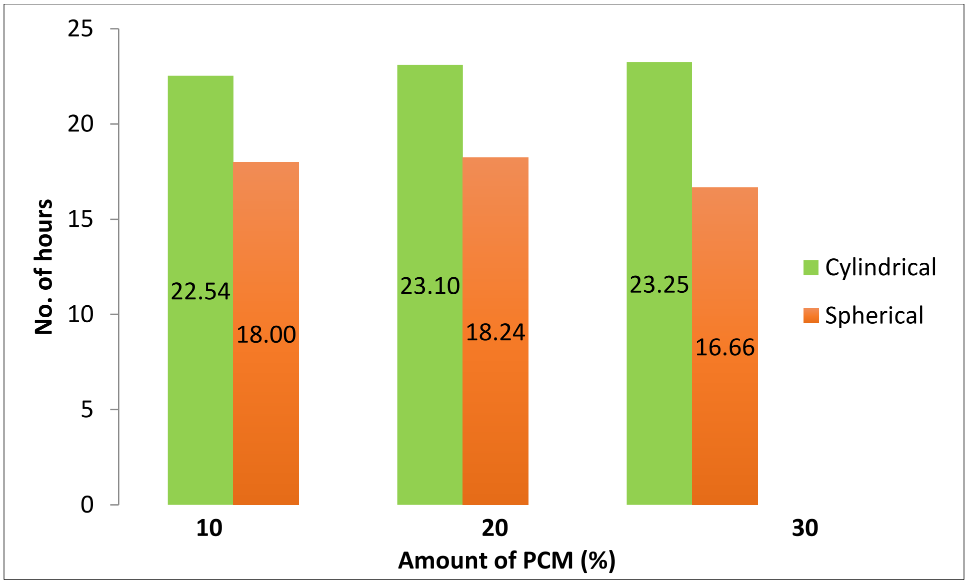

Figure 38 No of hours taken by PCM RT 60 to maintain water above 50 ºC (ASHRAE profile)

4.1.3. Energy accumulated

It is important to mention here again that simulations were run for 29th August which is 241st day of the year. The initial temperature of tank is set as 50 ºC. The accumulated energy refers to the maximum amount of energy that a PCM stored for this specific day just after its latent phase ends. If a PCM does not undergo latent phase completely, the maximum energy stored is taken as accumulated energy. It is to be noted that spherical modules have stored less amount of energy as compared to cylindrical modules. Now looking at equation 1 again, it can be seen that mass and value of C_p is same for both modules. The only difference can be either difference in temperature or the extent to which phase change phenomena progressed. Looking at the close difference of values, it can be safely assumed that PCM in both modules underwent phase change phenomena but cylindrical modules went a bit far and stored more energy because of fast heat transfer.

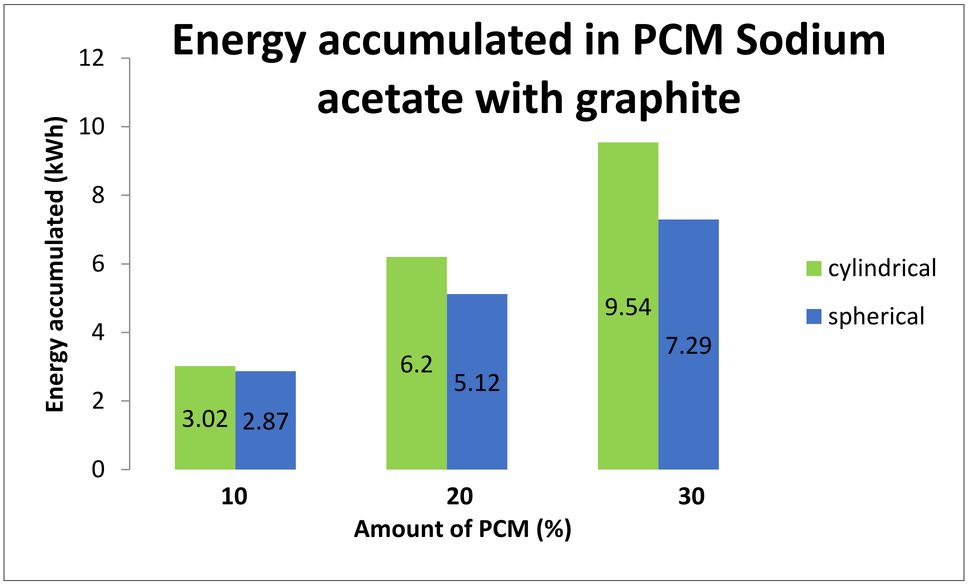

Figure 39 Energy accumulated in PCM Sodium acetate plus graphite (ASHRAE profile)

Figure 39 shows the amount of energy stored in PCM sodium acetate plus graphite. Amount of energy accumulated in cylindrical modules of sodium acetate plus graphite is 5, 21 and 31 percent higher as compared to spherical modules for 10, 20 and 30 percent volumes of PCM respectively.

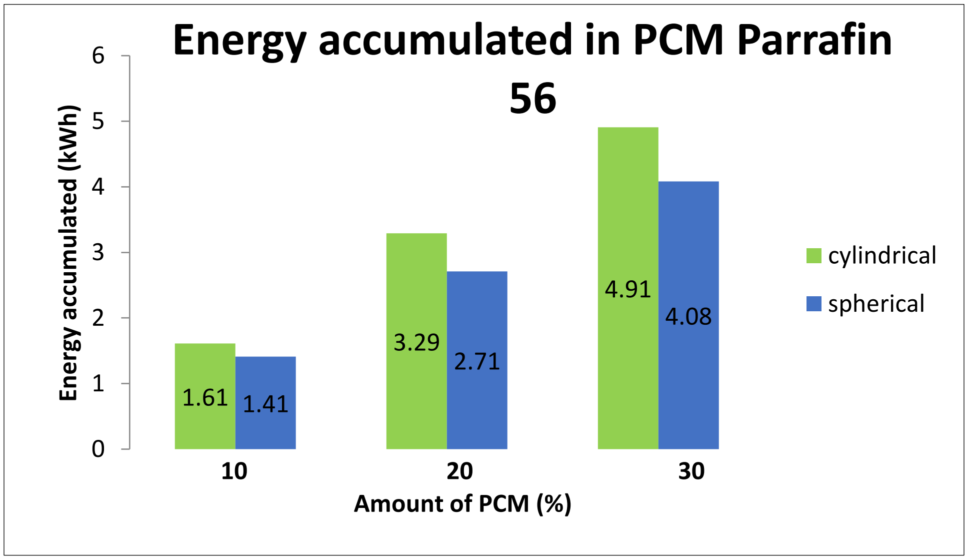

Figure 40 Energy accumulated in PCM Paraffin 56 (ASHRAE profile)

Figure 40 shows the amount of energy stored in PCM Paraffin 56. Amount of energy accumulated in cylindrical modules of PCM Paraffin 56 is 14, 21 and 20 percent higher as compared to spherical modules for 10, 20 and 30 percent volumes of PCM respectively.

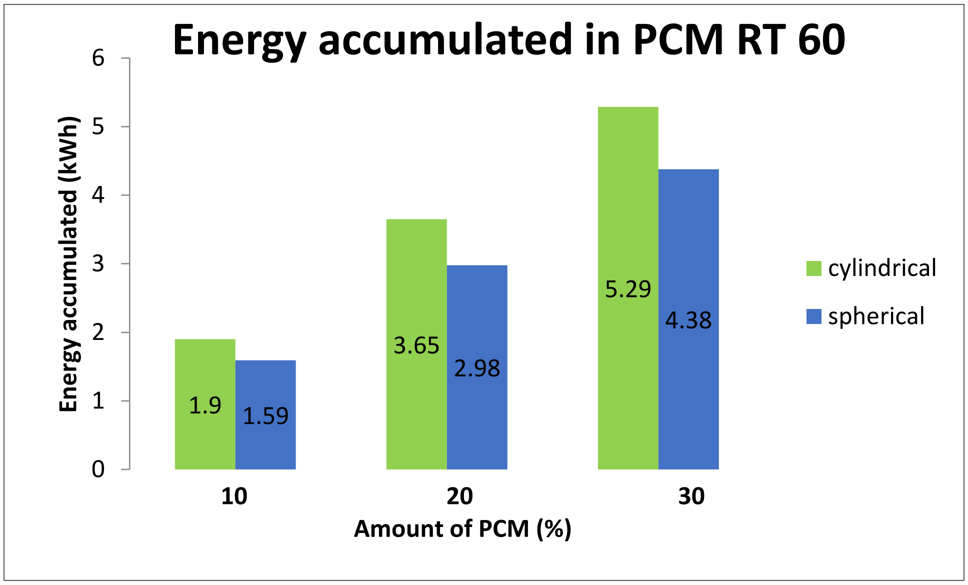

Figure 41 Energy accumulated in PCM RT 60 (ASHRAE profile)

Figure 41 shows the amount of energy stored in PCM RT 60. Amount of energy accumulated in cylindrical modules of PCM Paraffin 56 is 19, 22 and 21 percent higher as compared to spherical modules for 10, 20 and 30 percent volumes of PCM respectively.

4.1.4. Conclusion

After carefully evaluating all four criteria, it can be seen that PCM present in the cylindrical modules has much better performance as compared to PCM in spherical form modules. Therefore, for further simulations, only cylindrical shape will be taken into account. Moreover, cylindrical module is also more feasible from installation and manufacturing point of view.

4.2. Selection of volume of PCM

For evaluating the volume of PCM which will prove to be sufficient for heating up the water and work best according to the case under study, two criteria will be taken in to consideration. These criteria have been explained below along with results.

4.2.1. No. of hours taken by a certain PCM to maintain water above 50 ºC

It takes 21.38 hours to retain water above 50 ºC without the presence of any PCM. All the other values will be compared to this specific value in order to carry out a comparison.

Figure 42 shows the number of hours for which water can be supplied above 50 ºC and percentage increase in time as compared to time for which water remains above 50 ºC in absence of PCM. For 10% volume of PCM, the percentage increase in time to maintain water above 50 ºC is 12%. For 20 and 30 percent volume of PCM, the percentage increment in time is 40% and 54% respectively.

If we have a closer look at these values, we can see that the increment in time from 10% to 20% amount of PCM is 25% while increment in time from 20% to 30% volume of PCM is only 10%. This is relative increase. From this analysis, we can safely assume that 20% volume of PCM is relatively better.

While measuring the values for this criterion, PCM was assumed to be fully melted. The initial temperature given to PCM was 65 ºC. In real time scenario, it may happen that PCM is not fully melted and discharging starts because water temperature gets lowered than PCM temperature. This is why having a very high amount of PCM i.e. 30% PCM volume in the tank is not a feasible idea.

A lower volume will charge and discharge early as compared to a higher volume. It is evident that higher volume of PCM will result in higher temperature of water for a longer period but charging and discharging time may affect the supposed and hypothetical performance of PCM.

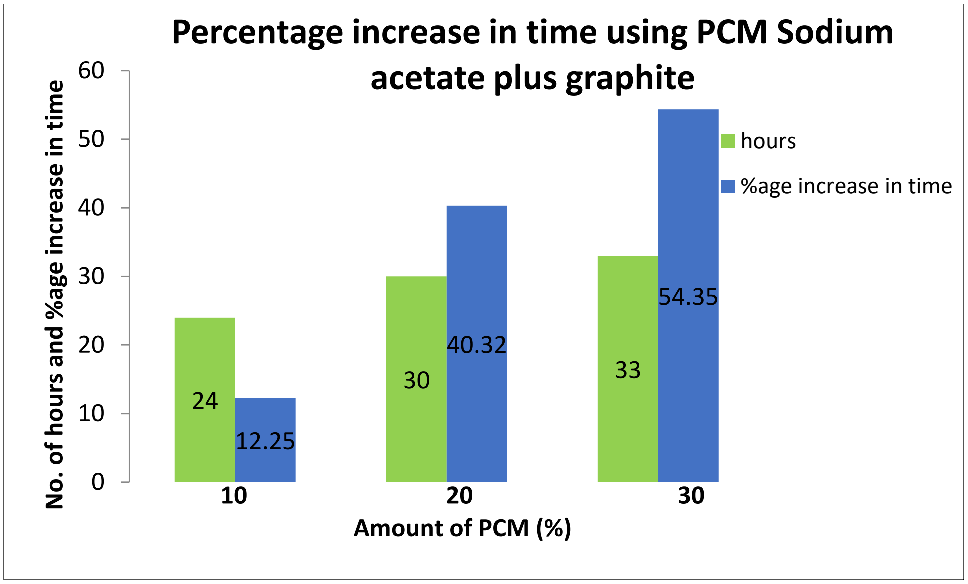

Figure 42 Comparison of no. of hours and percentage increase in time for three volumes of PCM SA with graphite (ASHRAE profile)

The results obtained for Paraffin 56 in Figure 43 are very interesting. They point out that presence of this specific PCM will not help at all in maintaining water at required higher temperature. Moreover, results show that it is not a suitable PCM for our case because the time to maintain water above 50 ºC has decreased. Reason is the low energy storage capacity. Although the time to release stored energy is really low which is a good characteristic but the released energy is not enough to maintain water at higher temperatures. We can see that as the amount of PCM is increased, the number of hours to maintain water above 50 ºC have been decreased. The results also depict that water alone in the storage tank would have fare better than this PCM and water together in the tank.

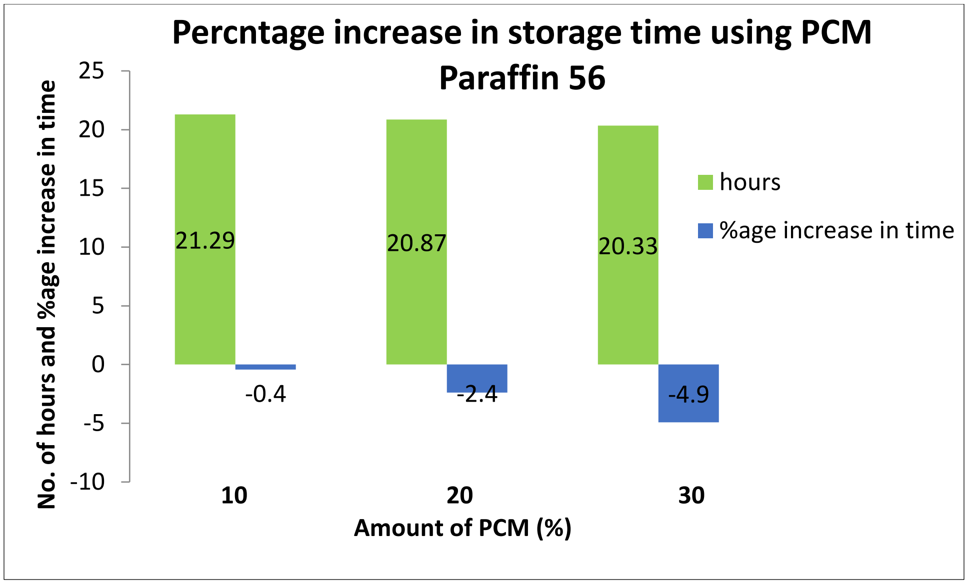

Figure 43 Comparison of no. of hours and percentage increase in time for three volumes of PCM Paraffin56 (ASHRAE profile)

The Figure 44 shown below is for RT 60. The results show that 10% volume of PCM gives better results as compared to other quantities. By increasing the volume of PCM and taking it to 20% and 30%, the percentage increase in number of hours to maintain water above 50 ºC is 2.5% and 0.65% which is really low as compared to value achieved by 10% volume of PCM i.e. 5.4%. This is to be noted that the values of percentage increase mentioned here are relative. Here again, the reason is low accumulation of heat. Obtained results also give us a hint that PCM RT 60 is performing better than PCM Paraffin 56.

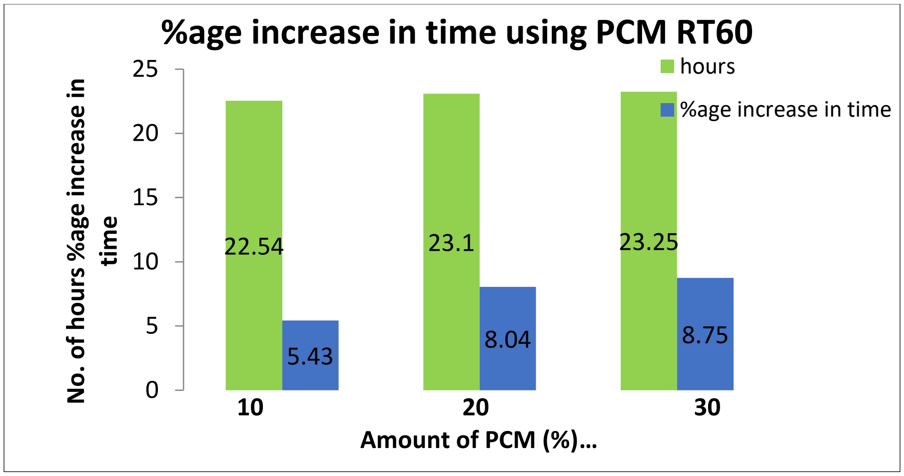

Figure 44 Comparison of no. of hours and percentage increase in time for three volumes of PCM RT60 (ASHRAE profile)

4.2.2. Compromise on volume of water

Increase in volume of PCM will result in decrease of volume of water in storage tank. So, a compromise is needed to decide the volume of PCM. It is to be noted that hot water requirement is 200 litres per day. Having 30% volume of PCM inside tank means that 210 litres of water will be available for storage which can affect the reliability of hot water supply, as there can be some irregularities in the water usage behaviour. To ensure enough water reliability, the volume of water should be a bit higher than 210 litres as 200 litres is the threshold. Using 20% volume of PCM will result in having 240 litres of water which is reasonable. The energy content of 20% volume will be higher as compared to 10% volume and although the former will take a bit more time in getting charged, its higher energy storage capacity and prolonged time to maintain water at a higher temperature will be of great help in meeting the hot water demand of a household of four people. Based on the above-mentioned remarks, it can be concluded that 20% volume of PCM is suitable. Further simulations will be carried out by selected shape and volume of PCM i.e. cylindrical shape and 20% volume.

4.2.3. Economic and other side factors

While deciding on the volume of PCM, one should keep in mind the cost associated with it. Although, higher energy density comes as a benefit of higher PCM volume, but increased charging and discharging time may supersede the benefits associated with higher volume of PCM. It is possible that 30% volume of PCM would not be able to get charged fully on certain days because higher charging time is needed. High volume of PCM will need bigger modules which need more material and will result in increase of cost of the system. The diameter of module required for 30% volume is 110mm while diameter needed for 20% PCM volume is 89.2 mm. The difference is quite understandable.

4.2.4. Conclusion

After carefully analysis, 20% volume of PCM is selected for further simulations. In this way, supply of water reliability will not be compromised. Optimum benefits will be obtained with this volume of PCM in terms of cost and energy accumulation. Moreover, number of hours for which water remains above 50 ºC are also quite better.

4.3. Selection of suitable PCM

All three PCMs have been tested in certain conditions and their performance has been assessed on the base of criteria mentioned in methodology. The results are obtained for each criterion against each water usage profile. It has been observed that values for each criterion are different for different water usage profiles. It was expected because water withdrawal rate at a certain time is different for each profile.

4.3.1. Charging time

Charging time of three PCMs for all four water profiles have been given in Figure 45 below. In real world scenario, there is no chance of a sudden phase change. There are many reasons for it. The diameter of module also matters because heat will take more time to penetrate the region with more thickness. Moreover, the thickness of capsule is also important. First, the PCM present at the sides of container starts melting. The material present inside core absorbs only sensible heat initially and by the time it starts melting, the PCM present around cylinder walls has already melted.

As mentioned earlier, temperature sensor at the bottom most node of module has been used for measuring charging time. This node of module remains at the lowest temperature as compared to all other nodes. Once it melts, it can be said with surety that whole PCM has been melted fully. The PCM present in the upper nodes gets charges early and easily as hot water is present in the upper part of tank because of density difference. Cold water enters from bottom according to the water usage profile. The charging times of all three PCMs for all four water profiles have been shown in Figure 45 below.

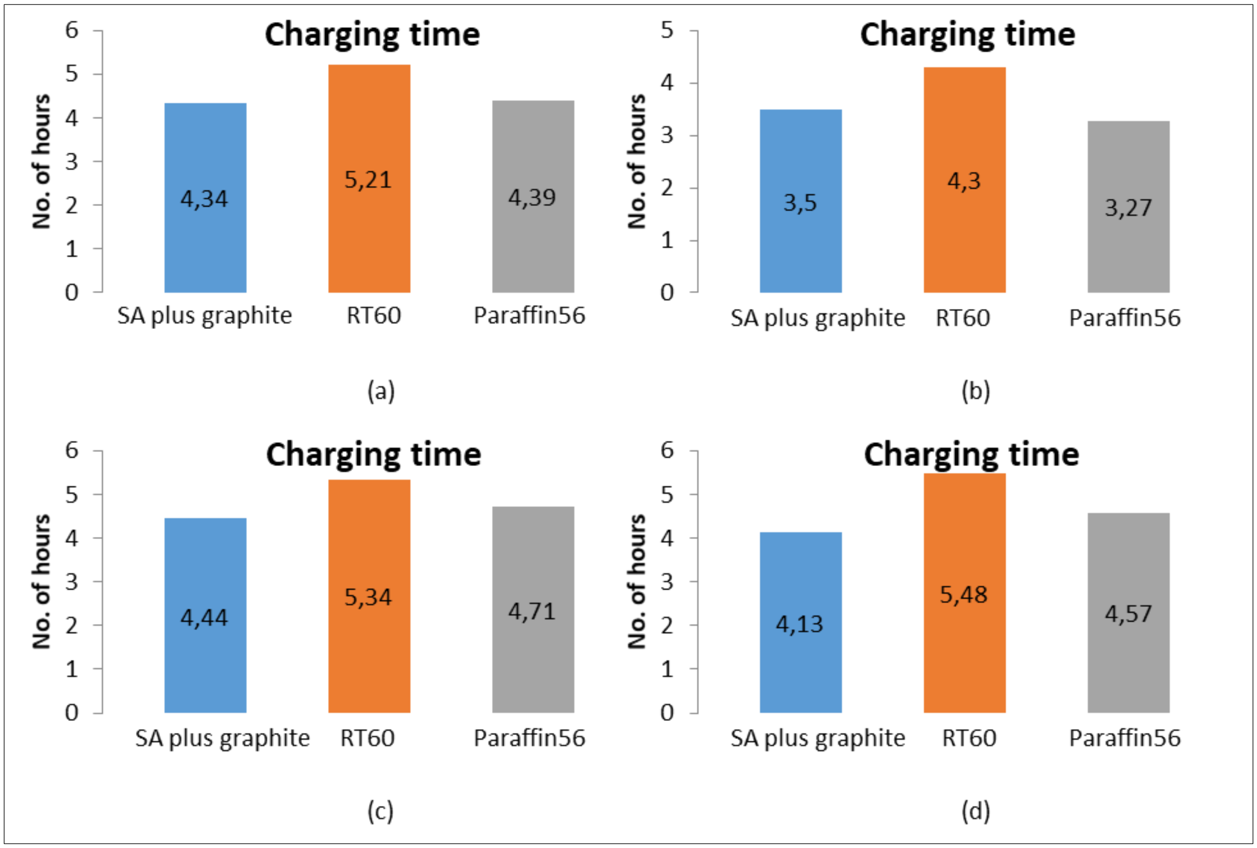

Figure 45 Comparison of charging time of three PCMs for (a) Multi dwelling profile (b) UK profile (c) Daily peak profile (d) ASHRAE profile

For multi dwelling profile, it can be seen that inorganic PCM RT60 is taking highest time to get charged. Sodium acetate with graphite is the quickest to get charged. Figure 45(b) represents charging time for UK profile. Sodium acetate plus graphite takes the least time to get charged.

In UK water usage profile, two peaks occur in morning and evening time. During the day, there is no hot water requirement. This is why, PCMs get charged in sufficiently quick time.

In daily peak profile, RT60 takes the most time for full melting. Sodium acetate takes 4.44 hours to get charged. The results obtained for charging times are coherent and consistent. In all water profiles, with the exception in UK profile, sodium acetate takes the least time to fully melt. RT60 takes a longer duration as compared to other two PCMs in order to melt. An important thing to mention here is the charging behaviour of Paraffin 56. As it is an impure paraffin, so it has different melting zones. It shows a discontinuous behaviour near 50 ºC and the temperature fluctuates in a range. Therefore, it is difficult to find the exact melting point of this PCM. All thermocouples placed on different heights along the module show discontinuous behaviour.

In ASHARE profile shown in 45(d), sodium acetate melts quickly followed by Paraffin56 and RT60 respectively.

4.3.2. Charging rate

Sodium acetate with graphite has the highest charging rate in all profiles followed by RT60 and Paraffin56 respectively. The results obtained are consistent throughout all water withdrawal profiles. The parameter of charging rate has units of kWh/h. From the Figure 46(a), it can be seen that sodium acetate with graphite has the highest charging rate of 0.58 kWh/h among the three PCMs. Paraffin 56 has the lowest charging rate of 0.27 kWh/h. Having a low value of charging rate corresponds to storing less energy in a certain amount of time.

For UK profile in Figure 46(b), sodium acetate with graphite has charging rate of 1.03 kWh/h; RT60 has 0.5 kWh/h whereas paraffin56 has a charging rate of 0.49 kWh/h. The highest value achieved of charging rate is for sodium acetate with graphite in UK profile. RT60 has close values in three water profiles except UK water withdrawal profile. It can be seen that charging rate of all PCMs is higher in UK water profile. It is because that water withdrawal rate during daytime is really low and hot water is available for long time for charging PCM.

In Figure 46(c), charging rates for daily peak profile are shown and Figure 46(d) contains charging rates for ASHRAE profile. In daily peak profile, sodium acetate with graphite has charging rate of 0.75 kWh/h, RT60 has 0.36 kWh/h and Paraffin 56 has charging rate of 0.28 kWh/h. For ASHRAE profile also, sodium acetate with graphite has highest charging rate i.e. 0.67 kWh/h followed by RT60 and Paraffin56 which have charging rates of 0.38 and 0.35 kWh/h respectively.

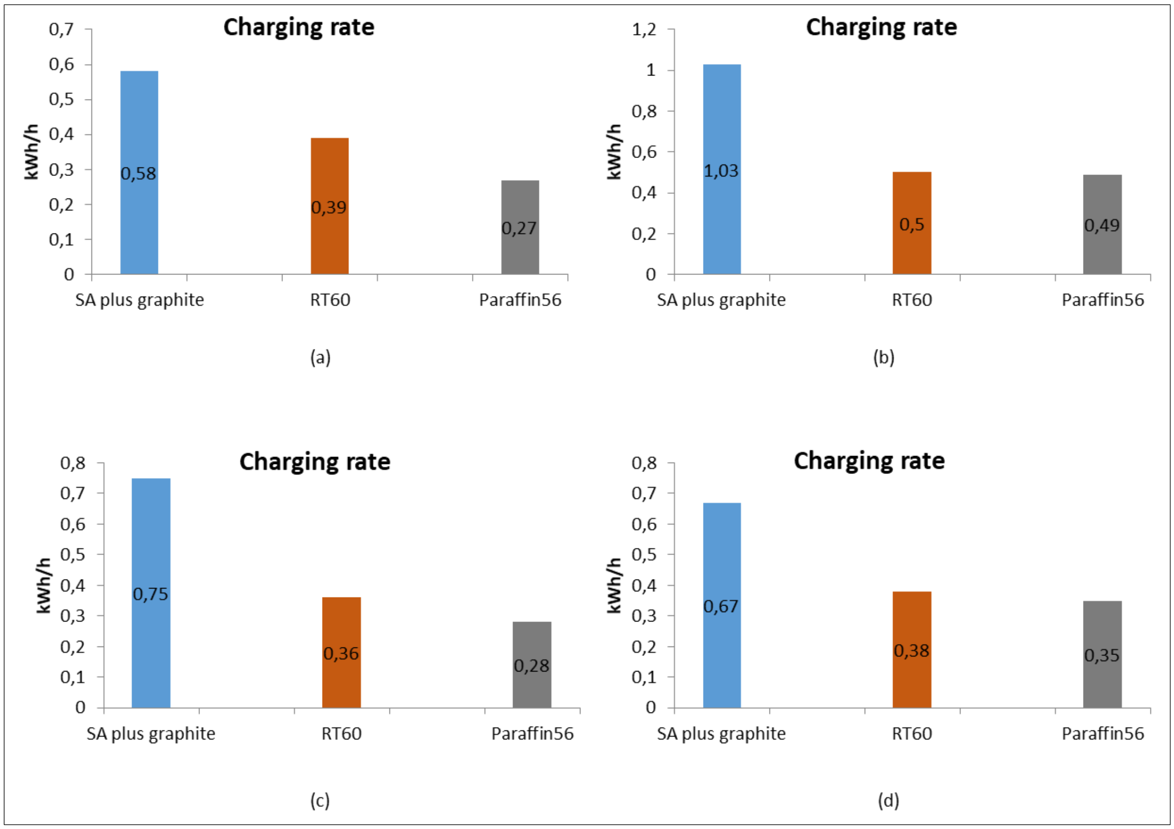

Figure 46 Comparison of charging rates of three PCMs for (a) Multi dwelling profile (b) UK profile (c) Daily peak profile (d) ASHRAE profile

4.3.3. Energy accumulated

Phase change materials have the ability to store very huge amount of energy during phase change phenomena. Energy is stored in the amount of heat and later released when material goes under phase change phenomena again upon cooling. So, these materials act as heat source. This is why such materials have caught the attention of researchers. An important thing to mention here is that if we look at the capacity to store sensible heat, water has the highest capacity as compared to all phase change materials under consideration for this thesis. The reason is water's high specific heat capacity which has a value of 4 kJ/kg.K. Sodium acetate with graphite has 1.86 while Paraffin 56 and RT60 have specific heat capacity value of 2 kJ/kg.K.

Sodium acetate with graphite which is an organic phase change material, has stored the maximum amount of energy in all four water withdrawal profiles followed by RT60 and Paraffin 56. The results obtained for accumulated energy are consistent for all water usage profiles. In Figure 47(a) which shows the amount of energy stored by each PCM during multi dwelling profile, sodium acetate with graphite has stored 5.54 kWh energy from 45 ºC till completion of phase change. Some portion of this heat stored is sensible and major portion is latent. RT60 has stored 3.71 kWh while Paraffin 56 has stored 3.3 kWh energy.

In Figure 47(b), comparison of energy stored for all PCMs for UK profile have been shown. Sodium acetate with graphite has again outperformed other PCMs by storing 5.75 kWh of energy followed by RT60 which absorbed 3.92 and Paraffin 56 which stored 3.09 kWh of energy.

In Figure 47(c), energy stored by each PCM during daily peak water usage profile is shown. Sodium acetate with graphite has stored 5.46 kWh i.e. the maximum amount of energy among all PCMs while Paraffin 56 has stored the least amount of heat i.e. 3.32 kWh. RT60 has stored 3.64 kWh oh energy.

Figure 47(d) shows the values of energy stored for ASHRAE profile. Among all PCMS, sodium acetate with graphite has stored 6.2 kWh, RT 60 3.65 kWh while paraffin 56 stored 3.29 kWh of energy.

As mentioned in methodology section, the values of energy mentioned above is the energy stored from 45 ºC onwards until phase change completion. If due to high hot water requirement, PCM could not charge fully, then maximum amount of energy stored on 29th August is taken. The difference in values of energy is because of the difference in the extent to which phase change phenomena was carried on.

Moreover, the thermocouple used for measuring the temperature was placed at the bottom of module and if it shows the value of temperature above the melting range of a PCM, it means that whole PCM has melted. If the temperature mentioned by thermocouple does not reach the end of melting range, it means that a certain amount of PCM is still not fully melt. This can affect the values of energy.

Moreover, it may happen that by the time PCM at bottom melts, the volume of PCM in the upper nodes have started storing the sensible heat because they have completed the phase change phenomena. That is why we have a difference in the values of energy stored for a PCM in different profiles. Sodium acetate with graphite stored maximum energy in ASHRAE profile. RT60 and Paraffin 56 stored maximum energy in UK and daily peak profile respectively.

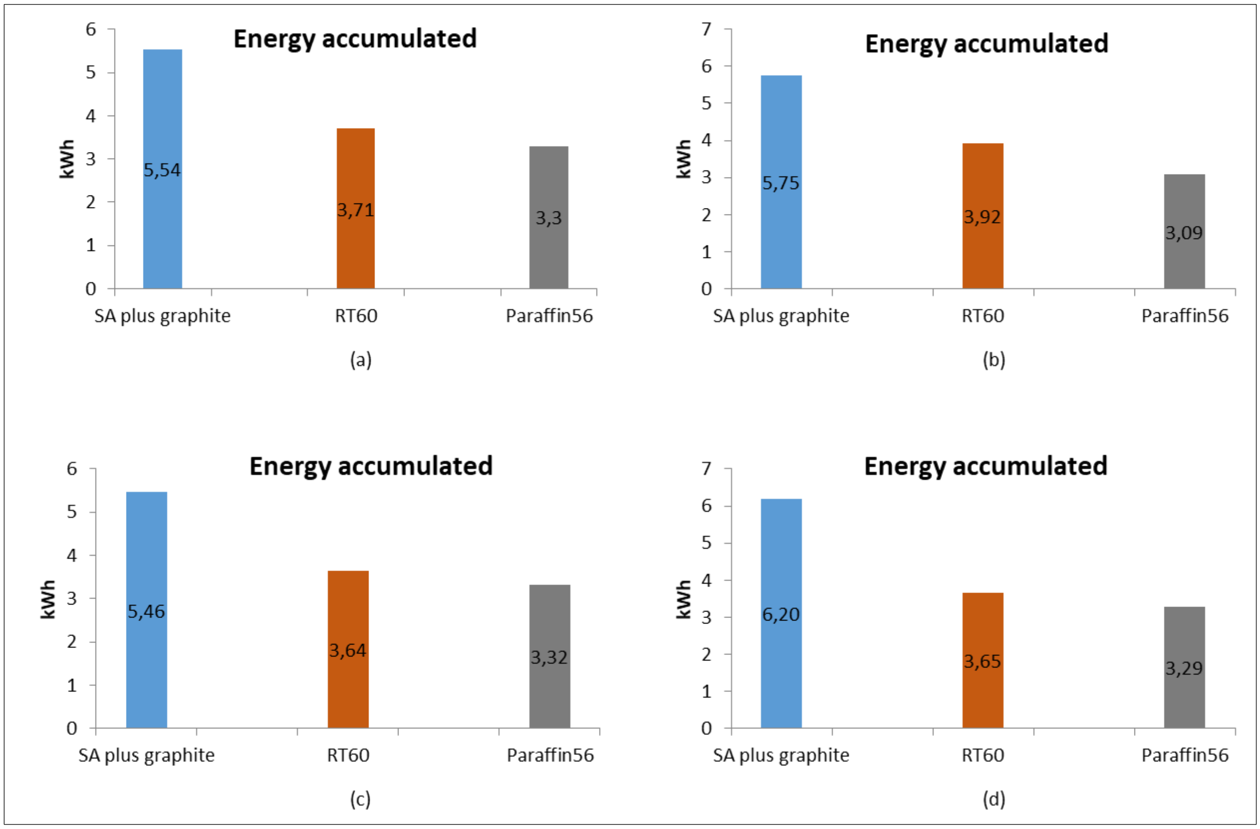

Figure 47 Comparison of accumulated energy of three PCMs for (a) Multi dwelling profile (b) UK profile (c) Daily peak profile (d) ASHRAE profile

4.3.4. Energy recovery ratio (ERR)

The ratio of heat released to heat stored taking into account the time needed for charging and discharging is called energy recovery ratio. It shows the amount of heat recovered as a result of discharging of a PCM. Looking at the result obtained for energy recovery ratio, it can be seen that RT60 has the highest recovery ratio among all PCMs. RT60 maintains this highest ratio among all water withdrawal profiles. Paraffin 56 has the highest recovery ratio after RT60 while sodium acetate with graphite has the lowest recovery ratio. Figure 48 displays all the results for energy recovery ratio for all water profiles.

The reason why RT60 has highest recovery ratio is because of the fact that there is no hysteresis present in this material. In reality, this is not possible as every phase change material has its shortcomings in the form of either hysteresis or subcooling. The data used for RT60 was taken from data sheet provided by Rubitherm and not by analysing the properties in thermal analyser. This datasheet can be seen in annex-A. The information provided in the datasheet shows RT60 as a perfect material with no hysteresis and subcooling effect. Both sodium acetate with graphite and Paraffin56 have hysteresis and subcooling and depict low energy recovery ratio.

Another important reason for low energy recovery ratio is the long duration of discharging process. From equation 11, it can be seen that if discharging time is higher, then recovery ratio will be low. The charging time of the PCMs is in the range of 3 to 5 hours. The discharging of PCMs is very slow. These PCMs take almost 20 to 25 hours to reach the temperature of 30 ºC.

It is important to mention here that the thermocouple used for measuring values is the one at the top of module. So, if this thermocouple gives a value lesser than the melting point of a PCM, it means that all other nodes of the module have already solidified. The procedure to determine the exact discharging and charging time is tricky. The best way to find these times will be to build a prototype and see the charging and discharging phenomena. It is possible to find out an estimated discharging time by taking average of temperatures of all the thermocouples when they reach 30 ºC. This is time consuming and that is why this idea was dropped. The results however direct towards long discharging times.

Looking at the values of energy recovery ratio in Figure 48, the PCM RT 60 has a higher value as compared to other two phase change materials. PCM RT60 has the highest value of ERR in daily peak profile. Sodium acetate has highest energy recovery ratio value in multi dwelling profile.

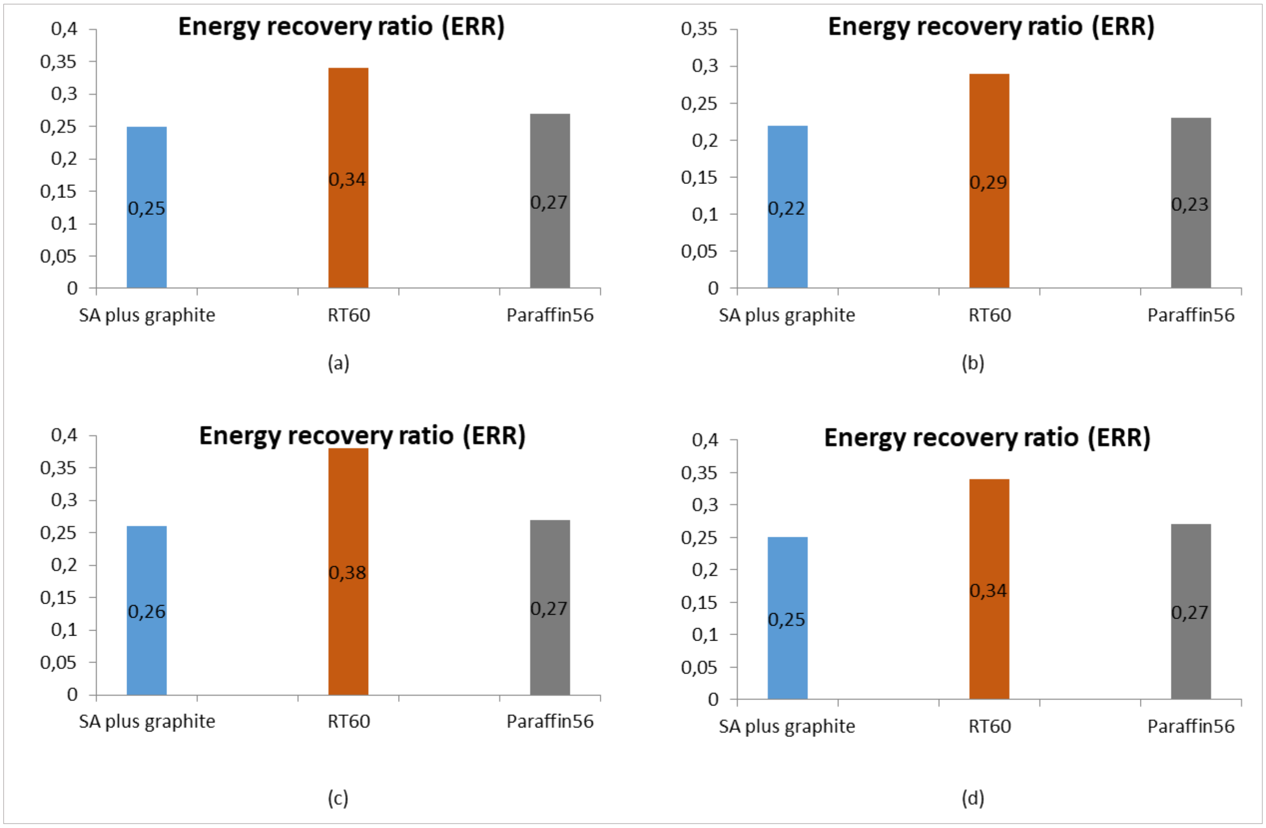

Figure 48 Comparison of ERR of three PCMs for (a) Multi dwelling profile (b) UK profile (c) Daily peak profile (d) ASHRAE profile

4.3.5. No. of hours taken by a certain PCM to maintain water above 50 ºC

In Figure 49, number of hours have been mentioned for which water is kept above 50 ºC. Sodium acetate with graphite has performed exceptionally well in this criterion. It is important to mention here that for this criterion, connection from heat exchanger was cut off and cold water was allowed to enter storage tank following a certain water profile. Water inside tank had a temperature of 65 ºC initially and it dropped as the cold water started flowing in. A visible difference in water temperatures can be seen because of PCM presence inside the tank.

It takes 21.38 hours to retain water above 50 ºC without the presence of any PCM. It can be seen from the Figure 42 that PCM sodium acetate with graphite prolongs the time for which water remains at an elevated temperature. RT60 has barely managed to prolong the time to keep water at an elevated temperature. In Figure 49(a), it can be seen that sodium acetate with graphite kept water at an elevated temperature for a longer period than RT60 and paraffin56. It means that if there is no heat source and once PCM temperature reaches 65 ºC, hot water at temperature above 50 ºC can be provided for more than one whole day.

Normally, electric heaters are present in the tank which keep water hot enough to meet the demand. In this thesis, no heater was present inside tank and solar irradiance was the only source of heat. In Figure 49(b), sodium acetate with graphite has again outperformed other two PCMs by keeping water above 50 ºC for 29 hours during water withdrawal according to UK profile. RT60 and Paraffin56 could do so only for 20 hours. As previously mentioned, in the absence of PCM, water temperature remains above 50 ºC for 21.38 hours.

Looking at the performance of RT60 and Paraffin56, it can be concluded that there is no significant improvement in the domestic water heating system. In Figure 49(c) and Figure 49(d), number of hours have been mentioned for profiles daily peak and ASHRAE. Sodium acetate with graphite has better performance for this profile as compared to RT60 and Paraffin56.

In Figure 50 below, discharging pattern of water is given when PCM sodium acetate with graphite is present in the tank. This discharging pattern is for ASHARE profile. PCM effect is very obvious in this discharging profile as the heat released by PCM keeps water warm for a longer period. If we analyse the figure carefully, we can see that presence of PCM keeps water above 50 ºC for a longer time duration as compared to the absence of PCM in storage tank.

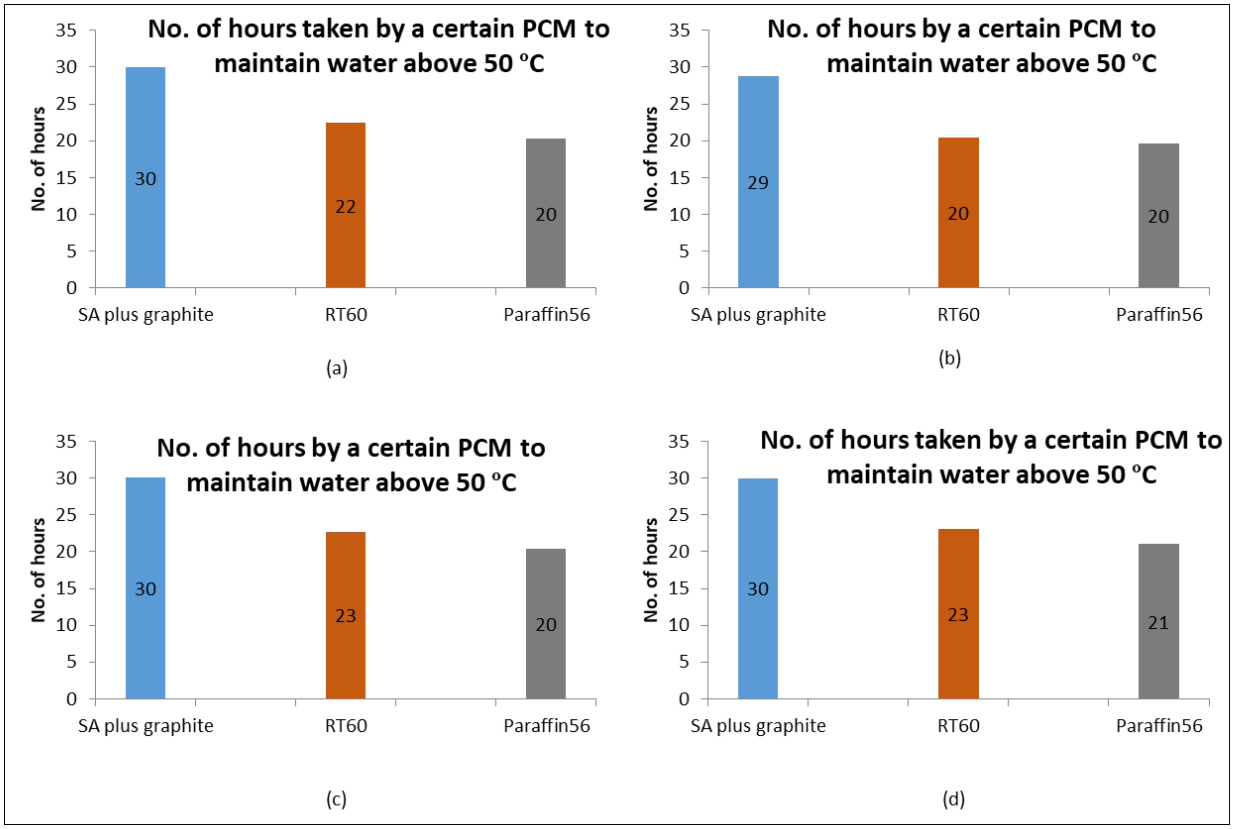

Figure 49 Comparison of No. of hours taken by three PCMs to maintain water above 50 ºC for (a) Multi dwelling profile (b) UK profile (c) Daily peak profile (d) ASHRAE profile

The PCM effect is visible in Figure 50 below. Sodium acetate with graphite has produced good results in terms of maintaining water at high temperatures. Water temperature remains stable inside the tank because of PCM presence. Sodium acetate also has a higher potential to store energy and that is why the PCM effect being produced is very obvious and significant.

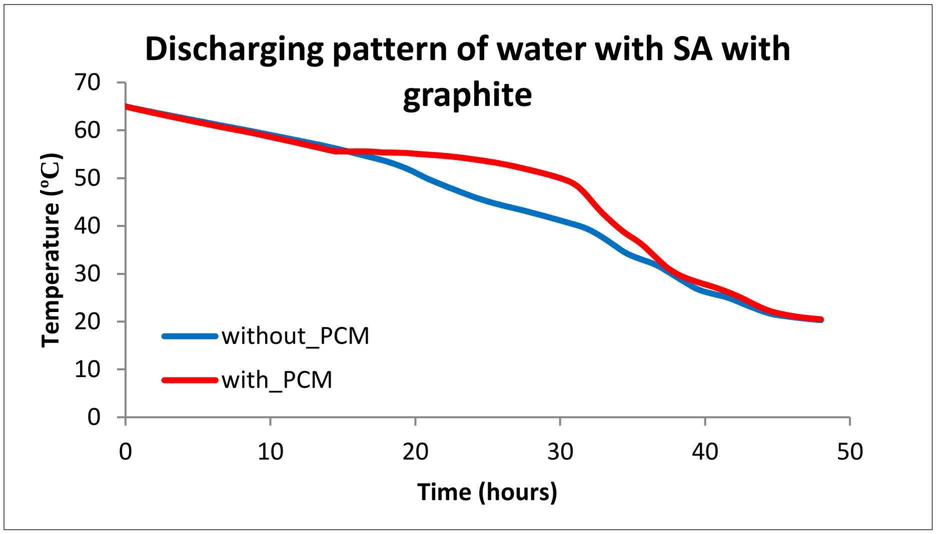

Figure 50 Discharging profile of water with SA plus graphite for ASHRAE

Looking at Figure 51 which shows the discharging pattern of water with PCM RT60, it can be seen that difference is not so obvious. So RT60 brought a very little improvement to system.

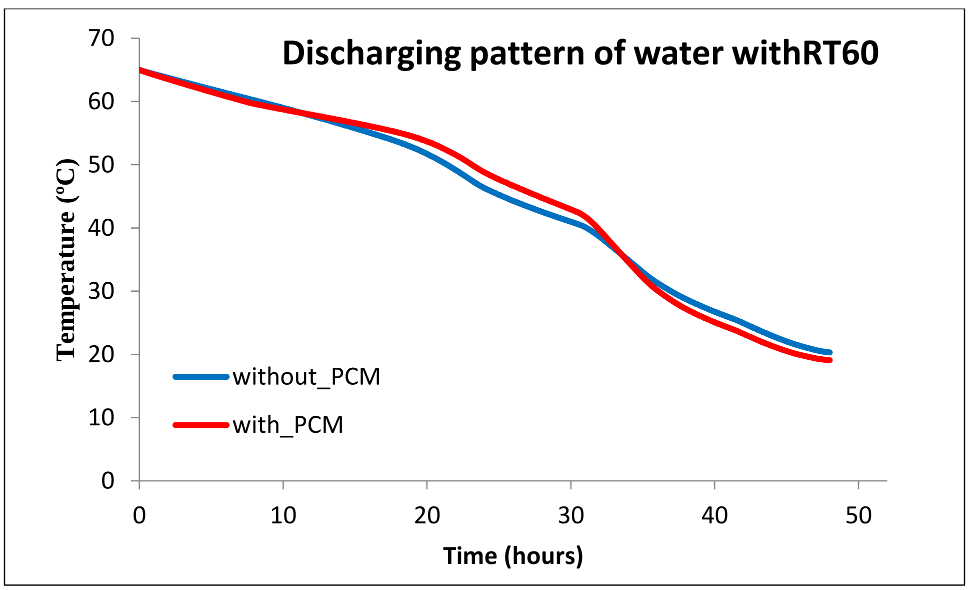

Figure 51 Discharging profile of water with RT60 for ASHRAE

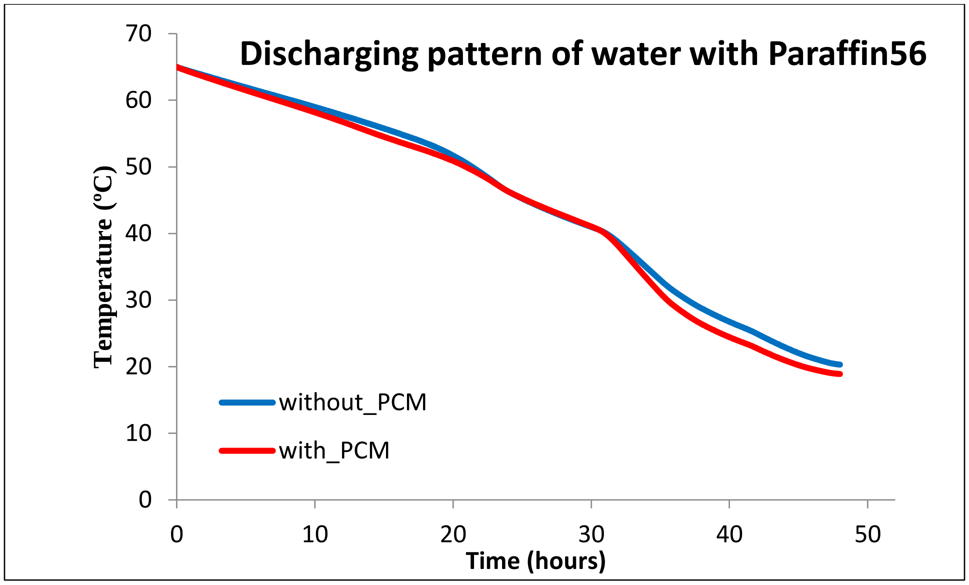

Figure 52 Discharging profile of water with Paraffin56 for ASHRAE

Figure 52, which shows the discharging pattern in the presence of Paraffin56, displays that Paraffin56 didn't bring any improvement to system. Throughout the discharging, water temperature in the presence of Paraffin56 remained at a lower temperature than water without Paraffin56.

The discharging of water along with PCM has been shown in Figure 53 below. This picture shows that PCM present in the bottom of module is the quickest to release heat. The reason is that cold water enters from bottom of tank. The PCM present at the top of module takes long in discharging all the heat. Water remains at a temperature lower than the maximum temperature of PCM. So, water is being charged every moment until the temperatures of both PCM and water become equal. Here, temperature sensors have been installed at bottom, top, 0.2 and 0.7 times height of water tank. The discharging profile of all other PCMs under study is almost the same. Therefore, only one illustration has been shown.

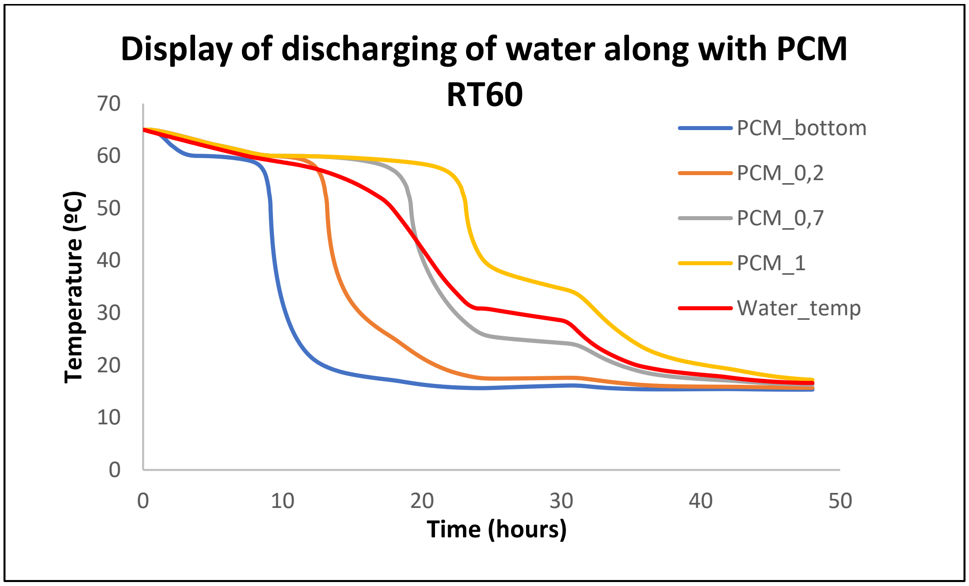

Figure 53 Discharging of water and PCM RT60

The discharging of PCM sodium acetate with graphite has also been shown along with the temperature of water in the Figure 54 below.

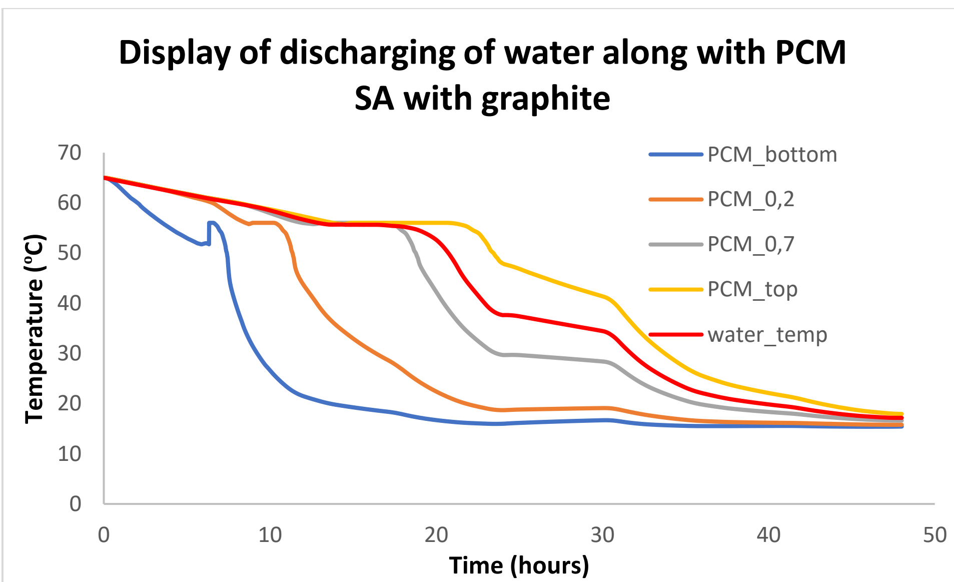

Figure 54 Depiction of discharging of PCM SA plus graphite along different heights

In Figure 55 below, the discharging of Paraffin56 along with water has been shown. The temperature of PCM at different heights of module is also given.

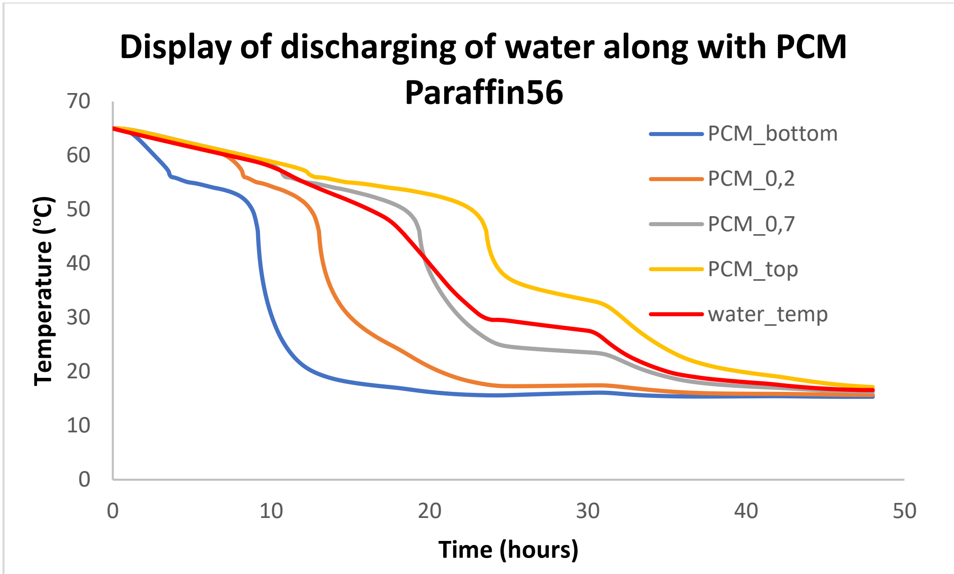

Figure 55 Depiction of discharging of PCM Paraffin56 along different heights

4.3.6. Conclusion

After looking carefully at all the results, sodium acetate trihydrate with graphite comes out to be most suitable PCM. Although it has high charging time, low energy recovery ratio but its performance, which was evident from number of hours for which it kept water above 50 ºC and energy accumulated, was impressive. It helped in saving money also and reduced the carbon footprint. Financial savings and reduction in carbon footprint are discussed in headings below.

4.4. Energy and financial savings

The increase in solar fraction represents improvement in system. This improvement is not only in terms of performance but also in financial terms. Presence of PCM inside tank acted as a heat source inside and reduced the working of electric heaters. Savings made are different for each profile. It is a well-known fact that prices vary throughout the day according to consumption and demand. However, for the sake of simplicity, 0.17 €/kWh was taken as unit price.

There was a sharp reduction in the usage of electric heater because of PCM effect. Heater working was reduced by 38% for UK profile, 22% for daily peak profile, 25% for multi dwelling profile and 23% for ASHRAE profile. Financial savings per year made for each profile by using sodium acetate trihydrate with graphite are given below in Figure 56.

A complete and accurate analysis have not been made. To get an estimate of the prices of PCM, a quotation from Rubitherm is in annex-A.

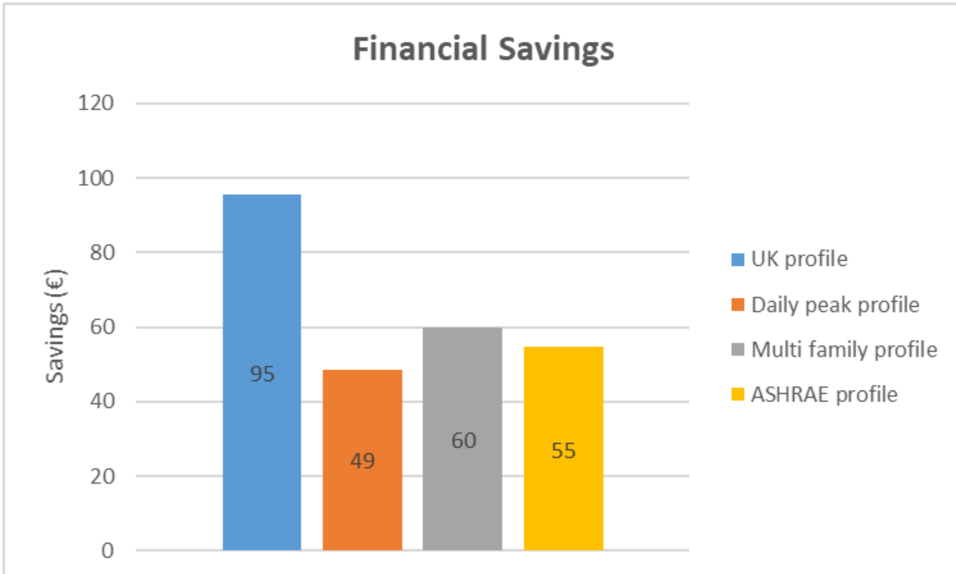

Figure 56 Financial savings per year for each profile

4.5. Reduction in carbon footprint

Carbon footprint is measured in terms of grams of carbon dioxide equivalent per kilowatt-hour. Carbon dioxide is the most harmful greenhouse gas. Therefore, carbon footprint of heating technologies is calculated in terms of CO_2 emissions.

The results obtained in the Figure 57 show that carbon footprint was reduced by 38% for UK profile, 22% for daily peak profile, 25% for multi-dwelling profile and 23% for ASHRAE water withdrawal profile. The carbon footprint of an electric heater is 370 gCO2eqkWh [42].

In the absence of PCM, lowest carbon footprint is reported for daily peak profile. The biggest reduction in footprint is for UK profile which is 38%. The values for carbon footprint in the absence of PCM for UK, daily peak, multi dwelling and ASHRAE profile are 542616, 485515, 518847 and 508108 gCO_2eq/kWh respectively. Figure 57 shows the carbon footprint for each profile.

Similarly, the values of carbon footprint for UK, daily peak, multi dwelling and ASHRAE profile after incorporating PCM came out to be 334897, 379734, 388726 and 389380 gCO_2eq/kWh respectively.

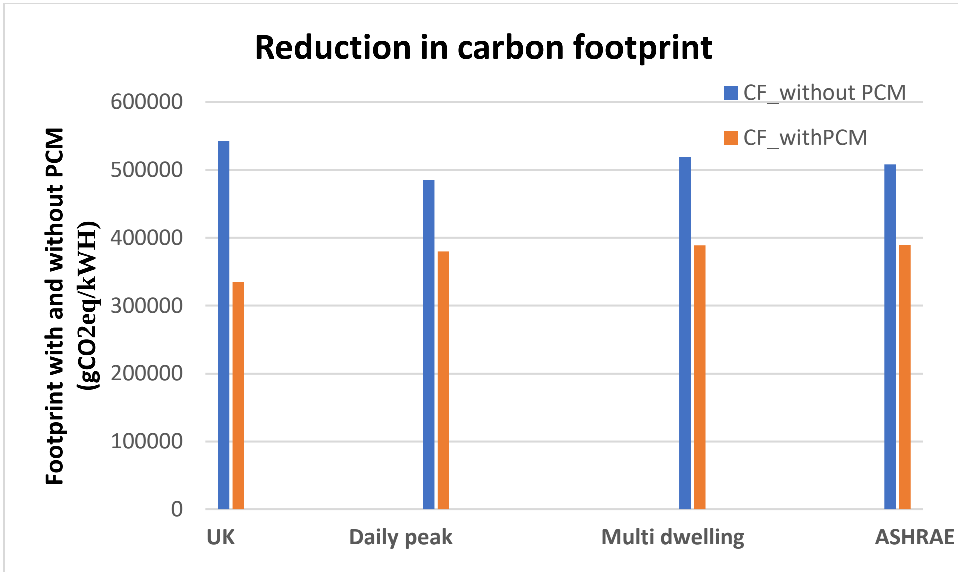

Figure 57 Comparison of carbon footprint in presence and absence of PCM SA plus graphite

5. Conclusions and future recommendations

In the past few decades, an extensive research has been made in the field of thermal energy storage. This field has a huge potential to increase the sustainability of systems. Moreover, carbon footprint can also be reduced by incorporating material exhibiting thermal energy storage behaviour in to certain systems. Use of phase change materials is one of the ways to store thermal energy. These phase change materials can be organic or inorganic. There have been many projects in progress which are trying to find more innovative ways of thermal energy storage. In this thesis, three different phase change materials have been studied for four different water withdrawal profiles namely sodium acetate with graphite, RT60 and Paraffin56. These phase change materials were incorporated with the domestic solar water heating system. The task was to find if the inclusion of PCM brings sustainability in the performance of systems. Two different shapes i.e. spherical and cylindrical and three different concentrations of selected phase change material were taken in to account to analyse the performance of system.

Shape and volume of PCM were first selected according to a pre-set criterion. This criterion included charging time, energy accumulated and number of hours for which water was kept above 50 ºC by a certain PCM. The response and behaviour of all PCMs were studied extensively. All of the relevant results have been mentioned in the results section. The results obtained can be useful for industry related to solar thermal and thermal energy storage. Moreover, results obtained can also serve as an introduction of behaviour of above mentioned three phase change materials.

There are certain drawbacks associated with phase change materials. The most important ones are cycle life, subcooling, hysteresis and prolonged charging times. The benefits of higher energy storage density, more stable and consistent water temperature and enhanced sustainability supersede the drawbacks. The savings associated with using phase change materials in solar hot water system have also been mentioned. The results obtained show that carbon footprint was also reduced considerably. The highest reduction was obtained for UK profile and results suggest that carbon footprint was reduced by 38%. Sodium acetate with graphite is tipped to be the most suitable phase change materials among the studied ones. Although, its high energy storage density and ability to stabilize water temperature for a prolonged time comes at the cost of subcooling and hysteresis but its performance was best among all the phase change materials.

All the results were obtained by carrying out simulations in TRNSYS software. Although simulations are a good way to avoid straightaway spending on experimental setup but results from a practical experimental setup would be needed to validate the model. The transient systems specially, need practical experiments for validation. As mentioned previously, properties of RT60 were taken from a datasheet and not from thermal analyser and that's why it didn't show any signs of subcooling and hysteresis. It is recommended that tests should be run on this material in thermal analyser. Moreover, pure paraffin in the range of 60 ºC should be tested in order to see the performance of system. Paraffin56 is not a pure material and it has been proved by the results obtained through thermal analyser. More organic, inorganic and eutectic PCMs should be analysed for integrating with solar water heating systems.

Moreover, it will be interesting to see the economic viability of incorporating PCMs to such systems. In this thesis, only savings have been mentioned and it would be better if a complete techno-economic analysis is carried out to see the investment return period. The calculations have been made with electric heater. It will be interesting to see the comparison in savings from gas and an electric heater.

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Annex-A

All the data sheets used for carrying out this thesis have been shown in this section. This section includes PCM RT60 datasheet. Moreover, quotation from Rubitherm for having an estimate of price of PCM is also given.

1. **Data sheet for RT60**

Data sheet

RUBITHERM

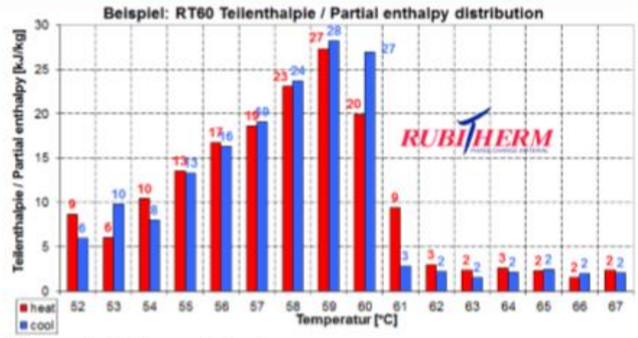
RT60

RUBITHERM® RT is a pure PCM, this heat storage material utilising the processes of phase change between solid and liquid (melting and congealing) to store and release large quantities of thermal energy at nearly constant temperature.
The RUBITHERM® phase change materials (PCM's) provide a very effective means for storing heat and cold, even when limited volumes and low differences in operating temperature are applicable.

We look forward to discussing your particular questions, needs and interests with you.

Properties for RT-line:
- high thermal energy storage capacity
- heat storage and release take place at relatively constant temperatures
- no supercooling effect, chemically inert
- long life product, with stable performance through the phase change cycles
- melting temperature range between -9 °C and 100 °C available

The most important data:	Typical Values	
Melting area	**55-61** main peak: 60	**[°C]**
Congealing area	**61-55** main peak: 61	**[°C]**
Heat storage capacity ± 7,5%	**160**	**[kJ/kg]***
Combination of latent and sensible heat in a temperatur range of 53°C to 68°C.	**40**	**[Wh/kg]***
Specific heat capacity	**2**	**[kJ/kg·K]**
Density solid at 15 °C	**0,88**	**[kg/l]**
Density liquid at 80 °C	**0,77**	**[kg/l]**
Heat conductivity (both phases)	**0,2**	**[W/(m·K)]**
Volume expansion	**12,5**	**[%]**
Flash point	**>200**	**[°C]**
Max. operation temperature	**80**	**[°C]**



Rubitherm Technologies GmbH
Imhoffweg 6
D-12307 Berlin
Tel: +49 (30) 7109622-0
Fax: +49 (30) 7109622-22
E-Mail: info@rubitherm.com
Internet: www.rubitherm.com

The product information given is a non-binding planning aid, subject to technical changes without notice. Version: 06.08.2018

Measured with 3-layer-calorimeter.

2. Quotation for RT60 and SP58

RUBITHERM

Rubitherm Technologies GmbH
Imhoffweg 6
12307 Berlin
www.rubitherm.com
Tel: +49 30 71 09 622-0
Fax: +49 30 71 09 622-22

OFFER

Instituto Superior Tecnico
Omais Abdur Rehman
Loisbon
PORTUGAL

Number : 20190000622
Date : 22.10.2019
Customer : 90001
VAT-ID : DE

Pos.	Part-ID / Description	Quantity	U-Price UQ	Ex-Price S
	We thank you for your interest in Rubitherm products and can offer as follows:			
1	16010060 RUBITHERM RT60 HS-code: 27122090	20 kg	5,95	119,00 1
2	16060058 RUBITHERM SP58 HS-code: 29152900	20 kg	6,70	134,00 1
3	96020104 Packaging	1	10,00	10,00 1
4	96020100 cost for shipping (*)	1	65,00	65,00 1

The prices are valid till 31st October 2019

By ordering our material you declare to accept and be bound by the conditions stated below.

Orders with a product value <150,00EUR or >5 products in sample quantity carry a 42,00EUR minimum order surcharge

Delivery terms: DAP Lisbon
If agreed Rubitherm can arrange the transportation with a third forwarder. (*)Please note, that the quoted shipping prices can differ from the shipping costs at delivery date due to surcharges that are included in the price which are subject to fluctuations on the market. Rubitherm reserves the right to charge the cost difference to the customer and the customer agrees to pay this difference.

Standard lead- time: within 4-6 weeks after payment
excl. shipping provided an uninterrupted production

Payment condition: New customers have to pay the first delivery upfront. Otherwise 10 days net after date of invoice via wire transfer or check. Credit cards are not accepted.

amount carried forward	EUR	328,00

RUBITHERM

Rubitherm Technologies GmbH
Imhoffweg 6
12307 Berlin
www.rubitherm.com
Tel: +49 30 71 09 622-0
Fax: +49 30 71 09 622-22

Offer 20190000622 Date 22.10.2019 Page 2

Pos.	Part-ID/ Description	Quantity	U-Price UQ	Ex-Price S
				328,00

Netto VAT.1	VAT 19,00%	Netto VAT. 2	VAT	%	Netto VAT. 0		Total Amount
328,00	62,32					EUR	390,32

Rubitherm Technologies GmbH, Imhoffweg 6, 12307 Berlin
CEO: Thomas Braun, Lutz Klinkner
Comm. Reg no.: Berlin-Charlottenburg, HRB 86322 B

Hypo-Vereinsbank, acc. No.: 572 64 17, bank code: 700 202 70
IBAN: DE12 7002 0270 0005 7264 17 SWIFT: HYVEDEMMXXX
VAT ID: DE 230 027 919

ITZERT ISO 9001:2015