Integration of Solar Domestic Water Heating System with Thermal Energy Storage based on Phase Change Materials

Omais Abdur Rehman
omais.rehman@tecnico.ulisboa.pt

Instituto Superior Técnico, Universidade de Lisboa, Portugal
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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(PCM) 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 hydrate 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.

Nomenclature

PCM	Phase change material
SDHW	Solar domestic hot water
SA	Sodium acetate
PV	Photovoltaic
STC	Solar thermal collector
H	Enthalpy
kWh	Kilo watt hour
ERR	Energy Recovery Ratio
TRNSYS	Transient system simulation
RT	Rubitherm

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 organic or inorganic. For high temperature applications, salts (e.g. NaCl salt) 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 a carbon footprint equals to zero and is energy efficient. Researches in many countries are underway to find suitable PCMs 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 SDHW systems.

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 disease 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.

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 important points here to consider will be the charging and discharging time of all these PCM used. Moreover, heat transfer along the length and breadth of PCM container also matters a lot, as this is one of the biggest limitations in using PCM.

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. In the previous studies, focus was on determining if thermal energy storage will help in increasing sustainability. In this research, one PCM would be selected according to the weather conditions of Lisbon, Portugal. The results of this research can also be used in the parts of world where solar irradiation and weather conditions match that of Lisbon and same 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 of methodology. All the details from selection of PCMs to TRNSYS simulation parameters have been discussed in this 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 section include all the results obtained through simulations via TRNSYS. All important results have been mentioned and explained. Conclusion and recommendations chapter consists of a recap of what has been done in this thesis. Recommendations have been given to improve and validate the simulation model.

2. LITERATURE REVIEW

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. 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.[5]

A comparison of power production from different renewable sources has been shown in table 1 below:

Table 1: Comparison of global power capacity of different renewable energy sectors[5]

Order	Power capacity	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	Solar therm.	3.4	4.4	4.8
7	Wind power	319	370	433

Solar water heating system consists of a solar panel, 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.[6] 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.[7] 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.[8]

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

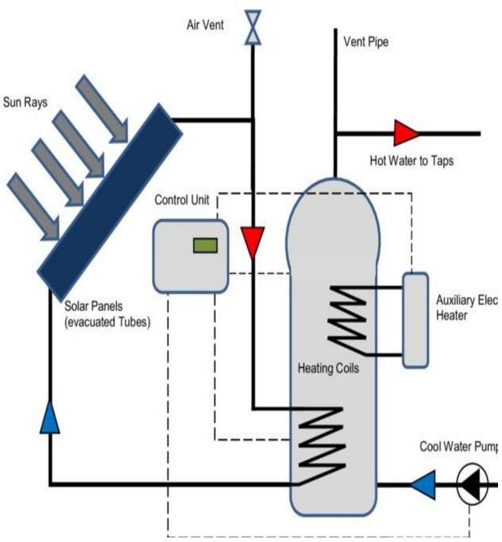

Figure 1 Solar water heating system[9]

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.[10]

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 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.[11]

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.[12]

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.

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.[13] 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.[13]

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.[13]

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.[14]

3. MATERIALS AND METHODS

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.[15] As the recommended temperature of domestic hot water systems is 60 ºC, so phase change materials with melting temperature around 60ºC were required.[16] 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. Heating and cooling curve of sodium acetate with graphite has been shown in figure 1 below.

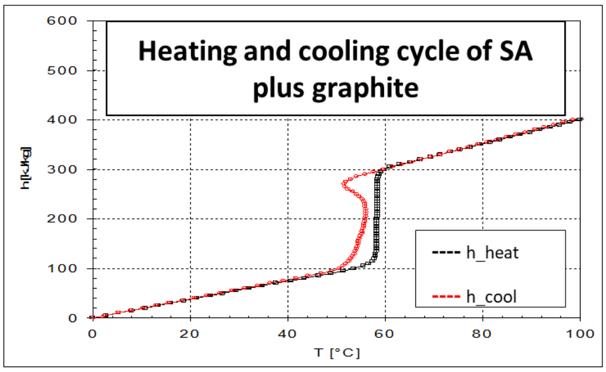

Figure 1: Heating and cooling curve of SA with graphite

Heating and cooling curve of RT60 has been shown in figure 2 below.

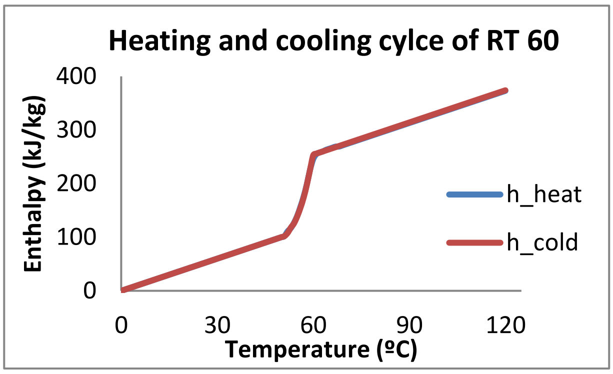

Figure 2: Heating and cooling curve of RT60

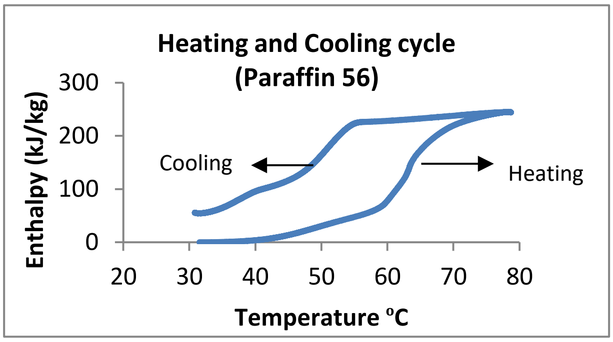

Figure 3: Heating and cooling curve of Paraffin56

Heating and cooling curve of Paraffin56 has been shown in figure 3 below.

User 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.
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 m3 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.[17]

3.2. TRNSYS simulations

For simulation purposes, TRNSYS software has been used. The mentioned software is being used for different transient systems. In fact, TRNSYS is originated 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. All important TRNSYS components have been explained below. These components include solar panel, water storage tank, weather file, electric heater and load profile. Simulation setup has been shown in figure 4 below.

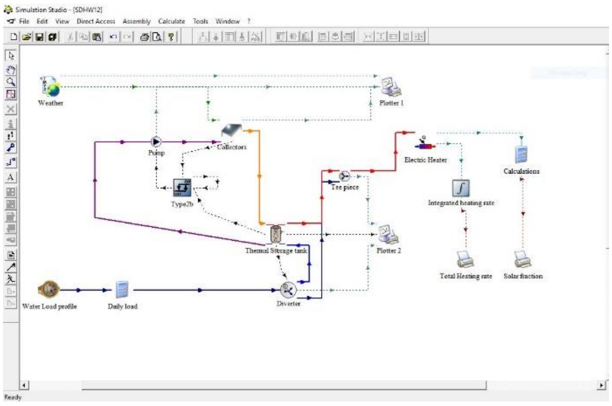

Figure 4: Simulation setup in TRNSYS

Type 840 water tank, shown in figure 5, 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. [18] 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.

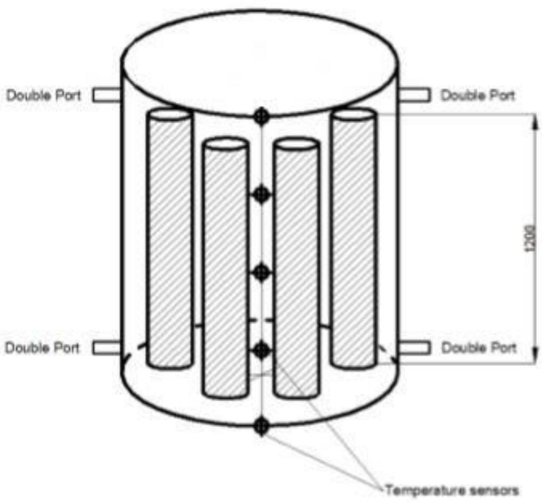

Figure 5: Type 840 with PCM modules

The basic equation for energy accumulation for PCM is as follows as equation 1:

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

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 as equation 2:

$$X = (T - T_s)/(T_l - T_s) \ (2)$$

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.
Total number of modules are selected to be 8. The diameters of modules for different volumes of PCM are given in the following table 2:

Table 2: Diameters of PCM module for respective 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

The simulation parameters are as follows in table 3:

Table 3: Simulation parameters

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
Outlet height (Both double ports) 1.33 m
Inlet height (Both double ports) 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 (Do) 22 mm
Inner diameter (Din) 20 mm
Length of HX pipe 20 m

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.

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 (3) also. The units of this parameter are 'hours'.

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.

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'.

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.

4. RESULTS AND DISCUSSION
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.

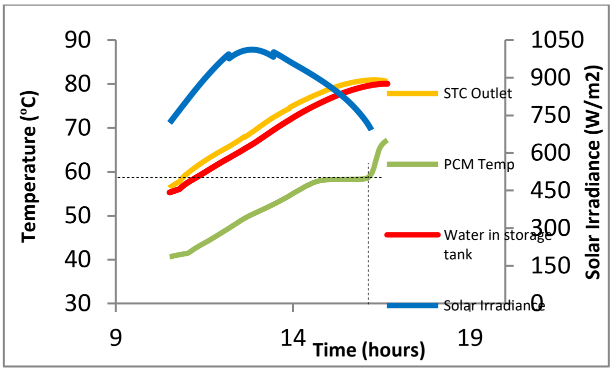

Figure 6: Charging of SA with graphite

Charging of sodium acetate is shown in figure 6.
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. Charging of RT60is shown in figure 7.

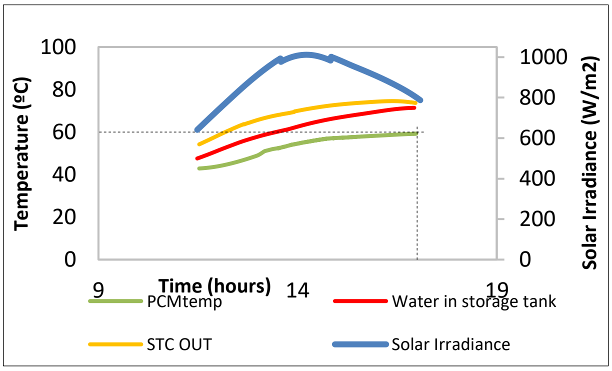

Figure 7: Charging of RT60

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. Charging of Paraffin56 is shown in figure 8.

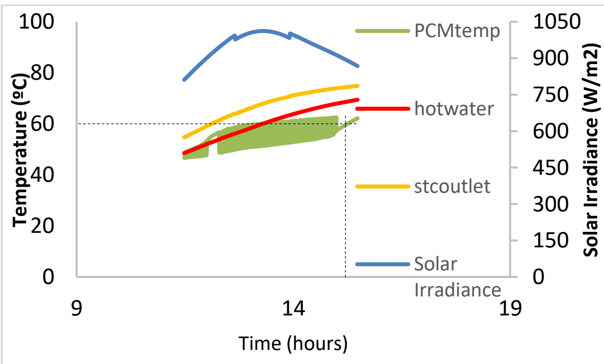

Figure 8: Charging of Paraffin56

Charging time of three PCMs for all four water profiles have been given in figure 9 below. In real world scenario, there is no chance of a sudden phase change.

There can be many reasons for it. The diameter of module also matters because heat will take more time to penetrate the region with more thickness. 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.

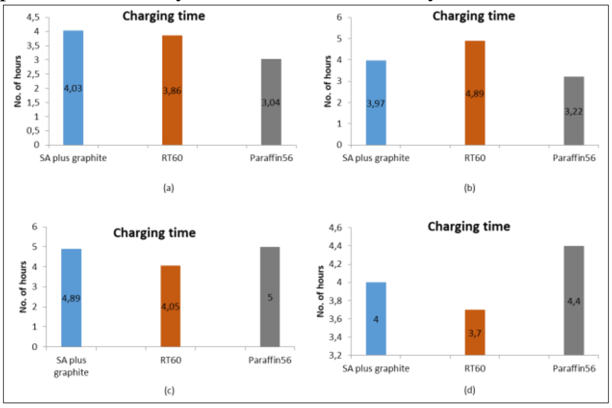

Figure 9: Comparison of charging times

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 10(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.

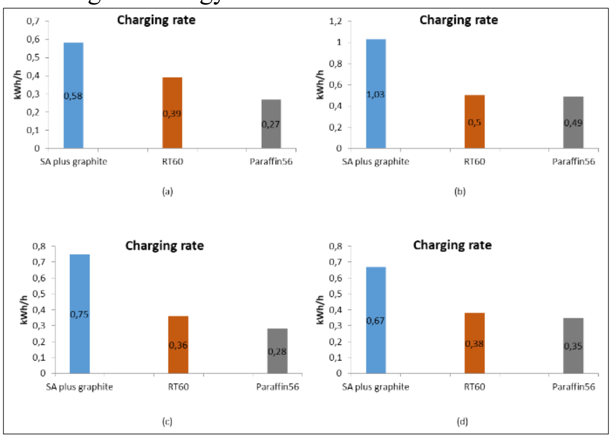

Figure 10: Comparison of charging rates

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 11(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.

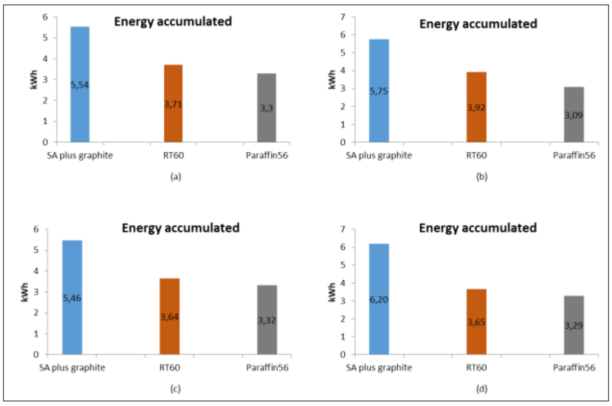

Figure 11: Comparison of energy accumulated

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 12 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.

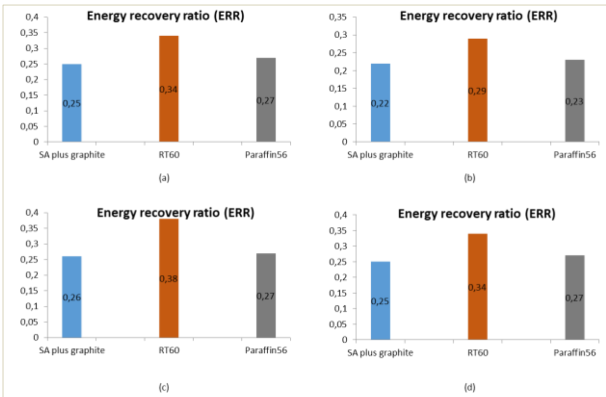

Figure 12: Comparison of energy recovery ratio (ERR)

Sodium acetate with graphite has performed exceptionally well in the criterion of keeping water at elevated temperatures. 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 as shown in figure 13.

It takes 21.38 hours to retain water above 50 ºC without the presence of any PCM. It can be seen from the figure 43 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.

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 (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.

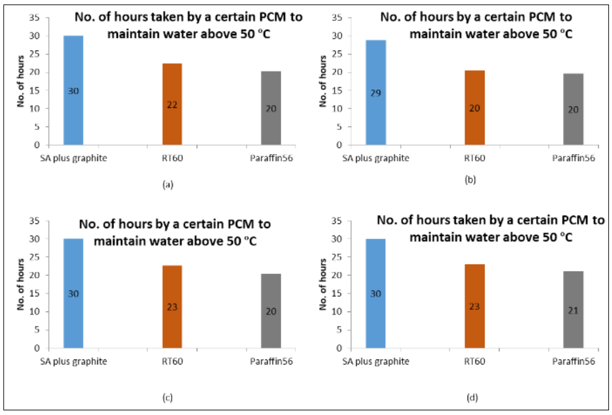

Figure 13: Comaprison of no. of hours for maintaining water at elevated temperatures

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 13(c) and (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.

The PCM effect is visible in figure 14 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.

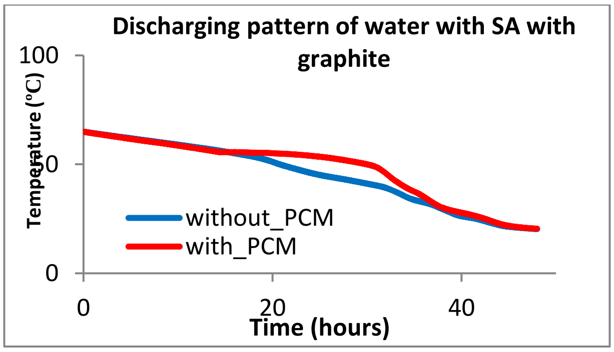

Figure 14: Discharging pattern of water with SA with graphite

Looking at figure 15 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.

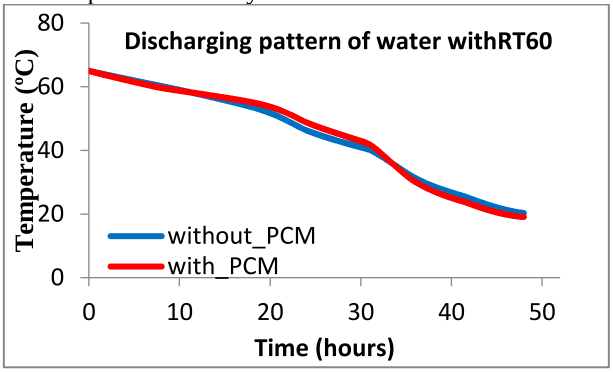

Figure 15: Discharging pattern of water with RT60

Figure 16, which shows the discharging pattern in the presence of Paraffin56, displays that Paraffin56 did not bring any improvement to system. Throughout the discharging, water temperature in the presence of Paraffin56 remained at a lower temperature than water without Paraffin56.

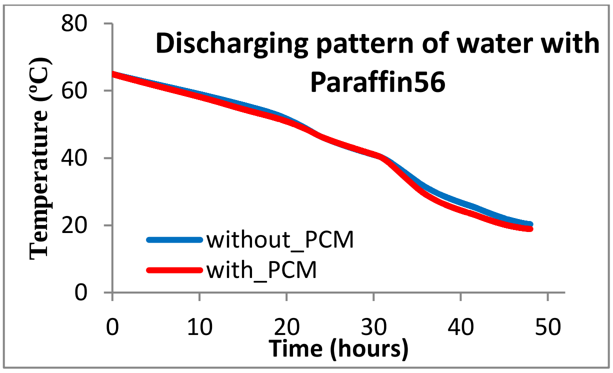

Figure 16: Discharging pattern of water with SA with graphite

5. Summary

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. Sodium acetate with graphite emerges as the most suitable PCM according to Lisbon climate.

6. Future work

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 paraffins 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.

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