Evelution and Comparison of Phase Change Materials (PCMs) in a Spherical Capsule

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Abstract:
The present study is focused on CFD simulation of constrained melting of Phase Change Materials (PCMs) in a spherical container. To investigate the melting process of the PCM, its melting fraction was analyzed at different times. The results indicated the existence of thermally stable layers on the top of the sphere. Moreover, inspection of the calculated temperatures at different points along the vertical axis indicates the existence of some disturbances at the bottom of the sphere due to the natural convection. After the validation of the results, the effects of different parameters such as the surface temperature of the capsule, the initial temperature and the size of the spherical capsules, on the melting process were investigated. The initial temperature did not affect the melting rate, whereas melting rate increased by increasing the surface temperature of the capsule and also decreasing the diameter of the sphere. The results showed that the surface temperature of capsule compared to geometrical parameters and other operational conditions can have a greater influence on the melting rate and the heat flux . Comparing with different materials to estimate the characteristics of phase change materials.

Keywords: Phase Change Material, SAT, Paraffin wax, characteristics of PCMs.

1. INTRODUCTION

Recently, latent heat thermal energy storage systems have been widely applied in cool storage for central air-conditioning, hot storage for air heating, solar energy, energy efficient buildings and waste heat recovery. Storage systems allow for the efficient and rational utilization of the available resources or renewable energies, by using the time lag between production, as well as the availability of the energy and its consumption in the demanding systems. Phase change materials (PCM) are mainly used to provide higher storage densities. As a serious problem PCMs have relatively low thermal conductivities. Therefore, increasing the surface/volume ratio of PCMs in order to increase the heat-transfer rate is very appealing. This can be done by packing a volume with a great number of PCM capsules. The spherical geometry is one interesting case for heat storage applications, since spheres are much employed in packed beds. Due to the complexity of such systems, it is often more effective to first model the behavior of an individual sphere and then describe it with a simple parametric model in the packed bed modeling. Roy and Sengupta (1989) examined the melting process with the solid phase initially uniformly super cooled. In order to include the effects of a temperature gradient in the solid core, they modified the heat transfer equation. At each time step, the unsteady conduction equation has been solved numerically using a toroidal coordinate system with a suitable immobilization of the moving boundary to transform the infinite domain into a finite one. In another paper (Roy and Sengupta, 1990), they investigated the outcome of natural convection on the melting process. In order to reduce the computational effort and the time, they made some simplifications. They obtained the non-dimensional melting time and the heat transfer coefficient as functions of the PCM property values, the operating temperature and the physical size. Ettouney et al. (2005) experimentally evaluated the heat transfer (during energy storage) and release for the phase change of paraffin wax in the spherical shells. They showed

that an increment in the Nusselt number of the sphere with a larger diameter is attributed to the increase in the natural convection cells in the PCM inside the sphere.The natural convection role is enhanced upon an increase in the sphere diameter and the air temperature. On the other hand, during solidification the wax layers are formed inward, nucleating on the sphere walls. As solidification progresses, the melt volume becomes smaller and the role of natural convection diminishes rapidly. Khodadadi and Zhang (2001) also considered the effects of buoyancy-driven convection on the constrained melting of phase change materials within spherical containers. They reported that during the initial melting process, the conduction mode of the heat transfer is dominant. As the buoyancy driven convection is strengthened due to the increase in the melting zone, the process at top region of the sphere is much faster than at the bottom due to the increment of the conduction mode of heat transfer. They found that buoyancy driven convection speeds up the melting process compared to the diffusion-controlled melting. Assis et al. (2007) numerically and experimentally explored the melting process of a PCM in a spherical geometry. The results of their experimental investigation, including visualization, were favorably comparable with the numerical results and therefore suitable for validation of the mathematical approach. Their computational results showed how the transient phase-change process depends on the thermal and geometrical parameters of the arrangement. Veerappan et al. (2009) investigated the phase change behavior of 65 mol% capric acid and 35 mol% lauric acid, calcium chloride hexa hydrate, *n*-octadecane, *n*-hexadecane, and *n*-eicosane inside the spherical containers to identify a suitable heat storage material. They created analytical models for solidification and melting of PCM in a spherical shell with conduction, natural convection, and heat generation and found a good agreement between the analytical predictions and the experimental data. Both models were validated with the experimental work of Eames and Adref (2002). Regin et al. (2006) examined the heat transfer

performance of a spherical capsule using paraffin wax as PCM placed in a convective environment during the melting process. The model results were in a good agreement with the experimental data. Tan (2008) investigated the melting of the phase change material (PCM) inside a sphere using n-octadecane for both constrained and unconstrained melting processes. For constrained melting, paraffin wax (n-octadecane) was immobilized, through the use of thermocouples when melting is done inside a transparent glass sphere. Their experimental setup provided a detailed temperature data that were gathered along the vertical diameter of the sphere during the melting process. Tan et al. (2009) also experimentally and numerically investigated the constrained melting of PCMs inside a spherical capsule to understand the role of the buoyancy-driven convection. In this study, a computational fluid dynamics (CFD) modeling on the constrained melting of phase change material (PCM) in a spherical container was performed. The effects of different parameters like the capsule size, the surface temperature, the initial temperature and the Stefan number, on the PCM melting process were investigated.

2 EXPERIMENTAL VERIFICATION Methods

2.1. Experimental apparatus
In order to perform the study, an experimental apparatus has been designed and developed. The main component of the apparatus is a container filled by PCM and water. The container made of a rectangular-shaped glass with dimensions of 300 mm x 100 mm x 100 mm. The objective of using glass is to make it easy for observation. The container is divided into three sections and blocked by an aluminium plate with thickness of 2 mm and area of 100 mm x 100 mm. Here, the PCM materials that are tested are Paraffin wax and Sodium acetate Tri hydrate acid. The experiments are carried out at three different heat source temperatures, they are 90oC, 85oC and 80oC, respectively. In every experiment the amount of tested PCM is 0.8 kg. The first section of the container is filled by hot water as a heat source. An electric heater is used to control its temperature. Power to the electric heater is controlled by temperature control system. The second section of the container is filled by the PCM material. The third section of the container is filled by cold water and it is kept at ambient temperature (270C - 280C) by flowing the water from hydrant. Since the first container is filled by hot water and the third container filled by cold water, while the PCM between them, the heat will be transferred from the hot water to the cold water through the PCM. In order to explore the characteristics of the system, temperatures of the PCM will be measured by using 9 J-type of thermocouples with an uncertainly of 0.1oC. Temperatures will be recorded with an interval of 1 minute by using data acquisition system Agilent 34972, a multi channels data logger. The coordinates of each thermocouple in the PCM are shown in Table 1.

Table .1. Locations of the thermocouples in the PCM

NO	THERMOCOUPLE	CO ORDINATES		
		X(mm) Z(mm)		Y(mm)
1	T1	25	25	25
2	T2	50	25	25
3	T3	75	25	25
4	T4	25	50	50

Observation of melting and solidification processes are performed using a camera by taking photos and videos. The experiments data will provide information related to the analysis of the speed of absorption and desorption of heat from the two types of the tested PCMs. As mentioned above, two types of PCM are tested in this study, they are Paraffin wax and Sodium acetate Tri hydrade acid. These PCMs are purchased from the local market in Medan city of Indonesia. Thermo-physical properties of the PCM are presented in Table 2. As a note, there are two main parameters that usually used to compare the performance of PCM as a thermal energy storage material. They are melting temperature and latent heat. It can be seen in Table 2, the melting temperature of Paraffin wax and Sodium acetate Tri hydrate acid are 59.8oC and 55.1oC, respectively. On the other hand, the latent heat of fusion of Paraffin wax and Sodium acetate Tri hydrade acid are 190 kJ/kg and 160 kJ/kg, respectively. These facts suggest that the melting point temperature and latent heat of Paraffin wax are higher than Sodium acetate Tri hydrade acid.

Table. 2. Thermo-physical properties of the phase change material on the use in research.

Table 2 – Thermophysical properties of n-octadecane.
Melting temperature 28.2 °C
Density 772 kg m−3
Kinematic viscosity 5×10^{-6} m2s−1
Specific heat 2330 Jkg−1 K−1
Thermal conductivity 0.1505Wm−1 K−1
Latent heat of fusion 243.5 kJ kg−1
Thermal expansion coefficient 0.00091 K−1

2.2. Melting and solidification process
As stated in the previous subsection, an electric heater is used to keep the temperature of the hot water in the first section of the container. The power and voltage of the used electric heater are 500 Watt and 220 Volts, respectively. The heating unit is coupled with a thermocouple as temperature control unit. By using this system temperature in the hot water can be fixed at 80oC, 85oC, and 90oC, respectively. However, there is a temperature swing for this experimental apparatus. For example, in the experiments for hot water temperature fixed at 900C, the electric heater will stop working when the thermocouple has shown a temperature of 920C and will return to work at a temperature of 880C. Thus the temperature swing is 4oC. The same principle will also occur in the experiment with 850C and 800C. In this study, two phase change processes will be investigated. The first process is melting and the second one is solidification process. In the melting process, the hot water is heated until reaching the fixed temperature. The temperature will be measured and the melting process will be pictured. After all of the PCM is melted, the process will be switched into solidification process. Here, temperature of the hot water decreases naturally. Temperature will be recorded and the solidification process is pictured.

2.3. Theoretical consideration

In order to carry out the performance analysis several parameters will be formulated. The first parameter is latent heat storage. The latent heat storage (LHS) is calculated based on heat absorption when the phase of the material changes from solid into liquid or from liquid into solid. The amount of heat required to convert material from one phase to another phase is formulated as follows:

$$QL = m \text{ x } am \text{ x } hm \qquad (1)$$

where $L\ Q$ [Joule], $m\ \Box h$ [Joule/kg], and m [kg] are total latent heat, latent heat specific, and mass of the PCM, respectively.

The parameter $m\,a$ [non dimensional] is melting fraction of the PCM material.

When the PCM in the solid or liquid phase (without any change in phase), the amount of heat stored can be calculated by

$$QS = m \text{ x } c \text{ x } T \qquad (2)$$

where $S\,Q$ [Joule] and $\square T$ [m2] are total heat stored and temperature difference, respectively.

The total heat that can be stored by a PCM if it is heated from $1\,T$ to $2\,T$ and between these temperatures, the phase of PCM changing at temperature $m\,T$ can be calculated by using the following equation:

$$Q = mc\,dT \text{ x } ma \text{ x } h \text{ x } mc\,dT \quad (3)$$

where $p\,c$ [kJ/kgK] is the heat capacity of the material. By using the above parameters, the analysis will be carried ou

3. EXPERIMENTAL VERFICATION

The experiments of melting and solidification processes at temperature 800C, 850C, and 900C have been carried out. Both PCMs, Paraffin wax and Sodium acetate Tri hydrate acid, are tested. The results will be analysed on the characteristics of melting process, solidification process and total heat stored by PCMs.

3 RESULTS AND DISCUSSION

3.1. Characteristics of melting

Here the characteristics of melting will be discussed by using the pictures captured during melting process. As a note, every experiments is performed in 10 hours. During experiment several pictures and video of PCM are recorded. The pictures of Paraffin wax in every hour of experiment are presented in Figure 2.
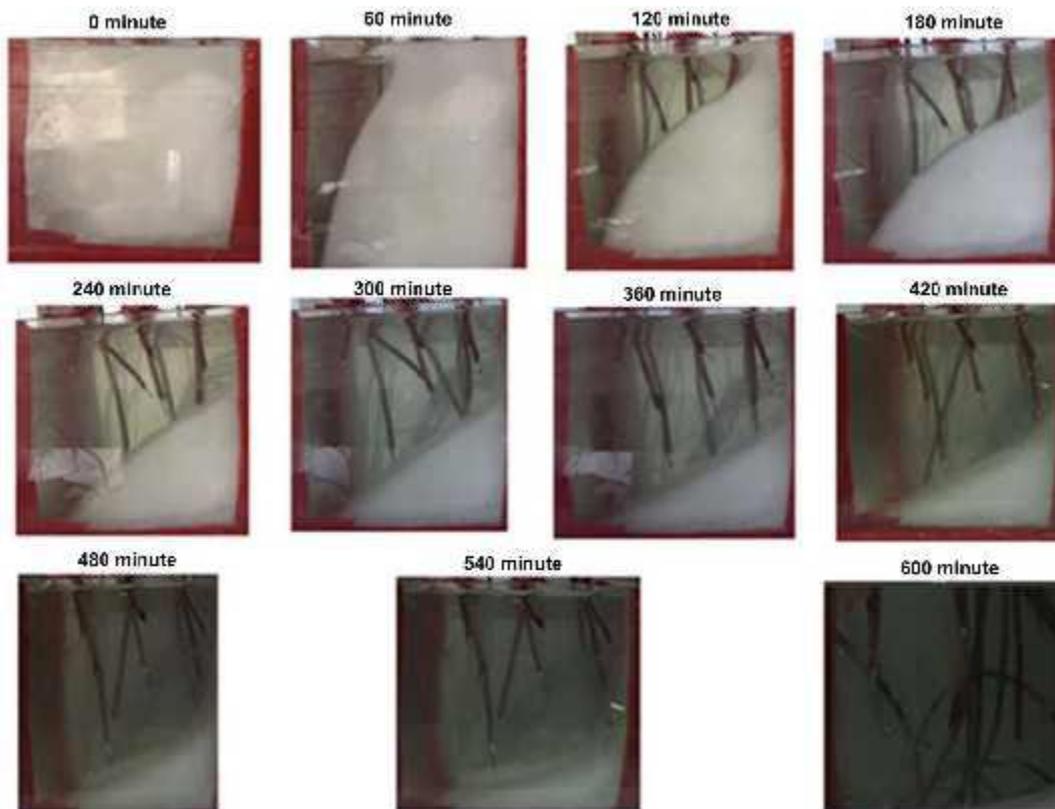

Figure.1. Melting characteristic of Paraffin wax at heat source temperature 90^{0} C

The melting characteristics of Sodium acetate Tri hydrate acid is shown in Figure 3 by a series of pictures. In this experiment, heat source temperature is also fixed at 90oC. It can be seen that after 60 minute more than 25% of the Sodium acetate Tri hydrate acid has been melted. The melting process, similar with Paraffin wax, starts from the upper part of the left side of the Sodium acetate Tri hydrate acid. After 120 minute, the pattern of the fluid phase of Sodium acetate Tri hydrate acid is similar to the pattern at 60 minute. However, the amount of melted Sodium acetate Tri hydrate acid is bigger, it is already more than 50%. At the end of experiment, there still solid Sodium acetate Tri hydrate Acid in the corner of the container. The comparison of melting characteristics of Paraffin wax and Sodium acetate Tri hydrate acid shows the followings. The melting characteristics of Paraffin wax and Sodium acetate Tri hydrate acid show the same trend, it starts from the top left and a small amount of solid PCM present in the right corner of the container. The melting rate of Paraffin wax is lower than Sodium acetate Tri hydrate acid.

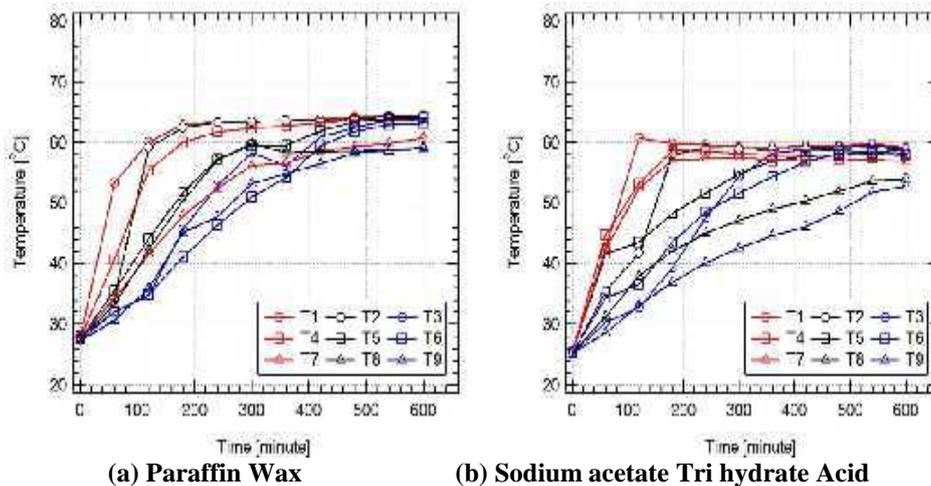### 3.2. Temperature of melting process

Figure 2 shows temperature history during melting process for both PCM when the heat source at 90oC. The temperature for Paraffin wax and for Sodium acetate Tri hydrate acid are shown by Figure 4a and Figure 4b, respectively. As mentioned before, there are 9 thermocouples used in this study. Those thermocouples can be divided into three groups and each group represents one section in the container. Three thermocouples, $1\,T$, $4\,T$, and $7\,T$, are placed and represent the left part of the PCM (shown by red lines). The middle part of the PCM are shown by $2\,T$, $5\,T$, and $8\,T$ (shown by black lines). And the right part of the PCM represented by $3\,T$, $6\,T$, and $9\,T$ (shown by blue lines). It can be seen in Figure 4a, in average, temperature of the left part is bigger than middle part and followed right part. This is because the heat source is on the left part of the PCM. The same trend is also shown by Figure 4b. Theoretically, if a PCM is heated from solid phase, its temperature increases as time increases until its melting point. In the melting process, its temperature will be constant after all

of the PCM material changes from solid to liquid. After the melting is finish, the temperature will increase as time increase. However, this experiment shows a different trend with theoretical one pattern. In Figure 4a, in the first 100 minute, temperature of Paraffin wax increases as time increases. It starts from ambient temperature of 27oC. After reaching its melting point, the temperature will be constant. This means the melting process is being occurred. After the melting is finish, temperature is constant and it should increase. This fact shows the discrepancy from the theoretical one. This is because the PCM is cooled from the right side of the container and keep some amount of PCM in the solid phase. In other word the melting process never finished. The same trend also shown by Sodium acetate Tri hydrate acid as shown in Figure 4b. The comparison between Figure 4a and Figure 4b shows the following facts. Temperature melting of Paraffin wax is bigger than Sodium acetate Tri hydrate acid.

Heat transfer rate of Sodium acetate Tri hydrate acid is bigger than Paraffin wax. This is shown by the bigger average temperature gradient of Sodium acetate Tri hydrate acid in comparison with Paraffin wax. Figure 2 shows temperature history during melting process for both PCMs when the heat source temperature at 80oC. The temperature for Paraffin wax and for Sodium acetate Tri hydrate acid are shown by Figure 2a and Figure 2b, respectively. In the figure, similar number and grouping of thermocouples as explained in Figure 2, are also used. The figure shows the similar trend with the previous figure. However, the constant temperature in here is lower. In addition, not all of the thermocouples reached the melting temperature, especially for Sodium acetate Tri hydrate acid. In other word, a significant amount of PCM does not melt. This fact reveals that by using hot source with temperature of 80oC is not suggested for both PCMs.
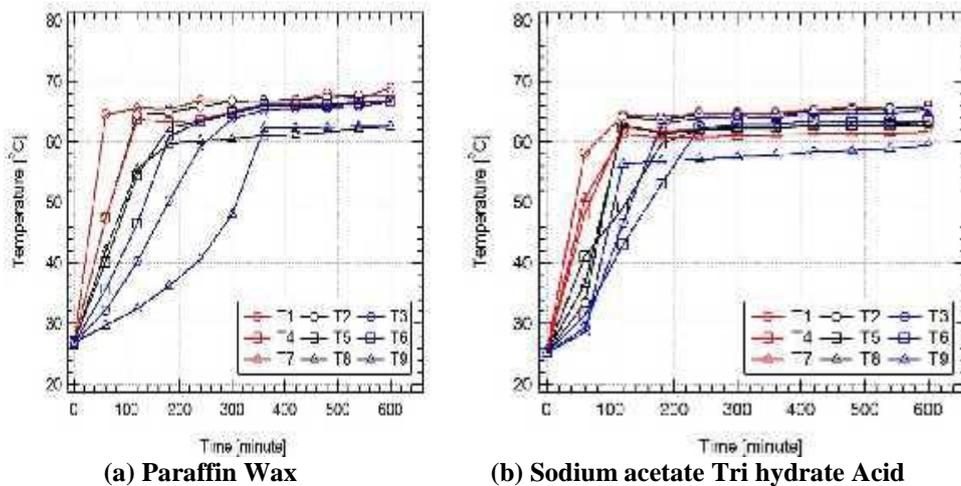
(a) Paraffin Wax   (b) Sodium acetate Tri hydrate Acid
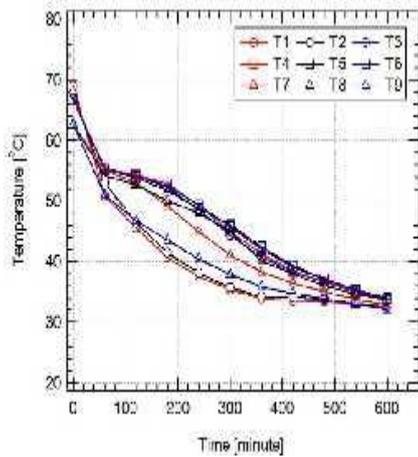**Figure .2. Temperature history of melting when heat source at 90 C**

(a) Paraffin Wax   (b) Sodium acetate Tri hydrate Acid
**Figure .3. Temperature history of melting when heat source at 80 C**

3.3. Temperature of solidification

Temperatures history on solidification are also recorded. For the heat source at 90oC, the temperature histories for Paraffin wax and for Sodium acetate Tri hydrate acid are shown in Figure 6a and Figure 6b, respectively. Figure 6a shows that the initial temperature of PCM is about 70oC. The temperature decreases as time increase until solidification temperature is reached. Theoretically, the temperature will be constant during the solidification. Here, only small portion of the temperature history shows a constant temperature. The same trend is also shown by Figure 6b, but with different initial temperature. In

Figure 6b, the initial temperature is about 65oC. However, the solidification time of Sodium acetate Tri hydrate acid is longer than Paraffin wax. After solidification finish, temperature will decrease gradually. Temperature history during solidification for heat source temperature of 80oC are shown in Figure 7a and Figure 7b for Paraffin wax and Sodium acetate Tri hydrate acid, respectively. It can be seen that Figure 6 and Figure 7 show the same trend. The difference is only in the initial temperature. This is because, the hot source temperature is different. These facts suggest that, the solidification process for Paraffin wax is faster than Sodium acetate Tri hydrate acid.
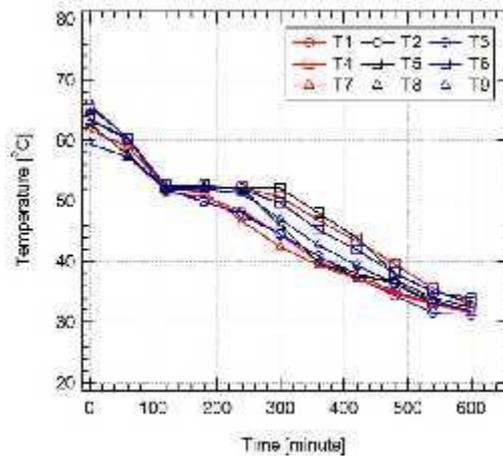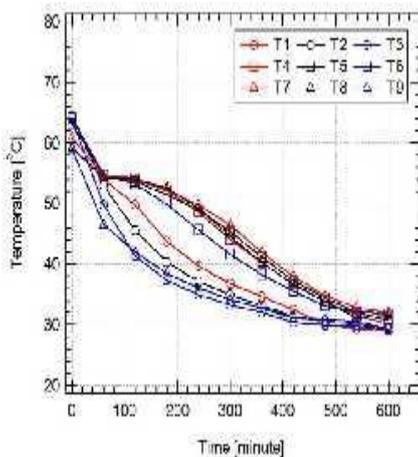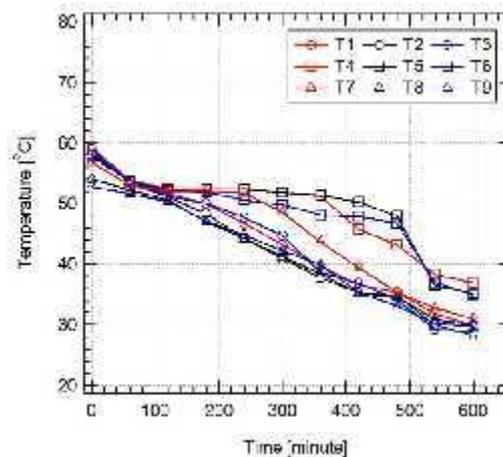
(a) Paraffin Wax   **(b) Sodium acetate Tri hydrate Acid**
Figure .4. Temperature history of solidification from hot water temperature fixed at 90 C

(a) Paraffin Wax   **(b) Sodium acetate Tri hydrate Acid**
Figure.5. Temperature history of solidification from hot water temperature fixed at 80 C

3.4. Total heat stored

The performance of the PCMs will be analysed by using total heat stored, defined by equation (3). The measured data are used and calculations are carried out. The results are presented in Table 3. Data of the table shows that the lower heat source temperature is the lower heat stored. Paraffin wax can store the heat better than Sodium acetate Tri hydrate acid for heat source temperature range 80oC to 90oC.

Table 3. The result of the calculation of the amount of heat stored

Marterials	Heat source temperature (ºC)	m(kg)	C (kJ/Kg ºC)	Tf (ºC)	Ti (ºC)	Q (KJ)
Paraffin wax	90	0.8	2	65.655	27	61.6848
Paraffin wax	85	0.8	2	64.78	27	59.584
Paraffin wax	80	0.8	2	62.24	27	56.846
SAT	90	0.8	1.6	62.80	27	57.367
SAT	85	0.8	1.6	62.29	27	45.171
SAT	80	0.8	1.6	57.98	27	38.528

4. CONCULSION

Melting and solidification processes of Paraffin wax and Sodium Acetate Tri hydrate acid as a PCM thermal energy storage have been investigated experimentally. Temperature measurements and recording the melting and solidification processes have been done. The results are analysed. The results show that the melting process starts from the upper part of the thermal storage. In the solidifying process, it starts from the lower part of the thermal storage. As a thermal energy storage, Paraffin wax is better than Sodium Acetate Tri hydrate acid. This is because Paraffin wax can store more energy. At temperature 90oC, thermal energy stored by Paraffin wax and Sodium Acetate Tri hydrate Acid is 61.85 kJ and 57.39 kJ, respectively. Thus in solar water heather coupled with thermal energy storage, **Paraffin wax is a good PCM.**

5. REFERENCES

[1]. Climate plan 2004: let's act together to challenge of climate change, Tech. rep., French Ministry of Ecology and Sustainable Developpment (2004).

[2]. I. Dincer, M. Rosen, Thermal Energy Storage - Systems and Applications, Jhon Wiley and Sons, 2002.

[3]. R. Baetens, B. P. Jelle, A. Gustavsen, Phase change materials for building applications: A state-of-the-art review, Energy and Buildings In Press, Accepted Manuscript (2010) –.

[4]. M. M. Farid, A. M. Khudhair, S. A. K. Razack, S. Al-Hallaj, A review on phase change energy storage: materials and applications, Energy Conversion and Management 45 (9-10) (2004) 1597 – 1615.

[5]. A. Pasupathy, R. Velraj, R. Seeniraj, Phase change material-based building architecture for thermal management in residential and commercial establishments, Renewable and Sustainable Energy Reviews 12 (1) (2008) 39 – 64.

[6]. A. Sharma, V. Tyagi, C. Chen, D. Buddhi, Review on thermal energy storage with phase change materials and applications, Renewable and Sustainable Energy Reviews 13 (2) (2009) 318 – 345.

[7]. U. Stritih, Heat transfer enhancement in latent heat thermal storage system for buildings, Energy and Buildings 35 (11) (2003) 1097 – 1104.

[8]. V. V. Tyagi, D. Buddhi, Pcm thermal storage in buildings: A state of art, Renewable and Sustainable Energy Reviews 11 (6) (2007) 1146 – 1166.

[9]. B. Zalba, J. M. Marn, L. F. Cabeza, H. Mehling, Free-cooling of buildings with phase change materials, International Journal of Refrigeration 27 (8) (2004) 839 – 849.

[10]. Y. Zhang, G. Zhou, K. Lin, Q. Zhang, H. Di, Application of latent heat thermal energy storage in buildings: State-of-the-art and outlook, Building and Environment 42 (6) (2007) 2197 – 2209.

[11]. N. Zhu, Z. Ma, S. Wang, Dynamic characteristics and energy performance of buildings using phase change materials: A review, Energy Conversion and Management 50 (12) (2009) 3169 – 3181.

[12]. K. Peippo, P. Kauranen, P. Lund, A multicomponent pcm wall optimized for passive solar heating, Energy and Buildings 17 (4) (1991) 259 – 270.

[13]. B. He, V. Martin, F. Setterwall, Phase transition temperature ranges and storage density of paraffin wax phase change materials, Energy 29 (11) (2004) 1785 – 1804.

[14]. M. Ahmad, A. Bontemps, H. Salle, D. Quenard, Experimental investigation and computer simulation of thermal behaviour of wallboards containing a phase change material, Energy and Buildings 38 (4) (2006) 357 – 366.

[15]. M. Ahmad, A. Bontemps, H. Salle, D. Quenard, Thermal testing and numerical simulation of a prototype cell using light wallboards coupling vacuum isolation panels and phase change material, Energy and Buildings 38 (6) (2006) 673 – 681.