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Experimental Study on Melting and Solidification of Phase Change Material Thermal Storage

H Ambarita[1*], I Abdullah[2], C A Siregar [3], R E T Siregar[1], A D Ronowikarto[1]

[1]Mechanical Engineering, University of Sumatera Utara, Medan 20155, Indonesia

[2]Mechanical Engineering, Medan Institute of Technology, Indonesia

[3]Mechanical Engineering, Muhammadiyah University of Sumatera Utara

*himsar@usu.ac.id

Abstract. Melting and solidification process of Phase Change Materials (PCMs) are investigated experimentally. The tested PCMs are Paraffin wax and Steric acid which typically used for solar water heater. The objective is to explore the characteristics of the PCM when it is being melted and solidified. The experiments are performed in a glass box. One side of the box wall is heated while the opposite wall is kept constant and other walls are insulated. Temperature of the heated wall are kept constant at 80°C, 85°C, and 90°C, respectively. Every experiment is carried out for 600 minutes. Temperatures are recorded and the melting and solidification processes are pictured by using camera. The results show that the melting process starts from the upper part of the thermal storage. In the solidification process, it starts from the lower part of the thermal storage. As a thermal energy storage, Paraffin wax is better than Steric acid. This is because Paraffin wax can store more energy. At heat source temperature of 90°C, thermal energy stored by Paraffin wax and Stearic acid is 61.84 kJ and 57.39 kJ, respectively. Thus it is better to used Paraffin wax in the solar water heater as thermal energy storage.

1. Introduction

Indonesia is a tropical country that receives abundant solar radiation, because it is located in the equator line. The solar energy that reaches the earth can be used as a renewable energy resource. The utilization of solar energy can be done by converting the radiation into heat, this is known as solar thermal system. The solar thermal system is more efficient than conversion using photovoltaic system. By using the most recent technology, the photovoltaic system can only reach efficiency lower than 17%, while the solar thermal system up to 70% [1]. One of the most promising application of solar thermal is solar water heater. However, in practice the water heater may requires additional energy source such as electricity to maintain the consistency of the water temperature. This is because solar radiation has intermittent characteristic. One of the solution to the intermittent is installing thermal energy storage material (Thermal Energy Storage/TES). Phase Change Material (PCM) is the most effective TES. The PCM can undergo a reversible process of melting process or freezing (solidification) which can be used to maintain a constant temperature for a certain period of time [2].

The PCM as a TES is a substance known with a high storage capacity [3]. It uses the latent heat when it is melting and solidifying at a certain temperature. This material is considered to be a solution to replace the role of electricity in application with of solar water heater. So it will overcome or reduce the use of electricity [4]. PCM has received much attention in recent years because of high density energy storage and the ability to provide heat at a constant temperature. This means the latent heat storage systems require a much smaller weight and volume of material in order to store an amount of energy compared with sensible heat storage system [5]. However, the heat transfer process during melting and solidification process need to be studied further. There are many PCM material found in the practical application. In solar water heater application, Paraffin wax is the most used TES. Several studies on application of Paraffin wax have been found in the literature [6,7].

In this study, the melting and solidification processes of PCMs are investigated experimentally. The tested PCMs are Paraffin wax and Steric acid which typically used for solar water heater. The objective is to explore the characteristics of those PCMs when it undergoes in melting and solidification processes. The results are expected to supply the necessary information on development high performance solar water heater that is suitable for Indonesian climate.

2. 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 Stearic acid. The experiments are carried out at three different heat source temperatures, they are 90°C, 85°C and 80°C, 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 (27^0C - 28^0C) 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 0.1°C. 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	Coordinates		
		X (mm)	*Y* (mm)	*Z* (mm)
1	T1	25	25	25
2	T2	50	25	25
3	T3	75	25	25
4	T4	25	50	50
5	T5	50	50	50
6	T6	75	50	50
7	T7	25	75	75
8	T8	50	75	75
9	T9	75	75	75

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. The experimental apparatus is shown in Figure 1.

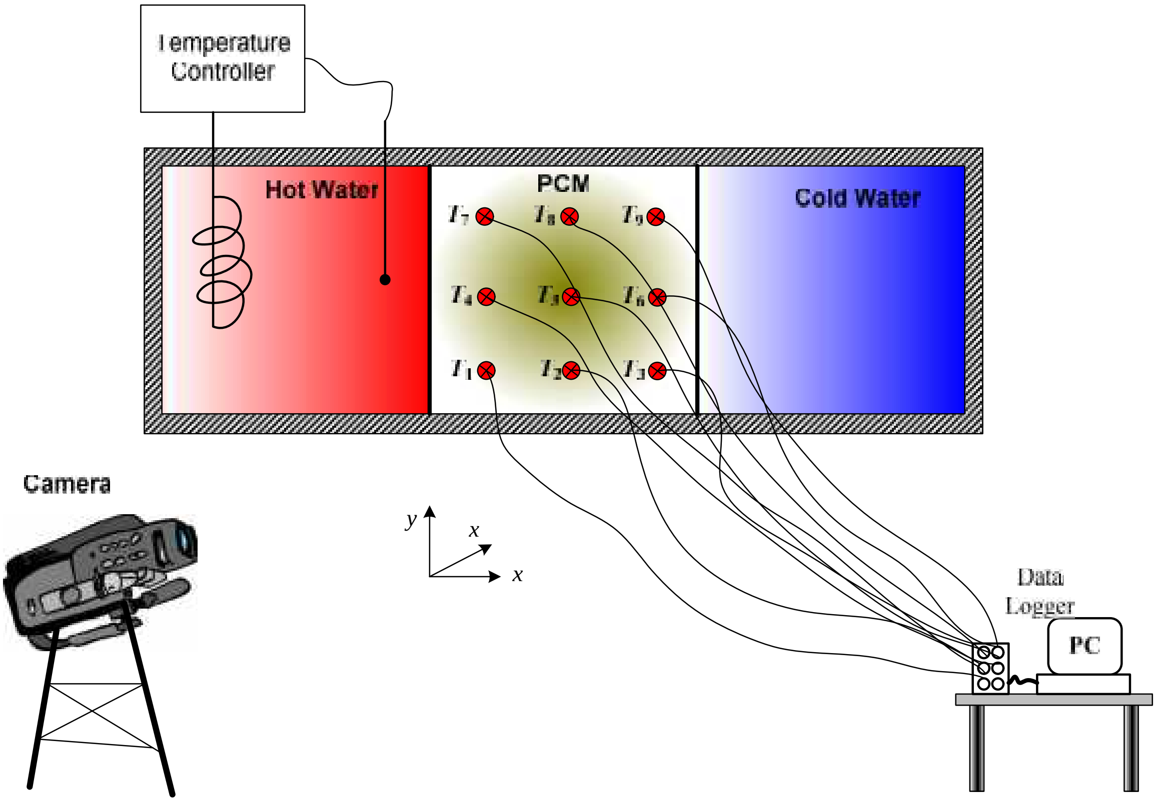

Figure 1. Experimental apparatus and data acquisition system

As mentioned above, two types of PCM are tested in this study, they are Paraffin wax and Stearic 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 stearic acid are 59.8°C and 55.1°C, respectively. On the other hand, the latent heat of fusion of Paraffin wax and Stearic 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 Stearic acid.

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

Properties	Paraffin wax [2]	Stearic acid [3]
Melting temperature (°C)	59.8	55.1
Latent heat (kJ/kg)	190	160
Density (kg/m^3) when it is:		
Solid	910	965
Liquid	790	848
Specific heat (kJ/(kg °C) when it is:		
Solid	2,0	1,6
Liquid	2.15	2.2
Thermal conductivity (W/m·K) when it is:		
Solid	0.24	0.36
Liquid	0.22	0.172

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 80°C, 85°C, and 90°C, respectively. However, there is a temperature swing for this experimental apparatus. For example, in the experiments for hot water temperature fixed at 90^{0}C, the electric heater will stop working when the thermocouple has shown a temperature of 92^{0}C and will return to work at a temperature of 88^{0}C. Thus the temperature swing is 4°C. The same principle will also occur in the experiment with 85^{0}C and 80^{0}C.

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:

$$Q_L = m \times a_m \times \Delta h_m \tag{1}$$

where Q_L [Joule], Δh_m [Joule/kg], and m [kg] are total latent heat, latent heat specific, and mass of the PCM, respectively. The parameter a_m [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

$$Q_S = m \times c_p \times \Delta T \tag{2}$$

where Q_S [Joule] and ΔT [m^2] are total heat stored and temperature difference, respectively.

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The total heat that can be stored by a PCM if it is heated from T_1 to T_2 and between these temperatures, the phase of PCM changing at temperature T_m can be calculated by using the following equation:

$$Q_t = \int_{T_1}^{T_m} mc_p dT + ma_m \Delta h + \int_{T_m}^{T_2} mc_p dT \tag{3}$$

where c_p [kJ/kgK] is the heat capacity of the material. By using the above parameters, the analysis will be carried out.

3. Result and Discussions

The experiments of melting and solidification processes at temperature 80^0C, 85^0C, and 90^0C have been carried out. Both PCMs, Paraffin wax and Stearic acid, are tested. The results will be analysed on the characteristics of melting process, solidification process and total heat stored by PCMs.

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.

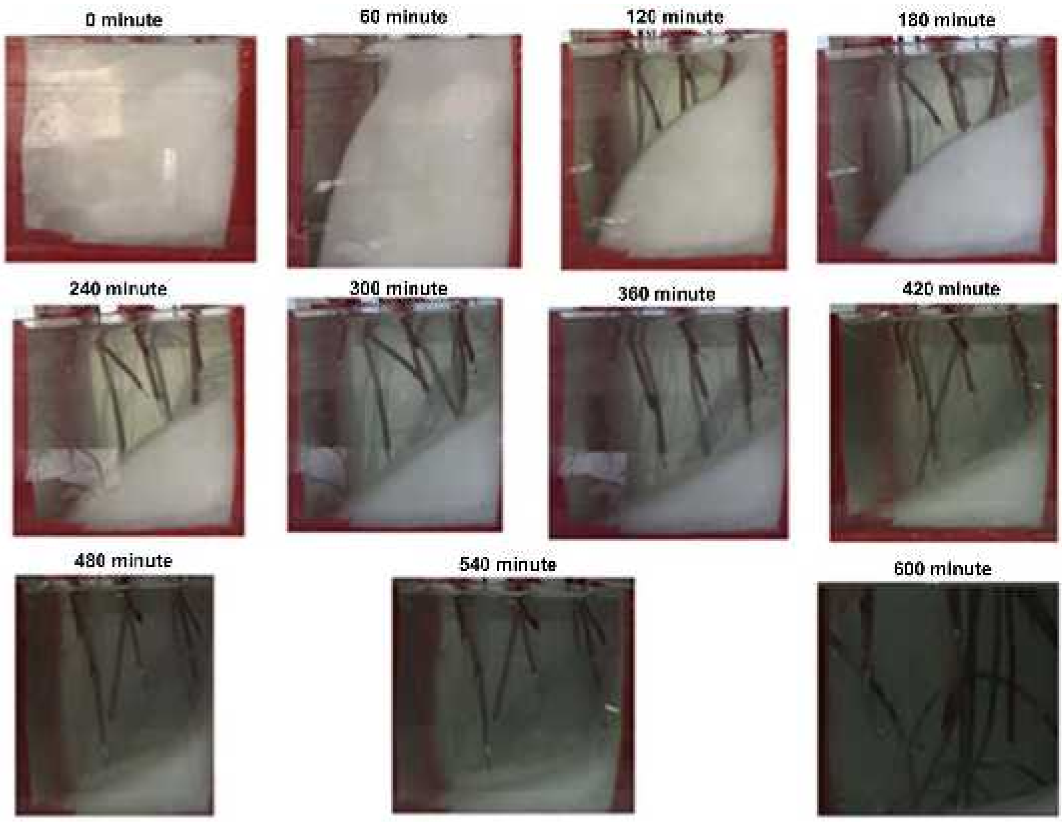


Figure 2. Melting characteristic of Paraffin wax at heat source temperature 90°C

In the figure, the experiment is carried out at heat source temperature at 90°C. The heat source is located on the left side and the cold medium is located on the right side of the Paraffin wax. The figure shows that at 0 minute all of the Paraffin wax is in the solid phase. After 60 minute, about 25% of the Paraffin wax has been melted. It can be seen that the melting process start from upper part of the left side of the Paraffin wax where the heat source is located. In addition, when the Paraffin wax is in the fluid phase, it will move to the upper part because of the buoyancy force. This suggests that the heat transfer process in the liquid Paraffin wax is governed by natural convection. After 120 minute, the pattern of the fluid phase of Paraffin wax is similar to the pattern at 60 minute. The difference is the amount of melted Paraffin wax is bigger, it is about 50%. It can be seen that the solid and liquid Paraffin wax are divided diagonally. After 180 minute, about 60% of Paraffin wax has been melted and the solid Paraffin wax present in lower part of the right side of the container. The same trend is also shown by Paraffin wax at 240 minute to 540 minute. Here, a small amount of solid Paraffin wax is still present in lower part of the right side of the container. After 600 minute of experiment, almost all of the Paraffin wax has been melted. However, a small amount of the solid Paraffin wax is present in the container. In other word, the melting process is not finish after 10 hours. This is because, the Paraffin wax in the bottom right corner of the container does not receive sufficient heat. This fact reveals that the rate of melting is very low.

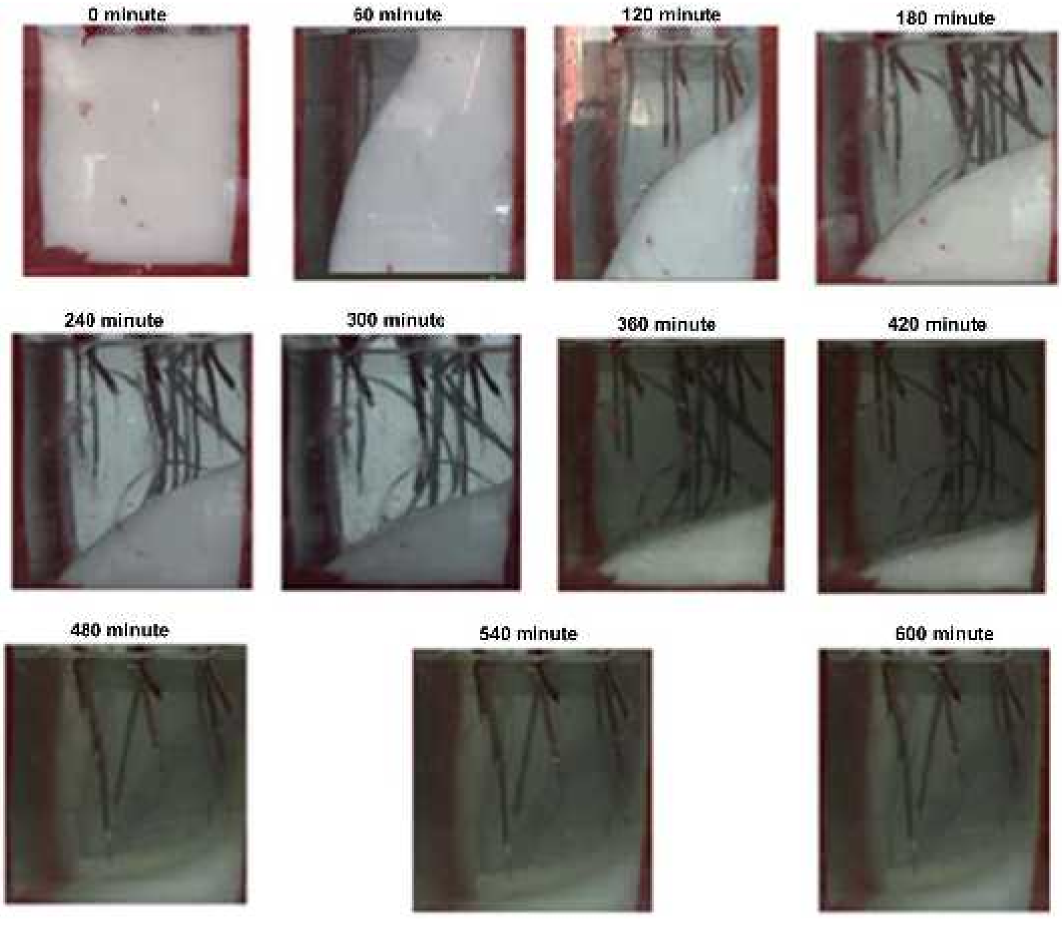


Figure 3. Melting characteristic of Stearic Acid at heat source temperature 90°C

The melting characteristics of Stearic acid is shown in Figure 3 by a series of pictures. In this experiment, heat source temperature is also fixed at 90°C. It can be seen that after 60 minute more than 25% of the Stearic acid has been melted. The melting process, similar with Paraffin wax, starts from the upper part of the left side of the Steric acid. After 120 minute, the pattern of the fluid phase of Steric acid is similar to the pattern at 60 minute. However, the amount of melted Stearic acid is bigger, it is already more than 50%. At the end of experiment, there still solid Steric Acid in the corner of the container.

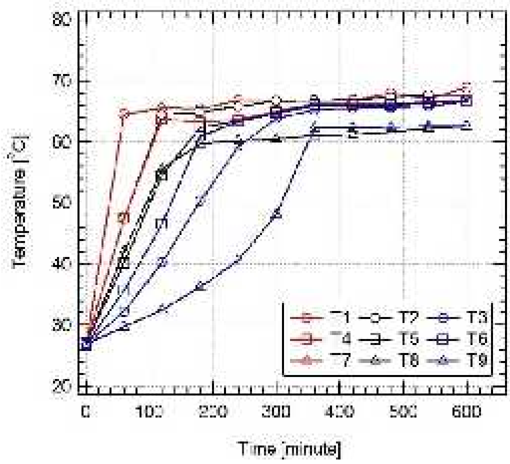
The comparison of melting characteristics of Paraffin wax and Stearic acid shows the followings. The melting characteristics of Paraffin wax and Steric acid show the same trend, it starts from the top left and a small amount of solid PCM present in the right corner of the container. The melting rate of Paraffin wax is lower than Stearic acid.

3.2. *Temperature of melting process*

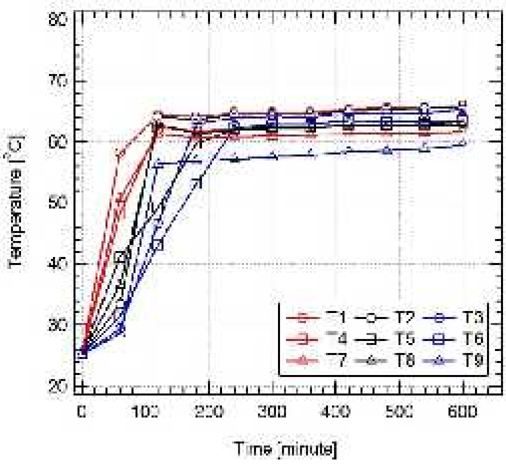
Figure 4 shows temperature history during melting process for both PCM when the heat source at 90°C. The temperature for Paraffin wax and for Stearic acid are shown by Figure 4a and Figure 4b, respectively. As mentioned before, there are 9 thermocouples used in this study. Those thermocouples can be divided into three groups and each group represents one section in the container. Three thermocouples, T_1, T_4, and T_7, are placed and represent the left part of the PCM (shown by red lines). The middle part of the PCM are shown by T_2, T_5, and T_8 (shown by black lines). And the right part of the PCM represented by T_3, T_6, and T_9 (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 27°C. 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 Steric 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 Stearic acid. Heat transfer rate of Stearic acid is bigger than Paraffin wax. This is shown by the bigger average temperature gradient of Stearic acid in comparison with Paraffin wax.



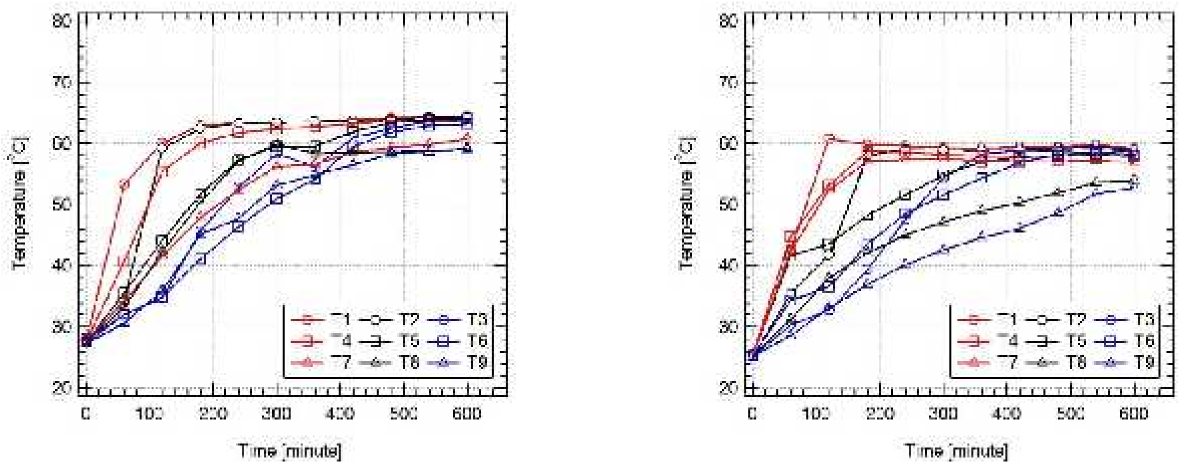
(a) Paraffin Wax



(b) Steric Acid

Figure 4. Temperature history of melting when heat source at 90°C

Figure 5 shows temperature history during melting process for both PCMs when the heat source temperature at 80ºC. The temperature for Paraffin wax and for Stearic acid are shown by Figure 5a and Figure 5b, respectively. In the figure, similar number and grouping of thermocouples as explained in Figure 5, 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 Steric 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.

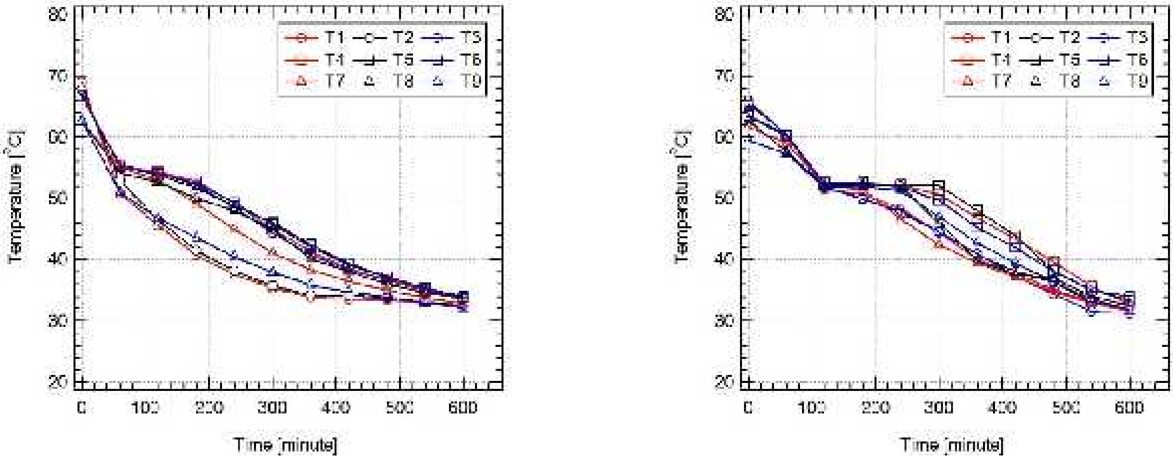


(a) Paraffin Wax (b) Steric Acid

Figure 5. Temperature history of melting when heat source at 80^{0}C

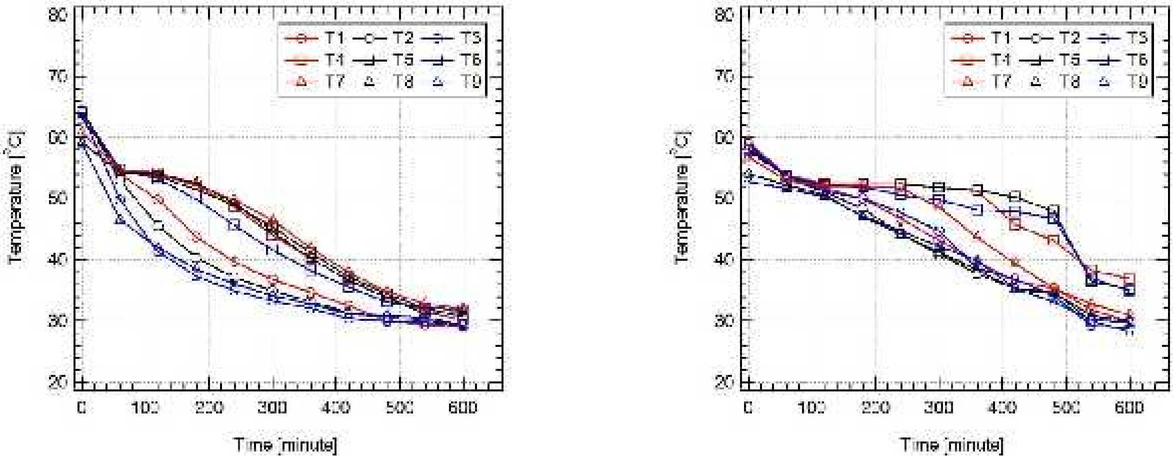
3.3. Temperature of solidification

Temperatures history on solidification are also recorded. For the heat source at 90ºC, the temperature histories for Paraffin wax and for Stearic 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 Stearic acid is longer than Paraffin wax. After solidification finish, temperature will decrease gradually.



(a) Paraffin Wax (b) Steric Acid

Figure 6. Temperature history of solidification from hot water temperature fixed at 90^0C



(a) Paraffin Wax (b) Steric Acid

Figure 7. Temperature history of solidification from hot water temperature fixed at 80^0C

Temperature history during solidification for heat source temperature of 80°C are shown in Figure 7a and Figure 7b for Paraffin wax and Stearic 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 Stearic acid.

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 Stearic acid for heat source temperature range 80°C to 90°C.

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

Materials	Heat source temperature (ºC)	m (kg)	c_p (kJ/Kg ºC)	T_f (ºC)	T_i (ºC)	Q_t (KJ)
Paraffix wax	90	0.8	2	65.655	27	61.848
Paraffix wax	85	0.8	2	64.24	27	59.584
Paraffix wax	80	0.8	2	62.54	27	56.864
Stearic acid	90	0.8	1,6	62.80	27	57.387
Stearic acid	85	0.8	1,6	62.29	27	45.171
Stearic acid	80	0.8	1,6	57.10	27	38.528

4. Conclusion

Melting and solidification processes of Paraffin wax and Stearic 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 Steric acid. This is because Paraffin wax can store more energy. At temperature 90ºC, thermal energy stored by Paraffin wax and Stearic 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.

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