An Experimental Study of Energy Charging and Discharging in a PCM Thermal Storage

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Abstract: In this work, a thermal energy storage system was designed and equipped with measuring instruments to study heat transfer characteristics and energy storage and release. In this system, a cubic container which is made of plexiglass was filled with dodecanoic acid as a phase change material. In order to transfer heat to the storage container, a constant temperature heat exchanger was designed and mounted on the side of the container. Several experimental tests were conducted for both the melting process (energy charging) and solidification process (energy discharging) with setting the temperature at 60 and 70 degrees of Celsius for the former experiments and 15 and 10 degrees of Celsius for the latter ones. Results indicated that the maximum amount of stored energy was 209 kJ/kg in the charging process. Furthermore, the charging process time was reduced, at most, by 42% and the absorbed energy was increased 9% when the temperature of heat exchanger was increased by 10°C. Also the discharging process time was decreased 9% as the temperature of heat exchanger reduced by 5°C.

Keywords: Heat Transfer, Thermal Energy Storage System, Phase Change Material

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1 INTRODUCTION

Research for new technologies to avoid the growing concern about environmental problems, the impending energy shortage and the high cost of energy and new power plants has been a scientific concern over the last three decades. Central to the problem is the need to store excess energy that would otherwise be wasted and also to bridge the disparity between energy generation and consumption. Scientists and engineers throughout the world are in search of strategies to reduce the demand, methods to ensure the security of the supplies, technologies to increase the energy efficiency of power systems, new and renewable sources of energy to replace the limited and harmful fossil fuels. One of the options to improve energy efficiency is to develop energy storage devices and systems in order to reduce the mismatch between supply and demand [1].

The storage of energy in appropriate forms, which can conventionally be converted into the required form, is a present day challenge to the technologists. Energy storage not only decreases the mismatch between supply and demand but also improves the performance and reliability of energy systems and plays an important role in conserving the energy. Thermal energy storage (TES) systems play a crucial role in many engineering applications and have played an important role in energy management. In recent years, thermal energy storage systems have been considered by many researchers.

Thermal energy storage can be stored as a change in internal energy of a material as sensible heat and latent heat. Among thermal energy storage methods, latent heat energy storage in a phase change material (PCM) is the most attractive form due to its advantages of high energy storage capacity in a small volume and charging or discharging heat from the system at a nearly constant temperature [2].

A PCM is a substance with a high latent heat which, melting and solidifying at a certain temperature, is capable of storing and releasing large amounts of energy. Heat is absorbed or released when the material changes from solid to liquid and vice versa. PCM absorbs and releases heat at a nearly constant temperature. They store 5–14 times more heat per unit volume than sensible storage materials such as water, masonry, or rock [3]. Over the last decade, a number of studies have been performed to examine the overall thermal behaviour and performance of various latent heat thermal energy storage systems. Suat et al. [4] presented a conventional open-loop passive solar water heating system combined with sodium thiosulfate pentahydrate as a PCM were experimentally investigated and compared with those of conventional system including no PCM. The results indicated that the storage time of hot water, the produced hot water mass and total heat accumulated in the solar water heating system having the heat storage tank combined with PCM were approximately 2.59–3.45 times of that in the conventional solar water-heating system.

Yanxia et al. [5] experimentally investigated the melting process of ethanolamine–water binary mixture with melting temperature of 8.2 °C used as PCM in a rectangular enclosure with internal dimensions 50 × 280 × 400 mm with a heated vertical wall. The liquid-solid interfaces were captured and the instantaneous liquid fraction was presented. The effect of natural convection was studied in terms of the molten fraction and the shape of the solid–liquid interface. The results indicate that natural convection enhances the rate of melting compared with the pure conduction model and that pure conduction mechanism only occurs at the initial stage of melting. Lamberg et al. [6] conducted numerical study on melting of PCM in a rectangular enclosure with and without the natural convection effect and the results were compared with experimental results. It was observed from the results that when the natural convection effect was ignored, the PCM took double the time of actually it takes in reality to reach the maximum temperature. Regin et al. [7] analysed the melting behaviour of paraffin wax encapsulated in a cylindrical capsule surrounded by hot water. The experimental results showed the influence of natural convection on the melting process as the process occurred axisymmetrically, i.e. melting in top region was much faster than that in bottom region.

2 EXPERIMENTAL SETUP AND PROCEDURE

2.1. Experimental apparatus

A schematic diagram of the present experimental apparatus is shown in Fig. 1. Rectangular thermal storage is used when it is possible to transfer heat via a water heat exchanger on one side of the thermal storage. The heat storage container has dimensions of 120 × 50 × 120 mm and made of plexiglass to enable the phase change interface to be observed visually. Due to the low thermal conductivity of plexiglass, it can be also used as a thermal insulation. However, the container is insulated by a 30 mm EPDM to minimize heat loss. In order to transfer heat to the storage container, a constant temperature heat exchanger was designed and mounted on the side of the container, where heat can be transferred from water to the PCM (melting process) or vice versa (solidification process). In order to maintain a uniform temperature distribution on the heat exchanger surface it was made from high thermal conductivity aluminium.

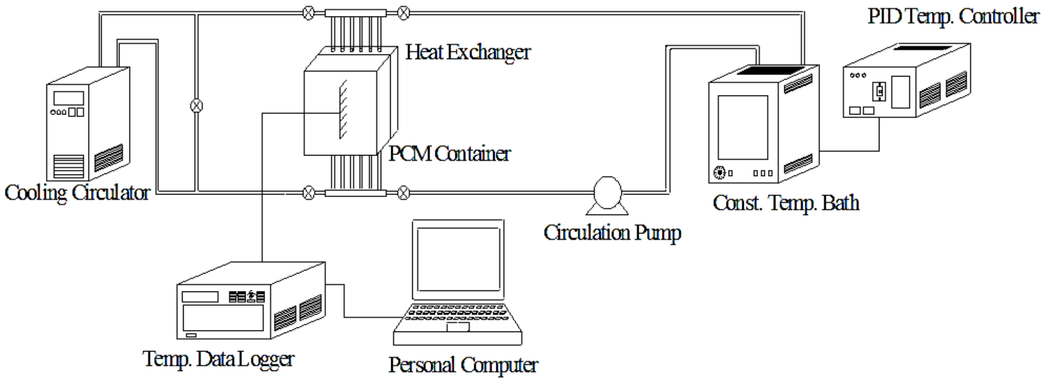

Fig. 1 Schematic of experimental setup

For melting process, the hot water provided by a constant temperature bath and its temperature was controlled by the PID temperature controller and for solidification process, the cold water provided by a cooling circulator. For thermal analysis, the temperatures were measured with 26 T–type thermocouples which placed at certain locations in the PCM as shown in Fig. 2. These thermocouples were selected as thin as possible (0.5 mm diameter) in order to minimize the influence of thermocouple body on flow pattern.

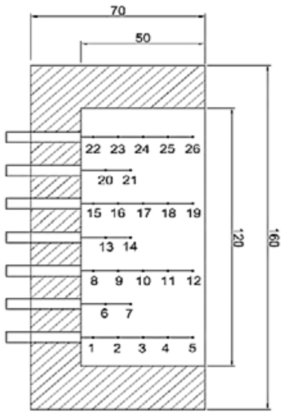

Fig. 2 Thermocouple arrangement in a storage container

The measurement uncertainty, as described by the standard IEC 584-2, was ± (0.5–0.8) °C in operating temperature system. However, all the thermocouples are calibrated before use, and they are observed to have an accuracy of ±0.1°C. A Yokogawa DR-230 data logger is used to collect the temperature measurements and record them every 2 seconds during the experiments.

2.2. Material

Fatty acids, as PCM for the energy storage, are preferred due to their large latent heat, the characteristic of constant temperature in the course of absorbing or releasing energy and low cost [8]. They have superior properties over many PCMs such as melting congruency, good chemical stability and nontoxicity. More important characteristics are their smaller volume change during phase transition and high latent heat of melting per unit mass and suitable melting temperature range [9]. On the other hand, the compatibility of construction material over a long period application is very important criteria for successful heat storage applications.

The PCM used in this study is a dodecanoic acid of 95% purity which is supplied by Acros company. Table 1 shows the thermophysical properties and the phase change ranges for the dodecanoic acid used for the present investigation.

Table 1 Thermophysical properties of dodecanoic

Property	Values
Melting range (°C)	41-49
Latent heat of melting (kJ/kg)	168
Density (kg/m^3)	883
Specific heat of Solid (kJ/kg°C)	1.4
Specific heat of Liquid (kJ/kg°C)	2.1

2.3. Experimental procedure

In this section, the experimental procedure is briefly described. At the first step, the PCM container was filled with the molten dodecanoic acid and a few runs were made in order to calibrate the system. The melting process was initiated by passing hot water produced with constant temperature bath into the heat exchanger. The PCM in the container was melted gradually and the interface was captured by a high resolution digital camera every five minutes interval. Also the temperatures were recorded by the data logger every two seconds. When all the PCM was melted, the melting process was terminated. After the melting process was completed, the solidification process was initiated by passing cold water into the heat exchanger at a constant temperature. Interface position and temperature values of the PCM were measured and recorded at the same time intervals similar to the melting process. The melting and solidification processes of the PCM were repeated at different water temperatures.

3 DATA PROCESSING

3.1. Image analysis and interface tracking

The location and shape of the phase-change interface was extracted from the digital images captured during the experiments using image analyzer software. Determination of the interface was enabled by the liquid phase being transparent while the solid phase is opaque. The quality of images was improved using contrast enhancement, intensity thresholding, and filtering operations, so that the edge of the solid region could be more easily detected. Since the heat transfer and phase change processes are two-dimensional in the storage container, we can obtain the liquid and mass fractions with image analysis for both melting and solidification processes. A similar approach using MATLAB is done by Benjamin et al. [10].

3.2. Calculation

First the amount of PCM at each phase must be determined. By analysing the photos and using Eq. (1), the liquid fraction is calculated at certain intervals.

$$\gamma_L(i) = \frac{V_L(\mathrm{i})}{V_0} = \frac{A_L(\mathrm{i}).l}{A_0.l} = \frac{A_L(\mathrm{i})}{A_0} \tag{1}$$

Where γ_L is the liquid fraction, V_L and A_L are the volume and the lateral area of liquid phase, respectively, V_0 and A_0 are the volume and the lateral area of container, l indicates the depth of container and i represents the time step. With the calculation of liquid fraction, the mass of PCM at liquid phase is obtained using Eq. (2).

$$m_L(\mathrm{i}) = \gamma_L(i).m_{tot} \tag{2}$$

Where m_L is the mass of liquid phase and m_{tot} is the mass of PCM. Then, Eq. (3) calculates the mass of solid phase

$$m_S(\mathrm{i}) = m_{tot} - m_L(\mathrm{i}) \tag{3}$$

Where m_S represents the mass of solid phase.

At each time step, the variations of sensible energy for both solid and liquid phases were calculated by using the mean temperature of each phase. At each time step, the variations of sensible energy for both solid and liquid phases were calculated by using the mean temperature of each phase. The thermocouples located in each phase were used to calculate the mean temperature. Determination of the total thermal energy stored in the PCM container, requires the concurrent calculation of both sensible and latent energy, which can be obtained by the following equation [12].

$$\begin{aligned} E_{Stored}(i) = & \int_{T_0}^{T_{S_{mean}}(i)} m_s(i).c_{p_S}\, dT_{S_{mean}} + m_{total}.\gamma_L.\lambda \\ & + \int_{T_f}^{T_{L_{mean}}(i)} m_L(i).c_{p_L}\, dT_{L_{mean}} \end{aligned} \tag{4}$$

Where E_{Stored} represents the stored energy, λ is the latent heat of melting, $T_{S_{mean}}$ and $T_{L_{mean}}$ are the average temperature of solid and liquid phases, T_f shows the melting temperature, T_0 is the initial temperature of PCM in processes and c_p is the specific heat. The Eq. (4) can be simplified as follows:

$$\begin{aligned} E_{Stored}(i) = & \, m_s(i).c_{p_s}\left(T_{S_{mean}}(i) - T_{S_{mean}}(0)\right) \\ & + \left(m_L(i) - m_L(0)\right).\lambda \\ & + m_L(i).c_{p_L}\left(T_{L_{mean}}(i) - T_f\right) \end{aligned} \tag{5}$$

In the left-hand side of Eq. (5), the first and third terms represent the sensible heat stored in solid and liquid phases, respectively, whereas the second term represents the latent heat stored when the phase change process occurs. The solidification process is similar to melting process, with the exception that during the solidification process, the mass of the liquid phase gradually is reduced and added to the mass of solid phase. Equation (6) is applied to calculate the amount of thermal energy in the PCM container during the solidification process.

$$\begin{aligned} E_{Content}(i) = & \, m_L(i).c_{p_L}\left(T_{L_{mean}}(i) - T_f\right) \\ & + \left(m_L(i) - m_L(end)\right).\lambda \\ & + m_s(i).c_{p_s}\left(T_{S_{mean}}(i) - T_{end}\right) \end{aligned} \tag{6}$$

Where $E_{content}$ is the energy content in storage container. The released energy from PCM during the solidification process express as:

$$E_{Released}(i) = E_{Content}(i) - E_{Content}(0) \tag{7}$$

The rate of storage and release energy are given by :

$$\frac{dE}{dt}(i) = \frac{\Delta E}{\Delta t} = \frac{E(i) - E(i-1)}{t(i) - t(i-1)} \tag{8}$$

4 RESULTS AND DISCUSSION

The experiments were made for the following reasons:

- To investigate the change of interface position between the solid and the liquid,
- To study the heat transfer in the heat storage container,
- To study the process of energy charging and discharging of the heat storage.

Heat transfer in latent heat storage is very complex. The process is non-stationary and there is also a phase change problem [11].

4.1. Charging process (Melting)

Fig. 3 shows the comparison of the liquid fraction for two different temperatures of the heat exchanger. From the results we can see that with increasing the temperature of heat exchanger as much as 10°C, the time of melting process reduces by 42%.

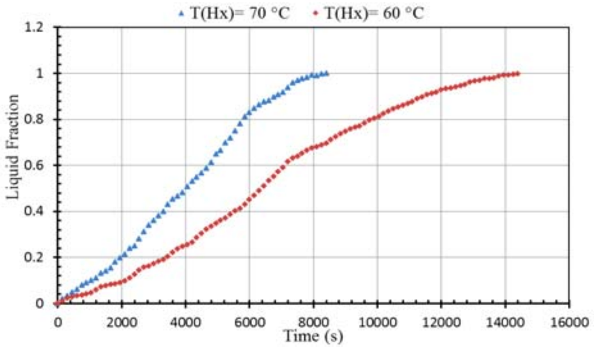

Fig. 3 Liquid fraction distribution versus time in melting process

Fig. 4 compares absorbed energy in the storage container for different temperatures of heat exchanger. From this figure, it can be concluded that as the temperature of heat exchanger increases, the total absorbed energy increases as much as 9%.

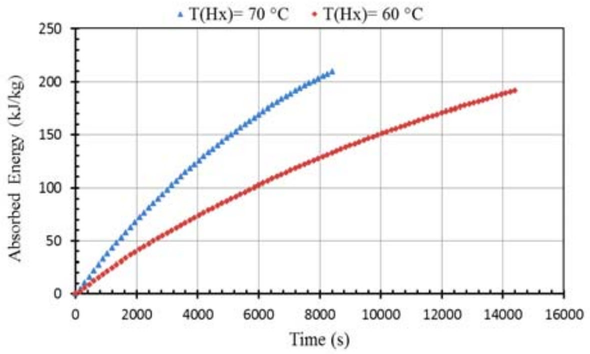

Fig. 4 Absorbed energy versus time in melting process

Fig. 5 shows the total time to complete the melting process of the dodecanoic acid and the total absorbed energy for different temperature of heat exchanger.

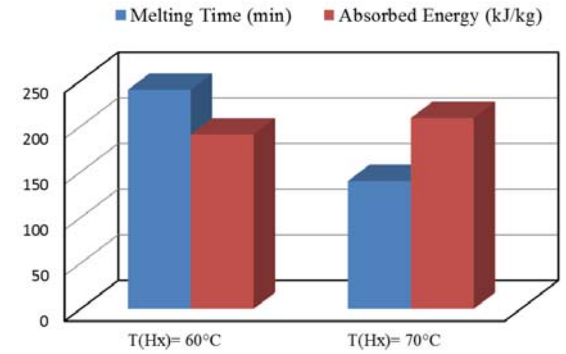

Fig. 5 Comparison of total melting time and total quantity of heat absorbed for different configuration

The heat transfer rate for different temperature of heat exchanger is shown in the Fig. 6.

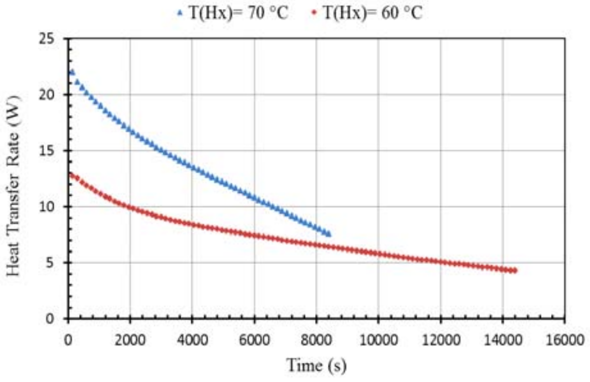

Fig. 6 Heat transfer rate versus time in melting process

Time-average heat transfer rate is used for comparison of heat transfer rate that was obtained by Eq. (9).

$$\overline{\dot{E}} = \frac{1}{t_{tot}} \int_{t_0}^{t_{tot}} \dot{E}\,dt \qquad (9)$$

It is observed that the heat transfer rate increases 77% as temperature of heat exchanger increases as much as 10°C. Also Fig. 6 shows that with an increase in the temperature of heat exchanger, the heat transfer rate decreases with greater slope due to the faster melting process.

At the beginning of the melting process, conduction is the dominant heat transfer mode and heat transfer rate is high because of the high temperature gradient. With the passage of time, due to decreasing temperature gradient, heat transfer rate decreases and natural convection gradually increases as the melted region grows and the heat transfer rate decreases gradually.

4.2. Discharging process (Solidification)

Fig. 7 shows the comparison of the solid fraction for two different temperatures of heat exchanger. It can be seen that with decreasing the heat exchanger temperature as much as 5°C, the time of solidification process reduces by 9%.

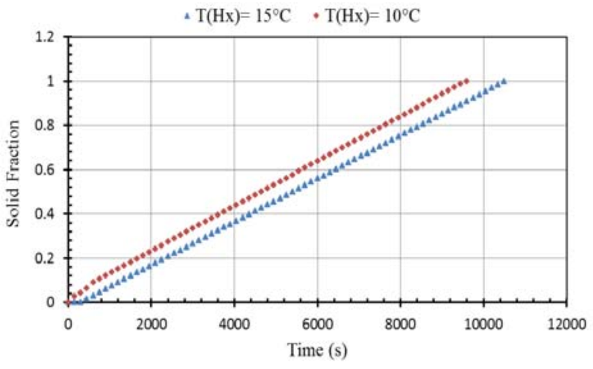

Fig. 7 Solid fraction distribution versus time in solidification process

Fig. 8 compares the released energy from the storage container in discharging process. This figure shows that when the temperature of heat exchanger is decreased, the released energy increases by 6%.

Fig. 9 presents heat transfer rate in discharging process. From this figure, it can be seen that the heat transfer rate increases 4% as temperature of heat exchanger decreases 5°C.

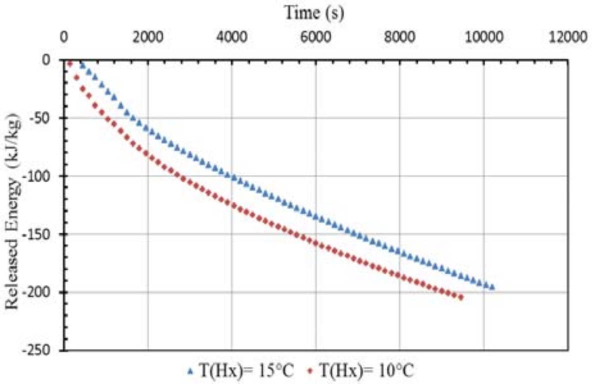

Fig. 8 Released energy versus time in solidification process

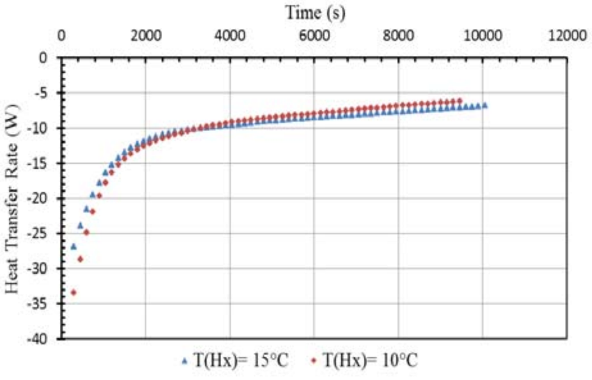

Fig. 9 Heat transfer rate as function of time in solidification process

An economic analysis of the system was carried out. The cost of the parts of the system is presented in Fig. 10.

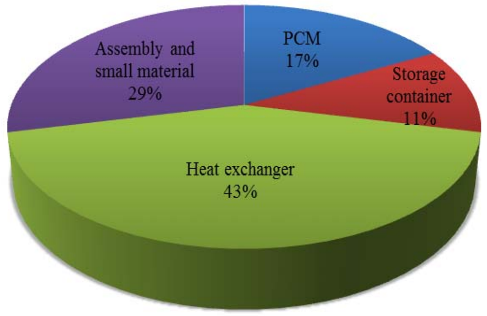

Fig. 10 Total cost break down of the storage system

5 CONCLUSION

In this research, the thermal energy storage system is investigated experimentally. According to our experimental results and the above discussion, we may conclude that the temperature of heat exchanger has important influences on both the total melting and solidification time. With increase of the heat exchanger temperature in melting process and by decreasing it in the solidification process, the whole melting time and solidification time are also reduced.

Also, at the beginning of the melting process, conduction is the dominant heat transfer mode. With the passage of time, natural convection gradually increases as the melted region grows. With increasing the temperature of heat exchanger as much as 10°C, the absorbed energy increases 9% and the heat transfer rate increases by 77%. In solidification process, with decreasing the temperature of heat exchanger as much as 5°C, the released energy increases 6% and the heat transfer rate increases by 4%.

6 NOMENCLATURE

V	volume (m^3)
A	lateral area (m^2)
γ	phase fraction
i	step time
t	time (s)
m	mass of PCM (kg)
E_{Stored}	absorbed energy (kJ)
$E_{Content}$	energy content (kJ)
$E_{Released}$	released energy (kJ)
λ	latent heat of melting (kJ/kg)
C_p	specific heat (kJ/kg^{o}C)
T	temperature (^{o}C)

Subscripts

L	liquid
S	solid
0	initial condition
tot	total
$mean$	average
Hx	heat exchanger

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