The effect of the inlet temperature of the heat transfer fluid in a rectangular latent heat energy storage

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Abstract. Solar energy is available during the day only. The excess heat energy collected during sunshine hours can be stored in the thermal energy storage and it can be reused during off sunshine hours. Latent heat energy storage systems by using phase change materials (PCMs) can be used effectively for storing thermal energy. It has high-energy storage density and the constant temperature storage process. In this paper, the performance of the latent heat storage system and phase change characteristics of PCM inside a rectangular latent heat energy storage unit will be presented. In this study, purified water is used heat transfer fluid (HTF) which is passed through the copper tubes inside the test unit and commercial-grade paraffin wax is used as PCM and indirect contact heat transfer method is used to heat exchange from the HTF to PCM. It was found that the PCM at the upper layer of the test section first melted during the melting process. Moreover, the effects of inlet temperature of HTF on the charging process was investigated. It can be concluded that increasing the inlet temperature of HTF effectively decreases the total charging time of the melting process. The amounts of heat storage for the inlet temperature of HTF 70 °C and 80 °C are 7400 kJ and 6555 kJ respectively during the melting process.

Keywords - Latent Heat Energy Storage, Paraffin wax, Test section, Melting process, Effect of inlet temperature

1. Introduction

Thermal energy storage can be used effectively in solar energy storage, building cooling or heating systems, and industrial waste heat recovery [1]. The phase change process of PCM can be performed at the desired temperature level in the latent heat energy storage system [2]. The performance of the solar air heater collector with phase change material was investigated to improve thermal efficiency [3].

Un-used waste heat energy from factories is effectively stored in thermal energy storage, and this stored energy can be used again at the desired place and time [4-5]. Koukssou et al. investigated the geometry of the PCM container for the application in solar water heating [6]. The cylindrical latent heat storage system is used to determine the heat transfer characteristics of PCM [7]. The heat transfer characteristics of PCM in a rectangular storage container was experimentally developed [8-10].

Ambarita, H., et al. have investigated that paraffin wax is a good PCM because it can store more energy than stearic acid [11]. The range of melting temperatures of paraffin wax has from 23 to 67 °C [12]. The paraffin compounds CₙH₂n₊2 have good properties such as non-corrosive, non-toxic, repeatability, and no sub-cooling [13]. Paraffin is cheap and is easily available from many manufacturers [14-15]. Xinbin H. et al. experimentally investigated the different design parameters of TES system [16]. The effects of changing the inlet temperature and its mass flow rate were investigated on both the charging and discharging processes [17-19].
The objective of this study is to investigate the melting behaviour of PCM and the performance of the storage system by changing the inlet temperature of HTF. The 15 kg of Paraffin wax is used as a PCM with the melting temperature of 58\textdegree-60\textdegree C for the heat storage of the solar water heating system. Purified water is used as HTF.

2. __Experimental setup and procedure__

2.1. __Experimental Setup__

The experimental test rig was built in a Laboratory which is situated in Yangon Technological University. Figure 1 shows the schematic diagram of the experimental device. The experimental setup includes constant temperature control water bath, water circulation pump, test section, flowmeter, water tank, variable frequency drive, data logger, and thermocouples.

The constant temperature control water bath has the following specifications: 45 L, the maximum operating temperature 200\degree C and the accuracy of temperature is \pm 1\degree C. The pump was responsible for the circulation of the hot water from the hot water bath to the thermal energy storage unit during the charging process and the cold water from the cold water tank to the TES unit during the discharging process. The pump is controlled by using a variable frequency drive to get the desired flow rate of heat transfer fluid. The acrylic EZ-View flowmeter with the model number (FL-9004) manufactured by OMEGA is used to measure the flowrate of HTF. The uncertainty of flow meter is within \pm 5\% of reading and it is installed on the exit pipeline of the test section. Figure 2 shows the actual setup of the experiment.

![Schematic Diagram of Experimental Setup](image1.png)

**Figure 1.** Schematic Diagram of Experimental Setup.

![Photographic View of Experimental Setup](image2.jpg)

**Figure 2.** Photographic View of Experimental Setup.
The main component of this experiment is the test section. The test section includes HTF tubes connected with a small water reservoir that connected to the bottom part of the test section. It has one entry at the bottom and one exit for HTF flow at the upper part of the test section. Two acrylic sheets with 4 mm of thickness are attached on the front and back surfaces of the test section to capture the behaviour of PCM inside the storage unit by using a digital camera. The whole part of the test section is covered with glass wool (thickness of 40 mm) to prevent the heat loss from the test section to the surrounding. Purified water is used as HTF and passed through the pipes inside the test section in the upward flow direction.

The instantaneous temperature of the PCM is measured by using K-Type thermocouples and collected by using a data logger. Six thermocouples are inserted symmetrically at each side of the test section to measure the temperatures of PCM at six different places and 3 different levels of test section: T2 and T3 at the lower, T4 and T5 at the middle and T6 and T7 at the upper part (include this description to Figure 3). Locations of thermocouples inside the test section are shown in figure 3. To measure the inlet and outlet temperature of HTF, the two thermocouples were used. The commercial-grade paraffin wax with the melting temperature of 58–60 °C is used as PCM. The only 80% of PCM volume is filled in the latent heat storage unit (test section) for accommodating the volume expansion of PCM. The thermos-physical properties of paraffin wax are described in Table 1.

![Figure 3. Locations of Thermocouples inside the Test Section.](image)

**Table 1. The Properties of Paraffin Wax [20].**

| Properties                  | Values          |
|-----------------------------|-----------------|
| Melting Temperature         | 58–60 °C        |
| Density (solid)             | 910 kg/m³       |
| Density (liquid)            | 795 kg/m³       |
| Latent heat of fusion       | 214 kJ/kg       |
| Specific heat of PCM        | 1.85 kJ/kg K    |
| Thermal conductivity        | 0.24 W/m K      |

### 2.2. Experimental Procedure

#### 2.2.1. Preparation

Before running the experiment, the test section was filled with 15 kg of PCM. At the beginning of the experiment, the paraffin wax in the test section is in the solid-state. Before starting the melting (charging) process, the water from the temperature-controlled water bath is heated to reach desire inlet temperature. All of the pipelines and test section were covered with glass wool. Camera
and stand are prepared to take photos and all thermocouples are connected to the data logger to record the temperature.

2.2.2. Experiment. The heated water flows from the water bath to the test section with a constant inlet temperature and constant flow rate of 9 L/min. The HTF was continuously circulated through the system during the whole experiment. The experiment was finished if the entire mass of solid PCM inside the test section was completely melted. When the charging process was completed, the discharging (solidification) process was immediately initiated by passing HTF from the cold water tank that has the room temperature to the system at a constant flow rate and a constant temperature. The water is continuously circulated through the system until the inlet and outlet temperature of HTF becomes the same. The temperatures of PCM that measured by the thermocouples are recorded with a data logger at the same time intervals of 30 seconds both in the charging and discharging periods.

2.2.3. Operating parameters. The constant flow rate of 9 L/min purified water is used. The influences of inlet HTF temperature were investigated with 70 °C and 80 °C. The temperatures of PCM that measured by the thermocouples are recorded with a data logger at the same time intervals of 30 seconds. The experiment was finished if the entire mass of solid PCM inside the test section was completely melted.

3. Results and Discussions

3.1. Melting Process with 70 °C inlet temperature of HTF

For the first time, the inlet temperature of HTF was kept 70 °C and the initial temperature of PCM is at room temperature. Figure 4 shows the temperature profiles of PCM with inlet HTF temperature of 70 °C and experiment time in minutes at three different layers along the vertical direction of the test section. In this figure, the average values of two PCM temperatures at the same level were plotted.

The melting behaviour of PCM for the inlet HTF temperature of 70 °C is shown in figure 5. At the top of the test section, space must be provided to allow for volumetric expansion or contraction of PCM. Thus, the PCM is not fully filled inside the test section. Several pictures of phase changing characteristics of PCM are taken by the digital camera and they were shown in Figure 5.

It may be observed that PCM temperatures increase rapidly till its melting temperature is reached and remain constant during phase change and then liquid PCM temperature rises again gradually. The upper layer of the PCM was first to melt about 30 min and the phase change process of upper layer PCM can be seen in figure 4. From this figure, the PCM at the upper layer reached its melting point faster than that of the middle and lower layers. The melting process was finished at about 380 min. The amount of heat store can be calculated as equation (1).

\[
Q_M = \int_{t_b}^{t_e} m_w C_{pw} (T_{in} - T_{out}) dt
\]

Where,

- \(Q_M\) = the amount of heat stored during the melting process (kJ)
- \(t_b, t_e\) = the beginning and ending time of experiment (min)
- \(m_w\) = mass of HTF (kg)
- \(C_{pw}\) = specific heat of HTF (4.18 kJ/kg-K)
- \(T_{in}\) = inlet temperature of HTF (°C)
- \(T_{out}\) = outlet temperature of HTF (°C)
The height of the PCM was 380 mm in the solid phase before starting the melting process. The upper part of the paraffin wax has been melted about 30 min after starting the melting process. The volume of solid PCM decrease and the volume of liquid PCM increase by experiment time as shown in figure 5. Half of the solid PCM changed to liquid about 240 min. All of the PCM was melted about 320 min. At the end of the experiment, the height of the liquid PCM was 395 mm. Thus, the height of the PCM was change about 15 mm at the end of the experiment because of the volume expansion of the PCM. By using equation (1), the amount of heat stored for the inlet temperature of HTF 70 °C is 7400 kJ during the melting process.

3.2. Melting Process with 80°C inlet temperature of HTF

In this time, the melting process with the inlet temperature of HTF 80°C was carried out again. The constant flow rate of HTF was also used 9 L/min. Temperature profiles of PCM with inlet HTF
temperature of 80°C are shown in Figure 6 and it can be seen that the PCM at the upper layer reached its melting point faster than the PCM temperatures of middle and lower layers.

The melting behaviour of that is shown in figure 7. The solid PCM start melts from the upper layer and the volume of liquid PCM was increased by time. From figure 6 and 7, it was clear that the melting process was finished about 180 min. Thus, it can be concluded that the melting time is effectively decreased by changing the inlet temperature of HTF. The amount of heat stored for that condition is 6555 kJ. Although the amount of heat stored is less, the charging time is effectively reduced in that process. It can be concluded that the amount of heat stored 6555 kJ can be received at a short time of period than inlet temperature of 70°C.

![Temperature profiles of PCM with inlet HTF temperature of 80°C](image)

**Figure 6.** Temperature profiles of PCM with inlet HTF temperature of 80°C

![Melting behaviour of PCM for the inlet HTF temperature of 80°C](image)

**Figure 7.** Melting behaviour of PCM for the inlet HTF temperature of 80°C
4. Conclusions and Discussions

An experimental setup was built to study the performance of the latent heat storage system and the characteristic of PCM during the melting process for the two different inlet temperature of HTF in 70 °C and 80 °C. It was found that the PCM melting first occurred in the upper region of the PCM and then the melted PCM increased with time from top to bottom. Charging time for the melting process of PCM in the latent heat storage unit can be reduced by increasing the inlet temperature of HTF.

The charging time during the melting process with the inlet temperature of HTF 70 °C and 80 °C was 400 min and 180 min respectively. The increase of the HTF inlet temperature from 70 °C to 80 °C resulted in a reduction in charging time of about 52 %. The amount of heat stored for the inlet temperature of the HTF 80°C is 6555 kJ. Although the amount of heat stored is less in HTF inlet temperature of 80°C, the charging time is effectively reduced in that process than that 70°C. It can be concluded that the amount of heat stored 6555 kJ can be received at a short time of period than inlet temperature of 70°C.

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