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Designing a Solar Heat Storage System using Heat Pipe and Phase-Change Material (PCM)

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ABSTRACT

Phase change material (PCM) is used as a storage medium in a thermal heating system. The PCM's ability to store heat for a long time is suitable for combining with solar energy. PCM can absorb or release large amounts of latent heat at relatively constant temperatures. However, the PCM has poor thermal conductivity. The superconductive heat pipe is suitable to enhance the heat transfer in the PCM. The study aims to prove the concept of a unique thermal storage system that combines solar Fresnel lens, heat pipe, and phase change materials technologies. This study presented a detailed design and testing of the combined system under an actual outdoor environment. Four Fresnel lenses refracted the sunlight and focused on a heat collector. The lenses can be manually adjusted according to the sun's position. The heat is transferred to the PCM storage tank via a finned heat pipe. The testing results showed that the paraffin wax (PCM) has a melting temperature between 54 -59 °C. The highest temperature recorded in the paraffin wax tank was 121 °C which is suitable for many future applications. The system could store the heat up to 730 kJ by using 2 kg of paraffin. During the solidification of PCM (discharging), the system retained 120 kJ of heat for almost 7 hours with minimal heat loss. The system was proven to function well for storing the heat after the sunset, and it can be used for a passive power generation system, such as using thermoelectric cells.

1. Introduction

Thermal energy storage is the heat captured from hot solids and liquids and stores the energy for later use [1-2]. Solar energy is one of the sources of heat that can be stored. The primary components of the thermal energy storage system are the storage tank and heat storage medium [3-4]. This study used solar energy to store heat and the phase change material (PCM) as the storage medium. Solar energy is a renewable energy resource identified as a significant energy source, economically efficient, and reliable. There are numerous different forms of heat storage mediums that have been

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employed in industry, but PCM is the most productive since it uses latent heat.Using PCM is a valuable and advantageous method to get a high storage density with a higher efficiency [5-8].

For maintaining a certain amount of heat storage, only a small amount of PCM is required. PCM can store or release large amounts of energy at constant temperatures and has high thermal energy storage densities [9]. Hydrated salt and paraffin wax are the most widely used phase change materials [10-11]. Hydrated salt or liquid salt is found in some commercial-scale solar farms. At the same time, paraffin wax is more commonly used in residential storage or waste heat storage where operating temperatures are relatively low [12] [4]. Phase change material (PCM) uses latent heat to store thermal energy. The operation and design of latent heat thermal storage can be influenced by the PCM used. Because it may gain heat while remaining in its phase change state, the phase change material can also be used as a constant temperature heat source [13]. PCM can work permanently and experiences little degradation over time [1].

The phase change material (PCM) thermal storage is needed for a solar power system to ensure an endless solar energy supply for domestic or industrial applications such as water heating, air-conditioning, waste heat utilization, and cooling. The high-energy storage density of phase change materials is essential for storing solar heat to reduce the space required for installation. PCM's physical and chemical characteristics are a significant factor in designing and operating the latent heat thermal storage [14]. The high-energy-density PCM should be selected for a high heat storage requirement. This will allow the designer to reduce the storage tank size. Such a design will cut costs for constructing a heat exchanger or provide a more significant storage capacity for the same volume.

Table 1 presented a critical assessment of the previous study trends integrating heat storage technology with various phase change materials and heat pipes.

Table 1
Summary of thermal energy storage using phase change materials (PCMs) and heat pipe

Author/ Date	Topic/Focus	Concept/ Theoretical Model	Method	Findings	Limitations/ Gaps
[15]	Energy storage using novel organic phase material/MXene composite.	Formulate novel PCM/MXene (Ti_3C_2) composite.	Paraffin wax (PCM) was mixed with an inorganic nanoparticle known MXene with three different concentrations.	Improving the thermal capacity, Cp by 43%, absorbance (UV-Vis) by 39%, and thermal conductivity by 16% with introducing 3wt.% mass fraction of MXene in the composite.	The melting point of PCM/MXene could only be increased by 2° C. It has a high final degradation temperature of 384° C. However, the study of the size, thickness, and number of layers has not been conducted.
[16]	Heat management using phase change materials (PCM) and heat pipe heat sink Lithium-ion battery	Study the effectiveness of a combination of soy wax (PCM) and heat pipe heat sink for heat management in	Conducted four different types of battery cooling experiments utilizing only PCM, only a	The combined soy wax (PCM) system and heat pipes provided the best cooling, lowering the	Soy wax has a slight temperature gap between the melting point (44◦C) and

		an electric vehicle Lithium-ion battery.	heat pipe heat sink, no cooling, and a mix of PCM and heat pipe heat sink.	battery temperature by 50 ° C.	solidification (38◦ C).
[17]	Enhancing the conductivity of nano-PCM-based graphene.	Introduction of graphene flakes in paraffin wax to increase the thermal conductivity of the PCM.	The parameters that affect the thermal conductivity of the nano-PCM-based graphene composite were determined using an empirical model created using a response surface approach.	The temperature was found to be the most influential parameter that affects the nano-PCM-graphene-based thermal conductivity.	This model is adequately represented by the most critical independent variables, including the average lateral size of graphene flakes, mass fractions, and rising temperatures.
[18]	Improved the thermal and electrical efficiency of solar concentrated photovoltaic/thermal (CPV/T) using nanomaterials composite of graphene-silver (Gr-Ag) and paraffin wax.	Characterizing the thermophysical properties of a hybrid graphene-silver (Gr-Ag) nanomaterial mixed with paraffin wax in a solar thermal system (CPV-T)	Three different compositions of PCM/graphene-silver have been investigated. Electrical and thermal performance was predicted using MATLAB 2017b simulation.	Improvement of the specific heat capacity by 40% and thermal conductivity by 11% using 0.3 mass% of hybrid PCM/graphene silver.	The thermal and electrical efficiency can only be increased by less than 5% with the introduction of hybrid PCM/graphene silver.
[19]	Utilizing a novel nanocomposite of palmitic acid/Ti_3C_2 MXene in the thermal energy storage system (TES).	Improved thermophysical use of phase change material using palmitic acid/Ti_3C_2 MXene composite.	A two-step process was used to synthesize the palmitic acid/Ti_3C_2 MXene composite.	The thermal conductivity and the thermal conductivity increased by 14% and 4%, respectively.	The melting temperature of the composition has not changed.
[20]	Using fatty acid/metal ion composite in thermal energy storage (TES) application.	The sodium - ion has been incorporated into lauric acid to improve its thermophysical properties.	Sodium metal with 0.2 – 1 wt% was doped in lauric acid to produce the composite using a simple method.	Enthalpy of fusion was enhanced by 11%, and the temperature decomposition was improved by 30%.	The melting point of the composite decreased slightly as the weight percentage of sodium metal in the composite increased.
[21]	Integration of heat pipes and PCM in a solar still system	A pulsating heat pipe was employed to convey stored heat in the PCM to prevent saline	Latent heat of vaporization was recovered using a pulsating heat pipe and PCM in	Produced 6.3 kg/m^3 of fresh waste with an increase of 43% efficiency compared to a	The proposed system's cost per liter (CPL) rose by 43% (0.0093 $\$$/L/m^2) compared to

		water temperature drops and continuous desalination after sunset.	a solar still environment.	typical passive solar still system.	the standard solar still system.
[22]	Investigation of the heat transfer performance of the combined heat pipe and CuO-paraffin nanocomposites.	The heat transfer characteristics of heat pipe-PCM were studied for both cooling and heating modes.	The fin was installed on the condenser side of the flat plate heat pipe. The PCM tank was installed in the adiabatic section.	The thermal conductivity of the PCMs rose by 24% when 1.2% of CuO nanoparticles were doped into the paraffin.	PCMs latent heat decreased by 1.5%, and the evaporator temperature reduced by 17%.
[23]	Investigation of a wall cooling technology using a combination of a microchannel heat pipe, sky radiative cooling, and PCM (MHP-SC-PCM).	Passive cooling of sky radiation was utilized via a radioactive plate for releasing heat from the PCM wall during the nighttime.	A preliminary study was conducted to determine the radiative plate emissivity and the paraffin (RT28HC) thermal properties. A numerical model was developed to simulate the MHP-SC-PCM thermal behavior.	The system could reduce the cooling load by 4%.	The MHP-SC-PCM wall was able to a year-round energy saving of 18% better than typical wall brick with the same thickness.

Most recent studies focused on improving the thermal properties of PCM by adding additives, including carbon-based and metal-based materials. Carbon fillers have many advantages, such as having stable chemical and thermal properties, high thermal conductivity, and compact and low density. However, they are challenging to prepare and process. Metal-based fillers, meanwhile, can enhance the thermal conductivity of the PCM but have problems with high density and cannot be easily dispersed evenly, resulting in unstable heat transfer. They also are highly reactive with other substances [24].

Some studies added heat pipes, fins, and meshes to overcome the issue of low thermal conductivity and leaking problems. This study has chosen heat pipe because it has high thermal conductivity, is affordable, and long lifespan [25].

Therefore, this study features a unique solar thermal heat storage design consisting of Fresnel lenses, heat collector, heat pipes, phase change material, and a tank. The study aims to prove the workability of such a concept where its performance was tested and analyzed under real conditions. The study did not add any additives in the PCM to lower the cost of the system. Four pieces of Fresnel lens were placed under the sunlight to focus the heat onto the heat collector, as shown in Figure 1. A large number of Fresnel lenses are used because it can prevent system failure if one of them is damaged. In addition, it can be adjusted independently according to the position of the sun to focus light rays. Wider frames were adjustable, which they could rotate about 360 degrees to make sure the sun's heat is continuously focusing on the heat collector. With a 42 mm × 37 mm dimension, the heat collector was connected to the heat pipe and fins, immersed in a thermal energy storage tank. The tank contained 2 kg of PCM to store enough heat for later use.

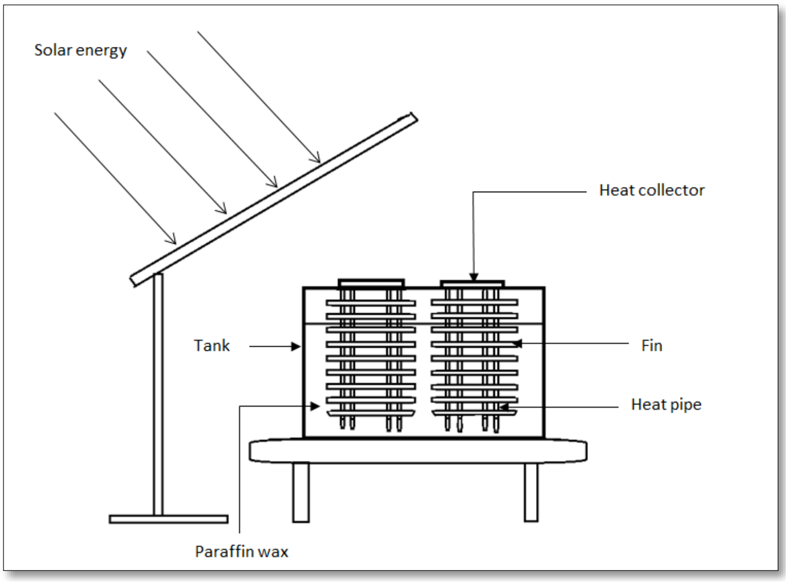

Fig. 1. An illustration of the experimental set-up

2. Materials and Methods

2.1 Fresnel Lens

Material selection for the model was decided based on reviewing the journals and related articles on solar Fresnel lenses. Most of the materials selected can easily absorb solar energy and convert it to heat energy at an optimum level. The Fresnel lens collector was mainly made from glass material with a glossy effect suitable for harnessing solar energy power to generate heat to the focal point of the heat pipe. The dimensions were taken according to the primary reference and scaled down so that the model can be placed on a level 21 Tower 1, Engineering Complex. However, the critical dimensions that need to be concerned are the Fresnel lens area, Fresnel lens collector area, the Fresnel lens stand's height, and the focal length. The dimension of the Fresnel lens is summarized in Table 2.

Table 2
Dimensions of the Fresnel lens

Descriptions	Dimensions, mm
Fresnel lens area	255 x 180
Fresnel lens collector area	42 x 37
Length of the focal length	250
Height of the Fresnel lens stand	1515

2.2 Thermal Energy Storage Tank Design and Heat Pipe

The thermal energy storage tank's primary goal was to store heat and be used after the sun goes down for as long as needed. The storage tank systems require a practical design to release thermal energy at constant temperatures. An immaculate and effective heat transporting system must be built to enable waste heat flow into and out of the suggested PCM thermal storage concept. The characteristic information about the PCM thermal storage tank is given in Table 3.

Table 3
Characteristics of Thermal Storage Tank

Parameter	Value
Width: mm	210
Height: mm	160
Length: mm	400
Thickness: mm	3
Area: m^2	0.084
Volume: m^3	0.01344

Table 4 shows the characteristic of the heat pipe heat sink in the testing. Two sets of heat pipe heat sinks were placed in the tank.

Table 4
Characteristics of The Heat Pipe

Parameter	Properties/Value
Material	Copper
Diameter: mm	6
Working fluid	water
Dimension (L x W x H)	80 x 40 x 117

2.3 Phase Change Material

The PCM used in thermal storage is paraffin wax, which is an organic material. It has a low melting point, with an enthalpy of fusion of 145-240 kJ/kg [4]. It is non-corrosive, exhibits thermal cycling, and readily available. All these properties are essential requirements for developing a maintenance-free and reliable thermal storage system. Paraffin wax, known as PCM, will undergo a three-phase change in that solid-liquid and liquid phase to reach its melting point under constant heat dissipation by the heat pipe condenser section. The equation for calculating the heat storage capacity of the PCM is given as:

$$Q_s = m_{pcm}C_{p\,pcm,solid}(T_m - T_i) + m_{pcm}L + m_{pcm}C_{p\,pcm,liquid}(T_f - T_m) \tag{1}$$

where m_{pcm} is the mass of PCM (kg), T_m is the melting temperature, T_i is the initial temperature, Tf is the PCM temperature, C_p is the heat capacity (kJ/kg), and L is the latent heat (kJ/kg).

Table 5
Thermo-physical properties of proposed paraffin wax as PCM

Description	Value
Melting temperature, °C	53.7
Mass, kg	2
Latent Heat Capacity, kJ/kg [26]	176
Specific Heat Capacity, Cp PCM solid, kJ/kgK [27]	2.95
Specific Heat Capacity, Cp PCM liquid, kJ/kgK [27]	2.51
Initial temperature, °C	32

2.4 Experimental Procedure

The test began by setting four Fresnel lens pieces in its frames, as shown in Figure 2. The Fresnel lens was then placed under the sunlight to focus the ray onto the heat collector. The lens is adjustable and can be rotated at about 340 degrees. The distance between the Fresnel lens and the heat collector is about 0.25 m. This distance is to ensure the solar radiation can precisely focus on the target (heat collector). The 42 mm x 37 mm heat collector was connected to an evaporator side of a heat pipe. The other end of the heat pipe was finned, acts as a condenser, and is immersed in the thermal energy storage tank. The tank contains two kilograms of PCM. The radiation and ambient temperature were recorded by the solar emitter and wireless digital thermometer, respectively. Four temperature sensors at a specific location were connected to a data logger. The concentrators were adjusted to track the sun's position, and readings were obtained every 5 minutes. This is to make sure the bright spot is always at the center of the focal point (heat collector) to gain the highest heat energy from the sun.

Fig. 2. Experimental set-up under the sunlight

3. Result and Discussion

Figure 3 shows the result of the preliminary test of the system. The collector temperature drastically increased from 3.10 p.m. until 3.40 p.m. Then, that brought it to a peak with a short duration, and the highest temperature was achieved at 116.1 °C with 1110 W/m2 solar radiation. The radiation reached the maximum plateau of the solar radiation between 3 p.m. until 5 p.m. The heat from the heat collector was transferred to the heat pipe, then lastly to the paraffin wax in the tank. The paraffin wax started to melt at 59.2 °C. Many clouds caused the temperature and solar radiation to drop slowly during the experiment due to convection heat loss. The experiments continued for another three days to collect reliable data. The data temperatures data were recorded using a data logger at the heat collector, heat pipe, paraffin wax (near to heat pipe), and paraffin wax (far from heat pipe). The data were collected from 3.28 p.m. to 4.19 p.m. due to good weather to run the experiment on day one. The highest temperature measured on the heat collector was 115 ^{o}C with 1149 W/m^2 of solar radiation, as shown in Figure 4. The heat from the heat collector was transferred to the heat pipe, and the highest temperature of the heat pipe was 101.6 ^{o}C. Two temperature sensors were placed in the PCM tanks, the first was close to the heat pipe surface, and the second was at the bottom of the tank. Near the heat pipe, a combination of heat conduction and radiation caused a paraffin wax temperature to rise from 35 °C to 56.7 °C before reaching the melting point. The paraffin wax started to melt at 3.48 p.m., with a record temperature of 59.2 °C.

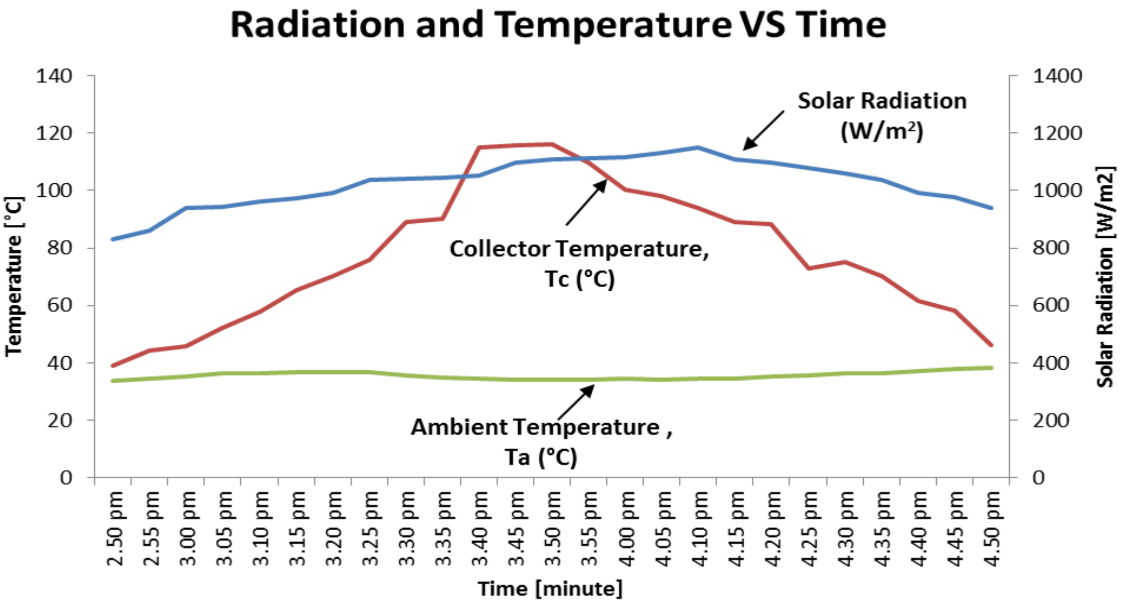

Fig. 3. The relationship between solar radiation and temperature

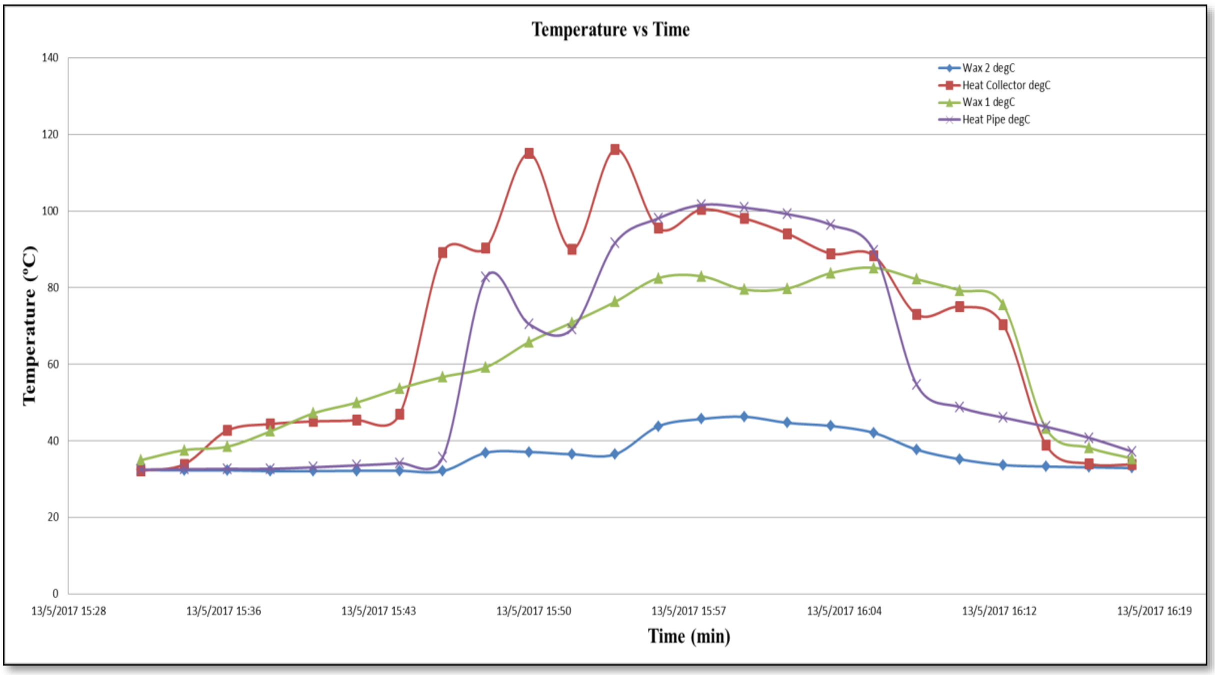

Fig. 4. Temperature Changes versus Time for Day One

Meanwhile, at the bottom of the paraffin wax tank, the temperature could only reach 46.3 °C because the heat could not be transferred efficiently. The sun became cloudy at 4.14 p.m., and the heat collector's temperature dropped from 116.1 °C to 46.2 °C. This caused the paraffin temperature to drop from 75.6 °C to 35.2 °C. The two-kilogram paraffin wax was not wholly melted due to the gloomy weather. The paraffin wax can store the heat within the 1200s (20 minutes) before returning to the experiment's average temperature. Figure 5 shows the molten paraffin wax (near to the heat pipe).

Fig. 5. Molten paraffin wax during testing

On day two, the data and the graph were collected and plotted using the data logger starting at 2.51 p.m. to 5.41 p.m., as shown in Figure 6. The paraffin wax (near to heat pipe) began to melt at 3.16 p.m., which reached the temperature of 53.4 ^{o}C and continued to melt until the paraffin wax changed from solid to liquid. The highest temperature of that phase change material was 104.5 ^{o}C. The fourth thermocouple at the bottom of the paraffin wax tank detected the temperature rise from 40.7 ^{o}C to 78.3 ^{o}C at 3.40 p.m. This is because the heat from the liquid wax started to diffuse toward the solid paraffin wax. Then, the day began cloudy at 3.51 p.m., and the temperature of the heat collector began to drop from 135.1 ^{O}C to 114.3 ^{O}C. This condition affected the heat transfer rate to the heat pipe, which caused a decrease in temperature. The thermal storage tank was moved to a shady place at 4.00 p.m. to measure the paraffin wax's ability to store the heat absorbed earlier. The temperature of the paraffin wax (near the heat pipe) dropped from 77.7 ^{o}C to 51.7 ^{o}C. It was found that the paraffin wax could store the heat for 6000s (100 minutes) before it went back to the average temperature, which is 32.3 ^{o}C.

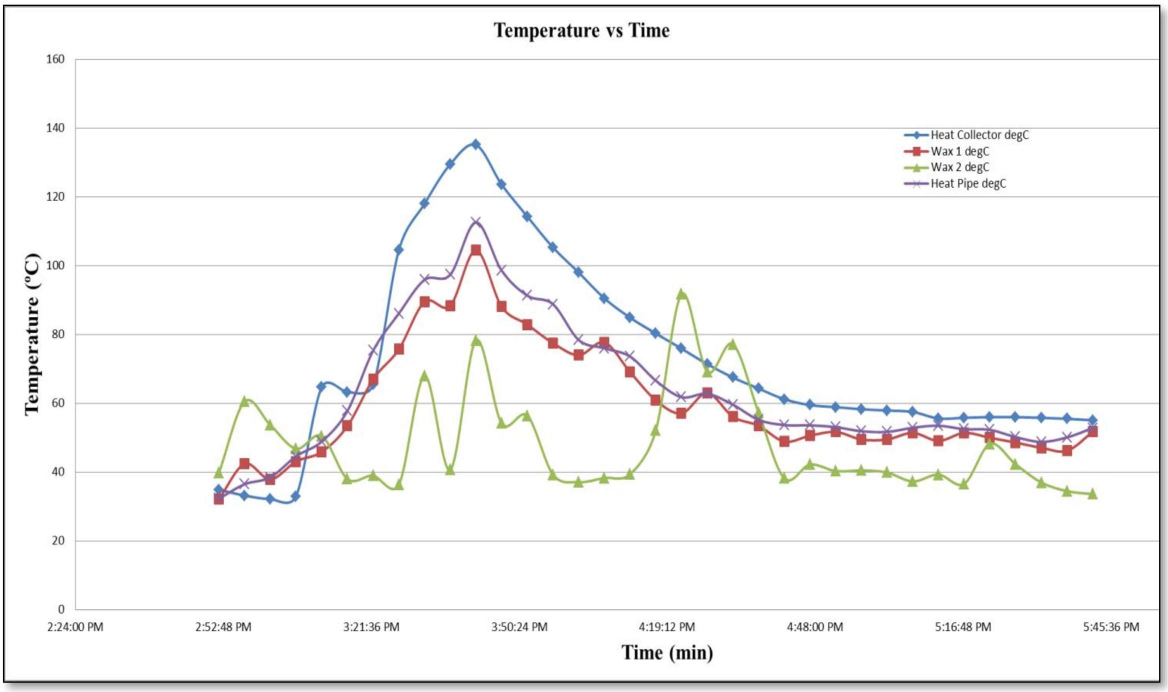

Fig. 6. Temperature Changes versus Time for Day Two

The experiment on day three is shown in Figure 7, starting at 12.43 p.m. to 10.43 p.m. Due to the excellent weather conditions, which was a sunny day and suitable for the experiment, took around ten hours to test the paraffin wax's ability to store the heat. The investigation showed that the heat collector's highest temperature was 121.3 °C, which had increased from 50.7 °C. The temperature of the heat pipe also rose from 33.7 ºC to 117.6 ºC. The paraffin wax (near heat pipe) melted in the range of temperature of 53.7 °C to 62.1 °C at 2.03 p.m. The heat from the heat pipe continued to flow to that paraffin wax, which caused the temperature to rise rapidly from 79.2 °C to 109 °C, the highest temperature of the phase change material recorded. At 3.53 p.m., the fourth thermocouple at the bottom of the tank detected a temperature increase from 64.4 °C to 99.1 °C. This is because the molten paraffin wax (near the heat pipe) is mixed with this paraffin wax. At 4.03 p.m., the availability of sun radiation started to drop. The heat collector's temperature decreased, followed by the heat pipe's temperature from 120.4 °C to 106.4 °C and 117.6 °C to 103.2 °C, respectively. At 4.33 p.m., the tank thermal storage was moved under a roof with no wind area. The heat collector was insulated with a rubber foam insulator. Figure 7 shows the paraffin wax's temperature (near to heat pipe) and (far from heat pipe) slowly decreased from 99.4 °C to 84.1 °C and 95.7 °C to 80 °C, respectively. The results showed better heat retention as the heat slowly dissipated into the environment when the insulation was introduced in the third experiment. The phase change material can store the heat for longer than 6 hours (360 minutes) from 4.33 p.m. to 10.38 p.m.

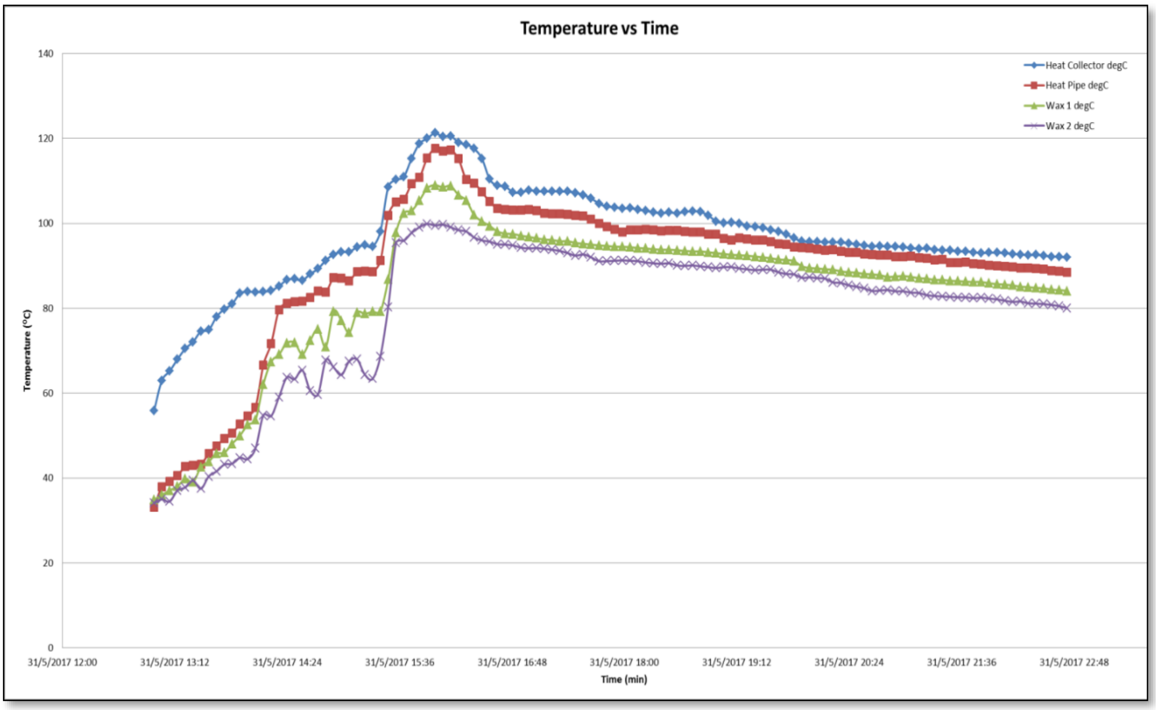

Fig. 7. Temperature Changes versus Time for Day Three

Figure 8 shows the storage capacity of paraffin wax from this experiment. Paraffin wax at room temperature heats up to a positive slope for the first 200 minutes. Heat storage reaches a peak capacity of 731 kJ. The hot paraffin wax began to cool as the sun's rays started to disappear. Although this system seemed to lose energy due to a lack of solar radiation, there was still much heat left in the tank, with 621 kJ at the end of the testing period. This occurs after 6.75 hours (405 minutes). The slow process of removing heat or solidification back from paraffin shows that the system can store heat for a more extended period by installing an excellent insulation system.

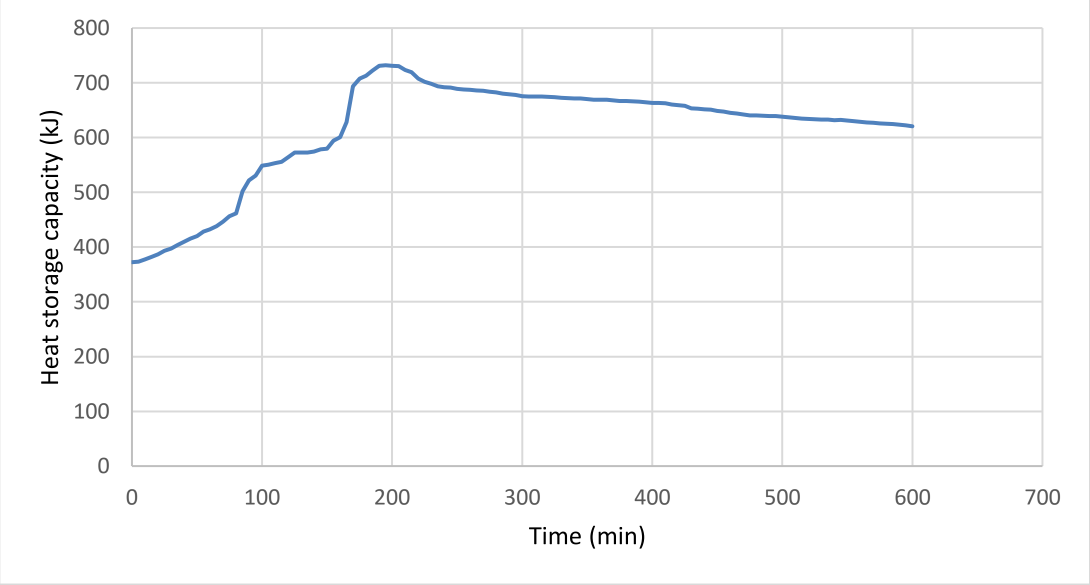

Fig. 8. Heat storage capacity versus time

4. Conclusions

The experiments revealed that paraffin wax melts at temperatures ranging from 55 to 62 °C. The maximum temperature of paraffin wax was 109 °C. Using the designed system, the 2 kg paraffin wax can retain heat energy from the sun for more than 400 minutes (6.6 hours). The highest recorded amount of energy stored was 730 kJ. Even after 6 hours of cooling, there was still much heat stored in the paraffin tank, of which approximately 621 kJ remained. The paraffin liquid was expected to take a few more hours to solidify and return to ambient temperature with this amount of heat. The heat collector was connected to the heat pipe used. It was found that when the ambient temperature is lower than the tank temperature, the heat from the tank will move in the opposite direction due to the high efficiency of the heat pipe. This will accelerate heat loss from the tank to the surrounding area through the heat pipe and heat collector. The heat collector was insulated using rubber foam to overcome this problem. By insulating the heat collector, the paraffin wax could retain the heat for a more extended period. It was also found that if the mass of paraffin were increased, it would take a long time to dissolve paraffin wax. This is because paraffin wax is known to have low thermal conductivity. To further speed up the paraffin wax's heat transfer rate, increasing the number of heat pipes installed in the system is recommended, reducing the time to dilute paraffin.

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