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Thermal Energy Storage Characteristics of Paraffin in Solar Water Heating Systems with Flat Plate Collectors

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ABSTRACT

Indonesia is a tropical country with a relatively stable intensity of solar radiation throughout the year, ranging from 10 to 12 hours a day, and averaging 4.8 kWh/m²/day. This great potential can be used for heating water for bathing. Water heating technology based on solar collectors is now widely available in the commercial market. Additionally, thermal energy storage from solar radiation is performed using sensible heat and requires a large volume. Assuming that the water is not used until the afternoon, then the heated water is stored in the tube. A phase change material (PCM) was used in several studies to maximize thermal energy storage (TES) from solar radiation. Also, PCM uses latent heat to absorb and release heat. This is adjusted to the water temperature produced from the solar collector, which attains 70°C. Hence, the potential PCM used is solid paraffin, which is widely available in the market with melting temperatures of 40° to50°C. The study was conducted on a solar water heating system using an 80 cm x 50 cm flat plate collector, and thermal energy storage using paraffin wax. Meanwhile, the heat exchanger used a tube with a diameter of 1 inch arranged in series with a pipe length of 50 cm and 36 rods. The mass of paraffin used was 15 kg or 17.7 liters. Furthermore, the test was performed with variations in the flow rate of water, namely: 2, 3, and 4 lpm, and solar radiation of: 997.5 W/m², 1183 W/m², and 1399.8 W/m². From the results, the thermal energy storage process in PCM paraffin with an amount of 15 kg, took 3.2 hours with a total stored energy of 3.6 MJ. Moreover, solar radiation of 1,399.8 W/m² was used as an energy source and water with a flow rate of 4 lpm as a medium heat transfer. Therefore, this radiation has a very significant effect on the heat transfer process to the PCM, while the flow rate with a value of 2 to 4 lpm does not have.

1. Introduction

Solar is an abundant energy source in Indonesia, with the potential of 4.8 kW/m²/day [1]. This country's geographical location provides advantages such as the long solar radiation of up to 10-12 hours/day, and not much different every month. Therefore, this potential is very useful as an energy source for bathing and other purposes. It reduces electrical energy consumption and carbon capture

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from the production process. The water heating system is prepared by converting solar into thermal energy in the collector. This system has been widely used in both residential homes including hotels and inns. In this system, thermal energy storage uses sensible heat, therefore, it takes a large volume.

Innovations are made to reduce the volume of energy storage while maintaining a large density to overcome thermal losses to the environment using PCM. There are three models of using PCM as thermal energy storage in water heaters, namely direct circulation, indirect circulation, and PCM in solar collectors. Several studies using direct circulation showed that thermal energy storage can be achieved by using latent heat. Englmair *et al.,*[2] used PCM of Sodium Acetate Trihydrate (SAT) to store thermal energy from a flat plate collector at 70°C. Also, Xie *et al*.,[3] used a composite PCM Stearic Acid (SA) and Coconut Shell Charcoal (CSC) to absorb heat from a solar collector with a phase change temperature and latent heat of 52.52°C and 76.69 J/g, respectively. Shalaby *et al*.,[4] conducted experiments on solar collectors for water heating with a direct solar source and water as a carrier of heat energy with a closed cycle. This is followed by heat transfer with PCM in a shell and tube heat exchanger. Paraffin wax was used as the PCM, with a phase change temperature of 60°C. The indirect cycle was the second model in thermal energy storage and the carrier fluid from the solar collector transfers heat into the PCM tube. Meanwhile, Zhao *et al.,*[5] used PCM as thermal energy storage with an indirect system. The fluid from the solar collector and the PCM have their respective cycles, and heat transfer occurs in an exchanger passed by the two fluids. Furthermore, the PCM mounted on the bottom of the solar collector was the third model. To stabilize the temperature and simultaneously store thermal energy, Vengadesan and Senthil [6] added a PCM at the bottom of the collector. In addition, the evacuated tube solar collector (ETSC) combined with PCM paraffin wax, as thermal energy storage, also increased the overall performance by 32% as in the research conducted by Algarni *et al.,*[7].

Paraffin wax has good thermal stability, high latent heat of 206 kJ/kg, with a melting temperature of 50-60°C and thermal conductivity of 0.2 W/m.K as a thermal energy store [8-11]. The thermal conductivity value of paraffin wax which is not high can still be increased, such as the addition of Cu in the form of nanoparticles up to 2.5 wt.%, it can increase the thermal conductivity of paraffin wax to 0.35 W/m^2.K [12]. Several other studies also show the same trend [13, 14]. This paraffin wax phase change temperature is very suitable for storing thermal energy from hot water produced by solar collector. PCM has the advantage that the change in temperature during the phase change is very small in a longer time so that the heat transfer rate does not experience a significant decrease [15]. The hot water produced by the solar collector is very high, reaching 85^{o}C as in the research conducted by Gooroochurn and Visram [16]. With the temperature difference between hot water and PCM reaching 35^{o}C, paraffin wax is very suitable for storing thermal energy. Another thing that supports this paraffin wax to be applied to SWH is that it is cheap and widely available in the market [17-19]. To utilize paraffin wax as a thermal energy storage in SWH, it is necessary to conduct research related to the thermal energy storage process for several conditions of solar radiation and the velocity of water flow as a medium for carrying heat from the solar collector. so that it is known the time required to exceed the melting temperature.

2. Methodology

An 80 cm x 50 cm flat plate solar collector made up of glass, black plate, copper pipe, glass wool, and plywood mounted on a wooden stand was used in this study. The copper pipe had a diameter of 3/8 inch arranged in parallel with a distance of 5 cm between the pipes. Also, the heat exchanger was a shell and tube for heating paraffin. The box-shaped shell was made of aluminum insulated with an absorber to keep heat stored in the exchanger. In the tube, a copper pipe with a diameter of 1 inch was arranged in series. The length of the entire series was 1800 cm and it was made up of 36 pipes with a size of 50 cm. Furthermore, the mass of paraffin was 15 kg or 17.7 liters and the test was performed with variations in the flow rate of water, namely 2, 3, and 4 lpm, while the solar radiation of 997.5 W/m², 1183 W/m², and 1399.8 W/m² was used. A solar simulator was used to heat the room. Subsequently, solar radiation, collector surface temperature, heat exchanger inlet and outlet temperatures, PCM temperature, and water flow rate were all measured. Figure 1 shows the test equipment schematic.

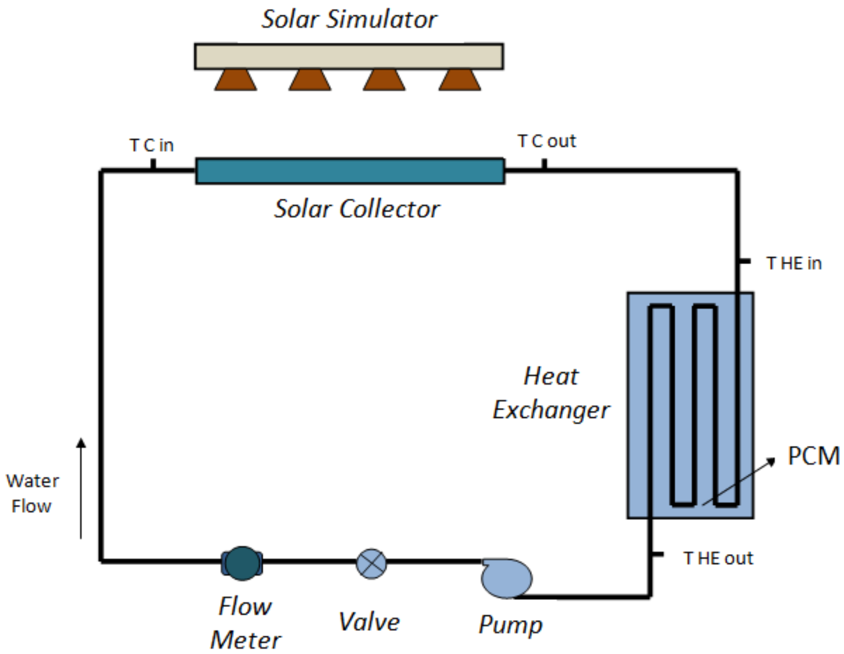


Fig. 1. The scheme of water heating test equipment using PCM

3. Results

Solar radiation of 997.5 W/m², 1183 W/m², and 1399.8 W/m² were produced with a simulator with three lamp variations. The test started at the environmental temperature conditions of 29°C, both, collector, water, and PCM. Furthermore, the collector was heated using a solar simulator, and water simultaneously circulated both in the collector and in the HE containing the PCM. The heat was absorbed by the flat plate collector top surface, raising the surface temperature. Also, the heat from water flowing through the parallel pipe, mounted on the collector's bottom surface was absorbed, increasing the temperature of the water leaving the collector. A pipe carried water to the heat exchanger containing the PCM and the absorbed heat was transferred by water through tubes arranged in series in the exchanger. Moreover, because the water flows in a closed cycle, the PCM temperature gradually increases. Figure 2 shows the changes in the temperature of the collector, inlet, and outlet of the HE, and PCM.

Figure 2 explains that the PCM temperature increased along with the collector surface temperature. The increase in collector temperature affected the water temperature outside the collector which then entered the HE. As the phase change occurred, the increase in PCM temperature slightly slopped in the range of 40°C – 50°C and then slopped down again at 60°C. Furthermore, data collection ended at 62°C – 63°C, and at this temperature, all PCM was in the liquid phase. Although the tubes were installed in series with the average during the heating process is 1.1°C, the changes in the temperature of the air inlet and outlet of HE was not large.

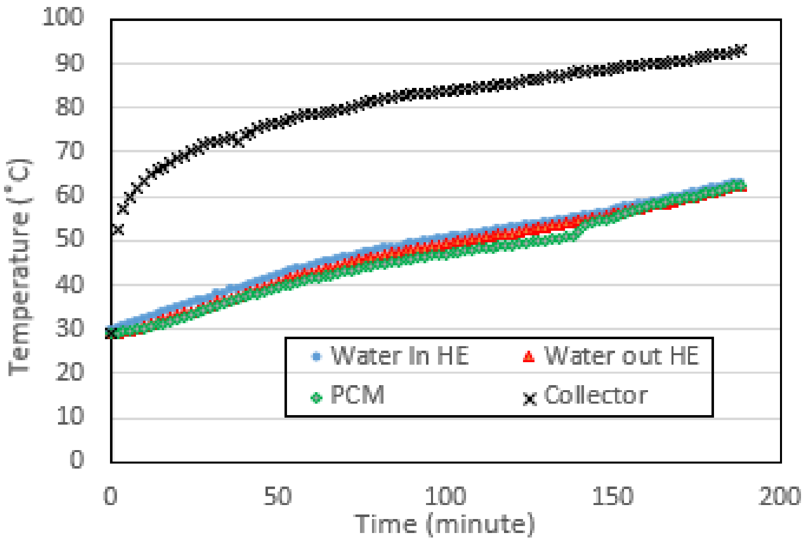
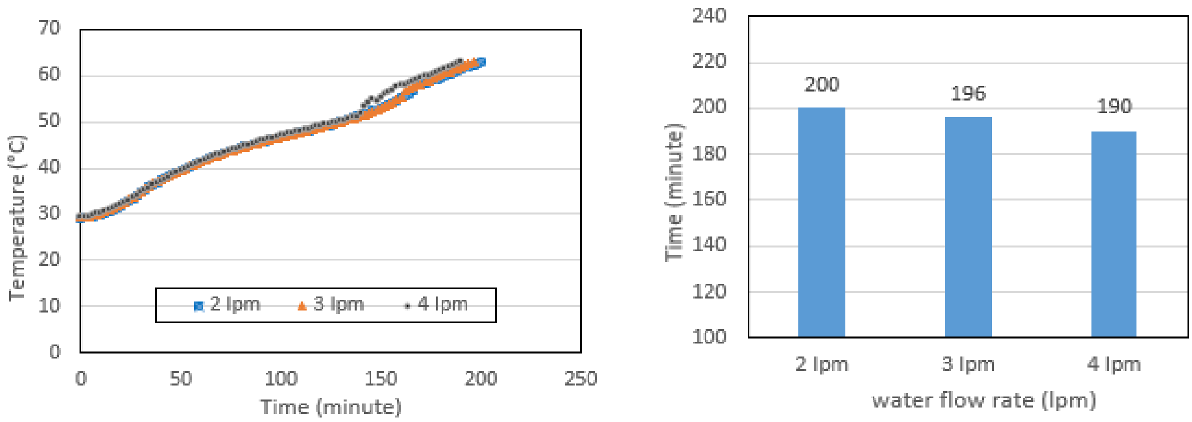


Fig. 2. The HE and the collector temperature in the heating process with solar radiation was 1393.8 W/m² and the water flow rate was 4 lpm

As shown in Figure 3, the increase in the water flow rate resulted in a faster increase in PCM temperature. The difference in PCM temperature with variations of 2, 3, and 4 lpm was not very significant. Attaining 63°C was only 10 minutes faster for the flow rate of 4 lpm compared to 2 lpm, hence, there was a 5% reduction in heating time. Moreover, with a significant increase in flow rate, this heating process was accelerated. Based on the calculation for this flow discharge variation, the Reynolds number (Re) was still low, ranging from 254.1 to 508.1. In this melting process, the average heating rate was in the range of 0.17°C/min – 0.18°C/min, and took minimum times of 3.2 hours to attain 63°C.

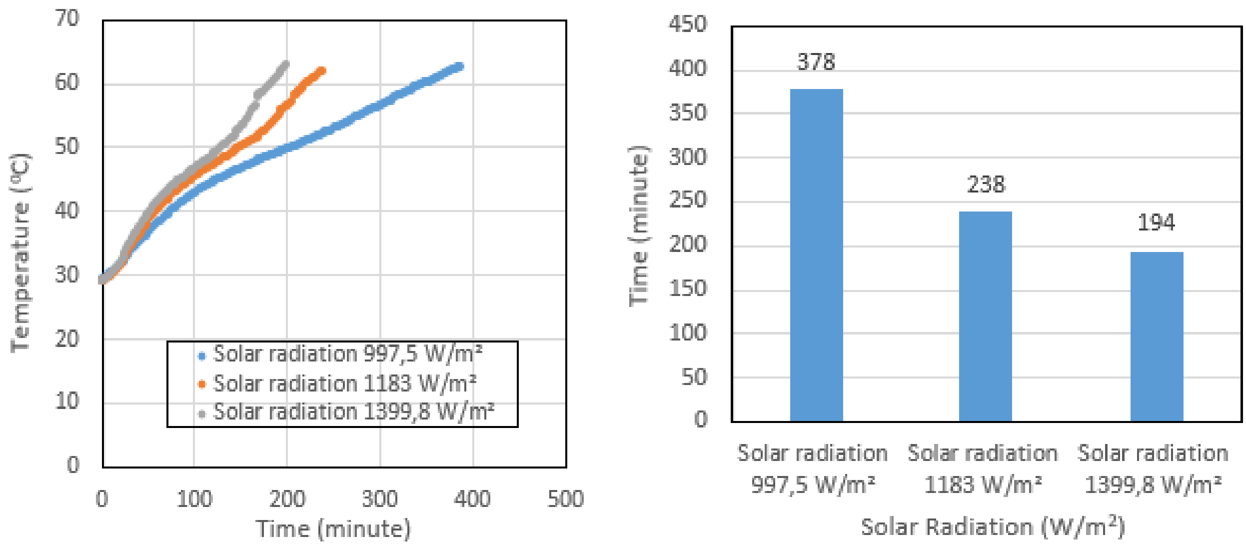


(a) PCM Temperature (b) Time to reach PCM temperature of 63°C

Fig. 3. Effect of water flow rate on PCM temperature and time required to reach 63°C at 1399.8 W/m² solar radiation

As shown in Figure 4, the increase in solar radiation had a significantly raised PCM temperature. Meanwhile, solar radiation reached 1,399.8 W/m² faster at 62 – 63°C as shown in Figure 4.a. At a flow rate of 2 lpm, the PCM heating rate for each solar radiation was 0.09° C/min for 997.5 W/m² solar radiation, 0.14°C/min for 1183 W/m², and 0.17° C/min. This shows that the time required for the heating process was 378 minutes for 997.5 W/m² solar radiation and this is 1.8 times the 1399.8

W/m² solar radiation. According to this test, the longer the time needed, the lower the solar radiation. This is exacerbated further by fluctuations in solar radiation in real conditions. Furthermore, a significant increase in the flow rate accelerates the heating process, allowing it to pass through the phase change temperature in a relatively short time.



(a) PCM Temperature (b) Time to reach PCM temperature of 63°C

Fig. 4. Effect of solar radiation on the average PCM temperature for a water flow rate of 2 lpm

As shown in Figure 5, the energy required for the PCM heating process of 15 kg with three variations of the hot water flow rate was 3.6 MJ. With this same energy value, the time required for each hot water flow rate was different. The shorter the time required, the greater the flow rate of hot water, while the average heat transfer rate was between 0.30 kW – 0.31 kW.

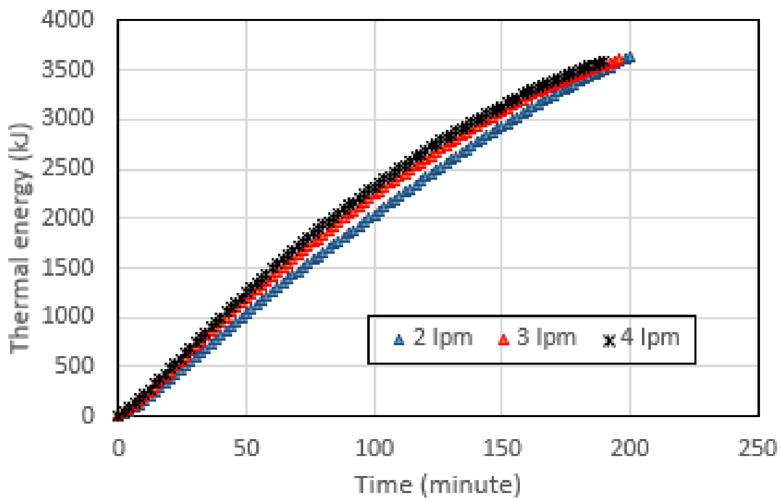


Fig. 5. Thermal energy released by water in PCM heating process in HE for solar radiation 1399.8 W/m²

4. Conclusions

The results of this research could be concluded as follows: The results of this research could be concluded as follows: Thermal energy storage in PCM paraffin of 15 kg takes 3.2 hours with a total stored energy of 3.6 MJ; and solar radiation of 1,399.8 W/m2 is used as an energy source with a water flow rate of 4 lpm serving as a medium heat transfer; This solar radiation has a significant effect on the heat transfer process to the PCM, while the flow rate of 2 to 4 lpm does not have. Therefore, the flow rate must be significantly increased as well.

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