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Experimental test of the effect of PCM volume as thermal energy storage solar power in solar cooking units

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Abstract

One solution that can be taken to reduce Greenhouse Gas (GHG) emissions is to reduce consumption of fossil fuels and replace them with renewable energy sources. Indonesia is rich in renewable energy sources, and one that has potential to be developed is solar energy. In line with Indonesia's development into a developed country, energy consumption is increasing. One of the activities that contributes to the largest energy use is cooking. The need for energy for cooking in Indonesia is large because the population and households are very large, number 4 in the world. Solar cooker is an alternative to reduce the use of fossil or traditional energy for cooking activities. Previous research has shown how the performance of a solar cooker can be improved if it is integrated with Phase Change Materials(PCM) thermal energy storage, making it possible to speed up cooking time, cook with low solar intensity and even make it possible to cook at night. However, the quantitative influence of the number of PCMs in a solar cooker has not been specifically explained or studied. A low quantity of PCM results in reduced performance, while a high quantity will increase the thermal load, and thus overheating. This research tested 4 units of simple tube type solar cooker with different quantities of PCM for each unit. From the results of testing the solar cooker with the PCM Thermal Energy Storage (TES) with variations in PCM volume, it showed performance in storing heat for longer even in conditions of high rainfall day and night conditions. This is shown from all observation results during the 6 days of the experiment. As evidenced by the low ambient air temperature and high humidity, especially at night, the temperature drop in the cooking vessel water is quite low. This applies to every variant. From the experimental results, it can also be seen that variants number 1 and 3, especially number 3, have quite good performance, in absorbing heat and storing heat with an outer diameter of 350 mm.

Keywords:
Optimization, PCM, solar cookers, renewable energy,thermal energy storage.

1 Introduction

Solar energy is a renewable energy source that plays an important role in and continues to develop so that it can reduce the use of traditional energy sources or fossil energy which are generally used throughout the world[1]. Even though the use of solar energy as the main source is still very small, if studied, using 5% of solar energy can produce 50 times more energy than current energy consumption [2][3]. Research shows that 35% of the greenhouse effect comes from global energy consumption to run industries in each sector. According to previous research, 40% of total energy consumption in Europe and 36% of CO_2 emissions come from consumption related to building activities such as air conditioning, cooking, lighting, heating and others [4]. One of the activities that contributes to the largest energy use is cooking, especially in developing countries such as Asia and Africa [5]. In 2020, countries in Africa, Asia and Central and South America recorded a demand for pollution-free cooking services of 71%, 44%, 11%, this shows that there is still a lack of pollution-free cooking services in these countries[6]. The need for energy for cooking in Indonesia is large because the population and households are very large, number 4 in the world. In some remote areas the energy source for cooking still comes from biomass, while in urban areas they use electricity or gas. Based on the white paper published by the Ministry of Research and Technology (2006), regions in Indonesia have a solar energy potential of 4.8 kWh/m^2/day or 17.28 MJ/m^2/day. This energy value is more than the calorific value contained in 1/3 kg of kerosene. This makes solar energy stoves an alternative to traditional fuels which have been used especially for cooking energy sources in rural areas [7][8].

Even though it is classified as environmentally friendly and free energy, the intensity factor greatly influences the performance of the solar cooker. If the intensity of the sun is low or the weather is cloudy and the exposure time is short, the performance of the solar cooker will be low. The location where the solar cooker is placed is also a factor that influences the performance of the solar cooker [9]. To improve the performance of the solar cooker, the solar cooker must be integrated with Thermal Energy Storage (TES) [10]. By integrating TES with a solar cooker, it allows the cooking process to be faster, the heating temperature will be maintained longer so that you get plenty of time to cook even in conditions of low solar intensity. Apart from that, the energy consumption stored in TES can be used for cooking at night[11][12]. The next challenge is how to improve the performance of the solar cooker which is integrated with an effective and efficient Phase Change Materials(PCM).Previous research shows the performance of integrating a solar cooker with TES with PCM media. The use of organic paraffin type PCM can maintain the temperature of a room or building from the influence of outside air temperature in a stable manner which has an impact on more efficient energy consumption[13]. Previous research also examined the increase in cooking performance of solar cookers, showing the performance of a simple box type solar cooker using PCM and then comparing it with without PCM, the time needed to cook a solar cooker type that uses PCM is 15 minutes shorter than a solar cooker type that does not use PCM. Increasing cooking performance is also carried out by increasing the thermal performance parameters of the solar cooker system using Al_2O_3 nanoparticles mixed with stearic acid PCM with Solar Cooker (SC) with normal PCM or without stearic acid PCM. Experiments show that the performance of SC with Al_2O_3 increases by around 17.6% compared to PCM which does not use Al_2O_3 [14]. The potential use of SC with PCM allows cooking at night, so previous researchers used 2.5 kg erythritol as PCM, with a certain SC design, then tested it at low solar intensity, showing that the cooling time of the SC was 315.16% longer, in the range 125^0C - 100^0C[15]. PCM heat transfer characteristics (such as melting and solidification rate and temperature distribution) play a major role in the performance of the solar cooker. Several studies show the effect of thermal parameters on solar cooker performance[16]. Previous researchers evaluated numerically the characteristics of the SC glass vacuum tube with PCM coating, and looked at the effect of the initial temperature of the food on the temperature in the PCM. Researchers used molten $NaNO_3/KNO_3$ salt as PCM, and the results were that adding a PCM layer with a PCM layer size of 40mm/80mm × 770mm increased the temperature inside the oven walls by 30°C -800°C higher than not using a PCM layer. Both experimental results also show that the initial temperature of eating also affects the PCM layer [17]. Improvements can also be made by varying the design or geometry of the PCM. This is proven to affect the rate of heat transfer and affect the performance of the solar cooker with PCM[18]. Not just in the solar energy sector, the application of TES can be applied in the construction sector such as buildings. It is proven that the PCM layer on building walls can absorb and store heat energy from the environmental air,The cooling load received by the Air Conditioner (AC) is lower than without using the PCM layer[20]. From previous research evaluations, it was found that the role of using PCM as a TES in SC can improve the performance of the SC itself. From the aspect of PCM type, geometry or PCM layer which has been presented in previous research. Parameters that have not yet been studied are the influence of the number or quantity of PCM. PCM quantity is an important consideration in PCM integration into SC. A low quantity of PCM results in reduced performance, while a high quantity will increase thethermal load, and thus overheating [16]. This is the basis of this research to see the performance of thequantity, or number of PCM variations of the solar cooker and find out which design is better from the 4 SC unit variants that will be tested.

2 Method

The location of this research was carried out at the Mechanical Achievement Laboratory of the Mechanical Engineering Study Program, Faculty of Engineering, HKBPNommensen University. From Fig. 1, it can be seen that the heat source comes from fluid flow which is circulated using a pump to the Thermal Energy Storage (TES) and back to the vacuum type solar water heater. This process will continue or circulate until the TES temperature reaches the highest value. The research diagram can be seen in Fig. 1.

The dimension that is varied is the outer diameter of the TES. The first design uses a diameter of 330 mm, the 2nd is 340 mm, the 3rd is 350 mm and the 4th is 360 mm. To analyze the performance of the solar cooker, supporting data is needed such as the environmental temperature in the solar cooker system. Fig. 1 shows the temperature data collection points from T1 to T6. T1 is the temperature of the fluid flow before it enters the solar collector, T2 is the temperature of the fluid leaving the solar collector, T3 is the temperature of the environment around the solar collector or solar cooker, T4 is the temperature of the vessel, T5 is the temperature of the PCM and T6 is the temperature of the outer wall of the solar cooker. Temperature data is recorded. This applies to every solar cooker variant observed. So the total temperature observed was 24 points. This can be seen in Fig. 2.

Fig. 1. Experiment diagram and geometry design of PCM cooking place [19].

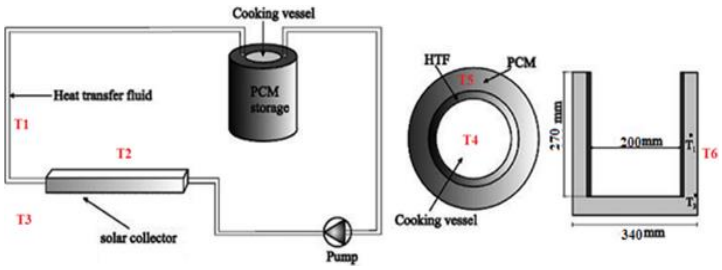

Fig. 2. Experimental setup with 4 PCM volume/dimension variations and PCM paraffin material melting process.

Testing was carried out for 6 days. Data was taken for 24 hours with a data collection time interval of 5 minutes.

Fig. 2 shows the experimental setup during testing. The PCM material used is paraffin. Paraffin is a hydrocarbon compound. Before being put into the solar cooker, the paraffin is first melted to make it easier for the PCM to enter the solar cooker unit. This process can be seen in Fig. 2. PCM functions as thermal energy storageto hold the heat energy that comes from the heat flow from the solar water heater. The total PCM used is around 70kg. For solar cooker variants, the PCM capacity varies depending on the TES volume usedin each variant. To measure solar radiation, a pyranometer with the HOBO brand is used.

3 Results and Discussion

3.1 First Day Test Result

The first day of testing will be held on August 23 2023 starting from 09.28 WIB - August 24 202308.26 WIB.

Fig. 3 shows that the highest temperature in the PCM occurs in the solar cooker variant for variant number 3, but the SC in

Variant 1 can maintain a higher average PCM temperature compared to other variants. From these results we can see that the use of thermal energy storage with PCM can slow down the SC temperature even though the environmental temperature around the SC is much lower.

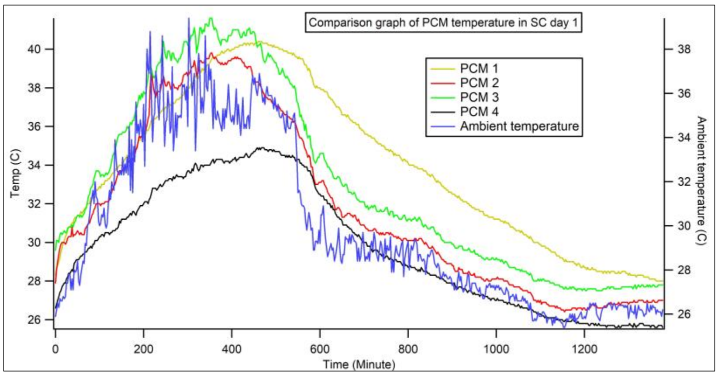

Fig. 3. First day PCM temperature comparison graph.

Fig. 4 shows that the highest water temperature occurs in the solar cooker variant for variant numbers 2 and 3, but the SC in variant 3 can maintain the average water temperature in the cooking container higher than the other variants.

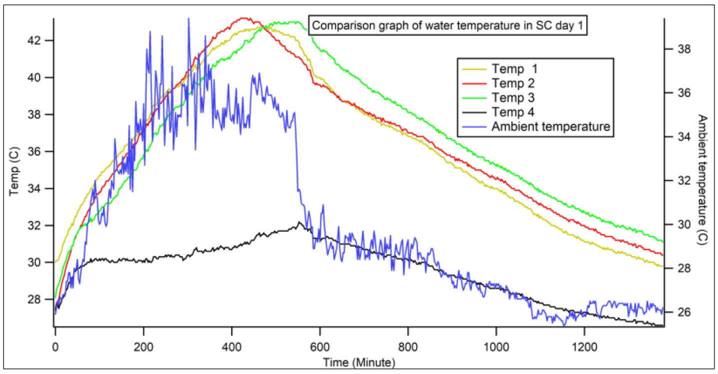

Fig. 4.Comparison graph of water temperature in SC on first day.

3.2 Second Day Test Result

The 2nd day of testing will be carried out on August 24 2023 starting from 10.11 WIB - August 25 2023 at 08.21 WIB.

Fig. 5 shows that the highest water temperature occurs in the solar cooker variant for variants 2 and 3, but the SC in variant 3 can maintain the average water temperature in the cooking container higher than the other variants. From these results we can see that the use of thermal energy storage with PCM can slow down the SC temperature even though the environmental temperature around the SC is much lower. Solar radiation on the 2nd day of testing was also low due to high rainfall during the test, shown in Fig. 5.

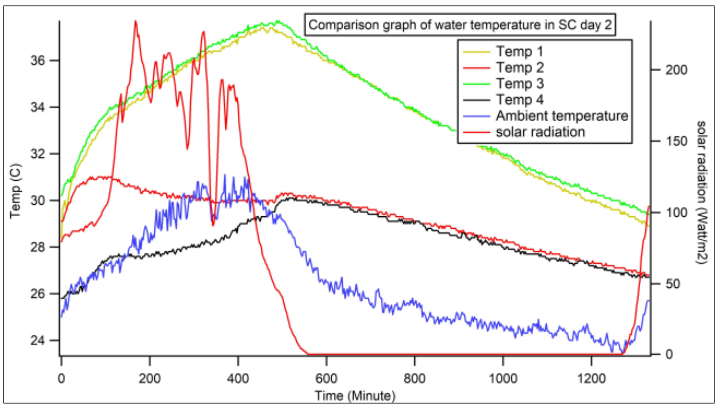

Fig. 5. Comparison graph of water temperature in SC on day 2.

Fig. 6 shows that the highest water temperature occurs in the solar cooker variant for variants 1 and 3, but the SC in variant 3 can maintain a higher average water temperature in the cooking vessel compared to other variants. On the second day of testing, it was seen that solar radiation had decreased due to high rainfall.

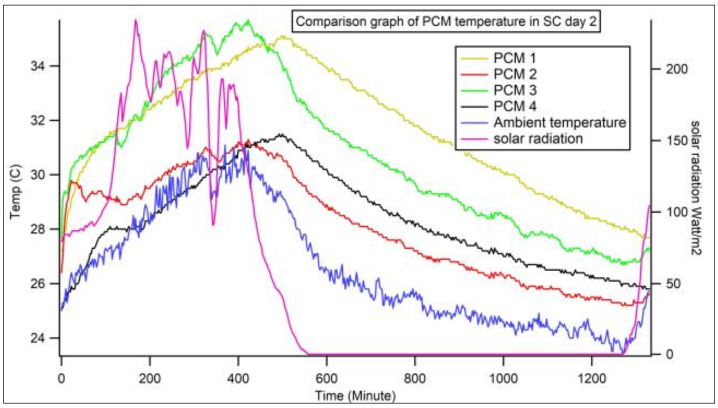

Fig. 6. Comparative graph of day 2 PCM temperature vs radiation.

3.3 Thirth Day Test Result

The 3rd day of testing will be carried out on August 25 2023 starting from 09.02 WIB – August26 2023 at 10.27 WIB.

Fig. 7 shows that the highest water temperature occurs in the solar cooker variant for variants 1 and 3, but the SC in variant 3 can maintain the average water temperature in thecooking container higher than the other variants.

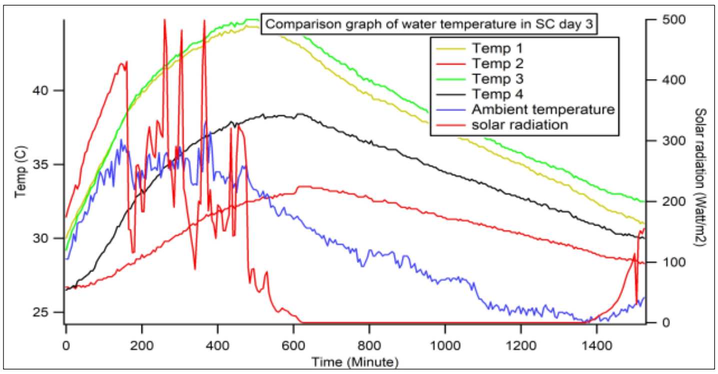

Fig. 7.Comparison graph of water temperature in SC vsradiationday 3.

Fig. 8 shows that the highest water temperature occurs in the solar cooker variant for variants 1 and 3, but the SC in variant 3 can maintain the average PCM temperature in the cooking container higher than the other variants. On the 3rd day of testing, it was seen that solar radiation had decreased due to the high rainfall that occurred until evening.

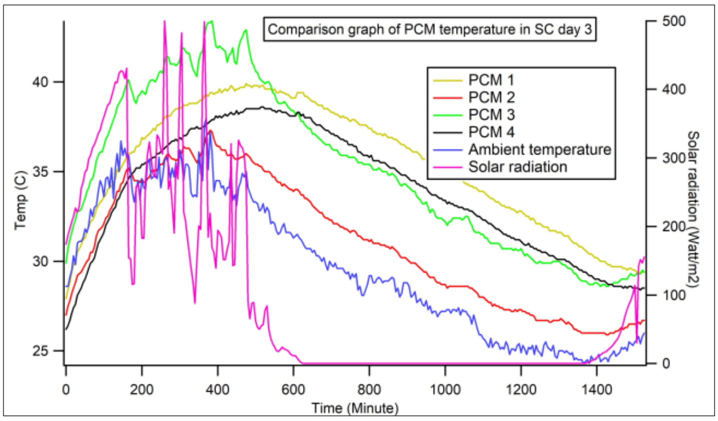

Fig. 8. Comparison graph of PCM temperature vs radiation day 3.

3.4 Fourth Day Test Result

The fourth day of testing will be held on August 26 2023 starting from 11.25 - August 27 2023 22.40WIB.

Fig. 9 shows that the highest PCM temperature occurs in the solar cooker variant for variant number 3, but the SC in variant 3 can maintain a higher average water temperature in the cooking vessel compared to other variants. On the 4th day of testing, it was seen that solar radiationhad decreased due to high rainfall.

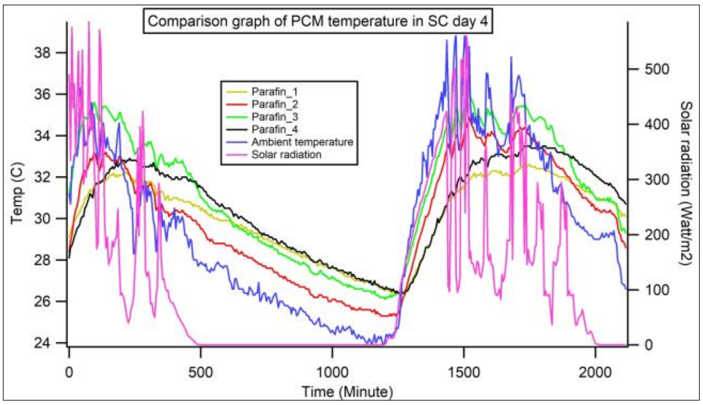

Fig. 9. Comparative graph of PCM temperature vsradiation day 4.

Fig. 10 shows that the highest water temperature occurs in the solar cooker variant for variant number 3, but the water temperature conditions for each SC are no higher than theambient temperature, this is caused by the pump not being active to distribute hot water from the solar water heater. Temperature transfer cannot occur naturally and occurs very slowly if the pump does not assist or circulate it.

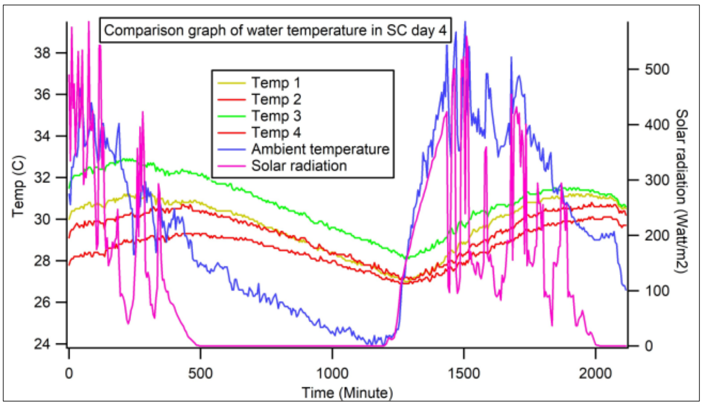

Fig. 10. Comparison chart of water temperature vs radiation in SC day 4.

3.5 Fifth Day Test Result

The fifth day of testing will be held on August 28 2023 starting from 08.49 - August 29 2023 01.24WIB.

Figure number 11 shows that the highest water temperature occurs in the solar cooker variant for variant number 3, but the SC in variant 1 can maintain the average PCM temperature higher than the other variants. On the 5th day of testing, it was seen that solar radiation had decreased due to night conditions, but the water temperature in the SC unit was still above environmental temperature even in night conditions. This is because the heat energy that is still stored by the PCM in the TES SC unit can still maintain the water temperature so that the decrease in water temperature is very low.

Fig. 12 shows that the highest water temperature occurs in the solar cooker variant for variants 1 and 2, but the SC in variant 3 can maintain a higher average water temperature in the cooking vessel compared to other variants. Likewise, testing on day 6 is the same as testing on day 5. It can be seen that solar radiation has decreased due to nighttime conditions, but the water temperature in the SC unit is still above ambient temperature even in nighttime conditions. This is because the heat energy that is still stored by the PCM in the TES SC unit can still maintain the water temperature so that the decrease in water temperature is very low.

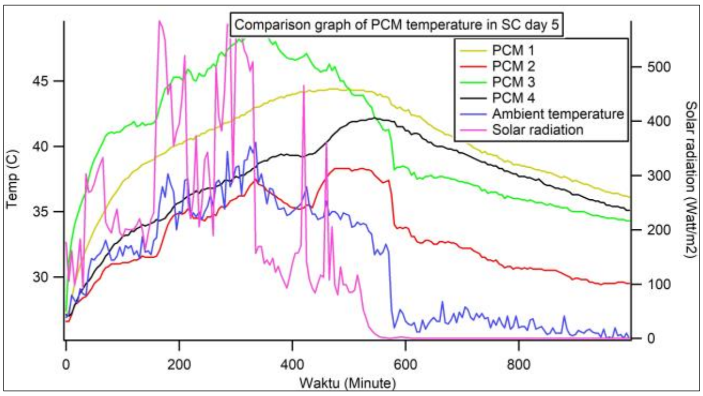

Fig. 11. Comparison graph of PCM temperature vs radiation day 5.

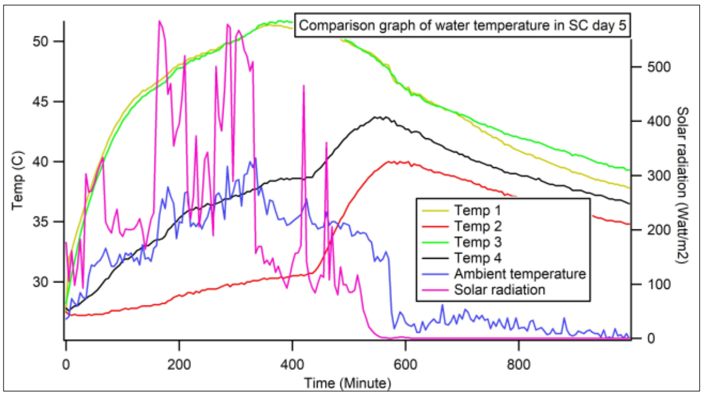

Fig. 12. Comparison chart of water temperature vsradiation in SC day 5.

3.6 Sixth Day Test Result

The sixth day of testing will be carried out on August 29 2023 starting from 08.55 WIB - August 30 2023 08.10 WIB.

Fig. 13 shows that the highest PCM temperature occurs in the solar cooker variant for variant number 3, but the SC in variant 4 can maintain a higher average PCM temperature compared to other variants. From these results we can see that the use of thermal energy storage with PCM can slow down the SC temperature even though the environmental temperature around the SC is much lower.

Fig. 14 shows that the highest water temperature occurs in the solar cooker variant for variant number 1, but the SC in variant 4 can maintain the average water temperature in the cooking container higher than the other variants. From these results we can see that the use of thermal energy storage with PCM can slow down the SC temperature even though the environmental temperature around the SC is much lower.

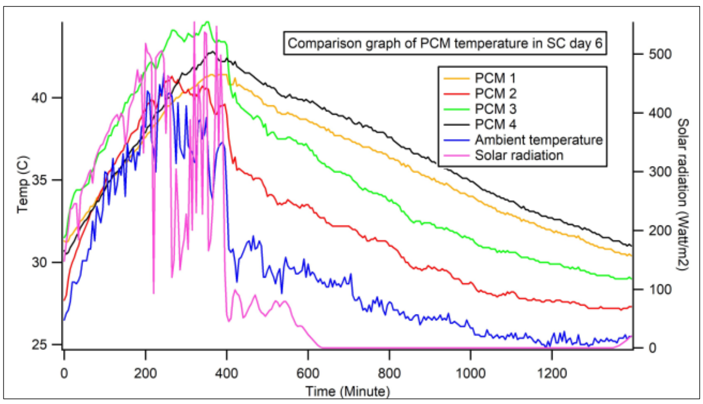

Fig. 13. Comparison chart of PCM temperature vs radiation in SC day 6.

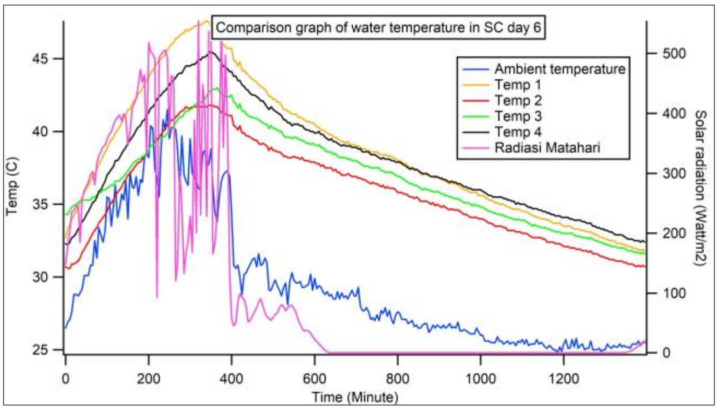

Fig. 14. Comparison chart of water temperature vs radiation in SC day 6.

4 Conclusionand Recommendations

From the results of testing the solar cooker with PCM thermal energy storage TES with variations in PCM volume, it shows that the performance in storing heat is longer than not using TES with PCM. This is shown from all observation results during the 6 days of the experiment. As evidenced by the low ambient air temperature and high humidity, especially at night, the temperature drop in the cooking vessel water is quite low. This applies to every variant.

From the experimental results, it can also be seen that variants number 1 and 3, especially number 3 with dimensions of solar cooker outer diameter of 350mm, have quite good performance, in absorbing heat and storing heat, compared to other variants with different PCM volumes even though variant 3 is not a larger volume from other variants. This shows that volume affects the performance of SC with TES.

What needs to be considered for this research is the weather factor which greatly influences the performance of the SC, high rainfall conditions in certain months, of course greatly influences the research process which utilizes solar energy, especially solar cookers with thermal energy storage.

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