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CORRELATION OF PHASE CHANGE MATERIALS ON INTEGRATED SOLAR WATER HEATING SYSTEMS

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ABSTRACT
The correlation of thermal energy storage on the efficiency of thermal storage integrated solar water heating system. The evaluation of the thermal storage and analyzing the efficiency of the collector for solar water heating systems were done in Sokoto. The system was investigated without phase change materials; with used engine oil and Shea butter oil in other determine the best thermal storage material that improves the collector's efficiency. The optimum performance analyzed has efficiencies of 4.7 %, 49.2 % and 78.8 % for the water heater without phase change materials and then with used engine oil and Shea butter oil, respectively. Indicating that the increase in temperature of the system using thermal energy storage is significant. Shea butter oil shows optimum performance compared to used engine oil.

Keywords: TES (Thermal Energy Storage); PCM (phase change material); used engine oil; Shea butter oil

INTRODUCTION

Africa has abundant renewable energy resources; however, the majority are not being completely utilized (Enemonaoguche *et al*., 2020). The entire continent of Africa is located on the sunshade belt, per the annual sum of the global irradiance map (Enemonaoguche *et al*., 2020). Due to insufficient renewable energy policy formulation, implementation, and low investment levels, Africa's potential for renewable energy resources has not yet been completely realized (Karekezi *et al*., 2003). Unquestionably, a possible solution to Nigeria's energy problem is renewable energy. In addition to being sustainable and inexhaustible, it may be built in smaller units, making it suited for management and ownership in rural communities and potentially essential to economic development (Rapu *et al*., 2015).

Because of its tropical location, Nigeria receives a lot of solar radiation, especially in its northern and middle belt regions, which seem to be sitting on a large potential energy store. These opportunities are developing economically at an astounding rate (Agbo & Oparaku, 2006; Newsom & SDN, 2012). However, there is insufficient information regarding Nigeria's solar energy technology, capability, and projects, making it challenging to determine the country's level of solar integration (Bamisile *et al.*, 2017). According to (Osueke & Ezugwu, 2011), a median annual daily solar radiation of about 5.25 kW/m^2/day at the coastal area and 7.0 kW/m^2/day at the northern boundary, with an annual average daily sunshine of 6.25 hours at a range of about 3.5 hours at the coastal areas to 9.0 hours at the far northern boundary, are both gifts to the nation.

The far northern region of Nigeria (Sokoto, Zamfara, Kano, Jigawa, Yobe, and Maiduguri) receives an annual average planetary horizontal irradiation of roughly 2200 kWh/m^2, according to the planetary horizontal irradiation map for Nigeria. The coastal states of the nation (Rivers, Cross River, and Bayelsa State) receive an average yearly planetary horizontal irradiation of just over 1000 kWh/m^2 (Solar Resource Map, 2017). This clearly demonstrates that Nigeria is located within a high sunlight region and has a tremendous potential for solar energy (Sambo, 2009). This suggests that solar energy is distributed fairly in Nigeria.

The sun, which is a vast source of energy, has several distinctive characteristics, such as seasonal and diurnal variation brought on by the earth's rotation around the sun and fluctuation due to cloud cover. Solar energy may be transformed into a variety of other forms of energy and is environmentally friendly and renewable. A solar water heating system transforms it into thermal energy to heat water (Kelechi *et al*., 2014). Storage from solar power plants is required to achieve a reliable and secure energy supply (Kronhardta *et al*., 2014). Solar thermal energy storage (STES) is essential to the use of solar energy due to the intermittent nature of solar radiation. This has uses in concentrated solar thermal power plants for generating electricity, solar space heating for drying buildings and heating water, and solar water heating systems (Tesfay & Venkatesan, 2013). The most versatile and efficient renewable energy systems are solar thermal ones (Asif & Muneer, 2013). Because of this, solar water heating and thermal storage systems require a great deal of technical considerations, such as material choice, insulation, methods, and thermal transfer.

Due to increased awareness of renewable energy sources and their favorable effects on the environment, home water heating using solar energy is becoming more popular for personal and commercial use. The disadvantage of using solar energy systems is their inability to run continuously at night because of a lack of sun radiation. In order to address this issue, thermal energy storage (TES) solutions have been put forth and assessed from the perspectives of the materials used for storage, the design of the storage, and the integration strategies with solar collectors (Al-kayiem & Lin, 2014).

Phase change materials (PCM)

In many thermal storage devices, PCM is underutilized while being a critical component for trapping and storing thermal energy. The features of PCMs can yet be improved, though, to make them even more suitable as thermal energy-trapping materials. PCM is advantageous because to their stability at high working temperatures and heat storage due to their high heat storage capacity. They will discover many more uses for solar energy storage and harvesting in the future (Sawant & Mohod, 2015).

The purpose of this paper is to investigate performance evaluation of integrated solar water heating systems using thermal storage materials and determine the effectiveness and thermal energy generated in order to lessen reliance on electrical energy, which is experiencing a severe supply constraint in Nigeria. The improved effectiveness of the system has also been tested with various working fluid kinds. The objectives of this paper are: to find the efficiency of the system without storage material, to analyze the thermal performance of the used engine oil and Shea butter oil, and to compare the efficiency of the system with and without storage material

MATERIALS AND METHODS

System Description

The system consists of two flat plate solar collectors (collector A and collector B) and a tank at the top. The interior of the tank consists of a water storage compartment, a thermal storage compartment, and lagging materials (insulation). The thermal storage compartment comprises an inlet and outlet passage, where thermal fluids are pumped into the storage tank and removed from the thermal storage tank, respectively. The flat plate solar collectors consist of transparent glass and the header and risers pipes. The system's output pipe returns heated water from the solar collectors to the tank after it has been heated in the solar collectors via the intake pipe from the tank.

To lower overall costs, the integrated solar water heater with thermal heat storage unit was tested utilizing used motor oil, and Shea butter oil. An integrated solar water heater with thermal heat storage is created by combining the PCM components, storage tank, and solar collector.

Calculation of solar collectors

The system consists of two flat-plate collectors

Collector A	Collector B
Length = 117 cm = 1.17 m	Length = 114 cm = 1.14 m
Breadth = 89.5 cm = 0.895 m	Breadth = 88.5 cm = 0.885 m
Area of solar collector A	Area of solar collector B
Area = length × breadth	Area = length × breadth
= 1.17 m × 0.895 m	= 1.14 m × 0.885 m
= 1.047 m^2	= 1.009 m^2

The Area of the two collectors (A_c) is 1.047 + 1.009 = 2.056 m^2

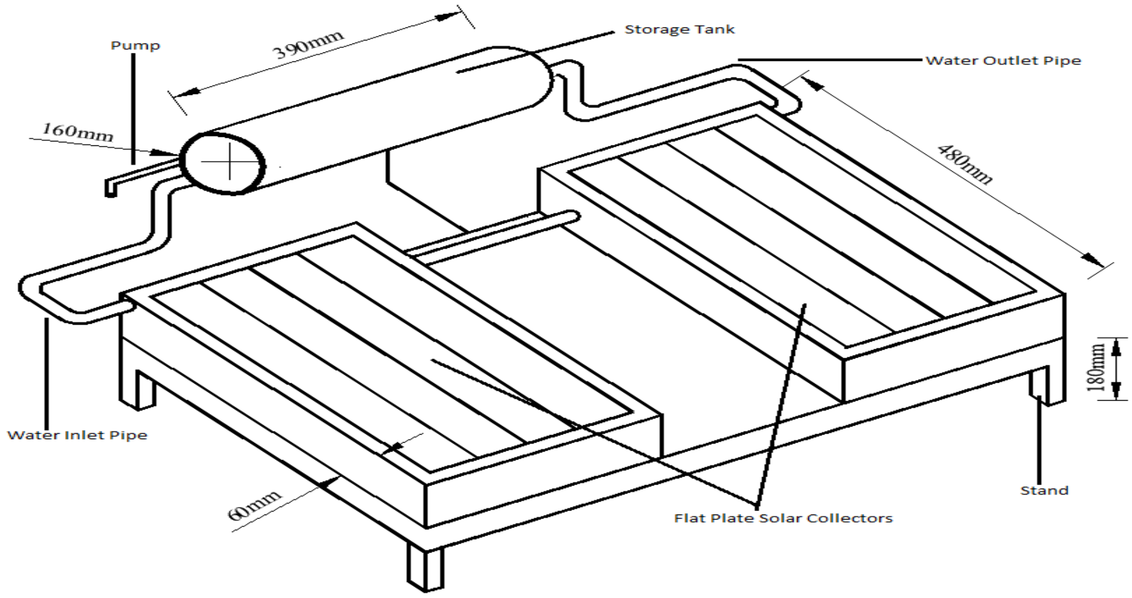

Figure 1**:** Schematic Diagram of Solar Water Heater

Performance Evaluation Procedures

By calculating the system efficiency with the help of the system's energy and mass balances, the performance of the integrated PCM water heater is assessed. To evaluate the thermal performance of used engine oil and Shea butter oil, measurements of temperatures (ambient, inlet and outlet) in (°C), mass flow rate (kg/s), wind speed (m/s) and solar radiation (W/m^2) were recorded.

We must determine the efficiency of the solar water heater in order to assess its performance.

The ratio of the usable heat (Qu) transfer rates caused by solar radiation to the cover plate is known as the collector efficiency. The equation below illustrates efficiency:

$$\eta = \frac{Heat\ energy\ out}{Heat\ energy\ in} = \frac{Qout}{Qin} \quad (1)$$

$$Q_{out} = m \times c_p (T_o - T_i) \quad (2)$$

Equation 2 demonstrates that the amount of heat transferred to the fluid passing through the collector may be used to calculate the rate at which heat is collected from the collector.

$$Q_{in} = A_c \times G_t \quad (3)$$

The thermal efficiency (Abolarin *et al*., 2019) can be found by Equation (4)

$$\eta = \frac{Qu}{Ac \times Gt} \text{ or } \eta = \frac{m \times cp(To - Ti)}{Ac \times Gt} \quad (4)$$

Test Procedure

Stagnation temperature test

The temperature of a solar system when there is no-flow of energy is known as the stagnation temperature. Here, air served as storage material, the test was conducted from 9:00 am to 5:00 pm at an interval of 30 minutes for four consecutive days, solar radiation, ambient, inlet, outlet temperature and mass flow rate are the parameters measured.

Testing samples of PCM

Tests were run from 9:00 am to 5:00 pm daily in January 2022. As soon as the sun rises, sunlight falls on the flat plate solar collector (FPSC), progressively heating the working fluid.

Initially, tap water at room temperature was poured into the inlet and output pipes of the solar water heating system (SWHS) that were inserted within the header's outer tank. The SWHS was exposed to light to start the test activity. For four days for each PCM, the data were collected from 9:00 am to 5:00 pm with 30-minute time intervals. The heat transfer fluid (HTF) that is loaded inside the pipes becomes hotter as a result of the sun intensity that strikes the flat plate solar collector (FPSC) and becomes trapped inside its annular space. Due to the difference in densities, hot HTF now rises while cold fluid descends toward the pipe's closed end. The thermosyphon phenomenon is what is causing this. The outer tank of the header also experienced a similar thermosyphon phenomena. The heated transfer fluid (water) then transfers its heat energy to the separate thermogenic fluids (used engine oil and Shea butter oil) kept inside the header's inner tank. The cycle continues, raising the temperature of the thermic fluid; afterwards, the water is heated during the night or other non-insolation periods using the thermic fluid's stored heat.

The water storage has already been filled, and the thermal storage tank was filled through the inlet passage using a syringe leaving the outlet passage of the thermal storage tank open in order to indicate whenever thermal storage tank is full. The following thermal fluids (used engine oil, and Shea butter oil) were tested for four consecutive days each following the same procedure. Solar irradiance, ambient temperature, inlet temperature, outlet temperature and mass flow rate are the parameters measured. These fluids were removed from the thermal storage tank using a bicycle air pump.

RESULT AND DİSCUSSİON

The test result discussed here was for the system without phase change materials, with used engine oil, and with Shea butter oil.

The experimental work was conducted in periods 9 am – 5 pm for 4 days.

System without Phase Change Materials (Stagnation Temperature Test)

The experimental test of the system without phase change materials was done for four consecutive days from 16 – 19 January 2022. After the experiment, As indicated in table 4.4, it was discovered that the system's efficiency without thermal storage materials was at its highest on day 4 at 4:30 pm, at a rate of 4.7 %. The ambient temperature rises from 17.2 °C in the morning to a maximum of 28.1 °C at 3:30 pm before dropping back to 25.5 °C to 24.6 °C in the late afternoon. At sunrise, solar radiation is 433 W/m^2, increases to its peak at noon, and then begins to decline in the late morning. The water flow in a closed system caused the water temperature at the inlet and outlet to fluctuate constantly, and the wind speed was typically high, ranging from 2.0 to 5.3 (m/s). It is observed that the change in (ΔT) values is almost similar to the change in collector efficiency as the temperature differences increase (Tout).

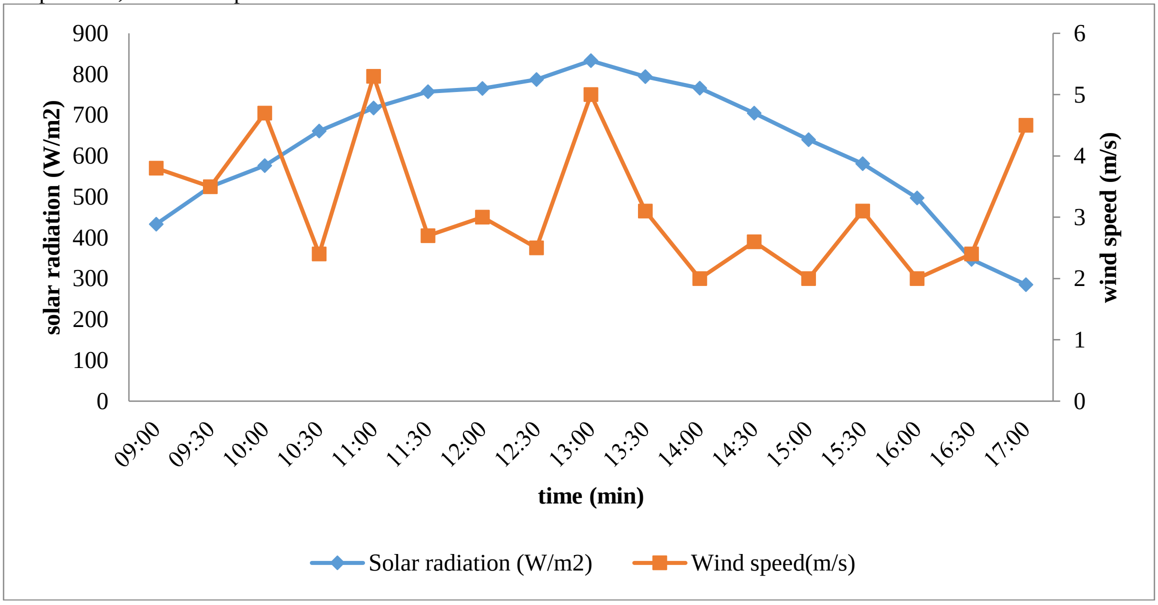

Figure 2: Variation of Solar Radiation against Wind speed for the system without PCM on day 4 (19/01/2022).

From the result in Figure 2, it is evident that the solar radiation did not affect the performance of the collector, where there was a steady increase in temperature even when the solar radiation dropped as shown in the figure. As shown in Figure 2, solar radiation begins at a rate of 433 W/m^2 at sunrise and reaches its peak value at noon, around 1:00 pm, with rates of 833 W/m^2, before declining in the afternoon. Most of the time, the wind's high velocity ranged from (2.0 to 5.0) m/s. The highest rate of solar radiation were around 1:00 pm with the rates of 833 W/m^2 at the same time the wind speed reaches high speed rates of 5.0 m/s, and it was noted that the optimum efficiency of the system was found to be at 4:30 pm with an efficiency of 4.7 % when the solar radiation is 347 W/m^2 and wind speed is 2.4 m/s which means that the solar radiation and wind speed did not affect the performance of the collector efficiency.

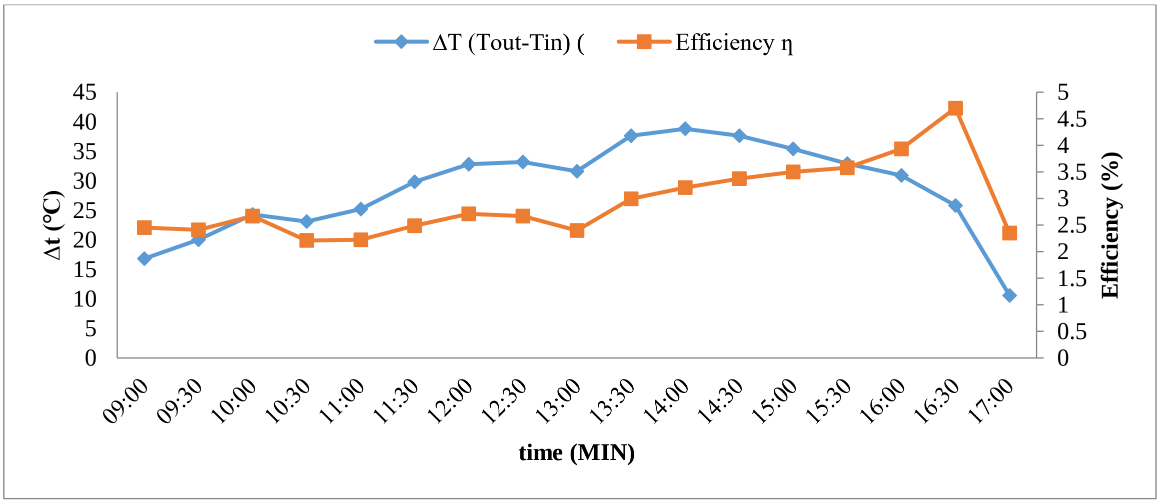

Figure 3: Variation of Change in Temperature (ΔT) against Efficiency for the system without PCM on day 4 (19/01/2022).

From the result in Figure 3, it is evident that the temperature difference is dependent on the ambient temperature, as the steady rise in both inlet and outlet temperature; can be attributed to the ability of the cloud to retain heat energy. The maximum temperature difference recorded for the day was 38.8 ℃, the temperature difference was high all through except for the hour 5:00 pm with the temperature of 10 ℃. It can be seen that the ambient temperature has a substantial impact on the system's performance as the trend of the ambient temperature needs to increase significantly to achieve good performance but the solar radiation and wind speed tend not to affect the system greatly.

System with Used engine oil as Phase Change Materials

The experimental test of the system with used engine oil as thermal storage materials was done for four consecutive days from 20-23 January 2022. After the experiment, it was noticed that the optimum efficiency of the system with used engine oil as thermal storage materials were found to be on day 1 with an efficiency of 49.2 % at 2:30 pm with a temperature difference of 24.3 ^{o}C. Here, it can be seen that the outlet temperature obtained is very high 73.6^{o}C and was yield higher efficiency.

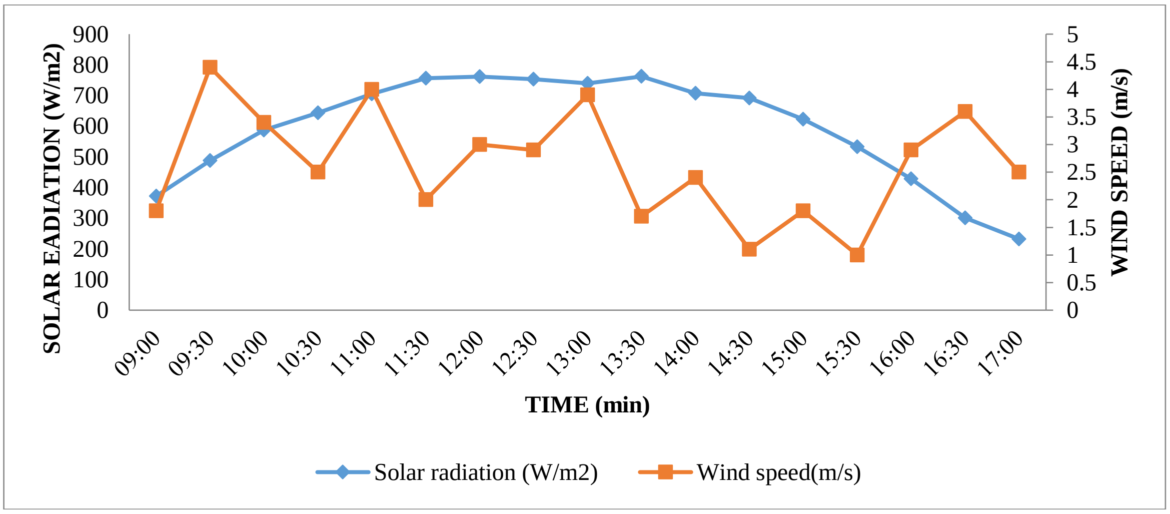

Figure 4: Variation of Solar Radiation against Wind speed for the system with used engine oil on day 1 (20/01/2022).

Here, it can be seen that the solar radiation rises slowly at dawn, reaches its peak at midday, and then begins to fall in the late morning and early afternoon, as depicted in Figure 4.

Figure 4 further demonstrates that the wind speed was generally high.

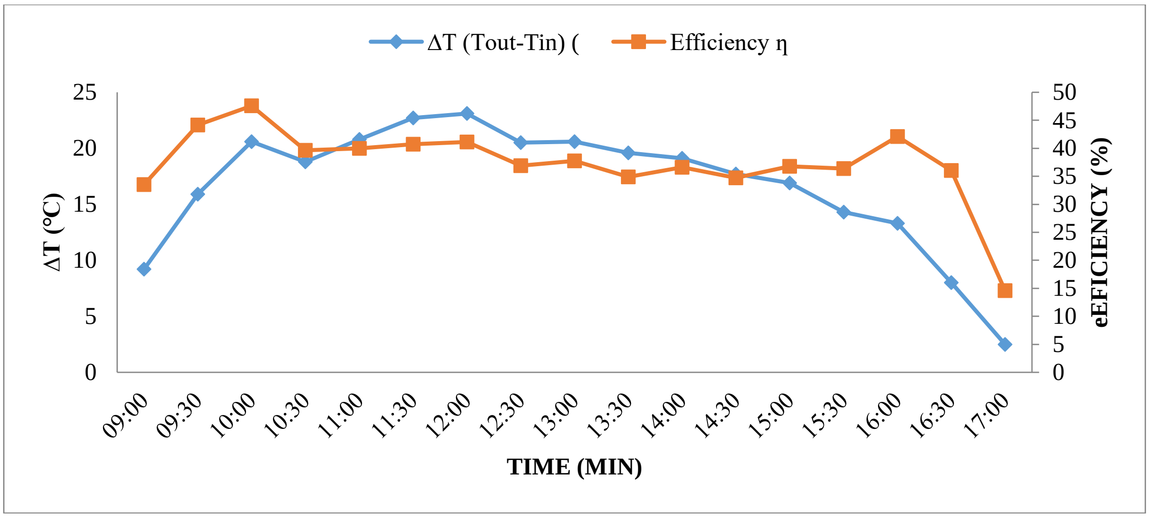

Figure 5: Variation of Change in Temperature (ΔT) against Efficiency for the system with used engine oil on day 1 (20/01/2022).

In Figure 5, the outlet and inlet changes were plotted against efficiency. The temperature difference starts out at low values at the start of sunrise and gradually rises to reach its highest value in the afternoon. According to Figure 5, the collector efficiency rises as the temperature difference rises as the temperature difference values start to fall in the afternoon and reach their lowest value at sunset.

System with Shea butter oil as Phase Change Materials

The tests were done for four sequential days from 24-27 January 2022. The results obtained for the system with Shea butter oil indicated that the optimum efficiency was noted to be on day 4 at 10:00 am with an efficiency of 78.8 %. According to Figure 6, solar radiation starts at 467 W/m^2 at sunrise, reaches its peak around noon, then starts to decline in the late afternoon. Due to the water flow in a closed system, the input and outlet water temperatures were constantly changing, and the wind speed was typically high, ranging from 1.8 to 6.5 (m/s). It is observed that the change in (ΔT) values is nearly similar to the change in collector efficiency as the temperature differences grow (Tout).

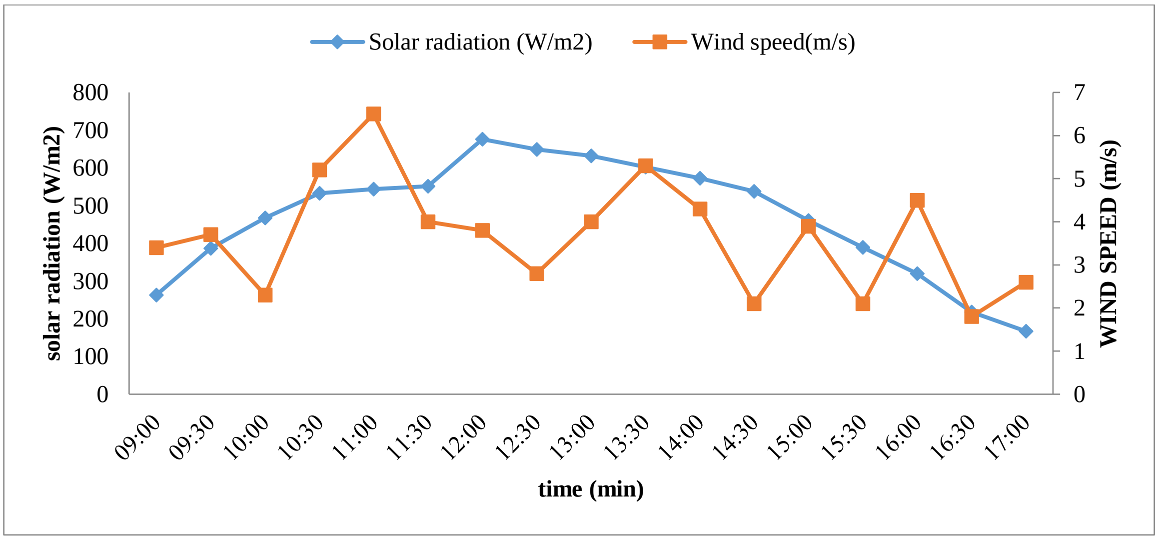

Figure 6: Variation of Solar Radiation against Wind speed for the system with Shea butter oil on day 4 (27/01/2022).

As shown in Figure 6 Most of the time, the wind was blowing at a high speed of (1.8 to 6.5) m/s. The highest rates of solar radiation were at 1:00 pm with the rates of 632 W/m^2, while the wind speed reaches high-speed rate of 6.5 m/s at 11:00 am, and it was noted that the optimum of the system effectiveness in this case was found to be at 10:00 am with an efficiency of 78.8 % when the solar radiation was 467 W/m^2 and wind speed of 2.3 m/s, this indicated that the solar radiation and wind speed did not affect the performance of the collectors' efficiency.

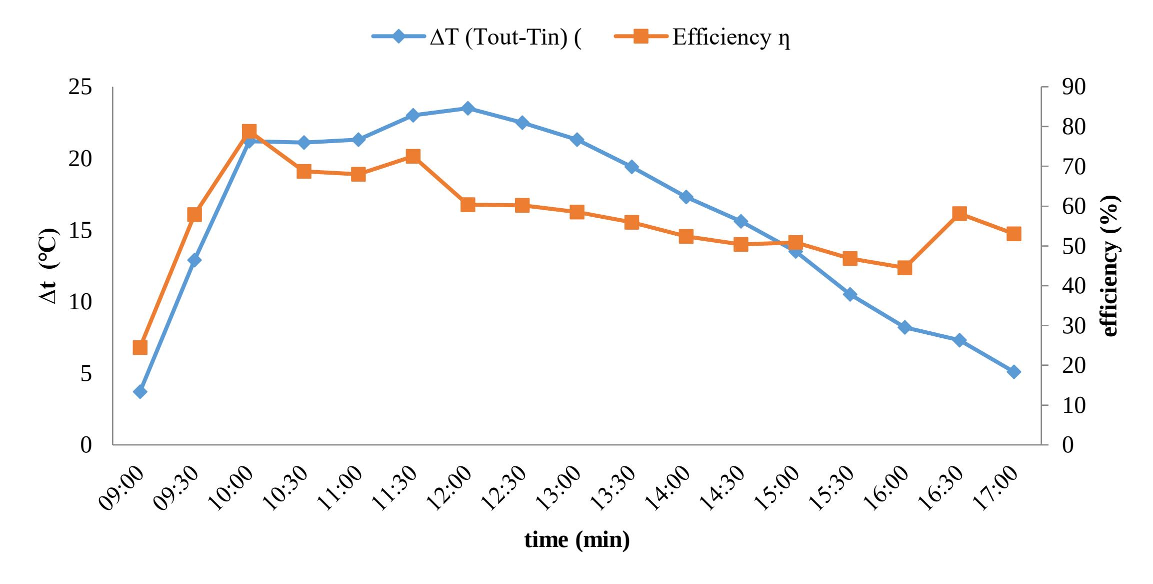

Figure 7: Variation of Change in Temperature (ΔT) against Efficiency for the system with Shea butter oil on day 4 (27/01/2022).

Figure 7 displayed the efficiency against the temperature difference (ΔT) between the collector's inlet and outlet water. Temperature differential (ΔT) is a measurement of how well a collector is able to heat its own water. Temperature difference demonstrates the collector's capacity to heat water and enables comparison of its performance with those of other collector types under same circumstances. as shown in Figure 7 there was a steady increase in temperature difference from morning to noon and reaches the highest value of 23.5 ℃ at 12:00 pm then returns to decrease from 2:30 pm to 5:00 pm with the lowest temperature of 5.1 ℃, and the efficiency is also increasing as temperature difference increases the optimum temperature was 78.8 % at 10:00 am which was noted as highest efficiency of the system in all the four cases.

Comparison of the system's efficiency with and without Phase Change Materials (PCM)

Equation 4 was used to calculate the system's efficiency. Because different working fluids have varying thermal properties, the type is one of the influencing elements to increase collector efficiency. The subject of the experiments was system without PCM materials from 16 to 19 January 2022, on the system with used engine oil as a storage material from 20 to 23 January 2022, Shea butter oil from 24 to 27 January 2022.

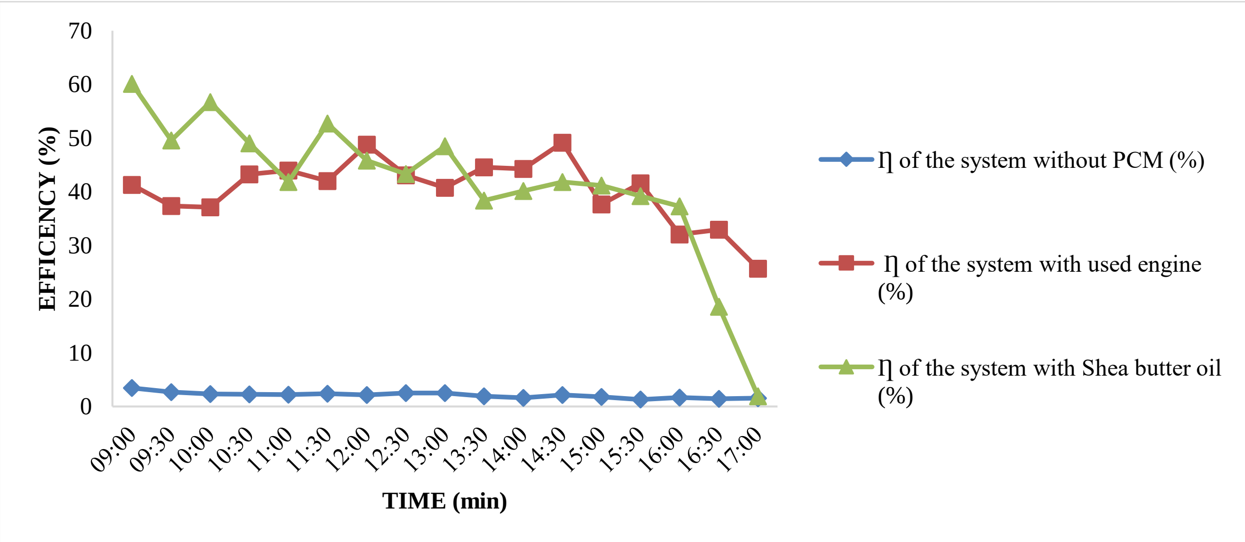

Figure 8: System effectiveness with and without PCM on Day 1

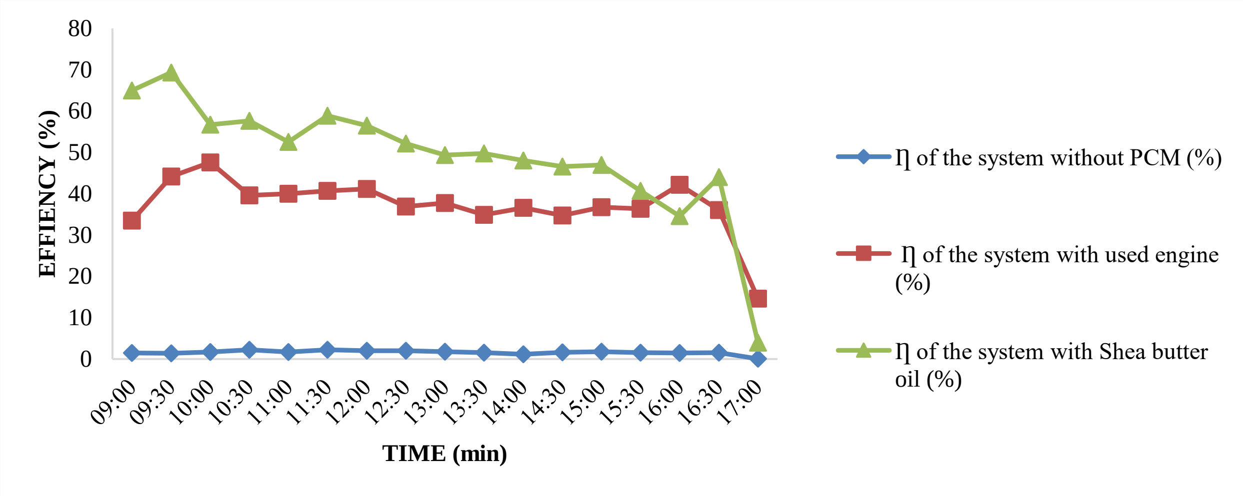

Figure 9: System effectiveness with and without PCM on Day 2

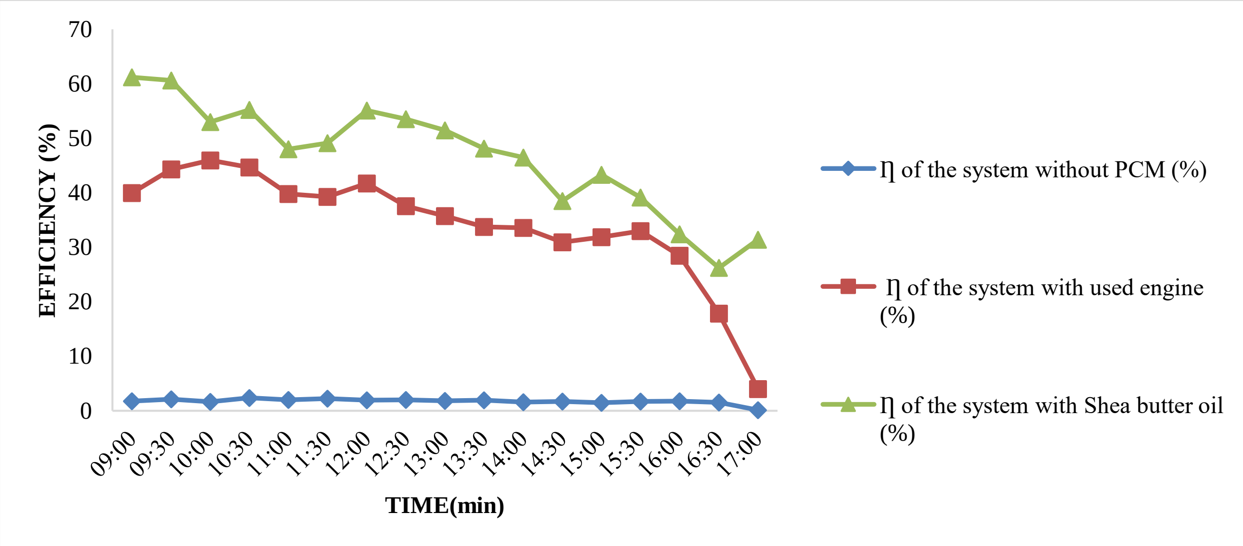

Figure 10: System effectiveness with and without PCM on Day 3

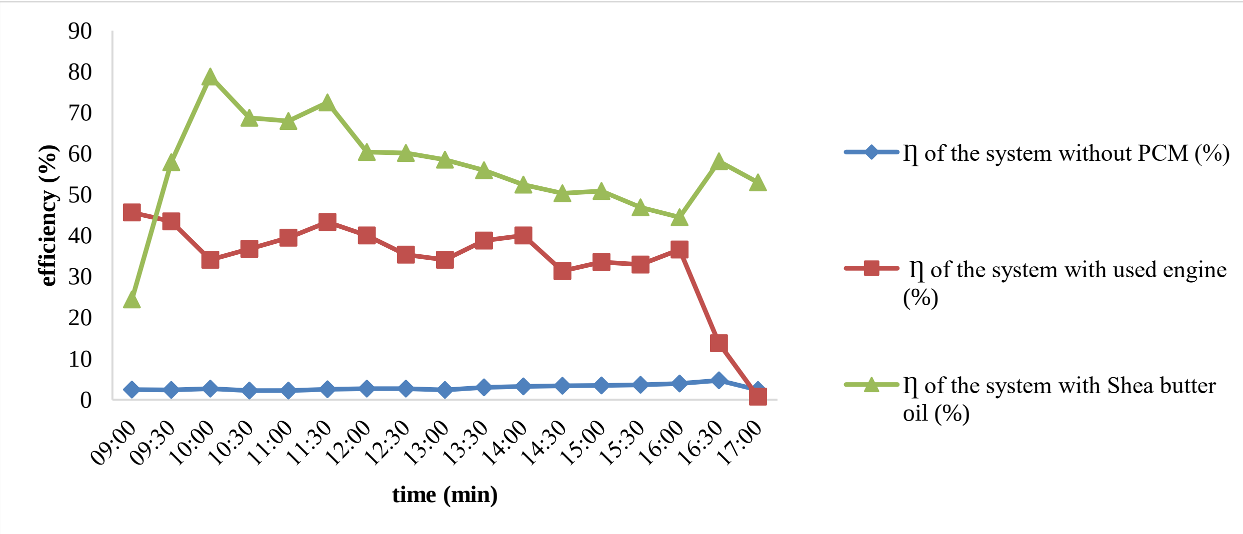

Figure 11: System effectiveness with and without PCM on Day 4

Due to their differing thermal properties, the kind of working fluid is one of the influencing elements to increase collector efficiency. The subject of experiments was system without PCM materials on 16 to 19 January 2022, with used engine oil as a storage material from 20 to 23 January 2022, and on Shea butter oil on 24 to 27 January 2022. The experiment revealed that the Shea butter oil produced a better result by enhancing effectiveness rather than the used engine oil and later the system without phase change materials as shown in the above Figures (5.7, 5.8, 5.9, and 5.10). The whole daily system effectiveness without PCM materials, with used engine oil, with Shea butter oil were 4.7 %, 49.2 % and 78.8 % respectively. The tests revealed that variations in physical parameters (density, viscosity, mass flow rate and specific heat capacity) and pointed out that specific heat capacity is the primary physical characteristic influencing the increase in heat transport. As the oil with the highest specific heat is shea butter (3400.00 J/kg. k), used engine oil (3062.59 J/kg. k) and air (1000 J/kg. k)

CONCLUSION

The analysis's finding is that adding PCM to SWHS is one way to influence how much heat is transferred from the storage tank, which can enhance the system's thermal efficiency. Results demonstrate the advantages of two distinct PCM materials for reducing nighttime heat losses.

After recording the performance of the system without PCM materials, with used engine oil and Shea butter oil each for four consecutive days, the optimum efficiencies were found to be 4.7 % on day 4, 49.2 % on day 1 and 78.8 % on day 4 respectively. In conclusion, the efficiency of the system with Shea butter oil is the highest followed by that with used engine oil and the efficiency of the system without PCM material is the least.

Nomenclature and units

G solar radiation, W/m^2
M mass flow rate, kg/s
ΔT difference in temperature, ^{o}C
Q_u useful energy gained by the solar water heater, J
T_o Temp. at the outlet, ^{o}C
T_i Temp. at the inlet, ^{o}C
η energy efficiency of the system, %

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