Performance Evaluation of Solar Water Heating System with PCM Thermal Storage

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***Abstract*— Impact of PCM on performance of solar water heating systems has been studied in this work. Two systems were analysed for storage tank water temperatures over a period of seven (7) days. One was equipped with 30 cm long in PVC pipes containing Phase change materials (PCMs) inserted into the hot water storage tank. Readings show higher daily maximum water temperatures for system with PCM compared with the other without PCM and a one-hour lag in time to reach daily maximum temperatures for system with PCM lagging behind system without PCM. Average minimum water temperatures in the early hours of the day, between 6am – 8am, were 57.8°C and 46.5°C for system with and without PCM respectively. This indicates that hot water availability is higher for system with PCM which would reduce requirement for supplementary water heating as well as water heating energy and cost.**

***Keywords*— Solar water heating, Temperature, Phase Change Material, Hot water Storage tank**

I. INTRODUCTION

Solar energy is particularly considered an attractive renewable alternative to fossil fuels for a wide range of applications, water and space heating [1]; [2], air conditioning [3], water distillation [4], hydrogen production [5] etc., for both domestic and industrial purposes because it is free abundant and clean with almost zero CO_2 emission. Solar energy systems are viable candidates for tackling global energy shortage problems and for improving quality of the environment [6].

As with most renewable energy systems, energy from the sun is periodic, following yearly and diurnal cycles. It is intermittent, often unpredictable and diffused. Consequently, energy storage is a requirement for assuring and/or guaranteeing availability, particularly during periods of low or no supply. As noted by [7], energy storage eliminates a major disadvantage of solar energy, its inconsistency. Energy storage can help popularise solar energy based heating systems like water heating [8], which takes up about 20% of total household energy consumption [9]. Subsequently design and development of energy storage systems is one of the biggest concerns in solar energy and systems research.

Application of energy storage methods permits better energy management and utilization. They, enabling storage of excesses for utilization at a later time when supply is low or non-existent, have the capacity to achieve reduction in the time or rate mismatch between supply and demand and are vital to energy conservation. They also improve energy system performance by smoothening supply and increasing reliability. This accounts for their wide applications [10]; [11]; [12]; [13]; [14]

Energy storage for solar applications is achievable through a number of processes, use of battery banks for electrical energy storage, thermal/heat storage, which can be either sensible or latent, or by thermo-chemical heat storage. Latent thermal/heat storage is preferable to sensible heat storage for solar heating due to their high storage energy density and the various melting temperatures that allow for various applications [15]. Latent heat storage systems provide a large heat capacity over a limited temperature range, acting, more or less, like isothermal reservoirs [16], and they experience relatively small volumetric changes [17].

For residential solar energy applications, latent heat storage systems are advantageous, as noted by [18], for reducing the temperature fluctuations, particularly due to incident solar radiation. Additionally, there is the opportunity of using low temperature heat and/or waste heat [19]. As observed by [20], phase change energy storage can reshape energy consumption, with particular emphasis on the domestic sector. [21]; [22]; [23]; [24] opined that the benefits and opportunities offered by latent heat storage for reducing building energy consumption are huge.

A number of research works have been carried out, and/or are ongoing, on solar heating and thermal storage for domestic application because they are relatively inexpensive and simple to fabricate [25]. In their review, [25] identified several new and innovative methods and designs of solar water heating systems with phase change heat storage material. They posit that high storage density and isothermal nature of storage process at melting temperature are factors that make thermal energy storage attractive and that solid to liquid phase change, or vice-versa, is preferred to liquid to gas or solid to gas phase change because of lower operating pressures.

[15] also did a review of thermal energy storage technologies and materials suitable for building applications. They reviewed recent developments on materials, classification, limitations and possible improvements for use in buildings. They noted that the paraffins, which although have low thermal conductivities, have negligible super-cooling, are non-corrosive, chemically stable, are self-nucleating, have no phase segregation, and the operational cost is considerably low in comparison to organic salt hydrates. [11] also identified the these properties of paraffins in their review, adding that they are safe and compatible with most of the materials used for constructing solar water heating systems. They also identified their non-compatibility with plastic containers, noting that they (paraffins) are prone to diffusing into and/or reacting chemically with plastics because of their similar molecular structure.

In a similar review and laying emphasis on materials and applications, [26] identified some of the undesirable properties of paraffins like "low thermal conductivity, non-compatibility with the plastic container and moderate flammability. They noted that slight modifications of the material and the storage unit can reduce and/or eliminate their impact on performance.

In their work to describe heat transfer during heat charge and water discharge in typical domestic hot water cylinder, [27] developed a mathematical model which they used to validate experimental data from a previous study by [28]. They concluded that the systems with PCM had higher hot water discharge capacity, with higher demand which would enable use of low cost electricity.

[29] evaluated the performance of two hot water tanks, one of which was modified to allow insertion of PCM modules, in an experimental solar pilot plant built at the University of Lleida, Spain. Thermal storage material was granular PCM–graphite compound containing 90% by volume of sodium acetate tri hydrate and 10% by volume of graphite. Varying the number of PCM modules inserted in the tank, for varying proportions of PCM to tank volume, they experimented with different trial tests to simulate different operating conditions classified as cooling down, reheating and solar operation. They observed that tank energy density increased with increasing proportions of PCM in tank and concluded that tank thermal energy storage capacity was increased, which could result in reduction in size of hot water tank.

This work, similar to [29], experimentally examines performance of two hot water tanks with one containing phase change thermal energy storage material. However commercial wax is in the PCM employed this study.

II. METHODOLOGY

The experimental set up consists of two (2) insulated flat plate solar collectors 2.13m, 1.09m and 0.1m, length, breadth and depth respectively, inclined at 17.5^{o} to the horizontal, being the appropriate inclination for optimum all year performance for Ado Ekiti, Ekiti State (latitude 7.5^{o} north) [30], and two (2) 0.225m^{3} capacity hot water storage tanks. The water storage tanks were insulated with fiber glass wool and covered with aluminum foil. PVC pipes, 0.5 cm and 0.33m, diameter and height respectively, containing commercial wax (melting point – 45^{o}C, heat of fusion – 189kJ/kg, thermal conductivity – 0.21W/Mk, density – 786 k/m^{3} and the volume – 0.0279m^{3}) were inserted in the upper half one of the tanks. This, according to [19], offers the advantages of stratification and higher thermal storage density in the upper part of tank, which improves performance of the storage system. K-type thermocouples temperature sensors, connected to a data logger (TecPel T-319), were inserted into both tanks to take water temperature readings. The tanks were connected to the solar collectors and water supply and utility. Both system were set up for thermo-syphon operation, which is self-regulating (31) and most suitable for small applications (30) and place in an un-shaded south-west facing area. 65 litres of hot water was drained for the tanks in the evenings and mornings to simulate hot water consumption and use.

The surrounding temperature was also measured and recorded along with hot water temperatures and, with data logger set to record temperature readings at 30 minute intervals, data was collected daily over a period of seven (7) days in May of 2016.

III. RESULTS AND DISCUSSION

Temperature of surrounding, of water in the storage tank without PCMs and of water in storage tank equipped with PCMs are denoted t1, t2 and t3 respectively. Figures 1 – 7 are plots of temperature-time profiles for each day of the experiment.

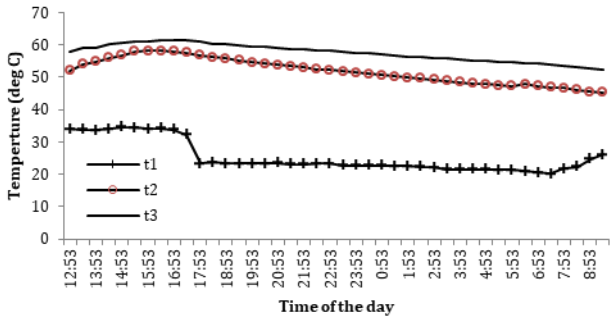

Fig. 1. Temperature-time profile graph for day 1

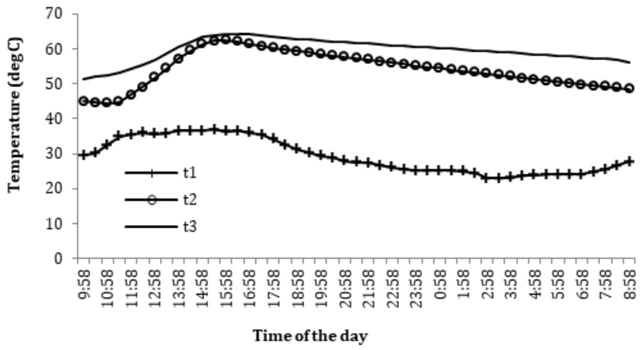

Fig. 2. Temperature-time profile graph for day 2

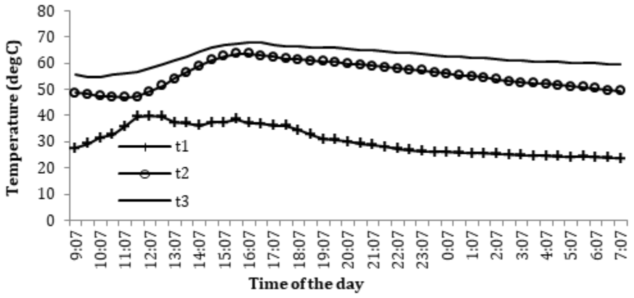

Fig. 3. Temperature-time profile graph for day 3

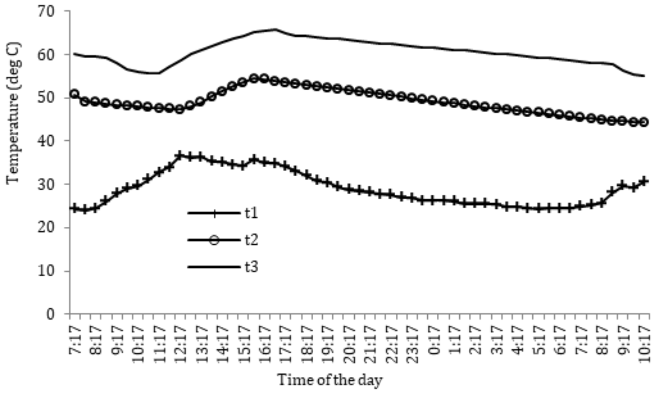

Fig. 4. Temperature-time profile graph for day 4

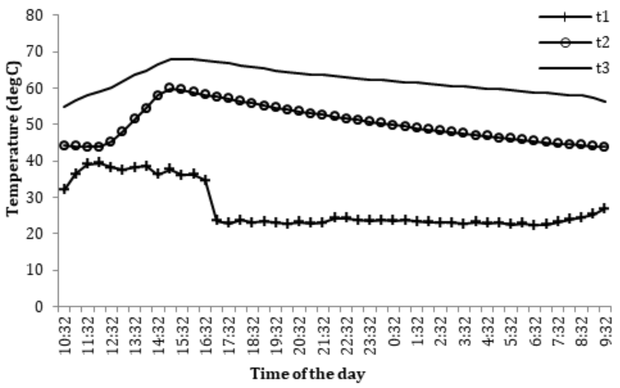

Fig. 5. Temperature-time profile graph for day 5

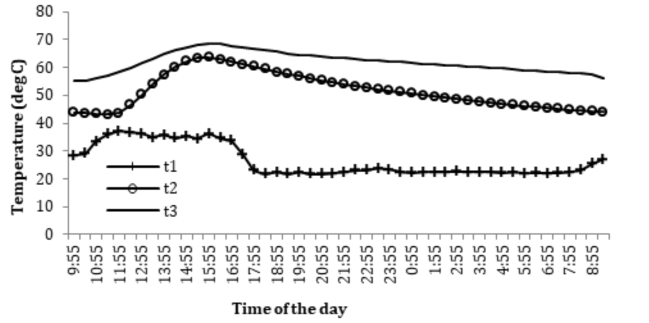

Fig. 6. Temperature-time profile graph for day 6

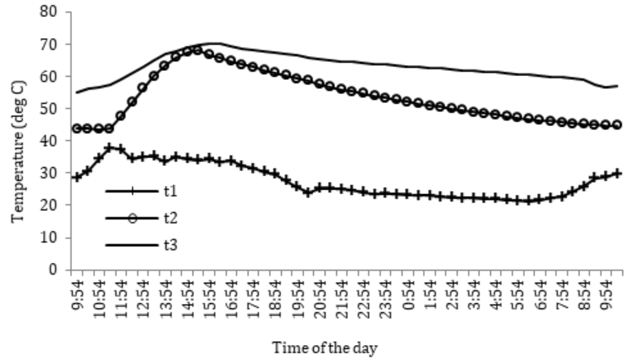

Fig. 7. Temperature-time profile graph for day 7

Table 1 shows maximum temperature readings for all the days of the experiment. From the table and figures 1 – 7, daily maximum water temperatures for system with PCM are clearly higher than those for system without PCM. Also system with PCM attained peak temperatures at least 30 minutes later than water in tank without PCM. For example figure 4, water temperatures for day 4, shows water in tank with PCM reached maximum temperature, 65.7^{o}C, at 4:47pm (16:47) while water in tank without PCM reached maximum temperature, 54.5^{o}C, at 3:47pm (15:47).

TABLE 1: DAILY MAXIMUM TEMPERATURE AND TIME ATTAINED FOR BOTH SYSTEMS

		Max temp (deg C)	Time (hrs)
Day1	with PCM	61.6	16:53
	No PCM	58.1	16:23
Day2	with PCM	64.4	16:28
	No PCM	62.4	15:58
Day3	with PCM	67.8	16:37
	No PCM	63.7	16:07
Day4	with PCM	65.7	16:47
	No PCM	54.5	15:47
Day5	with PCM	68.1	16:02
	No PCM	60.0	15:02
Day6	with PCM	68.5	16:25
	No PCM	63.7	15:55
Day7	with PCM	70.2	16:24
	No PCM	68.0	15:24

This attributable to additional thermal mass, due to PCM, heated by the same capacity solar heater as well as increased heat capacity of the combined water and PCM in tank.

The slopes of temperature-time graphs (figs. 1 – 7) also reveal the superior ability of system with PCM for heat retention. After Sun down (7pm – 7am), temperature drops of water in tank with PCM is slower (gentler slope) than for tank without PCM. This is due to higher temperatures attained during the day and greater amount of heat stored in water/PCM combo coupled with the slow release of heat by PCM to water in tank. The residual heat in PCM also resulted in the earlier commencement of temperature rise for water in tank with PCM on the following day. For day 2 (fig 2), t3 (water temperature in tank with PCM) began to rise around 10am (10.00) while t2 (water temperature in tank without PCM) began its rise around 11am (11.00), about 1 hour later. This trend is observed throughout all mornings following day the experiment.

Table 2 and figure 8 show a comparison between the systems for minimum water temperatures before 8am (08.00), taken on the morning following day of experiment, for all days of the experiment. Average minimum water temperature for system with PCM is 57.8^{o}C but 46.5^{o}C for tank without PCM.

TABLE 2: MINIMUM WATER TEMPERATURE (DEG C) BEFORE 8:00 AM FOLLOWING MORNING

	With PCM	No PCM
Day1	53.7	46.7
Day2	57.1	49.2
Day3	59.6	49.1
Day4	58.2	45.2
Day5	58.2	44.5
DAy6	58.0	44.8
Day7	59.7	45.7

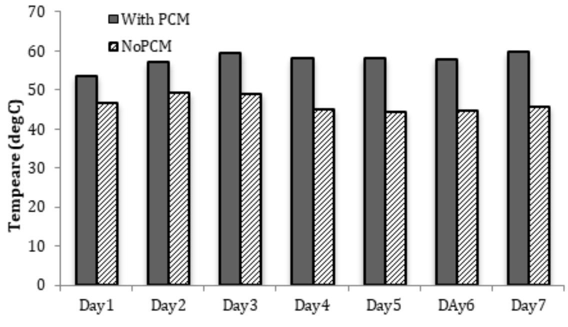

Fig. 8. Minimum water temperature (deg C) before 8:00 am following morning

The table also shows that daily minimum water temperature for system with PCM is averagely 11K higher than those for system without PCM. This is as a result of additional heat stored in PCM and is indicative of the ability of phase change materials to improve performance of solar water heating systems, increase hot water availability and reduce supplemental water heating requirement thereby reducing energy expenditure on water heating.

Water temperatures in both tank in the early hours of the morning, between 6am (06.00) and 8am (08.00), are relatively high and sufficient for average hot water baths as suggested by [27]. Supplementary water heating requirements would be less for system with PCM compared to system without PCM on account of the higher water temperatures at these periods of the day.

IV. Conclusion

Results of this study show that including phase change materials in hot water storage tanks of solar water heating systems for additional heat storage improved system performance in comparison to system where heat is stored in water only. Daily maximum water temperatures for system with PCM were higher than that for system without and water in former system reached maximum temperature about one hour later than water in the latter system.

Average minimum water temperatures in the early hour of the day, 6am – 8am (06.00 – 08.00), over period of experiment were 57.8^{o}C and 46.5^{o}C for system with PCM and system without PCM respectively. These are indications of increased hot water availability and reduction in supplementary water heating requirements for system with PCM compared to the system without PCM, as well as reduction in energy expenditure and cost for water heating.

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