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Experimental Study on the Performance of a PCM-Based Solar Energy Storage System

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Abstract: - A vegetable-based PCM-based solar energy storage system capable of simultaneous energy utilization and energy storage was developed. The PCM is non-toxic, renewable, non-flammable and biodegradable. The system consists of a solar collector that transfers thermal energy to water circulated by a pump. The water flows through a heat exchanger in the PCM in a storage tank. Energy is thus transferred to the PCM which changes phase and stores thermal energy. Another pump circulates water through a secondary heat exchanger also enclosed in the PCM tank to recover energy. The system is designed to divert heated water to a liquid-to-air heat exchanger by means of a three-way valve. A fan blows air through one of the heat exchangers so that hot air for building heating can be obtained. Experimental studies performed show that more than half of the energy collected at the solar collector can be stored by the system irrespective of the season. Also, despite maximum energy losses to the surroundings, in the summer, the efficiency of energy storage by the system based on actual energy collected was found to be highest during this period. The types of fluid flow rates for best energy storage and recovery were identified.

Keywords: – *Solar energy storage, Experimental studies, Phase Change Material (PCM), System performance*

I. INTRODUCTION

Environmental problems, electricity deregulation, and anxiety over energy security are contributing to growing attention being paid to more solar energy utilization. However, because of intermittent supply and low concentration of solar energy which varies, depending on geographical location, the need for more research such as this continues to exist. Phase change materials (PCMs) have been found to be very useful in solar energy storage applications [1-4]. They can be classified as organic, inorganic or eutectic compounds and can store a lot of energy as latent heat compared to sensible heat storage materials.

Studies related to this one include an experimental study by Vikram et al. [5] on the feasibility and thermal behavior of solar water heating systems using encapsulated PCM as thermal energy storage medium. It concluded that the system was able to effectively store sufficient amount of water to meet the needs of a family of four. Ibanez et al. [6] studied the monetization of a new technology in which PCM modules were implemented in domestic hot water (DHW) tanks to reduce their sizes without reducing the energy stored. This was after demonstrating that the use of PCM in DHW tanks was feasible. The studies concluded that the PCM used in the study is powerful for evaluating the performance of PCM modules in water tanks. Al-Hinti et al. [7] used paraffin wax contained in small cylindrical aluminum containers packed inside a storage tank on two levels to study the use of water-phase change material storage in conventional solar water heating systems. The results from the study showed a 13°C to 14°C advantage in the stored hot water temperature over extended periods compared to a setup without PCM. The study also showed that the use of short periods of forced circulation had little effect on the system performance.

Haillot et al [8] investigated the effect of using a PCM medium in the solar collector of a DHW system. The results showed that the ratio of the amount of energy contributed by a solar energy system to the total energy required (solar fraction), decreases by PCM addition in the solar collector during the simulated winter months but increases during summer months if PCM is added to the collector of the system for the case of a solar tank volume. The conclusion was based on the limits of the tank volume used in the study.

In this present study, an experimental system was designed, constructed and used to investigate the performance (charging and discharging) of vegetable-based PCM applied to a solar energy storage system for air and water heating. Solar energy was applied in the system to power all the electrical components to ensure applicability of the system in parts of the world where electricity is not readily available. Energy storage is essential in solar energy utilization to cater for its intermittence. For residential buildings that depend on relatively big hot water tanks to keep up with demand, the application of PCM energy storage helps to reduce the size of the tank. Experimental studies performed, investigated the performance of the system leading to useful results and new design strategies for high-efficiency building energy utilization.

II. BASIC EQUATIONS USED IN THE SYSTEM DEVELOPMENT

The energy balance equation on the solar collector side [9] is:

$$\dot{Q}_{coll} = \eta G A_{coll} \tag{1}$$

where: $$\eta = \eta_o - a\frac{(T_{avg} - T_a)}{G} - b\frac{(T_{avg} - T_a)^2}{G} \tag{2}$$

In these equations, $\dot{Q}_{coll}$ = heat energy collected per unit time, η = efficiency of the solar collector, G= incident solar radiation on the collector, A_{coll} = solar collector absorber surface area η_o =collector efficiency constant, a, b = solar collector efficiency constant, T_{avg} = average temperature of water in the solar collector, T_a = ambient temperature.

Thermal properties of a PCM changes rapidly during a phase change. The enthalpy approach was used to analyze the heat transfer in the tank. The energy balance expression is:

$$(MC)_{pcm}\frac{dT_{pcm}}{dt} = \dot{Q}_{hx} - \dot{Q}_{losses} \tag{3}$$

where: $$\dot{Q}_{hx} = \frac{1}{R_{hx}}(T_{co} - T_{pcm}), \qquad R_{hx} = \frac{ln\left(\frac{d_o}{d_i}\right)}{2\pi k_{hx} L_{hx}}$$

$$\dot{Q}_{losses} = \frac{1}{R_{tot}}(T_{pcm} - T_a)$$

$$R_{tot} = \frac{ln\left(\frac{r_{to}}{r_{ti}}\right)}{2\pi k_t L_t} + \frac{ln\left(\frac{r_{ins}}{r_{to}}\right)}{2\pi k_{ins} L_t} + \frac{1}{2\pi r_{ins} L_t h_{air}}$$

The total energy stored in the PCM tank over a finite temperature difference is given as:

$$Q_{pcm} = (MC)_{pcm}\Delta T_{pcm} + m_{pcm} L \tag{4}$$

Using Euler integration method, the temperature derivative can be written as:

$$\frac{(T'_{pcm} - T_{pcm})}{\Delta t} \tag{5}$$

Solving for the PCM temperature at the end of a time increment gives:

$$T'_{pcm} = T_{pcm} + \frac{\Delta t}{(MC)_{pcm}}[Q_{hx} - Q_{losses}] \tag{6}$$

The expression for the energy recovery process is:

$$(MC)_{pcm}\frac{dT_{pcm}}{dt} = -\dot{Q}_{load} - \dot{Q}_{losses} \tag{7}$$

where $\dot{Q}_{load} = \dot{m}_{tank} C_{p,w}(T_{pcm} - T_{w,avg})$

The efficiency of the solar energy storage system can be obtained by the relation: $$\eta_{sys} = \frac{Q_{pcm}}{Q_{coll}} \tag{8}$$

The volumetric storage capacity is given by the equation:

$$volumetric\ storage\ capacity = C_p \times \rho \times \Delta T \times volume \tag{9}$$

In equation (9), C_p is the specific heat capacity of the liquid PCM, ρ is the density and ΔT is the temperature difference. These equations can be solved to obtain the hourly temperatures of the PCM and water in the hot water tank.

Figure 1 is a picture of the experimental system (view from the back of the solar collector). Different PCMs are available for use in latent heat storage applications. Some examples are salt hydrate, paraffin waxes, fatty acids and sugar alcohols [10]. The PCMs can be classified as organic compounds, inorganic compounds and eutectics. Important properties of PCMs that enhance thermal energy storage include high latent heat of fusion per unit mass and high specific heat. Disadvantages of PCMs include, low thermal conductivity, high cost, being toxic and possessing flammability risks. Desired advantages include being chemically stable, non-toxic, and non-corrosive. Since sustainability is one of the focal points of this project, there was the need to select a PCM that is stable, non-toxic, non-flammable, renewable and biodegradable. The PCM used is a patented natural vegetable-based phase change material derived from 100% renewable resources [11]. It is stable, non-toxic, non-flammable and biodegradable. The relevant thermal properties are shown in Table 1. The three major subsystems in the experimental set-up shown in figure 1 are the thermal energy intake (evacuated tube solar collector), PCM storage (tank containing the PCM) and output (water and air with the

Figure 1. System setup (View from the back of the Solar Collector)

Table 1. Some Thermal Properties of the PCM

Melting temperature		56°C
Latent heat		237 kJ/kg
Density		810 kg/m^3
Specific heat capacity	Solid	2.47 kJ/kg°C
	Liquid	2.71 kJ/kg°C

water storage tank). The other parts of the system include piping, check valve, the water pump, thermocouples, cables, probes, heat exchangers, insulation, fittings, battery with the wiring system and the data acquisition system. The complete system is set on wheels so that it was easy to be wheeled out of the laboratory to the outside to enable experiments to be performed. Solar energy conversion was applied in the system to power all the electrical components to ensure applicability of the system everywhere including places where electricity is not readily available.

III. EXPERIMENTAL SETUP AND PROCEDURE

Figure 2 shows a line diagram illustrating the experimental setup. The storage tanks (3) and (6) are well insulated with tank (3) containing the PCM and two heat exchangers while tank (6) stores the hot water for other purposes, including air heating. The evacuated tube solar collector (1) is used to transfer thermal energy to water circulated by a solar energy-operated pump (2.1). This water flows through one of the two heat exchangers embedded in the PCM contained in the storage tank, thus transferring energy to the PCM. The PCM increases in temperature and eventually changes phase as it stores thermal energy. Another solar energy-operated pump (2.2) functions to circulate water through the second heat exchanger contained in the PCM storage tank to recover energy from the PCM. The heated water which can be diverted to a liquid-to-air heat exchanger by means of a three-way valve (4) is stored in tank (6). In order to obtain hot water for other purposes, a solar-powered heat exchanger fan (5) is installed to blow air through the heat exchanger so that hot air for example, building heating can be obtained from the system.

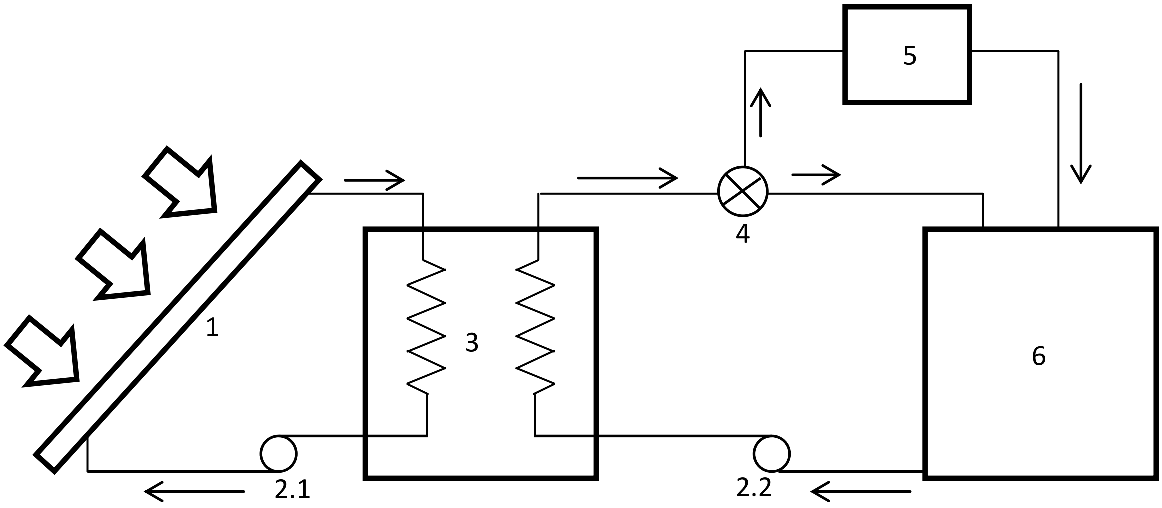

Figure 2. Schematic diagram showing the system setup

The experiments were conducted in Carbondale, Illinois, a city located at 37.7^{o}N, 89.2^{o}W with an elevation of 126 m above sea level. It can be seen from figure 2 that the system set-up has two heat transfer loops. One of the loops transfers thermal energy from the solar collector to the PCM while the other loop transfers thermal energy from the PCM to the water in the hot water tank. Before starting the experiment for investigating the storage performance at various flow rates, one of the loops was shut so that no heat transfer takes place between the PCM and the hot water tank. The required heat transfer flow rate was set and verified by the flow meter.

For the purpose of gaining heat from the solar collector and transferring the heat gained to the PCM, only the solar-powered battery pump for one of the loops was switched on to circulate the heat transfer fluid (HTF) across the loop. The data acquisition system was switched on so that temperatures of the HTF at the solar collector inlet, outlet and the PCM could be read and recorded at regular intervals. The experiments were each conducted for a period of at least six hours from morning to afternoon to ensure that adequate data were obtained for the period when the sun was shining. The experiments were repeated for a number of days during the summer, fall, winter and spring periods for each HTF flow rate. This was to ensure repeatability. The HTF flow rates used in the experiments were classified as high, medium and low. These are given respectively as:

(a) 10 LPM (0.16 kg/s).
(b) 5 LPM (0.083 kg/s).
(c) 3 LPM (0.05 kg/s).

The thermal energy available for storage compared to that which was stored for each of these operating HTF flow rates was investigated. These energy amounts were determined hourly. The basis used for the timing is such that, hour 0 is the time between 12 midnight and 1:00 a.m. while hour 1 is the time between 1:00 a.m. and 2:00 a.m. and so on. The performance of the system during energy recovery was also investigated.

IV. SUMMARY OF THE RESULTS AND DISCUSSION

Typical results for energy storage performance for the relatively high flow rate of 10 LPM (0.16 kg/s) of the HTF are shown in figure 3. Ambient temperature during these experiments ranged from 24°C to 32°C. From the figure it can be seen that the PCM temperature increased until about 56°C when it started to melt or undergo phase change. After melting, it gained heat sensibly and the temperature started to rise again. The experiments show the behavior of the PCM as it maintained an almost constant temperature near its melting temperature and then gained heat sensibly after melting. Figure 4 shows the results for the performance at medium HTF. It can be seen from the figure that the temperature of the PCM increased steadily with time even though the ambient temperature for the day was on the low side (about 21°C average temperature). The results for the storage performance for a relatively low HTF flow rate of 3 LPM (0.05kg/s) are shown in figure 5. It can be seen from the figure that the PCM temperature was steady for a long duration at an average temperature of about 56°C. When compared to the case for the high HTF, it can be seen that the beginning of the phase change and the end are more precisely defined. The figure shows that the performance of the system for the

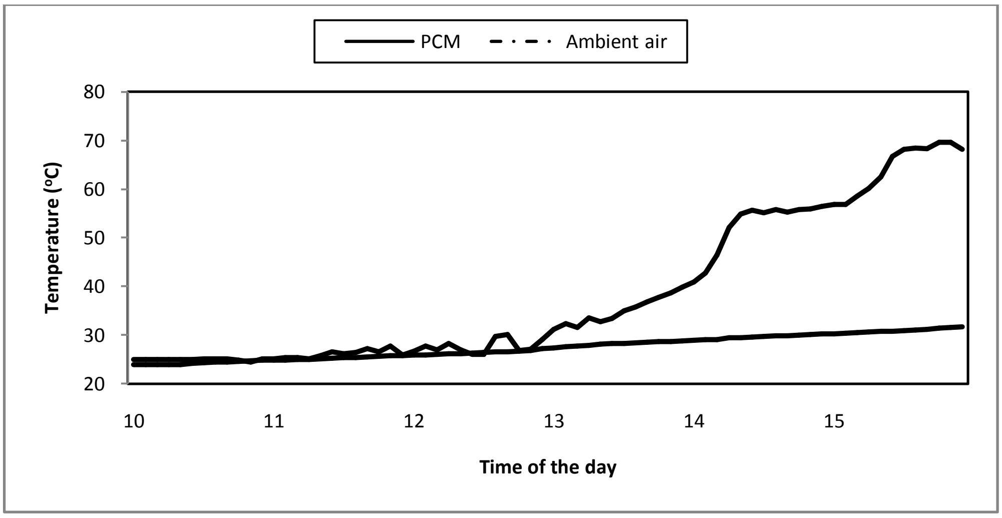

Figure 3. Thermal energy storage performance at the flow rate of 10 liters/minute

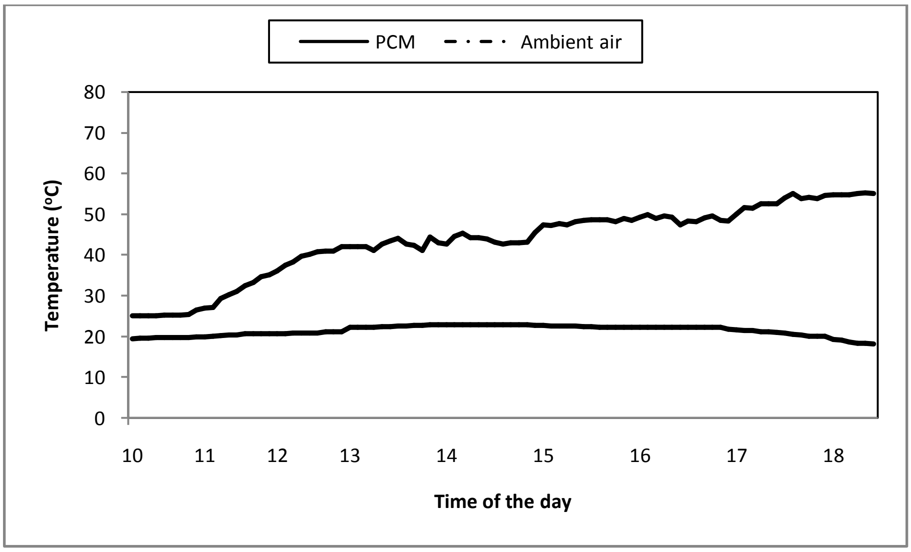

Figure **4.** Thermal energy storage performance at the flow rate of 5 liters/minute case of the low HTF allows the PCM to gain thermal energy much more steadily and without shocks. Thus the solid phase, the melting phase and the period of increase in temperature after melting are more clearly defined when the low HTF flow rate is used.

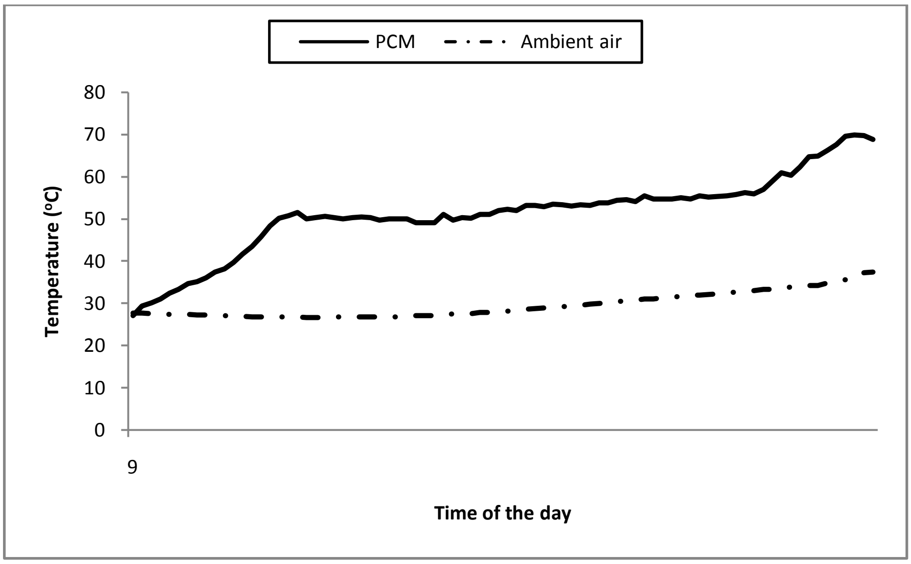

Figure 5. Thermal energy storage performance at the flow rate of 3 liters/minute

Figures 6 - 8 show the amounts of thermal energy stored hourly for the different operating HTF flowrates. The results for the thermal energy available at the collector and the amounts actually stored for the different flowrates are shown in Table 2. Evidence from the table shows that although large amounts of thermal energy were available for storage for the cases with high HTF flow rate, comparatively small fractions of the energy were stored. When compared to the cases with low HTF flow rate it is seen that a higher percentage of the available thermal energy was stored by the PCM. This can be explained by the fact that when the flow rate is low, more time was available for the PCM to extract the thermal energy from the HTF as it flowed through the PCM tank.

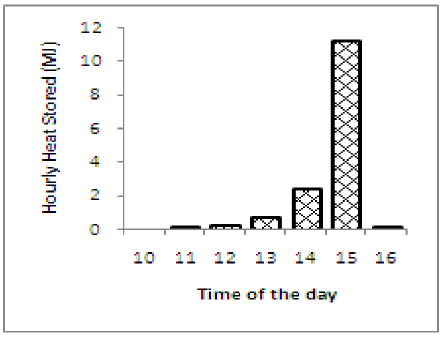

Figure 6. Energy Stored at 10 L/m flow rate

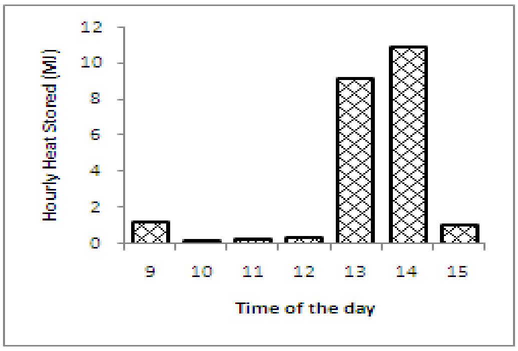

Figure 7. Energy Stored at 5 L/m flow rate

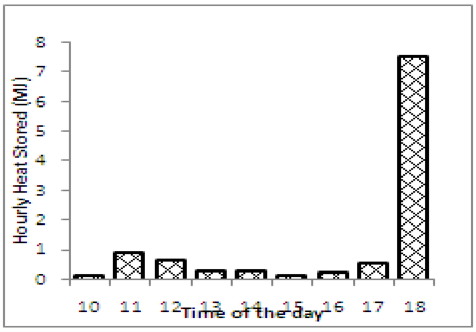

Figure 8. Heat Stored at 3 L/m flow rate

Table 2. Thermal energy availability and storage with varying flowrates

HTF Flow rate	Heat available (MJ)	Heat stored (MJ)	Percentage (%)
High (10 L/min)	98.4	14.9	15
Medium (5 L/min)	76	14.2	19
Low (3 L/min)	48.6	24.2	50

Table 3 shows typical results for the average thermal energy stored by the PCM during the seasons of the year. The table shows that as expected, the largest amount of daily thermal energy that could be stored by the system occurred during the summer season. The lowest amount occurred during the winter period. The results for the typical daily thermal energy losses from the system during various seasons of the year are shown in Table 4. The losses can be seen to be least during the summer period. This could be due to the fact that the average ambient temperature was relatively high (37.3^{o}C). The temperature difference between the PCM and ambient air was about 14^{o}C which is the least compared to the other seasons. This could be the main reason for the least thermal energy loss from the system.

Table 3. Average daily thermal energy stored by season of the year

Season	Thermal Energy Stored (MJ)
Summer	19.57
Fall	14.13
Winter	2.44
Spring	14.49
TOTAL	50.63

Table 4. Typical thermal energy losses from the energy storage system

Season	Heat loss (MJ)	Average PCM Temp. (^{o}C)	Average Ambient Temp. (^{o}C)
Summer	0.2	51.3	37.3
Fall	0.44	44.1	21.9
Winter	0.5	40.5	11.8
Spring	0.55	44.5	14.9

Table 5 shows the efficiency of the solar energy storage system obtained using equation (8). The values of the efficiency are seen to vary with season with the highest value occurring in the summer and the lowest occurring in the spring. It is noted that these average values are for the combination of the different HTF flow rates. Experiments were also performed to study thermal energy recovery from the system. These were to evaluate how much thermal energy that could be recovered from that stored in the PCM. Two types of HTF flowrates were used in these experiments. Typical results from these experiments are shown in figures 9 and 10. The results for the first flow rate of 5 L/min are shown in figure 9. It can be seen that the hot water temperature rose from about 28^{o}C to about 35^{o}C in the first hour and then the temperature increment started to decrease.

Table 5. Solar energy storage system efficiency for the seasons

Season	Q_{solar} (MJ)	Q_{pcm} (MJ)	Efficiency (%)
Summer	30.8	19.6	63.6
Fall	25.1	14.1	56.2
Winter	4.0	2.4	60
Spring	27.2	14.5	53.3

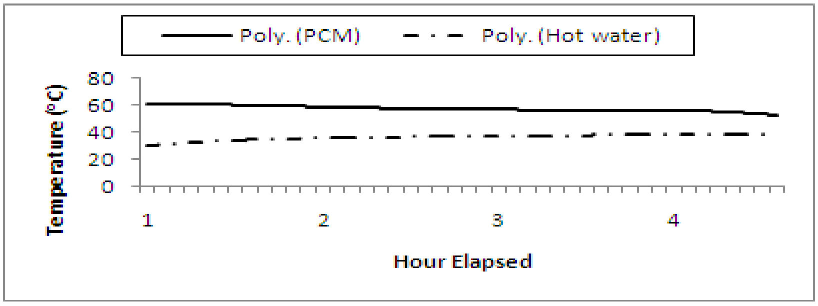

Figure 9. Hot water tank temperature during energy recovery at 5 L/min

Only a small rise in temperature was noticed for the rest of the recovery period. This is explained by the clogging which was noticed to occur around the heat exchanger coils in the PCM tank. The PCM was found to solidify around the coils causing an insulating effect. This reduced further heat transfer to the coils. It was found that the maximum temperature of water in the tank after the experiment was about 38.5^{o}C. A conclusion from this is that an auxiliary heater would be needed to bring the temperature of the hot water to about 40^{o}C, which is the temperature required for most usage in homes.

It was this inability of the hot water to reach the desired temperature of 40^{o}C and above that prompted the idea of a reduction in flow rate to 2 L/min. Figure 10 shows the results obtained for running the experiments using this reduced HTF flow rate. Compared to the case of HTF flow rate of 5 L/min, the hot water temperature rose at a very fast rate from 28^{o}C to about 40^{o}C within the first hour and then it quickly approached steady state. The maximum temperature achieved was about 44.3^{o}C which is some degrees higher than the required hot water temperature of about 40^{o}C. Thus, a low heat transfer fluid flow rate of 2 L/min (0.033 kg/s) produced the best thermal energy recovery process from the system.

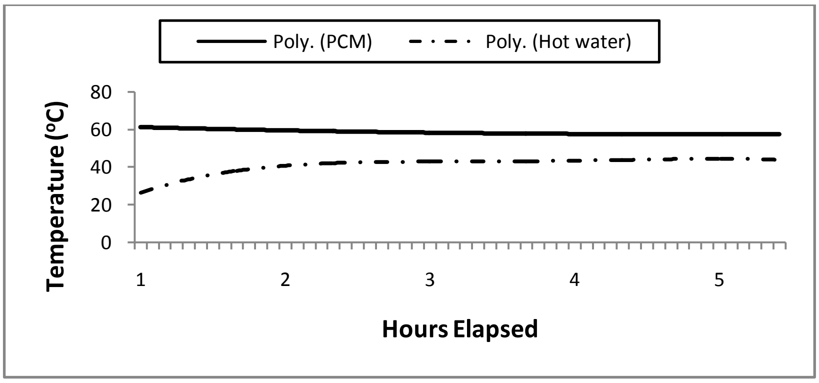

Figure 10: Hot water tank temperature during energy recovery at 2 L/min

V. CONCLUSION

Solar energy storage system based on a vegetable-based, non-toxic, non-flammable, renewable and biodegradable phase change material (PCM) was developed. The system involves the two storage tank system, one for the PCM and the other for the hot water storage. The system used was designed such that the heated water can be diverted to a heat exchanger by means of a 3-way valve such that a fan can be made to blow air through one of the heat exchangers so that hot air for other purposes such as air heating can also be achieved through the system. Solar energy was applied in the system to power all the electrical components to ensure applicability of the system in parts of the world where electricity is not readily available.

An experimental study on the performance of this system was done leading to a number of useful results. Based on the scale of this system, projections show that it can be extended to home building and commercial building applications. One of the results from this study shows that using the best or optimum low flow rate for the HTF for energy storage and energy recovery process gives the best performance by the system. The highest system efficiency of 63.6% was recorded for the summer period. However, results show that more than half of the energy absorbed at the solar collector was stored by the system irrespective of the season. A low heat transfer fluid flowrates of 3 L/min (0.05 kg/s) and 2 L/min (0.033 kg/s) produced the best heat storage and heat recovery processes respectively.

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NOMENCLATURE

a	1st order heat loss coefficient of the collector
A_{coll}	solar collector absorber surface area
b	2nd order heat loss coefficient of the collector
C	specific heat capacity
$C_{p,w}$	specific heat capacity of water
d_i	inside diameter of the heat exchanger tube
d_o	outer diameter of the heat exchanger tube
DHW	Domestic Hot Water
f	solar fraction
G	incident solar radiation

h	enthalpy of the PCM
h_{air}	heat transfer coefficient of air
HTF	Heat Transfer Fluid
k_{ins}	thermal conductivity of insulation material
k_{hx}	thermal conductivity of the heat exchanger material
k_t	thermal conductivity of the tank material
L	latent heat of fusion of PCM
L_{hx}	length of the heat exchanger material
L_t	height of the tanks
$\dot{m}_{coll}$	flow rate of water in the solar collector
$\dot{m}_{tank}$	mass flow rate of water in the PCM tank
M	mass
M_{pcm}	mass of the PCM in the tank
PCM	Phase Change Material
Q_{aux}	auxiliary heat energy
$\dot{Q}_{coll}$	useful heat supplied by the solar collector
Q_{coll}	energy gained by the solar collector in a time interval
$\dot{Q}_{hx}$	rate of heat exchange from the copper coils to the PCM
$\dot{Q}_{load}$	heat supplied to the load
$\dot{Q}_{losses}$	rate of heat loss from the PCM tank
Q_{losses}	energy lost by the PCM tank in a time interval
Q_{pcm}	energy stored in PCM tank in a time interval
r_{ins}	radius of insulation material
r_{ti}	inside radius of the tanks
r_{to}	outer radius of the tanks
R_{hx}	thermal resistance on the coils of the heat exchanger
R_{tot}	total thermal resistance of the PCM tank
t	time
T	temperature
T_a	surrounding ambient temperature
T_{avg}	average water temperature in the solar collector
T_{ci}	water temperature at the solar collector inlet
T_{co}	water temperature at the solar collector outlet
T_{pcm}	PCM temperature
T'_{pcm}	PCM temperature after a time interval
T_w	required water temperature for user
$T_{w,avg}$	Average water temperature in the hot water tank

Greek Letters

Δt	time increment
ΔT_{pcm}	temperature difference of the PCM
η	solar collector efficiency
η_o	solar collector optical efficiency
η_{sys}	solar energy storage system efficiency

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