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Experimental Investigation on the Performance Enhancement of Integrated PCM-Flat Plate Solar Collector

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Abstract: Extension of the operational time of a solar water heating system is essential for overnight industrial and domestic use. One technique is by integrating the solar water heater with thermal energy storage. In the present study, an outdoor experimental investigation of Integrated Phase Change Material (PCM)-flat plate solar collector was carried out with paraffin wax. The absorber plate was modified by installing extended surfaces into the PCM reservoir to increase the heat transfer area. Paraffin wax is used to store heat during the day time. Water is the heating medium and was circulated between a 120 L water tank and the solar collector by pumping. Two cases have been investigated that is with and without PCM. It was found that on the average, 0.5 kg min^{-1} 10 to 20° inclination angles with PCM can provide promising 38°C hot water temperature for daytime demand with 52±2.2% efficiency. PCM case gives the highest performance when considering the day and night time efficiency compared to the case of without PCM.

Key words: PCM, solar collector, solar water heating, thermal energy storage

INTRODUCTION

Domestic water heating which constitutes a significant share of the residential energy consumption is an excellent application for utilizing solar energy. However, due to the intermittent, unsteady environmental condition and time-dependant characteristics of solar radiation, the wide spread use of solar water heating systems relies heavily on the availability of reliable and feasible energy storage methods.

Solar thermal energy had been traditionally stored in the form of sensible heat by raising the temperature of water or rocks for later use (Canbazoglu *et al*., 2005). Despite the obvious simplicity of such storage methods, they are inefficient as their storage capacities are small and limited depending on the size of materials. In contrast, solar thermal energy can be stored in the form of latent heat by using suitable phase change materials, which can offer high storage capacity per unit volume and per unit mass (Dincer, 1999). This is essentially due to the fact that for most materials, the latent heat of fusion is very much larger than their enthalpy change (for example: the ratio of latent heat to the specific heat of water is around 80). The melting of a Phase Change Material (PCM) enables the absorption of larger amounts of heat which can be excessively available during the daytime. This stored heat can be then be released to the surrounding medium during the evening and night hours as the PCM change its phase again from liquid to solid. Such method of storage is also advantageous in reducing the temperature fluctuations in a solar thermal system by absorbing the extra heat at peak radiation hours and to release it when solar radiation is absent.

A wide range of PCMs can be used for latent heat storage applications such as salt hydrates, paraffin waxes, fatty acids and sugar alcohols (Farid *et al*., 2004; Abhat, 1983). Kumaresan *et al*. (2011) introduce sugar alcohol (D-mannitol) as PCM but it is more suitable for medium temperature application because of it high melting point. For use in domestic solar water heating applications, paraffin waxes represent the most suitable option due to their congruent melting temperatures, availability, low cost and non-corrosiveness. However, they usually suffer from relatively high volumetric expansion ratios and low thermal conductivity values. The poor thermal conductivity can be overcome by using the PCM through geometries with large surface area to volume ratios.

Over the past two decades, research on latent heat thermal energy storage has generated a great deal of interest. Farid *et al*. (2004) and Zalba *et al*. (2003) presented detailed reviews of phase change materials, applications, and theoretical and experimental investigations. Different designs of integrated and

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compact phase change material solar collectors have been proposed and experimentally evaluated (Kurklu *et al*., 2002; Mettawee *et al*., 2006). Encapsulation and microencapsulation is another trend of storing PCM, this method can reduced space of storing PCM by encapsulate the PCM inside The sphere capsule. Al-Kayiem and Alhamdo (2012) experimentally investigate the thermal behaviour charging and discharging of encapsulate PCM. Alternatively, the use of different PCMs with different configurations in the storage tanks of solar collector systems has been experimentally investigated under various conditions (Canbazoglu *et al*., 2005; Nallusamy *et al*., 2007; Mehling *et al*., 2003). Natural material (coconut coir) was used as insulation to solar water heater. This coconut coir was used to replace glass wool in the solar water heater. Although, the efficiency of collector slightly lower but is save about 25% of manufacturing cost (Andoh *et al*., 2007). Local material, local technology, local manufacturing were identified by researcher (Sako *et al*., 2007) as another source to reduce cost of solar water heater fabrication. The objective of this paper is to experimentally investigate the effect of using paraffin wax as a phase change material in a rectangular cavity of an integrated solar water heater collector. In this study, the investigation includes sets of day long experiments with three different flow rates and tilt angles. The suggested storage configuration is simple and can be easily used with existing conventional system without major or expensive modifications.

The objective of the present study is to investigate the possibility of enhancing the performance of flat plate solar collector by using thermal energy storage. The storage in the present experimental investigation was integrated with a flat plate collector in one single unit. The wax paraffin is in direct contact with the lower surface of the absorber plate and extended surfaces are introduced to increase the contact area. The system is tested at three different inclination angles of 10, 20 and 30° for the 0.5 kg min^{-1} flow rate. The system performance is evaluated for a full day cycle.

Experimental set up: The Thermocouple positions at the solar collector are as shown in Fig. 1. The positions of thermocouples in the water pipe as shown in Fig. 2. Graphtec data logger is used to capture temperature signal for 24 h with an accuracy of ±0.05%. Shenitech ultrasonic flow meter is used to measure and control the water flow rate with an accuracy of 0.0001 L sec^{-1} ±1%.

At every hour, a 0.5 HP pump is used to circulate water for every 15 min and then stop for 30 min before resuming the water pumping again for another 15 min. A timer is used to set the ON/OFF pumping operation time. The pumping operation is continued for 24 h. This

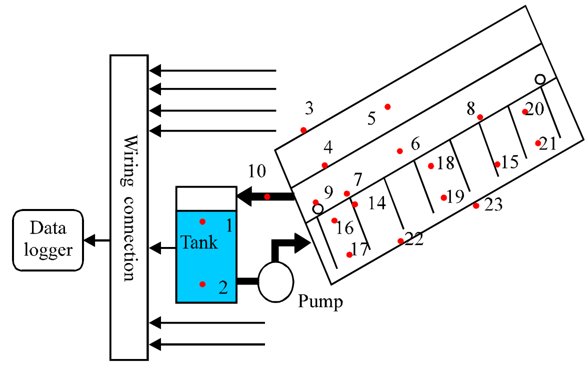

Fig. 1: Position of thermocouples in the solar collector

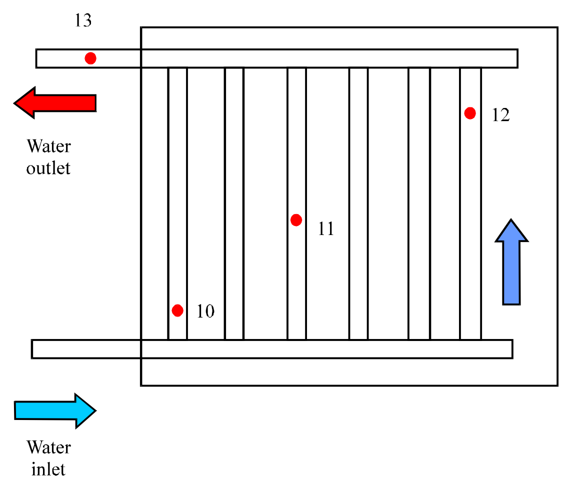

Fig. 2: Position of thermocouples in water pipes

continuous timing is planned for the absorber plate and paraffin wax to absorb more heat from solar radiation. This also helps to reduce electricity consumption and provide for a longer life span of the water pump. Water is scheduled for withdrawal at 7.00 a.m. and 7.00 p.m. every day. All the 120 L of water is withdraw and replace with new fresh water. By this way, the performance of absorber plate and paraffin can be tested with absent of solar radiation.

Table 1 shows 23 sets of thermocouples used in the solar collector system. Six thermocouples located in the cavity to measure bottom, center and top of PCM temperature. Two thermocouples placed on top and bottom of water tank and also on surface of absorber plate. Four thermocouples position in the water pipe shown in Fig. 2 to observe the temperature different at different length of water pipe.

Solar collector is placed facing south with latitude 4.57° to capture optimum solar radiation but because of dust and rain water collection. Solar collector is advisable

Table 1: Description positions of thermocouple

Thermocouples	Position
Probe type	Bottom tank
Probe type	Top of tank
Surface type	Top glazing
Surface type	Bottom glazing
Probe type	Air convection between top and bottom glazing
Probe type	Air convection between absorber plate and bottom glazing
Surface type	Absorber plate 1
Surface type	Absorber plate 2
Surface type	Water pipe 1
Surface type	Water pipe 2
Surface type	Water pipe 3
Surface type	Water pipe 4
Surface type	Inlet to tank
Surface type	Fin 1
Surface type	Fin 2
Probe type	PCM 1
Probe type	PCM 2
Probe type	PCM 3
Probe type	PCM 4
Probe type	PCM 5
Probe type	PCM 6
Surface type	Cavity
Surface type	Back loss

to tilt 5 to 10° higher than it latitude (Kalogirou, 2004; Henderson *et al*., 2007). In this experiment, 10, 20 and 30° are selected for the investigation. 120 L of water is filled in the tank to be circulated through solar collector all time. 120 L of water is capable to cater 10 persons in the family to use hot water. The full system connection is shown in Fig. 3. The system consist of one unit 0.5 HP centrifugal pump, 180 L water tank, solar collector with paraffin wax, a hydraulic jack to set the inclination angle and an ultrasonic flow sensor to measure the inlet flow rate of water into collector.

Efficiency evaluation procedures: The PCM-integrated solar water heater efficiency is predicted from the energy and mass balances involved in the system. The useful energy converted from the solar radiation to useful heating energy is:

$$\text{Heat Gain, } Q_u = m\,C_p \Delta T \tag{1}$$

The useful heat gain general equation above can be further elaborate into three equations when involved PCM. Since PCM is a phase change material, it consists of sensible heat and latent heat. The equations are as below:

Heat gain when PCM is in solid state:

$$\text{Sensible Heat, } Q = m\,C_{ps}(T_{S2} - T_{S1}) \tag{2}$$

Heat gain during phase change:

$$\text{Latent Heat, } Q = m\,C_{pL} \tag{3}$$

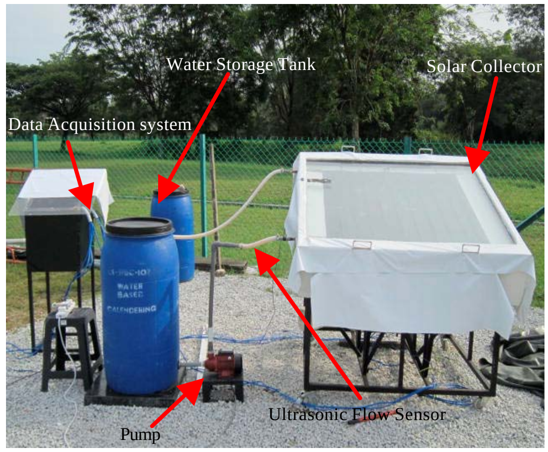

Fig. 3: The integrated solar-PCM water heater

Heat gain when PCM is in liquid state:

$$\text{Sensible Heat, } Q = m\,C_{pl}(T_{L2} - T_{L1}) \tag{4}$$

The solar water heater operation strategy in the experiment is into day and night time. The day time heat source is solar radiation whereas heating for the night time is obtained from PCM. The prediction of the solar collector efficiency is transformed into equation as follows:

Day time Efficiency (with and without PCM):

$$\begin{aligned}\text{Collector Efficiency, } \eta &= \frac{Q_u}{A_c\,G_T} \\ &= \frac{\dot{m}\,C_{pWater}\,\Delta T}{A_c\,G_T - m_{PCM}\,C_{p\,PCM}(T_{S2} - T_{S1})} \\ &= \frac{\dot{m}\,C_{p\,Water}\,\Delta T}{A_c\,G_T - m_{PCM}\,C_{p\,PCM}(T_{L2} - T_{L1})}\end{aligned} \tag{5}$$

Experiment with and without PCM use the same equation that is Eq. 5 to predict day time efficiency. The night time efficiency prediction is represented below where the heat gain by water is from discharge of heat by PCM.

Night time Efficiency involve latent heat:

$$\begin{aligned}\text{Collector Efficiency, } \eta &= \frac{Q_u}{\frac{m_{PCM}\,C_{pPCM}\Delta T}{3600}} \\ &= \frac{\dot{m}\,C_{pWater}\,\Delta T}{m_{PCM}\,C_{pL} + \frac{m\,C_{pPCM}\,\Delta T}{3600}}\end{aligned} \tag{6}$$

Night time Efficiency without latent heat:

$$\text{Collector Efficiency, } \eta = \frac{Q_u}{\dfrac{m_{PCM}\ C_{pPCM}\Delta T}{3600}} = \frac{\dot{m}\ C_{pWater}\ \Delta T}{\dfrac{m_{PCM}\ C_{pPCM}\ \Delta T}{3600}} \quad (7)$$

RESULTS AND DISCUSSION

The graph of with and without PCM collector efficiency of three inclination angles versus flow rate is plotted in one graph. Three tilting angles that are chosen are to test the effects of paraffin liquids convection on transferring heat to water in the night. Table 2 below showed the thermophysical properties of PCM to use in the efficiency calculation.

Uncertainty analysis for the measurement has been calculated by considering random uncertainty and systematic uncertainty as below. As the calculated, the total uncertainty, W_η range ±2.2% so overall efficiency should include total uncertainty range.

$$W_\eta = \sqrt{(B_\eta)^2 + (P_\eta)^2} \quad (8)$$

Four days set of data for each case has been collected and averaged. ASHRAE 93-2007 method is applied for standard measurement and analysis. The collector efficiency combined for the overall day and night time with and without PCM cases are plotted in Fig. 4 and 5 for 0.5 kg min^{-1} flow rate.

When considering day and night time performance, with PCM collector achieved thermal absorption coefficient as high as, $F_R\tau\alpha$ = 0.7115 and reduced the thermal heat loss FRU_L to lower than 4.343 W m^2 °C compared to without PCM case. This can be shown that the PCM-integrated hot water is able to reduce the thermal heat loss (F_RU_L) and provide good collector efficiency.

Inclination angle 10° shows a better efficiency for with PCM case (52±2.2%) compared to without PCM case (43±2.2%) as showed in Fig. 4 and 5. It shows that PCM is working very well to reduce the thermal heat loss and to supply heat to warn the water in the night. However, the thermal heat loss, FRU_L is high for all the inclination angles for without PCM case showed in Table 3 as the temperature and heat flux is high for this case. In the day time, the collector efficiency of without PCM case is higher than with PCM case but in the night time, the without PCM case efficiency is very low. 30° inclination angle collector efficiency is below 46% for both cases as 30° inclination angle is not an optimum radiation angle for this location.

Although, the collected radiation is optimum at 5° and should get a higher efficiency but surface contact between PCM and absorber plate at such angle becomes small. This is resulting in some of heat loss because of

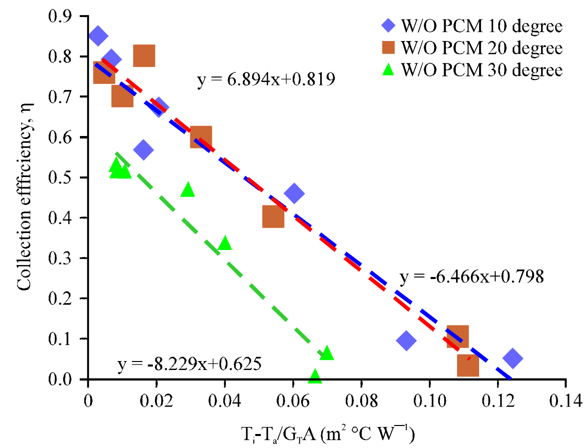

Fig. 4: Collector efficiency at 0.5 kg min^{-1} flow rate of without-PCM case

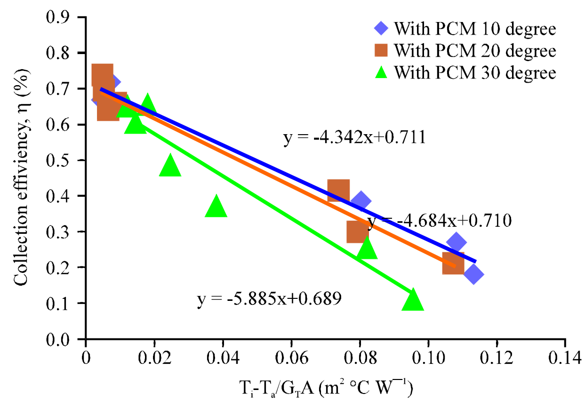

Fig. 5: Collector efficiency at 0.5 kg min^{-1} flow rate of with-PCM case

Table 2: Thermophysical properties of paraffin wax

PCM	Paraffin wax
Melting point (°C)	60.45
Solidification point (°C)	58.84
Latent heat (kJ kg^{-1})	166.7
Thermal conductivity (W m^{-1} °C^{-1})	0.172
Density (kg m^{-3})	908.6

Table 3: Integrated Solar-PCM water heater efficiency characteristic for 0.5 kg min^{-1} flow rate

θ	Efficiency equation	$F_R\tau\alpha$	F_RU_L (W m^2 °C^{-1})	Overall efficiency(%)
With PCM				
10°	y = 0.7115-4.3428x	0.7115	4.343	52
20°	y = 0.7102-4.6844x	0.7102	4.684	51
30°	y = 0.6897-5.8852x	0.6897	5.083	44
Without PCM				
10°	y = 0.7982-6.466x	0.7982	6.466	43
20°	y = 0.8191-6.894x	0.8191	6.894	42
30°	y = 0.6254-8.2292x	0.6254	8.229	30

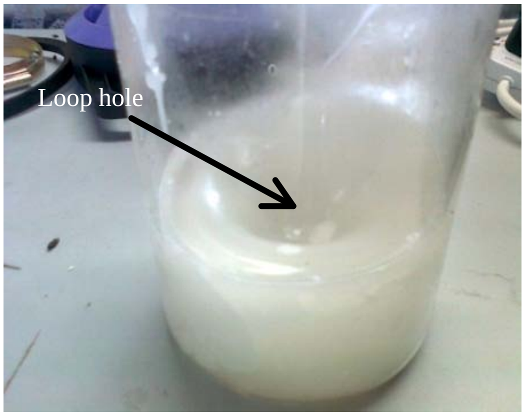

Fig. 6: Loop hole in the Middle of Paraffin Wax

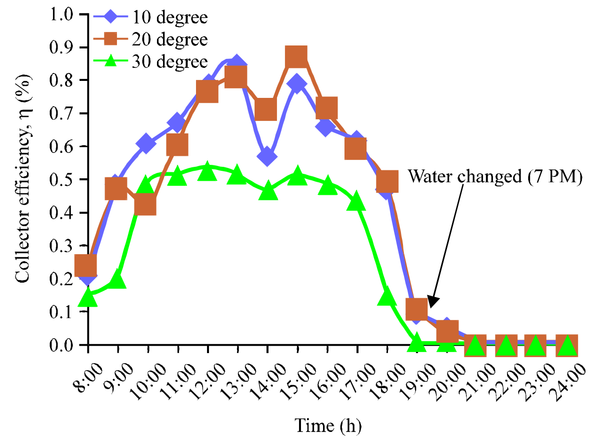

Fig. 7: Hourly collector efficiency at 0.5 kg min^{-1} flow rate without PCM case

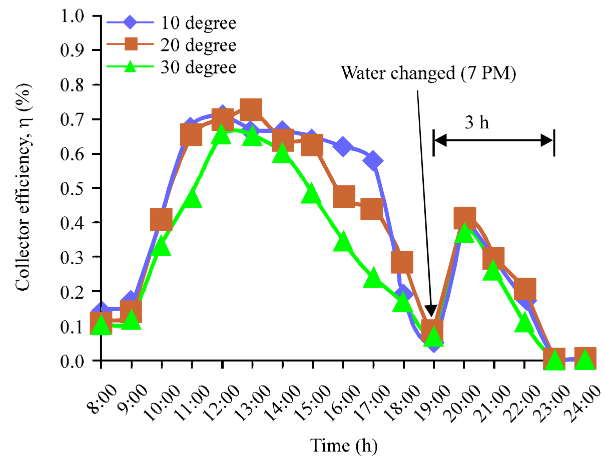

Fig. 8: Hourly collector efficiency at 0.5 kg min^{-1} flow rate with PCM case

heat transfer resistance when heat transfer through fins and loss to surrounding. Also, the 5° inclination angle is not recommended as rain water and dust can easily accumulated on the glazing of solar collector. Figure 6 showed the loop hole that cause the surface contact between PCM and absorber plate become small.

At day time, without PCM case showed higher collector efficiency as all the solar radiation was absorbed by water as showed in Fig. 7. However, in the night time, without PCM case showed very low collector efficiency. The remained heat stored in the absorber plate not able to generate medium temperature hot water in the night when new fresh water changed at 7.00 p.m.

With PCM case showed lower efficiency compared to without PCM case at day time as part of solar radiation was absorbed by water and the other part by PCM. At the night time after changing the new fresh water, with PCM case was able to provide medium temperature range (38- 42°C) depending on the PCM temperature. An average the extension of hot water is 3 h after changing water at 7.00 p.m. then all cases will reach equilibrium temperature for PCM and hot water. After the equilibrium, the hot water temperature starts to drop in the range of 2-5°C till early morning at 7.00 a.m. depending on ambient temperature. Figure 8 showed that the efficiency of collector increased after 7.00 p.m. as the PCM supplying the heat to the water. The efficiency of collector in the night time is not high as the limitation of PCM heat stored and the high resistance of heat transfer on the absorber plate to water in the riser. However, at night time, 20° inclination angle can achieve 41% compared to 10° (38%) and 30° (36%) inclination angle due to higher surface contact and stored thermal energy.

When considering day and night time performance, with PCM collector achieved thermal absorption coefficient as high as, $F_r\tau\alpha$ = 0.7115 and reduced the thermal heat loss FRU_L to lower than 4.343 W m^2 °C compared to without PCM case. This can be shown that the PCM-integrated hot water is able to reduce the thermal heat loss (F_RU_L) and provide good collector efficiency.

CONCLUSIONS

A 1×1 m solar collector with 28 kg of paraffin wax as thermal storage has shown a reasonable result when using 120 L water tank. The hot water produced however, depends on:

- Higher solar radiation
- Large surface contact between PCM and absorber plate
- Suggested optimum inclination angle (10-20°)
- High stratification in storage tank
- Phase Change Material (PCM)

Although 0.5 kg min^{-1}, 10° inclination angle for with PCM case showed a good performance (52±2.2%) but the surface contact of PCM to the absorber plate is not the highest. This can be observed that 20° inclination angle showed efficiency at 51±2.2%. The surface contact at 20° inclination angle helps to transfer heat from PCM to the absorber plate better than 10° inclination angle, although the solar radiation received is lower.

Overall, optimum operational condition when water flow rate is 0.5 kg min^{-1} for day and night time can be achieved through combination of 10° inclination angle with PCM case as the solar radiation harvested is the most and help to melt PCM faster. The combination also can produce extended production the hot water produced for extra 3 h before both hot water and PCM reached equilibrium thermal conditions after sunset.

It is recommended to investigate the system performance at various water flow rate.

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NOMENCLATURE

C_p	=	Specific heat (J/kg °C)
m_{PCM}	=	Specific heat of PCM (J/kg °C)
C_{pWater}	=	Specific heat of water (J/kg °C)
C_{pl}	=	Specific heat of PCM during liquid phase (J/kg °C)
C_{ps}	=	Specific heat of PCM during solid phase (J/kg °C)
C_{pL}	=	Specific latent heat (J kg^{-1})
m_{PCM}	=	Mass of PCM (kg)
$\dot{m}$	=	Mass flow rate (kg sec^{-1})
ΔT	=	Temperature different (°C)
A_c	=	Area of solar collector (m^2)
G_T	=	Solar radiation (W m^{-2})
Q_u	=	Useful heat gain (J)
T_S	=	Temperature at solid state (°C)
T_L	=	Temperature at liquid state (°C)
B_η, P_η	=	Random and Systematic Uncertainty

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