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An Experimental Study to Improve Solar Heating Water Using PCM and Integrated with Helical Heat Exchanger

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Abstract

Solar energy can only be used when it's sunny outside. Therefore, solar heating is only efficient during the day and decreases at night or on overcast days. Consumer energy needs have a distinct seasonal structure, and solar energy cannot completely meet those needs. In order to satisfy customer demand, energy storage is essential. In order to maximize the use of solar energy and to increase the energy and efficiency of the solar absorption system, superior thermal properties of sophisticated materials, such as phase change materials, are important [1].

In the current study, 20 kg of phase change material (PCM) is integrated with solar water heating and fed into a storage tank to enhance the solar water heating efficiency. Helical coil heat exchangers were added to the storage tank as an external load. The trials were conducted in four separate months (September 2021, April, May, and June 2022) that were chosen on the first day. The effectiveness, heat gain, and significance of the phase change material in increasing heating efficiency throughout the day were studied using a range of variables, including water volume flow rate (2, 3, 4, 6, and 8 L/min) and inlet water temperature (25, 30, and 35 °C). The results showed that, given an initial temperature of 25 °C, the daily efficiency range, was 0.58 to 0.65, and that the daily final outlet temperature was enhanced outlet temperature over 65 °C. Additionally, on all test days, the heat released by the phase change material was audible in the evening and increased the utilization time.

Keywords: Heat transfer, Solar energy, PCM, Heat exchanger.

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1. Introduction

It is believed that there would be considerable difficulties with heat storage for the long-term and wide spread to use solar energy for domestic cooling and heating in all regions. The majority of storage devices on the market today use water as their main ingredient. The majority of systems require storage optimization to increase performance. This can be done by lowering the cost of storage or increasing storage density, which enables the storage and withdrawal of more energy from a given volume of storage (reduce losses, use other materials, use other designs). While passive methods don't require any direct external power, active methods need it [2]. PCM is thought of as passive heat transfer improvement technique, Murali et al. [3], Kiyaroudi [4] conducted an experimental investigation on the improvement of heat transport in SHTHEs. It has been found that rising the loop measurement, curl pitch, and mass stream rate in helical curl cylinders and shells can accelerate heat move. The cool water stream rate and loop not set in stone to be the most urgent factors utilizing the Taguchi technique. Interestingly, sun powered nuclear power can be put away as idle intensity by utilizing reasonable stage change materials, which can offer high accumulating limit per unit volume and per unit mass [2]. This is basically in light of the fact that most materials' inactive power of blend is far higher than their enthalpy changes (for example, the extent of idle force to the specific power of water is around 80). When phase change material (PCM) melts, more heat can be absorbed, which is sometimes more heat than necessary during the day. When the PCM returns from the liquid to the solid phase in the evening and at night, it can then release this heat into the surrounding medium. Such a technique for capacity is likewise useful in decreasing temperature changes in a sun oriented warm framework by engrossing the additional intensity during top radiation hours and it is absent to deliver it when sun-based radiation. Albeit unsaturated fats and paraffin wax have been utilized as warm stockpiling in sun powered warming and cooling applications, their essential downside is unfortunate warm conductivity. Along these lines, less intensity is held during dissolving and more is transmitted during hardening. In natural PCMs, for example, metal nanoparticles, nanofibers, or embedded metal framework, scientists commonly disperse nanoparticles with high intensity conductivity, Kiyaroudi [4]. Mettaweea and Assassa [5] performance of a compact phase change material (PCM) solar collector based on latent heat storage with experimental investigation. The charging process, the average heat transfer coefficient increases sharply with increasing the molten layer thickness, as the natural convection grows strong.

The objective of the present paper is to enhance solar heating power by building an experimental station for heating solar water consisting of a flat plate solar collector (FPSC) filled with PCM for domestic purposes during the night and integrated with helical heat exchanger.

2. Experimental mythology

The test equipment primarily consists of two parts:

1. Solar flat plate collector with a ten-pass water tube and PCM fill.
2. Helical coil tube heat exchanger and PCM-equipped hot water storage tank.
3. Thermocouples and measuring devices.

The following sections provide explanations of each component's specifics:

- Flat plat Solar collector: Wood frame with dimensions: 1 × 1 × 0.08 m. Glass cover with dimensions: 1 × 1 × 0.005 m. Copper U tube with ten passes and diameter: 8 mm. PCM layer covers U tube with thickness: 5 cm. Black observer plate with dimensions: 0.1 cm.
- Connection of PVC water pipes: 12.5 cm diameter and check valves.
- Flowmeter for inlet water to collector and flowmeter for inlet water to heat exchanger type.
- Storage tank size (80 Liter) consists: PCM capsules size (10 kg).
- The test rig consists of two main components: flat plate collectors loaded with 10 kg of PCM and a heating pipe.

Table 1. Component of flat plate collector and dimensions.

No.	Component	Dimensions	Properties
1	Absorber plate (galvanized steel)	1 × 1 × 0.003 m	Thermal conductivity = 60 W/m °K
2	Copper pipe	D_o = 10 mm D_i = 8 mm	Thermal conductivity = 400 W/m °K
3	Insolation (cork)	1 × 1 × 0.03 m	Thermal conductivity = 0.04 W/m °K
4	Glass cover	1 × 1 × 0.004 m	Absorptivity = 0.88
5	Collector high	10 cm	-
6	PCM thickness	5 cm	-

- Hot water storage tank with 10 kg PCM and a heat exchanger. The details of each component are explained in the sections below.
- Thermocouples type K (No 16) location as follows: at collector (8) thermocouples: 6 at PCM layer, 2 at inlet and outlet water at storage tang (8) thermocouples: 4 at PCM capsules, 2 at inlet and outlet water of shell. 2 at inlet and outlet water of helical coil.
- Frame with a suitable angle to Basrah position 30°.

To support the symmetrical expansion of paraffin wax in all directions and ensure there is no leakage in the container, the PCMs were designed to be cylindrical in shape.

- Copper helical tube coil diameter: D-Measuring devices consists of Rotameters No. (2), Water pump No. (2), TES-1333 Solar Power Meter, (MPD-580) Multi-Channel Data Logger, (GM-550) Infrared Thermometer, Twenty thermocouples' types K. Frame with a suitable angle to Basrah position.

Table 2. Thermophysical properties of paraffin wax [2].

Parameters	Values	Units
Density	834.36	kg/m^3
Specific heat	2.9 (solid), 2.2 (liquid)	kJ/kg °K
Thermal conductivity	0.22	W/m °K
Melting temperature	324	°K
Melting heat	70.006	kJ/kg
Solidus temperature	292	°K
Liquidus temperature	300	°K
Viscosity	0.008	kg/m.s

Fig. 1 Photograph view of solar water heater 1. Storage tank. 2. Solar collector. 3. Flowmeter. 4. Valve. 5. Insulation pipes. 6. Pump. 7. K-type thermocouple of the inlet, outlet, and storage tank, 8. Collector inlet, and 9. Collector outlet.

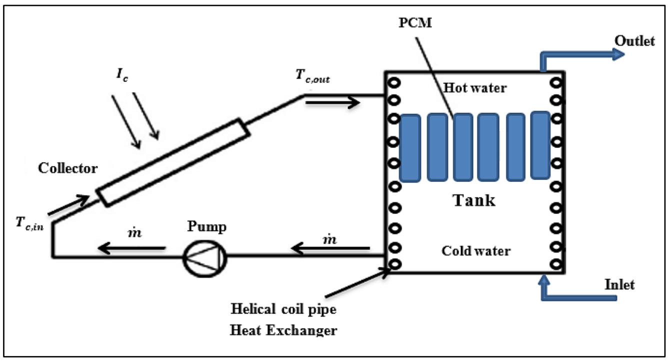

Fig. 2 Typical diagram of soler collector and thermal energy storage tank with PCM integrated and helical coil heat exchanger.

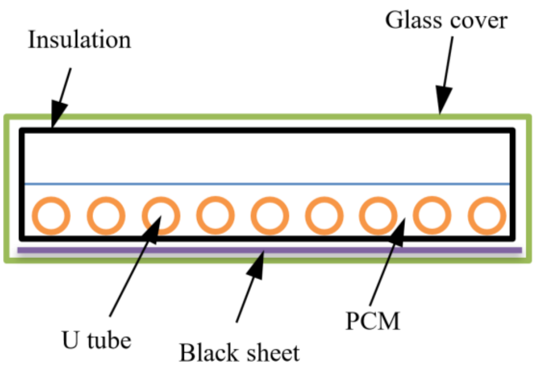

Fig. 3 Heating solar flat plate collector with PCM layer.

3. Experimental analysis

The experimental results can be obtained from the flowing equations which are dependent on the measuring temperatures, flow meter, and solar intensity.

- Estimation of collector and tank PCM amount: The mass of PCM layer in solar collector = 10 kg. The mass of each one capsule with PCM = 0.25 kg. The mass of PCM in the layer:

$$m_p = N_{caps.} \times M_{PCM} \tag{1}$$

N_{caps}: Number of capsules in one layer is 20. For one two layers of PCM, $m_p = 40 \times 0.25$ kg = 10 kg.

- Calculation of the thermal energy for the water tank: the target of the present study's analysis into the PCM's effects on the thermal energy storage Q (kJ). Equations are used to calculate the thermal energy with and without PCM in the water tank.
  Heat losses from the solar hot water = Heat giant by helical coil heat exchanger + Heat storage by tank PCM.
- Heat losses from the solar water = Heat giant to the storage tank.

$$Q_{in} = \int_{T_i}^{T_f} m_w\, c_{pw}\, dT = m_w\, c_{pw}\, \Delta T \tag{2}$$

Where:

m_w: the mass of water (kg), $m_w = \rho_w \times V_w$

ρ_w : the density of water (kg/m^3), ρ_w = 1000 kg/m^3

V_w: the volume of water in the storage tank per liter, (1000 liter = 1 m^3).

C_{pw}: the water specific heat (kJ/kg K), C_{pw} = 4.180 kJ/kg °C.

T_i : initial temperature (°C).

T_f : final temperature (°C).

ΔT : difference in water temperature is calculated for each time interval 1 hour.

- Heat giant by PCM [9].

$$Q = m_p\, c_{p,s}(T_m - T_i) + m_p\, \beta\, \Delta h_m + m_p\, c_{p,l}\, \Delta T \tag{3}$$

$C_{p,s}$: Specific heat of solid PCM (kJ/kg °C).

$C_{p,l}$: Specific heat of liquid PCM (kJ/kg °C).

T_m : Melting temperature of PCM (°C).

Δh_m: Melting heat (kJ/kg).

B : Thermal expansion of PCM, its value is calculated as:

$$\beta \begin{cases} 0 & \text{if } T < T_S \quad \text{solid} \\ \dfrac{T - T_S}{T_L - T_S} & \text{if } T_S < T < T_L \quad \text{two phase} \\ 1 & \text{if } T > T_L \quad \text{liquid} \end{cases} \tag{4}$$

T : PCM temperature (°C).

Ts: Solid phase temperature (°C).

T_L: Liquid phase temperature (°C).

Heat giant by the helical coil heat exchanger [10]:

- $Q_{exchanger} = UA_s\, \Delta T_{ln}$ (5)

Where:

U = Overall heat transfer coefficient (W/m^2 °C).

A_s = Surface area (m^2).

ΔT_{ln} = Logarithm mean temperature difference (LMTD) (°C).

- Calculate total heat transfer coefficient in current flow obtain Q for cold and hot flow as follows:

$$Q_c = \dot{m}\, C_p\, \Delta T_c \tag{6}$$

$$Q_H = \dot{m}\, C_p\, \Delta T_h \tag{7}$$

Get C_p of water at average temperature of inlet and outlet by using references because of heat loss. For better result put average of Q_c and Q_h instead of Q [10].

$$U = \frac{Q}{A_s}\, \Delta T_{LMTD} \tag{8}$$

- Calculation of flat plate solar collector and storage tank efficiency:

The amount of heat transmitted to the water Q_u (watt) divided by the total amount of solar energy that reached the solar collector during the same time period is known as the collector's efficiency (C) in this study. This is how it calculates:

The system's energy and mass balances can be used to anticipate the efficiency of the PCM-integrated solar water heater. $I_i\, A_c$ is the useful energy that solar radiation can be used to turn into.

Day and Night time efficiency without PCM, collector, η_c [9].

$$\eta_c = \frac{Q_u}{I_i\, A_c} = \frac{\dot{m}_{water}\, C_{p,\ water}\, \Delta T_{water}}{I_i\, A_c} \tag{9}$$

Day and Night time efficiency (with PCM), collector, ηc [9].

$$\eta_c = \frac{Q_u}{I_i\, A_c} = \frac{\dot{v}_w\, \rho_w\, c_{pw}\, \Delta T_{c\, +\, (PCM)\ heat\ gain}}{I_i\, A_c} \tag{10}$$

Where:

$\dot{v}_w$: Volumetric flow rate of water (lit/min).

ΔT_c: The difference between the outlet T_{out} and inlet T_{in} temperatures of the solar collector (°C).

I_i : Radiation falling on the collector (W/m^2).

A_c : The solar collector area (m^2).

When using PCM, the above useful general equation for heat gain can be further broken down into three formulae. PCM contains both sensible and latent heat because it is a phase-change material. Below are the equations:

- Heat gain when PCM is in a solid state [9]:

$$Heat\ Gain\ (PCM) = Q_{sencible}\ \frac{m_{PCM}\, C_{ps,\, PCM}\, (T_{s2} - T_{s1})}{60} \tag{11}$$

Where:

C_{psPCM} : Specific heat of PCM during solid phase (J/kg °C).

T_S : Temperature at solid state (°C).

m_{PCM} : mass of PCM (kg).

- Heat gain during phase change:

$$Latent\ heat = Q_{latent}\ \frac{m_{PCM}\ C_{p,\ latent,\ PCM}}{60} \tag{12}$$

where: $C_{p,\ latent,\ PCM}$: Specific latent heat PCM (J/kg).

- Heat gain when PCM is in liquid state:

$$Q_{sencible} = \frac{m_{PCM}\ C_{pl,\ PCM}\ (T_{l2} - T_{l1})}{60} \tag{13}$$

Where: $C_{pl,\ PCM}$: Specific latent heat PCM (J/kg).

T_l = Temperature at liquid state °C.

In the experiment, there are daytime and nighttime operational strategies for the solar water heater. Solar radiation serves as the daytime heat source, whereas PCM provides the nighttime heat.

The equation above, which predicts daytime efficiency, is used in both the experiment findings without PCM and with PCM. The predicted nighttime efficiency is shown, where the heat gain by water comes from the heat discharged by PCM alone.

4. Result and Discussions

In order to improve the accuracy results, the experimental results show the average value of each test at the start for all four months. The performance of the FPSC with the water heating pipe tilted 30 degrees and filled with PCM from the outside. The flow rate of the collector heating pipe is 4 L/min. With a fixed 90-liter capacity and volume flow rates ranging from 2 to 10 liters per minute and cold-water inlet temperatures of 25, 30, and 35 °C, the performance of the storage tank unit for hot water storage is examined. All cases are conducted with and without the PCM. Controlling the melting time is another method of confirming PCM's impact on performance. The readings are kept track of throughout the day for 12 hours every day. The thermal energy is initially stored as sensible heat within the PCM until the PCM reaches its melting point, at which point the energy is superheated and deposited as latent heat in the liquid PCM. The PCM and HTF average temperatures are measured every hourly interval. A helical coil heat exchanger transferred all stored heat to the exterior load for the external user.

4.1. Collector experimental results

Figures 4 and 5 present the Basrah city water condition at four months from morning 9:00 AM to evening 4:00 PM at the first day of each month respectably. Maximum solar intensity reaches 1000 Watt at June 2022 with compare to other months. Also, weather temperature reaches to 45 degree at the same month and 12:30 PM.

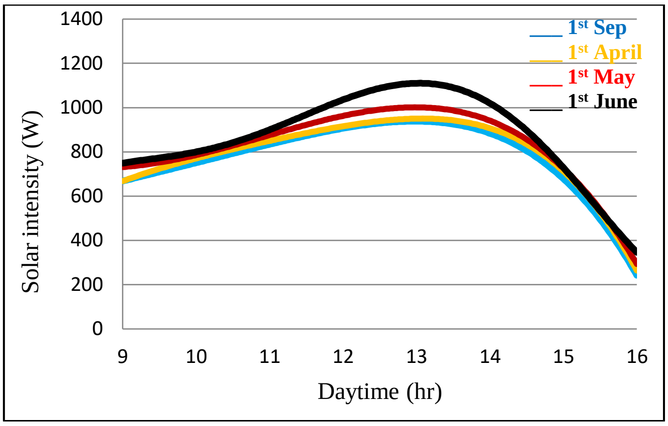

Fig. 4 Solar intensity on the FPSC with different month and daytime.

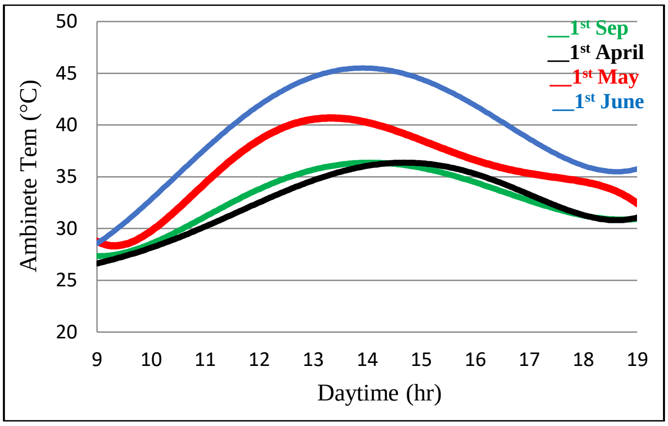

Fig. 5 Water temperature with different month and day time.

Figures 6, 7, 8 and 9 show the collector performance along daytime (ten hours) from 9:00 AM to 7:00 PM for each four months and volumetric flow rate to heat exchanger is fixed 4 L/min and inlet temperature is 25 °C. Collector performance presents the inlet, outlet and wax temperature respectively. Collector outlet water holds maximum temperature compared to the inlet and wax temperature due to heat gain from the solar radiation. The behavior of water temperatures from morning until four o'clock in the afternoon is similar for the four months. Maximum temperature reaches 70 °C at June 2022 due to high solar intensity. The effect of storage PCM appears at the sunset and low solar intensity. The latent heat in the phase change material will give the water energy at sunset. The energy stored in the PCM will help the water continue to heat up for a longer period of the day.

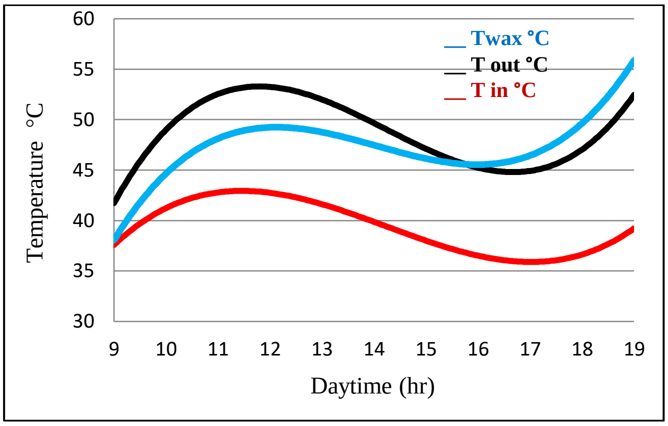

Fig. 6 Collector performance vs daytime with tank flow rate 4 L/min collector flow rate 4 L/min (1st Sep 2021).

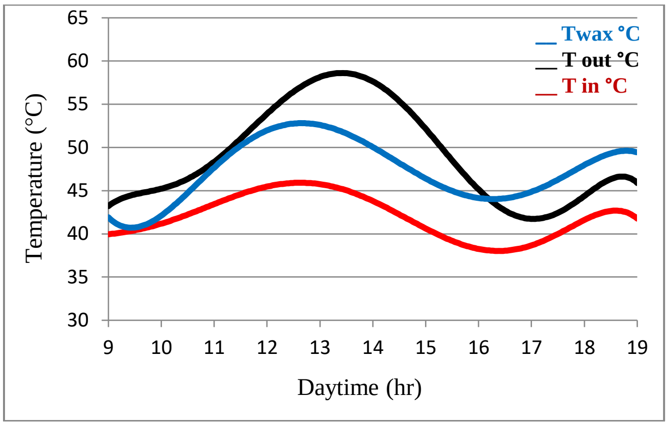

Fig. 7 Collector performance vs daytime with tank flow rate 4 L/min collector flow rate 4 L/min (1st April 2022).

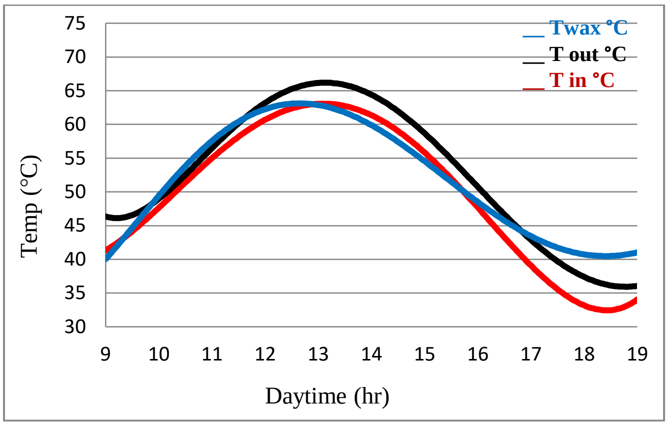

Fig. 8 Collector performance vs daytime with tank flow rate 4 L/min collector flow rate 4 L/min (1st May 2022).

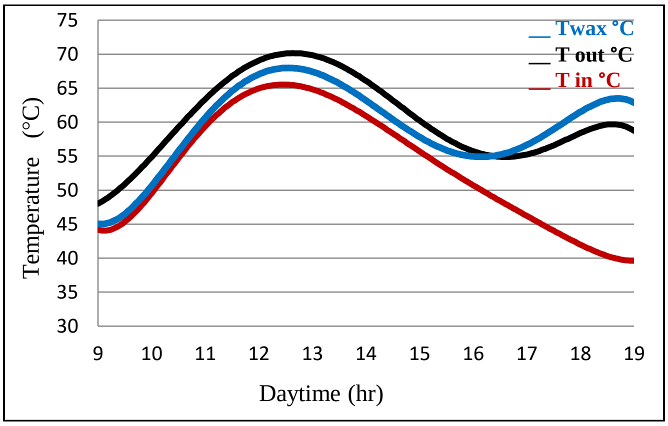

Fig. 9 Collector performance vs daytime with tank flow rate 4 L/min, collector flow rate 4 L/min (1st June 2022).

Figure 10 shows the experimental results of the collector outlet temperature with different helical heat exchanger inlet water temperature (25, 30 and 35 °C) at all daytime of 1st May 2022, and volumetric flow rate is 4 L/min respectively. The effect of the entry temperature is almost having a little effect on the performance of the solar collector, except in the peak hours of the day, while the greatest effect PCM at sunset of the day due to the stored energy.

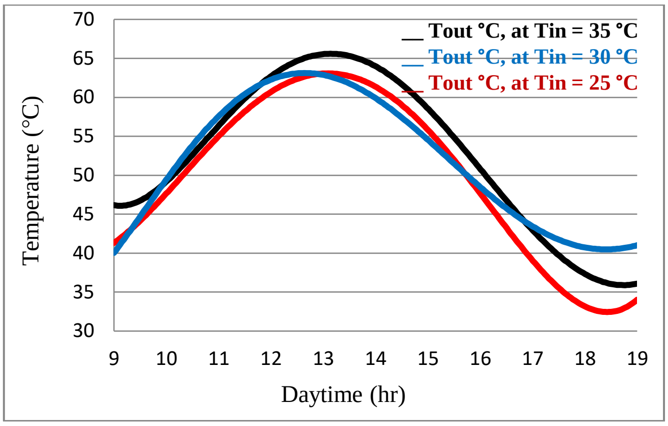

Fig. 10 The effect of the helical heat exchanger inlet temperature on the collector performance, (May 2022), V_{in} = 4 L/min.

Figure 11 presents the effect of phase change material on the collector outlet water temperature. The results indicate comparison of collector with and without PCM at the same weather conditions and water flow rate. High outlet temperature shows at all daytime when the collector integrated with PCM layer. Maximum difference accurses at the phase change period, both 11:00 AM and 7:00 PM due to the discharge phenomena.

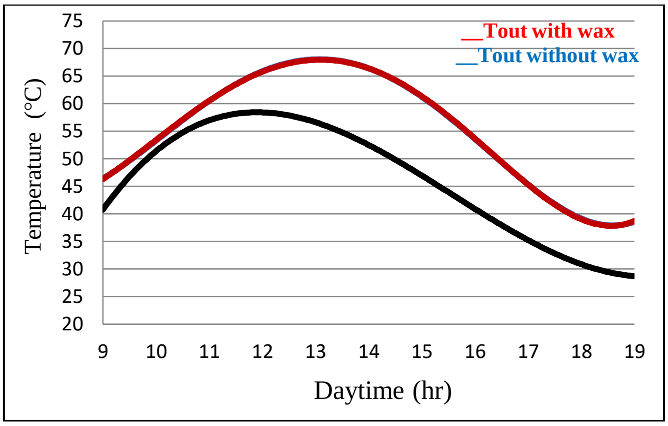

Fig. 11 Experimental outlet collector temperature with and without wax (May 2022), V_{in} = 4 L/min, T_{in} = 25 °C.

The effect of inlet water volume rate flow from 2 to 10 L/min on the collector efficiency (May 2022) is presented in Fig. 12. Collector efficiency increases with high inlet flow of the external load (helical heat exchanger). Maximum collector efficiency reaches to 58 % at high solar intensity.

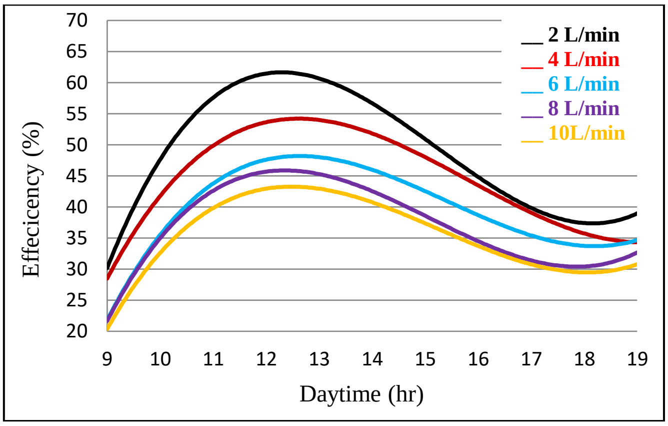

Fig. 12 The effect of inlet water volumetric flow on the collector efficiency (May 2022) at constant T_{in} = 25 °C.

4.2. Storage tank results

At this section of the present study the storage tank consists results of two parts: Storage tank with PCM capsules and helical coil heat exchanger (external load).

Figueres 13 and 14 illustrate the storage tank performance with daytime (ten hours) at inlet volume flow 2 and 4 L/min respectively. Storage tang inlet indicates the outlet collector temperature, while the outlet tank water temperature indicates the collector inlet water temperature. The results show the high effect of PCM capsules on the tank through the increase in the temperature of the PCM during the evening or the decrease in the intensity of sunlight.

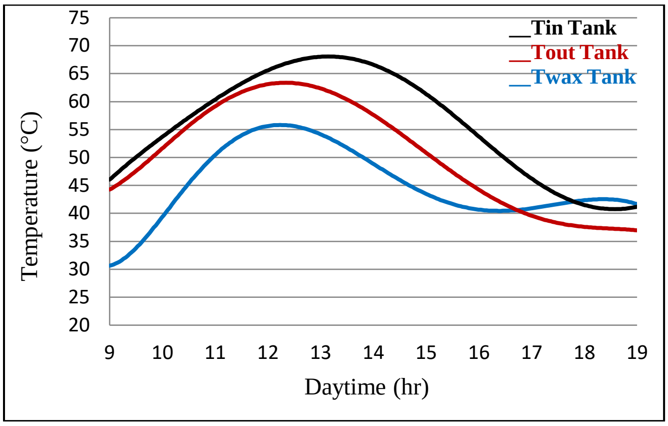

Fig. 13 Storage tank performance with daytime (ten hours) at inlet volume flow 2 L/min, (May 2022), T_{in} = 25 °C.

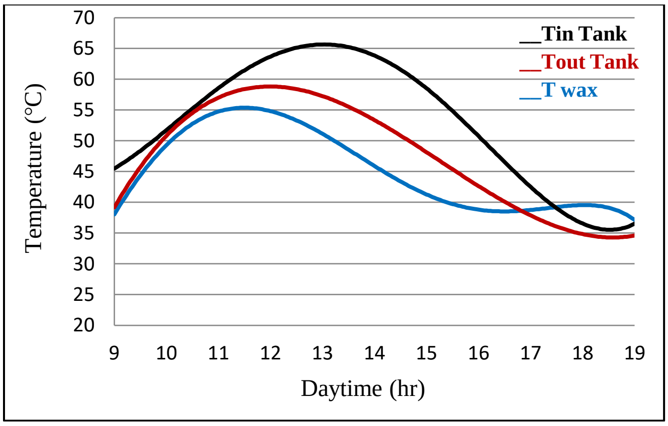

Fig. 14 Storage tank performance with daytime (ten hours) at inlet volume at flow 4 L/min, (May 2022), T_{in} = 25 °C.

Heat exchanger temperature distribution is recorded at flow rate V_{in} = 2 and 4 L/min and T_{in} = 25 °C at 1st may 2022. Figures 15 and 16 show water temperature at both tank as shell and helical coil tube along the daytime with counter flow. All results of the heat exchanger are enhanced at the sunset time due to discharge heat from PCM. At time 7:00 PM outlet shell temperature reaches 43 °C, while the outlet of tube at 40 °C at the same time and conditions for both volume flow rate 2 and 4 L/min. Maximum temperature for inlet water through shell reaches 71 °C at low flow rate compared to 67 °C at high flow rate according to the convection Newton law.

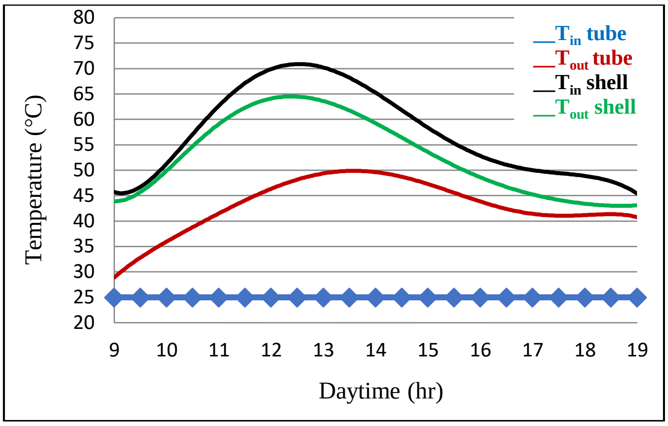

Fig. 15 Heat exchanger temperature distribution, Vin = 2 L/min (May 2022) at constant inlet temperature.

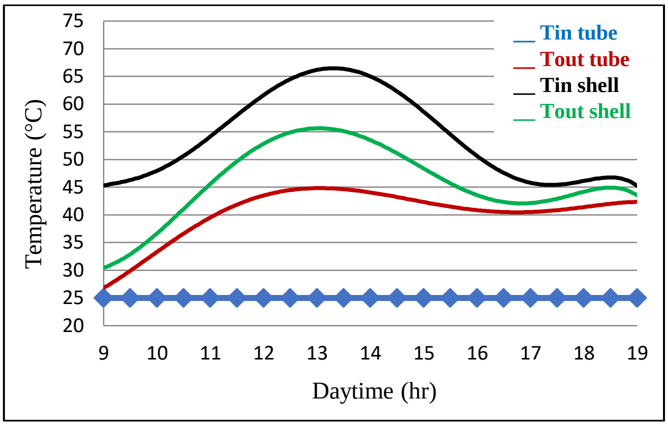

Fig. 16 Heat exchanger temperature distribution, T_{in} = 25 °C, V_{in} = 4 L/min (May 2022), at constant inlet temperature.

Main thermal parameter for heat exchanger is the overall heat transfer coefficient (U). Fig. 17 presents the results of shell and helical coil tube heat exchanger integrated with PCM capsules for different daytime at 1st May 2022. The effect of PCM occurs at 5:00 PM and began to increases for all heat exchanger. The maximum value of heat coefficient at midday indicates at shell inlet temperature.

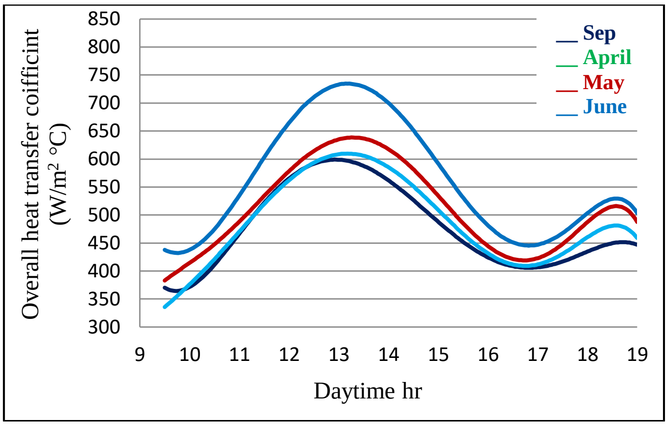

Fig. 17 Heat exchanger overall heat transfer coefficient with different months and daytime, V_{in} = 2 L/min, T_{in} = 25 °C.

Figure 18 presents the thermal storage for the storage tank with different inlet water temperature at constant Vin = 2 L/min, May 2022. The effect of the inlet water temperature increases the storage energy through PCM for daytime at the period of phase change region from 11:00 AM to 1:00 PM respectively and it will increase in the evening.

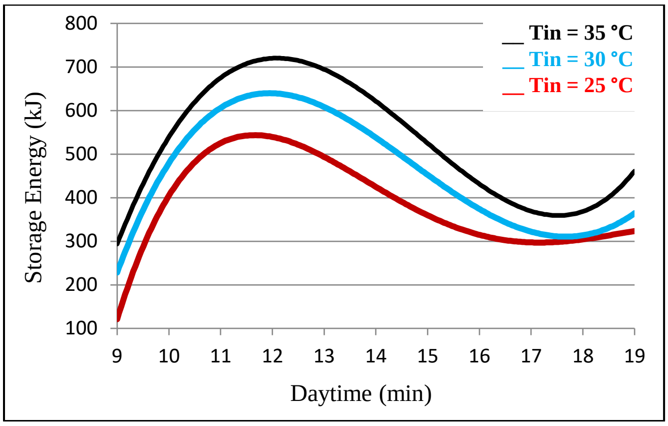

Fig. 18 Thermal storage for the storage tank with different inlet water temperature, Vin = 2 L/min, (1st May 2022).

Heat exchanger effectiveness with different months and daytime, V_{in} = 2 L/min, T_{in} = 25 °C is shown at Fig. 19. Maximum effectives reach 57 % at 1st June 2022 due to high solar intensity. The effeteness is enhanced about 10 % at the sunset time from the sunrise time.

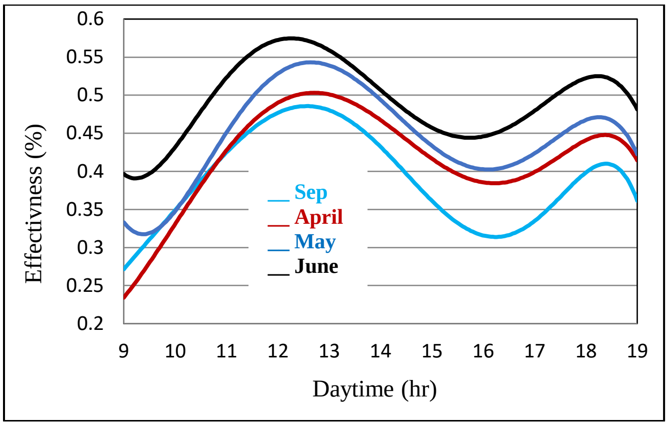

Fig. 19 Heat exchanger effectiveness with different month and daytime, V_{in} = 2 L/min, T_{in} = 25 °C.

Figure 20 shows the comparison results for heat exchanger effectiveness with and without PCM VS daytime, V_{in} = 2 L/min, T_{in} = 25 °C. 1st May 2022. The enhancement of PCM on the heat exchanger effectiveness reaches 18 % at sunset of May 2022.

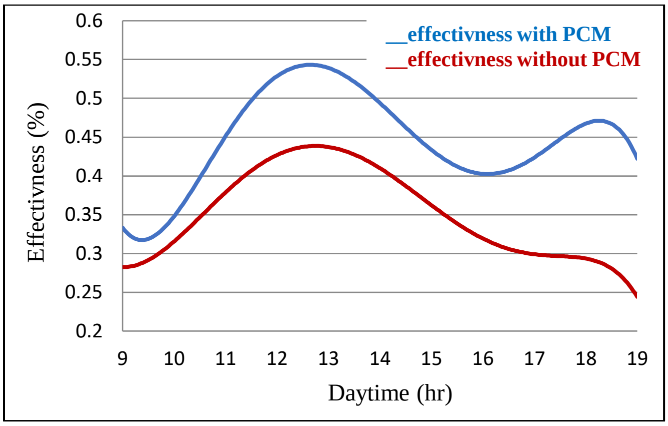

Fig. 20 Comparison results for heat exchanger effectiveness with and without PCM VS daytime, V_{in} = 2 L/min, T_{in} = 25 °C. (1st May 2022).

5. Conclusions

From the experimental investigation of the solar water heating improvement in Iraq climate conditions, the following conclusions can be extracted:

1. Both volumetric flow rate and inlet water temperatures play a great role to effect on the outlet collector temperature. The maximum value reaches more than 70 °C at midday of June.
2. The use of the PCM layer into the flat plate collector increases the outlet temperature of the water, compared to the collector without PCM. The maximum collector efficiency reaches to 58 % at high solar intensity.
3. The use of a PCM layer into the flat plate collector enhance the collector performance at sunset time.
4. The effectiveness of the heat exchanger is enhanced about 10 % at sunset time from sunrise time.
5. The enhancement of PCM on the heat exchanger effectiveness reaches 18 % at sunset of May 2022 when compared with storage tanks without PCM.

Nomenclature		
Symbol	**Description**	**Units**
A_s	Surface area.	m^2
C_p	Specific heat.	kJ/kg K
C_{pw}	The water specific heat.	kJ/kg K
D_i	Inner diameter.	mm
D_o	Outer diameter.	mm
FPSC	Flat plate solar collector.	-
HTF	Heat transfer fluid.	-
K	Thermal conductivity.	W/m K
LMTD	Logarithms mean temperature difference.	°C
m_w	Mass of water.	kg
PCM	Phase change material.	-
$Q_{storage}$	Thermal storage energy.	J
SWHC	Solar water heater collector.	-
TES	Thermal energy storage.	J
T_F	Fluid temperature.	°C
T_f	Final temperature.	°C
T_i	Initial temperature.	°C
T_{in}	Inlet temperature	°C
T_l	Liquid temperature.	°C
T_{PCM}	PCM temperature.	°C
T_s	Solid temperature.	°C
T_w	Water temperature.	°C
V_{in}	Volume of inlet water.	m^3
V_w	Volume of water in the storage tank per liter.	m^3
ΔT	Difference in water temperature is calculated for each time interval 1 hour.	°C
Greek Symbols		
Symbol	**Description**	**Units**
ρ	Density.	kg/m^3
ρ_w	Density of water	kg/m^3
β	Thermal expansion.	K^{-1}

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