Experimental study of a PCM storage system integrated with a thermal solar collector

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Abstract. Recently, phase change materials (PCM) have become widely used in thermal storage systems for both industrial and domestic applications. These materials have good thermal properties, like thermal capacity and phase change temperature, however low thermal conductivity and high viscosity limits their heat transfer coefficient. This paper experimentally investigates the execution of a water-PCM storage system integrated with a flat plate solar collector. Paraffin wax is used as the PCM material and is packed in small cylindrical aluminum containers and accommodated in a hot water tank. In this study, an experimental test facility was designed and built and experiments were carried out in the City of Kerbala in Iraq. The study includes two different heat source types, namely a flat-plate solar collector and an electrical heater element. Experimental results show that the proposed configuration with the PCM material can produce hot water with up to 9.5 °C higher than that of the basic warm water storage system. In the case of the flat plate solar collector, the water remained hot, at about 28.5 °C more than the surrounding temperature during the solar system tests. This study highlights the potential of using PCM materials in heat storage systems and thermal solar energy.

Keywords: Solar water heaters; energy storage; PCM; paraffin wax

1. Introduction.

Solar energy offers a solution to the problem of electricity in Iraq, as that country has good geographical features like high solar intensity and good annual levels of sunshine. The main characteristics of solar energy are that it is clean, cheap, and sustainable: so, this energy can be used in heating, cooling and hot water purposes in both domestic and commercial applications [1].

The amount of solar radiation is variable and obtainable only during the daytime. As a result, solar energy applications need active thermal energy storage so that the amount of thermal energy collected during the day can be stored and reused during the night. Hence, a heat storage system is required [2].

Thermal energy storage (TES) methods used in a thermal solar system can be divided into two categories:

- Sensible heat storage (SHS)
This system such as (water, rocks, and bricks) depends on heating storage material, where the amount of thermal storage store depends on the materials’ specified heat and the temperature difference between initial and final material conditions.

- Latent heat storage (LHS).

In this group, the thermal energy is stored by absorbing the energy (the latent heat of the fusion or evaporation) during the phase change process and then releasing the heat to return to the initial state.

The amount of energy stored in the LHS is very large if compared with the energy of SHS. The materials that store this energy are called phase change materials (PCMs). There are many types of PCM, but they are generally arranged into the three categories of organic, inorganic and eutectic.

Natural paraffin is a mixture of pure alkanes, with chemical formula CₙH₂ₙ₊₂, melt temperature range from 20 to 70°C, and the most widely-used PCM due to its advantages of a sufficiently high latent heat capability, limited volume changes through phase change, no sub-cooling effects, self-nucleating behavior, chemically stable, long freeze-melt cycle and availability at low cost. However, its thermal conductivity is low, therefore, heat transfer needs a large area [3][4].

Three techniques are utilized to harness the thermal conductivity of PCMs. The first uses macro-scale metallic inclusions, such as fins and meshes, to extended surface area for heat transfer. The second method uses macro-scale carbon inclusions, i.e. a porous material with high heat transfer capacity, and the third one uses nanoscale materials[5]. Among the most important factors used to select the PCM material are the liquefication point and the latent heat fusibility [6][4]. Choosing PCMs depends mainly on the application temperature level. Residential, and trade buildings usually use a hot water temperature of about 50 to 60°C. As a result, the PCM melting point must range between 40 and 50°C [7].

Many researchers have studied the effects of phase-changing materials and their thermophysical properties in many industrial, domestic and commercial applications. Olubunmi, 2017 [1] deliberated the impact of PCM on a solar water system containing commercial wax with a melting point of 45°C. Experimental tests showed that a higher maximum daily water temperature can be achieved with PCM, compared with the absence of PCM. Pakalka, et al. 2017 [4] studied experimentally the main parameters that affect the rendering of a PCM storage system (paraffin with melting temperature 77–82°C) including the geometry and the thermic possessions of the PCM container. Depending on the temperature range of application, it may be possible to increase the heat transfer area by inserting a set of fins inside the PCM, although there is a defect in this method which is a reduction in the ability of the PCM to store energy.

Chaichan, et al. 2014 [8] improved the thermal storage obtained for a solar heater used for the household applications, and in this study, pebbles were used as sensible storage material, while the latent heat storage substance used paraffin wax. The use of these materials led to increased system efficiency in heat storage and storage hours increased; however, the PCM material was more efficient than the pebbles. Reddy, et al. 2014 [9] experimentally investigated use of Na2S2O3·5H2O as a PCM with melting temperature 480°C Packed in stainless steel capsules in various forms including spherical, cylindrical and square capsules. The results produced from this study showed that when the flow rate or temperature of the incoming water increased, the charging time decreased.
Division, 2015 [10] studied melting/freezing issue of the PCM. Spiral thermal energy as the heat exchanger and pure paraffin wax as PCMs were used. Results showed that the geometry of the storage system affected on the PCM heat transfer rate. It is noted as the number of heat exchangers filled with PCM increased, the overall efficiency of the thermal storage system increased. Xue, 2016 [11] considered the thermal rendering of a household solar water heater and tested the mass flow rate effect. The amount of solar radiation and the primary water temperature had an effect on system performance. If global radiation increased and water temperature decreased, the system was more efficient and vice versa. Naeem, et al. 2016 [12] studied experimentally the charging and discharging processes in a thermal storage system using a PCM. Spherical capsules with paraffin wax (liquefaction point 58 °C) were utilized. The PCM capsules were packed in four fixed bed layers in a cylindrical tank. The results produced from this study showed that the storage time decreased when the mass flow rate increased.

Kumar et al. 2016 [13] designed a hot water tank with two parts. The first part contained cold water and attached with the inlet and the second part contained a spiral copper tube surrounded by PCMs. This research used a coconut oil as a phase change substance because it was freely available and cheap. Experimental results showed that the mass flow rate had a significant effect on the system temperature difference. Also, ANSYS modeling showed that a 16% reduction in heating time could be achieved. Kane, et al. 2016 [14] studied experimentally an indoor test facility to analyze the dynamic behavior of a hot water storage tank. It contained three packs of 3-liter units filled with PCM (melting temperature 58°C). Experimental tests showed the advantages of using PCMs as a storage medium.

Profile, 2017 [15] experimentally improved the thermal transfer of phase change materials during loading and unloading operations by adding materials with high thermal conductivity, such as copper. That study used paraffin wax with a soft temperature of 63.7 °C. Experimental tests showed that the addition of the brush to the PCM greatly improved heat transfer within this material and lessened the solubility time to (90%) compared to the absence of a brush. Nasir et al. 2018 [16] researched numerically and empirically the melting processes of 12 kg of black pure paraffin in a shell and tube heat exchanger, utilizing solar thermal energy. Experimental results showed that increasing heliacal radiance and air ambient temperature minimized the thaw timing of black pure paraffin; the entry line, and air temperatures had a big effect on the fusion approach match with the volume flow rates. Numerical results showed that the temperature distribution of black pure paraffin gave perfect effectiveness.

In this study, we used paraffin wax (which was packed into small cylindrical vessels with a volume of about 0.3 liters each) in a heating storage system joined with a solar warming water system in the city of Kerbala, Iraq. Kerbala has a latitude of 32.5 ° N, and longitude of 44.3 ° E. Experiments were carried out outdoors using two cases. In the first case a flat plate solar collector was used as a heat source while in the other, a heater element was used as an external heat source.

2. Experimental investigation.

The copper absorbing plate has dimensions of 1 m, 0.85 m, and 0.001 m and it was painted in a black paint with absorption of 0.9, to increase the portion of solar radiance realized by the plate and to diminish long wavelength radiation losses from the absorbing surface. The absorber plate was surrounded by a wooden box and it was insulated with glass wool from the bottom and sides by 10 cm, 5 cm thickness respectively to reduce the conduction losses. Two copper headers had a diameter of 20 mm and were 97 mm long, and ten copper risers had 10mm diameter and were 96 mm long.
A cylindrical steel storage tank with a capacity of 49 liters was used, 750 mm high and 285 mm inner diameter. It was sheltered with 100 mm glass wool. The tank contained 32 thin cylindrical containers made of aluminum. These containers were chosen to reach a relatively large heat transmitting surface area and to reduce the thermal resistance between the PCM material and the fluid that conveys heat. The container capacity was 0.3 liters and it was filled with 0.2 kg of paraffin wax. The PCM containers were placed inside the water tank and gathered on two rows, with the assistance of two metal clips that were pre-drilled, each containing 16 containers. The thermo-physical properties of the paraffin wax are listed in Table 1. A 1000-Watt electric heater was connected to the lower section of the storage tank.

| No. of thermocouple | Location                     |
|---------------------|------------------------------|
| 1,2,3               | Top surface of riser tube    |
| 4,5                 | Absorber plate               |
| 6                   | Air gap between the plate and glass |
| 7                   | Inlet tube                   |
| 8                   | Outlet tube                  |
| 9                   | Ambient                      |
| 10,11               | Water temperature in the tank|
| 12                  | The temperature of pcm       |

The temperature recording and measuring system included thirteen thermocouples of type K that had been pre-calibrated. One on the inlet tube and one on the outlet tube of the collector, two thermocouples of which one was in the upper and the other in the lower section of the water tank, to calculate the average water temperature. One thermocouple was inserted into one of the PCM ampules at the central section of the tank, and one used to measure the surrounding air temp, two were on the absorbing plate, to calculate the average absorbing plate temperature, three thermocouples were on raiser pipes, and one thermocouple at the air gap between the plate and glass.
Figure 1. Schematic of network thermocouple distribution in the solar collector.

A standard 0.37 Kw circulation pump, with maximum amplitude 32 Lpm, was used to force circulation, and to change the volumetric rate of water (1, 3, 5 Lpm).

Figure 2. Schematic of storage tank

Figure 3. Schematic of solar hot water.
2.1 Energy balance
The beneficial energy transformer from solar radiation to useful heating energy as in Equation (1).

\[ Q_w = m_w \, c_{pw} \, \Delta T = Q_u \]  

(1)

where \( m \) = Mass flow rate of water \((\text{kg/s})\), \( c_{pw} \) = Specific heat of water \((\text{J/kg} \, ^\circ \text{C})\) and \( \Delta T \) = Temperature different of water \((^\circ \text{C})\), \( Q_u \) = heat gain \((\text{W})\).

The efficiency of the collector is one of the most important factors in evaluating the solar collector’s performance, which can be defined as the ratio between the useful energy gained in a period and the solar energy incident on the collector during the same time as in Equation (2).

\[ \eta = \frac{\int Q_u \, dt}{A_C \int I \, dt} \]  

(2)

\( \eta \) = Overall efficiency (%) , \( A_C \) = Collector absorbing plate area \((\text{m}^2)\).

\( I \) = solar radiation which is incident on the Collector \((\text{W/m}^2)\).

The heat removal factor is a coefficient that expresses the amount of heat transferred to the working fluid relative to the amount of heat absorbed by the absorbing plate.

\[ Fr = \frac{Q_u}{A_C \int (T_p - \tau) \, dt} \]  

(3)

\( Fr \) = Heat removal factor.  \( \tau \) = Glazing transition coefficient.  \( U_L \) = Overall heat loss coefficient \((\text{w/m}^2 \, ^\circ \text{C})\).

\( T_p \) = the mean absorber plate temperature \((^\circ \text{C})\).  \( T_a \) = Ambient temperature \((^\circ \text{C})\).

3. Results and discussion

3.1 Use of the solar system
The PCM’s performance has been tested in the storage tank under real operating conditions. The performance of solar domestic hot water systems depends on the local climatic conditions, such as solar radiation and ambient temperature. The measurements of solar radiation and temperature within the flat solar complex and the storage tank were recorded using specialized measuring instruments and a 10-minute interval between readings and from 9:00 am to 3:00 pm from 15 to 30 March 2019.

Initially the system was run in the absence of PCM \((32 \text{ L water only})\), to measure the amount of heat that the water could store, the temperatures that it reached and the duration of the time for which this water would remain hot, as well as the efficiency of the solar collector and the amount of coefficient of heat removal.

Then we re-tested the system with a variable flow rate of water by controlling the flow valves and observing the flowmeter.
Figure 4. The temporal variation of the average water temperature in the storage tank without PCM with variable flow rate.

Figure 5. The useful thermal energy with daylight time at a variable flow rate.

The effect of increasing the volumetric rate in the difference between the inlet and outlet water temperatures of the collector was evident. At the larger volumetric flow rate the water temperature outlet of the collector was less. Figure 4 shows that water temperature in the storage tank rose faster when the water flow rate increased. This is most evident in Figure 5, which shows the heat gained by the water. The amount of heat gained was greatest at 12:30 pm with a volumetric flow rate of 5 liters per minute.

The effect of increasing the volumetric flow rate on the difference between the inlet and outlet water temperatures of the collector, overall efficiency, and heat removable factor are shown in Table 3.

| volume flow rate | Maximum\((T_o-T_i)\) ⁰C | overall efficiency \(\eta\) % | Collector heat removal factor \(F_R\) |
|------------------|--------------------------|--------------------------------|----------------------------------|
| 1 L/m            | 5.8                      | 43.9                           | 0.693                            |
| 3 L/m            | 3.1                      | 61.46                          | 0.814                            |
| 5 L/m            | 2.1                      | 67.83                          | 0.91                             |
The same test was conducted under similar surrounding conditions with using 32 cylindrical containers containing 0.2 kg of paraffin wax (6.4 kg PCM) at ratio 70 % water 22.4 L, 30 % PCM 9.6 L. Figure 6 shows that the water temperature rose faster than PCM at the beginning of the heating period, where the material was in the solid phase, and then at a temperature of about 42 °C (which is close to the liquefaction temperature stated in Table 1) the PCM material’s temperature slightly increased until it reached 47 °C for a period time. This is because PCM at this stage undergoes a phase change and therefore absorbs large amounts of heat at a constant temperature. Then, the PCM temperature starts to rise at a quicker rate, to catch up with the water temperature, and then exceeds it before reaching the end of the heating stage. After 3:00 pm, the pump was turned off, and thus began the loss of heat from the tank, so that the temperature of the water was less than the temperature of the PCM by 1-2 degrees and continued until the end of the experiment at eight o’clock the next morning. During this stage, the PCM continued to release the stored heat into the water, keeping the water hot for a longer period of time.

Figure 6. The average water temperature, PCM temperature, and the ambient temperature vs time.

Figure 7 shows the main advantage that was obtained from using the PCM in this study, as it is clear that the water temperature using PCM was higher than that without PCM by about 9.5 °C. This is most obvious in Figure 8, which shows the final water temperatures with and without PCM.
Regarding Figure 8, we note the benefit of using PCM to keep the water warm at a higher temperature than in the absence of PCM, as well as the effect of increased flow rate. The difference in temperature was the highest value (9.3 °C) at the flow rate 5 liters per minute. Figure 9 shows that the water remained hot, at about 28.5 °C more than the surrounding temperature. Table 4 shows the improvement in hot water temperature during solar system tests.

**Table 4.** The improvement in hot water temperature solar system tests.

| Volume flow rate (Lpm) | Improved water temperature |
|------------------------|----------------------------|
| 1                      | 19.95 %                    |
| 3                      | 22.47 %                    |
| 5                      | 23.1 %                     |

### 3.2. Storage performance with external heat source

In this state, the storage water tank was isolated from the solar collector by closing the input and output line valves. The electric heater was turned on for two hours to heat the water to the highest temperature, from 9:00 am to 11:00 am. Then, the heater was switched off and we continued recording the water temperature measurement for another 22 hours.
Figure 10. The temporal variation of the average water temperature in the storage tank, with and without PCM.

Figure 11. The temporal variation of the difference in temperature between the tank water and the ambient, with and without the PCM containers.

Figure 10 shows average tank water temperatures with and without using PCM. We notice that the water warms faster in the absence of PCM due to the large volume of the heat absorbed by the PCM. The maximum tank water temperature at 11:00 am reaches 76.5 °C, 71.9 °C without and with PCM respectively, the advantage obtained by using the PCM is that of keeping the water temperature higher (by about 7.5 °C) than was the case without PCM. Figure 11 shows that the water remained hot, at about 27.9 °C more than the surrounding temperature, as a result of using PCM.

3.3. Comparison with similar work

To make sure that the results of our research were correct, we compared them to a similar study by Al-Hinti, et al. 2010 [17]. That research was conducted in Jordan during April 2008, the author used a 107-liter iron tank containing 38 vessels of aluminum with a volume of 1.3 liters filled with 1 kg of wax, which dissolves at 52 °C. The total amount of wax was 38 kg. The volume of wax bottles accounted for 46% of the tank and 54% of the volume of the water. The water tank was heated by 2000 watt for 3 hours, and the highest water temperature was 76 °C. Results showed that water temperature using paraffin wax was 13 °C higher than that of water alone, and the water remained at a level of 36 °C higher than the surroundings. In the present work, 6.4 kg of paraffin wax was used, and the volume of wax bottles accounted for 30% of the volume of the tank. The main advantage of the current work is the maintenance of a higher water temperature (by about 7.5 °C) than that without PCM. Also, the water remains hotter, about 27.9 °C above the ambient temperature. Figure 12 illustrates this comparison. The difference in results between the current work and previous work [17] is due to the different amounts of paraffin wax and different packaging size used in the experiments, and the effect of totally different weather conditions.
4. Conclusion

An experimental test facility, of a water PCM storage system integrated with a flat plate solar collector, was designed and built under the climate conditions of the city of Kerbala in Iraq to improve the performance of both the storage system and the solar collector for residential and commercial applications.

The main results of this study can be listed as:

- The use of PCM in the storage of solar thermal energy has proved to be an effective solution to reduce fossil energy consumption and to permit greater reliance on solar energy.
- Excess heat can be stored in a PCM during the day in the form of latent heat, and used at night to keep the water warm and suitable for use in all household applications.
- As the volume flow rate decreased, the outlet collector water temperature increased.
- Use of the proposed configuration (with PCM) provided 9.3 °C in stored hot water temperature, the storage water temperature remained higher at 28.5 °C above ambient temperature.
- The improvement in hot water temperature during the solar system tests was 23.1 %.

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