Utilization of paraffin wax as phase change material for solar thermal energy storage

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Abstract

In this work, a thermal energy storage system based paraffin wax as phase change material (PCM) was designed, constructed and tested when it was integrated with a solar water heater (SWH). For the purpose of comparison, the SWH was also tested when water was used as a storage medium. The system was tested for successive days at different mass flow rates of the heat transfer fluid varied from 0.08 to 0.16 kg/s. The maximum energy stored in 110 kg of water used as storage material is 15.9 MJ/day, compared to 11.9 MJ when 50 kg of paraffin wax was used as storage material. This means that the PW not only capable of store 75% of the energy stored in water per day but also it achieves a 50% reduction in the storage volume. The low storage temperature gives also more superiority to the wax as storage material especially in the domestic application where just warm temperature is needed.

Keywords: solar water heater, PCM, paraffin wax, energy storage

1. Introduction

The solar water heater integrated with insulated water storage tank is commonly used in most heating applications. On the other hand, the phase change materials are used in certain applications that needs constant temperature. Many PCMs were used for thermal energy storage such as paraffin wax (PW) (Desgrosseilliers et al. 2011; El Qarnia 2009; Mazman et al. 2009; Wang et al. 2017; Korti and Tlemsani 2016; Kanimozhi, Ramesh Bapu, and Pranesh 2017; Meng and Zhang 2017; Liang et al. 2017; Fazilati and Alemrajabi 2013; Al-Hinti et al. 2010; de Gracia and Cabeza 2015; López-Navarro et al. 2014), stearic acid (El Qarnia 2009; Sari and Kaygusuz 2001), palmitic acid (Sari and Kaygusuz 2002) and myristic acid (Sarı and Kaygusuz 2001) which are considered organic compounds. These organic materials showed superior performance compared with other PCMs used within solar water heater (SWH) (Dincer and Rosen 2002; Zalba et al. 2003) due to their low cost, high capacity for storing energy, and appropriate melting temperature. Amongst all PCMs, PW has many privileges like stability of material construction for long time, not poisonous, and cheap (Daystar et al. 2015; Vasu et al. 2017; Yousef and Hassan 2019; Macauley et al. ; Kabeel et al. 2016; Shalaby and Bek 2014). (Chen et al. 2020) studied the PW as PCM in an experimental and numerical investigation for solar thermal storage applications. However, PW has some disadvantages like low thermal conductivity, and problem of leakage because of PW volume increase at melting. Many innovative designs of LHSS using organic compounds (mostly PW) are introduced to issue that weakness. These novel designs include using spherical capsules (Fazilati and Alemrajabi 2013), cylindrical bottles (de Gracia et al. 2011), vertical pipes (López-Navarro et al. 2014), bottles (Al-Hinti et al. 2010), and balls (Zhou et al. 2018) filled with PW contained by the storage tank. Also, using fins inside the PW introduce a solution for the low thermal conductivity of PW by providing a large heat transfer area. This fins was studied by (Mahfuz et al. 2014) and (Badiei, Eslami, and Jafarpur 2020), they found that overall system daily efficiency increased by 13.3%.

So, in this work, a LHSS based paraffin wax as storage material was studied when it integrated with SWH. The utilization of water as storage material was also investigated. The results showed that PW not only capable of store 75% of the energy stored in water per day but also it achieves a 50% reduction in the storage volume.

2. Thermal energy storage equations

In this section, all equations used for calculating the energy stored in all systems are presented:

The storage energy in water (Qw-s) is given by (Shi et al. 2018; Al-Kayiem and Lin 2014);

$$Q_{w-s} = m_{w-s} C_w (T_f - T_i) \quad (1)$$

Where mw-s is the water quantity in the storage tank (kg), Cw is the specific heat of water (J/kg. ºC), Tf is the final temperature of water (˚C), and Ti is the initial temperature of water (ºC).

The storage energy in the PCM (QPCM) is given by (Al-Kayiem and Lin 2014; Shukla, Buddhi, and Sawhney 2009);

$$Q_{PCM} = m_{pcm} C_{pcm} (T_{pcm-f} - T_{pcm-i}) + L m_{pcm} \quad (2)$$

Where mpcm is the mass of the PCM (kg), Cpcm is PCM specific heat (J/kg ºC), Tpcm-f is the final temperature of the PCM (˚C), and Tpcm-i is the initial temperature of PCM (˚C) and L is the latent heat of the PCM (J/kg).

3. Experimental setup and measuring devices

The SWH that has a copper collector with an area of 2.5 m² was connected to the LHSS as shown in Fig. 1. A small water pump was used to circulate the HTF (tab water) through the SWH then flowed across the LHSS. The flow rates were controlled and measured using valves and flow-meters, respectively. Also, the air vent and pressure relief valves were integrated with the HTF loop to empty the loop from air bubbles and forbid sudden pressure increase inside the tubes, respectively. The test rig was used in two cases, first, a small pump was utilized to rotate the HTF between the SWH and the water storage tank on successive days of August 2018 at different $m^{\cdot}_{HTF}$ (0.08, 0.1, 0.12, 0.14, 0.16 kg/s) when 110 kg of water was used as storage material. While in other cases 50 kg of PW as PCM was used to store the thermal energy instead of water when the $m^{\cdot}_{HTF}$ equal 0.14 Kg/s. The storage system consists of an insulated storage tank filled with the storage material. The heat transferred from SWH to the PCM using 3 groups of copper tubes, each one consists of 8 tubes. Each group of tubes attached with about 70 longitudinal aluminum fins. All these tubes are connected in series. All experiments were started at 8:00 am and ended at 6:00 pm (sunset). DS-digital temperature sensors are used to measure the temperatures of HTF at the inlet $T_{HTF,in}$ and outlet $T_{HTF,out}$ of the system. The properties of the PW used in this study are summarized in Table 1. Four temperature sensors are immersed in the PCM to measure the temperature of the PCM at different positions, then the average value is calculated and sampled as T_{PCM}.

Table 1. The properties of PW

Latent heat (kJ/kg)	190
Specific heat (J/kg. K)	2110
Melting point (ºC)	63.5
Density (kg/m^3)	900

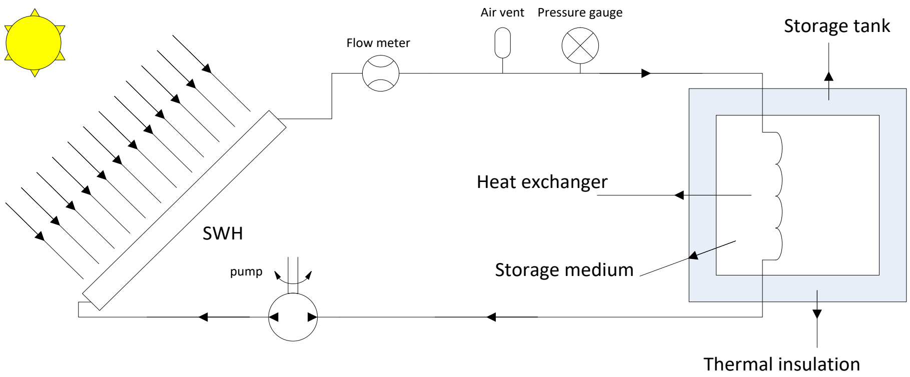

Figure 1. Schematic diagram of the solar collector with LHSS.

4. Results and discussions

The proposed system tested at many values $m^{\cdot}_{HTF}$ during successive days of August 2018 (31/7/2018 to 7/8/2018). The temperature of storage water T_{w-s} and HTF temperature at the inlet of storage tank $T_{HTF,in}$ measured on 5 August 2018 when the $m^{\cdot}_{HTF}$ equals 0.14 kg/s are shown in Fig. 2.

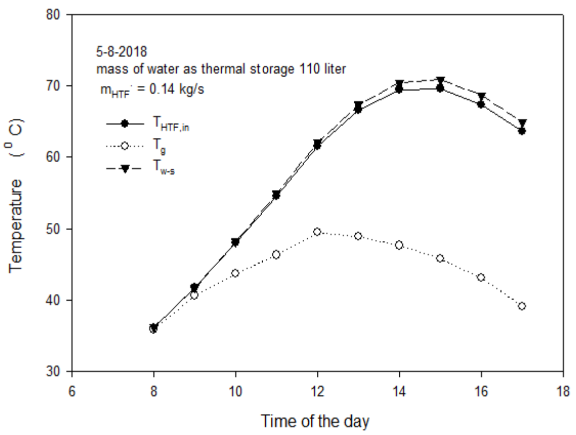

Figure 2. The variation of HTF, water, and glass cover temperatures during a typical day of August 2018.

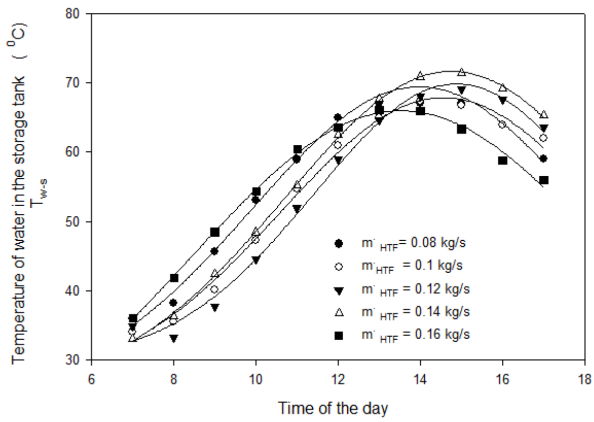

Figure 3. The variation of storage water temperature versus time at a different mass flow rate of HTF.

The temperature of the SWH glass cover is also displayed in Fig. 2. From the results indicated in Fig. 2, the maximum temperature of the HTF is 71 ˚C measured at 3:00 pm, with two hour lag from solar radiation peak. Beyond this time, it gradually decreases to reach 63 ˚C at the sunset. The same attitudes were noticed for the temperature of SWH glass cover (T_g) and the temperature of the HTF at the inlet of the water storage tank except that the maximum value T_g is measured at 12:00 am simultaneous with the solar radiation due to the low heat capacity of the glass cover. The maximum values of T_g and T_{w-s} are found to be 56 and 71 ˚C, respectively. The temperature of water in the storage tank measure at different $m^{\cdot}_{HTF}$ is seen in Fig. 3. The maximum value of the Tw-s of 71 ˚C is achieved when the $m^{\cdot}_{HTF}$ is 0.14 kg/s followed by 69 ˚C when the $m^{\cdot}_{HTF}$ is 0.12 kg/s. The lowest value of Tw-s of 66 ˚C is recorded when the $m^{\cdot}_{HTF}$ is 0.16 kg/s as represented in Fig. 4.

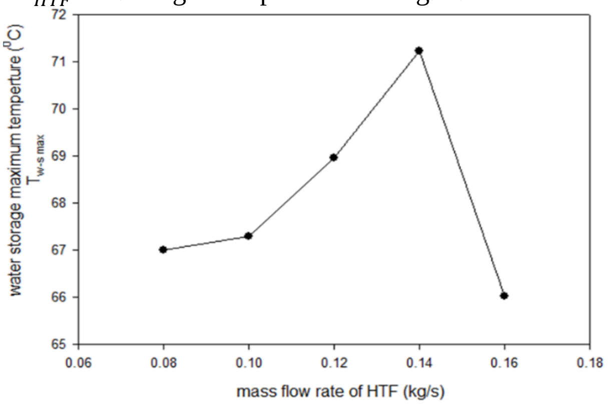

Figure 4. The variation of storage water maximum temperature versus mass flow rate of HTF.

Figure 5 shows the increment in water storage temperature from its starting value when the $m^{\cdot}_{HTF}$ is changed from 0.08 to 0.16 kg/s with the increment step equals 0.02 kg/s. Increment in water temperature across the water storage tank of 35 ˚C is achieved when the $m^{\cdot}_{HTF} = 0.14$ kg/s. This happens because of a large quantity of heat is turned from the HTF to the tank at higher values of $m^{\cdot}_{HTF}$ to a certain point when it became larger of this point it had reverse behavior that makes heat transfer low again. The highest value of Tw-s achieved at the peak value $m^{\cdot}_{HTF}$ is also support this explanation. The lowest values of increment in water temperature are found when the lowest and highest value $m^{\cdot}_{HTF}$ is used as obviously displayed in Fig. 5. From the results of Fig. 5 the maximum energy stored in the water as storage material was calculated as 15.9 MJ/day.

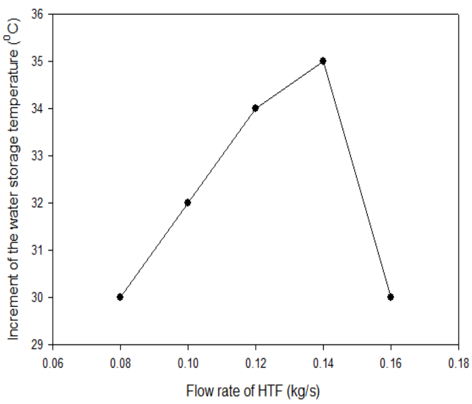

Figure 5. The increment of storage water temperature versus the flow rate of HTF.

To compare between the PCM and water as storage material, the SWH integrated with PCM is tested at when the $m^{\cdot}_{HTF} = 0.14$ at which the optimum performance is achieved when the water was used as storage material. The temperature of HTF at the inlet of the LHSS and PCM measured when the $m^{\cdot}_{HTF}$ equals 0.14 kg/s are shown in Fig. 6. The temperature of the SWH glass cover is also displayed in Fig. 6. The maximum measured value of solar radiation during this day is 980 W/m2 measured at 12:00 am. Whereas; the maximum ambient temperature of 34 ˚C is recorded during the period from 1:00 to 2:00. From the results indicated in Fig. 6, the temperature of the HTF increases to 68 ˚C at 1:00 pm, with one hour lag from solar radiation. Beyond this time, it gradually decreases to reach 55 ˚C at the sunset. The same attitudes were noticed for the temperature of SWH glass cover (T_g) and the temperature of PCM (T_{pcm}) except that the maximum value T_g is measured at 12:00 am simultaneous with the solar radiation due to the low heat capacity of the glass cover. The maximum values of T_g and T_{pcm} are found to be 33 and 68 ˚C, respectively.

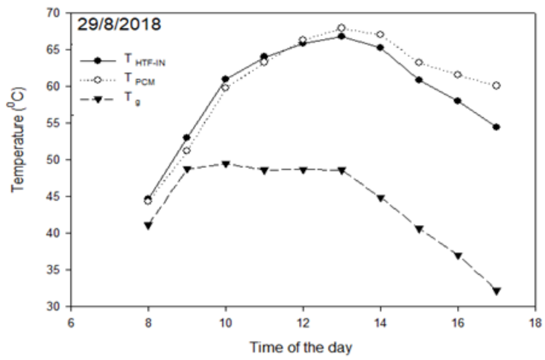

Figure 6. The variation of HTF, PCM, and glass cover temperatures during a typical day of August 2018.

Figure 7 shows the comparison between the temperature of the PCM and water used as a thermal storage measure at $m^{\cdot}_{HTF}$ equal 0.14 kg/s. From the results illustrated in Fig. 7. It is noticed that the PCM temperature increases more than the water temperature until 1 PM; this happens because of the low specific heat of the PCM compared to the water specific heat. After this time, the temperature of the water increase more than the PCM temperature; and this happens because at this point the storage medium in both cases reaches about 63.5 °C which is the point of melting the PCM. So the huge latent heat of the PW makes the energy given to the PCM is stored inside it without raising the temperature of the PCM. While the water at this point does not reach the evaporation point of water so it continues to raise the temperature of the water.

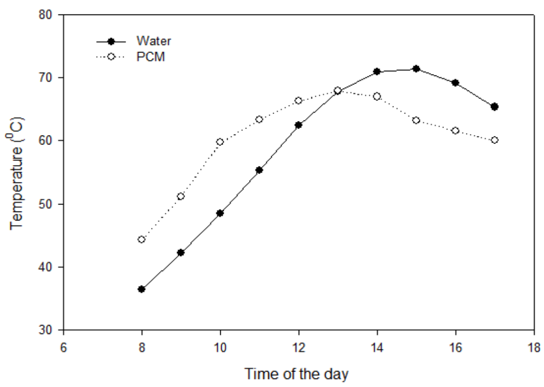

Figure 7. Comparison between the temperature of the PCM and water as thermal storage material.

From the results illustrated in Fig. 7, the maximum energy stored in the PCM is calculated as 11.9 MJ which is 75% of the energy stored in water as thermal storage material. The PW not only capable of store 75% of the energy stored in water but also achieves a 50% reduction in the storage volume. The low storage temperature gives also more superiority to the PW as storage material especially in the domestic application where just warm temperature is needed.

5. Conclusions

From the experimental results presented in this work, the optimum performance of the thermal storage system is obtained when $m^{\cdot}_{HTF}$ equals 0.14 kg/s when water was used as energy storage material. It is also found that the PW is capable of store 75% of the energy stored in water with only 50% of storage volume.

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References:

Al-Hinti, I., A. Al-Ghandoor, A. Maaly, I. Abu Naqeera, Z. Al-Khateeb, and O. Al-Sheikh, (2010), Experimental investigation on the use of water-phase change material storage in conventional solar water heating systems, *Energy Conversion and Management*, 51, 1735-40.

Al-Kayiem, Hussain H, and Saw C Lin. (2014), Performance evaluation of a solar water heater integrated with a PCM nanocomposite TES at various inclinations, *Solar Energy*, 109, 82-92.

Badiei, Z, M Eslami, and K Jafarpur, (2020), Performance improvements in solar flat plate collectors by integrating with phase change materials and fins: A CFD modeling, *Energy*, 192, 116719.

Chen, Guijun, Yunpeng Su, Dongyue Jiang, Lujun Pan, and Shuai Li, (2020), An experimental and numerical investigation on a paraffin wax/graphene oxide/carbon nanotubes composite material for solar thermal storage applications, *Applied Energy*, 264, 114786.

Daystar, Jesse Sky, Trevor Treasure, Ronalds Gonzalez, Carter Reeb, Richard Venditti, and Steve Kelley, (2015), *The NREL Biochemical and Thermochemical Ethanol Conversion Processes: Financial and Environmental Analysis Comparison*.

de Gracia, A., E. Oró, M. M. Farid, and L. F. Cabeza, (2011), Thermal analysis of including phase change material in a domestic hot water cylinder, *Applied Thermal Engineering*, 31, 3938-45.

de Gracia, Alvaro, and Luisa F. Cabeza, (2015), Phase change materials and thermal energy storage for buildings', *Energy and Buildings*, 103, 414-19.

Desgrosseilliers, L., Robynne Murray, A. Sefati, G. Marin, J. Stewart, Nick Osbourne, M. A. White, and Dominic Groulx, (2011), *Phase Change Material Selection in the Design of a Latent Heat Energy Storage System Coupled with a Domestic Hot Water Solar Thermal System*.

Dincer, Ibrahim, and Marc Rosen, (2002), *Thermal energy storage: systems and applications* (John Wiley & Sons).

El Qarnia, Hamid. (2009), Numerical analysis of a coupled solar collector latent heat storage unit using various phase change materials for heating the water, *Energy Conversion and Management*, 50, 247-54.

Fazilati, Mohammad Ali, and Ali Akbar Alemrajabi, (2013), Phase change material for enhancing solar water heater, an experimental approach, *Energy Conversion and Management*, 71, 138-45.

Kabeel, AE, A Khalil, SM Shalaby, and ME Zayed, (2016), Investigation of the thermal performances of flat, finned, and v-corrugated plate solar air heaters, *Journal of Solar Energy Engineering*, 138, 051004.

Kanimozhi, B., B. R. Ramesh Bapu, and Venkat Pranesh, (2017), Thermal energy storage system operating with phase change materials for solar water heating applications: DOE modelling, *Applied Thermal Engineering*, 123, 614-24.

Korti, Abdel Illah Nabil, and Fatima Zohra Tlemsani. (2016), 'Experimental investigation of latent heat storage in a coil in PCM storage unit', *Journal of Energy Storage*, 5, 177-86.

Liang, Fei, Yin Zhang, Qinjian Liu, Zhenghao Jin, Xinhui Zhao, and Enshen Long, (2017), Experimental Study on Thermal Energy Storage Performance of Water Tank with Phase Change Materials in Solar Heating System, *Procedia Engineering*, 205, 3027-34.

López-Navarro, A., J. Biosca-Taronger, J. M. Corberán, C. Peñalosa, A. Lázaro, P. Dolado, and J. Payá, (2014), Performance characterization of a PCM storage tank, *Applied Energy*, 119, 151-62.

Macauley, Jeffrey, Jake Shaw, Edwin Beraud, and Will Legrand. 'Project 4-Red Feather Thermal Energy for Homes Preliminary Report'.

Mahfuz, M. H., M. R. Anisur, M. A. Kibria, R. Saidur, and I. H. S. C. Metselaar, (2014), Performance investigation of thermal energy storage system with Phase Change Material (PCM) for solar water heating application, *International Communications in Heat and Mass Transfer*, 57, 132-39.

Mazman, Muhsin, Luisa F. Cabeza, Harald Mehling, Miquel Nogues, Hunay Evliya, and Halime Ö Paksoy, (2009), Utilization of phase change materials in solar domestic hot water systems, *Renewable Energy*, 34, 1639-43.

Meng, Z. N., and P. Zhang, (2017), Experimental and numerical investigation of a tube-in-tank latent thermal energy storage unit using composite PCM, *Applied Energy*, 190, 524-39.

Sari, Ahmet, and Kamil Kaygusuz, (2002), Thermal performance of palmitic acid as a phase change energy storage material, *Energy Conversion and Management*, 43, 863-76.

Sari, Ahmet, and Kamİl Kaygusuz. (2001), Thermal energy storage system using stearic acid as a phase change material, *Solar Energy*, 71, 365-76.

Sarı, Ahmet, and Kamil Kaygusuz, (2001), 'Thermal performance of myristic acid as a phase change material for energy storage application', *Renewable Energy*, 24, 303-17.

Shalaby, SM, and MA Bek, (2014), Experimental investigation of a novel indirect solar dryer implementing PCM as energy storage medium, *Energy Conversion and Management*, 83, 1-8.

Shi, Juan, KaiWei Lin, ZhenQian Chen, and Hao Shi, (2018), Annual dynamic thermal performance of solar water heaters: A case study in China's Jiangsu Province, *Energy and Buildings*, 173, 399-408.

Shukla, Anant, D. Buddhi, and R. L. Sawhney, (2009), Solar water heaters with phase change material thermal energy storage medium: A review, *Renewable and Sustainable Energy Reviews*, 13, 2119-25.

Vasu, Anusuiah, Ftwi Y Hagos, MM Noor, R Mamat, WH Azmi, Abdul A Abdullah, and Thamir K Ibrahim, (2017), Corrosion effect of phase change materials in solar thermal energy storage application, *Renewable and Sustainable Energy Reviews*, 76, 19-33.

Wang, Yong, Xun Yang, Teng Xiong, Wenxin Li, and Kwok Wei Shah. (2017), 'Performance evaluation approach for solar heat storage systems using phase change material', *Energy and Buildings*, 155, 115-27.

Yousef, Mohamed S, and Hamdy Hassan, (2019), Energetic and exergetic performance assessment of the inclusion of phase change materials (PCM) in a solar distillation system, *Energy conversion and management*, 179, 349-61.

Zalba, Belén, José M. Marín, Luisa F. Cabeza, and Harald Mehling, (2003), Review on thermal energy storage with phase change: materials, heat transfer analysis and applications, *Applied Thermal Engineering*, 23, 251-83.

Zhou, Zhihua, Junwei Liu, Chendong Wang, Xin Huang, Feng Gao, Shuzhen Zhang, and Bing Yu, (2018), Research on the application of phase-change heat storage in centralized solar hot water system, *Journal of Cleaner Production*, 198, 1262-75.