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Original scientific paper*

A COMPARATIVE STUDY OF SENSIBLE AND LATENT THERMAL STORAGE TECHNOLOGIES COUPLED TO FLAT PLATE SOLAR COLLECTORS

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Abstract. *Storage systems are important technologies that aid renewable energy sources in increasing their penetration in the energy grid and making them sustainable choices. Solar thermal collectors need thermal storage devices in order to store heat for short or long periods. This paper investigates two of the most usual thermal storage systems coupled to a classical flat plate solar collector. More specifically, the sensible storage with a water tank and the latent storage tank with phase change materials (PCM) are studied in this paper. Energy and exergy investigations are performed for different operating temperature levels. The system is monitored daily with both storage technologies. The results show that the use of PCM is more efficient energetically for all studied scenarios. On the other hand, the use of sensible storage leads to higher exergy performance due to the temperature increase of the stored water, especially for the scenarios with lower initial temperature levels in the storage tank in the morning. It is useful to state that the daily energy efficiency with the latent storage ranged from 21.9% to 69.1%, and the sensible storage from 14.2% to 55.3%. Furthermore, the exergy efficiency ranged from 1.23% to 5.64% for the latent storage, and from 3.99% to 7.53% for the sensible storage. Also, it must be pointed that the optimum temperature for the phase change material is 75℃, while the optimum initial temperature in the water storage tank is 40℃. These results indicate that PCM can be a beneficial choice for applications of high temperatures, such as solar cooling systems with absorption or sorption machines.*

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1. INTRODUCTION

Exploitation of renewable energy sources is one of the most promising techniques for facing the recent energy problems and achieving sustainable development goals [1]. Solar energy is one of the most used renewable energy sources due to its high abundance and it can be converted into useful thermal energy with high efficiency [2]. A flat plate collector (FPC) is the most usual and mature solar thermal collector for low-temperature applications up to 100ºC [3]. These systems are used for space heating, domestic hot water production, desalination, solar cooling with sorption machines (absorption or adsorption) and low-grade power cycles [4].

Usually, solar collectors are coupled to a storage system in order to achieve optimum energy management during the day. More specifically, the highest useful energy amounts around midday could be stored for utilization during the afternoon or night. The sensible heat storage system is the most common one. A storage tank of water is commonly used in order to store useful heat through temperature increase. This is a simple, mature and inexpensive technique to store energy, but it has some disadvantages. For example, hot water easily reaches high-temperature levels, so the collector thermal efficiency is reduced, while the storage tank thermal losses increase. Another option is the use of a latent storage system with phase change materials (PCMs). PCMs can be organic or inorganic materials that change phase from solid to liquid in the desired temperature range in K. Therefore, these materials can store high amounts of heat without any temperature increase or with a small temperature increase (~5 K). Paraffin is the usual PCM, which is widely used due to its reasonable cost. Generally, a PCM is an efficient alternative to conventional sensible heat storage. However, they face some limitations considering stability issues and increased costs.

In the literature, there are many studies about the utilization of PCMs coupled to solar thermal collectors. Recently, Ndukwu et al. [5] reviewed the exergy behavior of solar thermal collectors coupled to a PCM. They concluded that the PCM enhances the exergy efficiency of the system, but it needs a more complex control system. Serale et al. [6] concluded that the use of a latent storage system in the FPC could enhance the instantaneous thermal efficiency up to 10%, while the energy production enhancement in the winter period can reach up to 20%. In another paper, Enibe [7] studied a solar air heater coupled to a PCM and found performance enhancement up to 18%. Also, Haillot et al. [8] investigated a solar thermal system with a PCM for a building and they found a 15% higher yearly performance of the system. Furthermore, Nallusamy et al. [9] found that the use of PCMs could reduce the storage tank volume up to 28% for a system with packed bed latent heat thermal energy storage.

The aforementioned literature review shows that there is great scientific interest in the use of PCMs with flat plate collectors. However, there is a lack of studies that examine these systems both in energy and exergy terms daily. Therefore, this paper covers this scientific gap and investigates a solar system with latent storage with energy and exergy analysis during a typical day. The system is investigated for different phase change temperature levels and it is compared to a respective system with sensible heat storage. The results of this paper can be used for the proper design of a latent storage system coupled to a FPC in order to achieve high thermodynamic efficiency.

2. MATERIALS AND METHODS

The investigated unit is a conventional solar thermal system with a flat plate collector (FPC) coupled to a storage system. The FPC is a module of 2 m^2 in collecting area operating with the water mass flow rate of 0.04 kg/s. The thermal efficiency of the system (η_{th}) is defined as the ratio of the useful heat production (Q_u) to the solar irradiation (Q_{sol}):

$$\eta_{th} = \frac{Q_u}{Q_{sol}} \quad (1)$$

Moreover, the thermal efficiency can be calculated as below:

$$\eta_{th} = a_0 - a_1 \cdot \frac{T_{in} - T_{am}}{G_T} \quad (2)$$

where the water inlet temperature (T_{in}), the ambient temperature (T_{am}) and the incident solar irradiation (G_T) are the quantities used in the previous equation. Typical values for the efficiency parameters are used (a_0 = 0.75 and a_1 = 5 W/m^{2}K) [10].

Fig. 1a illustrates the system with the PCM storage system (latent storage), while Fig. 1b illustrates the system with the water storage system (sensible storage). The studied PCM is modeled theoretically by testing different phase change temperatures. Paraffin is the most suitable PCM material for solar thermal applications in low temperatures because of its low cost. The latent heat of this material is assumed to be 200 kJ/kg for all cases [11].

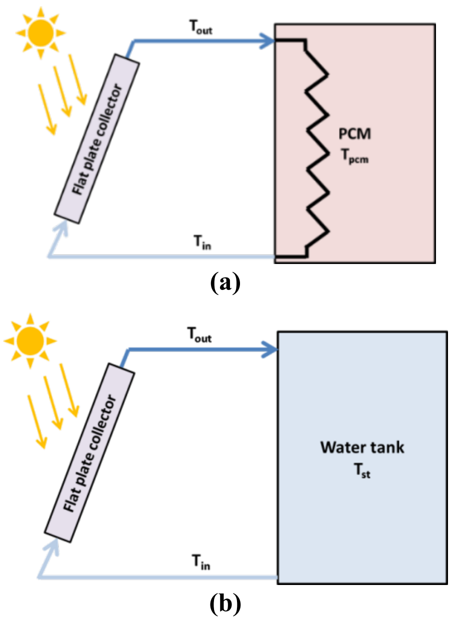

Fig. 1 Examined system with a) PCM and b) water as a storage medium

In this study, the system is monitored daily. The PCM is assumed to absorb all the useful heat during its phase change. In every case, the PCM is assumed to be solid at sunrise and liquid at sunset. This technique makes it possible to calculate the demanded mass of the PCM in order to design the examined system properly. This methodology is followed in [12].

On the other hand, the sensible storage system is assumed to have a water mass equal to the calculated mass of the PCM for every case. The water tank is a fully mixed tank and the initial temperature in the morning is assumed to be the phase change temperature of the respective PCM. The thermal losses are neglected in all cases by assuming a well-insulated storage tank for both systems. These assumptions make the proper comparison of the two examined systems possible, as shown in Fig. 1.

Below, the main aspects of the developed mathematical modeling are given.

The solar irradiation is assumed to follow a sinusoidal profile [13]:

$$Q_{sol} = A_c \cdot \frac{\pi \cdot H_T}{2 \cdot N} \cdot sin\left(\frac{\pi \cdot t}{N}\right) \tag{3}$$

The duration of the day (N) is assumed to be 12 hours, the daily total energy on the collector aperture (H_T) is 7 kWh/m^2, the collecting area (A_c) 2 m^2 and the ambient temperature (T_{am}) equal to 25ºC.

Therefore, the useful heat production (Q_u) is calculated as:

$$Q_u = \eta_{th} \cdot Q_{sol} \tag{4}$$

The outlet temperature of the solar collector working fluid (T_{out}) is calculated by using the working fluid energy balance:

$$T_{out} = T_{in} + \frac{Q_u}{m \cdot c_p} \tag{5}$$

The energy balance in the water storage tank is modeled by the following differential equation:

$$M \cdot c_p \cdot \frac{dT_{st}}{dt} = Q_u \tag{6}$$

The mass of the water (M) and its specific heat capacity (c_p) are the parameters used in the previous equation.

In the storage tank with the PCM, there is a heat exchanger with effectiveness (η_{hex}) of 70%, which is defined as below:

$$\eta_{hex} = \frac{T_{out}(t) - T_{in}(t+dt)}{T_{out}(t) - T_{pcm}} \tag{7}$$

The inlet temperature (T_{in}) in Eq. (7) is the inlet temperature in the collector at the next time moment (t+dt), while the outlet temperature (T_{out}) is the temperature at the time moment (t). This model can predict the system performance reasonably. The stored energy (Q_{st}) in the PCM, in every moment, is given as:

$$Q_{st} = m \cdot c_p \cdot \eta_{hex} \cdot \left(T_{out} - T_{pcm}\right) \tag{8}$$

It is important to state that the initial system temperature is (T_{pcm}), so as to achieve the convergence of the problem without any issues. Also, when the thermal efficiency of the solar collector is lower than 1, then the system stops operating and the outlet temperature of the system is equal to the inlet.

The mean daily thermal efficiency of the system ($\eta_{th,m}$) can be calculated as below:

$$\eta_{th,m} = \frac{E_{st}}{E_{sol}} = \frac{\int_{t=0}^{t=N} Q_{st} dt}{\int_{t=0}^{t=N} Q_{sol} dt} \tag{9}$$

The mean daily exergy efficiency of the system ($\eta_{ex,m}$) is calculated as below:

$$\eta_{ex,m} = \frac{Ex_{st}}{Ex_{sol}} = \frac{E_{st} \cdot \left(1 - \frac{T_0}{T_{st}}\right)}{E_{sol} \cdot \left(1 - \frac{4}{3} \cdot \frac{T_0}{T_{sun}} + \frac{1}{3} \cdot \left[\frac{T_0}{T_{sun}}\right]^4\right)} \tag{10}$$

It should be noted that the exergy flow of the solar irradiation is calculated with the suggested model by Petela [14]. Moreover, it is useful to note that the temperature levels for the exergy calculation must be expressed in Kelvin. T_{st} is the temperature of the water at the end of the day for the sensible storage system, while it is equal to T_{pcm} for the system with the latent storage. Also, the sun temperature (T_{sun}) is taken as 5770 K and the reference temperature (T_0) as 298.15 K.

Lastly, it is notable to state that the system stores the daily useful heat produced and there is no load during the day. At the end of the day, the obtained energy and exergy are evaluated. This methodology is in accordance with ISO 9459-2 [15].

3. Results and discussion

This section includes the results of the present work, as well as the respective discussion comments. The results indicate the system energy and exergy performance for the different PCM temperatures.

Fig. 2 shows the daily system performance in energy and exergy terms. The solar irradiation, the useful production and the stored energy with the PCM are given in these Figures. It is useful to say that these results are related to the case of the PCM temperature equal to 50ºC, which is a typical case for space-heating or domestic hot water production. It is obvious that the stored energy is approximately equal to the useful energy production for the PCM, but it is a bit higher after the solar noon. The maximum heat production is about 1000 W and it appears close to the solar noon. This value can be characterized as the nominal useful power production of the examined system (~1 kW).

For the system with water storage, the useful heat produced is lower, which is obvious from Fig. 2. The stored energy with water is equal to the useful energy produced from the collector and thus it is not given separately in Fig. 2. During the morning hours, the difference between the systems is not so great but, in the afternoon, the difference is huge. The main reason for this is the increase in the temperature level in the sensible storage system with water, the fact that leads to lower solar collector efficiency. Moreover, this system stops working at 16:00, as after this moment its thermal efficiency is not positive.

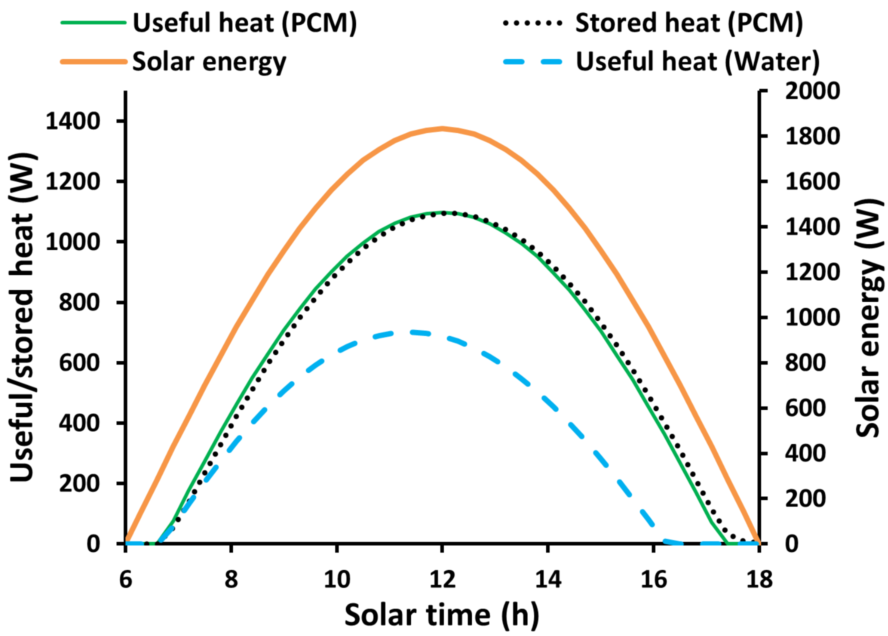

Fig. 2 Daily system performance with PCM and water for T_{pcm} = 50ºC

Fig. 3 shows the variation of the energy storage of both units during the day for four different temperature levels of the PCM (30ºC, 50ºC, 70ºC and 90ºC). It is important to note that the water tank temperature in the morning is the same as the selected PCM temperature. Additionally, the water mass is selected to be equal to the demanded PCM mass for the ideal latent storage (only solid in the morning and only liquid in the afternoon).

Fig. 3 clearly proves that higher amounts of energy can be produced with the storage in PCM compared with the storage in water. Moreover, a lower system temperature level leads to higher system performance due to the increased performance in the solar collectors. It is worth stating that the system with water storage stops operating in the afternoon (around 16:00), because after that point, the temperature in the tank is high and the available solar irradiation is low, the facts that do not permit solar energy utilization. Moreover, it can be said that up to 11:00, the two systems have similar performance because the water in the tank has not been warmed up a lot at this period. Lastly, it can be also concluded that all the curves of the same storage scenario have similar trends, which proves the smooth performance of the system.

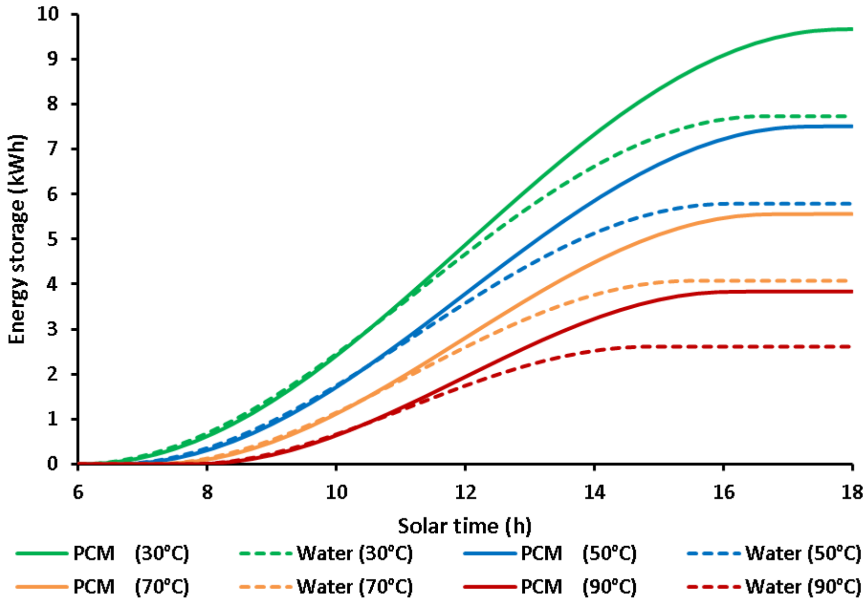

Fig. 3 Energy storage during the day for both investigated storage systems

Figs. 4 and 5 show the energy performance of the systems for different operating temperature levels. More specifically, Fig. 4 shows the energy stored and Fig. 5 shows the energy efficiency. It is clearly proven that the use of the PCM leads to higher energy performance due to overheating avoidance. Furthermore, the higher operating temperature reduces the energy performance due to the reduced efficiency of the solar thermal collector.

The thermal efficiency of the PCM ranges from 21.9% up to 69.1%, while the energy performance with water storage ranges from 14.2% up to 55.3%. The average thermal performance with the PCM is about 36%, a great value that indicates this technology to be a preferable and promising one. Moreover, it is useful to state that the results shown in Figs. 4 and 5 are in accordance with the results shown in Fig. 3.

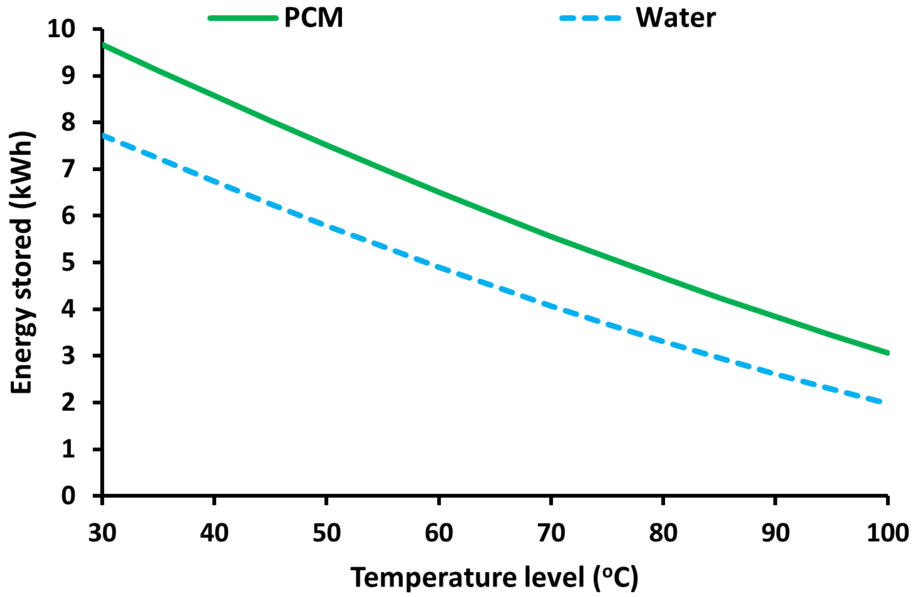

Fig. 4 Daily energy (thermal) yield of the systems for different operating temperatures

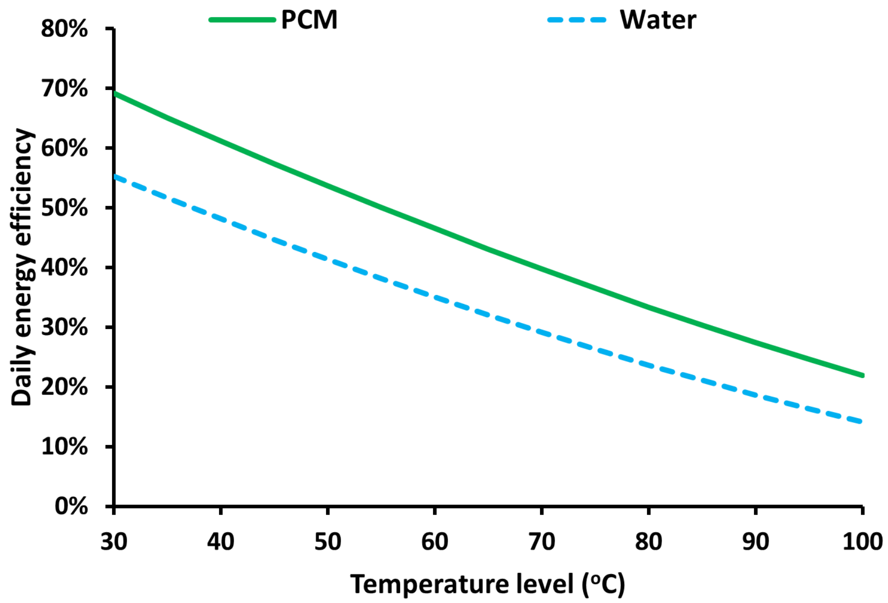

Fig. 5 Daily energy (thermal) efficiency of the systems for different operating temperatures

The next step is the presentation of the exergy performance of the systems. Fig. 6 depicts the stored exergy and Fig. 7 the exergy performance for different operating temperature levels. It can be said that the system with water storage presents higher exergy efficiency for the most cases compared to the system with the PCM. For temperature levels up to 85ºC, the water system has higher performance than the PCM system. After this point, the thermal performance of the water system is too low and so its exergy performance is also reduced. The main reason for the high exergy efficiency of the water storage system, up to 85ºC, is based on the temperature increase in the storage tank that gives the high potential for work production and so the exergy efficiency is higher. At high temperatures up to 85ºC, the PCM storage system is the best option according to both energy and exergy criteria.

More specifically, the exergy efficiency of the water storage system ranges from 4.0 - 7.8%, while the exergy efficiency for the system with PCM is in the range 1.2 - 5.6%. The optimum temperature for the water system is at 40ºC while for the PCM system at 75ºC. These results show that the sensible system should operate generally at lower temperatures, while the PCM system is the proper choice for the cases that need higher temperature levels (e.g. power production or cooling with sorption machines).

The last presented parameter is the required mass of the storage material (PCM) which is depicted in Fig. 8. The latent heat of 200 kJ/kg was used and with this value, the storage mass is found to be in the range from 55 kg up to 174 kg for the PCM case. In order to perform a suitable comparative study, the same mass flow rate was also used in the case of sensible storage.

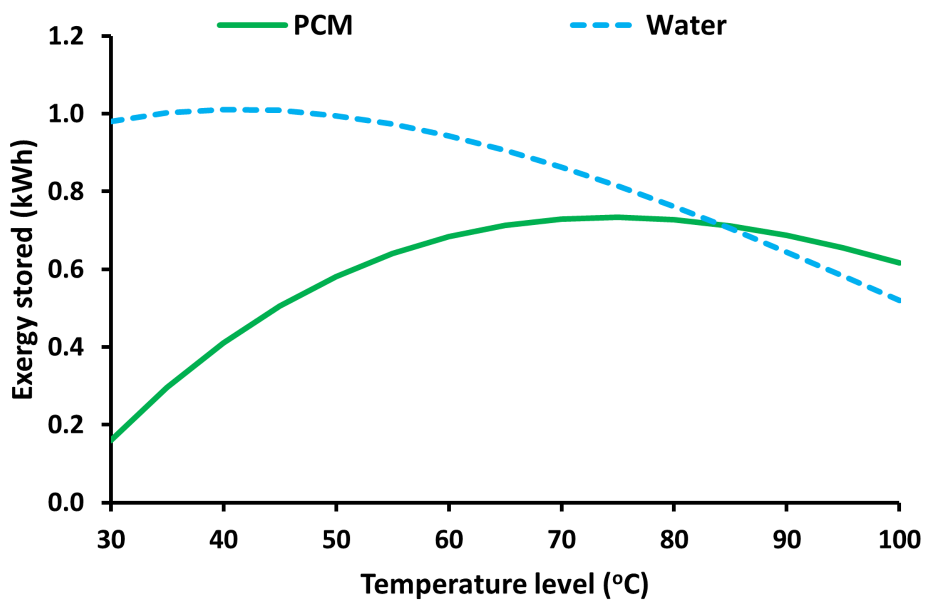

Fig. 6 Daily exergy yield of the systems for different operating temperatures

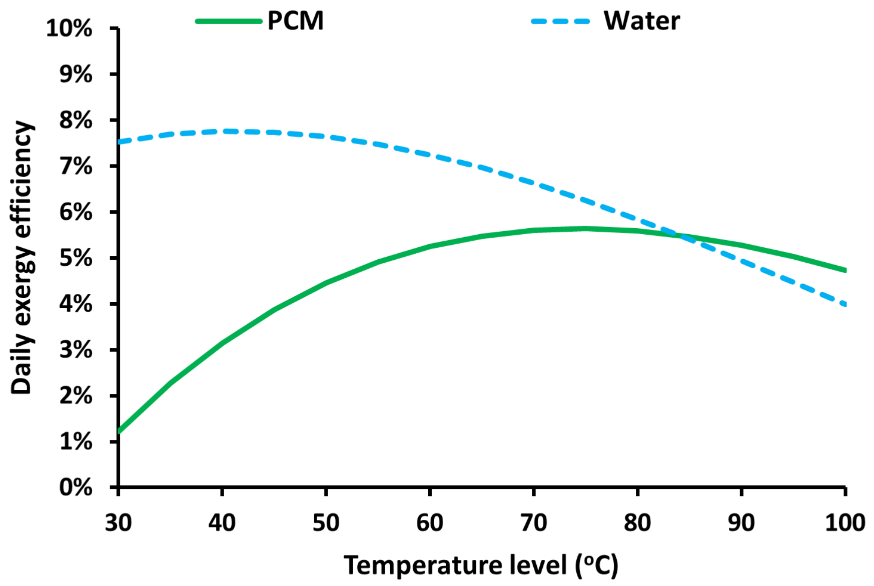

Fig. 7 Daily exergy efficiency of the systems for different operating temperatures

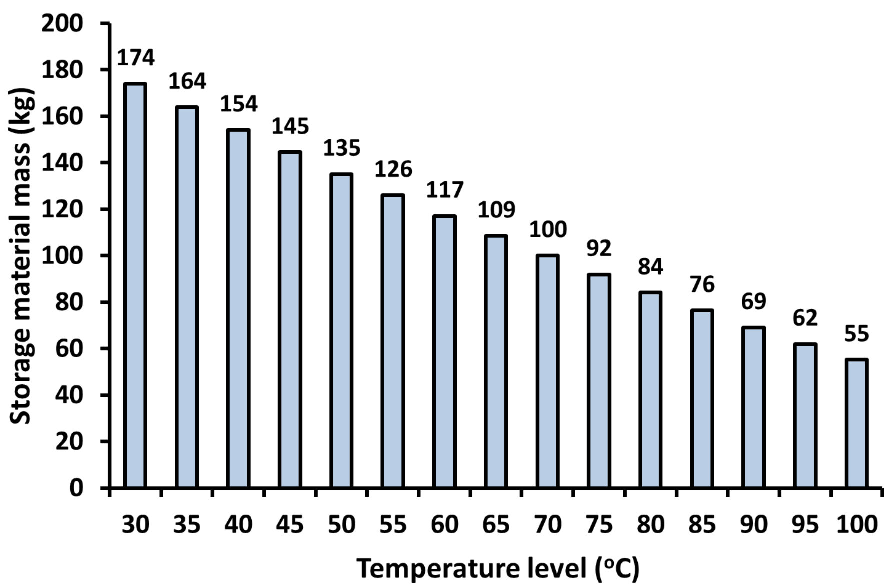

Fig. 8 Storage material mass for all cases

4. Conclusions

The present work is a comparative study of two storage systems for a solar thermal collector with a 2 m^2 collecting area. The use of sensible storage with water and latent storage with the PCM were compared in terms of energy and exergy performance. Moreover, a daily analysis was conducted for a typical day. The most important conclusions of this investigation are listed below:

- Higher energy performance was found with the use of the PCM for all the examined cases. It is notable to state that the mean thermal efficiency enhancement for the system with the PCM is 36% compared to the sensible storage case with water.
- The mass of the PCM storing material was found to be in the range from 55 kg up to 174 kg for all the examined cases.
- The exergy performance is higher for the system with sensible storage up to 85ºC, while at higher temperature levels the PCM is the best choice.
- It is found that the daily energy efficiency ranges from 21.9% to 69.1% for the system with the PCM, while it is in the range 14.2 - 55.3% for the system with water.
- It is found that the daily exergy performance is in the range 1.2% - 5.6% for the system with the PCM, while it ranges from 4.0% to 7.8% for the system with water.
- According to the exergy investigation, the optimal operating temperature level for sensible storage is 40ºC and for latent storage is 75ºC.
- Finally, it is important to point that sensible storage has to be used in applications with low-temperature needs, while the PCM is ideal for higher temperatures. Moreover, the PCM has higher energy efficiency for all cases but the cost increases compared to the sensible systems.

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Nomenclature

A_c Collecting area, m^2
α_0 Zero order coefficient of thermal efficiency
α_1 First order coefficient of thermal efficiency, W/m^2K
c_p Specific heat capacity, kJ/kgK
dt Time step, h
E_{sol} Solar energy, kWh
E_{st} Stored thermal energy, kWh
Ex_{sol} Exergy of solar irradiation, kWh
Ex_{st} Exergy of stored energy, kWh
G_T Solar incident irradiation on tilted surface, W/m^2
H_T Daily incident solar energy on tilted surface, kWh/m^2
m Mass flow rate, kg/s
M Mass, kg
N Duration of the day, h
Q_u Useful heating production rate, kW
Q_{sol} Solar energy rate, kW
Q_{st} Storage energy rate, kW

t Time, h
T_{am} Ambient temperature, ºC
T_{in} Inlet temperature in the collector, ºC
T_{out} Outlet temperature in the collector, ºC
TPCM PCM melting temperature, ºC
T_{sun} Sun temperature, K
T_0 Reference temperature, K

Greek Symbols

$\eta_{ex,m}$ Mean daily exergy efficiency
η_{hex} Heat exchanger efficiency
$\eta_{th,m}$ Mean daily thermal efficiency
η_{th} Instantaneous thermal efficiency

Abbreviations

FPC Flat Plate Collector
PCM Phase Change Material

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