



Experimental Study of an Integrated Solar Water Heater Containing Polyethylene Glycol as Phase Change Material

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Abstract The reduction of the costs represents the most important factor in the popularization of the solar water heaters in the developing countries. On the other hand, integrated solar water heaters seem to be the most cost effective under all types of solar water heaters because of their simple design.

In this paper the thermal performance of an integrated solar water heater (ISWH) is investigated. For the first time, iron tubes containing polyethylene glycol 4000, as PCM-material, are placed inside the water tank in order to increase the energy storage capacity and to mitigate the heat losses during the cooling periods.

Thermal performance tests of the heater have been performed before and after the insertion of the PCM-tubes.

The positive effect of the PEG 4000 on the thermal behavior of the heater is clearly demonstrated.

Keywords Integrated solar water heater, Polyethylene glycol 4000

1. Introduction

Hot water supply belongs to the most energy consumable applications in many sectors like households, hotels and hospitals. Therefore, the popularization of solar water heaters could reduce the fossil energy consumption significantly leading to the reduction of the environmental pollution and the monetary expenditure for energy of these facilities [1].

The most commonly used solar water heater for domestic purposes is the natural circulation type wherein the water is circulated between collector and storage water tank according to the thermosyphon principle. However, integrated collector storage systems (ICSSs) are much simpler in design and therefore have lower installation costs. These systems have unfortunately lower energy output. They suffer especially from increased energy losses during the night [2, 3]. Many investigations have been conducted targeting the attenuation of this effect [4].

In order to mitigate the constraint of night cooling double normal silica glassing have been tested [5]. A difference of 20 °C between water and ambient temperature has been reported at the sunrise which follows the heating day for a tank thickness of 5 cm. An insulating plate has been used to separate the collecting area from the storage area within the integrated tank [6-8]. This attempt leads to improved water heat storage during the night. A thermal diode is introduced into the collector storage system to prevent the reverse thermosyphon water circulation leading to decrease the cooling process at night [9]. M. S. Mohsen et al. studied the influence of the storage tank depth on the thermal performance of the heater [3]. Among the three studied depths of 5, 10 and 15 cm, it is found that the solar heater with the 10 cm depth is most effective.

The effect of a transparent insulating methyl methacrylate sheet on the performance of a triangular integrated collector storage solar water heater has been theoretically studied by Prakash et al. [10]. The sheet was in direct contact to the collecting surface of the storage tank. It is found that the sheet enhances the maximal water temperature and reduces the cooling effect during the night.



The temperature stratification within the tank plays a crucial role in the determination of the useful heat output of any integrated collector storage system. Many researchers investigated the factors which influence the stratification. These factors include the dimensions of the tank, the angle of inclination, the intensity of the solar radiation, the time of exposure to the radiation as well as the initial degree of stratification of the water inside the tank [11, 12]. A computational model has been developed to analyze the temperature stratification inside a rectangular shaped integrated Collector Storage Solar Water Heater [13]. The model is able to compute the water temperature along the height of the collector for a given hourly incident solar radiation, ambient temperature and inlet water temperature.

Phase change materials are known for their high heat storage capacity during the isothermal melting process. Therefore many researches have been carried out in order to utilize this property in solar water heating systems [14]. During the daytime, PCM stores extra thermal energy in the form of latent heat by changing its phase. The stored energy is released to heat the water when it is extracted from the system to meet the demands of hot water in the night or during the overcast sky conditions. The use of PCM in solar water heaters leads also to decrease of the maximum collector's temperature during stagnation which in turn increases the collector's life time expectancy.

Eames and Griffiths predicted the collection and retention of heat in the rectangular cross section solar collector/storage systems filled with water and various concentrations of PCM slurries of a 65 °C phase change temperature [15]. The slurry system collected heat less effectively than the system filled with water. The storage of heat at a higher temperature in the PCM slurry allowed higher solar saving fractions.

Tarhan et al. tested three trapezoidal built in storage solar water heaters, one with myristic acid, second with lauric acid and third with water [16]. The lauric acid was placed in a storage unit that acts as a baffle plate, while myristic acid was stored in a storage unit that acts as an absorbing plate. The tests results indicated that the use of lauric acid stabilized the temperature and reduced the volume of the water tank but effectively retained the water temperature during night. The system with myristic acid was also found quite effective in retaining the water temperature since it solidified at 51–52 °C temperatures and acted as a thermal barrier.

Fazilati et al. used paraffin wax as PCM in spherical capsules as storage material in the tank of solar water heater [17]. It was observed that the energy storage density is increased up to 39%. Improvement in thermal stratification has also been observed by examining temperature histories of different water layers in the tank.

Karaman et al. prepared polyethylene glycol (PEG)/diatomite composite as a form-stable composite phase change material for utilizing as building material [18].

Aji et al. investigated polyethylene glycol with an average molecular weight of 2000 g/mol as a phase change material for thermal energy storage applications [19]. They found that PEG degrades in the presence of oxygen but not under nitrogen atmosphere. Therefore it may be concluded that some stabilisers or antioxidants may be added to the polymer.

This paper presents the results of thermal performance tests conducted on an integrated solar water heater equipped with iron tubes including polyethylene glycol with an average molecular weight of 4000 g/mol as a phase change material. This material has not been used previously in integrated solar water heater. The influence of the PEG on the water temperature inside the tank as well as on the stratification is studied.

2. Description of the designed system

The used materials in the fabrication of the Integrated Collector storage solar water heater in this work are locally available. Additionally simple fabrication techniques are chosen. These measures were applied in order to minimize the installation costs of the system, which is the main advantage of an ICS solar water heater.

The designed heater consists of a rectangular storage tank with side lengths of 60 cm, 60 cm and 7 cm (fig. 1). The tank has been made of galvanized steel sheets of 2 mm thickness. All sides of the tank have been painted with normal non-selective matt black paint. A 5 cm thick glass wool layer is used to insulate the bottom and sides of the tank.



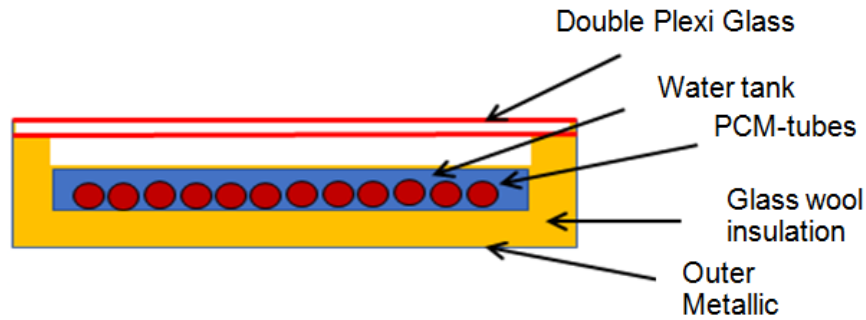


Figure 1: Cross section of the designed solar water heater

It is well known that the thermal conductivity of acrylic (plexi glass) is 5 times lower than that of silica glass; additionally the optical transmission coefficient of acrylic sheets is as high as that of iron free silica glass. Therefore a double plexi glass layer of 4 mm thickness for each layer is used as transparent insulation for the sun faced side of the tank. The distance between the tank and the first layer is 5 cm. whereas the distance between the two plexi glass layers is 2 cm. No aggressive chemical agents should be used in the cleaning of the acrylic sheets, because such solutions could negatively influence the surface of the sheets leading to decrease their transmission properties.

Twelve iron tubes, filled with PEG 4000, are placed inside the heater. The total weight of the phase change material is 3.47 Kg. The total weight of the heater including the water within the tank, the weight of the iron tubes, the weight of the PCM and the weight of the galvanized steel sheets amounts to 39.5 Kg. Therefore the PCM is being 8.8 % of the total weight of the heater.

In this work PEG 4000 was chosen as phase change material because of its high density in comparison to other materials being recorded in the literature with melting range between 50 °C and 60 °C which is suitable for domestic applications. Table 1 shows the main thermo physical properties of PEG 4000 and Paraffin wax.

Table 1: The main thermo physical properties of PEG 4000 and Paraffin wax

Property	Paraffin [17]	PEG 4000 [20]
Melting point range(°C)	52-58	53-59
Specific heat (solid) (KJ/KgK)	2	-
Specific heat (liquid) (KJ/KgK)	2.15	2.13
Latent heat (KJ/Kg)	187	188
Solid density (Kg/m ³)	910	1200
Liquid density (Kg/m ³)	790	1090

Differential Scanning Calorimetry (DSC) measurements are performed in order to test the heating and cooling behavior of the utilized PCM material. Fig. 2 shows the recorded thermograms in nitrogen atmosphere with heating/cooling rate of 10 °C/min. It can be seen that the PEG 4000 melts and crystalline in reasonable manner, which means that this material is suitable for thermal energy storage.

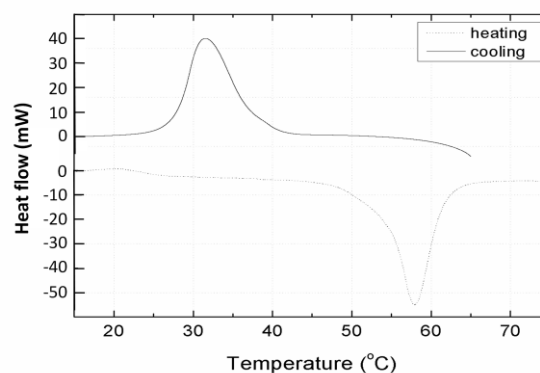


Figure 2: DSC thermograms of the used PEG 4000



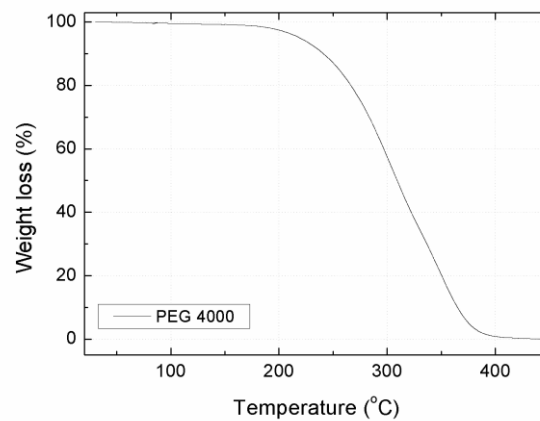


Figure 3: TG thermogram of the used PEG 4000

A thermogram of the used PEG-4000 material was recorded using a thermogravimetric analyzer (TGA50) at a heating rate of 10 °C/min in a nitrogen atmosphere in order to determine the thermal decomposition temperature of the polymer as shown in fig. 3. The thermogram does not show any remarkable weight loss at temperatures below 150 °C, therefore the PEG 4000 polymer can be considered as stable for long term energy storage and temperatures below 150 °C.

The collector has been tilted 33° above the horizon. This tilt angle ensures that the solar radiation is perpendicular to the surface of the collector at the midday of the vernal and autumnal equinoxes, taking into account the latitude of Damascus of approximately 33°. This chosen tilt angle allows maximum benefit of the solar heater during spring and autumn. We have in these seasons mostly sunny days, whereas the ambient temperature is relatively low. Therefore, solar water heaters are very useful in these two seasons. However, solar water heaters are less useful in summer and winter because the air temperatures are high in summer whereas the sunny days are rare in winter.

Three thermocouples, with the accuracy of ± 0.1 °C, were fixed on the surface of the heater to measure the water temperatures inside the tank. They were located along the centerline of symmetry belonging to the absorbing surface of the heater. The thermocouples were thermally isolated to the upper side. Therefore the recorded temperatures by them represent the water temperatures in the tank underneath the thermocouple places. The distances between two adjacent thermocouples were 20 cm, and the distances of the thermocouples from the top and bottom sides of the water tank were 10 cm.

The thermocouples were labeled T1, T2 and T3 starting from the top side of the water tank. The ambient temperature was also measured using a fourth thermocouple labeled as T4.

Free runs were done before recording temperatures for two consecutive days to let the heater stabilize. The temperatures were taken and stored every 10 minutes during the measuring periods. The experiments were done 20 km in the west of Damascus, Syria. The latitude and longitude of the experiment's place are 33.5° and 36.1° respectively.

3. Results and Discussion

Three tests were conducted, on the heater, in order to determine the thermal performance of the system with and without the phase change material. The first two tests were done without the PCM tubes on 6-7.03.2017 and 24-25.07.2017, whereas the third test was performed with the PCM tubes on 28-29.07.2017.

Fig. 4 shows the recorded temperatures during the first test on 6 and 7 March 2017. Whereas fig. 5 shows the difference between the average water temperature ($T_{w,ave} = \frac{T1+T2+T3}{3}$) and the ambient air temperature T4. This difference is labeled in the following text as ΔT . It represents the temperature increasing of the water because of the solar energy collected by the heater. Any shift in the water temperature because of the ambient air temperature is thus eliminated.



The temperatures T1 and T2 are identical during the discharging phase between 15:30 and 06:30 o'clock, whereas they differ slightly from each other during the charging phase. This indicates that the water temperature distribution in the upper half of the tank is approximately homogeneous. The temperatures T2 and T3 differ clearly from each other during the charging phase as well as the discharging phase, which indicates that the stratification in the lower half of the tank is much pronounced than in its upper half. The maximum value of ΔT is 43°C which occurs at 14 o'clock approximately, whereas the minimum value is 14 °C at approximately 7 o'clock.

The heat loss coefficient c of the collector can be calculated using the measured temperatures by the following two equations:

$$\Delta Q = (c_1.m_1 + c_2.m_2).[T_{w,ave}(t_1) - T_{w,ave}(t_2)] \quad (1)$$

$$\Delta Q = c.A.[\overline{T_{w,ave}} - \overline{T_a}]. \Delta t \quad (2)$$

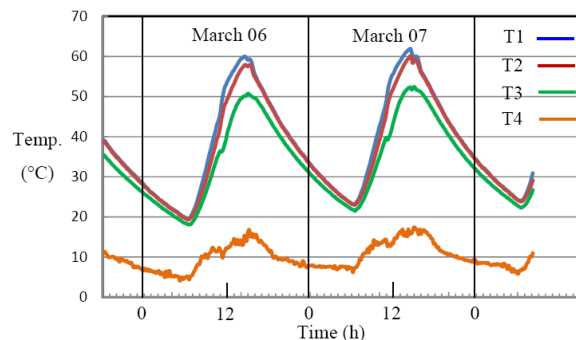


Figure 4: Recorded temperatures of the water and the ambient air on 6 and 7 march 2017

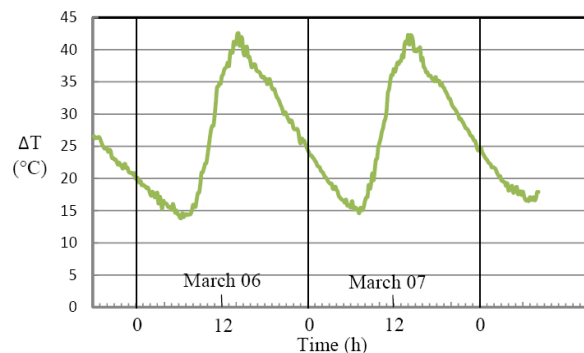


Figure 5: The difference between the average water temperature and the ambient air temperature

ΔQ represents the lost energy during the time interval $\Delta t = [t_1, t_2]$, whereas m_1 and m_2 represent the water mass inside the tank and the mass of the tank, respectively. c_1 and c_2 are the heat capacities of water and iron. A represents the front surface of the heater which is thermally not isolated and acts as the absorbent surface. $\overline{T_{w,ave}}$ is the water average temperature during the time interval Δt , whereas $\overline{T_a}$ is the ambient average temperature during the same interval.

All terms in (1) and (2) are known except the heat loss parameter c , therefore it is possible to calculate c for a given interval Δt .

Δt was chosen between 18 o'clock of 6 march and 5 o'clock of 7 march. In this interval the sun is absent and the heater loses energy because of the temperature difference between the water inside it and the ambient air. The calculated value of c using equations (1) and (2) is 6.7 W/(m².°C). The maximum efficiency (intercept efficiency) η of the heater has been calculated using the determined value of the heat loss parameter c and the measured solar radiation on the plane of the solar heater between 12 o'clock and 13 o'clock of 7 march. In this time period, the angle between the solar radiation and the normal on the heater surface is less than 5 degrees. The maximum efficiency obtained was 72%. The value of the heat loss parameter is relatively high whereas the value of the maximum efficiency is relatively low. This can be attributed to the use of non-selective absorbent paint. The use of a selective paint would lead to lower value of c and higher value of η which means that the thermal performance of the heater will be improved.



Fig. 6 shows the recorded temperatures on 24 and 25 July 2017. The PCM tubes were put in the water tank on 26 July 2017 and after two days the temperatures were recorded again for a period of two days.

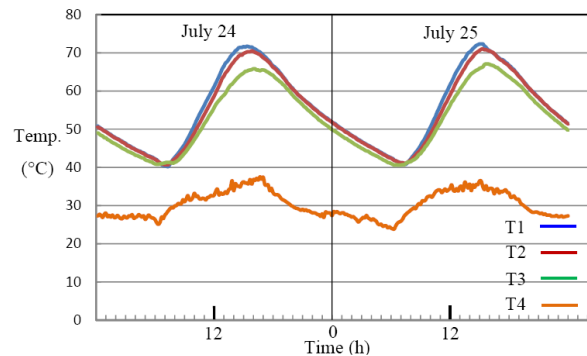


Figure 6: Recorded temperatures of the water and the ambient air on 24 and 25 July 2017

Fig. 7 shows the recorded temperatures on 28 and 29 July 2017. The sky was clear and the daily solar radiation distribution was approximately constant during this period of time. However, the ambient air temperatures on 24 and 25 July differ clearly from the temperatures on 28 and 29 July. Therefore it is important to calculate ΔT between the average water temperature $T_{w,ave}$ and the ambient air temperature T_a to eliminate the shift caused by the different air temperatures and to make the comparison between the thermal performance with and without PCM tubes more reliable.

Fig. 8 shows ΔT for the tests performed without PCM tubes and with PCM tubes. It can be seen that ΔT increases when PCM tubes are used almost in the whole time range. However, this increase is maximal between 6 o'clock and 10 o'clock. In this time interval there is usually increased demand on hot water in most households. Therefore the utilization of PCM tubes has a positive effect at the right time.

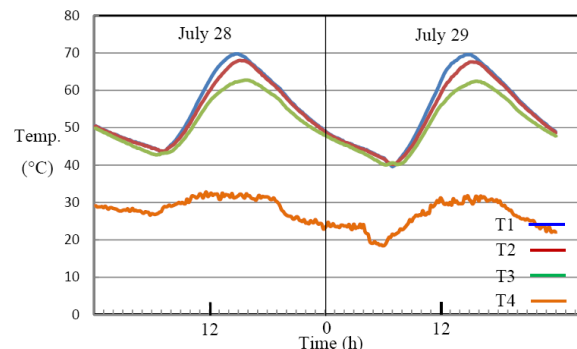


Figure 7: Recorded temperatures of the water and the ambient air on 28 and 29 July 2017

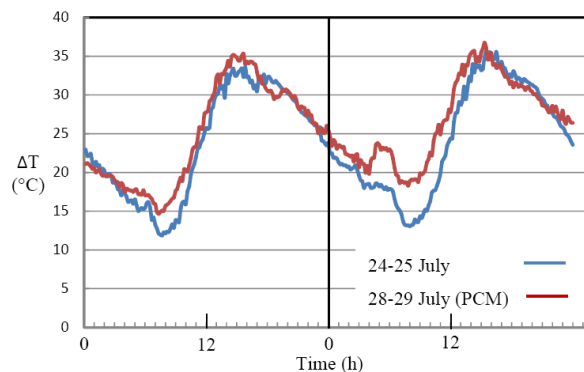


Figure 8: The difference between the average water temperature and the ambient air temperature with and without PCM tubes

In order to accurately assess the performance of an integrated solar water heater, it is necessary to investigate the influence of the amount of water inside the heater because the stored energy (Q_{stor}) inside the tank depends on the difference ΔT between the water temperature and the ambient air temperature as well as on the amount of



water inside the tank. This energy is stored in the tank as sensible heat and can be expressed by the following equation for the case that only water is inside the tank (no pcm):

$$Q_{\text{stor}} = (c_1.m_1 + c_2.m_2).[T_{w,\text{ave}} - T_a] \quad (3)$$

m_1 and m_2 represent the water mass inside the tank and the mass of the tank, respectively. Whereas c_1 and c_2 are the heat capacities of water and iron. $T_{w,\text{ave}}$ is the water average temperature and T_a is the ambient temperature. In the case of the tank with the PCM-tubes, the latent heat of the PCM must be taken into account in the stored energy formula:

$$Q_{\text{stor,pcm}} = (c_1.m_1 + c_2.m_2 + c_3.m_3).[T_{w,\text{ave}} - T_a] + d.c_f.m_3 \quad (4)$$

m_2 represents in this formula the mass of the tank and the iron tubes which contain the PCM. Whereas m_3 represents the mass of the PCM and c_3 represents its sensible heat capacity. c_f is the latent heat of fusion and d is a parameter which can have 4 values according to the temperatures T_1 , T_2 and T_3 . If T_1 to T_3 are below the melting point T_f of the PCM (56°C), then d takes the value 0, because the whole PCM is solid and no melting occurred. Whereas d takes the value 1 if all three temperatures are above the melting point as the whole PCM is melted. If only one temperature (T_1 or T_2 or T_3) is higher than T_f then only a third of the PCM is melted and the value of d is 0.333 whereas its value is 0.667 for the case that two temperatures are above T_f , where two thirds of the PCM are melted. Fig. 9 shows the stored energy in the tank without PCM on 24-25 July and with PCM on 28-29 July. For quantitative comparison, the relative variation $\left(\frac{Q_{\text{stor,pcm}} - Q_{\text{stor}}}{Q_{\text{stor}}}\right)$ is represented in fig.10. This variation is positive in almost the whole range, which means that the PCM improves clearly the thermal performance of the heater. The average value of this variation is 9.4%, whereas it achieves maximal values of about 30% at the midday.

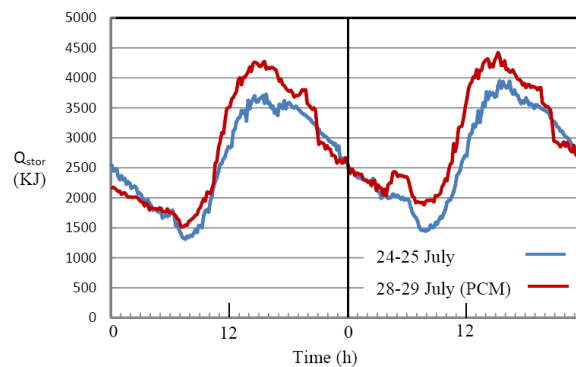


Figure 9: The stored energy inside the tank with and without PCM tubes

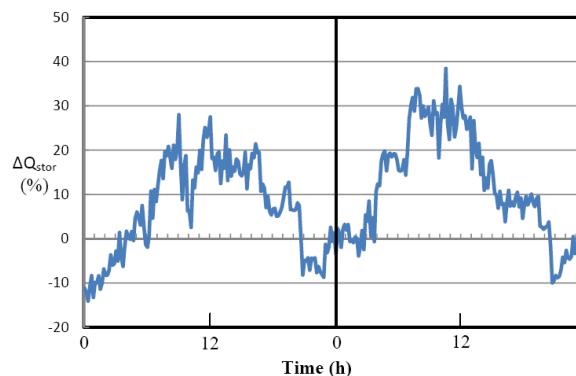


Figure 10: The percentage variation of the stored energy inside the tank because of the PCM tubes

Fig. 11 shows the difference between the readings of thermocouples T_1 and T_3 for the three performed tests in March and July. This difference is a good measure for the stratification inside the water tank because T_1 is placed 10 cm underneath the upper edge of the tank, whereas T_3 is placed 10 cm above the lower edge of the water tank. It can be seen clearly that the stratification in the first test (6-7 March) is much higher than in the other two tests.



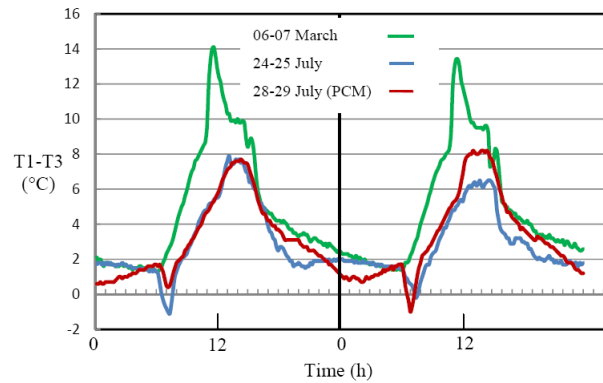


Figure 11: The difference between the water temperatures at the upper thermocouple position T1 and the lower thermocouple position T3

The stratification increases at the beginning of the charging phase at the morning. It reaches its maximum at the solar noon in the first test in March, whereas it reaches the maximum point approximately one hour after the solar noon in the other two tests in July. A sharp decreasing of the stratification occurs after reaching the maximum on 6 and 7 March and it continues until 4:30 p. m. After this point the decreasing becomes slower until the morning of the next day.

4. Conclusion

An integrated solar water heater is presented in this paper. Plexi glass has been used as a transparent cover because of its superior heat isolation and light transmission properties. Iron tubes containing polyethylene glycol as a phase change material are inserted inside the water heater. As a result of the utilizing of the PCM tubes, the average water temperature and the stored energy inside the tank are clearly improved despite the low weight percentage (8.8 %) of the PCM to the total weight. The stratification has not been clearly affected by the PCM. However it was much more pronounced in the test performed in March in comparison to the tests in July. The use of the PCM mitigates clearly the night cooling. This effect could be enhanced if the amount of the PCM is increased.

Table 2: The main features of the presented heater in this work and the commercially available flat plate heater

Property	Flat Plate heaters	Presented heater without PCM	Presented Heater with PCM
Zero loss Efficiency (%)	80 [21]	72	72
Heat loss coefficient (W/(m ² .°C))	4.8 [21]	6.7	<6.7
Night losses	low	high	moderate
Locally Installation	300	70	100
Costs (USD/m ²)			
Maintenance	moderate	low	low

For comparison, table 2 shows the main features of the presented heater in this work and the commercially available flat plate collector heater. The thermal performance of the presented heater with PCM is slightly lower than the thermal performance of the flat plate heater. However, this disadvantage is compensated by the markedly lower manufacturing costs because only low cost material and simple techniques are used in the fabrication process. In low income countries, such as Syria, the price plays an essential role in the spreading of solar water heaters, therefore the presented heater can be a good alternative to commercially available types.

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