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PCM storage for solar DHW: From an unfulfilled promise to a real benefit

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The present numerical study is concerned with the use of phase change materials (PCMs) in solar based domestic hot water (DHW) systems. During the last decade, the majority of the studies related to that issue concluded that the recourse to PCMs based storage units was quite promising in order to enhance the overall performances of solar based DHW systems. One recently interesting published numerical study (Talmatsky and Kribus, 2008), suggested though that this beneficial impact is not guaranteed since the gains observed over the day period brought by the presence of PCMs to store the solar energy were compensated by the losses undergone by the storage tank during the night. The origin of this absence of any beneficial impact of the use of PCMs in a DHW system has to be clearly understood in order to reconcile studies which indicated apparently contradictory findings. In that framework, the goal of the present contribution is to analyze the conditions under which such an absence of advantage of the use of PCMs in a DHW system were obtained in order to propose some possibilities of improvement for demonstrating the interest in using PCMs in solar based DHW systems. Thus, the mathematical model based on the one reported in Talmatsky and Kribus (2008) is considered. This model describes the heat storage tank with PCM, collector, pump, controller and auxiliary heater. Realistic environmental conditions and typical end user requirements are imposed.

Keywords: Solar energy; PCM; Domestic hot water; Latent storage

1. Introduction

As well known from the engineering practicing, the time delay and available power between production or availability of energy and its consumption is an important problem in solar energy applications. Phase change materials (PCMs) can be a good solution for these problems due to their low cost, high energy security for supplying of energy and easy construction to the system. The main advantages

of PCMs are high storage density and isothermal operation (Dincer, 1999; Kousksou et al., 2010, 2007).

Several different types of solar domestic hot water (DHW) systems with and without PCM have been tested within the past few years (Buckles and Klein, 1980; Lenel and Mudd, 1984; Esen and Durmus, 1998; Mehling et al., 2003; Canbazoglu et al., 2005; Ibanez et al., 2006; Cabeza et al., 2006; Mazman et al., 2009; Al-Hinti et al., 2010). The full economic benefit of PCM in solar water heating system cannot be realized unless it is properly designed and sized for its intended application. Needed at this time are designed methods which provide reliable estimates of

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Nomenclature

A	area (m^2)
c	specific heat ($\text{J kg}^{-1} \text{K}^{-1}$)
$C0$	characteristics of the collector
$C1$	characteristics of the collector ($\text{W m}^{-2} \text{K}^{-1}$)
h	convection coefficient ($\text{W m}^{-2} \text{K}^{-1}$)
I	incident solar flux (W m^{-2})
k	thermal ($\text{W m}^{-1} \text{K}^{-1}$)
L_{sf}	latent heat of PCM (J kg^{-1})
m	mass (kg)
\dot{m}	mass flow rate (kg s^{-1})
Q	thermal power (W)
T	temperature (K)
t	time (s)
U	overall heat transfer coefficient ($\text{W m}^{-2} \text{K}^{-1}$)
X	normalized temperature difference ($\text{m}^2 \text{K W}^{-1}$)

<i>Greek symbols</i>	
Δx	distance between two water layers (m)
η	efficiency
ρ	density (kg m^{-3})

<i>Subscripts, superscripts</i>	
a	ambient
C	collector
i	layer index
in	inlet
out	outlet
pcm	phase change material
w	water

the long-term average annual thermal performance for the various types of systems commercially available.

A wide range of PCMs can be used for latent heat storage applications, including salt hydrates, paraffin waxes, fatty acids, and sugar alcohols (Zabla et al., 2003). Canbazoglu et al. (2005) made a study on the enhancement of solar thermal energy performance using sodium thiosulfate pentahydrate as PCM in a solar water-heating system. They found that the storage time of hot water, the produced hot water mass and total heat accumulated in the solar water-heating system having the heat storage tank combined with PCM were approximately 2.59–3.45 times that of the conventional water-heating system. Recently, experiments were done with the inclusion of a water tank with a PCM module in a complete solar water heating system (Cabeza et al., 2006). The PCM was contained in several cylinders at the top of the water tank. A granular sodium acetate trihydrate-graphite was chosen as the PCM. The experiments were classified as cooling down process, re-heating process and solar operation. The energy density was evaluated by comparing the sensible heat stored in the tank when only water was there, with the sensible and latent heat stored in the tank when PCM modules were present. It was concluded from those results that the consumer would have hot water for a longer period of time in case with PCM than in case without PCM. In case with PCM, hot water will be still available after the full discharge of the storage tank since the water will be heated up by the PCM. Ibanez et al. (2006) have demonstrated that for a single-family DHW system in Lleida, Spain, the solar fraction has increased by up to 8% due to the addition of PCM in the storage tank.

Different methods to incorporate the PCM into DHW system were proposed, including integration of the PCM into the solar collector (Rabin et al., 1995) and addition of PCM elements inside a standard water storage tank (Esen and Durmus, 1998, Mehling et al., 2003). Some researchers have stated that adding PCM to the storage

tank is aimed at compensating for losses at the top surface and to reheat the top layer after a period of discharge (Mehling et al., 2003). These effects would improve the availability of hot water to the end-user. However, the auxiliary heater that is present in practically every DWH system can also accomplish these functions.

The most significant criterion for evaluating the addition of PCM is whether the presence of the PCM will lead to an overall annual increase in the solar fraction, i.e., a better use of the collected solar energy and a reduction in the required amount of auxiliary energy. Talmatsky and Kribus (2008) have constructed a physical model to describe the heat storage tank with and without PCM. Their results indicate that contrary to expectations, the use of PCM in the storage tank does not yield a significant benefit in energy provided to the end-user. The main reason for this undesirable effect is found to be increased heat losses during nighttime due to reheating of the water by the PCM. In the framework of the IEA SHC Task 32 programme (<http://www.iea-shc.org/task32/publications/index.html>), which investigates advanced solutions for storing thermal energy in systems providing heating or cooling for buildings, the potential of new PCMs is studied to increase the energy density of small sized water stores. In that programme an interesting PCM model, using the TRNSYS type of water tank storage (Bony and Citherlet, 2007), was developed for different shapes (plates, cylinders and spheres) and numbers of PCM modules in the tank. In this model, subcooling, hysteresis and convection of the liquid part of the PCM in the modules was modeled. Comparisons between measurements and simulations has been undertaken to evaluate the potential of the proposed model. At Graz University of Technology (Schranzhofer et al., 2006; Hein and Streicher, 2006) the effect of PCM storage and water storage on the cycling rate, efficiency and emissions of boilers for various hydraulic systems was analyzed. At the University of Lleida, Spain (Ibanez et al., 2006) the

reference solar combisystem equipped with PCM containers in the top of the space heating store was simulated. Unfortunately most of the applications (IEA SHC Task 32) could not show a significant improvement of PCM stores compared to conventional water stores. It seems that there is also large temperature variation in the solar tanks, which greatly reduces the PCM gain. Indeed, the sensible heat of PCM is much lower than for water. The little effect of PCM compared to water is also due to the temperature loss of the heat transfer to the PCM from the surrounding water and vice versa and additionally the temperature loss of heat conduction in the stored PCM. Due to this temperature losses higher charging and lower discharging temperature from the surrounding water compared to a pure water store is needed.

The objective of this paper is to analyze the conditions under which such an absence of advantage of the use of PCMs in a DHW system were obtained in order to propose some future research axis for improving PCMs solar-based DHW systems. The mathematical model recently published by Talmatsky and Kribus (2008) is used in the present study. This model describes the heat storage tank with PCM, collector, pump, controller and auxiliary heater. Realistic environmental conditions and typical end-user requirements are imposed.

2. Numerical model of the solar DWH with PCM

The system consists of a storage tank, solar collector, pump, controller and auxiliary heater (Fig. 1). The heat store of 120 cm height and 40 cm diameter is divided into N fully mixed horizontal layers. Each layer contains water and PCM (Fig. 2) except the top and bottom layers of the tank which are PCM free in order to avoid direct losses from the PCM to environment. The PCM is arranged in cylindrical containers spaced apart in each layer, rather than in a single unit, in order to increase the surface area for convection. Water inlets and outlets are defined at the top and bottom layers.

The main assumptions of the approach are identical to those retained by (Buckles and Klein, 1980; Talmatsky and Kribus, 2008) namely:

- A forced circulation system with a pump rather than a thermosiphon natural circulation system.

- The problem is one-dimensional, with temperature variations and flow in vertical direction only.
- The PCM is of a composite type with high thermal conductivity, and therefore the lumped system assumption can be used.
- For the i th layer (Fig. 3), the variation of the internal energy of the fluid and PCM per time unit is due to energy fluxes exchanged at the bottom and the top of the layer, between fluid and PCM and the loss through the wall of the storage tank.

Fluid

$$m_i^w c^w \frac{dT_i^w}{dt} = \dot{Q}_i^{flow} + \dot{Q}_{i-cond}^{pcm/w} + \dot{Q}_{i-loss} + \dot{Q}_{i-pcm} \quad (1)$$

PCM

$$m_i^{pcm} c^{pcm} \frac{dT_i^{pcm}}{dt} = \dot{Q}_{i-cond}^{pcm} + \dot{Q}_{i-w} \quad (2)$$

where \dot{Q}_i^{flow} is the contribution of energy change of layer i due to charging/discharging via direct inlet/outlet flow including the flow upward/downward in the tank. $\dot{Q}_{i-cond}^{pcm/w}$ represents the contribution of the thermal conduction to neighboring layers. The contribution of conduction between water in layer i and water in one of the neighboring layers ($i \pm 1$) has the form: $k^w \Delta A_{i,i\pm 1}^{w-w} (T_{i\pm 1}^w - T_i^w) / \Delta x_i$ where $\Delta A_{i,i\pm 1}^{w-w}$ is the contact area of the water element i to the neighboring water element. The contribution of the conduction between the PCM in layer i and PCM in one of the neighboring layers ($i \pm 1$) has the form: $k^{pcm} \Delta A_{i,i\pm 1}^{pcm-pcm} (T_{i\pm 1}^{pcm} - T_i^{pcm}) / \Delta x_i$ where $\Delta A_{i,i\pm 1}^{pcm-pcm}$ is the contact area of PCM element, if it exists in the relevant layer. \dot{Q}_{i-loss} stands for the losses through the tank envelop to the ambient. The heat loss from each layer to the environment takes the form $U_a \Delta A_i (T_i^w - T_a)$ where U_a is the overall loss coefficient, taking into account the tank insulation and external convection to the ambient air and ΔA_i is the relevant heat transfer area to the ambient, including the bottom and top bases of the cylindrical tank for the two relevant layers. $\dot{Q}_{i-pcm/w}$ corresponds to the convection between the storage medium and the PCM modules. Convection occurs between water and PCM element in the same layer, and possibly between water and a PCM element in a neighboring layer, in case that the layer does not contain PCM, or its PCM has a different geometric configuration

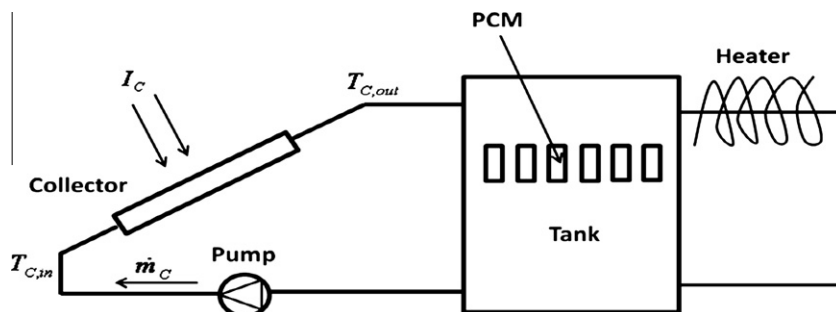


Fig. 1. Layout of the DHW system.

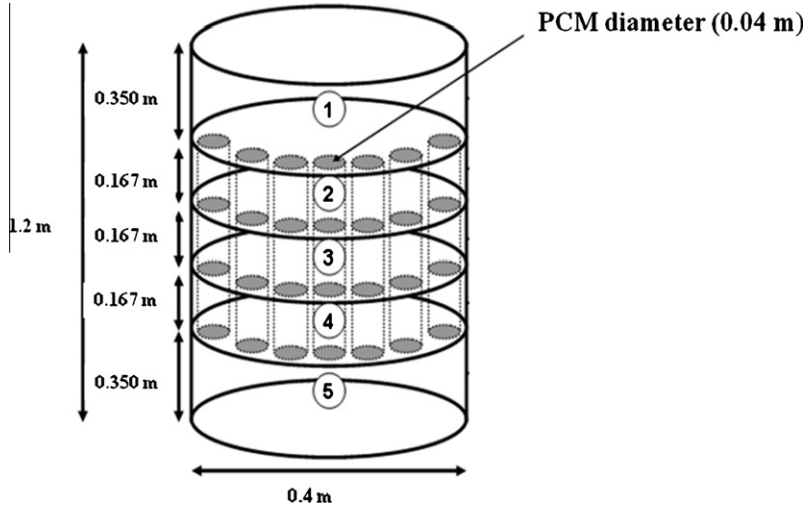


Fig. 2. Tank dimensions and arrangement of the PCM cylinders.

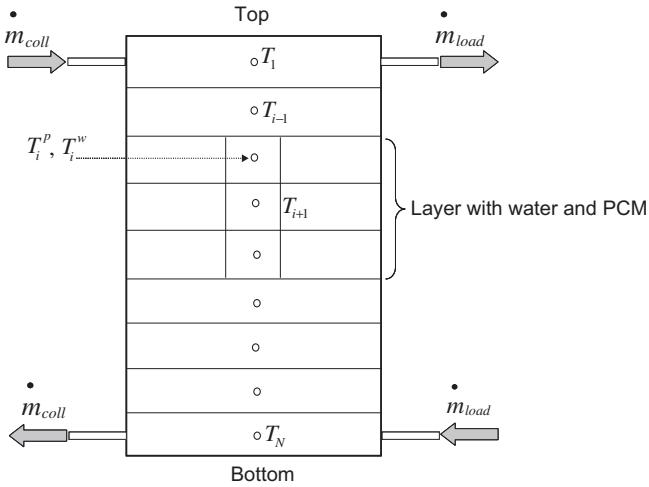


Fig. 3. Discretisation of the tank domain.

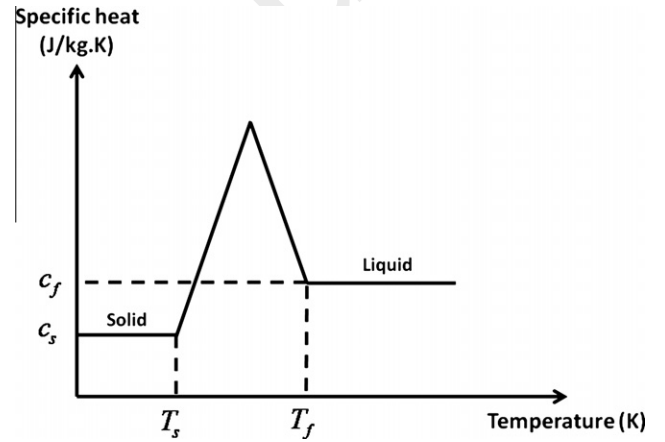


Fig. 4. Specific heat model for the composite PCM.

Table 1
Thermophysical properties model parameters for one composite PCM: NaOAc 3H₂O graphite (SAT G).

SAT G	
L_{sf} (kJ/kg)	173
T_s (°C)	57.31
T_f (°C)	60.75
C_s (kJ/kg K)	4.02
C_f (kJ/kg K)	3.68
k (W/m K)	5.0
ρ_s (kg/m ³)	1340
ρ_l (kg/m ³)	1300

relative to the neighboring layer. The contributions of the two types to the energy balance of the water are: $h_{i,i} \Delta A_{i,i}^{w-pcm} (T_i^{pcm} - T_i^w)$ and $h_{i,i+1} \Delta A_{i,i+1}^{w-pcm} (T_{i+1}^{pcm} - T_i^w)$. The value of the convection coefficient h was estimated during times when the fluid is stationary (no flow through the tank) using standard correlation for vertical and horizontal surfaces (Incropera and Dewitt, 2002) and during times with net flow, using correlations for parallel flow along cylinders (El-Wakil, 1971; Esen and Durmus, 1998).

The variation of the PCM properties during the phase change process was modeled by a variable specific heat, with values taken from measurements for several types of materials (Zabla et al., 2003). For many composite PCM's the phase change is not at a single temperature, but spread over a range of several degrees. The specific heat is modeled by using an apparent specific heat capacity (Fig. 4). The model parameters and other thermo-physical properties for one type of composite PCM are given in Table 1.

The solar collector model is derived by assuming a linear variation of its efficiency with respect to the normalized temperature difference, namely:

$$\eta_c = C_0 - C_1 X \quad (3)$$

The constants were taken from the performance data of real collectors (Table 2). The normalized temperature difference is defined as:

Table 2
Storage tank and solar collector data.

Collector area	2.67 m ²
Collector C0	0.735
Collector C1	4.6 W m ⁻² K ⁻¹
Maximum flow rate	0.0225 kg s ⁻¹
Tank volume	150 l (height = 1.2 m; radius = 0.4 m)
Tank heat loss coefficient	(0.57 1.13) W m ⁻² K ⁻¹

$$X = \frac{\frac{1}{2}(T_{C,in} + T_{C,out}) - T_a}{I_C} \quad (4)$$

The collector energy balance provides another equation for the collector efficiency, namely:

$$\eta_C I_C A_C = \dot{m}_C c^w (T_{C,out} - T_{C,in}) \quad (5)$$

Eqs. (3) and (5) are solved simultaneously to determine the collector water outlet temperature. The pump controller activates the variable-speed pump when the collector water temperature exceeds 34 °C, or when the difference between inlet and outlet of the collector exceeds 4 °C. The detail of the pump operation logic can be found in Talmatsky (2007). These conditions are typical of control schemes used by DHW system manufacturers in Israel (Talmatsky and Kribus, 2008).

In many DHW systems, an auxiliary electrical heating element is installed inside the storage tank. This may lead though to activation of the auxiliary heater in some situations when solar heat is available and there is no need for auxiliary heat. In the present work, the auxiliary heater is placed on the outlet pipe outside the storage tank (Fig. 1). The auxiliary heater is equipped with a thermostat that measures the temperature of the water delivered to the end-user: when this temperature falls below 40 °C, the heater is activated at an average power sufficient to bring the temperature back to 40 °C. This setup enables a clear separation between solar derived heat and auxiliary heat, and definition of the minimum amount of backup electricity that is needed to satisfy the user's requirements.

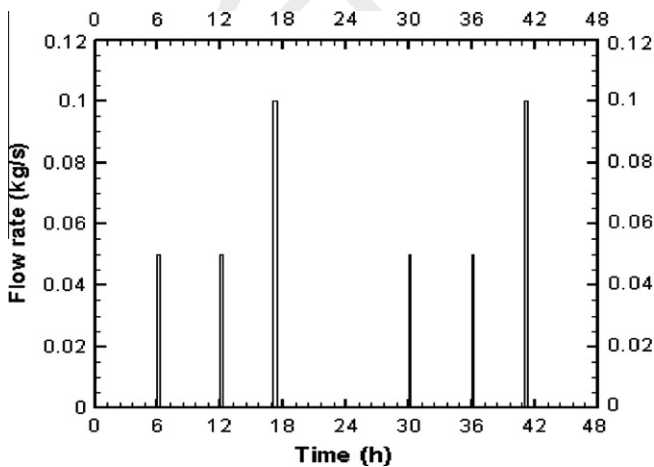


Fig. 5. End user daily load profile: mass flow rate of water provided to the end user at 40 °C.

Environmental data for a typical meteorological year at Tel-Aviv (latitude 43°19'N, Israel) were taken from (Talmatsky and Kribus, 2008) who used the meteorological software METEONORM (Meteotest, Switzerland). A second location was chosen in France, at Pau (latitude 32°05'N) for which the data were taken from the daily recordings performed by Météo France.

A simple user load profile that concentrates hot water consumption during three periods per day is used, as shown in Fig. 5. For this profile, the overall daily consumption was normalized to 180 l/day of water at 40 °C. The water from the tank was diluted with cold water whenever its temperature was above 40 °C, and the auxiliary heater was turned on when the inverse situation prevailed. All component models were implemented in FORTRAN and the overall system model was integrated in time for an entire year.

3. Results and discussion

In order to illustrate the temperature history inside the tank, Fig. 6 presents the 2-day (January 30-31) temperature evolution of the top and bottom layers of the tank filled with PCM. The temperature drops that are seen in that figure at 6:00, 12:00 and 17:00 are due to the hot water consumption load. As expected, during the afternoon, the temperature of the top layers in the tank with PCM is lower than that observed without PCM (see Fig. 7). The reverse situation is observed overnight. After 17:00, when there is no insolation, there is a reheating of water: as a result of heat transfer from the PCM to the water, the temperatures in the storage tank with PCM become higher than in the case without PCM.

Two more days of the year were examined. Fig. 8 shows the temperature of the bottom layer in the cases with PCM and without PCM during April 1-2. In the evening, the

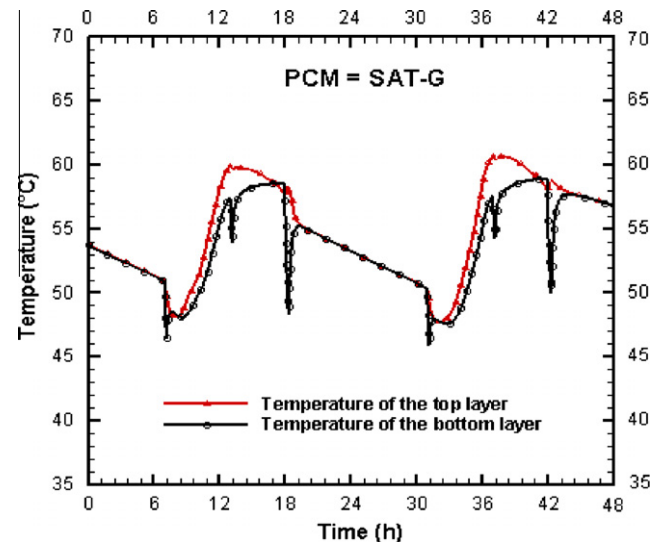
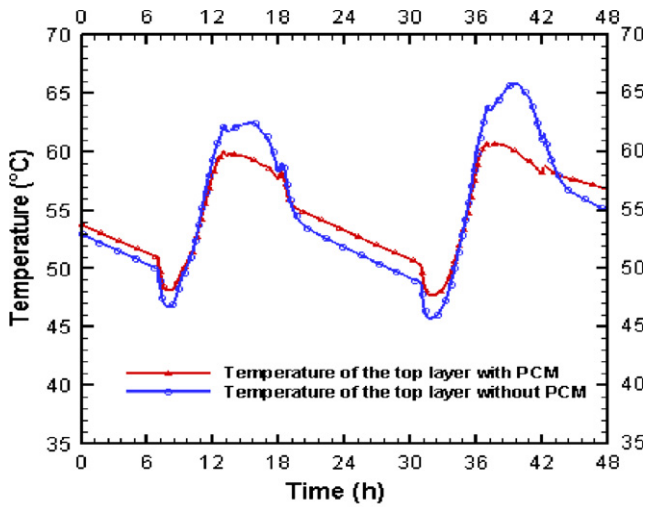
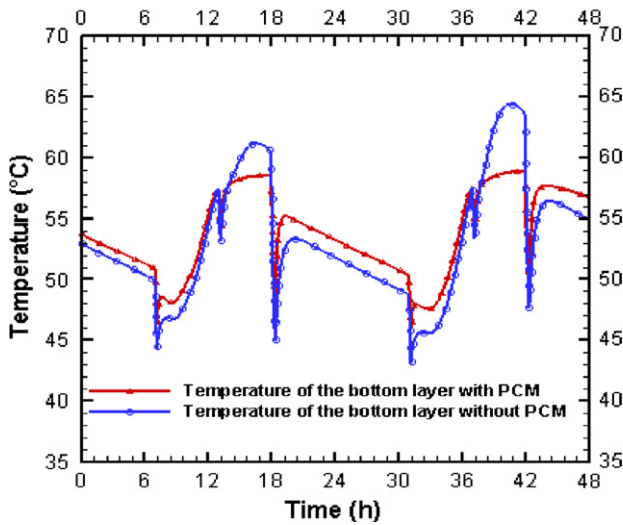


Fig. 6. DHW system with PCM (Tel Aviv, Israel, January 30 and 31, see PCM properties Table 1): 2 day temperature evolution of the top and bottom layers in the tank.



(a) (Tel Aviv – Israel)



(b) (Tel Aviv – Israel)

Fig. 7. DHW systems with PCM (see properties Table 1) and without PCM (Tel Aviv, Israel, January 30 31): 2 day temperature evolution of the top layer (a) and bottom layer (b).

temperatures in both cases are very similar. The temperature scenario reported by Talmatsky and Kribus (2008) with and without PCM is clearly recovered: lower water temperature levels in the storage top layer with PCM during the day (lesser loss to the ambient) but higher water temperature level during the night due to re-heating by the PCM. As a result, the gain in efficiency during the day hours is negated during the night.

An annual simulation using the real properties of the SAT-G (as defined in Table.2) was carried out and the results are presented in Table.3. The storage tank that contains PCM has lower energy losses to the surrounding compared to storage without PCM. The amount of electrical energy required in case of storage with PCM is also lower. However, the differences between two systems (with and without PCM) are still very small. The differences are still within the uncertainty of the simulation, and are there-

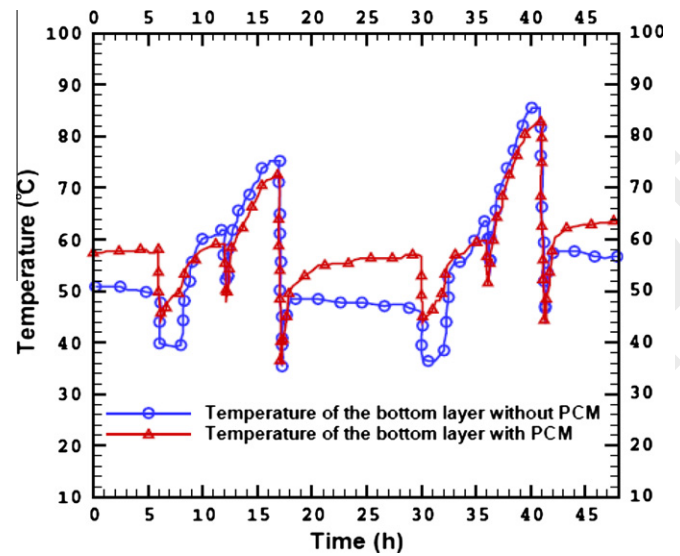


Fig. 8. DHW system with PCM (see properties Table 1): 2 day temperature evolution of the top and bottom layers in the tank.

fore not significant. Such a behavior is in qualitative accordance with that reported by Talmatsky and Kribus (2008).

This is a clear confirmation that the findings of these authors can be reproduced and indicates that their conclusion regarding the non-beneficial impact of the use of PCM in a DHW system has to be considered with great care. The PCM NaOAc-graphite, used in the present simulations, undergoes a phase change in a small temperature range around 58 °C. Since the temperatures in the storage tank during January 30 31 are frequently below the phase change temperature level, most of the time both systems (with and without PCM) store energy as sensible heat only, and the potential of the PCM is thus far from being fully utilized. It should be possible though to find a better if not optimal PCM melting temperature considering the specific climate of the site over the year. A first step paving the way towards that objective is to illustrate the sensitivity of the tank behavior to the choice of the PCM melting temperature. Accordingly, simulations were carried out with another type of PCM whose melting temperature (around 50 °C) was chosen to be lower than the one previously considered by Talmatsky and Kribus (2008). All the properties but the phase change temperatures were chosen to fit those of NaOAc-graphite (see Figs. 9 and 10).

The results obtained are quite encouraging. Indeed, as can be seen in Fig. 9, the recourse to a lower PCM melting temperature yields an overnight evolution which is

Table 3
Results of the annual simulations (Tel Aviv, Israel SAT G).

	With PCM	Without PCM
Solar energy to consumer (MJ)	6640	6457
Electrical backup required (MJ)	787	843
Tank losses (MJ)	2346	2378
Collector efficiency (%)	45.4	45.2

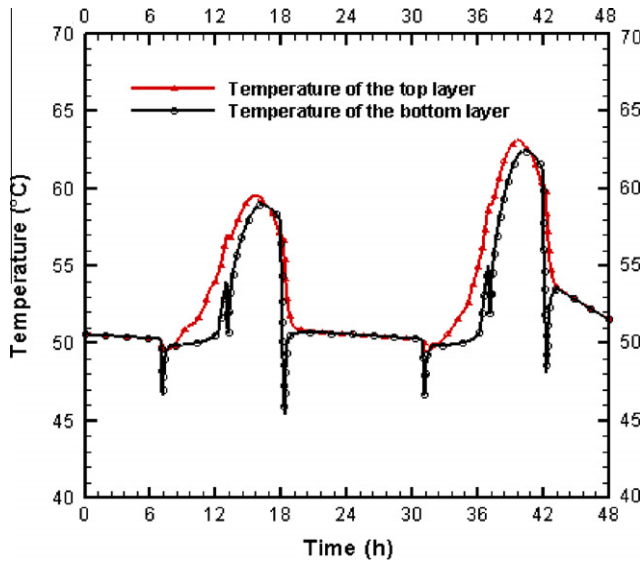


Fig. 9. DHW system with PCM (reduced melting temperature of around 50 °C): 2 day temperature evolution of the top and bottom layers in the tank (Tel Aviv, Israel, January 30 and 31).

characterized by a quasi-constant level of the temperature to be compared to the 5° decrease observed in Fig. 6 during the same period. Such a plateau is clearly related to the permanent reheating of the water due to the phase change process (solidification) undergone by the PCM. The same phenomenon appears in all five layers, but is more pronounced for the bottom layer because of its lower temperature level. This reheating affects the thermal losses between the tank and its surroundings in a way similar to that reported by Talmatsky and Kribus (2008) but with a lesser intensity due to the lower temperature level attained. Thus, the good news is that the reduction of the annual electrical energy backup amounts now to 14% (see Table.4) which is twice as much as the figure obtained with the former PCM. A slight increase of the collector efficiency is also noted.

Another site (Pau-France) was chosen in order to examine the influence of environmental data on the system performances. Accordingly, simulations were carried out with another type of PCM whose melting temperature (around 35 °C) was chosen to be lower than the one previously considered by Talmatsky and Kribus (2008). In the case of Pau, more electrical power from the auxiliary heater is required as a result of the lower insolation. However, again there is no significant difference in the total amounts of energy between the system with PCM and the conventional system. The two systems provide almost identical annual performance, even with a slight advantage to the system with PCM (see Table 5).

Thus, these preliminary results show that to be efficient, the design of DHW systems with PCM cannot be solely based on a trial and error basis as it proved to be highly sensitive to first order parameters such as the PCM melting temperature or the PCM confinement geometry. Moreover, it is clear that the choice of the PCM has to be done on a

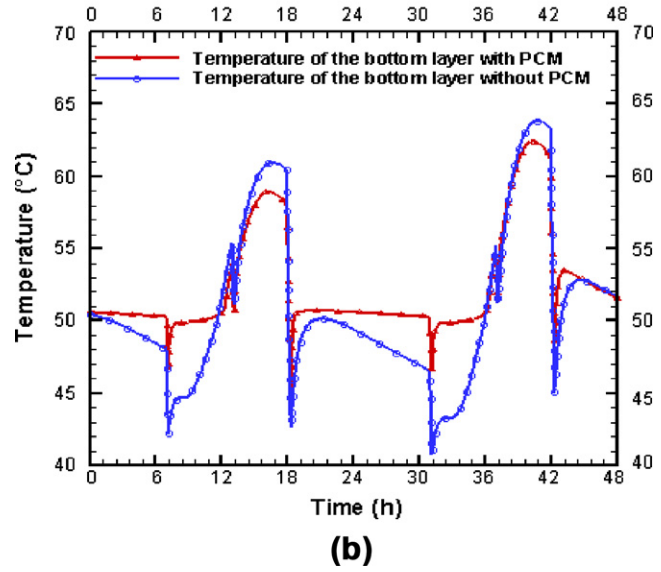
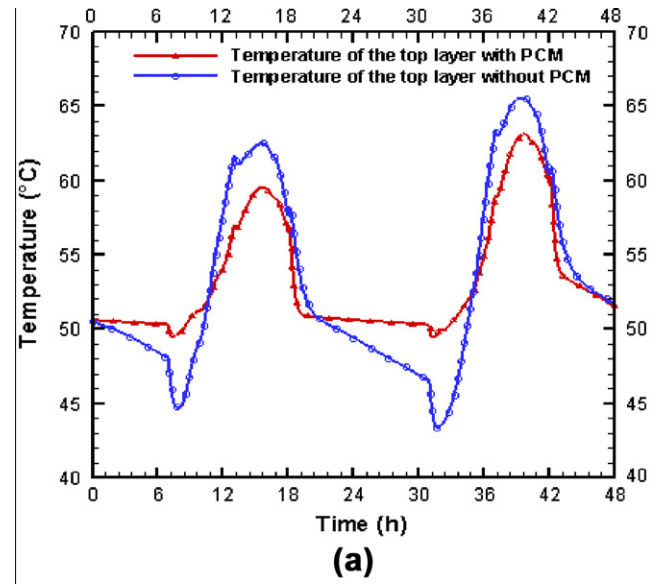


Fig. 10. DHW systems with PCM (reduced melting temperature of around 50 °C) and without PCM: 2 day temperature evolution (January 30 31) of the top layer (a) and bottom layer (b).

Table 4
Results of the annual simulations (Tel Aviv, Israel) of the artificial PCM (melting temperature = 50 °C).

	With PCM	Without PCM
Solar energy to consumer (MJ)	6692	6457
Electrical backup required (MJ)	723	843
Collector efficiency (%)	46.5	45.2

case by case basis depending on the precise location of the DHW system installation. This may render the industrial process a bit complicated to handle and could be rather detrimental in terms of return on investment. Clearly, a mathematical optimization procedure has to be used in order to design such systems considering the complexity of their response to the relevant design parameters.

Table 5

Results of the annual simulations (Pau, France) (PCM = NaOAc 3H₂O graphite (SAT G)) (melting temperature = 35 °C).

	With PCM	Without PCM
Solar energy to consumer (MJ)	5621	5439
Electrical backup required (MJ)	1051	1135
Collector efficiency (%)	32.1	31.6

4. Conclusion

The results of the present study confirm the findings by Talmatsky and Kribus (2008) regarding the use of PCM in DHW systems that may prove not to be substantially beneficial. It has been shown though that the high sensitivity of the DHW system to the choice of first order design parameters such as the PCM melting temperature may open the perspective of successfully designing a PCM based DHW system that may be more efficient than its PCM free counterpart. Considering the quite specific sensitivity of the DHW system to the nature and layout of the PCM, it seems highly desirable to incorporate a mathematical optimization at the early stages of the design process.

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