Energetic Interest of the Use of Phase Change Materials in a Solar Domestic Hot Water System

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Abstract

The introduction of phase change materials (PCM) into domestic hot water (DHW) systems is currently studied to try to increase their performances. However the effectiveness of such a use is not really proved in all configurations. The concepts of effectiveness and optimum can correspond to several definitions, which make the analysis even more complex. In this paper some elements of reflexion based on the exploitation of a model using energy balances have been developed. Simulations were performed to compare the performance of a solar DHW system with PCM to a similar system without PCM. The results depend on many factors, including site conditions, load profile, design of the system, type and amount of PCM. For the climate of Pau (south-west of France), the results indicate that the use of PCM into the selected storage tank does not provide a significant benefit.

Keywords: Solar energy, Domestic Hot Water, Phase Change Material

1. Introduction

Amongst the elements of comfort for houses, one main point is the production of domestic hot water permanently, in sufficient quantity and at the adequate temperature. The equipments satisfying this request are many but more or less effective. Their choice depends on many criteria: existing heating installation, size and practises of the family, supplied energy, characteristic of housing, etc.

The types of domestic hot water systems can be broken down into two categories: hot water is stored in a cylinder (tank) or cold water is heated on demand. When heated water is stored, it is maintained in temperature in an insulated container. In the instantaneous production, water is heated at the time of the request.

Electricity is often used to produce domestic hot water independently, using a storage tank in which an immersed resistance heats water to the required temperature. So that this system is economic, it is necessary to subscribe a rate which makes it possible to heat water for the periods when electricity rates are at their cheapest and use it during the day. This installation can be complementary to equipment using solar energy.

The production of domestic hot water (DHW) is currently the object of studies relating in particular to its energy effectiveness as well as the size and the volume of the storage tanks. A lot of configurations are possible.

The introduction of phase change materials (PCM) may provide solutions, by using the latent heat instead of the sensible heat, as mentioned in the abundant literature in the field [1, 2, 3]. The insertion of PCM in domestic hot water system is not new but the conclusion about the utility of their use is not obvious [4].

Melhing et al. [5] carried out experiments and simulations using different cylindrical PCM modules. Using paraffin as PCM, they showed that energy density could be improved by 20 to 45%, the measured time gains to delay heat loss was in the order of 50–200% and reheating of water was verified to be more rapid thant without PCM.

Tests using cylindrical PCM modules were also performed under real operating conditions in a complete solar domestic water heating system (SDHW) in Lleida, Spain [6, 7]. Cabeza et al. [6] showed that the use of sodium acetate trihydrate as PCM in modules gives a very good performance of the tanks. Mazman et al. [7] tested new PCM-graphite compounds with optimized thermal properties, such as 80:20 weight percent ratio mixtures of paraffin and stearic acid (PS), paraffin and palmitic acid (PP), and stearic acid and myristic acid (SM). The PCM is confined in three cylindrical modules. They concluded that PS gave the best results for thermal performance enhancement of the SDHW tank (74% efficiency). The modelization of these systems by Ibanez et al. [8] confirmed the experimental results.

In the work of Tamalsky and Kribus [4], annual simulations were done to compare the performance of a storage tank with PCM to the same tank without PCM. Realistic environmental conditions and typical end-user requirements were imposed. Annual simulations were carried out for different sites, load profiles, different PCM volume fractions, and different kinds of PCM. The results of all simulation scenarii 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 authors concluded that the main reason for this undesirable effect is the increase in heat losses during night-time due to reheating of the water by the PCM.

These different results show the necessity to complete studies to confirm or not the pertinence of the use of PCM inside domestic hot water tanks. Until now, the performed works mainly deal with the detailed study of the heat transfers within domestic hot water systems of fixed designs, with numerical and/or experimental approaches. We propose here a different approach by analysing a system described by a set of characteristic parameters (dimensions of the system, inlet water temperature, type of control, type of drawing, nature of PCM, etc). The evaluation of a particular configuration, which is coupled with a solar collector, requires the definition and the calculation of various criteria such as for example the ratio of the useful energy to the total energy supplied for its operation.

2. Studied systems

The studied DHW system is a solar DHW tank presented in Figure 1. PCM can be added into the tank. Solar hot water heaters can provide households with a large proportion of their hot water needs while cutting back on home energy costs. The amount of hot water that solar energy will provide depends on the type and size of the system, the climate, and the quality of the site in terms of solar access. The DHW tank is here coupled with a solar flat plate collector. A back-up heating system for water will be necessary during times when solar radiation is insufficient to meet hot water demands. At night and on cloudy days, the conventional backup heater boosts the water to the desired temperature. On sunny days, however, when a typical solar system can raise water to the desired temperature, the backup heater remains off.

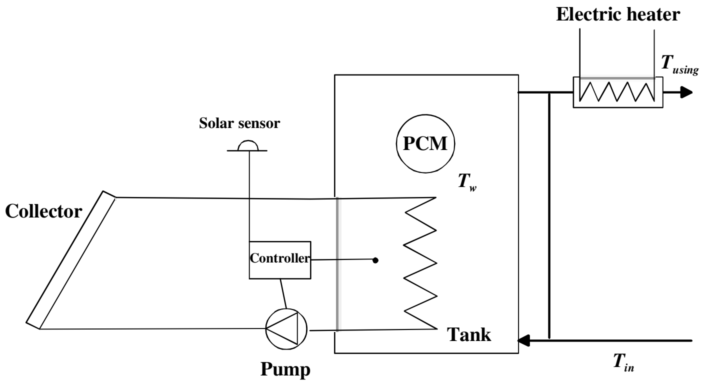

Fig. 1. Layout of the DHW system

We choose an indirect (closed loop) active system using an electrically driven pump and valves to control the circulation of the solar loop. A solar radiation sensor (pyranometer) combined with a controller activates the pump when the incident solar flux is higher than a minimum value and when the water temperature inside the tank is lower than the boiling temperature. The heat collected from the absorber plate is transferred to the water through a heat exchanger such as for example a coil either inside or wrapped around the storage tank. The type of heat exchanger system can affect the overall efficiency of the solar system since heat exchanger efficiencies range from less than 40 percent to about 90 percent.

The expected using temperature T_{using} is obtained mixing water from the tank at temperature T_w with water coming from the network at temperature T_{in}. When $T_w < T_{using}$, the additional electric heating element heats water to the expected temperature, consuming an additional power P_a.

3. Model

The DHW tank is considered as a cylinder of total volume V_{tot} and of external surface S_{ext}. A fraction of this volume is filled with the PCM and the remaining volume V_w corresponds to the hot water. First, the temperature of water T_w(t) and PCM T_{PCM}(t) (melting at T_M) are supposed to be uniform. This restrictive assumption permits to use a simple description of the system to limit the number of characteristic parameters. Indeed, the consideration of the thermal stratification inside the tank would force us to choose with precision the place and the geometry of the PCM.

A dimensionless number β has been defined as the ratio of the exchange surface between the PCM and the water, S_{int}, to the area of a sphere of same volume. So, $S_{int} = \beta\sqrt[3]{36\pi V_{PCM}^2}$.

The energy balance of the water inside the tank under unsteady behaviour is written:

$$\rho_w V_w C_w \frac{dT_w(t)}{dt} = H_{ext} S_{ext} \left(T_\infty - T_w(t)\right) + H_{int} S_{int} \left(T_{PCM}(t) - T_w(t)\right) + \dot{m} C_w \left(T_{in} - T_w(t)\right) + P_s(t) \qquad (1)$$

where ρ_w and C_w are respectively the density and the specific heat of the water. H_{ext} and H_{int} are respectively the global exchange coefficients between the water and the ambient medium (temperature T_∞) and between the water and the PCM. $\dot{m}(t)$ is the drawing water mass flow rate. T_{in} is the inlet water temperature. The total heat power P_s(t) corresponds to the received solar power.

The energy balance of the PCM is calculated according to the solid, liquid or solid-liquid states of the PCM: m_{PCM} is the mass of the PCM.

$$m_{PCM}\frac{du_{PCM}(t)}{dt}=H_{int}S_{int}\left(T_w(t)-T_{PCM}(t)\right) \qquad (2)$$

For a pure PCM, the internal energy u_{PCM} is calculated as function of the temperature T, the specific heat of the solid and liquid PCM, the latent heat and the melting temperature of the PCM.

The solar collector is based on linear variation of the efficiency with the normalized temperature difference X :

$$\eta_C=\eta_o-aX \qquad (3)$$

Where η_o is the optical efficiency and a the loss coefficient. X is given by:

$$X=\frac{\left(\frac{T_{C,in}+T_{C,out}}{2}\right)-T_\infty}{I_s} \qquad (4)$$

where $T_{C,in}$ and $T_{C,out}$ are respectively the inlet temperature and the outlet temperature of the collector. I_s is the incident solar flux.

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

$$\eta_C I_s A_C=\dot{m}_C C\left(T_{C,out}-T_{C,in}\right)=P_s(t) \qquad (5)$$

Where A_C is the collector area, $\dot{m}_C$ and C are respectively the mass flow rate and the specific heat of the fluid inside the solar loop. As the most part of the thermal inertia is situated in the tank (water and PCM), this equation is written under steady states conditions.

The heat is transferred to the tank thanks to a heat exchanger whose efficiency ε is defined by:

$$\varepsilon=\frac{T_{c,out}-T_{c,in}}{T_{c,out}-T_w} \qquad (6)$$

Equations (3) and (5) are solved simultaneously to find the collector water outlet temperature (which corresponds to the inlet temperature of the exchanger) and Equation (6) permits to determine the water temperature inside the tank.The previous equations were solved using an Euler scheme with constant step. The simulation is made for several consecutive days in order to limit the influence of the initial conditions.

The selection of comparison criteria of different running scenarii is not really evident. The first selected criterion is the mean efficiency during the last 24 hours which is defined by:

$$\eta=\frac{Q_{useful}}{Q_s+Q_a}=1-\frac{Q_{losses}}{Q_s+Q_a} \qquad (7)$$

Q_s, Q_a and Q_{losses} are respectively the heating solar energy, the additional electrical energy and the lost energy during the period. Q_{useful} is the useful energy which is :

$$Q_{useful}=\int \dot{m}C\left(T_{using}-T_{in}\right)dt=C\left(T_{using}-T_{in}\right)\int \dot{m}dt \qquad (8)$$

The integration period corresponds to the last 24 hours of the simulation and the efficiency is always compared to the reference case without PCM (η_{ref}).

Another criterion can be the ratio between the amount of electrical energy and the useful energy:

$$\sigma = \frac{Q_a}{Q_{useful}} \tag{9}$$

This value is always compared to the reference case without PCM (σ_{ref})

4. Results

The type of users load profiles is presented in Fig. 2. The daily volume is 180 liters

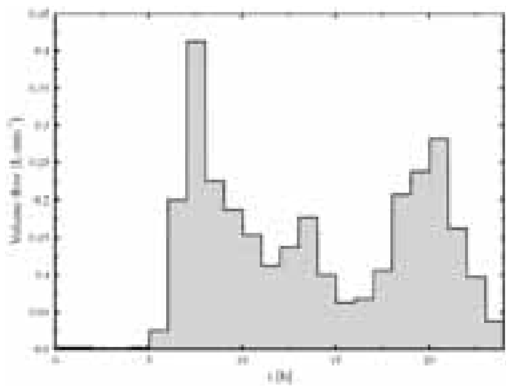

Fig. 2. End user load profile: volume flow of water provided to the end-user at 50 °C.

The regulation is on-off feedback control and the pump controller is activated when the incident solar flux is higher than 50 W.m^{-2} and when the water temperature is lower than 95 °C. The temperature of the inlet water T_{in} does not vary and is equal to 15 °C. The other values used in the simulation are given in Table 1.

Table 1 Storage tank and solar collector data

Collector	area = 4 m^2 Optical efficiency: η_o = 0.8 Loss coefficient: a = 3.5 W m^{-2} K^{-1} Flow rate for the solar loop: 90 L.h^{-1}.m^{-2}
Tank	Volume: 300 liters Exchanger efficiency: 60% Tank heat loss coefficient (including insulation): 2 Wm^{-2}K^{-1} Heat transfer coefficient (PCM – water): 50 Wm^{-2}K^{-1} β = 1 (the PCM container is spherical)
PCM	Melting temperature between 25 and 65 °C Latent heat of melting = 150 kJ kg^{-1} Solid and liquid specific heat = 2 kJ kg^{-1} K^{-1}

Fig. 3 shows the evolution of the water and PCM temperatures during a day when considering a proportion of PCM (α) of 20 %. These results stand for the month of July for the city of Pau (France, latitude 43 degrees north).

Globally, the presence of PCM induces a decrease in the daily average temperature of the water, thereby reducing the thermal losses of the tank with the ambiance. In this example, the entire PCM is melted from approximately 10:00 to 15:00 thanks to the heat delivered by the solar collector. After that, the solar heat is converted in sensible heat, leading to the increase of the PCM temperature. Due to the domestic hot water loads profile and the lack of sun during the late evening and the night, this temperature starts decreasing until reaching the melting temperature, approximately at 0:00 in this case. When hot water temperature becomes lower than the melting temperature, the heat stored in the PCM is then released at constant temperature (here 48 °C) leading to its crystallization (from 0:00 to about 10:00).

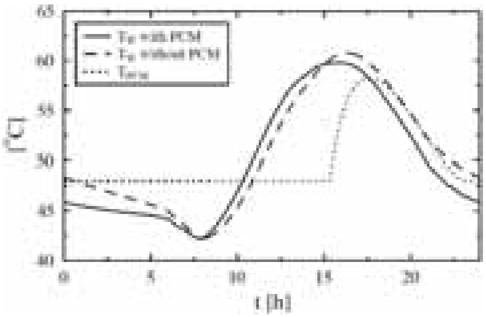

Fig. 3. Evolution of the temperatures inside the tank

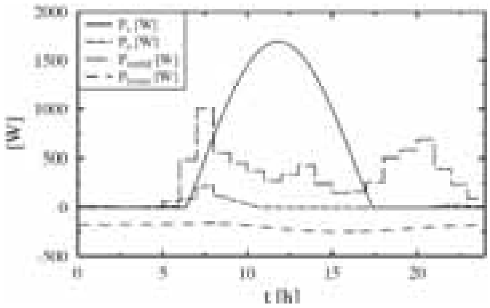

Fig. 4. Evolution of the various power levels reached during a day

Fig. 4 shows the evolution of the different power levels exchanged at every time during all day. The solar power brought by the collectors is classical and does not bring any particular comment. Having in mind the loads presented in the fig 2, the useful power delivered to the users is relatively easy to interpret and follows this profile. Concerning the thermal losses (negatives in this figure), they are correlated to the temperature inside the tank. The additional electrical heater is turned on in the morning when the needs are higher than the heat stored at that moment and at the required temperature in the tank. It appears in these figures that the PCM does not really affect the thermal behaviour of the domestic hot water tank.

Concerning energetic aspects, integration over time of power information has been preferred and compared to the reference case (without PCM) through the dimensionless numbers η and σ.

Several simulations were performed. The amount of PCM α has been varied between 0 and 50 % of the total volume of the tank (the remaining volume corresponds to water). The melting temperature of the PCM has been also varied from 25 to 65 °C in the following.

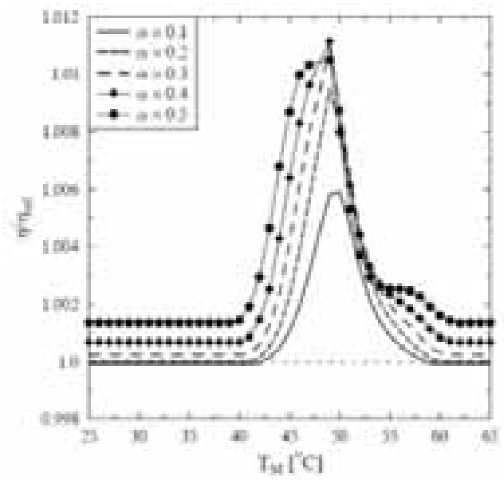

Fig. 5. Evolution of η/η_{ref} versus the melting temperature for several PCM quantities

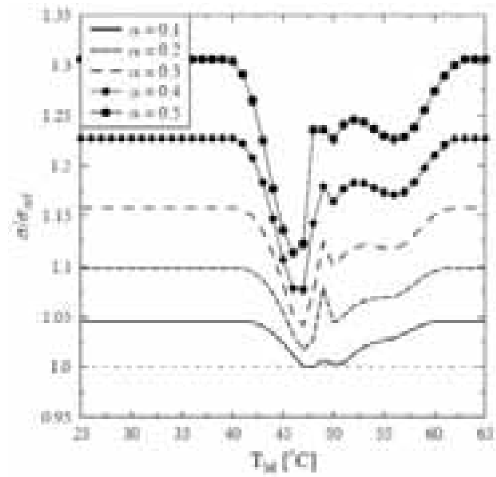

Fig. 6. Evolution of σ/σ_{ref} versus the melting temperature for several PCM quantities

Fig. 5 shows that the introduction of PCM inside the simulated tank does not really improve η (only 1% in our case). This is not really surprising since the introduction of PCM only changes the way of storing energy not its amount. It seems from this figure that the melting temperature choice influences the results, so as the proportion of PCM (α). These results do not highlight the energetic interest of using PCM and the differences are only situated in the amount of thermal losses between each investigated case.

On the other hand, the Fig. 6 shows that the introduction of PCM increases the use of the additional electrical energy compared to the value without PCM. This phenomenon is less sensitive in the case where the melting temperature is about 48°C.

As the daily usable energy is constant, the efficiency increases as losses decrease, i.e. when the water temperature decreases. The search for optimum efficiency thus leads to limit the temperature rise of the stock and thus to introduce a PCM having the lowest melting temperature compatible with the desired output temperature T_{using}. But in doing so, the additional energy required increases, inducing the increase of σ_{ref}.
Thus the optimum will be different depending on whether one considers a purely energetic criterion or an economic one.

Additional results for two identical systems but with and without PCM are shown in Table 2. The results correspond to the best case in July in Pau. The melting temperature of the PCM is 48°C and the PCM amount α is 20 %.

Table 2 Results of required daily energy with and without PCM

	With PCM	Without PCM	Variation (%)
Solar energy to consumer [kJ]	41506	41858	-0.84
Electrical backup required [kJ]	1974	1928	+2.35
Tank losses [kJ]	17120	17442	-1.84

The differences between the results with and without PCM are not really important. The electric backup required with PCM is slightly higher, the solar energy to consumer slightly lower and the tank losses slightly lower. The solar fraction is the same at 0.1 % but the variations are so small that one wonders if the use of materials is really an interest

5. Conclusions

The presented results show that the addition of PCM inside a solar domestic hot water system for the selected parameters and for the climate of Pau does not provide a significant improvement of the system. It is difficult to analyse the reasons. The losses to the environment seem to decrease in comparison of a system without PCM but the electrical backup required increases.

It should be noted that the results are calculated using a simplified model without thermal stratification inside the tank. The consideration of a stratification temperature in the volume of water, which, for example, forces to describe the position and the geometry of the PCM precisely, can moderate these conclusions.

It is important to note that the results depend on many factors, including site conditions, load profile, designs of the system, type and amount of PCM and therefore cannot be considered as a general result.

The sensitivity of the results to various parameters used in the model will be also investigated. The variation of the heat loss coefficient of the tank, the convective heat transfer coefficient between the PCM and the water, the PCM properties could change the conclusions. As an example, the exchange surface between the PCM and the water has been changed in the case of figure 7 and 8. Here β takes the value of 3, all other parameters being maintained at their same values. Globally the mean temperature of the tank remains lower with PCM, leading to lower thermal losses. On the other hand, the use of the additional electrical heater is less important in the case of the PCM ($\frac{\sigma}{\sigma_{ref}}$ = 80 %) as the temperature of water inside the tank remains relatively high when in the morning, the loads are important.

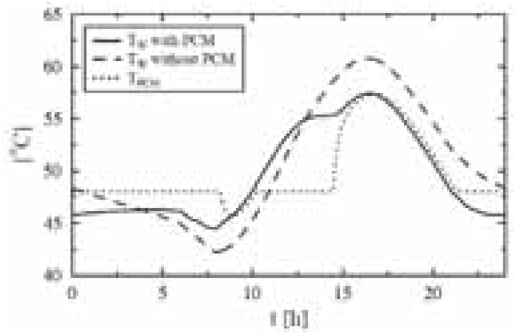

Fig. 7. Evolution of the temperatures inside the tank

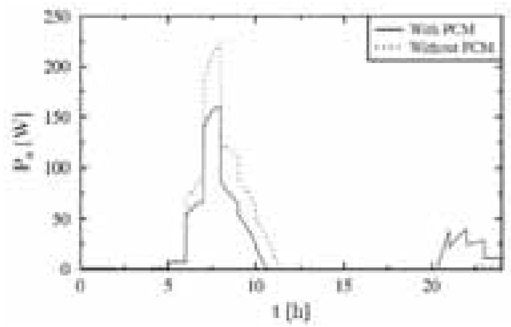

Fig. 8. Evolution of the required additional power during a day

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