Thermal Energy Storage with Phase Change Materials – A Promising Solution ?

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Abstract

Solar combisystems for space heating and domestic hot water (DHW) preparation mostly use a water tank for the storage of solar energy. In systems that are to achieve a high solar fraction relatively large water volumes are necessary. Alternative storage technologies such as phase change materials (PCM) and thermochemical materials (TCM) are a topic of research since many years, as they promise a higher storage capacity in comparison to the sensible storage of heat in water. Especially PCM technologies are claimed to be near to the market and there are already commercial products available.

In this paper the potential for the improvement of the solar fraction by using PCMs in solar combisystems is analyzed by means of dynamic system simulations. A reference solar combisystem is used to compare different configurations concerning the collector area, the storage volume and the type of storage, meaning water storage and PCM storage. The objective is to analyze the potential for improvement compared to water storage with PCM materials that are already available. On the other hand it is discussed, which properties a PCM material should have, in order to enable a significant improvement.

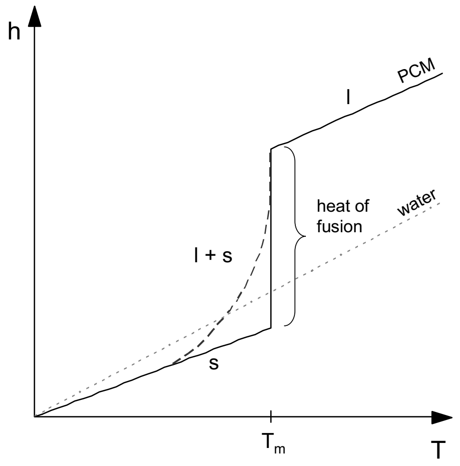
1. Introduction

PCMs make use of the latent heat of fusion that is involved in the phase change between solid and liquid. At the phase change temperature T_m a large amount of heat can be stored within a narrow temperature range (compare Fig. 1). If such materials are integrated into conventional water tanks, they can help to both increase the storage capacity and - with a suitable melting temperature - to maintain an appropriate temperature level over a longer period of time.

In this work it is analyzed, to which extent the solar fraction of a combisystem can be improved by incorporating cylindrical PCM modules inside a water storage tank. This is done by means of simulations in TRNSYS [1] using the reference solar combisystem and reference conditions that were defined in IEA SHC Task 32 [2] and a PCM storage model that was developed at the Institute of Thermal Engineering [3]. Different configurations with a variation of the following parameters are evaluated:

- Collector Area
- Storage Volume
- Amount of PCM in the tank
- Thermal properties of the PCM (latent heat, melting temperature, subcooling etc.)
- Diameter of the PCM modules

Fig. 1: Stored enthalpy h [kJ/kg] as a function of temperature T [°C] for a PCM material undergoing a phase transition at the melting temperature T_m. The heat of fusion is the amount of energy that must be added in order to fully transform the material from the solid (s) to the liquid (l) phase. For impure materials the phase transition occurs over a temperature range as indicated by the dashed line (l+s); the dotted line shows a material without phase change in this temperature range (e.g. water between 0 and 100 °C)



2. Boundary Conditions for the Simulations

2.1 Climatic conditions, building, loads

The ***climate*** of Zürich is used for the simulations with a climate data set based on hourly values generated in Meteonorm 5.1 [4]. The design ambient temperature is -10 °C.

In the framework of Task 32 four reference buildings were defined. For the work presented here the ***reference building*** with a heating demand of 30 kWh/m²a (heated floor area 140 m²) is used. The simulation of the building was done independently prior to the simulations of the solar heating system. A load file was generated out of this simulation, which contains the flow and return temperature and the water mass flow rate that is needed by the heating system in every simulation time step. This was done to save simulation time, as a lot of simulations with different configurations of the solar heating system were to be performed.

The reference building is equipped with a gas boiler as the heat source and a low temperature hydronic ***heating system*** (radiators). The flow temperature is controlled depending on the ambient temperature according to a heating curve (35/30 °C at T_{amb}=-10 °C, radiator exponent 1.3).

The used profile for the ***domestic hot water*** (DHW) demand was generated with a tool that considers the evolution of the demand over the year, different weekdays, during the day and also times of absence (e.g. holidays) [5]. Different studies, ranging from telephone surveys to detailed measurements, were used as a basis for this tool. The profile consists of a dataset, in which a DHW flow rate is assigned to each time step (step size three minutes) of the simulated year. A DHW demand of 200 l/d (4 persons with 50 l/d.person) with a DHW temperature of 45 °C is used in the simulations. This results in an annual DHW heat demand of about 3000 kWh.

2.2 Solar Combisystem

Figure 2 shows a schematic of the reference solar combisystem of IEA SHC Task 32, which is used in this work. The TRNSYS models (Types) that are used for the simulation of the individual components of the system are indicated in the figure.

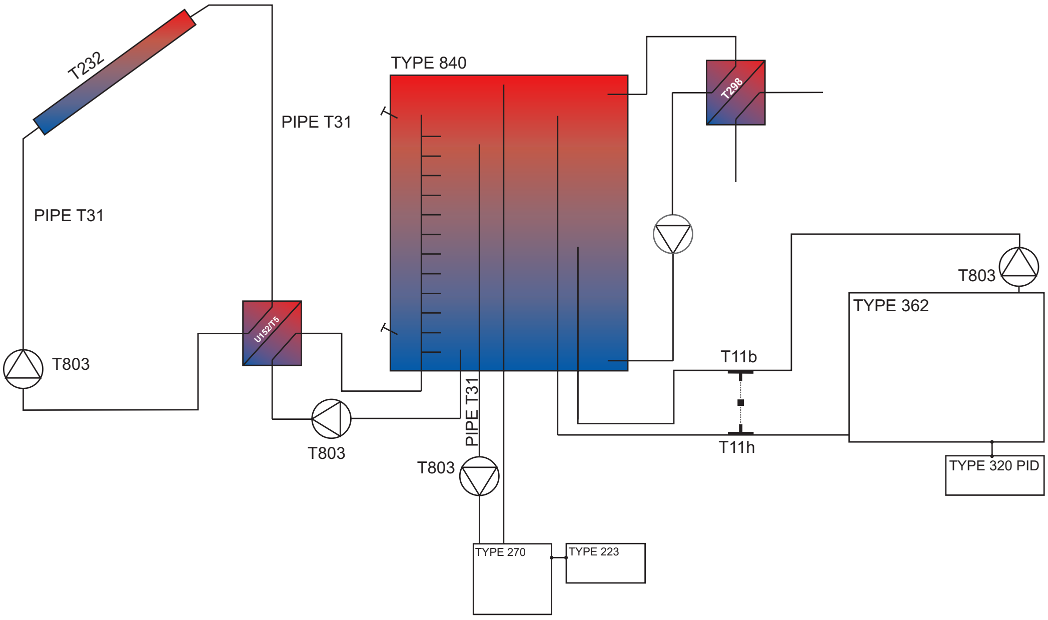


Fig. 2: Reference solar thermal system of Task 32 [2]

The main components of the system are the storage tank (Type 840), the solar collector field (Type 232), which charges the tank via a plate heat exchanger (Type 5), a gas boiler as the auxiliary heater (Type 270) and a plate heat exchanger for the instantaneous preparation of DHW (Type 298). In the version of the simulation deck used in this work the heating system (radiator → Type 362) is replaced with a load file. The flow temperature given in the load file is provided in every time step via a mixing valve (Type 11b). Also the return temperature from the heating system and the mass flow are predetermined by the load file. If the required temperature and power for the heating system or the DHW preparation can for any reason not be provided by the system, this is considered by means of "penalty functions". Details about the reference system are documented in [2].

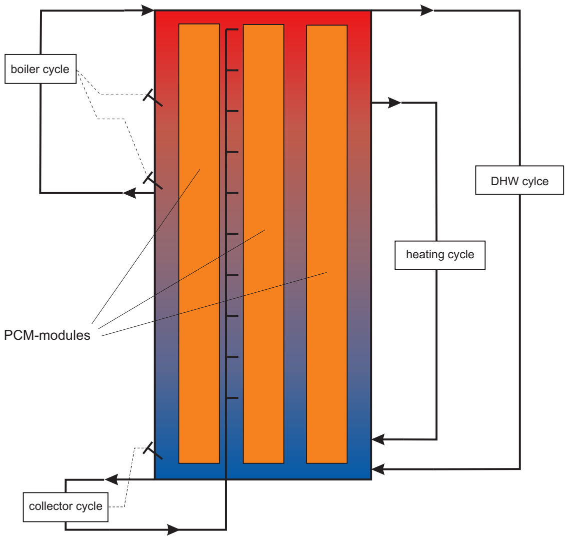


Fig. 3: Schematic of the solar tank with integrated PCM modules

2.3 Integration of PCM into the storage tank

The PCM is assumed to be incorporated in cylindrical modules, which are integrated into the storage tank and reach from the top of the tank to the bottom (see Fig. 3).

3 Simulated Configurations

Different configurations were defined for the solar thermal system concerning both the dimensioning of the collector area and the storage volume and also concerning the amount and kind of PCM in the tank. Table 1 shows an overview of the different storage tank configurations.

The theoretical heat losses of the storage tank (calculated with the tank geometry and insulation thickness) are increased by a factor (compare Table 1) in order to consider additional heat losses due to e.g. pipe and sensor connections, internal pipe circulation or imperfect insulation. This factor depends on the volume of the storage and is calculated according to an equation proposed in [6] and [2].

Table 1: Data of the simulated storage tank configurations

Storage volume	**Storage height**	**Insulation (λ=0.04 W/mK)**	**Nr. of PCM modules (50 %)***	**Nr. of PCM modules (75 %)***	**Factor for storage losses**
m³	m	m	-	-	-
0.4	1.8	0.15	25	38	2.60
0.8	1.9	0.16	48	71	2.42
1.2	2.0	0.17	67	100	2.32
1.6	2.2	0.17	84	126	2.24
2	2.3	0.18	99	148	2.19
4	2.9	0.22	155	232	2.01
8	4.2	0.30	215	323	1.83
16	6.2	0.46	293	439	1.68
32	7.7	0.78	472	708	1.68
48	9.2	1.00	593	889	1.68
64	10.7	1.00	680	1020	1.68

* % of the storage volume filled with PCM

The data of the used PCM materials is shown in Table 2. On one hand the properties of the well-known PCM Sodium Acetate Trihydrate are used. Additionally, simulations with a material that has a two times higher latent heat are performed. The authors are aware that such a material does not exist, but nevertheless the effect of a much higher latent heat shall be investigated.

Table 2: Data of the used PCM materials

Melting point	°C	58 [1]
Latent heat	kJ/kg	220 [1] / 440 [2]
Density	kg/m³	1400
Thermal conductivity	W/mK	0.4 [1]
Subcooling	K	5 [1]
Diameter of modules	mm	75

[1] Properties of Sodium Actate Trihydrate

[2] Fictive material

Although the used storage tank model allows a calculation of the two-dimensional heat conduction within the cylindrical PCM modules [3], the conduction in radial direction was not accounted for in the base case of the simulations. This means that no discretization of the modules was done in radial direction (only one node). This was done due to two reasons:

- In order to save simulation time.
- The module diameter used is quite small and therefore the effect of radial conduction is assumed to have only a small effect.

For additional simulations that were performed to analyze the effect of larger module diameters the heat conduction in radial direction was considered. Here a discretization of one node per cm of the module radius was used. The heat conduction in axial direction of the modules was accounted for in all simulations.

Modules with a larger diameter are particularly advantageous for the big tanks, because the necessary number of modules, which would otherwise be very large (compare Table 1), can be strongly reduced.

4 Simulation Results

The simulations were performed as annual simulations with the different configurations described above. Especially for the cases with a high solar fraction it was necessary to simulate several months (or even years) in advance in order to get the right starting conditions for the actual simulation year. For every simulated case it was therefore controlled, whether the conditions at the start and at the end of the simulation year are in good agreement.

The performance indicator that is used to evaluate the results are the ***fractional energy savings*** (also referred to as ***solar fraction***) of the system. These are calculated according to equation 1 using the heat provided by the auxiliary heater (aux) and the total useful heat consisting of the heat for space heating (SH) and for the preparation of domestic hot water (DHW).

$$f_{sav} = 1 - \frac{Q_{aux}}{Q_{SH} + Q_{DHW}} \tag{1}$$

The results for the configurations with water and with a volume fraction of 50 % of Sodium Acetate Trihydrate in the tank (latent heat = 220 kJ/kg) are shown in Fig. 4.

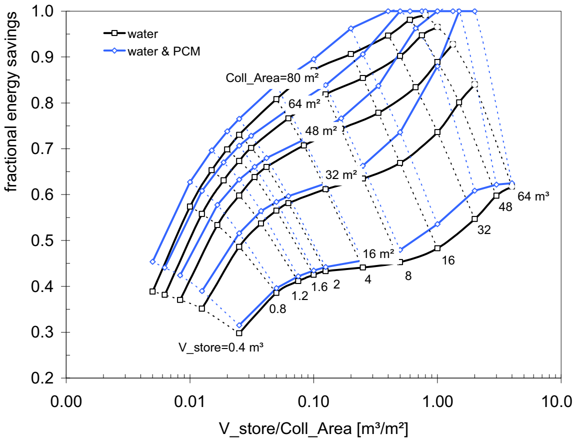


Fig. 4: f_{sav} with and without PCM in the tank (50 % volume fraction, Δh=220 kJ/kg)

The integration of the PCM results in an improvement of the fractional energy savings for all configurations. However, for small collector areas and small storage volumes – and thus for relatively low solar fractions – the improvement is not very pronounced. For higher solar fractions, that tend towards seasonal storage, the advantage increases. For example the configuration with 32 m² collectors and a storage volume of 32 m³ with PCM achieves a better result than a system with the same collector area and a 64 m³ water tank. Additionally, the results of some configurations show that a solar fraction of 100 % is possible with 2-3 times smaller storage volumes compared to water tanks.

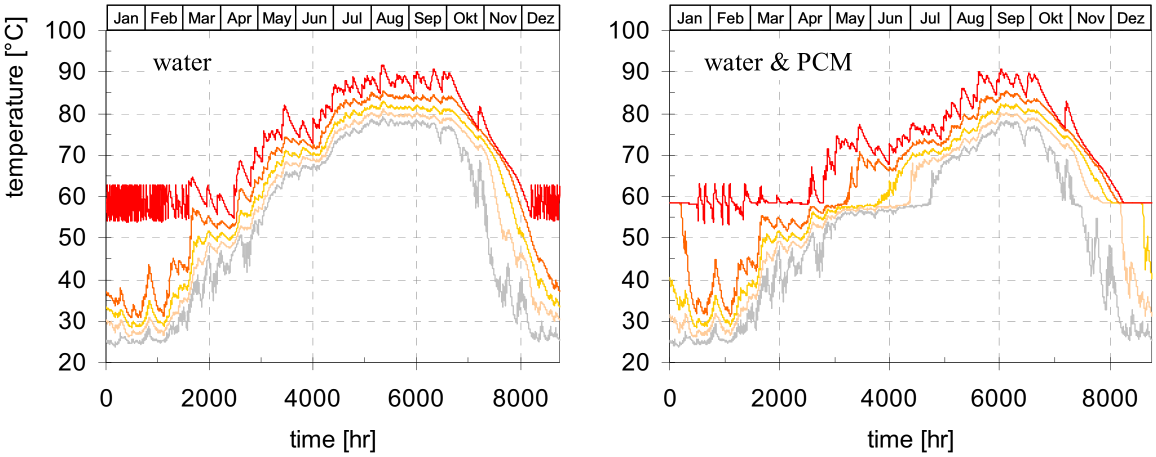


Fig. 5: Configuration with 32 m² collector area / 32 m³ storage volume: Evolution of the water temperatures in the storage tank in the course of the year in five different heights (from the top to the bottom); Left: water tank; Right: water & PCM tank

Fig. 5 shows the evolution of the water temperatures over the year inside the storage tank for the configuration with 32 m² collectors and a storage volume of 32 m³. It can be seen that in the case with the water tank the temperature at the top drops below the on-temperature of the auxiliary approximately at hour 8000. After that the auxiliary is covering a large part of the demand until April, when the storage temperature increases strongly due to the solar input. In the case with PCM (Fig. 5, right side) the auxiliary does not have to switch on before the end of January, as the water temperature can be kept warm for a longer period of time by the PCM. In this case a solar fraction of 88 % is reached with the water & PCM tank compared to 74 % with the water tank.

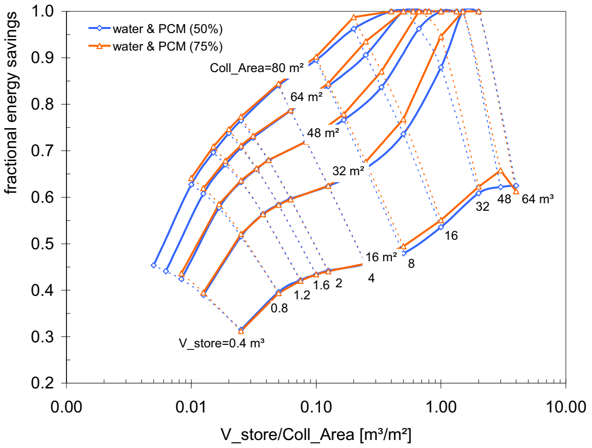


Fig. 6: f_{sav} with different volume fractions of PCM in the tank (50 % and 75 %) (Δh=220 kJ/kg)

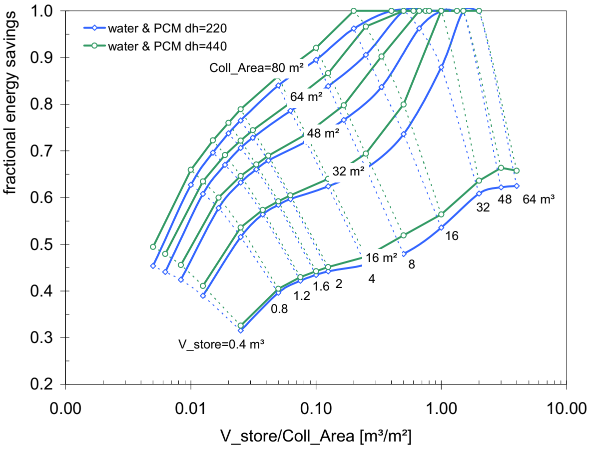


Fig. 7: f_{sav} with the real PCM (Δh=220 kJ/kg) and the fictive PCM (Δh=440 kJ/kg) (50 % volume fraction)

If cylindrical modules are used in a cylindrical tank a higher volume fraction of PCM than 50 % is possible. The maximum fraction depends on the diameter of the modules in relation to the diameter of the tank. In the here used configuration it should be 75 %.

Fig. 6 shows the results that were obtained from the simulations performed with a PCM volume fraction of 75 % compared to 50 %: While there is little to no effect for relative small tanks and collector areas, the results improve for larger tanks.

If the assumption is used, that the PCM has a 2 times higher latent heat (440 kJ/kg), the results improve as shown in Fig. 7. Especially for higher solar fractions the increased latent heat results in an improvement, due to a prolonged period of time, in which the auxiliary does not switch on in winter. However, this is of course a theoretical consideration as such a material does not exist.

4.1 Module diameter

As mentioned above, the module diameter that was used for the simulations shown above was relatively small. Due to the small diameter and in order to save simulation time the heat transfer in radial direction inside the modules was not considered.

Additional simulations should show the effect of larger diameters of the PCM modules, this time taking into account the heat transfer in radial direction. Fig. 8 shows the results for a collector area of 48 m² and a storage volume of 16 m³. For all configurations the diameter and the number of the modules was chosen in a way to result in a PCM volume fraction of 50 %. The results show that up to a diameter of 400 mm there is almost no change in the solar fraction. With this diameter the number of modules reduces from 293 to 10 compared to the original configuration. With larger diameters the solar fraction begins to decrease, as the limited heat transfer into and out of the PCM starts to be a disadvantage. It has to be mentioned that the assumed thermal conductivity of the PCM material is relatively low (though realistic). It is assumed that an enhancement of the thermal conductivity of the material by using certain additives like e.g. graphite (compare [7], [8]) would result in an improvement also for larger diameters.

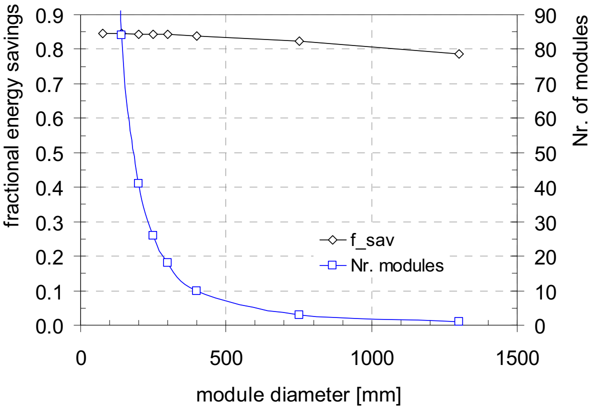


Fig. 8: f_{sav} using different module diameters (48 m² collectors, 16 m³ storage, 50 % PCM fraction, Δh=220 kJ/kg)

In general it has to be noted, that the requirement for a high thermal conductivity and/or a small module diameter is strongly reduced if the necessary discharge load is low in relation to the tanks volume. This is the case for the larger tanks in the application shown here. The necessary discharge load is normally never higher than 30 kW, which occurs when a bath tub is filled with a relatively high flow rate. Then it is a strong difference for the specific discharge load whether the tanks volume is e.g. 1.2 m³ (25 kW/m³) or 32 m³ (0.94 kW/m³).

5. Conclusions and Outlook

The simulations performed in this work show an improvement of the solar fraction of a solar combisystem when PCM is incorporated into the water tank of the system. The improvement is much more pronounced for configurations with high solar fractions, tending towards seasonal storage. According to the simulation results a solar fraction of 100 % is possible with much smaller storage volumes compared to water tanks.

The diameter of the PCM modules can be chosen relatively large for configurations with a high solar fraction, where the tank is large compared to the maximum heat load, which also reduces the necessary number of modules and therefore the cost.

The question is whether the use of PCM for heat storage in solar combisystems can be competitive compared to the traditionally used sensible heat storage in water. According to the results obtained with the simulations in this work the answer for small tank volumes and low solar fractions is no. Here the advantage compared to water is relatively low. For seasonal storage of solar heat PCM shows a potential to reduce the necessary storage volume and/or collector field area strongly. However, it is questionable if this cost reduction can compensate the additional cost for the PCM and its integration into the tank. An analysis in this direction was not done in this work, but will be part of future investigations.

Acknowledgement

This work was carried out in the framework of the Austrian participation in the Energy Technology Programme of the IEA and funded by the Austrian Ministry for Transport, Innovation and Technology.

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